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Wave-forced porewater mixing and nutrient flux in a coral reef framework

Haberstroh, Paul Richard, Ph.D.
University of Hawaii, 1994
WAVE-FORCED POREWATER MIXING AND NUTRIENT FLUX IN
A CORAL REEF FRAMEWORK

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ABSTRACT

Surface waves passing over coral reef flats should induce an oscillatory motion of framework interstitial waters and, in the presence of a downward increase in porewater nutrient concentrations, may enhance through dispersion the flux of interstitial nutrients to the overlying waters and marine organisms at the reef surface. These processes were examined through the use of a cross-reef array of well point-samplers, and electronic recording of hydraulic head variations on and within the framework of a small patch reef, Checker Reef, located in central Kaneohe Bay, Oahu, Hawaii. Spectral analyses of the head time series allowed the development of two hydrological models of wave-induced chemical flux, macroscopic dispersion and megadispersion, and allowed the comparison to fluxes driven only by molecular diffusion. Wave-induced pressure head was usually measured at 1 and 2 m framework depth, although it was measured in detail over the upper meter of the fore-reef framework. Spectral analysis of the time series of pressure head variations yielded relationships between wave frequency and (1) the spectral variance of the mean normalized amplitude, and (2) the cross-spectral phase and coherence between the mean-normalized amplitude and the net head. At sediment depths of 2 m, waves with periods >2-20 s were not detected, although internal waves with periods of around 30-60 s were still present. The ranges of the calculated mean fluxes due to macroscopic dispersion for February, 1992, were 1-10 μmoles PO₄ m⁻² d⁻¹, 1-73 μmoles NO₃+NO₂ m⁻² d⁻¹, 6-41 μmoles NH₄ m⁻² d⁻¹, and 10-198 μmoles Si m⁻² d⁻¹. The mean fluxes for February 1992 by wave-driven megadispersion were 140-1540 μmoles PO₄ m⁻² d⁻¹, 60-27220 μmoles NO₃+NO₂ m⁻² d⁻¹, 640-15560 μmoles NH₄ m⁻² d⁻¹, and 1780-70170 μmoles Si m⁻² d⁻¹. The close agreement between the megadispersive fluxes and flux estimates by previous researchers using independent techniques suggests that wave-induced flux by megadispersion was the controlling mechanism driving nutrient fluxes through the framework pore space. The large difference between the modelled megadispersive flux and observed benthic chamber-derived fluxes indicated substantial (90%) autotrophic consumption of interstitial nutrients within the upper few centimeters of the framework, and at rates similar to that of the overlying reef autotrophs.
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Chapter 1. INTRODUCTION

Introduction

The exchange of materials between nearshore coastal waters and sediments can influence both the chemistry and biological productivity of overlying waters. Sediments insulate interstitial fluids from overlying water and impose limits on the rate of material exchange across the sediment-seawater interface. In addition, sediments occlude light and prevent photosynthetic activity below the uppermost sediment layers. In the relatively calm benthic systems of the deep sea the exchange of materials is slow and usually controlled by molecular diffusion (Berner 1980). The advective exchange that does occur in such sediments is due to bioturbation, the slow compaction of the sediments due to burial, and the possible intrusion of groundwater. In more well-ventilated marine sediments of nearshore waters, macrofaunal bioturbation, or "porewater-pumping", can account for approximately five times the flux due to molecular diffusion (e.g., Grundmanis and Murray 1977; McCaffrey et al. 1980). In contrast, and much less well studied, are the influences of wave-induced advection and mixing on material exchange, especially within shallow water sedimentary systems such as reefs and sandy beaches.

It has long been viewed a paradox that coral reef communities can apparently maintain between 100-to 1000-fold greater biomass, and 10-fold greater areal productivity than planktonic communities of the surrounding, nutrient (N and P) impoverished oceans (Lewis 1977). Most studies within the last decade, however, have demonstrated that while the net production of organic material is not high compared to other marine ecosystems, gross production rates are relatively high because of the high biomass and, presumably, efficient mechanisms for recycling nutrients (Crossland et al. 1991). Wave-driven exchanges may be particularly important within coral reef systems if such fluxes of essential microbially-regenerated nutrients are rapid enough to sustain autotrophic production and physical growth of the upper reef.
Coral reefs are formed primarily from calcium carbonate precipitation associated with the growth of hermatypic corals and many other calcifying organisms (Gladfelter 1985). The continuous cycles of coral growth, accretion, and destruction result in the construction of fringing-, patch- or barrier-reef formations. Growth of coral communities is limited to the euphotic zone of continental margins and shelves, around islands, and their embayments. In addition, coral reef growth on slowly subsiding seamounts can lead to the formation of isolated atolls. The growth of coral reef communities on the energetic periphery of most reefs usually results in the accumulation of particulate debris and carbonate sands within the relatively lower-energy backwater areas, typically forming lagoons and sand flats (Roberts 1980).

The primary producers of coral reefs include not only zooxanthellae and cyanobacteria symbiotically associated with corals and reef sponges, but also various fleshy macroalgae, turf algae, coral mucus-microlayer algae, interstitial algae, and, to a lesser extent, phytoplankton species (Gladfelter 1985, Paul et al. 1986). The term "turf algae" refers to a complex association or community of small (<2 cm tall) filamentous benthic algae of diverse taxonomic status which form matlike structures over substrata (Dahl et al. 1974; Morrissey 1980, 1985; Hackney et al. 1989). Coral reef turf assemblages are among the most productive algal assemblages (Adey and Steneck 1985; Carpenter 1985, 1986), with enhanced primary productivity when subject to oscillatory as compared to vortical fluid flow (Carpenter et al. 1991). Previous studies indicate that reef autotrophs are likely to exist in close association with heterotrophic bacterial communities (e.g. Laycock 1974; Cundell et al. 1977). Protozoan, meiofaunal, and macrofaunal grazing on bacterial and microalgal populations may also influence microbial distribution and rates of nutrient cycling (Hansen et al. 1987).

The observation that coral reefs are apparently more productive than the surrounding oligotrophic ocean led many investigators to conclude that inorganic nutrients were efficiently retained and recycled within coral reef communities (Odum and Odum 1955; Pomeroy 1970; Johannes et al. 1972; Pomeroy et al. 1974). Various sources and mechanisms of nutrient flux have been expounded over the years, and it is likely that
they all play an interactive role in supporting coral reef autotrophic productivity. The physical isolation of many reefs led some investigators to hypothesize that the surface ocean is the principal source of nutrients for primary production and that nutrient recycling mechanisms were primarily biological interactions occurring on the exterior of the reef framework (Pomeroy 1970; Muscatine and Porter 1977; Meyer and Schultz 1985 a,b; Hansen et al. 1987; Hamner et al. 1988). Others recognized that nutrients could be provided from more hydrographic processes or as the result of the particular geographical location and spatial isolation of a coral reef. These hydrographic nutrient sources include groundwater (D'Elia et al. 1981, Lewis 1987), terrestrial runoff (Marsh 1977) upwelling (Andrews and Gentian 1982) and a more recent concept, "endolithic upwelling", which describes the geothermal circulation of deep oceanic waters penetrating porous reef carbonates and ascending through atoll flanks by thermo-convective advection (Rougerie and Wauthy 1986, 1993; Rougerie et al. 1991).

The interiors of reef frameworks were considered to be relatively abiotic sites where inorganic processes controlled the deposition of fine-grained material and the precipitation of carbonate cements (Alexandersson 1969, Ginsburg and Schroeder 1973, McIntyre 1977, Ginsburg 1983). This viewpoint persisted despite DiSalvo's (1971) early investigations of opened coral heads, revealing blackened reduced zones that were obviously the result of microbially-mediated, anaerobic diagenesis. In the past two decades many biogeochemical studies have demonstrated the common existence of nutrient-rich, oxygen-depleted, low pH interstitial water within the framework of coral heads and coral reefs (Zankl and Müller 1977; Andrews and Müller 1983; Buddemeier et al. 1983; Risk and Müller 1983; Szmant-Froelich 1983; Sansone 1985; Buddemeier and Oberdorfer 1986; Ferrer and Szmant 1988; Sansone et al. 1988, 1989; Tribble et al. 1989, 1990). Similar biogeochemical conditions have been shown to exist in marine lithified carbonates ranging from active reefs, to buried Pleistocene reefs, to large-scale carbonate platforms (Sansone et al. 1990; Rougerie and Wauthy, 1993). Coral reefs can therefore be viewed as a sedimentary matrix, with various aerobic and anaerobic microbial communities competing and interacting within the interstitial cavities of the framework. The definition of the outer boundary of reefs, which is inclusive of the
above-described microbial habitats within the reef framework, is "the bottom of the photic zone or transition to < 80% reefal sediments (whichever comes first) surrounding structures of coral reef framework which support a living veneer of predominately (> 50%) tropical organisms" (Crossland et al. 1991).

Various authors (Andrews and Müller 1983, Atkinson 1988), however, caution that while nutrient concentrations of reef interstitial water (RIW) may be high, the net flux through framework interstitial spaces may be controlled by molecular diffusion or, at best, a very slow advection of water through the spaces. High concentrations of framework nutrients may not necessarily imply conditions for fast turnover of nutrients, or high specific growth-rates by sedimentary bacteria (Atkinson 1988). Instead, elevated concentrations of interstitial nutrients may be the result of net mineralization and not net growth (Corredor and Capone 1985; Williams et al. 1985 a,b).

Atkinson (1988) argued that there is probably sufficient flux of nutrients for reef autotrophs from the constant flow of water and its constituents over the reef. Since benthic reef autotrophs are apparently composed of species with low overall growth rates and biomass with much higher mean C:N:P ratios than pelagic autotrophs, 550:30:1 vs. 106:16:1, respectively, (Redfield et al. 1965; Atkinson and Smith 1983), reef autotrophs may simply not require as high a nutrient flux to sustain growth and biomass as do phytoplankton (Atkinson 1981). Phosphate uptake rates in overlying seawater (OSW) of reef flats have in any case been found to be very low relative to the flux of water and dissolved phosphate across reef flats of Disappearing Island, Indian Ocean, and Kaneohe Bay, Hawaii (Atkinson 1987; Atkinson and Smith, 1987). Atkinson estimated that given an average flow of water over a typical reef flat of 0.6 m³ s⁻¹ m⁻¹ of reef front, and an average P concentration of 0.2 mmol m⁻³, the delivery rate of P is approximately 20 mmol P m⁻² d⁻¹ (Atkinson et al. 1981; Atkinson 1987). The delivery rate of P was over an order of magnitude higher than most P uptake approximations from the overlying water column by reef flats, which range from 0.4-1.0 mmol P m⁻² d⁻¹. Hopkinson et al. (1987) also found very low nutrient (NH₄) uptake in the water column over the relatively well-flushed Davies Reef.
Atkinson and Smith (1987) further showed that the rates of alkaline phosphatase in a variety of benthic algae and a mixed reef community were high enough to provide a major flux of phosphate through the remineralization of dissolved organic phosphorous. Sufficient flux of dissolved nutrients may result from the steady onflow of surrounding waters, yet it is possible that measured uptake rates might be obscured by the release from the sediments of inorganic (and organic) compounds containing N or P. Thus, while significant biological uptake can possibly occur, OSW nutrient concentrations may not be observed to decrease across a reef flat and low net uptake would be inferred.

Comprehensive studies of total-reef net metabolism indicate that high rates of gross reef photosynthetic fixation are approximately matched by high rates of gross respiratory consumption, resulting in low rates of net community organic carbon production (Kinsey 1979, 1985; Smith 1988). The gross community production and respiration of most reef flats is around 7 g C m\(^{-2}\) d\(^{-1}\) (Kinsey 1985). Tribble et al. (1989) estimated that the organic carbon respiration (0.5 g C m\(^{-2}\) d\(^{-1}\)) of the upper meter of the Checker Reef framework represents about 10% of the gross community production, which is around 5.3 g C m\(^{-2}\) d\(^{-1}\) for the Kaneohe Bay barrier reef (Kinsey 1979). Tribble et al. (1989) concluded that the upper meter of the Checker Reef framework is a significant zone of organic decomposition, nutrient recycling, and perhaps nutrient efflux to the overlying water column.

Waves wash over large areas of these reef flats, inducing a variety of currents and pressure or "head" gradients within the sedimentary bed (Buddemeier and Oberdorfer, 1988). As will be explained in Chapter 3, the oscillatory head gradient of passing waves in the shallow waters of a reef flat may theoretically result in the energetic dispersion of dissolved interstitial constituents, yet there is a lack of field data corroborating such wave-driven fluxes. Nutrient requirements of benthic algae which are in intimate contact with the sediments may be satisfied by the uptake of nutrients supplied from sediments by this wave-driven dispersive flux. The interstitial and turf algae, growing over the large expanses of the carbonate sand flats typical of many patch reefs, could theoretically receive most of their nutrients from such wave-driven sedimentary fluxes. The uptake of
nutrients by interstitial and turf algae may actually prevent a significant nutrient flux to other reef autotrophs.

The salient issue therefore is whether the magnitudes and the length scales over which these putative sedimentary fluxes may obscure the measured net nutrient uptake across a reef flat. Clearly, the development of methods which demonstrate high RIW mixing rates would be useful since high turnover rates of sedimentary nutrients would be clearly implicated. The aims of this dissertation are to understand how waves may regulate sedimentary biogeochemistry and nutrient fluxes on a coral reef flat, and the degree to which such processes support primary production. Unequivocal measurements of framework nutrient fluxes are clearly necessary in order to evaluate their relative degree of support for reef autotrophic productivity.

Study Site Description

Checker Reef, a small lagoonal patch reef located in Kaneohe Bay, Oahu, is one of numerous patch reefs lying behind an extensive system of sandy shoals that form a complex "barrier-reef" across the mouth of Kaneohe Bay (Fig. 1.1). The close proximity of the Hawaii Institute of Marine Biology on Coconut Island (Moku O' Loe) permits easy access. A cross-reef array of well point samplers has been in place for several years and has been used to acquire RIW from framework depths of 1-4 m (Sansone et al. 1988).

Located in the central section of the bay, Checker Reef is relatively sheltered from the large winter swells characteristic of the N-NE windward coast of Oahu, Hawaii (Fig. 1.2). The average rainfall over the semi-tropical bay is approximately 125 cm yr⁻¹, occurring mostly in the winter and spring, and winds are predominately NE trades, sustained by high pressure areas to the north of the Hawaiian Islands (Bathen 1968; Smith et al. 1981; Morrissey 1985). Shimada (1973) concluded that the strong local tradewinds produce more wave energy than do distant storms in the north and south Pacific and about twice the energy of weak local tradewinds. Strong and variable S-SW
"Kona" storms, generated by low pressure systems to the south of the Hawaiian Island chain, may reverse the usual wind direction. The energy of the Kona winds is usually less than the tradewinds (Shimada 1973). The mean bay tide range is 63 cm, with a maximum amplitude of 112 cm (Bathe 1968). Tides are predominantly semi-diurnal, ranging from a slightly diurnal inequality to almost diurnal at certain times (Bathe 1968; Smith et al. 1981). Currents in the bay are weak and depend chiefly upon the wind direction and tides. Bathe (1968) concluded that a rising tide directs weak currents across the reef from the N-NE direction; these currents reverse with the falling tide. The Checker Reef flat can be exposed during low spring tides, although the surface level of the reef is on average about 0.35 m below the mean bay sea level.

Checker Reef is irregularly-shaped, 780 m long in the N-S direction and 460 m wide. The total area of the patch reef is $1.855 \times 10^5$ m$^2$ (Morrissey 1985). The aerial schematic of the reef shown in Figure 1.1 illustrates how the outer windward eastern side is almost uniformly convex and even, and the inner leeward side is strongly lobate with small embayments. Rising steeply (~45°) to 12 m above the floor of Kaneohe Bay, the reef is composed of coral and coral rubble loosely cemented together. The sediments of the Checker Reef flat have not been systematically examined, e.g., for grain size or sorting, although Morrissey (1985) does describe and map large areas covered with algal communities, rubble and sand, or simply bare sand banks. The lower half of the slopes of Checker Reef are devoid of live coral and covered with muddy calcareous sediments. The patch reef is characterized by two, nearly oval, enclosed pools, about 12 m deep. These pools may be the result of the gradual isolation of part of the lagoon following growth and coalescence of the reef. The embayment on the NW edge of the reef may represent an intermediate stage in pool formation.

Previous research of Bathe (1968), Shimada (1973), and Tribble (1990) generally concluded that waves from outside the bay, as well as those developed locally across the fetch of the bay, direct most of their energy to the "fore-reef" station A (Fig. 1.1). Waves that derive from outside the bay are usually the result of longer-period (e.g., ~1-5 min) gravity waves generated by distant storms in the north Pacific Ocean and
from sustained N-NE trade wind-driven swell. Waves coming from outside the bay are dampened by interaction with the barrier reef formation, which defines the outer perimeter of the bay and by various patch reefs further out in the bay than Checker Reef. Gusty trade winds can also generate short-period (1-60 s wave period) gravity waves across the NW fetch of Kaneohe Bay and onto the outer reef. Station E, located on the back reef, is sometimes subject to the above-mentioned N-NE waves due to partial refraction around the patch reef (personal observation). The mid-reef stations C and D are relatively more protected than either A or E. Wave height is generally greatest at the fore-reef, but usually does not exceed one meter under even the roughest conditions and most extreme low tides (Tribble 1990). There are also periods of low wind and swell, when the reef is covered by dead calm water. The S-SW Kona winds can blow across the small fetch of Kaneohe Bay that exists between Oahu island and Checker Reef and may direct short-period waves across the inner reef from the S-SW direction.

Specific Hypotheses and Objectives

This study focuses on the uptake and sedimentary distribution of reduced endproducts resulting from early diagenesis, the development of reliable methods to monitor water movement within the framework, and the effect this RIW movement may have on nutrient distributions and fates. As Atkinson (1988) noted in his review on nutrient limitation in coral reefs: "As yet, there are no adequate studies that compare the rate of nutrient uptake from the interstitial sources of nutrients to the rate of nutrient uptake from the water column." This research seeks to combine geochemical and hydrological approaches to address the larger question: "What are the rates of diagenetically associated fluxes between the Checker Reef framework and the neighboring environments?" The overall goals of this study are to quantify such rates and identify possible hydrodynamic and microbial mechanisms for nutrient cycling in a coral reef system.
In this dissertation I address the following hypotheses:

1) Wave-driven mixing and concomitant flux by dispersion in the upper two meters of the reef framework is a function of wave direction and type, overlying water depth, and particular location on the reef flat.

2) The diagenetic reactions within the upper meter of the framework are influenced by the wave-driven mixing, and the degree to which such mixing varies is a function of wave direction and type, overlying water depth, and the particular location on the reef flat.

3) Nutrient fluxes from the framework by wave-driven dispersion exceed nutrient fluxes driven strictly by molecular diffusion.

4) Wave-driven fluxes from the framework are a significant source of recycled nutrients to the overlying autotrophic communities.

5) Wave-driven fluxes from the framework are comparable to previous measurements of nutrient supply from on-flowing waters.

6) Chemical fluxes by wave driven dispersion may be empirically-determined by methods typically employed to directly-measure fluxes by molecular diffusion.

With these fundamental hypotheses in mind, I:

1) extended the spatial scale of the interstitial water sampling at Checker Reef, Oahu to sample in detail the upper 1 m of the reef framework in order to examine the chemical gradients just below the reef-seawater interface;

2) examined the sedimentary characteristics of the upper 5-15 cm of the reef flat in order to further delineate the interstitial pore sizes at the sediment-seawater interface;
3) directly measured, using benthic chambers, the fluxes of diagenetic reactants and products between the reef framework and the surrounding environment at several points across the reef;

4) collected data to construct two hydrological models of dispersive mixing of interstitial waters within the reef, and generated two classes of wave-induced nutrient flux;

5) continued measurements of the spatial and temporal distribution of inorganic and organic diagenetic reactants and products within the reef; and

6) used these concentration data to calculate and compare gradient-driven fluxes by molecular diffusion, and by the two hydrological models of wave-induced mixing, in order to estimate the degree to which the various nutrient flux mechanisms support benthic autotrophic productivity of Checker Reef.
Figure 1.1. Location of Checker Reef. Large well point locations are identified by letters A-E from framework depths of 1-4 m (Sansone et al., 1988).
Figure 1.2. Waves approaching Kaneohe Bay, Oahu, Hawaii. Modified from Moberly and Chamberlain (1964) and Shimada (1973).
Chapter 2. BIOGEOCHEMISTRY OF RIW IN SHALLOW CORAL REEF SEDIMENTS

Introduction

In this chapter I will examine the chemical composition of RIW in order to understand the diagenetic processes occurring within coral reef frameworks. The net dissolved end products of early diagenesis accumulate as RIW is transported through the framework. Consumption of the end products occurs by biotic uptake and abiotic (mineral) adsorption/exchange processes. Assuming that these processes are at steady state, the RIW chemical composition can be interpreted as a signature of the dominant diagenetic processes occurring in the sediments. The net effect of these processes will be to control the concentrations of inorganic nutrients within the pore spaces near the sediment-seawater interface, and thus influence the efflux of nutrients by physical forces to be described in Chapter 3 of this dissertation.

Microbial Reactions Within the Reef Framework

Previous work by Tribble and others has shown that the carbon and nutrient compositions of interstitial waters of Checker Reef are dominated by the oxidation of organic matter. Tribble et al. (1989) acquired porewater from sediment depths of 1 m and greater and thus his conclusions do not consider reactions occurring within the upper meter of the framework. Using a stoichiometric mass-balance model of RIW, and assuming steady state, Tribble et al. (1989) described the predominant diagenetic reactions as the following:

Oxic Respiration: \( \text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} \) \hspace{1cm} (2.1)

Denitrification: \( 5\text{CH}_2\text{O} + 4\text{NO}_3^- + 4\text{H}^+ \rightarrow 5\text{CO}_2 + 2\text{N}_2 + 7\text{H}_2\text{O} \) \hspace{1cm} (2.2)
Sulfate Reduction: \[2\text{CH}_2\text{O} + \text{SO}_4^{2-} \rightarrow 2\text{HCO}_3^- + \text{HS}^- + \text{H}^+\] (2.3)

Methanogenesis: \[2\text{CH}_2\text{O} \rightarrow \text{CO}_2 + \text{CH}_4\] (2.4)

Carbonate Precipitation/Dissolution: \[\text{CaCO}_3 + \text{H}^+ \rightarrow \text{HCO}_3^- + \text{Ca}^{++}\] (2.5)

where \(\text{CH}_2\text{O}\) represents average organic matter. Oxic respiration and sulfate reduction are the dominant modes of organic matter oxidation and occurs despite the lack of significant sulfate depletion (Tribble 1990). Dissimilatory nitrate reduction, or denitrification, occurs under microaerophilic conditions, but Tribble (1990) did not consider this metabolism a major pathway of organic matter oxidation. \(\text{NO}_3\) is used by interstitial denitrifying-bacteria as an alternative terminal electron acceptor, which generates \(\text{N}_2\) and may result in a loss of nitrogen from the system (Smith 1984). Methane production occurs in the absence of sulfate depletion in the bulk RIW, in contrast to what is normally seen in diffusional-controlled sediments, and carbonate dissolution occurs in association with anaerobic diagenesis and decreasing pH (Tribble 1990).

Many RIW constituents exist in thermodynamic disequilibrium: oxygen and sulfate coexist in many places with sulfide, methane and ammonium (Sansone et al. 1989). This disequilibrium has been explained by invoking the presence of relatively stagnant, anaerobic microenvironments (or "microzones"), ranging in size from sub-millimeter to tens of centimeters, where organic matter is oxidized and carbonate material is dissolved. Metabolic endproducts (e.g., phosphate, ammonium, methane) are hypothesized to diffuse out from the microzones into the more advectively-dominated interstitial portions of the framework. The concept of sedimentary microenvironments was developed by Jorgensen (1977) to explain the coexistence of both sulfate-reducing (\textit{Desulfovibrio} spp.) and sulfide-oxidizing (\textit{Beggiatoa}) bacteria in sandy intertidal sediments. Sansone et al. (1990) confirmed the structure necessary for establishment of microbial microenvironments by examinations of near-surface reef rock with scanning electron microscopy and energy dispersive X-ray fluorescence spectroscopy. Numerous dissolution
cavities were found to contain mineralogical assemblages, such as pyrite framboids, characteristic of highly reduced conditions.

Actively metabolizing marine bacteria can induce the precipitation of calcium carbonate, with the exact form dependent upon the diffusion characteristics of the medium (Buczynski and Chafetz 1991). When the ion diffusion rate is relatively high, aragonite forms; when it is relatively low, calcite is precipitated. The Checker Reef framework maintains itself at aragonite saturation, with the aragonite probably acting as a solid phase buffer by dissolving in response to acids (e.g., \( \text{H}_2\text{CO}_3 \), \( \text{H}_2\text{S} \)) released during anaerobic decomposition (Tribble 1993).

Microbial activities are likely to be more dynamic and operating at higher rates in the upper meter of the reef sediments than at greater sediment depths. This is because the influence of waves on RIW movement, and presumably the degree of organic matter supply and RIW oxygenation, is likely to be more energetic in the upper meter of the framework than in deeper areas, and at the fore-reef rather than the mid- to back-reef. Since many of Tribble's (1993) conclusions were constrained by the inability to sample the upper meter of framework, a major goal of the research for this dissertation was to examine in detail the fluctuations over time, if any, of RIW chemistry within the upper meter of the framework. As will be explained in Chapter 3, the chemical fluxes across the sediment-seawater interface depend in part upon the chemical gradients existing at the sediment-seawater interface, which presumably could vary with the time scale of the variability of the intensity of wave-induced mixing.

Nitrogenase activities are likely to be enhanced in the anaerobic microzones existing in the predominantly aerobic areas of the upper Checker Reef framework, given that there is a sufficient supply of labile organic matter. Nitrogen \((\text{N}_2)\)-fixation on and in reef sediments is a common feature of almost all coral reefs (Wiebe et al. 1975; Paerl et al. 1981; Corredor and Capone 1985). \(\text{N}_2\)-fixing organisms include autotrophic cyanobacteria that occur as mats or epiphytes (Capone 1988) and heterotrophic bacteria inhabiting coral sediments (Hanson and Gunderson 1976). \(\text{N}_2\)-fixation is usually inhibited
by high O$_2$ and NH$_4$ concentrations and limited by organic substrate availability. Coral sands allow the development of microzones wherein N$_2$-fixation may be found to be enhanced (Patriquin and Knowles 1975). Paerl and Prufert (1987) observed enhanced nitrogenase activity in nutrient-enriched microenvironments of benthic detritus. Nitrogenase activity has been found to be significantly higher in fine grained reef carbonate sediments than in coarser grained sediments, and was apparently controlled by organic substrate availability (O'Neil and Capone 1989). O'Neil and Capone (1989) also found O$_2$ availability to have a variable effect on N$_2$-fixation rates, suggesting that physical disturbance of sediments during their core sampling influenced the microzonation necessary for N$_2$-fixation. N$_2$-fixation can account for up to 50% of the NH$_4$ production in the upper 2 cm of coral reef sediments (Capone et al. 1992). Nitrogen fixation must be considered a potentially substantial source of nitrogen to shallow sedimentary ecosystems such as reef flats if microzonal habitation is preserved over sufficient time scales.

The results of past biogeochemical studies of other reef and sandy sediments (Wiebe 1985; Williams et al., 1985 a,b; Hopkinson 1987) suggest that the large ammonium pools at 1-2 m sediment depth in the Checker Reef framework (Tribble 1990) may be microbiially oxidized for chemical energy in the upper meter of the framework. This may occur by the sequential action of two separate groups of specialized and interacting autotrophic microorganisms inhabiting the more oxygenated portions of sediment. The chemolithotrophic oxidation of ammonium to nitrite:

$$\text{NH}_4^+ + 1-1/2 \text{O}_2 \rightarrow \text{NO}_2^- + 2\text{H}^+ + \text{H}_2\text{O} \quad (2.6)$$

is accomplished by nitrosifying bacteria such as *Nitrosomonas* (Brock 1979). Nitrite oxidation to nitrate:

$$\text{NO}_2^- + 1/2 \text{O}_2 \rightarrow \text{NO}_3^- \quad (2.7)$$
results from the chemolithotrophic action of nitrifying bacteria such as *Nitrobacter* and *Nitrococcus*. Nitrosofying and nitrifying bacteria are all inhibited by high ammonium concentrations. In addition, under low oxygen concentrations nitrifiers produce significant quantities of N₂O (Jorgensen *et al.*, 1984). Thus, nitrification under microaerophilic conditions may also result in a loss of fixed nitrogen in the form of the gas N₂O.

In addition to the above pathways, nitrate and nitrite can also be assimilated by interstitial bacteria and autotrophs (Wiebe 1985). Therefore, nitrate and nitrite may form concentration maxima as a balanced function of available oxidants (dissolved oxygen) delivered by wave action from above the sediment-seawater interface, the supply of accumulated ammonium from greater sediment depths, and the competitive interactions of the various nitrifying-, nitrosofying-, and denitrifying-bacterial communities. The results of Capone *et al.* (1992) indicate the NH₄ and NO₃ porewater pools of the upper 2 cm of coral reef sediments were highly dynamic, with turnover times of substantially less than one day. The vertical porewater concentration profiles of the inorganic nitrogen species may likewise be expected to vary drastically over several days. While NO₂ is an intermediate in both nitrification and denitrification, its presence may not necessarily be observed if it is consumed as rapidly as it is produced. Similarly, the ability of these competing microbial communities to control the chemical distributions within reef sediments is likely to vary according to OSW chemical composition and the relative impact of wave-induced advection on various areas of the patch reef.

*Checker Reef: Framework Organic Matter Sources*

The sources of organic matter driving diagenetic reactions within the framework include benthic plants, plankton and terrestrial detritus (Entsch *et al.*, 1983, Tribble *et al.*, 1989, Tribble 1990). The decomposition of organic matter from different sources and with varying molecular compositions within the framework should dictate variation in the end-product composition of RIW. If chemical fluxes out of the sediments are demonstrated to be relatively high, then the end-product composition of RIW should reflect the relative availability of various nutrients for autotrophic consumption.
Checker Reef is typical of many inshore patch reefs in which fleshy macroalgae are often the dominant algal component (Fig. 2.1). Offshore reefs, in contrast, are characterized by encrusting calcareous algae and turf algae, and fleshy macroalgae are rare. Morrissey (1985) assessed the biomass distribution, primary production, detritus production and degradation of fleshy macroalgae and turf algae on Checker Reef. Morrissey distinguished between turf algae, a matlike, multi-species, benthic algal community, and the more easily characterized fleshy macro-algae of various species. On this basis, she found that turf algal communities had a higher rate of primary productivity per unit area (1.8-2.6 g C m\(^{-2}\) d\(^{-1}\)) than the dominant species of fleshy macroalgae, the rhodophyte Acanthophora spicifera and the phaeophyte Sargassum echinocarpum (0.5-0.6 g C m\(^{-2}\) d\(^{-1}\)). However, when algal type abundance and distribution are considered, A. spicifera is a major contributor (60 g C d\(^{-1}\)) to Checker Reef primary productivity. Turf algae grow within a more restricted zone on the reef front and outer reef sand flats, and thus have a smaller reef primary production (22 g C d\(^{-1}\)). Macroalgal particulate detritus was exported from the reef during storm events and was estimated to be 3-51% of the annual macroalgal net productivity. However, most detrital particulates appear to remain within the reef system, where they are probably microbially degraded and their nutrients regenerated.

Organic matter in the ocean has an average C:N:P molar ratio of 106:16:1 (Redfield et al., 1965) and its decomposition to inorganic nutrient end products results in a dissolved inorganic N:P ratio of 16:1. Decomposition of benthic plant matter, which has a higher average C:N:P ratio of 550:30:1 (Atkinson and Smith 1983), would result in an inorganic N:P of 30:1. Tribble et al. (1989) utilized the differences between the C:N:P ratios of benthic and planktonic organisms, and the inorganic N:P ratio of Checker RIW (21:1) compared to that of OSW, as the basis for estimating that the organic matter undergoing biogeochemical transformation was derived from about half benthic and half planktonic materials. Tribble et al. (1989) used this N:P ratio to scale the C flux after correcting for carbonate flux, and determined a N flux. The difference between their predicted N flux based on their dissolved inorganic carbon flux, and their calculated N flux based on residence time estimates and a 0-1 m sediment nutrient
gradient was a reflection of the fact that the phosphate supply needed to maintain reef microorganisms cannot be generated *in situ* like fixed nitrogen.

Denitrification within the framework may result in the loss of fixed nitrogen as N\(_2\) (see Equation 2.2) or N\(_2\)O. However, this N loss can be counteracted by nitrogen fixation in other areas of the reef framework which receive relatively little advective import and in which anaerobic microzones presumably develop. Nitrification can only proceed with an adequate oxygen supply, which should be enhanced within the framework at the more wave-impacted fore- and back-reef. The mid-reef areas of the framework of Checker Reef are likely to be subject to less wave-driven ventilation and should be areas of enhanced N\(_2\)-fixation compared to the fore- or back-reef framework. The two opposing processes therefore function as "negative feedback loops" to regulate the concentration of fixed nitrogen (Smith and Hollibaugh 1989). In the more well mixed upper meter of the framework, advective import of both organic matter and oxygen may result in a loss of fixed nitrogen. Inorganic N:P should therefore vary according to sediment depth, location on the reef, and the degree of wave-driven import of organic matter and oxygen. Interstitial water of the upper 10 cm from Davies Reef, Australia, sediment showed a N:P ratio ranging from 4-9 (Entsch et al., 1983). Waves should direct POM/DOM with a more planktonic origin at the reef peripheries. Benthic reef plant POM/DOM may be a more important source to sediments of the more-protected mid-reef framework, where the increased residence time of the overlying waters and, presumably, also of the mid-reef RIW, allow more accumulation of benthic plant POM and DOM and elevated microbial re-mineralization rates. Because of the above described processes, it is important to examine in detail over the upper meter of the framework the stoichiometric variation of dissolved nutrients in RIW and OSW as it relates to reef location and hydrographic conditions.

*Sediment Characteristics of the Checker Reef Flat*

Carbonate sediments in general have been well characterized for a variety of reefs, banks and shelves (Enos and Sawatsky 1981), but have yet to be examined for the
Checker Reef system. Tribble (1990) did find much a lower hydraulic conductivity at station A (13 m d⁻¹) than at the mid- to back-reef stations (40-60 m d⁻¹), and speculated that a higher degree of lithification at the seaward edge was responsible. Sediments on the seaward edge of reefs are likely to experience a much higher degree of wave-action, and concomitant transport and sorting, than at the more sheltered mid- to back reef areas.

The mean grain size of coarse, nutrient poor, oxidized sediments from a back-reef area of Tague Bay, St. Croix, U.S. Virgin Islands, decreased progressively away from the fore-reef, from 2.24φ-0.58φ or 0.66-0.33 mm (Williams et al., 1985 a,b). A more recent study by Hansen et al. (1987) of Davies Reef, Australia did, however, establish decreasing median grain size from the fore-reef (1.14 mm) to the back-reef (0.37 mm). O'Neill and Capone (1989) also found a wide range of sediment types across many different reef systems. Sediment grain size has already been mentioned as an important factor influencing N₂ fixation rates, and, as will be explained in Chapter 3, also can be used to estimate the mean interstitial pore sizes. Since chemical fluxes will be evaluated at the sediment-seawater interface, it will be necessary to examine the mean grain size distribution of those sediments closest to the interface, and the variance of this distribution as a function of location across the Checker Reef flat.

The purpose of this chapter is to examine (1) the sediment grain size distribution of the surficial sediments of the Checker Reef flat, and (2) the short (i.e., daily to weekly) and long term (i.e., monthly) variation in inorganic nutrients in OSW and RIW of Checker Reef. During the month of February 1992, samples of OSW, and RIW from sediment depths of 10, 25, 50, 100, and 200 cm were acquired from four cross-reef stations (A, C, D and E) four separate times (2/1/92, 2/6/92, 2/24/92 and 2/29/92). Wave magnitude and direction varied widely during the sampling periods. In addition to the cross-reef sampling of February, 1992, station C was sampled once during fall, 1991 (0-0.5 m only) and once during fall, 1992. Station D was sampled twice during fall, 1991, and twice during the summer of 1992 (only phosphate analyzed). Station E was sampled once in the fall, 1992. The sediment-seawater nutrient gradients will be computed from the chemical distributions described in this chapter and presented in Chapter 3. The sediment-seawater gradients and the mean grain sizes will be used in
Chapter 3 to estimate nutrient fluxes due to molecular diffusion and wave-driven dispersive mixing, and these fluxes will be compared to direct measurements of total diffusive flux conducted with benthic chambers.

Methods

_Sediment Grain Size Distribution_

Sediment samples from the upper 3-14 cm of the reef flat were acquired by use of a sand corer constructed of PVC pipe (length 15.2 cm, diameter 4 cm) with one end ground to a fine edge, and a No. 6 butyl stopper. The corer was driven manually into the sediments as far as possible, and the No. 6 butyl stopper inserted into the top of the corer and the sediments around the corer excavated until the corer could be twisted up and inverted. The sediment sample was emptied into a plastic zip-lock bag. While the sediment-penetration depth of the corer could be documented (3-14 cm), the inclusion of OSW into the corer and sediment sample could not be prevented. Since this disturbed the sediment structure of the sample, porosity determinations were not attempted. Four core samples were acquired from an approximately 2 m² area surrounding each reef station (A-E) as well as from the prominent sand patch ("SP") characterizing the region extending between stations C, D, and E, and the larger blue hole (Fig. 2.1). The sampling area of the sand patch was located mid-point on a line between station D and the edge of the central portion of the blue hole. Three sediment samples were wet-sieved through five screens, achieving a separation of the sediment into six size categories: 1) very fine- to very coarse-gravel or \( \leq -1 \phi \) (\( \geq 2-64 \) mm); 2) very coarse sand or \( 0 \phi \) (1-2 mm); 3) coarse sand or \( 1 \phi \) (0.5-1 mm); 4) medium sand or \( 2 \phi \) (0.25-0.5 mm); 5) very fine- to fine-sand or \( 3-4 \phi \) (0.06-0.25 mm); 5) silt or \( \geq 4 \phi \) (\( \leq 0.06 \) mm). In general, the silt fraction was negligible and was not saved.
Types of Well Points

A well point (or "well point sampler") is a long stiff tube with internal plumbing which, after insertion into sediment, allows the sampling of interstitial fluids. Two types of well points were used to sample reef interstitial waters:

1) Large stainless steel well points of 3.2 cm outer diameter (O.D.), previously installed and described by Sansone et al. (1988), were used to acquire RIW from 1 and 2 m sediment depths (Fig. 2.2).

These custom fabricated well points were manually driven into reef sediments by Sansone et al. (1988) in a windward-to-leeward transect (see Fig. 1.1). RIW is acquired by pumping the 0.64 cm O.D. polypropylene tubing, which extends internally through the well point down to screened segments open to the framework at either 1 m or 2 m below the sediment-seawater interface. Vertical flow down the sides of the well points was prevented by the application of underwater cement around the well point at the sediment-seawater (Fig. 2.2). The present study utilized the 1 m well point at the fore-reef (windward edge) station A, and the 1 m and 2 m well points at the two mid-reef stations C and D and at the back-reef (leeward edge) at station E. The 1 m well point at station B and the 4 m well point at station D were not sampled during this study.

2) Short, smaller well points, of 1.2 cm O.D. and 0.96 cm inner diameter (I.D.), were used to acquire RIW from sediment depths of 0.1, 0.25, and 0.5 m (Fig. 2.3). In some limited cases RIW was successfully sampled from 5 cm sediment depth (described below).

While Figure 2.2 shows only the 0.1 m small well point, the well points for acquiring porewater from framework depths of 0.05 m (limited to stations D and E), 0.25 m, and 0.5 m were similarly constructed and sampled. The small well points were constructed from seamless stainless steel tubing, and the ends were sealed with a hydraulic press and ground to a sharp edge. Twelve to fifteen 3.2 mm diameter holes
were drilled in a 1.4 to 1.8 cm wide pattern just above the chiseled point to allow RIW to enter when the well point was in the reef sediment. The well point was first sheathed with a slightly larger diameter steel pipe which prevented sediment from entering the well point as both it and sheath pipe were manually driven into the reef sediment. The sheath pipe was then removed while holding the well point in the sediment with an aluminum rod inserted into the well point, after which the aluminum rod was removed and a No. "000" rubber stopper inserted into the top of the small well point.

**Sampling the Small Well Points**

Initially, sampling of the well points was attempted by inserting a flexible polyethylene tube (3.2 mm O.D., 1.6 mm I.D.) into the well point so that one Nitex-screened end of the tube was adjacent to the drilled holes, and the other end was attached to a syringe needle (16-1/2 gauge) which had been inserted through the No. "000" rubber stopper. When this rubber stopper was inserted into the top of the well point, it formed a seal which prevented OSW from entering the well point. Attempts to withdraw sample through the needle proved unsuccessful, possibly due to the high resistance of the small diameter polyethylene tube to fluid flow, or to its tendency to get clogged with fine sand particles. Therefore, a stiff acrylic tube (9.6 cm O.D., 3.2 cm I.D.) was inserted so that one end of the tube was adjacent to the drilled holes. The acrylic tube fit snugly inside the inner diameter of the well point, with little dead volume. A one-hole rubber (Vacutainer) stopper attached to the top of the well point prevented OSW from flowing into the well point, and sealed the acrylic tube to the well point. After the RIW sample was withdrawn, the tube and stopper were removed, and a No. 000 rubber stopper was inserted into the top of the well point. This prevented OSW from flowing into the well point until the next sampling.

Efforts to sample RIW through the acrylic tube of the well point were first attempted by using a 140 ml syringe, then by using an underwater Rule 360 bilge pump, and finally by using a hand-operated vacuum pump; all of these proved unsuccessful. Thereafter, a peristaltic pump and a 3-10 m length of polyethylene tubing attached to the
respective well point tubes were used to sample RIW from both the large and small well points, essentially the same method followed by Sansone et al. (1988).

Uniform sampling protocols for pumping replicable RIW volumes were developed for both the large and small well points in order to avoid inclusion of seawater or "dead-volume" water contained within the internal plumbing of the well points, and to sample the same spherical volume of framework. Upon pumping either type of well point, a sand "plug" was easily discernable and approximately marked the boundary between RIW and the seawater in the tube. For the large well points the appearance of the sand plug initiated the collection of a 1 liter "discard"-volume, and the second liter was collected and treated as genuine RIW. This protocol is a bit more strict than that followed by Tribble (1990), who discarded only the first 200 ml before collecting the RIW sample from the large well points. If the sediment porosity at 1 and 2 m sediment depth is assumed to be 30%, the 2 liters of withdrawn water would be contained within a sphere in the reef framework having a radius of 12 cm. Since such a large radius is obviously unsatisfactory for the small well points, the sampling protocol for the small well points was established by serially collecting 180 ml aliquots of RIW for nutrient analysis (see Results for protocol)

**Orientation of Small Well Point Array**

The first small well point arrays were inserted at station D and station E on March 10, 1991. Both arrays were later repositioned as described below. The fore-reef station A array was completed September 27, 1991. The station C well point array was completed October 31, 1991. The 0.1, 0.25, and 0.5 m small well points at stations C, D, and E were arranged in a SE-to-NW line, roughly perpendicular to the prevailing NE trade wind direction and the general windward-to-leeward direction of the large well point array (Fig. 2.4 A). The 0.5 m well point was placed 60 cm from the large well point, the 0.25 m well point placed 60 cm from the 50 cm well point, and the 0.1 m well point 60 cm from the 0.25 m well point. Space limitations within the small sand patch where station A is located necessitated a more constrained arrangement for the small well
points (Fig. 2.4 B). The 0.5 m well point was placed only 30 cm from the large well point, and the 0.25 m and 0.1 m well points were placed in a line with 30 cm spacing. The orientation of the line was in a SW-to-NE, leeward-to-windward direction, with the 10 cm well point at the windward end of the array line. As previously mentioned, a 0.05 m well point was fabricated and inserted 60 cm from the 0.1 m well point along the transect line at stations D and E. However only a limited number of 0.05 m RIW samples were successfully withdrawn because the 0.05 m well point had a tendency to be easily dislodged from the sediment. In addition, the 0.05 m well point at station E was lost or removed sometime after the initial samples were withdrawn.

**Analytical Methods**

Most samples were analyzed for dissolved phosphate (e.g., soluble reactive phosphate), nitrate plus nitrite, ammonium, and silica using a Technicon AutoAnalyzer II (as modified by Ted Walsh, Analytical Services, Department of Oceanography, University of Hawaii). Samples collected during the summer of 1992 were analyzed manually only for dissolved phosphate by the standard ascorbate method (Strickland and Parsons 1968).

**Results**

**Sediment Characteristics and Size Distribution**

It was very difficult to core the sediments to a uniform depth at each reef station. Sediment samples were very difficult to obtain from the highly lithified sediments of the fore-reef station A. Maximum penetration of the corer for station A was 3 cm, for station C was 4 cm, for station D was 6 cm, and for station E was 10 cm. The corer easily penetrated the sand patch sediments to the total effective sampling-length of the corer, or a sediment depth of 14.2 cm. The mean sediment weight recovered by triplicate cores was 76 ± 28 g at station A, 94 ± 7 g at station C, 73 ± 37 g at station D, 84 ± 17 g at station E, and 204 ± 16 g at the sand patch. Carbonate sands consisting of various
sizes of coral, mollusc and crustacean shell, coralline algae, and meiofaunal tests characterized part of the sample from each station and the sand patch.

Figure 2.5 shows the relative distribution of the sediment size fractions for each reef station and the sand patch. Station A sediments were poorly sorted and frequently characterized by large (10-60 mm) coral fragments ("rocks"). In general, the mean grain size progressively decreased as a function of distance from the front of the reef ($r^2 = 0.7$, $n=5$, $p<0.05$), defined as a point 10.8 m N-NE from the station A well point, though this correlation was not highly significant. The mean grain size was 1.59 mm (-0.67$\phi$) at station A, 0.96 mm (0.06$\phi$) at station C, 0.34 mm (1.56$\phi$) at station D, 0.41 mm (1.29$\phi$) at station E, and 0.20 mm (2.33$\phi$) at the sand patch. The weight percentage of gravel was highly variable at each reef station but in general the mean gravel percentage decreased progressively from the fore- to back-reef: 56% ± 10% at station A, to 40% ± 8% to 16% at station C, to a low of 16% ± 13% at station D. The gravel percentage increased to 23% ± 10% at station E. The mean weight percentage of the fine- to very-fine sands (3-4$\phi$) increased progressively from reef station A (21% ± 7%) to station E (48% ± 6%). It is difficult to make quantitative assessments of the grain size distributions with such a coarse sampling divisions, but qualitatively, it appears that the mid- to back-reef sediment size distribution was negatively skewed (McLaren 1981). Sorting was calculated according to the phi Quartile Deviation (Tucker 1988), or "Q.D.". Based on this sorting index, the sand patch sediments were moderately sorted (Q.D. =0.86), at stations A (Q.D. =2.32), C (Q.D. =2.54), and D (Q.D. =3.59) the sediments were very poorly sorted, and at station E (Q.D. =5.13) the sediments were extremely poorly sorted.

Small Well Point Pumping Experiment

Collection of RIW from a large sedimentary radius would be unsatisfactory for accurate sampling of RIW from the shallow sediment depths. Excessive pumping of the 0.1 m well point could result in overlying seawater being sucked down and diluting the RIW sample. Therefore a simple experiment was conducted in which 180 ml water
samples (i.e., the total volume of a sample bottle) were collected in series, beginning with water just after the sand plug cleared, from the 0.25 and 0.50 m well points. All samples were analyzed for inorganic nutrient concentrations and pH (Fig. 2.6). Only the fourth bottle volume pumped from the 0.1 m well point was saved for analysis, and it is not shown in Figure 2.6. RIW concentrations of PO$_4$, NO$_3$+NO$_2$, NH$_4$, and Si, and pH values all level off, or are increasing at a slower rate with volume pumped, after approximately 400-500 ml have been pumped from either the 0.25 cm or 0.5 m well point. The concentrations of nutrients such as PO$_4$, NH$_4$, and Si were higher in porewater from the 0.5 m well point than from the 0.25 m well point. While not shown in Figure 2.5, the NO$_3$+NO$_2$ RIW concentrations from the 0.1 m well point were much higher (4.64 μM when 630 ml was pumped) than from either the 0.25 m well point (0.25 μM when 630 ml was pumped) or the 0.5 m well point (0.17 μM when 450 ml was pumped).

It was concluded that RIW from 0.25 m and 0.5 m well points could be accurately sampled by collecting sample after pumping at least 400 ml after the sand plug had cleared the exit of the collection tube. This volume was measured in the field by overflowing at least two nutrient bottle volumes before collecting the sample, and was therefore established as the sampling protocol for the remainder of this study. The upper 0.5 m of the framework is likely to have a bit higher porosity, 50%, than the 30% assumed by Tribble (1990), based on studies by Capone et al. (1992). The 400 ml of withdrawn water would therefore be contained in a sediment volume with a radius of 6 cm. No more than 400 ml was ever withdrawn in a single sampling from a 0.1 m well point at any station.

Sampling Conditions

Some stations, particularly C and D, were sampled during the fall of 1991, and the summer and fall of 1992. During February, 1992, the complete set of fore-to-back reef-stations, A, C, D and E, was sampled for OSW and RIW on the same day a total of four times: February 1, 6, 24, and 29. Sampling was also conducted at station D on February 19, and at station A on February 22, 1992. The wind-direction usually dictated
which station would be sampled first (i.e., either fore-reef station A, or back-reef station E), because the usual procedure was to let the wind blow the boat used to hold sampling gear across the reef to the next station to be sampled.

February Weather Conditions

The weather and wave conditions on the reef varied on each of the sampling days, and over the course of a particular day. The weather conditions observed on the February 1992 sampling dates can be summarized as:

February 1: Strong (15-25 m.p.h.), occasionally gusty NE trade winds. The wave height at the first station sampled, A, was approximately 15 cm and from the NE direction. After approximately five hours, the wave conditions at the more protected station E were calm and flat.

February 6: Strong, occasionally gusty NE trade winds, estimated to be up to 30 knots. Though somewhat rougher conditions than February 1, the wind, wave, and station sampling-order direction were essentially the same as those on February 1.

February 19: Strong, occasionally gusty SW "Kona" winds, estimated to be about 20-30 knots. At mid-reef station D waves of approximately 4 cm amplitude and 60-100 m wavelength were observed coming from the inner bay (SW direction).

February 22: Extremely calm, glassy conditions at fore-reef station A. Very little wind, and small, 1 cm amplitude waves coming from outside the bay, from the N-NE direction.

February 24: Strong, occasionally gusty SW "Kona" winds, estimated to be 20-30 knots. Very rough conditions were experienced at the back-reef where sampling began. The back-reef experienced high-frequency, choppy waves sometimes in
excess of 30 cm height, but usually around 15 cm wave height, and wavelengths of approximately 60-100 cm from the SW, or inside bay, direction. At fore-reef station A there was still Kona-driven local high frequency waves, but, in addition, a small 3 cm high wave component from the N-NE, or outside bay, direction.

February 29: Strong, occasionally NE trades, with passing rain squalls. Waves at station A were 15-30 cm in height, from the NE direction. Wave height had decreased considerably, to 4 cm at station C.

The February 1992 weather conditions were therefore a fair representation of the yearly range of weather and waves influencing Checker Reef porewater mixing and sedimentary diagenesis.

The following sections describe the temporal and spatial variation in OSW and RIW nutrient concentrations at Checker Reef. The dominant metabolic processes occurring within the upper meter of the framework will be examined by stoichiometric analyses of the respective OSW and RIW chemical concentrations. In Chapter 3 the sediment-seawater gradients will be extrapolated from the OSW and RIW chemical concentrations, described below, and used in the determination of diffusive fluxes.

Cross-Reef Variation in OSW Inorganic Nutrients

The effect of framework diagenesis on the overlying waters can be understood by the chemical distributions on and within the framework and as a function of reef location (e.g., fore-to-back reef). The OSW inorganic nutrient concentrations and compositions obtained during the one month cross-reef sampling period can be compared to those measured over an eighteen month period by Tribble (1990). Figure 2.7 shows (1) the mean concentrations of nutrients in surface seawater over Checker Reef during the cross-reef sampling of February 1, 6, 24 and 29, 1991 and (2) the mean surface seawater nutrient concentrations reported in the appendix of Tribble (1990). Tribble (1990) sampled at (1) a location in front of Checker Reef in a deep navigable channel
("CHNL"), (2) a mid-reef location ("MID"), and (3) a site in the deep embayment directly SW of station E, off of the Checker Reef platform ("OFF"). The word "FORE", as shown in Figure 1.1, marks the approximate location of the CHNL site, and, similarly, "BACK" is the approximate location of the OFF sampling site. Some values in the Tribble (1990) data set were greater than 2 standard deviations from the means and were excluded from the mean determinations as outliers. Since the Tribble (1990) surface seawater nutrient concentrations were the result of 18 months of sampling, the variability (standard deviation of the means) was expected to be greater than the values obtained from the same-day cross-reef sampling of February, 1992. Nevertheless, Tribble's (1990) mean concentrations were partially generated by sampling the OFF- and MID-sites on the same day twice, the MID- and the CHNL-sites on the same day once, and the OFF- and CHNL-sites on the same day seven times.

Concentrations of phosphate, nitrate plus nitrite, and ammonium had the lowest variation (range ± 10-13 % of mean concentration) at station A compared to all other stations during February, 1992. OSW nutrient concentrations were from several times to an order of magnitude higher than the analytical detection limits, which were 0.01 μM for PO₄, 0.03 μM for NO₃+NO₂, 0.03 μM for NH₄, and 0.20 μM for Si (T. Walsh, personal commun.). Therefore, these trends are not likely due to analytical error. The only exception to this February 1992 trend was silica, which had the lowest variation (± 9 % of mean concentration) at station D and the highest variation at station E. The variability of both my and Tribble's (1990) data sets was high enough, with the above exception of station A, to preclude any definitive conclusions on the effect of Checker Reef on the chemical composition of overflowing seawater, and tests of significance (i.e, F-tests) were not calculated. It is interesting, however, that the mean concentrations of PO₄ and NO₃+NO₂ were higher in the surface seawater collected from over the reef than from in front (CHNL) or in back (OFF) of the reef. The mean NH₄ concentration from the front of the reef (CHNL) was higher than that of any surface seawater collected over or in back of the reef at any period. Mean silica concentrations from the CHNL were similarly higher than that of any surface seawater from over or back of the reef, with the exception of the mean Si concentration at MID.
Cross-Reef Trends in RIW Nutrient Concentrations and Compositions With Sediment Depth

Figures 2.8, 2.9, 2.10 and 2.11 show the depth profiles of the mean concentrations, and standard deviations from the means, of the framework inorganic phosphate, nitrate plus nitrite, ammonium, and silica, respectively, for February, 1992. The sediment depth profiles of nutrient concentrations at each station on a particular day displayed considerable station-to-station variability. The shape of the vertical profiles of phosphate, ammonium, and silica were similar to each other at a particular station, and each of these nutrients reached maximum concentrations at approximately 1-2 m framework depth. Nitrate plus nitrite concentrations peaked at around 0.05-0.10 m framework depth at each station.

Phosphate

PO₄ concentrations at station A were usually higher over the upper 25 cm of framework than at any other station (Fig. 2.8). PO₄ concentrations of station A usually decreased slightly from maximum values at 10-50 cm depth, to the lowest levels of any station at 100 cm sediment depth. Station C was characterized by a distinct concentration maximum at 10 cm, while concentrations at station D showed relatively little variation in the upper 25 cm. At both stations C and D, PO₄ concentrations increased sharply below 25 cm sediment depth to approximately 2-2.5 μM, although PO₄ concentrations at station C consistently decreased to approximately 1.5-1.8 μM at 200 cm. PO₄ concentrations at station E increased to about 0.8 μM at 10 cm sediment depth, and remained at approximately that concentration with increasing sediment depth.

Inorganic Nitrogen

Nitrate plus nitrite concentrations usually peaked at 5-10 cm sediment depth at all stations during February, 1992 (Fig. 2.9). These peak concentrations usually increased progressively from the fore-reef to back-reef stations. Station A had the lowest
NO$_3$+NO$_2$ mean concentrations in the upper 50 cm of framework when compared over this depth interval to all other stations, and rarely exceeded 0.8 $\mu$M at any depth. Station C had the highest maxima in mean subsurface concentrations during early February, ranging from 2.8 to 3.8 $\mu$M at 10 cm depth. Station D also exhibited a distinct concentration maxima over February, 1992, with mean concentrations of about 1.6-1.8 $\mu$M over 5-10 cm sediment depth. A distinct NO$_3$+NO$_2$ concentration maximum was observed at station E by late February at 5-10 cm depth. The mean concentration of the 10-cm porewater collected at station E from 2/1 to 24/92 was 0.8 ± 0.1 $\mu$M. However, concentrations as high as 4.3 $\mu$M were detected in the 5-cm porewater at station E on 2/24/92, and 5.4 $\mu$M in 10-cm porewater on 2/29/92. The wide disparity in the early February and late February concentrations at 10 cm depth at station E was manifested in the high variability shown in Figure 2.8. It is likely that the distinct nitrate plus nitrate maxima were typical of the Checker Reef porewaters year round. While not shown in Figure 2.9, the mean porewater NO$_3$+NO$_2$ concentration from 10-25 cm sediment depth was (1) 1.9 ± 1.9 $\mu$M (n=4) at station C during October, 1991 and 1992 (2) 1.3 ± 0.3 $\mu$M (n=4) at station D during November and December, 1991 and (3) 1.5 $\mu$M (n=2) at station E during November, 1992.

Ammonium usually increased to high concentrations just below respective NO$_3$+NO$_2$ maxima at each station (Fig. 2.10). At stations C and D, interstitial pools of NH$_4$ below 25 cm sediment depth increased in concentration to 15-47 $\mu$M. Stations A and E had the lowest mean NH$_4$ concentrations with increasing sediment depth, ranging over just 1.8-12 $\mu$M below 10 cm sediment depth. Suspiciously high NH$_4$ concentrations for the station D 0.05-m porewater samples were collected February 1 and 29, 1992, greater than two standard deviations from the mean. These values may have resulted from NH$_4$-contamination and were therefore excluded as outliers (i.e., > 2 s.d. of the mean) from the 5-cm porewater mean concentration shown in Figure 2.10. Note that while stations A and E had very low inorganic nitrogen concentrations below 25 cm sediment depth when compared to that of stations C and D, the extrapolated sediment-seawater gradients for stations A and E were higher than for C or D. The results of these nutrient-gradient determinations will be presented later in Chapter 3.
Silica

The overall station-to-station trend in silica distribution (Fig. 2.11) across the Checker Reef framework essentially mirrored that of phosphate and ammonium. The silica profile at station C changed very little over February, with mean concentrations approximately 4-8 μM in the upper 25-cm porewater, which gradually increased to about 43-56 μM in the 50-100 cm porewater. Station D concentrations also did not vary much in the upper 10-25 cm porewater, but gradually increased to about 60-70 μM in the 100-200 cm porewater. Station E porewater usually was characterized by a shallow (10 cm) concentration maxima of around 20 μM, but had fairly uniform levels of around 25-32 μM in the 50-200 cm porewater.

Inter-Nutrient Relationships

The relationship between concentrations of total inorganic phosphate and (1) nitrate plus nitrite, (2) ammonium, (3) total inorganic nitrogen (TIN, the sum of NO₃+NO₂ and NH₄ concentrations), and (4) silica were examined by correlation analysis (Sokal and Rohlf 1981). Correlation analyses were also calculated for the relationship between concentrations of silica vs. ammonium, and silica vs. TIN. The significance of the product-moment (or sample) correlation coefficient (r), sometimes referred to as the coefficient of determination, was calculated as described in Sokal and Rohlf (1981). The square of the correlation coefficient, or r², describes the proportion of the variance accounted for by the linear regression (Hays and Winkler 1970). The correlation analyses were based on concentrations in samples of (1) OSW and (2) RIW from the upper meter of the framework, and only from the February, 1992 sampling period, since this was when cross-reef sampling was most frequent. However, the relationship between PO₄ vs. TIN concentrations was examined both for (1) the upper meter and February, 1992, and (2) all sampling periods and all 2 m porewater concentrations. The analysis of (2) was therefore restricted to stations C, D, and E. Finally, the significance of the relationship between the station slopes of the 0-1 m correlations were examined using analysis of covariance.
Phosphate vs. Nitrate Plus Nitrite (0-1 m)

The correlations between PO₄ and nitrate plus nitrite were negative and very weak at all stations and therefore were not plotted. PO₄ and NO₃+NO₂ were significantly correlated only at station D (r² = 0.38, n = 28, p < 0.001). The correlations at stations A (r² = 0.004, n = 25), C (r² = 0.12, n = 24) and E (r² = 0.05, n = 20) were all statistically insignificant.

Phosphate vs. Ammonium (0-1 m)

The correlations between PO₄ and NH₄ concentrations were by comparison all positive and highly significant (p < 0.001) for all stations (Fig. 2.12). The correlations at stations C (r² = 0.96, n = 20) and D (r² = 0.82, n = 30) were higher than at stations A (r² = 0.52, n = 25) or E (r² = 0.54, n = 20). The regressions (y = mx + b) for PO₄ vs. NH₄ concentrations ([PO₄] vs. [NH₄]), were:

\[
\begin{align*}
[\text{NH}_4] &= (5.2 \pm 1.0) \times [\text{PO}_4] + (-0.1 \pm 2.2) \quad \text{Station A;} \\
[\text{NH}_4] &= (15.1 \pm 0.8) \times [\text{PO}_4] + (-3.3 \pm 3.6) \quad \text{Station C;} \\
[\text{NH}_4] &= (14.1 \pm 1.3) \times [\text{PO}_4] + (-1.5 \pm 6.4) \quad \text{Station D;} \\
[\text{NH}_4] &= (13.9 \pm 3.0) \times [\text{PO}_4] + (-4.1 \pm 4.7) \quad \text{Station E.}
\end{align*}
\]

The porewater at station A therefore was characterized by a NH₄:PO₄ ratio of around 5:1, while that of all the other stations was around 14-15:1. While the y[NH₄]-intercepts of all the regression equations were negative, the standard errors were so great as to make these intercepts indistinguishable from zero. Analysis of covariance between stations of the slopes of [PO₄] vs. [NH₄], however, yielded an F value of 5.60 with 3 and 85 degrees of freedom. Interpolation of critical values of the F-distribution for 3 and 85 degrees of freedom yields an F_{0.005(3,85)} = 4.63 (Sokal and Rohlf 1981), indicating that the slopes do vary significantly at this level of probability; that is, the probability that the slopes have the same mean values is less than 0.5% (p < 0.005).
The inclusion of samples from all other dates and the 2 m-porewater (at stations C, D and E only) in the linear regressions of [NH₄] vs. [PO₄] resulted in progressively steeper (higher N:P) regression slopes from the fore-to-back reef direction:

\[
\begin{align*}
[NH_4] &= (14.3 \pm 0.7) \times [PO_4] + (-3.3 \pm 3.6) & \text{Station C;} \\
[NH_4] &= (16.2 \pm 0.9) \times [PO_4] + (-2.0 \pm 6.6) & \text{Station D;} \\
[NH_4] &= (20.2 \pm 3.9) \times [PO_4] + (-7.0 \pm 7.8) & \text{Station E.}
\end{align*}
\]

The highest proportion of the variance described by the linear regressions were again at stations C \((r^2 = 0.94, n = 34)\) and D \((r^2 = 0.88, n = 47)\), and lower at station E \((r^2 = 0.49, n = 30)\). All correlations were highly significant \((p < 0.001)\). The slopes of the regressions were clearly influenced by the more complete data set, and the higher NH₄:PO₄ ratios, of the 2 m porewaters.

The correlations between [PO₄] and [TIN] were also very positive and highly significant \((p < 0.001)\) for the upper meter of all stations in February, 1992 (Fig. 2.13). Stations C \((r^2 = 0.97, n = 20)\) and D \((r^2 = 0.80, n = 30)\) had the highest variance accounted for by their respective linear regressions, while those for stations A \((r^2 = 0.54, n = 25)\) and E \((r^2 = 0.52, n = 20)\) were much lower. The regressions for PO₄ vs. TIN were:

\[
\begin{align*}
[TIN] &= (5.2 \pm 1.0) \times [PO_4] + (0.4 \pm 2.1) & \text{Station A;} \\
[TIN] &= (14.6 \pm 0.6) \times [PO_4] + (-1.8 \pm 2.8) & \text{Station C;} \\
[TIN] &= (13.6 \pm 1.3) \times [PO_4] + (-0.2 \pm 6.5) & \text{Station D;} \\
[TIN] &= (13.1 \pm 2.9) \times [PO_4] + (-2.5 \pm 4.6) & \text{Station E.}
\end{align*}
\]
The mean TIN:PO$_4$ ratio at station A was around 5:1, while that of all other stations was about 13-15:1. The inclusion of the N of NO$_3$+NO$_2$ therefore only slightly changed the N:P stoichiometry. As with the [PO$_4$] vs. [NH$_4$] regressions, the y[TIN]-intercepts were indistinguishable from zero. Analysis of covariance between the sample slopes of [PO$_4$] vs. [TIN], however, yielded an F value of 5.30 with 3 and 85 degrees of freedom. Therefore the slopes do vary significantly at p < 0.005 (3,85 d.f.).

**Phosphate vs. Total Inorganic Nitrogen (0-2 m)**

At stations C, D and E, however, the slopes of the linear regressions of [PO$_4$] vs. [TIN] from the inclusion all sampling dates and the 2 m-porewater were progressively steeper (higher N:P) from the fore-to-back reef direction:

\[
\begin{align*}
[TIN] & = (13.9 \pm 0.6) \times [PO_4] + (-2.0 \pm 3.0) \quad \text{Station C;} \\
[TIN] & = (15.8 \pm 0.9) \times [PO_4] + (-0.8 \pm 6.7) \quad \text{Station D;} \\
[TIN] & = (19.4 \pm 3.8) \times [PO_4] + (-5.5 \pm 7.7) \quad \text{Station E.}
\end{align*}
\]

The highest proportions of the variance described by the linear regressions were again at stations C ($r^2 = 0.95, n = 34$) and D ($r^2 = 0.87, n = 45$). The lowest proportion of the variance described by the regression was at station E ($r^2 = 0.48, n = 30$), or about the same as those from the previous regressions of just the upper meter during February, 1992. All correlations were highly significant ($p \ll 0.001$). The mean TIN:PO$_4$ ratios of the 2 m porewaters for station C was $12.1 \pm 0.6 \ (n = 5)$, for D was $18.7 \pm 1.0 \ (n = 7)$, and for E was $14.8 \pm 13.8 \ (n = 5)$. The slopes of the regressions were clearly influenced by the more complete data set, and the higher TIN:PO$_4$ ratios of the 2 m porewaters.

**Phosphate vs. Silica (0-1 m)**

Within the upper meter during February, 1992, the correlations between [PO$_4$] and [Si] were all strongly positive (Fig. 2.14). The correlations for stations A
(r² = 0.86, n = 25), C (r² = 0.92, n = 24), D (r² = 0.95, n = 30), and E (r² = 0.84, n = 20) were all highly significant (p < 0.001). The regressions for PO₄ vs. Si were:

\[
\begin{align*}
[Si] &= (25.0 \pm 2.1) \times [PO_4] + (4.0 \pm 4.5) \quad \text{Station A;} \\
[Si] &= (19.4 \pm 1.3) \times [PO_4] + (1.4 \pm 6.0) \quad \text{Station C;} \\
[Si] &= (21.5 \pm 0.9) \times [PO_4] + (1.4 \pm 4.5) \quad \text{Station D;} \\
[Si] &= (32.2 \pm 3.3) \times [PO_4] + (-2.9 \pm 5.1) \quad \text{Station E.}
\end{align*}
\]

The all-station Si:PO₄ ratio therefore had a mean value of around 24 ± 6. The mid-reef stations C and D had similar Si:PO₄ ratios with a mean value of about 20, while the Si:PO₄ of the fore- and back-reef stations, A and E, respectively, also were similar with a mean value around 29. Analysis of the covariance of the slopes of PO₄ vs. Si resulted in an F value of 6.23 (3,85 d.f.), indicating that the slopes do vary significantly at p ≤ 0.001.

**Phosphate vs. Silica (0-2 m)**

At stations C, D and E, however, the slopes of the linear regressions of [PO₄] vs. [Si] from the inclusion all sampling dates and the 2 m-porewater were progressively steeper (i.e., higher N:P) from the fore-to-back reef direction:

\[
\begin{align*}
[Si] &= (17.8 \pm 1.1) \times [PO_4] + (1.5 \pm 6.0) \quad \text{Station C;} \\
[Si] &= (26.1 \pm 1.0) \times [PO_4] + (1.7 \pm 8.1) \quad \text{Station D;} \\
[Si] &= (31.2 \pm 2.9) \times [PO_4] + (-2.2 \pm 5.8) \quad \text{Station E.}
\end{align*}
\]

The highest proportion of the variance described by the linear regressions were at stations C (r² = 0.89, n = 34) and D (r² = 0.93, n = 45), and slightly lower at station E (r² = 0.81, n = 30), all a bit lower r² values than those from the previous regressions of just the upper meter during February, 1992. All correlations were highly significant (p ≪ 0.001) and the regressions were clearly influenced by the more complete data set.
Silica vs. Nitrate Plus Nitrite (0-1 m)

The correlations between Si and nitrate plus nitrite were negative and very weak at all stations, and therefore were not plotted. The correlations between Si and NO$_3$+NO$_2$ concentrations were significant only at station D ($r^2 = 0.31$, $n = 30$, $p < 0.001$), and were insignificant at stations A ($r^2 = 0.02$, $n = 25$), C ($r^2 = 0.23$, $n = 20$), E ($r^2 = 0.07$, $n = 20$).

Silica vs. Ammonium (0-1 m)

The correlations between Si and NH$_4$ concentrations in the upper meter of the framework were all positive, and highly significant ($p < 0.001$) for all stations (Figure 2.15). The correlations between Si vs. NH$_4$ at stations C ($r^2 = 0.95$, $n = 20$) and D ($r^2 = 0.91$, $n = 30$) were more linearly related than at stations A ($r^2 = 0.58$, $n = 25$) or E ($r = 0.4$, $n = 20$). The regressions for Si vs. NH$_4$:

$$[\text{NH}_4] = (0.20 \pm 0.04) \times [\text{Si}] + (-0.81 \pm 2.06) \text{ Station A;}$$
$$[\text{NH}_4] = (0.74 \pm 0.04) \times [\text{Si}] + (-3.63 \pm 3.89) \text{ Station C;}$$
$$[\text{NH}_4] = (0.68 \pm 0.04) \times [\text{Si}] + (-3.11 \pm 4.54) \text{ Station D;}$$
$$[\text{NH}_4] = (0.48 \pm 0.06) \times [\text{Si}] + (-3.77 \pm 3.19) \text{ Station E.}$$

Analysis of covariance of the slopes of Si vs. NH$_4$ concentrations yielded an F value of 20.6 (3 and 87 degrees of freedom), indicating that the slopes do differ significantly since the $F_{0.001|3,87} = 6.00$.

Silica vs. Total Inorganic Nitrogen (0-1 m)

The correlations between Si and TIN concentrations in the upper meter of the framework were all positive, and highly significant ($p < 0.001$) for all stations. The correlations between Si vs. TIN at stations C ($r^2 = 0.95$, $n = 20$) and D ($r^2 = 0.89$, $n$
= 30) were more linearly related than at stations A (r² = 0.59, n = 25) or E (r = 0.77, n = 20). The regressions for Si vs. NH₄ were:

\[
[NH_4] = (0.20 \pm 0.03) \times [Si] + (-0.22 \pm 1.98) \text{ Station A;}
\]
\[
[NH_4] = (0.72 \pm 0.04) \times [Si] + (-2.03 \pm 3.64) \text{ Station C;}
\]
\[
[NH_4] = (0.66 \pm 0.04) \times [Si] + (-1.81 \pm 4.79) \text{ Station D;}
\]
\[
[NH_4] = (0.45 \pm 0.06) \times [Si] + (-2.23 \pm 3.19) \text{ Station E.}
\]

Analysis of covariance of the slopes of Si vs. TIN concentrations yielded an F value of 18.76 (3 and 87 degrees of freedom), indicating that the slopes do differ significantly since the F[3,87] = 6.00.

Discussion

It was fortuitous that weather conditions of February, 1992 essentially spanned much of the variation in the wave conditions experienced by the reef over the course of a year. The waves ranged from short-wavelength chop to longer-period swell, and the Kona wind conditions directed waves in the direction opposite to the normally prevalent trade-wind pattern. Heavy rainfall due to occasional squalls and stormy weather was interspersed with calmer, sunnier days. The weather can be calmer during other months, particularly during the summer periods of low tradewind flow, little N-NE long-period swell, and light rain. The reef therefore may not express the same chemical variability at these times as detected during February. The weather can also be a lot rougher during storm activity, which can induce white caps throughout Kaneohe Bay and direct much heavier wave action onto Checker Reef. These periods probably promote higher ventilation of the reef framework, yet the rough conditions preclude sampling with current techniques due to safety considerations.

The distribution of inorganic nutrient levels of the OSW during the cross-reef sampling in February, 1992 was consistent with those observed during somewhat similar
sampling by Tribble (1990). The CHNL and OFF nutrient levels observed during the long-term sampling of Tribble (1990) permit more robust conclusions on the roles of microbial processes within the framework play in controlling nutrient concentrations of the surrounding surface sea water of Kaneohe Bay. The distributions of OSW nutrients can be understood as the result of the influence of the relative direction of water flow that occurred during February, 1992, though it is difficult to draw definitive conclusions on the impact of framework diagenesis on the chemistry of the overlying water column since the OSW cross-reef differences in mean concentrations were statistically insignificant. \( \text{PO}_4^-, \text{NO}_3^-+\text{NO}_2^-+\text{NH}_4^+ \), and Si levels in the OSW all, however, displayed more restricted concentrations at the fore-reef compared to any other region of the shallow waters on or around Checker Reef that were sampled. Phosphate and nitrate plus nitrite concentrations were usually lowest (0.08 \( \mu \text{M} \) \( \text{PO}_4^- \), 0.14-0.19 \( \mu \text{M} \) \( \text{NO}_3^-+\text{NO}_2^- \)) in the waters off of the reef (CHNL and OFF), highest (0.14-0.15 \( \mu \text{M} \) \( \text{PO}_4^- \), 0.20-0.34 \( \mu \text{M} \) \( \text{NO}_3^-+\text{NO}_2^- \)) at the fore- and back-reef (stations A and E), and somewhere between these overall ranges (0.10-0.13 \( \mu \text{M} \) \( \text{PO}_4^- \), 0.22-0.33 \( \mu \text{M} \) \( \text{NO}_3^-+\text{NO}_2^- \)) within the mid-reef waters (C, MID, and D). Ammonium and silica appear to decrease in surface seawater passing over the reef. Phosphate and nitrate plus nitrite may be exported from the reef, yet the low levels in the OFF waters suggest they are rapidly taken up or diluted within the water column located off the back of Checker Reef. The variability of the TIN:PO\(_4\) values also were remarkably low (the range was \( \pm 11-17\% \) of the mean TIN:PO\(_4\)) at the fore- and back-reef OSW sites, and the mean TIN:PO\(_4\) ratio of waters collected at the fore- and back-reef (A and E) was only 4.2 \( \pm 0.7 \). The water "column" over the fore-reef is almost always more well-mixed due to the prevailing wave-action and wave-breaking than the more protected and stagnant waters of the mid-reef. These data however, were based partially on sampling during a Kona wind event, when the back-reef was also subject to wave-action, the back-reef water "column" being well mixed and of shorter residence time than other areas over the reef. Perhaps more complete uptake, incorporation, and remineralization of relatively low levels of dissolved organic matter may occur, with apparently greater nitrogen than phosphorous conservation in this location than that occurring in off-reef waters or mid-reef OSW. In this context it is interesting that the y-intercepts of the regressions of concentrations of \( \text{NH}_4^+ \) vs. \( \text{PO}_4^- \), and
TIN vs. PO₄ were almost all negative. The y-intercepts of Si vs. NH₄ and Si vs. TIN, were also all negative. Therefore, after microbial uptake and abiotic absorption removes all inorganic nitrogen there was still some phosphate and silica present. It is uncertain whether the framework system could be classified as functionally N-limited however, since the errors in the y-intercepts were so great as to make them statistically indistinguishable from zero.

The grain size measurements confirm Morrissey’s (1985) visual observations that the Checker Reef sediments of the mid-reef sand patch area were more well sorted (quantified by the phi Quartile Deviation values) compared to any of the other reef site sediments. This is the usual result of cross-reef transport of sediments by the prevailing NE-SW cross-reef direction of wave-induced currents due to trade winds (Suhayda and Roberts 1977; Roberts 1980; Roberts and Suhayda 1983). The sand patch area lies in a relatively low wave-energy area on the reef flat, and is protected from wave action by interference of the coral and coral rubble found at stations A-D, and is located almost equidistant from the fore- and back-reef edges. Station E is also exposed to wave action from refraction during trade-driven swells, and from direct wave-action during Kona-driven swells, which results in the observed extremely poor sorting. Sorting was "very poor" at stations A-D. The range of the mean grain size distributions across Checker Reef (0.20-1.59 mm) was remarkably similar to those found across the wave-impacted reef flat of Davies Reef, Australia, which ranged from 1.14 mm at the fore-reef station and decreased progressively from 0.73 to 0.24 mm in the mid- to back-reef sediments (Hansen et al. 1987). The Checker Reef mean grain sizes were a bit coarser than the wave-impacted sediments (0.66-0.33 mm) of a back-reef region located behind the barrier reef protecting Tague Bay, St. Croix, U.S. Virgin Islands (Williams et al. 1985 a,b). Williams et al. (1985 a,b) also found the sediments becoming increasingly finer as a function of distance from the front of the reef.

The coarse, poorly sorted sediments of station A were very hard to sample, and the mean grain size for this station can only be considered as representative of a thin layer of loose sand/gravel covering solid reef pavement. More accurate sampling of the
fore-reef sediments could probably be accomplished with a stainless steel corer which could be hammered deeper into the rubble/pavement than the PVC corer I used. The very fine, well sorted sediments of the sand patch represent the other extreme of Checker Reef surficial sediments. While the mean grain size generally decreases across the reef, there was a small increase in mean grain size at the back-reef (0.41 mm) compared to those at station D (0.34 mm) or at the sand patch (0.20 mm). Finer sediments do not accumulate over the back-reef as much as over the more-sheltered mid-reef areas. This is probably due to an elevation in wave-induced sediment transport from both (1) wave-refraction around the perimeter of the reef platform from the prevailing trade-wind waves, and (2) occasional S-SW wind-driven waves during Kona events. Sediment resuspension and sorting due to wave-driven mixing should be more intense in the upper layers of sand at all reef locations (Bagnold and Barndorff-Nielsen 1980; McLaren 1981).

Fore-reef frameworks are generally considered to be much more lithified than those of the mid-to-back reef (Marshall 1983). The lower hydraulic conductivity and enhanced lithification and calcification at the fore-reef is due to geochemical conditions imposed by the prevailing direction of wave-driven delivery of calcium, bicarbonate, and carbonate ions to these regions (Enos and Sawatsky 1981). The hydraulic conductivity of the framework at one meter sediment depth at station A is only 1/4-1/5 that of the framework at the mid- to back-reef sites (Tribble 1990). Similarly, residence times for RIW at one meter sediment depth were estimated by Tribble et al. (1992) to be approximately 6 days, or around three times as high at station A as at the mid-reef sites (station E residence time was not measured). Station C, however, was found to have the most elevated hydraulic conductivity (68 m d⁻¹) and shortest porewater residence time (1.6 d) at one meter sediment depth.

The increased wave-action, concomitant lithification, and decreased permeability influenced the three-dimensional structure of the microbial habitats of the fore-reef framework. Carbonate frameworks have been characterized as containing voids and pore spaces which can be microzones of chemical gradients wherein anoxic processes may proceed despite a more aerobic bulk porewater (Sansone et al. 1990). The more lithified fore-reef framework likely has a much lower degree of interconnected pore space than
the mid- to back-reef framework, which may decrease flow through the matrices and perhaps increased porewater residence time. This presumed decrease in interconnected pore space and overall porewater flow may decrease the flux of DOM, POM, and dissolved O\textsubscript{2} through the fore-reef compared to other regions. However, it is also possible, and perhaps more likely, that the lateral flow into the fore-reef flanks of the Checker Reef platform flushes up and through the fore-reef framework, resulting in the RIW at station A being more characteristic of well-oxygenated, Kaneohe Bay waters. The organic matter that does flow into the fore-reef framework is likely comprised of less benthic plant biomass than at the mid- to back-reef framework, though this conclusion cannot be determined from this data set. The increased oxygen supply should drive a more complete mineralization of the relatively poor planktonic organic matter source, and also drive the loss of nitrogen as N\textsubscript{2} (or N\textsubscript{2}O), and therefore the RIW at the fore-reef would be characterized by a lower inorganic N:P. The framework at the mid- to back-reef regions should benefit from increased organic matter supply (POM and DOM) from benthic plant growth and detrital flow from the trade-wind driven transport, as well as a relatively higher water residence time than at the reef-periphery. The development of endproduct concentrations to a more or less constant level should occur at a shallower sediment depth and be of lower relative concentrations at the fore- and, to a lesser extent, back-reef sediments than within the mid-reef sediments.

The interaction of these physical, geological, and biological processes all drive the observed chemical variations on and within the reef. The lower, more variable TIN:P of the fore-reef (5:1) compared to the near-Redfield TIN:P ratio of the mid-reef (14-15:1), and the slightly lower and more variable TIN:P of the back-reef (13:1), are all consistent with the above conclusions. The more complete consumption of lower levels of organic matter at the fore-, and, to a lesser extent, the back-reef, may also result in less export of organic matter to the overlying water column. The increased ventilation of the fore-, and, to a lesser extent, back-reef, results in a loss of fixed nitrogen by denitrification, and thus the lower inorganic N:P observed at both the fore- and back-reef compared to the mid-reef RIW. Since the fore- and back reef OSW is usually more well-mixed than the mid-reef OSW, the heterotrophic oxidation of the OSW-organic matter
should be more complete, resulting in the restricted OSW concentrations and TIN:P ratios.

The physical forcing by the prevalent wave action and advective import therefore controls the framework three-dimensional structure, the respective microbial activities within the pore space, and the resulting interstitial nutrient chemistry. For instance, at framework depths of $\geq 50$ cm PO$_4$ pools are much richer in the less ventilated mid-reef framework than within the more ventilated reef peripheries. The PO$_4$ depth profile at station D is consistent with PO$_4$ being actively consumed within the upper 0-25 cm. PO$_4$ levels generally increase more sharply with sediment depth at the reef periphery stations than within the mid-reef framework, and this may result in higher PO$_4$ flux at the reef peripheries, particularly at the more wave-impacted fore-reef. However, an interesting exception to this trend was observed as a shallow (10 cm) subsurface peak of PO$_4$ at station C. This peak was persistent at station C over February, 1992 and was not observed at the other mid-reef station D. When compared to station D, station C is located only about 50 m from the fore-reef edge, while station D is located over 120 m further back from C. Station C's hydraulic conductivity is over 30% higher, porewater residence time probably much shorter, and intensity of wave-driven transport likely higher. Therefore this peak may be due to an increased flux of POM/DOM and organic phosphate, and elevated heterotrophic activity, at station C compared to station D. These factors result in the accumulation of PO$_4$.

Pronounced NO$_3$+NO$_2$ concentration peaks at 5-10 cm sediment depth were observed at stations C, D, and E, yet were barely observable at station A. These peaks could not be detected with the previous sampling scheme of Tribble (1990), and demonstrate the previously mentioned importance of a more intensive sampling scheme of porewaters within the more dynamic upper meter of the reef framework. As previously explained in the Introduction of this chapter, these peaks developed as a balanced function of available oxidants delivered by wave-action from above, and the mutualistic metabolic interactions of the various nitrifying-, nitrosofying-, denitrifying-, and N$_2$-fixing-bacteria. The work of others (Entsch et al., 1983; Hopkinson 1987)
suggests that ammonium pools deeper within the framework are microbially-oxidized for chemical energy by the sequential action of autotrophic nitrosofying- and nitrifying-bacteria. Capone et al. (1992) demonstrated by $^{15}$NO$_3$ isotope dilution techniques that the nitrification rates in the upper 2 cm of reef flat sediments were eight fold higher than concurrent NO$_3$ reduction rates. Nitrification is inhibited by high O$_2$ and NH$_4$ concentrations and enhanced by organic substrate availability. As oxygen is progressively depleted within the framework, successively less efficient electron acceptors (NO$_3$, SO$_4$) are used by the microbial communities inhabiting the framework habitat (Tribble 1990). Therefore the variability and magnitude of the NO$_3$+NO$_2$ pools reflects the relative physical stability of the microbial habitats within the reef framework.

Trade-wind reversal has been shown to increase the Mn/Ca ratio and decrease $\delta^{18}$O within coral skeletons of a Tarawa atoll, primarily by generating waves which resuspend particulates within the shallow inner reef (Shen et al. 1992). The Kona wind events during February, 1992 drove waves onto the back of Checker Reef, essentially ventilating the back-reef sediments with dissolved oxygen and presumably increasing the POM/DOM supply. This resulted in enhanced nitrification of the ammonium pools and the development of a NO$_3$+NO$_2$ peak in what must have been a matter of only days. It is unfortunate in this context that 5-cm porewater was available for only one sampling date (2/24/92). However, the high variability of the NO$_3$+NO$_2$ concentrations at 10 cm at station E demonstrates why it is important to carefully examine the variability of sediment-seawater gradients since physical forcing can radically influence the values. In the absence of Kona winds the NO$_3$+NO$_2$ porewater profile at station E should resemble the more stable station D, though further sampling should be conducted to confirm this conclusion. The sharp gradients in NO$_3$+NO$_2$ should result in enhanced NO$_3$+NO$_2$ flux at the mid- to back-reef areas and low relative flux at the fore-reef.

The depth distribution of porewater ammonium essentially mirrored the PO$_4$ profiles in that they were uniformly low within the framework at the reef peripheries, and elevated at depth within the more protected mid-reef. The negligible NH$_4$ levels in
the upper 10 cm of the mid-reef were presumably due to consumption by nitrifying bacteria as well as assimilatory uptake by mixed microbial assemblages.

The dissolved silica profiles further substantiate Tribble's (1990) conclusion that either diatoms or siliceous sponges are significant contributors to the organic matter pool undergoing oxidation within the framework. The sharp increase in Si at stations A and E (Fig. 2.11) supports a primarily diatomaceous source for Si, since the reef peripheries are more likely to receive advective import from the surrounding water column, which is characterized by phytoplanktonic growth. The low hydraulic conductivity of the fore-reef framework results in an overall decreased supply of organic matter from whatever source to the fore-reef pore spaces. Remineralization of the relatively low amount of siliceous organic matter within the upper 10-25 cm of the mid-reef framework may be responsible for the low Si concentrations observed in these porewaters.

Conclusions

In conclusion, this chapter has demonstrated the spatial and temporal variations in the porewater chemistry of the upper meter of the Checker Reef framework. In order to understand the importance of these variations on the flux of porewater constituents, the following chapter will attempt to more thoroughly examine the sediment-seawater gradients and to quantify the physical forces that can drive chemical fluxes within the reef.
Figure 2.1. Zonation of Checker Reef flat and the position of well point samplers and the sand patch ("SP"). Adapted from Morrissey (1985).
Figure 2.2. (A) Schematic diagram of the large well point components. (B) Cross section view of assembled large well point. From Sansone et al. (1988).
Figure 2.3. Schematic diagram of well-point sampling tube, 0.1 m small well point with stopper, and sampling tube inserted into well point. O.D. is outer diameter and I.D. is inner diameter.
Figure 2.4. Small well point array orientation for (A) stations C, D, and E, and (B) station A. "N" points north; "WP" means well point.
Figure 2.5. Histograms of the sediment grain size distribution in the upper 3-14 cm at Checker Reef stations A, C, D, and E, and the sand patch, on 3/22/94. The vertical lines centered on each size fraction indicate ± one standard deviation from the mean weight percentage for that size fraction. The sediment was separated into six size categories: 1) $\leq -1\phi$ ($\geq 2-64$ mm); 2) $0\phi$ (1-2 mm); 3) $1\phi$ (0.5-1 mm); 4) $2\phi$ (0.25-0.5 mm); 5) $3-4\phi$ (0.06-0.25 mm); 5) $\geq 4\phi$ ($\leq 0.06$ mm).
Figure 2.6. Small well point pumping experiment, station C, October 31, 1991 for the 25 cm well point (■) and 50 cm well point (□).
Figure 2.7. Mean concentrations of OSW inorganic nutrients (solid lines) from (1) cross-reef sampling of February 1, 6, 24, and 29, 1992, at Checker Reef stations A, C, D, and E; (2) Tribble (1990) surface seawater sampling of Checker Reef from 7/1986 to 2/1988, at locations just off the back reef (OFF), the middle of the reef (MID), and in the deep channel in front of the reef (CHNL). Dotted lines are ± standard deviations of mean concentrations at each site.
Figure 2.8. Cross-reef pattern of phosphate concentrations with depth, with ± standard deviations (horizontal lines), during February, 1992. The 5-cm value for station E represents one sampling date (2/24/92).
Figure 2.9. Cross-reef pattern of nitrate plus nitrite concentrations with depth, with ± standard deviations (horizontal lines), during February, 1992. The 5-cm value for station E represents one sampling date (2/24/92).
Figure 2.10. Cross-reef pattern of ammonium concentrations with depth, with ± standard deviations (horizontal lines), during February, 1992. The 5-cm value for station E represents one sampling date (2/24/92).
Figure 2.11. Cross-reef pattern of silica concentrations with depth, with ± standard deviations (horizontal lines), during February, 1992. The 5-cm value for station E represents one sampling date (2/24/92).
Figure 2.12. PO$_4$ vs. total NH$_4$ concentrations in the upper meter of framework and OSW during February, 1992 at stations A (■), C (▲), D (+) and E (□). The solid lines are the linear regressions for each station, which are identified by station letter (A-E).
Figure 2.13. Phosphate vs. total inorganic nitrogen concentrations in the upper meter of framework and OSW during February, 1992 at stations A (■), C (▲), D (+) and E (□). The solid lines are the linear regressions for each station, which are identified by station letter (A-E).
Figure 2.14. $\text{PO}_4$ vs. Si concentrations in the upper meter of framework and OSW during February, 1992 at stations A (■), C (▲), D (+) and E (□). The solid lines are the linear regressions for each station, which are identified by station letter (A-E).
Figure 2.15  Si vs. NH$_4$ concentrations in the upper meter of framework and OSW during February, 1992 at stations A (■), C (▲), D (+) and E (□). The solid lines are the linear regressions for each station, which are identified by station letter (A-E).
Chapter 3. HYDROLOGICAL MODELS OF WATER EXCHANGE BETWEEN CORAL REEF SEDIMENTS AND SURFACE SEAWATER

Introduction

The purposes of this chapter are (1) to describe how waves may mix interstitial waters and constituents within the reef flat framework, and (2) to examine the relative impact such processes have in supporting primary production of the reef system. Since quiescent periods of wave-action on the reef are possible, a significant component of interstitial mixing may at such times be due to molecular diffusion. Wave-driven diffusive fluxes will hereafter be characterized as "dispersive" fluxes to avoid confusion with fluxes due to molecular diffusion. The "dispersive" fluxes will be compared to those due strictly to molecular diffusion, and, as will be shown, both will be calculated assuming that the flux of nutrient species i is described by Fick's First Law of Diffusion or:

\[
\text{Flux}_i = \phi D \left( \frac{\partial C_i}{\partial z} \right)_{pw}
\]

(3.1)

where \( \phi \) is the effective porosity; \( D \) is the respective diffusion coefficient, that is, either a molecular diffusion coefficient or the appropriate wave-driven dispersion coefficient; \( C_i \) is the porewater concentration of nutrient species i; \( z \) is the sediment depth; and \( \left( \frac{\partial C_i}{\partial z} \right)_{pw} \) is the concentration gradient of nutrient species i near the sediment-seawater interface (Fick 1855; Maxwell 1860; Rayleigh 1880). In this expression positive \( \frac{\partial C_i}{\partial z} \) values indicate an increase in concentration with sediment depth and positive flux values are upwards, out of the sediment.

Molecular diffusion coefficients were developed in the early 1900s when it was recognized that the integrated effects of individual molecular motions could be described by the product of the mean molecular velocity times the mean length between
intramolecular collisions (Smoluchkowski 1916; Einstein 1926). Taylor (1921) extended this theory of intramolecular motion by analogy to the macroscopic (as opposed to molecular) flow of water and used an eddy-diffusion coefficient similar to the molecular diffusion coefficient. "Mixing length" theory was formalized by Prandtl (1925) and has proven very useful in describing how the majority of the momentum in macroscopic flow is transported by the largest eddies, whose boundaries are coupled to the length scale set by the maximum gradient of velocity.

In this chapter I will examine the relative magnitude and variability of both the nutrient gradients and the different coefficients in estimating nutrient flux. Nutrient gradients at the sediment-seawater interface will be extrapolated from the interstitial profiles presented in chapter 2. Molecular diffusion coefficients will be calculated from a model based on extensive literature values for carbonate reef sediments. Wave driven dispersion coefficients will be calculated from two hydrological models using measurements of naturally-occurring waves and wave parameters derived from spectral analysis, but which are based upon radically different assumptions of mixing-length magnitudes. The validity of the flux models will be tested by comparing the modelled fluxes to those measured directly with benthic chambers and from the previous flux estimates based on radon and salinity fluctuations within the Checker Reef framework (Tribble 1990). The fluxes will then be compared to the estimated nutrient requirements of reef autotrophs.

**Nutrient Flux by Molecular Diffusion**

Models which describe fluxes of ions in marine sediments by molecular diffusion require accurate estimates of diffusion coefficients. These coefficients may be measured directly, but this can be time consuming and may require independent estimates of adsorption behavior and reaction rate in the sediments under study (Li and Gregory 1974; Jørgensen 1979; Krom and Berner 1980). The bulk sediment diffusion coefficient may alternatively be determined by correcting the free solution diffusion coefficient for the effect of sediment structure (Ullman and Aller 1982). Free solution coefficients are
estimated from extensive compilations of self-diffusion or tracer coefficients modified for solution viscosity (Li and Gregory 1974). Berner (1980) expressed the theoretical relationship between diffusion in water and in the bulk sediment as:

\[ D_{si} = \frac{D_{oi}}{\Theta^2} \]  

(3.2)

where \( D_{si} \) is the bulk sediment diffusion coefficient of solute \( i \); \( D_{oi} \) the free solution diffusion coefficient of solute \( i \); and \( \Theta \) the geometric tortuosity. Since tortuosity is essentially impossible to determine in practice, an indirect relationship between tortuosity and the electrical resistivity of a body was derived (Klinkenberg 1951). In a porous sediment, the formation resistivity factor, \( F \), is the ratio of the electrical resistivity of the saturated bulk sediment to the resistivity of the interstitial solution. Ullman and Aller (1982) derived and expressed the relationship between formation resistivity factor and \( \Theta \), as:

\[ \Theta^2 = \phi F \]  

(3.3)

where \( \phi \) is porosity. Formation resistivities are relatively easy to measure, and extensive tabulation of \( F \) in different sediments led Archie (1942) to propose an empirical relationship between \( F \) and \( \phi \):

\[ F = \phi^{-m} \]  

(3.4)

Many subsequent studies have shown that: \( m = 2 \) for sandy sediments with a wide range of porosities, \( \phi = 0.2-0.7 \) (Manheim and Waterman 1974; Andrews and Bennett 1981; Ullman and Aller 1982), and this value of \( m \) will be used in calculating Checker Reef fluxes by molecular diffusion. After substitution into Fick’s first law of diffusion the molecular diffusive flux of nutrient species \( i \) can then be expressed in terms of \( D_{oi} \):

\[ \text{Flux}_{\text{molec},i} = \phi^2 D_{oi} (\frac{\partial C_i}{\partial z})_{pw} \]  

(3.5)
Again, in this expression positive flux values are upwards, out of the sediment, and positive $\partial C/\partial z$ values indicate an increase in concentration with sediment depth. It should be cautioned, however, that Archie's empirical model of diffusion within sands evolved from observations of sediments which may have contained a component of flux not due to molecular diffusion, since sands are more common in higher-energy sedimentary environments than are silts or clays.

Field Studies of Wave-Induced RIW Flow in Reef Systems

Field studies of advection through reef frameworks have been made in only a few areas, yet they are useful in identifying the dominant modes of turbulent exchange. Buddemeier and Oberdorfer (1988) classified the forces that generate pressure head gradients in a coral reef system as either sustained or oscillatory (Fig. 3.1). Sustained head gradients may result from wave setup on the fore-reef areas, lagoon ponding, impinging currents, and cross-reef wave-induced RIW flow. The flow of groundwater and density gradients may also result in sustained head gradients (Simms 1984; Rougerie and Wauthy 1986, 1993). Oscillatory head gradients may originate from forces exerted by short-period gravity waves as well as long-period tidal oscillations.

Davies Reef, a patch reef located within the central Great Barrier Reef, Australia, is subject to wave-driven flow on its outer edges. Oberdorfer and Buddemeier (1983) installed an array of PVC wells on Davies Reef and, using dye-tracers and water-level measurements, calculated horizontal RIW velocities of 3-10 m d$^{-1}$ and residence times of 3-90 days. They concluded that most exchange occurs in the vertical rather than horizontal direction (Oberdorfer and Buddemeier 1986; Buddemeier and Oberdorfer 1986, 1988). Parnell (1986) injected dye tracers into boreholes to investigate flow within a protected sand flat of a fringing reef on an inner (western) bay of Orpheus Island, located inside of the central Great Barrier Reef. Horizontal RIW flow, at velocities around 40 m d$^{-1}$, apparently dominated during ebb tide when the flat was exposed. A "dispersive" type of water movement was described as dominating flow when the flat was
covered by the tide. "Considerable" vertical mixing was observed, yet no specific rates or mechanisms were proposed (Parnell 1986).

Other fringing reefs are subject to much more energetic and dynamic wave conditions, as shown by studies using wells on the north coasts of Jamaica (Land et al. 1989) and at St. Croix, U.S. Virgin Islands (Roberts et al. 1988; Carter et al. 1989). At times the wells which sampled at an intermediate framework depth (3 m) were more hydrodynamically-sensitive to surge than the shallow wells, and this paradox was theorized to be the result of cavernous flow underneath a well-cemented reef plate (Land et al. 1989). In another case, an integrated RIW flow velocity as high as 86 cm s\(^{-1}\) was measured in a 3 m deep hole, yet no apparent cause from local wind-driven wave surge, tides or meteoric water dispersion was apparent. Such incredibly high flow velocities suggest that perhaps wave-driven surge was focussed through caverns within the reef framework and emerged out of the framework in a manner similar to a wave-impacted coastal "blow-hole". Roberts et al. (1988) used pressure transducers to demonstrate that sea surface slope between the fore-reef and lagoon, as modulated by long infragravity waves (periods \(< 27\) min.), controlled a rather slow net flow across the reef. However, they also concluded that the dominant mechanism of porewater exchange was induced in the vertical direction by higher-frequency (4.5-14.2 sec), wind-driven oscillatory waves.

Tribble et al. (1992) similarly concluded that most advective water flow occur in the vertical direction and that wave-induced short term oscillations apparently were the chief mechanism that driving mixing, particularly within the upper meter of the Checker Reef framework (Fig. 3.2). Using piezometers, their conclusions were based on rather exhaustive visual measurements of head differences between the framework and overlying seawater. Lagoon ponding, tides, RIW salinity or temperature variations do not apparently play significant roles in sustaining head differences and thus porewater movement in Checker Reef (Tribble 1990). Sustained head differences occur deeper within Checker Reef, at sediment depths of 4 m, yet the origin of these deep long-term head gradients has yet to be resolved. They were hypothesized to be due to periodic recharge and discharge of the Ghyben-Herzberg freshwater aquifer of Oahu Island, which
may be channelled through porous carbonate substrata beneath less permeable silty sediments of Kaneohe Bay.

Residence times were estimated from net head measurements and from the flux of two RIW tracers, radon and salinity (Tribble 1990). After a heavy rainfall Tribble (1990) monitored the temporal salinity variations of RIW to model the flux of RIW from one meter sediment depth to the surface. In effect, the return of RIW salinity over time from its freshwater-diluted value back to that of normal overlying seawater should be the result of wave-induced dispersive fluxes occurring after the storm event. The best estimates for RIW residence time in the upper meter were 1-2 days, while the residence time of the deeper RIW was approximately weeks to months. The resulting computed average PO$_4$ flux was $620 \pm 310 \mu$moles m$^{-2}$ d$^{-1}$; NH$_4$ flux was $4660 \pm 5290 \mu$moles m$^{-2}$ d$^{-1}$; and Si flux was $14100 \pm 630 \mu$moles m$^{-2}$ d$^{-1}$ (Tribble 1990). NO$_3$+NO$_2$ flux was very low and negative, $-20 \pm 6 \mu$moles m$^{-2}$ d$^{-1}$, as reported in Tribble et al. (1989), because the NO$_3$+NO$_2$ had been consumed at 1 m framework depths by bacterial denitrification. Tribble (1990) apparently assumed that the mixing driving the salinity and nutrient fluxes was uniformly distributed within the upper meter at all reef stations. That is, he assumed a uniform residence time at all reef locations in his calculations of flux. One can back-calculate his inferred dispersive-mixing coefficient from his calculated fluxes and mean nutrient concentrations, arriving at a value of approximately $17600 \times 10^{-5}$ cm$^2$ s$^{-1}$. Tribble’s (1990) results infer that dispersive forcing drives a flux some 4 orders of magnitude higher than molecular diffusion, since molecular diffusion coefficients are typically around $10^{-5}$ cm$^2$ s$^{-1}$.

Using these nutrient fluxes in combination with a stoichiometric mass balance model and reef production and respiration values tabulated by Kinsey (1985), Tribble (1990) estimated that the outward flux of inorganic carbon from organic respiration within the interstitial matrix resulted from at least 10% of the gross community organic production. While the reef framework is probably a significant pathway for nutrient recycling, Tribble’s (1990) values may be underestimates since they assumed a linear mixing of the chemical gradients between 0-1 m, a conservative assumption based on his
inability to sample RIW between 0-1 sediment depths. Tribble et al. (1989) acknowledged that it was more likely that the actual 0-1 m gradients were concave downward due to the greater net release of diagenetic end-products within the upper meter, and that such steeper gradients would result in greater flux of RIW constituents. These likelihoods have now been confirmed by the detailed examination of the nutrient profiles in Chapter 2 of this dissertation. Gradient-based NO₃+NO₂ fluxes, for example, should be much higher due to the pronounced concentration peaks at 10-25 cm sediment depth. Alternatively, at station D the vertical gradients of PO₄, NH₄, and Si are curved concave upward; implying that there may be more uptake within the sediments at these reef sites than at the fore- and back-reef sediments. Most field studies of reef hydrology infer that vertical exchange is the dominant mechanism controlling mixing within the framework. Therefore the theory of fluid flow in the vertical direction will be examined in the following sections to show how precisely-measured vertical mixing can be combined with chemical gradients to calculate wave-induced chemical flux.

*Theory of Wave-Induced RIW Flow*

The flow of fluid through porous media such as reef sediments is a mechanical process in which the forces driving fluid flow overcome the frictional forces between the moving fluid and grains of the media (Cherry and Freeze, 1979). During fluid flow mechanical energy is irreversibly transformed to thermal energy through frictional resistance. The fluid potential \( \Phi \) (the mechanical energy per unit mass of fluid, in units of \( \text{m}^2 \text{s}^{-2} \)) for an incompressible fluid is the sum of the gravitational potential energy, the flow or kinetic energy, and the elastic energy associated with pressure:

\[
\Phi = ge + \frac{v^2}{2} + \int p \frac{dP}{\rho}
\]  

(3.6)

where \( g \) is the gravitational acceleration constant (\( \text{m s}^{-2} \)); \( e \) (m) is the elevation of the unit water mass from elevation \( e = 0 \) m; \( v \) (\( \text{m s}^{-1} \)) is the velocity the fluid achieves from an initial velocity equal to \( 0 \) m s\(^{-1} \); \( p \) (N \( \text{m}^{-2} \)) is the pressure the fluid achieves from an initial
pressure equal to \( p_0 \); and \( \rho \) is the density (kg m\(^{-3}\)) of the unit mass (Cherry and Freeze 1979). Equation 3.6 is a form of the Bernoulli equation, the classical formulation of energy loss during fluid flow. For most porous-media, the velocities of flow are very low. Thus, if \( p_0 \) is atmospheric pressure at standard state, the Bernoulli equation can be reduced to:

\[
\Phi = gh
\]  

(3.7)

where \( h \) is the hydraulic head, which is the sum of the elevation head, \( e \), and the pressure head \( \psi \) (Cherry and Freeze, 1979). \( \Phi \) and \( h \) are therefore nearly perfectly correlated, because \( g \) is almost uniformly constant in the vicinity of the earth's surface. Water will flow from regions of higher \( \Phi \) or \( h \), at velocities directly proportional to the gradient of \( \Phi \) or \( h \) existing between the regions. This relationship, as described by Equation 3.7, was derived empirically by Henry Darcy (1856). Darcy observed that the velocity of porewater flow between two locations is a linear function of the head gradient between the locations, separated by a distance \( l \) and the intrinsic resistance of the sedimentary matrix:

\[
V_p = (K/\phi) \left( \frac{dh}{dl} \right)
\]  

(3.8)

where \( V_p \) is the porewater velocity (m d\(^{-1}\)), \( \phi \) (dimensionless) is the effective porosity of the medium (drainable fraction of the bulk volume), \( K \) is the hydraulic conductivity (m d\(^{-1}\)), and \( dh/dl \) is the head gradient (dimensionless). Thus, at a given sediment depth, net advection of RIW occurs down the pressure gradient (i.e., in the direction of the lower head) in portions of the reef exhibiting hydraulic head differences.

There are limitations to the validity of Darcy's Law for porewater flow within reef frameworks. The first is that RIW flow must be laminar. At environmentally realistic flow velocities (< 2 cm s\(^{-1}\)) intergranular flow tests of most natural sediments result in low Reynolds numbers, indicating that flow is laminar and not turbulent (Muskat 1946). Interstitial flow velocities in excess of 2 cm s\(^{-1}\) should occur only in rare situations
such as high-energy surf zones or large solution cavities (Buddemeier and Oberdorfer 1988).

The second limitation of some concern is the assumption of a homogeneously porous medium. Coral reef frameworks are well known to be heterogeneous over a wide range of horizontal and vertical distance scales, and may therefore have a porewater advection component which displays cavernous flow (Buddemeier and Oberdorfer 1986). Carbonate fragments usually have very high intraparticle porosities in addition to interparticle pore space, although most flow occurs between the fragments rather than through them (Choquette and Pray 1970). Dissolution cavities or channels formed by non-uniform packing of coral and shell fragments may be volumes which dominate RIW flow. Therefore, the tortuosity of the path that a flowing interstitial water particle follows may be significantly lower in carbonate reef sediments than in well-sorted sandy sediments. Calculations of wave-driven mixing in this study will apply only to that portion of the internal flow environment where water flows through zones of elevated permeability in the upper portions of Checker Reef (Oberdorfer and Buddemeier 1986). This effective mixing rate therefore does not apply to interstitial regions relatively isolated from flow, where molecular diffusion likely dominates, or which are simply excluded from flow altogether due to complete lithification around the pore space.

**Wave-induced Dispersion Models**

Since homogeneity cannot be assumed, two models of wave-driven flux will be developed which are based on very different mean mixing-lengths of RIW-particle movements under an oscillatory pressure field. The first model, the "macroscopic dispersion" model, assumes that an RIW-parcel mixes with a pathlength dimension proportional to the mean pore space geometry, which in homogeneous beds can be approximated by the mean sediment grain diameter (Phillips 1991). Waves then induce RIW parcels to move in multiple small-radii steps, orbiting around and against the sediment grains, a behavior that could be referred to as "percolatory". The second model, the "megascopic dispersion" or "megadispersion" model, assumes that the
majority of mixing is focussed within more permeable sediment heterogeneities (e.g., lenses, internal channels, dissolution cavities), so that mixing and chemical flux is enhanced because of a much higher mean effective pathlength (Phillips 1991). The maximum effective vertical pathlength is then twice the root-mean-square vertical pressure head amplitude of the RIW internal wave.

It may not be intuitively obvious how net transport can occur due to a time-varying pressure field induced by passing waves. Linear wave theory predicts that a perfectly sinusoidal wave will induce oscillating pressure gradients that can pump water into an underlying matrix as fast as it can pump water out. While no net transport of waters occurs, the water being pumped may be biogeochemically transformed through its interaction with the matrix (e.g., Riedl et al., 1972). Most previous research of the effect of waves on natural sediments were engineering studies concerned with modelling energy dissipation with depth (Putnam 1949; Reid and Kajiura 1957; Hunt 1959; Murray 1965; Sleath 1970). Riedl et al. (1972) improved these models by boundary-layer analysis (Huang 1970), which assumes that the sand bed could be understood as a semi-infinite homogeneous permeable structure. They calculated that a considerable amount of water was being filtered through coastal sand beds due to subtidal oscillations.

Understanding the flow trajectories of fluid parcels within a wave-impacted matrix involves a combination of aspects of both deep- and shallow-water wave models. The use of the term "fluid parcels" here refers to small "boxes" of fluid, bigger than molecules but smaller than the passageway through which the fluid is flowing. Deep water waves occur at water depths greater than about half their wavelengths. The fluid parcel trajectories of deep water waves are circular and decrease exponentially in radii with water depth (Fig. 3.3 A). Deep water waves do not frictionally interact with, or "feel", the sea bottom. At water depths less than around 1/20th of the wavelength, the waves are described by the shallow-water approximations of linear wave theory. As waves move into shallow water, the horizontal velocities at the surface become greater than vertical velocities, and the fluid parcel trajectories become progressively more elliptical with decreasing water depth. The shallow-water approximation assumes that the seabed is
impermeable, and this boundary condition is satisfied only if vertical water velocities are zero at the sediment-seawater interface. The horizontal axis of the elliptical fluid parcel trajectories remains relatively unchanged with water depth, while the vertical trajectory axis decreases exponentially with water depth (Fig. 3.3 B).

The vertical trajectories of waves passing over a permeable bed, however, are obviously not zero at the sediment-seawater interface. The wave-induced radii of RIW parcel movement within homogeneous sandbeds may be limited to a "percolation" type of advection, where the parcels of water are agitated by the passing waves to move in small step-lengths between the sediment grains. This degree of frictional interaction may result in a rapid attenuation of wave-induced pressure head variations with sediment depth. In more heterogeneous sediments, however, it is possible that flow is channeled through areas of enhanced permeability. The dominant water parcel trajectories within the framework could then be visualized as an extension of aspects of both deep-water and shallow-water approximations (Fig. 3.3 C), with the interstitial fluid parcel radii perhaps retaining close to the same dimensions as in the overlying water column, especially within the upper, more wave-impacted portion of the permeable sediments. Figure 3.3 C shows an exponential decrease in elliptical radii with sediment depth, an approximate result of the waveform interacting with the framework and, ultimately, with the impermeable bedrock that underlies most reef platforms at some depth. Wave-induced vertical pressure head would not decrease as rapidly with sediment depth as in the percolation model, and the predominant porewater eddies in a heterogeneous bed may have orders-of-magnitude larger radii than pore space dimensions of an homogeneous bed. The vertical dimensions of the elliptical orbits shown in Fig. 3.3 B and C are exaggerated approximately 2-3 orders of magnitude over the horizontal dimensions.

Checker Reef's platform rises steeply some 12-15 m above the Kaneohe Bay lagoonal floor and is thought to rest on an antecedent limestone platform of earlier reef development (Hollet 1977). Since there is growing evidence of the porous nature of these older carbonate formations (e.g., Sansone et al. 1990), it is very likely that the depth of
significant wave-induced RIW movement (i.e., \( \geq \) Brownian molecular motion) may extend well below the Checker Reef platform.

Webb and Theodor (1968, 1972) originally suggested that circulation cells of 10-35 cm in diameter must be occurring within coarse wave-impacted sandbeds. They based their conclusions on observations of the dimensions of sandbed ripples (~75 cm wavelength) subjected to passing waves of 6-21 m wavelength. In research of pressure head fluctuations within a reef framework, Roberts et al. (1988) present pressure-transducer data showing wave heights of 30-40 cm at the reef-sediment interface and at 1 m sediment depth, thus inferring vertical elliptical radii of 30-40 cm. Carter et al. (1989) noted that (1) "numerical modelling indicates that the oscillating nature of wave-pressure variations exerts a strong effect on porewater flow" and (2) "each oscillation produces a pattern of porewater particle motion of vertically-oriented ellipses a few centimeters in diameter or less, and decreasing exponentially in size with depth", yet they present relatively little data corroborating these broad statements.

Van der Loeff (1981) was one of the first to formulate "turbulent diffusion coefficients" for wave-impacted sediments. These coefficients are analogous to eddy diffusion coefficients and essentially assume a mixing length even smaller than the estimated porespace dimensions. The use of the word "turbulent" is actually a misnomer since Van der Loeff (1981) specifically assumed Darcian, hence laminar, flow in his formulations. Turbulence used in Van der Loeff's (1981) context loosely describes a mixing process with eddy dimensions much larger than those by molecular motion.

When waves propagate a distance \( x \) in time \( t \) over an impermeable seabed (Fig. 3.4), they induce an amplitude of pressure variation, \( p_o \), at the sediment-seawater interface which can be computed as:

\[
p_o = \rho_{pw} A (coshAd)^{-1} \quad (3.9)
\]
where \( \rho_{pw} \) is the porewater density (kg m\(^{-3}\)); \( g \) is the gravitational acceleration constant, \( A \) is the wave amplitude (m); \( \Lambda \) is the wave number (m\(^{-1}\)), and \( d \) is the water depth (m) (Lamb 1945). Van der Loeff (1981) used Equation 3.9 as a boundary condition, as in Putnam (1949), for the calculation of viscous flow in a permeable seabed. Assuming that the thickness (\( h \)) of the permeable bed was much greater than the water depth (i.e., \( h \gg d \)), he found that the pressure distribution within the sediment could be described as:

\[
p = p_0 e^{\Lambda z} \sin(\Lambda x - \omega t)
\]  
(3.10)

where \( x \) is horizontal distance (m), and \( z \) is the vertical distance (m) from the sediment-seawater interface, positive upward, such that \( z = 0 \) at the surface of the impermeable bed. From Darcy's Law (Equation 3.8) the horizontal \( (U_{pw}) \) porewater velocity, assuming \( z \) is constant is:

\[
U_{pw} = -(K/g \rho_{pw}) (\partial p/\partial x)
\]  
(3.11)

and the vertical \( (w_{pw}) \) porewater velocity, assuming \( x \) is constant is:

\[
w_{pw} = -(K/g \rho_{pw}) (\partial p/\partial z_{in})
\]  
(3.12)

where the hydraulic conductivity, \( K \), is defined in Equation 3.8. The porewater velocity at one point in horizontal space at the sediment-seawater interface is then:

\[
w_{pw} = KA\Lambda \cosh(\Lambda d)^{-1}
\]  
(3.13)

Van der Loeff (1981) thought it reasonable to assume that the "percolation" of water by wave action gives rise to eddies with dimensions not greater than \( 2A_{pw} \), where \( A_{pw} \) was the amplitude of the vertical porewater movement which he expressed as:

\[
A_{pw} = \Lambda^{-1} w_{pw} e^{2\Lambda z}
\]  
(3.14)
expression for a macroscopic dispersion coefficient at the sediment-seawater interface

\begin{equation}
D_{t,0} = (\pi K^2 T H^2)/(2 \lambda^2 \cosh^2(\Lambda d))
\end{equation}

where \( T \) is the wave period (s); \( H \) is the wave height (m) or twice the wave amplitude \( A \); \( \lambda \) is the wave length (m); and the other parameters are as listed above. During a SW storm over the shallow (\( d = 1.65 \) m) exposed sediments in the Wadden Sea, waves with a dominant period of 3.57 s and a wave height of 50 cm were recorded. These wave conditions and water depths were similar to conditions over a reef flat. Bioturbating macrofauna were apparently scarce in these sand flats and were not a significant source of porewater mixing (Van der Loeff 1981). Using the formula for wavelength

\begin{equation}
\lambda = (gT^2/2\pi) \tanh(\Lambda d)
\end{equation}

Van der Loeff (1981) calculated through reiteration a wave length of 13.1 m. The \( K \) of medium to fine sand, which has a mean grain size range of about 200-333 \( \mu \)m, is equal to \( 4 \times 10^{-2} \) cm s\(^{-1} \) (Kessler and Oosterbaan 1979). From Equation 3.16, the above variables and \( K \), the amplitude and vertical porewater velocity at the sediment-seawater interface were found to be 20 \( \mu \)m and 20 \( \mu \)m s\(^{-1} \), respectively. A theoretical-\( D_{t,0} \) of \( \leq 3 \times 10^{-5} \) cm\(^2\) s\(^{-1} \) was calculated. This \( D_{t,0} \) value is a larger than typical coefficients for molecular diffusion, which in the case of chlorine is approximately \( 0.5 \times 10^{-5} \) cm\(^2\) s\(^{-1} \) (Duursma and Bosch 1970). Van der Loeff (1981) measured a larger apparent-\( D_{t,0} \) value of \( 5 \times 10^{-5} \) cm\(^2\) s\(^{-1} \) by monitoring the Cl\(^-\) diffusivity in a chamber (an aluminum cylinder) inserted to a sediment depth of 13 cm during low-to-moderate wave activity. The theoretical-\( D_{t,0} \) was also low compared to apparent diffusion coefficient values of approximately \( 10 \times 10^{-5} \) cm\(^2\) s\(^{-1} \) calculated for a similarly wave-impacted area of the Dutch Wadden Sea (Billen 1978). Van der Loeff conjectured that the upper layers of sediment may be fluidized by wave action, leading to elevated diffusion and apparent \( D_{t,0} \). He concluded that the flow pattern in coarse, unconsolidated sands must differ from
Putnam's (1949) theory, and may be more in keeping with the much larger circulation cell dimensions suggested by Webb and Theodor (1968, 1972).

Within the last decade, there has been a number of theoretical and applied studies concerning wave-induced pore pressure within sandbeds. Maeno and Hasegawa (1985a,b; 1987a,b; 1988) demonstrated from the spectral analyses of pressure fluctuations in model (wave-tank) and natural sand beds that low-frequency components (< 0.6 Hz) of wave-induced pressure propagate more easily through sandbeds than higher frequency components (> 0.6 Hz). These authors predicted that pressure fluctuations at the sediment-seawater interface could be described by the non-linear Stokes ("II") second order wave theory. Stokes II predicts that the theoretical pressure at the sediment-seawater interface is

\[
p = \left[ \frac{\rho_{pw} g H}{2 \cosh(\Lambda d)} \right] - \left[ 3 \rho_{pw} g \lambda H^2 \tanh(\Lambda d) \right] \left[ 16 \sinh^2(\Lambda d) \right] \\
- \left[ \frac{\rho_{pw} g \lambda H^2 \tanh(\Lambda d)}{2 \cosh^2(\Lambda d)} \right] \\
\left[ 16 \sinh^2(\Lambda d) \right] (3.17)
\]

where all variables have been previously defined. There does not seem to be a great advantage gained in using a Stokes II model since wave-tank measurements of pressure were observed to be much lower than that predicted by Stokes II when pressure head variation exceeded about 4 cm, which can occur on and within the Checker Reef framework (Tribble 1990). Stokes II and linear theory both suffer when estimating wave dynamics in shallow water (Denny 1988). Since Madsen (1978) showed that linear wave theory was adequate for describing wave transmission and induced pore pressures, linear theory will be considered an adequate model of pressure fluctuations, at least for the present goals of this study. The spectral techniques introduced by Maeno and Hasegawa do, however, provide a valuable set of tools to explore in the future the heterogeneity of the Checker Reef framework, in particular, the sediment bulk modulus (volume elasticity) and porosity, which apparently can be predicted by the slope of the "spectral ratio" versus frequency. The spectral ratio is defined as the division of the spectral density
function of the pressure fluctuations at the seabed surface by those within the seabed (Maeno and Hasegawa 1987 a,b).

Phillips (1991) developed an expression for a macroscopic dispersion coefficient using linear wave theory, in an approach very similar to the Van der Loeff (1981) formulations. Again, a very thick (h), uniform and permeable bed overlies impermeable bedrock (Fig. 3.4). At the permeable sediment-seawater interface \( z = h \), and at the permeable sediment-bedrock interface \( z = 0 \) and \( \partial p/\partial z = 0 \). When long ocean waves or swell travel across a shallow sandy bed linear wave theory predicts the pressure at the top of the sand bed to be:

\[
p = \rho_{pw} g A \left[ \frac{\cos(\Lambda x - \omega t)}{\cosh \Lambda d} \right]
\]

where the variables are as defined above (Phillips 1977; 1991). In the shallow water overlying the reef \( \Lambda d \) is of the order of unity or less, so \( \cosh \Lambda d \approx 1 \). Therefore, variations in pressure at the sediment-seawater interface are the variations in hydrostatic head between the wave troughs and crests. These variations trace the mean vertical RIW-particle trajectories, which can be accurately measured with pressure transducers in very shallow water (Denny 1988). Phillips arrived at an expression of the pressure field inside the sand layer, consistent with the boundary condition at \( z = h \):

\[
p = \rho g A \left[ \frac{\cosh \Lambda z}{\cosh \Lambda h \cosh \Lambda d} \right] \cos(\Lambda x - \omega t)
\]

According to Darcian flow and noting that \( K = (g\kappa/\nu) \), the wave-induced transport velocity components of horizontal (\( u \); assuming \( z \) is constant) and vertical (\( w \); assuming \( x \) is constant) transport can be expressed as:

\[
u_{pw} = -\left(\frac{\kappa}{\nu}\right)(\partial p/\partial x)
\]

\[
= (A\Lambda K)[\cosh \Lambda z/(\cosh \Lambda h \cosh \Lambda d)]\sin(\Lambda x - \omega t)
\]

\[\text{(3.20)}\]
\[
W_{pw} = -\frac{\kappa}{\mu} \frac{\partial p}{\partial z} = -(\Delta K)[\sinh \Delta z/(\cosh \Delta h \cosh \Delta d)] \cos(\Delta x - \omega t)
\] (3.21)

where \( \kappa \) is the intrinsic permeability (m\(^2\)); \( \mu \) is the dynamic viscosity (N s m\(^{-2}\)); \( \nu \) is the kinematic viscosity (m\(^2\) s\(^{-1}\)); and other variables are as previously defined. Since most previous field studies indicated the importance of vertical transport, the root-mean-square vertical transport velocity at the sand surface (i.e., where \( z = h \)), pumping in and out of the sand bed, can be expressed as

\[
(\text{mean } w^2)^{1/2} = \left( \frac{\Delta A K}{2} \right) (\tanh \Delta h / \cosh \Delta d)
\] (3.22)

and the root-mean-square porewater velocity is \( \phi \) times Equation 3.1, or

\[
(\text{mean } w^2)^{1/2}_{\text{rms-pw}} = \left( \frac{\Delta A K}{2\phi} \right) (\tanh \Delta h / \cosh \Delta d)
\] (3.23)

(Phillips 1991). This expression yields identical values for vertical porewater velocity at the sediment-seawater interface as those calculated by Van der Loeff (1981) in Equation 3.13. The velocity of vertical RIW flow is therefore proportional to the product of the hydraulic conductivity (K) and the maximum wave slope \( \Delta A = 2\pi\Lambda /\lambda \).

Phillips (1991) defined an effective macroscopic dispersion coefficient within the sandy sediment as the product of the characteristic root-mean-square porewater velocity (Equation 3.23) and the maximum step length. I will identify this term as "\( D_{\text{macro}} \)." In a uniformly-packed sediment the maximum step length is confined by the mean geometry of the pore space, which Phillips (1991) assumed to be convoluted on a length scale of the mean sediment grain size, \( l_g \), so that

\[
D_{\text{macro}} \approx \left[ (\Delta A / 2)(l_g / \phi) \right] (\tanh \Delta h / (\cosh \Delta d)).
\] (3.24)

\( D_{\text{macro}} \) therefore applies to the agitation of a RIW particle under a pressure gradient force in an average step-length of dimensions no larger than the interstitial pores before
changing direction. Note that the porosity terms cancel when \( D_{\text{macro}} \) is substituted into the flux equation (3.1); thus

\[
\text{Flux}_{\text{macro-i}} = [(AA/2)(K)(l_o)\{(\tanh \Delta h)/(\cosh \Delta d)\}](\partial C/\partial z)_{pw} \tag{3.25}
\]

As mentioned previously \( \cosh \Delta d \approx 1 \). Assuming a reasonably deep framework, \( \Delta h > 1 \), and \( \tanh \Delta h = 1 \). Therefore "macroscopic" flux is dependent on the wave amplitude and number, sediment hydraulic conductivity, mean sediment grain size, and the sediment-seawater interstitial nutrient gradient.

Since both Van der Loeff (1981) and Phillips (1991) agree on the estimation of porewater velocity at the sediment-seawater interface, the correct choice of step length is crucial for a realistic expression of a wave-induced dispersion coefficient. The macroscopic model assumes that the interstitial flow pathways are fairly tortuous. However, flow may be focussed through internal channels, lenses, or dissolution cavities. Flow through these voids essentially "short-circuits" flow through the neighborhood, drawing in fluid at one end and releasing it at the other end. Phillips (1991) describes this process as "megadispersion". Megadispersion would result in an effective mixing length orders of magnitude higher than the mean pore space dimensions, thus increasing mixing and the transport of dissolved solutes. Such large mixing lengths can be inferred if there was little measured difference between the pressure head fluctuations of naturally occurring wave-forms over and within the reef framework. Essentially, megadispersion assumes that the measured head variations accurately represent the vertical extent of wave-induced mixing within the framework, just as the measured head variations detected by a seabottom-mounted pressure transducer accurately represent the vertical extent of wave-induced motion at the air-sea interface if the water is sufficiently shallow (i.e., at water depths of only a couple of meters; Denny 1988). If small differences are observed, then the mixing is "megadispersic", and the megadispersion coefficient, or \( D_{\text{mega}} \), can be calculated assuming that the maximum mixing-length \( l = 2A_{pw} \). Denny (1988) describes how a seabottom-mounted pressure transducer in shallow water accurately measures the wave-height of a passing wave, and therefore should also measure internal
(in the framework) waveheights. Since the geometry of the channels can not be characterized, I will assume that the root-mean-square vertical porewater velocity (i.e., Equation 3.23) will be an average value for the volume of sediment through which flux is occurring. Assuming that $A_{pw}$ just below the sediment-seawater interface is approximately the same as the wave amplitude at the air-sea boundary ($A$), and substituting $2A$ for $l_s$ into Equation 3.16, $D_{mega}$ can be expressed as

$$D_{mega} \approx [(A^2\Lambda)(K)(\phi^{-1})((\tanh \Lambda h)/(\cosh \Lambda d)^{-1})]$$

(3.25)

After substituting the expression for $D_{mega}$ into the flux equation (3.1) or

$$Flux_{mega} = [(A^2\Lambda)(K)(\phi^{-1})((\tanh \Lambda h)/(\cosh \Lambda d)^{-1})](\partial C/\partial z)_{pw}. \quad (3.26)$$

the porosity term again cancels out, as in the expression for $D_{macro}$ (Equation 3.24). In shallow waters overlying the reef $\cosh\Lambda d \approx 1$, and, assuming a deep framework, $\Lambda h > 1$ so $\tanh \Lambda h \approx 1$. Wave-driven "megadispersive" flux is then essentially dependent on the approximate square of the surface wave amplitude, the sediment hydraulic conductivity and the interstitial gradient. If the amplitude of the internal porewater wave occurring near the sediment-seawater interface can be measured accurately, then estimates of gradient-driven, wave-induced dispersive fluxes will be robust. In this study I will estimate the porewater wave-amplitude occurring within the upper 10 cm of sediment by extrapolating between the wave-amplitudes measured at just above the sediment-seawater interface, or "reference level", and at 1 m sediment depth.

The fluxes predicted by macroscopic dispersion versus those predicted by megadispersion are very different both in magnitude and distribution across Checker Reef, especially under variable wave-conditions. Waves impacting Checker Reef may be (1) directed onto the fore-reef, as during a typical N-NE trade-wind day, or (2) directed onto the back-reef, as during a S-SW Kona wind condition. The range of these conditions is similar to what was observed during February, 1992 on Checker Reef. If the maximum
amplitude ($A$) of waves impacting the fore-reef (station A) during the trade-wind day is 50 cm, and a 10-cm amplitude decrease is reasonable (Suhayda and Roberts 1977; Roberts 1980, Roberts and Suhayda 1983), then $A_{Sn,A} = 40$ cm, $A_{Sn,B} = 30$ cm, and $A_{Sn,E} = 20$ cm. Similarly, let the maximum amplitude of Kona wind-induced waves impacting the back-reef be 50 cm, which also decreases 10 cm between stations. Assume that water depths range in magnitude from a typical high-tide condition ($d = 1$ m) to a low-tide condition ($d = 0.1$ m). Wave period will be assumed to be the same across the reef and equal to ten seconds, and that $A_{pw} \approx A$. At high tide the wavelength at either station A during the trade-wind day or station E on the Kona-day, by the shallow-water approximation ($\lambda = \frac{T}{\sqrt{gd}}$), is 31.3 m ($A = \frac{2\pi}{\lambda} = 0.2$ m$^{-1}$). In this shallow water $Ad = 0.2$, so cosh $Ad = 1$, and the boundary condition presumes a reasonably deep framework, so that $Ah > 1$ and tanh $Ah = 1$. During low tide the water depth is around 0.1 m, the wavelength shortens to 9.9 m (i.e. at A or E), the wave number increases to 0.635 m$^{-1}$, and cosh($Ad$) = 1.21. Hydraulic conductivity is $1.50 \times 10^{-2}$ cm s$^{-1}$ at station A, $7.87 \times 10^{-2}$ cm s$^{-1}$ at station C, $5.90 \times 10^{-2}$ cm s$^{-1}$ at station D, and $6.25 \times 10^{-2}$ cm s$^{-1}$ at station E (Tribble 1990). The mixing-length set by the macroscopic model is the mean pore space, which is approximated by the mean sediment grain size, or 1.593 mm at station A, 0.961 mm at station C, 0.339 mm at station D, and 0.409 mm at station E (see Chapter 2). Effective porosity is assumed to be 0.5, based on the mean porosity measured by Capone et al. (1992) in the upper 10 cm of fine-to-coarse grained unconsolidated coral reef sediments at Hopkinson Reef, Great Barrier Reef, Australia. This value (0.5) of Checker Reef framework porosity is a bit higher than the 0.3 assumed by Tribble (1990) from Enos and Sawatsky (1981) and Ayers and Vacher (1986) for the entire upper two meters of the framework.

The trade wind-driven range and mean values of the $D_{macro}$ and $D_{mega}$ derived from the high- and low-tide wave conditions are shown as a function of location on Checker Reef in Figure 3.5. The Kona wind-driven ranges of $D_{macro}$ and $D_{mega}$ are shown in Figure 3.6. The megadispersion model results in dispersion coefficients over two orders of magnitude higher than the macroscopic dispersion model during both wind-conditions and tides. The predicted $D_{meca}$ values for both wind-conditions are also within
an order of magnitude of the inferred dispersion coefficient value of $176 \times 10^{-3} \text{ cm}^2 \text{s}^{-1}$ back-calculated from Tribble (1990). Station C is clearly identified as an area of enhanced wave-driven dispersion by both models during the tradewind day, and by the macroscopic model during the Kona-wind day. The megadispersion model of the Kona wind condition, however, not surprisingly identifies the back-reef as an area of enhanced mixing, since it is more sensitive to the wave-amplitude magnitude. During Kona conditions the megadispersion model results in orders-of-magnitude higher mixing at the back-reef, which progressively decreases to the fore-reef. This "back-flushing" during Kona-conditions is particularly effective due to the higher hydraulic conductivity of the back- and mid-reef framework. Similarly, the enhanced dispersion at station C versus station A during trades is the product of both the proximity of station C to most of the wave action impacting the fore-reef and a 5-fold higher hydraulic conductivity at station C compared to that at station A. These hypothetical wave conditions are admittedly rough, but even when wave amplitudes are smaller, the predicted cross-reef trends during the different conditions of wind, wind-driven waves, and tides remain the same. The megadispersion model predicts dramatically different cross-reef patterns of dispersive mixing during Kona conditions. Wow these conditions influence nutrient fluxes, however, must depend on the magnitudes of the cross-reef interstitial gradients.

Natural waves are of course not perfect sinusoids. Frictional interactions with a rough sandbed of a reef flat (e.g., sand ripples or coral heads), the sediment grains of the framework, and suspended sediments may lead to greater asymmetries. The horizontal flow of a passing wave over a rough surface should also induce small pressure gradients around the roughness elements (Denny 1988). Bernoullii’s principle predicts that unidirectional horizontal currents moving along the sediment-seawater interface accelerate and decelerate locally upon passing small protrusions and depressions, inducing pressure gradients and porewater and solute exchange. Flume studies with dyed sand have shown conclusively that unidirectional flow over typical biogenic sediment topography (e.g., a crab) will induce mixing ("dye-washout") down to several cms (Huettel and Gust 1992 a,b). Moderate boundary layer flow can enhance effective diffusion 7-10 fold (Huettel
1988). Huettel and Gust (1992a) also discussed how benthic chambers subject to unidirectional flow may result in artifactual fluxes.

The effect of oscillating horizontal flow on the pressure gradients localized around "bioroughness" elements has, however, not yet been demonstrated. Oscillating flow should nullify the bioroughness-induced localized gradients, since flow-reversals would cancel out the temporarily-induced pressure gradients. However, even though most field studies discussed in the previous section have concluded that vertical-, rather than horizontal-flow dominates porewater exchange in a wave-impacted environment, there are demonstrable horizontal currents flowing across reef flats due to wave-setup and tides (Buddemeier and Oberdorfer 1988; personal observation). While the bioroughness pressure gradients cannot be discarded, the net pressure fluctuations from waves flowing over a "biorough" reef can in any case be measured with sensitive pressure transducers.

Clearly, the accuracy of both wave-induced dispersion models increases as the ranges of the various parameters are better resolved. Hydraulic conductivity in the upper two meters of the framework (Tribble 1990) and mean grain size in the upper 3-14 cm (Chapter 2) have now been well established for Checker Reef. Detailed analysis of cross-reef patterns of wave dispersion would be useful in evaluating wave-driven flux. Accurate measurements of natural wave period and amplitudes on, within, and across Checker Reef can be accomplished using sensitive pressure transducers and electronic data-logging methods. The initial explorations of others (Roberts et al. 1988; Carter et al. 1989) in the use of pressure transducers and data loggers will be exploited during this study of the more easily accessible Checker Reef system. Directly measuring fluxes with benthic chambers will be used to corroborate the variability and magnitude of fluxes predicted by the macroscopic and megadispersion models. The validity of the fluxes predicted by the models, and measured by the chambers, will be further substantiated by comparison to the flux measurements of Tribble (1990) that were based on salinity and radon fluctuations in the Checker Reef porewater.
Methods

Wave-Induced Flow and Pressure Measurements

Initial measurements of wave-induced flow at the sediment-seawater interface utilized first a 2 L inverted beaker and later a 1600 cm$^2$ flat plate with flanges. Beaker and plate samplers were inserted into Checker Reef sediments at station D, and fluorescein dye dissolved in seawater was injected into graduated tubes, 2 m in length, attached to ports on the top of the sampler. The rate of movement of the dye front was determined by visual observation while using skindiving apparatus and a stopwatch. While this method was useful in demonstrating at times a continuous outflow of porewater from the sediments, occasionally flow would reverse and disperse the dye front, making accurate flow-rate determinations very difficult.

Flow determinations were greatly improved with the acquisition of three model TH-LVA (T-Hydronics, Westerville, Ohio) piezoelectric pressure transducers. The sensitivities of the transducers were factory-set to 14.1-21.6 p.s.i.a., and the transducers delivered an output of 4-20 mA under an applied voltage of 12 V. The output was measured by the voltage drop across a 200 Ω resistor placed in series so that it could be measured by a Fluke Model 2625A Data Logger set to the 0-3 V range. Each transducer was calibrated by measuring the incremental increases in pressure head due to additions of distilled water to a graduated tube attached to the transducer port. Linear regression of the output (V) to measured head (cm) typically resulted in an $r^2 = 0.99$. With this arrangement the mean sensitivity of the three transducers was 5 mV cm$^{-1}$ (± 1.4%), and pressure head variations of less than 1 mm could be measured. Each transducer was sealed in a waterproof case constructed of threaded PVC parts, with only the wettable sensor-surface exposed through a threaded brass tube fitting. The three encased pressure transducers were attached to an acrylic plate, and an 25 m length of shielded PVC electric cable was connected to power the transducers and transmit output signals to the onboard logger. Power was supplied to the 20 mA current loop by two model JC 640
6 V rechargeable gel cells (Johnson Controls, Milwaukee, Wisconsin) connected in series.

During measurements on the reef flat an outboard motor boat was double anchored approximately 20 m from the well point site in the lee of the mean wave and wind direction. This arrangement prevented possible interference or reflection of natural oncoming waves by the boat. Before submerging the sensor array, the cavity created by the brass tube fitting attached to each transducer sensor port was carefully filled with seawater from a syringe. Flexible (6.4 mm i.d., 9.4 mm o.d., 1.6 mm wall thickness) Tygon (Fisher Scientific, Pittsburgh, Pennsylvania) tubing was first submerged, cleared of air bubbles, and then attached to each transducer tube-fitting of the submerged three transducer array (Fig. 3.7). Lead weights (not shown in Fig. 3.7) held the array firmly on the bottom, and prevented the array from moving with the wave surge. Two transducers were usually connected via the flexible tubing to individual well point sample tubes. The third transducer was attached with the flexible tubing to a 20 cm long, 6.4 mm i.d. stiff acrylic tube which was vertically oriented and attached to either the large well point casing, or a section of 12.7 mm diameter iron reinforcing bar that had been driven into the reef near the wellpoint.

The distance, R, from the top of the stiff tube to the sediment-seawater interface was measured and in this manner the third transducer served as a reference for seawater level ("Ref. SW"). The reference level above the seabed typically ranged from 20-40 cm. Thus, the total amount of pressure felt at the sediment-seawater interface was due to a hydrostatic water column extending from the top of the reference tube to the seabed plus that measured by the mean pressure head of the reference transducer, plus the time-varying pressure head felt at the top of the reference tube measured by the reference sensor.

Pressure transducer output was usually monitored at 1 scan s⁻¹ and recorded with the onboard gel cell-powered Fluke data logger, which had a total memory of 2047 scans. A quasi-synoptic measurement of pressure head gradients for the whole reef was
performed on two separate days in October, 1992. During these cross-reef assessments, head gradients were measured first at station A, then C, D, and finally E. At station A pressure head was measured at the seawater reference level, and at 0.5 m and 1 m framework depth. At stations C, D, and E, head gradients were monitored at 1 m and 2 m framework depth, as well as at the seawater reference level. The first cross-reef assessment (10/8/92) was completed within three hours, the second (10/27/92) within four hours. During the first cross-reef measurement of pressure heads the average scan length at each reef site was approximately 8 min. By the time of the second cross-reef assessment, the total scan length per site was improved to approximately 34 min per reef site, since the entire logger memory (i.e., 2047 scans x 1 sec scan\(^{-1}\) x (1 min/60 sec) = 34 min) was batch-downloaded between the reef site sampling times into a battery-operated NEC MS-DOS laptop computer. The logger was then reset at the next reef site. During several overnight field trips at single stations over the fall, 1992, the pressure heads were monitored at 1 scan s\(^{-1}\) during several separate periods, and on occasion at 1 scan min\(^{-1}\) continuously for about 12 h.

**Pressure Transducer Field Evaluation/Intercalibration**

All logged signals were transformed to ASCII code, then converted from volts to cm-pressure head via the calibration expression determined previously by linear regression. No effect on the wave-record was apparent when the flexible tubing was or was not attached to a sensor. Intercalibration experiments were performed by attaching all three transducers to the stiff tubes, which were then fixed vertically, side-by-side, to the well casing so as to measure the same reference pressure head. Excellent linearity ($r^2 = 0.95$) was typically observed between the measured output of the transducers to each other (Fig. 3.8). During some intercalibration experiments the three attached-stiff tubes were oriented in vertical and horizontal positions, yet no difference in head was detected as long as the ends of the tubes were at the same level above the sediment. Similarly, as long as the stiff tubes were firmly attached to the wall casing, no differences in pressure measurements were observed when the interconnecting flexible tubing was vibrated and perturbed by hand or simply left undisturbed. Other investigators using pressure
transducers to measure water movement within sediments either attached the transducers directly to the well point sampling tube (Roberts et al. 1988), buried the transducer directly into the sediment (Raubenheimer and Guza 1993), or fixed the transducers at various depth intervals inside a casing similar to a well point (Sakai et al. 1992). However, since no obvious effect could be observed from the use of the flexible Tygon, the current setup was deemed appropriate and convenient for the quick measurement of pressure variations during a cross-reef assessment, especially since only three pressure transducers were available for this study.

**Pressure Head Measurements**

The magnitude of wave-induced pressure head fluctuations above and below the sediment-seawater interface can be visualized using a 100 s representative section of the scan at station D, 10/8/92 (Fig. 3.9). The reference sensor tube during this scan was 37 cm above the bottom, and head variations of the reference are plotted around this mean distance above bottom. The head variations within the framework are similarly plotted around their respective mean depths, 1 or 2 m. Assuming Darcian flow, this diagram clearly shows movement of RIW within the framework, ranging vertically to several cms even at 2 m depth, and in apparent synchrony with the overlying reference wave form.

**Spectral Analysis of Pressure Head Variations**

Most of the short-term scans (e.g., approximately 8 min) created data sets containing approximately 450 data points. Each scan time-series was mean-detrended using MATLAB by fitting a least squares regression to each series, yielding a time series with a mean of zero. The detrending reduces the energy contained in oscillations significantly longer than the record length which are not resolved by the time series, thus reducing spectral leakage (Chatfield 1991). Using the Signal Processing Toolbox of MATLAB, the detrended series were converted from the time domain to the frequency domain via the Welch method of power spectrum estimation (Welch 1970). The Welch algorithm divides the short-term scans into 6-8 successive 64-point sections, smoothing
each section by multiplying each with a Hanning window, transforming each section with a 64-point Fast Fourier Transform (FFT), and averaging the FFT sections. This method decreases the confidence intervals and frequency leakage, and smooths discontinuities at the ends of each section. The section length, or "truncation point" ("m"), was required to be an integral power of two (Welch 1970). The choice of m was selected to balance gains in resolution with losses in variance and satisfied the general rule of thumb that $m = \sqrt{N}$, where N is the total sample size (Chatfield 1991). The resultant averaged vector was multiplied by its complex conjugate, generating a power spectral density distribution which is equivalent to the variance in the frequency domain. The confidence intervals of the power spectra were estimated by calculating the variance of the unaveraged spectral estimates assuming a normal distribution.

Parseval's theorem states that the sum of the squared values of a sequence is equal to the sum of the squared values of the sequence's Fourier transform (Oppenheim and Schafer 1975). The units on the MATLAB power spectral density distribution (cm$^2$ Hz$^{-1}$) are such that, using Parseval's theorem, the square-root of the sum of the power spectra is the root-mean-square (RMS) value for the signal, which in this case is the mean-detrended root-mean-square wave amplitude, $A_{rms}$ (Little and Shure 1988). For instance, a pure sine wave with an amplitude of $A$ has an RMS value of $A/\sqrt{2}$, so, using MATLAB power spectra, $A_{rms} = \sqrt{\sum(\text{power spectra}(2))}$. $A_{rms}$ is used in the calculation of both the energy contained by the scanned waveform and the wave-driven dispersion coefficients. Total (kinetic plus potential) energy (E) of the scanned waveforms was estimated according to the formula $E = 1/2 \rho g H_{rms}^2$ (Denny 1988), where $\rho$ is seawater density (kg m$^{-3}$), $g$ is the gravitational acceleration constant (m s$^{-2}$), and $H_{rms}$, the root-mean-square wave height (m), is twice the $A_{rms}$. Total energy thus has units of J m$^{-2}$. In the calculation of dispersive fluxes the $A_{rms}$ of the porewater head variation at 5 cm sediment depth ($A_{rms-pw}$) was interpolated from the $A_{rms}$ of the pressure head at the reference level ($A_{rms-ref}$) and at the shallowest well point depth available (usually at 1 m).

The exaggeration of the low-frequency variance (cm$^2$ Hz$^{-1}$) compared to the high-frequency variance was decreased for graphical clarity by multiplying the power spectral
density by frequency, resulting in the "variance-preserving" expression for variance, with units of cm$^2$. "Variance" hereafter will refer to this variance-preserving expression. Figure 3.10 shows an example of the distribution of the spectral variance (cm$^2$) of the reference waveform versus frequency (Hz) and period (s) with 95% confidence intervals. The variance is plotted from the lowest frequency possible (1/[0.5 x total scan length in seconds]) to the Nyquist frequency (usually 1/(2 sec) = 0.5 Hz). The infragravity part of the spectrum (~0.003-0.03 Hz) is usually flattened because the sampling period did not provide sufficient repetitions at these frequencies to clearly resolve a peak.

Cross analysis between the spectra of the reference level scans and the well point scans, or between scans of different well points, yielded coherence and phase relationships. Coherence is a quantity that measures the square of the linear correlation between the two waveforms at a particular frequency. The value of coherence ranges from 0 to 1, and is analogous to the square of the usual linear correlation coefficient in that the closer it is to one the more closely related the two waveforms are at a particular frequency (Chatfield 1991). The cross-spectral phase of the frequency response, or "transfer" function, describes the relative shift in phase between two waveforms as a function of frequency. As with the variance spectra, the scan length limitations typically prevented accurate cross-spectral coherence and phase at the very low frequency end of the spectrum (< $10^{-1.5}$ Hz).

Benthic Chambers

The net flux of RIW constituents out of the reef framework by molecular diffusion, macroscopic dispersion and megadispersion was directly measured with hemispherical plexiglass domes 44 cm in diameter (Fig. 3.11). The area of reef sediment covered by the open bottom half of the hemisphere was 0.15 m$^2$. The enclosed volume was 17-21 L depending upon the depth of penetration into reef sediments by a sharpened equatorial flange, 7.5-cm deep, attached to the bottom of the dome. Lead weights attached to the dome and along the circumference of a 15-20 cm wide circular skirt on the dome assisted in anchoring the domes on the reef. The skirt was composed of a 15
cm wide, 0.5 cm thick solid plexiglass "ring" that was part of the preformed plexiglass dome, and was overlain with another "ring" of flexible plastic, attached at the base of the dome. The domes and plastic skirts were covered with plasticized aluminum foil ("airplane tape") to prevent light from entering. Small bilge pumps (Rule 360 g.p.h., Gloucester, MA.) powered at 1.5 v by rechargeable batteries gently stirred the chamber volume at ~ 1 gal min\(^{-1}\) to prevent water stagnation at the sediment-seawater interface. The mixing of water within the dome was estimated by injecting fluorescein dye into water-filled inverted domes with the stirrers on. The chamber mixing-time was approximately five minutes. A dome with a sealed bottom was also constructed to serve as a control for nutrient turnover within the water column.

The placement of the chambers in the typically shallow waters overlying the reef flat (0.1-1.0 m depth) required great care so as not to disturb the sediments and cause possible release of porewater nutrients. However, sediment disturbance could not be ruled out due to the practicality of the situation. The usual procedure was to wait until the tide had risen to a depth sufficient to cover the top ports of the chambers. The domes were then placed approximately one meter apart from each other (Figure 3.11 Inset), about two meters from a given well point array. The chambers were aligned along a generally N-S line which was transverse to the mean easterly- to north easterly-direction of the typical trade wind-driven swell, in order to expose each chamber to approximately the same oncoming wave action. The bilge pump and stopcocks were left off during the initial placement of the chambers, decreasing the dome resistance to emplacement into the sediment. In order to allow any possibly resuspended sandy sediments to settle, the pumps and stopcocks were not attached until at least an hour after initial placement, after which samples were withdrawn with 140 ml plastic syringes from a port on the top of the dome. A second stopcock was opened during sampling to assure replacement of the sample volume with ambient seawater rather than causing the possible and artifactual efflux of sediment interstitial water. When chamber water was being sampled for methane (not reported in this study), three 80 ml volumes were withdrawn with three separate syringes, before the 140 ml was withdrawn for inorganic nutrients. The nutrient samples were filtered through combusted Whatman GF/F filters (0.7 \(\mu\)m pore size), and
stored on Blue Ice (Gott Corp.) until frozen at H.I.M.B. on Coconut Island. A dome with a sealed bottom was also deployed, stirred and sampled for nutrients along with the domes open to the sediment, and thus served as control for possible net nutrient uptake or release within the enclosed volume of seawater. Samples were subsequently withdrawn from the chambers over a period of 6-18 h, depending upon whether the next low tide would uncover the chambers. The chamber experiment was terminated if the water level decreased to below the top chamber port.

Benthic fluxes of an inorganic nutrient species $i$ per unit area of reef sediment were calculated using the equation:

$$
\text{Flux}_i = \frac{[V(C_{t-i} - C_{o-i}) - (V_c(C_{t-c-i} - C_{o-c-i}))]}{(AT)}
$$

(3.28)

where $V$ is the volume of water enclosed by the open-bottom dome over the sediment, $C_{o-i}$ and $C_{t-i}$ are the dissolved concentrations before and after time $T$, $V_c$ is the volume enclosed by the control dome, $C_{o-c-i}$ and $C_{t-c-i}$ are the dissolved concentrations in the control dome before and after the same time $T$, and $A$ is the sediment area covered by the open dome. $C_{t-i}$ and $C_{t-c-i}$ values were corrected for dilution effects during sampling.

Analytical Methods

Most samples were analyzed for dissolved phosphate, nitrate plus nitrite, ammonium, and silica using a Technicon AutoAnalyzer II (as modified by Ted Walsh, Analytical Services, Department of Oceanography, University of Hawaii). Samples collected during the summer of 1992 were analyzed manually only for dissolved phosphate by standard methods (Strickland and Parsons 1968).

Results

Molecular diffusion was assumed to be inherently independent of wave-induced dispersion. However, since wave-induced mixing was likely to be most intense and
variable in the upper-regions of the reef framework it was essential to examine the relationship of the specific wave conditions occurring during the porewater sampling periods from which the sediment-seawater gradients were derived. In order to calculate dispersive fluxes, the wave-induced dispersion coefficients derived from pressure transducer measurements were therefore matched with the wave-conditions observed during the porewater sampling dates.

Wave conditions during the nutrient profile determinations at Checker Reef can be broadly characterized as being of either large or small amplitude, and from either the N-NE (trade winds) or the S-SW (Kona winds) direction. During periods when the trade winds and N-NE swell were noticeably weak (10/31/91, 2/22/92, 7/2/92, 10/2/92, 11/20/92), waves of relatively low amplitude (A ≤ 2-3 cm) were passing over Checker Reef. Periods of strong trade winds (11/22/91, 12/5/91, 2/1/92, 2/6/92, 2/29/92, 6/12/92) resulted in waves with larger amplitudes (A ~ 7-8 cm) impacting the reef from the N-NE. The effect of a N-NE long-period swell should also result in relatively large amplitude waves (A ~ 7-8 cm) impacting the fore-reef, especially when superimposed on a vigorous trade wind-induced wave pattern. When strong Kona winds were observed (2/19/92 and 2/24/92) large (A ~ 7-8 cm) waves were directed onto the back-reef from the S-SW. A weak Kona wind was also observed during an overnight benthic chamber-experiment on 2/8-9/91, resulting in low wave heights (A ≤ 2-3 cm). As will be shown, waves of relatively large and small amplitude from the N-NE direction were fairly well characterized by pressure transducer measurements. However, I was unable to measure the episodic Kona wind-driven waves with transducers, and instead must rely of visual estimates of wave heights and direction.

This admittedly broad characterization of waves as either large- or small-amplitude, and from the N-NE or S-SW, does not consider the effect of longer-period (i.e., > 5 min) northern swells, since transducer scan-length limitations and a lack of field-opportunities prevented an accurate assessment of these waves. However, the results of Tribble et al. (1992) and others suggest the infragravity waves were not as important as ordinary gravity waves (T ≈ 1-30 s) to vertical porewater exchange. The waves
occurring during the roughest days on the reef were also not measured with pressure transducers due to safety considerations. It should also be noted that the characterization of wave-conditions during the long-term overnight experiments with the benthic flux chambers can only be considered a rough approximate, since the wind and wave direction and magnitude can shift considerably over the course of a day.

Quasi-Synoptic Cross-Reef Experiments

Pressure Head Variation

There were discernible differences in wave conditions at different reef locations during the two quasi-synoptic cross-reef assessments. During the first cross-reef experiment (10/8/92) the winds were light, though there was a sustained N-NE swell. Periodically strong, or "gusty", trade winds characterized the second cross-reef experiment (10/27/92), yet the waves were noticeably smaller in amplitude and of higher-frequency components. The variation with time of the wave-induced hydraulic head for the reference level, and at framework depths of either 0.5 m and 1 m (for station A only) or 1 m and 2 m (for stations C, D, and E), are shown in Figures 3.12 and 3.13 for 10/8/92, and in Figures 3.14 and 3.15 for 10/27/92. The head variations have been normalized around their mean (still water) value, and detrended so that all means were equal to zero.

Figures 3.13-3.15 also show short periods of several seconds when the pressure differences between different levels were up to several centimeters of head. However, the sum of the instantaneous one-second differences between two different levels (i.e. between reference and 1 m, or 1 m and 2 m) for an entire scan is essentially zero. Therefore, since Darcian flow is dependent on pressure gradients, there is little if any net transport of porewaters between framework depths, or between the framework and the overlying waters. This does not imply that nutrient fluxes were zero, however, since they are dependent on the interstitial nutrient gradients existing within this agitating RIW
field and the maximum gradient in vertical velocity, which is set by the root-mean-square internal wave amplitude.

The positive and negative root-mean-square amplitude of reference-waveforms ($A_{\text{rms-ref}}$) are plotted as horizontal lines in Figures 3.12-3.15. The difference between the positive and negative $A_{\text{rms-ref}}$ or $2A_{\text{rms-ref}}$, is the root-mean-square wave height of the reference-waveform ($H_{\text{rms-ref}}$), as indicated. The $H_{\text{rms-ref}}$ clearly brackets most of the vertical variation above and below the zeroed mean. Figures 3.12-3.15 show the dampening of the wave-oscillations of the overlying reference-waveform with increasing framework depth. The framework at all sites is, however, clearly hydrodynamically responsive to the wave-induced seasurface water movement, with root-mean-square amplitudes of 2-5 cm even at framework depths of 2 m (Fig. 3.16). $A_{\text{rms-ref}}$ and $H_{\text{rms-ref}}$ generally decreased across the reef from A to E on both dates. Station C, however, usually had a higher $A_{\text{rms}}$ than station A, on both cross-reef sampling dates (Fig. 3.16). The $A_{\text{rms}}$ at 2 m sediment depth at station C was greater than the $A_{\text{rms-ref}}$ at the back-reef station E on 10/8/92. The $A_{\text{rms}}$ values generally decrease linearly with sediment depth.

Spectral Analyses and Wave-Energy Relationships

Spectral analysis of the waveforms yields a more complete picture of these overall cross-reef trends. The variance, cross-spectral coherence and phase functions are plotted in frequency-space for stations A, C, D, and E (10/8/92) in Figures 3.17, 3.18, 3.19 and 3.20, respectively. Spectral analyses for stations A, C, D, and E on 10/27/92 were shown in Figures 3.21, 3.22, 3.23, and 3.24, respectively. Note the 10-fold difference in the variance scales between the two dates. Clearly, the conditions during 10/8/92 were several fold more energetic than on 10/27/92. While the magnitude of spectral variance is directly proportional to wave energy, the exact energy relationships will be examined in detail after presentation of the cross-reef spectral analyses.
Both days were characterized by a predominant swell which at the fore-reef had a frequency of approximately 0.11 Hz, or 9.20 s period (Figs. 3.17 and 3.21). On 10/8/92 the 0.11 Hz frequency was still observed at station C, though diminished, and higher-frequency components (> 0.16 Hz) were apparent, mostly at two peak frequencies of 0.316 and 0.422 Hz, or 3.2 and 2.4 s periods, respectively. By the time waves had traveled to station D most energy was contained by waves with frequencies about 0.182 Hz (5.5 s period), with a much smaller higher-frequency component broadly distributed around 0.269 Hz (3.7 s period). Waves were greatly diminished at station E, with variance peaks at frequencies of 0.102, 0.214, 0.293, and 0.429 Hz, or 9.8, 4.7, 3.4, and 2.3 s periods, respectively.

The mild trade-wind conditions of 10/27/92 apparently introduced more seasurface ripple in the higher frequency (> ~ 0.19 Hz) end of the spectrum than during the calmer breezes characterizing the larger swell of 10/8/92. On 10/27/92, station A had a large seasurface component at about 0.137 Hz (7.28 s period), with a broad, higher-frequency peak centering around 0.307 Hz (3.26 s period). Seasurface reference variance for station C was also characterized by two broad frequency bands, one from about 0.178-0.114 Hz (5.62-8.80 s period), the other peaking at 0.476 Hz (2.10 s period). The wave energy was greatly diminished at station D, with two small spectral variance peaks around 0.146 and 0.25 Hz (6.84 and 4.00 s period). While station E had a small variance peak at 0.122 Hz (8.20 s period), the trend would suggest that very high frequency (> 0.5 Hz) surface ripples, or wavelets, may have been present but were not resolved due to scan length aliasing dictated by the 1 scan s⁻¹ sampling rate. The higher frequency components all seem to be rapidly attenuated with sediment depth, while the dominant peak at 0.138 Hz (7.28 s period) was transmitted with greater efficiency through the framework.

These relationships are better understood by cross-spectral analysis of the variance between the surface waveforms and the RIW waveforms occurring at either 0.5 m depth (for station A only), or at 1 m depth (all other stations), and between the RIW
waveforms to each other (0.5 m vs. 1 m, for station A only; 1 m vs. 2 m, all other stations). In general there was a lack of coherence in the transmission of the higher frequencies (> 0.16-0.19 Hz) through the framework on both days. Waves were generally transmitted more coherently through the framework during the higher-energy conditions of 10/8/92 compared to 10/27/92. On both days the predominant frequency was transmitted with greater coherency through the framework than higher or lower frequencies. Sometimes there was greater coherence between waveforms occurring in the framework than between the surface and framework waveforms. This was so for stations A and D on 10/27/92. Usually, however, there was greater coherence between the surface waveform and the 0.5 (station A only) or 1 m waveforms, than between the 0.5 and 1 m (station A only) or between the 1 m and 2 m waveforms.

Phase shifts generally were greater with lower wave energy and greater sediment depth. Considerable phase lags develop in wave transmission through the framework. This is especially apparent, on both days, between the 1 m and 2 m depth waveforms at station E. On the higher-energy day (10/8/92) at station C the reference-waveform and the 1 m-waveform, and the 1 m-waveform and 2 m-waveform become progressively out of phase from each other as frequency increased, essentially forming mirror-images of each other, while on the low-energy day (10/27/92) they were clearly more in phase.

The calculated energies of the waves at a uniform reference level or sediment depth peaked at station C on both 10/8/92 and 10/27/92 (Fig. 3.25). As with the vertical profile of $A_{ms}$ (Figure 3.16), the wave-energy decreased from the reference level to 2 m sediment depth (Fig. 3.26). The wave conditions were thus about five fold more energetic on 10/8/92 than on 10/27/92. The internal wave energy of Station A indicated an attenuation of about half of surface wave energy within the upper 0.5 m, but not much more attenuation from 0.5-1.0 m. There also appeared to be greater energy at 2 m depth of station C than in the surface wave energies of the back-reef area. Although wave energy decreases generally across the reef (Fig. 3.25), it is interesting that on both dates (10/8/92 and 10/27/92) station C received more wave energy than station A on the fore-
reef. This may have been a result of both the physical location of the station A wellpoint and the practical realities of sampling on the fore-reef (see Discussion, this chapter).

**Single Reef-Site Experiments**

**Spectral Analyses and Wave-Energy Relationships**

Over the fall of 1992 single sites were examined in greater detail than could be achieved during the cross-reef assessments. Pressure was monitored for longer scan periods (e.g., 10-34 min) at several reef sites and at station A for better resolution with sediment depth. Appendix 1 summarizes the wave parameters derived from spectral analyses of these single-site high-frequency time series.

Station A was the only site examined in detail (i.e., at framework depths of 0, 0.1, 0.25, 0.5, and 1 m) for pressure head variation over the upper meter of framework. During two separate scans on a relatively low-energy day, 9/28/92, the trade winds were mild and a relatively small N-NE trade wind-driven swell ($A_{mn-ref} = 1.77$ cm; Appendix 1) was apparent. There was a frequency-dependent attenuation between the reference level and 0.5 m, but little further attenuation between 0.5-1 m (Fig. 3.27). This result is similar to what was observed in the cross-reef spectral analyses (Figs. 3.17 and 3.21). There was high coherence between the reference- and 0.5 m-waveforms (Ref./0.5 m), and less coherence between 0.5 m- and 1 m-waveforms (0.5 m/1 m), especially at the higher-frequencies. There was very little phase shift with sediment depth, as was also observed during the calmer N-NE swell of the cross-reef assessment of 10/27/92. Spectral analyses of the station A waveforms at 0, 0.10, and 0.25 m show very little frequency-dependent loss in spectral variance with depth (Fig. 3.28). Only the very highest frequencies were attenuated over the 0.25 m depth interval. Cross-spectral coherence between the surface and 0.1 m waves was high except at the very high frequency end and, curiously, at around 0.046 Hz (∼ 21.4 s period). The decrease in coherence at the lower frequency (0.046 Hz) may have been due to insufficient wave-energy in this region, since the spectral variance was very low at frequencies lower than
approximately 0.09 Hz, or an 11 second period. The high coherence between the 0.1 m-and 0.25 m-waveforms (0.1 m/0.25 m) was consistent if most of the frequency-dependent filtering occurs within the upper 0.1 m of the framework. The reference waveform was transmitted through the upper 0.25 m of framework with very little phase shift.

Low phase shifts were also observed at station A on 10/22/92 (Fig. 3.29), again another low-energy day with mild trade winds and a N-NE swell ($A_{rms-ref} = 3.02$ cm, Appendix 1). Unlike 9/28/92, and similar to 10/27/92, the coherence between surface and 0.5 m waveforms of 10/22/92 fell off at frequencies higher than 0.2 Hz.

Mild trade winds and fairly "glassy" wave conditions characterized a long-term overnight monitoring of pressure heads at station C, 10/10-11/92. Station C was monitored at 1 scan min$^{-1}$ for almost 11 h (19:05-07:00), then again briefly after completion of the long-term scan (time 07:00) at 1 scan s$^{-1}$. The spectra of the long-term scan therefore is plotted from $-5.1 \times 10^{-5}$ to $8.3 \times 10^{-3}$ Hz (Fig. 3.30). The spectra of the long-term scan shows a variance maximum at a frequency of 0.003 Hz (330 s period) and several other higher-frequency maxima from $-0.005-0.006$ Hz ($\sim 170-200$ s period). The scan interval was not long enough to determine tidal frequencies with sufficient confidence, and the $A_{rms-ref}$ was less than 3 cm (Appendix 1). The spectra of the longer scan was similar to the spectra from shorter scans in showing a progressive loss of variance intensity with increasing frequency, though most of the dominant reference peaks were present at the same frequencies at 2 m depth. There is again an interesting lack of coherence at two separate lower frequencies, at just above 0.001 Hz (1000 s period) and at just below 0.002 Hz (500 s period). There is relatively low spectral variance and, therefore, energy at these frequencies. The longer-period swell does appear to be coherently transmitted through the framework with little shift in phase.

The spectra of the short-term scan at station C, 10/11/92 (Fig 3.31), taken after the long-term scan, displays a prominent peak at 0.13 Hz (7.55 s period) and several smaller components at 0.26 Hz (3.84 s) and 0.39 Hz (2.56 s). This pattern was similar to the typical pattern observed during a mild trade-induced N-NE swell at station C,
10/27/92 (e.g., compare Figs. 3.22 and 3.31). The total energy of this short term, morning scan was approximately 60% of the total energy of the much longer scan, implying that most energy was usually contained in waves of frequencies $\geq 0.1$ Hz. Cross-spectral coherence of the long-term scan was erratic at frequencies $> \sim 0.0030$ Hz, and was very low at 0.0012 Hz and 0.0010 Hz. Cross-spectral coherence of the short-term scan was strong at 0.13 Hz even between 1 and 2 m sediment depths, and the hydraulic pressure wave was transmitted with little phase shift at this frequency. Coherence breaks down at very high frequencies ($> 0.450$ Hz) and also below about 0.034 Hz. The coherence between the 1 m- and 2 m- waveforms was similarly lower at the lower frequencies. Coherence begins to break down at lower frequencies (frequencies $> 0.2$ Hz) than that between the surface and 1 m spectra. In the short term scan the surface and 1 m waveforms become slowly out of phase as frequencies increased. Larger phase shifts developed between the 1 m- and 2 m-waveforms with increasing frequency.

Similar trends were observed at station C during another overnight experiment from 11/4-5/92, a period characterized by a N-NW swell of about 0.6 m on the outer reef, and moderate trade winds. Pressure head was monitored during three separate times at 1 scan s$^{-1}$ at 16:55 and 19:39, 11/4/92, and at 03:18, 11/5/92. Over this period $A_{\text{rms-ref}}$ increased steadily from 3.1 to 5.5 cm, and the energy increased from 9.9 to 30.0 J m$^{-2}$. The spectra of the three scans (Figs. 3.32, 3.33, and 3.34) show the same bimodal frequency-distribution as observed 10/11/92, with prominent peak frequencies around 0.075 Hz (13 s period) and 0.135 Hz (7.4 s period). Relatively good coherence existed at the dominant frequencies between the waveforms at the reference level and at 1 m sediment depth. Phase shifts were negligible except at frequencies where there was low spectral variance. Poor coherence and considerable phase shifts developed between 1 and 2 m spectra.

Pressure heads were monitored at station E twice, at 1 scan s$^{-1}$, separated by a period of around 11 h. Scan 1 was taken around 16:00, 11/20/92, during extremely calm wind and wave conditions ($A_{\text{rms-ref}} = 1.2$ cm), and a fairly shallow ($\sim 27$ cm) water depth. The spectra indicate that the lower-frequency waves were comparable to the
higher-frequency waves on this noticeably low-energy period (Fig. 3.35). During the night of 11/20-21/92 the winds picked up from the N-NE, the boat shifted and almost pulled the logger overboard, resulting in the loss of a long-term scan (scan 2, at 1 scan min\(^{-1}\)) monitoring of pressure heads. The boat was re-anchored, and by the time of scan 3, 03:08, 11/21/92, the water depth had increased (\(\sim 94.8\) cm), stronger N-NE winds and larger waves (\(A_{\text{rms-ref}} = 6.1\) cm) had developed, and the higher-frequency waves dominated over the lower-frequency waves (Fig. 3.36). The cross-spectral coherence between the reference and 1 m pressure heads from both scans show how the lower-frequency waves (< \(\sim 0.1\) Hz) were almost perfectly transmitted, and in phase, from the surface to 1 m framework depth (Figs. 3.35 and 3.36). The higher frequency components were not coherently transmitted through the framework, and were out of phase between 1 and 2 m framework depth.

Examination of the wave energy profile at station A (Fig. 3.37) shows a rapid linear loss of energy (> 50% of mean surface wave energy) with depth over the upper 0.5 m of the framework. As found previously, there was relatively little further attenuation of energy between 0.5 m and 1 m. Wave energy for the total 11 hr scan (10/10/92) at station C was \(\sim 1.5\) times that of the total 7 min scan. Therefore, considerable energy was missed during the long-term scan at C due to aliasing caused by the 1 min\(^{-1}\) scan rate. During the 11/4-5/92 scans, wave energy developed with regularity over the course of the 11 h, and peak energy was observed on the morning of 11/5/92. The depth profile of wave energy at station E on 11/4-5/92 shows clearly how small the total energy was for scan 1 (beginning 15:52, 11/4/92) in comparison to scan 2 (beginning 03:08, 11/21/92). The energy in the > 0.1 Hz band in scan 2 was about half of the total energy for that period.

**Variation of Wave Amplitude and Energy Across and Within Checker Reef**

The maximum depth to which wave action and energy can drive mixing within the Checker Reef framework can be estimated from linear regression analyses of all cross-reef and single-site determinations of hydraulic head variations (\(A_{\text{rms}}\)) and calculated
wave energy (E), as a function of framework depth (Appendix 2 and 3). This depth is, theoretically, the beginning of the zone where porewater and chemical motion is controlled by molecular diffusion. As previously mentioned, wave-energy (J m$^2$) is proportional to the square of $A_{ms}$ or $E = \frac{1}{8} \rho g H_{rms}^2$, where $\rho$ is the density (kg m$^3$) of the OSW or RIW, $g$ is the gravitational acceleration constant (m s$^{-2}$), and $H_{rms}$ is the root-mean-square wave height (m) or twice the $A_{ms}$ (Denny 1988). The calculation of these regressions assumes that the $A_{ms}$ and wave-energy at the sediment/seawater interface was the same as that measured at the reference level, since there should be negligible frictional losses over the small vertical distance (i.e., 20-40 cm) the reference level is above the interface. Since there were only three data points for each regression the standard deviations for the slopes and y-intercepts were large.

The mean decrease in $A_{ms}$ with framework depth was approximately 1-1.1 cm-$A_{ms}$/m of framework at station A-C, but only 0.5 cm $A_{ms}$/m at station E. The mean framework depth at which $A_{ms}$ was projected to be zero was the shallowest at station A (2.8), deepest at station C (4.7 m), and intermediate (3.4-4.1 m) at stations D and E. The $A_{ms}$ decreased for the most part in a linear manner at stations C-E (mean $r^2 = 0.94-0.96$), and slightly less so at station A ($r^2 = 0.80$). The mean dissipation of wave-energy with framework depth was around 6-8 J m$^{-2}$/m of framework depth at all stations. The framework depth at which wave-energy was projected to be zero was shallowest at station A (1.6 m), and deepest at station C (3 m). Wave-energy decreased linearly with framework depth at stations C-E (mean $r^2 = 0.94-0.96$) and less so at station A (mean $r^2 = 0.79$). The framework depth where solute vertical motion becomes controlled by molecular diffusion is shallower at the fore-reef (station A) and deeper behind the fore-reef (station C).

The regression equations can also allow an estimation of the depth where $A_{ms}$ is the same as the mean pore space dimensions, which are approximated by the mean grain size determinations in Chapter 2. The framework depth where such small $A_{ms}$ occurs is only 2-28 cm above the level of zero $A_{ms}$ and is the thickness of the mixing zone controlled by macroscopic dispersion.
Calculation of $D_{\text{macro}}$ and $D_{\text{mega}}$

The wave parameters and coefficients of macroscopic dispersion ($D_{\text{macro}}$) and megadispersion ($D_{\text{mega}}$) that will be used to estimate wave-driven nutrient flux were derived partially from electronic logging of the natural waveforms during the cross-reef assessments of 10/8/92 and 10/27/92. These days were characterized by either large or small amplitude waves arriving from the N-NE. Estimation of wave parameters, $D_{\text{macro}}$, and $D_{\text{mega}}$, when waves were driven by the S-SW Kona winds, however, were estimated from visual observations of wave amplitudes during the Kona days.

The wave-parameters and wave-induced coefficients derived from the N-NE swells of 10/8/92 and 10/27/92, the days of the cross-reef experiments, are summarized in Table 3.1. Since nutrient flux at the sediment-seawater interface will be interpolated from the nutrient gradient existing across the upper 5-10 cm of sediment, the root-mean-square amplitude of the porewater waveform at 5 cm sediment depth ($A_{\text{rms-pw-5 cm}}$) was interpolated from the root-mean-square reference amplitude ($A_{\text{rms-ref}}$), and the root-mean-square porewater amplitude at 1 m depth, assuming that the root-mean-square amplitude decreases linearly over the vertical distance between the reference level and 1 m sediment depth. For reasons of simplicity in comparing the different reef locations during the two cross-reef scans (10/8/92 and 10/27/92), the $A_{\text{rms-ref}}$ and $A_{\text{rms-pw-5 cm}}$ were assumed to be the product of a monochromatic (single frequency) sine wave. The wave periods ranged from 5.5-9.9 s on both days. The $A_{\text{rms-pw-5 cm}}$ was highest at station C, and lowest at station E, on both days.

The wave-parameters, $D_{\text{macro}}$, and $D_{\text{mega}}$ for the large amplitude S-SW Kona wave event of 2/24/92 are summarized in Table 3.2. Wave period was assumed to be 10 s at all reef locations. The amplitude of $A_{\text{rms-pw-5 cm}}$ was estimated from visual determinations of the significant surf height ($H_s$) using a vertically-oriented meter stick. Munk (1944) determined that a skilled observer of wave heights actually estimates the average height of the one-third-highest waves. $H_s$ at station E was estimated to be approximately 15 cm, and only 3 cm at all other stations. Longuet-Higgins (1952) determined that the root-
mean-square wave heights ($H_{rms}$) were 0.71 of $H$. Therefore the root-mean-square wave amplitude of the wave at the air-sea boundary was 5.3 cm at station E and 1.1 cm at all other stations. From the pressure transducer measurements in the previous sections, it was found that the root-mean-square amplitude of the porewater waveform at 1 m sediment depth was on average 80% of the root-mean-square amplitude of the reference waveform. Therefore, it will be assumed that the root-mean-square wave amplitude at 5 cm-porewater sediment depth is 80% of the root-mean-square amplitude of the waveform observed at the air-sea boundary. Therefore the $A_{rms-pw-5 cm}$ during the Kona event of 2/24/92 was 4.2 cm at station E and 0.9 cm at all other stations.

The Kona S-SW swell of 2/24/92 induced radically different cross-reef patterns of root-mean-square vertical porewater velocity ($w_{rms-pw}$) and residence time (RT$_{upper 10\text{ cm}}$) than those during the N-NE swell (Fig. 3.38). The combination of the different wave direction with higher hydraulic conductivity of the back- and mid-reef framework induces almost an order of magnitude higher vertical porewater velocities in the back- and mid-reef on 2/24/92 than did the N-NE swells of 10/8/92 and 10/27/92. Station A had elevated porewater residence times regardless of the wave-direction, which reflects the strong influence of its almost one-fifth lower hydraulic conductivity than at other stations. During the N-NE swells the $w_{rms-pw}$ within the upper 10 cm of sediment was very low at station A (0.05-0.21 m d$^{-1}$) but an order of magnitude higher at C (0.5-2.17 m d$^{-1}$). It decreased progressively at station D and E. The cross-reef pattern of $w_{rms-pw}$ was reversed during the Kona event, with highest $w_{rms-pw}$ at station E (8.7 m d$^{-1}$), which decreased progressively to a low at station A (0.3 m d$^{-1}$).

The residence times of porewater within the well-mixed upper 10 cm of the framework were estimated by dividing 0.1 m by $w_{rms-pw}$. Station A had the highest RT$_{upper 10\text{ cm}}$ on all dates, 8-48 h (Table 3.2). The lowest RT$_{upper 10\text{ cm}}$ was very low at stations C, D, and E during the Kona day, ranging from only 0.3 h at station E to 0.6 h at station C (Fig. 3.38). The RT$_{upper 10\text{ cm}}$ was lower during the N-NE swell on 10/8/92 (range 1-11 h) than on 10/27/92 (range 5-48 h).
Figure 3.39 illustrates how the macroscopic dispersion coefficients were up to an order of magnitude higher during the S-SW swell (range 14-85 x 10^{-5} cm^2 s^{-1}) than during the N-NE swells (range 1-24 x 10^{-5} cm^2 s^{-1}), again a reflection of the S-SW swell flushing through areas of the reef framework with higher hydraulic conductivities than the fore-reef. D_{macro} was highest at station C on either S-SW or N-NE swells. The range of the D_{macro} values at stations A, D, and E during the N-NE swells were in the approximate range of typical molecular diffusion coefficients.

The megadispersion coefficients were one to two orders of magnitude higher than the macroscopic dispersion coefficients at all stations. Figure 3.39 also shows the cross reef pattern of D_{mega}, which was highest at the back-reef during the Kona condition (31000 x 10^{-5} cm^2 s^{-1}), decreasing progressively away from the back-reef to the fore-reef (300 x 10^{-5} cm^2 s^{-1}). The D_{mega} cross-reef pattern is clearly sensitive to the magnitude and direction of the S-SW swell through the more hydraulically-conducive framework of the back- to mid-reef. D_{mega} during the N-NE swell was highest at station C on both days (range 360-4120 x 10^{-5} cm^2 s^{-1}), and about an order of magnitude higher at all stations on 10/8/92 than on 10/27/92.

**Nutrient Gradients at the Sediment-Seawater Interface**

The sediment-seawater gradients were estimated from the difference in nutrient concentrations between the OSW and the RIW acquired from the shallowest sediment depth available divided by the depth interval. Unless specifically noted, "gradient" will hereafter refer to the concentration gradient interpolated to the sediment-seawater interface. All field data on gradient determinations for phosphate, nitrate plus nitrite, ammonium, and silica are summarized in Appendices 4, 5, 6, and 7, respectively. As mentioned previously, PO_4 was measured more often than any other single nutrient at station D, resulting in gradient determinations for autumn, 1991, spring, 1992, and summer, 1992 (Appendix 2). Also, station A was sampled only during February, 1992. Autumn (1991 or 1992) gradient values were available for stations C and E. Figure 3.40
shows the cross-reef distribution of the mean nutrient gradients \( \pm \) standard deviations for February, 1992.

**Phosphate**

The mean PO\(_4\) gradients for February, 1992, were highest at station A and lowest at station D (Fig. 3.40 and Appendix 4). At station A, PO\(_4\) gradients generally decreased over February from a high of 0.13 \( \mu \text{M cm}^{-1} \) on 2/1/92 to a low of 0.05 \( \mu \text{M cm}^{-1} \) on 2/24/92, but then recovered to 0.11 \( \mu \text{M cm}^{-1} \) by 2/29/92. At station C PO\(_4\) gradients increased steadily from a low of 0.04 \( \mu \text{M cm}^{-1} \) (2/1/92) to a high of 0.08 \( \mu \text{M cm}^{-1} \) (2/29/92). The low phosphate gradients at station D did not vary much over February, 1992 from their mean value of 0.02 \( \mu \text{M cm}^{-1} \). The gradients at station E, however, decreased steadily over February, from a high of 0.07 \( \mu \text{M cm}^{-1} \) (2/1/92) to a low of 0.01 \( \mu \text{M cm}^{-1} \). PO\(_4\) gradients therefore changed similarly over February, 1992 at stations A and E, the stations located on the edge of the Checker Reef platform.

The PO\(_4\) gradients measured at station D on 11/22/91 and 12/5/91 had a mean value of 0.006 \( \mu \text{M cm}^{-1} \), the lowest value observed, while those measured on 6/12/92 and 7/2/92 had a mean value of 0.02 \( \mu \text{M cm}^{-1} \), equal to the mean February gradient. The PO\(_4\) gradient at station D therefore did not seem to change very much over the almost year-long period of sampling. Similarly, the mean phosphate gradient at station C for February was not much different from the mean value for October (1991 and 1992) of 0.06 \( \mu \text{M cm}^{-1} \). The mean phosphate gradient at station E for February, 0.04 \( \mu \text{M cm}^{-1} \), was not much different than that measured 11/20/92 (0.03 \( \mu \text{M cm}^{-1} \)). The rapid shift in wind/wave directions did not seem to have a clearly interpretable effect on phosphate gradients, although the onset of strong trades around 2/29/92 may have resulted in a substantial increase in the gradients at station A, C, and D, with a concomitant decrease in the gradient at station E.
Inorganic Nitrogen

Station A had the most uniformly low, sometimes negative, nitrate plus nitrite gradients during all of February (Figure 3.40, Table 3.4, and Appendix 5). During early February, stations C and D had the steepest NO$_3$+NO$_2$ gradients, and for all of February these stations had relatively stable mean values of 0.29 μM cm$^{-1}$. By late February, however, station E displayed the steepest NO$_3$+NO$_2$ gradients observed during this field study, which may be related to the reversal of the usual trade wind-driven wave pattern by the strong Kona winds of 2/24/92. It is interesting that the gradients at stations C and D generally decreased over February. Station E therefore had the most variable yet highest mean NO$_3$+NO$_2$ gradient, which decreased from station E to a low at station A. The mean gradient for station C determined for October (1991 and 1992) was 0.29 μM cm$^{-1}$, the same as the mean February gradient. The mean gradient for station D determined during the fall of 1991 (0.09 μM cm$^{-1}$) was several fold lower in magnitude than the mean February gradient. Similarly, the 11/20/92 gradient (0.18 μM cm$^{-1}$) at station E was one-half the mean February gradient.

The mean NH$_4$ gradients for February were highest at stations A, D and E, and about 15% lower at station C (Fig. 3.40 and Appendix 6). Station D had low, sometimes negative NH$_4$ gradients in mid-February in contrast to the very high values of 2/1/92 and 2/29/92. The high gradient values can not be excluded statistically as outliers since they were within 2 standard deviations of mean values, yet very low NH$_4$ gradients were also observed on 11/22/91 and 12/5/91. It is difficult to derive a strong relationship between the high gradient values and the strong trade-driven waves occurring on those days, since a low gradient was also observed during a strong trade wind condition on 2/6/92.

Silica

Station A and E had the steepest mean silica gradients during February, 1.5-2.4 μM cm$^{-1}$ (Figure 3.40 and Appendix 7). Lower mean Si gradients characterized the mid-reef stations, C and D, during February, 1992. Station D displayed negative Si gradients
on 12/5/91 and 2/24/92. The strong Kona wind-induced waves of 2/24/92 were coincident with the highest Si gradient observed at the back-reef and the lowest Si gradient observed at the fore-reef.

**Nutrient Flux by Gradient-Generated Molecular Diffusion**

Since Checker Reef occasionally experiences calm periods of low wave-action, molecular diffusion may at these times control nutrient fluxes. Gradient-generated molecular diffusive fluxes of nutrients were calculated by Equation 3.5, using the sediment-seawater gradients and the free solution molecular diffusion coefficients \( D_{so} \) from the literature (Li and Gregory 1974; Ullman and Aller 1982; Wollast and Mackenzie 1984), and a squared geometric tortuosity \( \Theta^2 \) of 3.33. This \( \Theta^2 \) value was arrived at by choosing \( m = 2 \), a value typical for most sandy sediments, in Equation 3.4 for the calculation of a formation resistivity factor (F). This choice resulted in \( F = 4 \), assuming a porosity of 0.5. Because of the low adsorption capability of carbonate sands, no correction was made for nutrient adsorption (Rosenfeld 1979; Mackin and Aller 1984; Williams et al. 1985 a,b; Atkinson 1987; Capone et al. 1992). The following trends in the magnitude and variability of molecular fluxes therefore reflect the same pattern as the nutrient gradients summarized in Tables 3.3-3.6. The cross-reef trends of the mean February fluxes by molecular diffusion will be compared to those by macroscopic dispersion, megadispersion and Tribble's (1990) estimations.

**Phosphate**

During February, 1992, station A had the highest mean molecular diffusive flux of PO₄ \((0.15 \mu \text{moles m}^{-2} \text{ d}^{-1})\), followed in descending order by stations C, E and D (Fig. 3.41 and Table 3.7). The highest PO₄ flux on a single day occurred at station A 2/1/92 \((0.20 \mu \text{moles m}^{-2} \text{ d}^{-1})\), while the lowest was at station D on 11/22/91 and 12/5/91 \((0.01 \mu \text{moles m}^{-2} \text{ d}^{-1})\). The February mean PO₄ flux for station D was no more than 50% of the mean fluxes from stations C and E, and only 25% of the station A flux. Inclusion of flux values from other dates for stations C, D, and E results in mean fluxes not much
different than the February values, though there is higher variability (standard deviation) at stations C and D.

**Inorganic Nitrogen**

The mean molecular diffusive flux of NO$_3$+NO$_2$ was highest (0.15 $\mu$moles m$^2$ d$^{-1}$) at station E during February 1992 (Fig. 3.41 and Table 3.8). During this month the mean molecular diffusive NO$_3$+NO$_2$ fluxes at stations C and D were equal (0.12 $\mu$moles m$^2$ d$^{-1}$). Station A had the lowest mean February NO$_3$+NO$_2$ flux (< 0.01 $\mu$moles m$^2$ d$^{-1}$), less than 7% of the station E mean flux. The highest single-day flux was at station E (0.33 $\mu$moles m$^2$ d$^{-1}$) on 2/24/92, when waves were directed onto the back-reef and a pronounced peak in the NO$_3$+NO$_2$ gradient developed. The lowest flux (-0.02 $\mu$moles m$^2$ d$^{-1}$) was at station A on 2/22/92. Compared to the mean February fluxes, the inclusion of flux values from other sampling dates resulted in slightly lower mean fluxes at stations D and E, while that for station C remained the same. For both February, 1992, and when all other sampling dates were included, the % standard deviation of mean values was lowest at the mid-reef stations and highest at the fore- and back-reef stations.

The variability of mean NH$_4$ fluxes was highest at the mid-reef stations and lowest at the fore- and back-reef stations. During February, 1992, the mean ammonium flux due to molecular diffusion was highest at stations A, D and E, about 1.6-1.9 $\mu$moles m$^2$ d$^{-1}$ (Fig. 3.41 and Table 3.9). During this month station C had the lowest mean NH$_4$ flux, only 14-16% of the mid-reef station mean fluxes. While station A generally had the highest NH$_4$ flux, station D had some of the highest single-day fluxes on 2/1/92 and 2/29/92, ranging from 3.6 - 4.9 $\mu$moles m$^2$ d$^{-1}$. The very low fluxes occurring at station D between these dates, ranging from only -0.1 - 0.3 $\mu$moles m$^2$ d$^{-1}$, resulted in the observed high variability in mean flux at this station. When all other sampling dates were included the mean flux at station E was higher than the mean flux for February, 1992 levels, while the mean fluxes at stations C and D decreased from their respective mean fluxes for February, 1992.
During February, 1992, the mean silica molecular diffusive flux was highest at stations A and E (1-1.5 \( \mu \) moles m\(^{-2}\) d\(^{-1}\)) and several fold lower at stations C and D (Fig. 3.41 and Table 3.10). The variability was greatest at station D but lower and about the same at stations A, C, and E. When the other sampling dates were included, stations D and E had lower mean fluxes than in February, opposite of the case for station C. The highest silica flux occurred on 2/1/92 at station A (1.9 \( \mu \) moles m\(^{-2}\) d\(^{-1}\)), while the lowest occurred on 12/5/91 at station D (-0.2 \( \mu \) moles m\(^{-2}\) d\(^{-1}\)).

**Nutrient Flux by Wave-Induced Macroscopic Dispersion**

All nutrient fluxes by wave-induced macroscopic dispersion were calculated by Equation 3.25.

**Phosphate**

The mean February wave-driven phosphate flux by macroscopic dispersion ranged from approximately 2-10 \( \mu \) moles m\(^{-2}\) d\(^{-1}\) (Fig. 3.41 and Table 3.11), over two orders of magnitude higher than the mean molecular diffusive PO\(_4\) fluxes. Mean macroscopic PO\(_4\) flux was highest at station C, about 2-4 fold greater than the values of the other stations. Station D had the lowest mean macroscopic PO\(_4\) flux during February, 1992 (1.4 \( \mu \) moles m\(^{-2}\) d\(^{-1}\)). Inclusion of data from other sampling dates (stations C, D, and E only) resulted in slightly lower fluxes but did not change the overall station-to-station trends. Therefore, while station A had the highest molecular diffusive PO\(_4\) flux, station C had the highest macroscopic dispersion PO\(_4\) flux.

**Inorganic Nitrogen**

The mean February nitrate plus nitrite flux by macroscopic dispersion (Fig. 3.41 and Table 3.12) ranged from 1-73 \( \mu \) moles m\(^{-2}\) d\(^{-1}\), over two orders of magnitude higher.
than the mean molecular diffusive flux. The mean February NO$_3$+NO$_2$ flux was highest at station E (73 $\mu$moles m$^{-2}$ d$^{-1}$), the result of both the development of a sharp gradient and the direction of waves onto the back-reef during the Kona condition on 2/24/92. At station A, the low hydraulic conductivity and lack of a sharp NO$_3$+NO$_2$ gradient resulted in relatively low macroscopic dispersive fluxes. Not much difference in cross-reef trends in mean flux was discerned when data from other sampling dates were included. The cross-reef trends in mean February flux and mean overall flux were similar to that for molecular diffusive flux.

Mean February ammonium flux by macroscopic dispersion ranged from 6-41 $\mu$moles m$^{-2}$ d$^{-1}$, again about two orders of magnitude higher than the mean molecular diffusive flux (Fig. 3.41 and Table 3.13). The highest mean macroscopic NH$_4$ flux was at station E (41 $\mu$moles m$^{-2}$ d$^{-1}$). During the Kona wave-conditions of 2/19/92 and 2/24/92, station D had very low macroscopic NH$_4$ fluxes (-3 to -5 $\mu$moles m$^{-2}$ d$^{-1}$).

Silica

The range of the mean silica flux by macroscopic dispersion from approximately 10 to 200 $\mu$moles m$^{-2}$ d$^{-1}$ during February, 1992 (Fig. 3.41 and Table 3.14). The mean February silica flux was highest at station E (198 $\mu$moles m$^{-2}$ d$^{-1}$) and much lower at station D (10 $\mu$moles m$^{-2}$ d$^{-1}$). Therefore, while the silica gradients were highest at station A (Table 3.6), the relatively high silica gradient at station E, combined with the direction of waves onto the more hydraulically-conducive back-reef during the Kona condition, resulted in higher silica flux by macroscopic dispersion at station E than at station A.

**Nutrient Flux by Wave-Induced Megadispersion**

All nutrient fluxes by wave-induced megadispersion were calculated by Equation 3.27. For graphical convenience the flux estimates of Tribble (1990) for Checker Reef will be presented (Figure 3.42) with the following calculated fluxes by megadispersion.
Phosphate

The mean February wave-driven phosphate flux by megadispersion was 140-1540 μmoles m⁻² d⁻¹ (Fig. 3.42 and Table 3.15), 2 to 3 orders of magnitude higher than mean PO₄ fluxes by macroscopic dispersion, and over 5 orders of magnitude higher the mean fluxes by molecular diffusion. The mean February PO₄ flux by megadispersion was highest at station E and lowest at station A. Inclusion of data from other sampling dates (i.e. for stations C, D, and E only) resulted in slightly lower fluxes but did not change the overall station-to-station trends.

Inorganic Nitrogen

Mean wave-driven nitrate plus nitrite flux by megadispersion (Fig. 3.42 and Table 3.16) was 60 to 27200 μmoles m⁻² d⁻¹, about 2-4 orders of magnitude higher than flux by macroscopic dispersion and over 5-6 orders of magnitude higher than mean molecular diffusive flux. Mean wave-driven NO₃⁻+NO₂⁻ flux was highest at station E (27200 μmoles m⁻² d⁻¹), again the result of both the development of a sharp gradient and the direction of waves onto the back-reef during the Kona condition on 2/24/92. At station A, the low hydraulic conductivity and lack of a sharp NO₃⁻+NO₂⁻ gradient resulted in relatively low fluxes by megadispersion. Not much difference in cross-reef trends in mean flux was discerned when data from other sampling dates were included.

Mean ammonium flux by megadispersion (Fig. 3.42 and Table 3.17) was 640-15560 μmoles m⁻² d⁻¹, again 2-4 orders of magnitude higher than fluxes by macroscopic dispersion, and about 5 orders of magnitude higher than fluxes by molecular diffusion. The highest and most variable mean megadispersive NH₄⁺ flux was at station E (15560 ± 28310 μmoles m⁻² d⁻¹). During the Kona wave-conditions (2/19/92 and 2/24/92) station D had very low macroscopic NH₄⁺ fluxes (-770 to -670 μmoles m⁻² d⁻¹).
Silica

The mean silica flux by megadispersion was about 1470-70170 μmoles m⁻² d⁻¹ during February, 1992 (Fig. 3.42 and Table 3.18). The mean February silica flux by megadispersion was highest at station E, about an order of magnitude less at C, and about 3 orders of magnitude less at stations A and D. Therefore, while the silica gradients were highest at station A (see Table 3.6), the relatively high silica gradient at station E combined with the S-SW direction of waves onto the back-reef during the Kona condition resulted in higher silica flux by megadispersion at station E. At station C the silica gradient was not as high as at station A or E. At station C the higher hydraulic conductivity (68 m d⁻¹) combined with the reception of most of the trade wind-driven N-NE wave action during February, 1992 resulted in higher wave-induced Si flux by megadispersion than at stations A or D.

The ranges of the mean fluxes of PO₄, NH₄, and Si by wave-induced megadispersion during February, 1992 compare well with the only other flux determinations for Checker Reef based on Tribble's (1990) residence times and gradients over the upper meter of the framework. The residence times of Tribble (1990) were estimated by three different methods: (1) dissolved ²²²Rn concentrations, (2) salinity flux, and hydrological measurements. The first two methods used natural chemical constituents as direct tracers of mixing between OSW and RIW; the latter method estimated exchange based on physical forcing functions (high frequency wave oscillations and long-term pressure gradients). The extremely small and negative NO₃+NO₂ fluxes calculated by Tribble (1990) were not distinguishable from the abscissa on this plot (Fig. 3.42) because Tribble (1990) used an NO₃+NO₂ gradient established between the OSW, and RIW acquired from one meter framework depth, where most of the high porewater NO₃+NO₂ had been consumed (see Chapter 2). When compared to Tribble's (1990) estimates, the high NO₃+NO₂ fluxes calculated by gradient-based, molecular diffusion, wave-induced macrodispersion and megadispersion clearly demonstrate the importance of better resolving the nutrient gradient within the upper layers of the reef framework. The range of PO₄ flux-determinations calculated by the megadispersion model, 0.1-1.5 mmoles PO₄
m² d⁻¹, agrees very well with Tribble’s (1990) reported range, 0.2-1.2 mmoles PO₄ m⁻² d⁻¹. Similarly, the range of NH₄ fluxes calculated by the megadispersion model, 0.6-15.6 mmoles NH₄ m² d⁻¹, agrees well with Tribble’s (1990) reported range, 4-11 mmoles NH₄ m² d⁻¹. The range of mean Si fluxes by megadispersion, 1-70 mmoles Si m² d⁻¹, was also well matched by Tribble’s (1990) mean range, 8-26 mmoles m⁻² d⁻¹. The different cross-reef patterns of PO₄⁻, NH₄⁺, and Si-fluxes by megadispersion and Tribble (1990) may be the result of the pronounced post-rainfall, trade-wind driven waves flushing the framework during Tribble’s (1990) sampling.

**Nutrient Flux by Benthic Chamber-Derived Determinations**

Dissolved nutrient concentrations usually increased with time in the open-bottomed chambers compared to the control chamber with the sealed bottom (Fig. 3.43). The rough and unsafe conditions prevented any overnight diffusive-chamber experiments at the fore-reef station A. Because of the likelihood that the distribution of framework chemical and microbial process is patchy, each dome emplacement should be considered a separate experiment. In some cases only beginning and end-point sampling was possible, while in other cases mid-point sampling allowed greater confidence in the estimates of the net rates of chemical flux. When multiple-point sampling was possible, the reported standard deviations for a single sampling date were based on the error of differences between the rates (slopes) of nutrient accumulation over time in the open-chamber and the rates of nutrient accumulation in the closed-bottomed control chambers. Mean fluxes and standard deviations of the mean fluxes were calculated based on all determinations at a single station.

**Phosphate**

Phosphate flux was measured more often than any other nutrient with the benthic chambers at stations C, D, and E (Table 3.15). Station E had the highest mean PO₄ diffusive flux (90 μmoles m⁻² d⁻¹). The mean PO₄ flux at station D (17 μmoles m⁻² d⁻¹) was around 19% of the station E flux. Station C had the lowest mean PO₄ flux (0.3
μmoles m⁻² d⁻¹), which was only 0.3% as high as the station E mean flux. The high variability of the mean flux at station E, ± 190% of mean flux, was due to the very high flux (413 μmoles m⁻² d⁻¹) determined 7/16-17/92, and the very low flux (-160 μmoles m⁻² d⁻¹) determination of 11/20-21/92. Exclusion of these two outlier values resulted in approximately the same mean flux (75 μmoles m⁻² d⁻¹) with much lower variability (± 39 μmoles m⁻² d⁻¹). The high standard deviation of the mean flux for station C was probably due to analytical error in measuring low PO₄ concentrations.

Inorganic Nitrogen

The fluxes of nutrients other than PO₄ were determined with benthic chambers only once at station D. It is therefore difficult to interpret broad cross-reef trends for these nutrient fluxes compared to those for PO₄ fluxes. However, it is interesting that the lowest mean NO₃+NO₂ flux (Table 3.16) and NH₄ flux (Table 3.17) also occurred at station C. Station C had a mean negative NO₃+NO₂ flux (-6 ± 28 μM m⁻² d⁻¹), while Station D had a very high flux (1233 ± 1406 μM m⁻² d⁻¹). Station E flux (273 ± 183 μM m⁻² d⁻¹) was also considerable, but less than Station D. Chamber-derived mean NH₄ flux was very low and negative at station C (-15 ± 249 μM m⁻² d⁻¹), with substantial variability. Station D had the highest NH₄ flux (318 μM m⁻² d⁻¹), while station E was almost as high (180 μM m⁻² d⁻¹).

Silica

Unlike the station-to-station trend observed for all other chamber-derived nutrient fluxes, silica flux was high at station C (303 ± 682 μM m⁻² d⁻¹) yet very low and negative (-553 ± 1270 μM m⁻² d⁻¹) at station E (Table 3.18). The single chamber-derived determination of silica flux at station D yielded a very high value (1015 ± 166 μM m⁻² d⁻¹), similar to the trend observed for mean NO₃+NO₂ and NH₄ flux but not like that observed for mean PO₄ flux.
Comparison of Flux Determination Methods

The results of the four different methods of flux determination, that is, by molecular diffusion, macroscopic dispersion, megadispersion, and benthic chamber measurements, are shown in Figure 3.44. Megadispersion fluxes were in all cases (PO$_4$, NO$_3$+NO$_2$, NH$_4$, and Si) greater than any of the other flux determinations. Benthic chamber-derived fluxes were usually intermediate between those by megadispersion and macroscopic dispersion. At station C however, the flux of phosphate and nitrate plus nitrite by macroscopic dispersion exceeded those by benthic chamber determinations. Fluxes by molecular diffusion is clearly 4-5 orders of magnitude lower than those by megadispersion, and about 1-3 orders of magnitude lower than those by macroscopic dispersion or by benthic chamber determinations.

Discussion

Pressure Transducers

The T-Hydronics TH-LVA pressure transducers were durable and sensitive indicators of as little as 1 mm of hydraulic head. The use of the sensitive pressure transducers and electronic data logging techniques were clearly successful in demonstrating considerable porewater movement within the framework, up to an $A_{rms}$ of 9 cm even at framework depths of 2 m. Internal wave amplitudes of this magnitude were consistent with the channeling of most RIW flow through the voids and interconnected pore spaces characteristic of carbonate reefs and the coral rubble/sediment of the Checker Reef flat. The large variation in hydraulic head within the framework was consistent with the results of others for wave-impacted reef systems (Roberts et al., 1988, 1992; Carter et al., 1989; Land et al., 1989). Wave amplitudes in excess of 10 cm have also been observed within much more homogeneously-composed sandy beds of both wave-impacted beaches (Sakai et al., 1992) and in experimental wave-tanks (Maeno and Hasegawa 1987 a,b). Fluxes of interstitial solutes within homogeneous beds may also be described by
megadispersion and, given a steep vertical gradient in RIW concentration, could be quite extensive in the more wave-impacted coasts around the world.

The vertical dimensions of mixing by wave-induced hydraulic head variations were two orders of magnitude larger than the approximately 1 mm scale of typical framework pore space dimensions. Mixing by megadispersion was shown to dominate a substantial 3-5 m deep portion of the upper framework, assuming that pressure fluctuations decrease linearly down through the framework. The framework depth at which the vertical $A_{\text{ms}}$ and wave energy become zero, and where mixing is by molecular diffusion, was estimated to be shallowest at the station A framework and deepest at the station C framework, in agreement with their respective hydraulic conductivities of 15 m d$^{-1}$ and 68 m d$^{-1}$ (Tribble 1990). Macroscopic dispersion presumably dominates only over a 2-30 cm thick zone underlying the megadispersion layer, before water motion is controlled by molecular diffusion. Periods of more intense wave action and wave-direction reversal (Kona conditions) may be expected to extend the level of zero dispersion down perhaps another meter at all stations. These estimations could be corroborated in the future by examination of the hydraulic head variation deeper within the framework by using (after repairing) the much deeper well point sampler that exists at station D. The Checker Reef framework has in any case been clearly identified as hydraulically conducive to wave-induced pressure head variations.

Cross-Reef Wave and Wave-Energy Relationships

The cross-reef measurements of vertical wave-induced water motion on and within Checker Reef identified the regions behind the fore-reef proper as areas of greatest wave-energy and mixing between the framework and the overlying waters. However, this unlikely result may be more a product of the "quasi-synoptic" sampling scheme adopted to measure the three hydraulic heads at four reef sites with only three pressure transducers. The cross-reef assessments of hydraulic head took from 3-4 hours to complete. The physical location of the fore-reef well-point sampler, and the practical realities of safely conducting the sampling protocol, prevented measurements of pressure
head at the fore-reef during periods of heavy wave-action and during low-tides. When conducting the cross-reef pressure measurements during typical N-NE trade-wind conditions, station A was the first station monitored and always close to high tide because the waves and the hard coral made it dangerous to study or boat over at lower water depths. By the time station C was monitored the mean water depth had usually decreased by 15-20 cm, resulting in less frictional loss of surface wave energy over and through the framework than was observed at station A. In addition, station A is situated at a slightly deeper site on the patch reef than the other stations (Tribble 1990) and is best described as a small (~2 m²) sand/rubble area closely surrounded by large, lobate coral heads. When the stiff reference-rod, which was connected on one end via flexible tubing to the reference transducer, was fixed vertically to the well-point casing of station A, the top (open) end did not protrude much (if any) higher than the top of the coral heads surrounding the station A sand/rubble area. The coral heads may therefore interfere with some of the wave energy from being transmitted across this sand pocket. Modifications in sampling strategies and techniques which could achieve a truly synoptic assessment of cross-reef hydraulic head will be suggested in the next chapter.

Despite the limitations of the present quasi-synoptic measurements, the general cross-reef distribution of hydraulic heads and wave-energy dissipation were very similar to the few studies by others (Roberts 1980; Roberts and Suhayda 1983; Roberts et al. 1992). Roberts (1980) found that dissipative processes on a St. Croix reef with a low amplitude 10 s swell accounted for a wave energy loss of 65% at high tide when wave attenuation was minimized and about 8% at low tide when the wave-breaking process was maximized. The dissipation of the fore-reef wave energy impacting Checker Reef was around 62-67% at the back reef. Shimada (1973) monitored wave-induced pressure variations with a single, bottom-mounted pressure transducer fixed at 8 m water depth at a site located approximately 700 m north of Kapapa Island. The island is situated on the northern periphery of Kaneohe Bay and forms part of barrier reef which defines the northern extent of the bay. The pressure signals were transmitted via a long cable to an FM transmitter situated on Kapapa Island, which relayed the signal to a receiver/tape recorder at the Hawaii Institute of Marine Biology on Coconut Island (Moku o Loe). The
long-term record of the wave-energies derived from spectral analyses by Shimada extended almost six months, and essentially documented a considerable amount of wave-energy impacting the outer flanks of the barrier reef and framework. The range of total wave energy impacting the barrier reef during weak-to-strong trade-wind conditions was calculated to be approximately 120-500 J m\(^{-2}\) (Fig. 66 in Shimada 1973) compared to 10-70 J m\(^{-2}\) impacting stations A and C during similar conditions. If 70 J m\(^{-2}\) is the amount of wave-energy impacting the fore-reef areas of Checker Reef during a strong trade-wind swell, then I can conclude that wave-energy impacting the barrier reef of Kaneohe Bay is about 60-90\% dissipated by the time the waves impact Checker Reef. The wave amplitudes measured by Shimada (1973) for these energies ranged from 30-60 cm, about an order of magnitude greater than the amplitudes of waves impacting Checker Reef or other similarly-sheltered patch reefs located within the bay. The water depth at which the transducers were placed and the monitoring rate (1 scan/2 s), however, prevented the resolution of waves and associated energies at frequencies higher than 0.25 Hz (or periods \(\geq 4\) s). However, Shimada (1973) documented a concentration of wave energy density centered around wave frequencies from 0.6-1.1 Hz, in good agreement with what I observed in this study.

Shimada (1973) concluded that the relative direction of the local wind or direction of a storm is very important to the amount of wave generation within Kaneohe Bay. Tradewinds usually produce higher waves than do southerly winds, while storms to the northeast, north, or northwest will have a greater effect on the bay than do storms to the southeast, south, southwest, or west (Shimada 1973). Storms to the north or northeast should generate the greatest wave energy, yet neither Shimada nor I were able to electronically document such wave events on the bay. Waves in the 0.6-1.1 Hz frequency band are generated by the strong trade winds, which blow across vast fetches northeast of the Hawaiian Islands. While surface waves over Checker Reef are sometimes composed of higher-frequency components (Figure 3.18 or 3.34) it is the 0.6-1.1 Hz component which is still present at 2 m framework depth and which predominantly drives interstitial mixing deeper within the framework. This component is in almost all cases driven coherently and in phase through the framework. In contrast, the less-energetic
higher-frequency components are progressively filtered, become less coherent, and become out of phase through interaction with the framework. The existence of such a phase lag was also observed by Tsui and Helfrich (1983) and Maeno and Hasegawa (1987 a,b). Okusa (1985) has postulated that such lags are due to the complicated process of energy transfer around the sediment-seawater interface, which involves the roughness of the seabed surface, such as dunes and ripples, the boundary layer thickness over sediments, and the concentration of suspended sediments. The head variations used to calculate wave-induced fluxes are based on wave amplitudes occurring at 5 cm porewater depth from the interpolation of the pressure felt just above the seabed bottom and that measured at either 0.5 m or 1 m framework depth. Therefore the hydraulic head at 5 cm framework depth is a measurement of the net effect of the energy transfer processes through the sediments and does distinguish between bioroughness, boundary-layer influences or other frictional interactions. The $A_{nm}$ derived from spectral analyses seems to be a reasonable averaging parameter for natural waves and wave-induced dispersion. The higher-frequency components (> 0.6 Hz), generated as wave-chop across the fetch of the Bay proper certainly play a role in mobilizing interstitial nutrients near the sediment-seawater interface even though they are extensively filtered with increasing sediment depth.

**Laminar vs. Turbulent RIW Flow in Checker Reef**

The vertical dispersion of solutes does not occur from disorderly turbulence, but from the root-mean-square vertical amplitude of the organized elliptical trajectories followed by the wave-induced RIW particles. Even though the horizontal dimensions of the elliptical paths followed by the RIW particles (Fig. 3.3 C) is approximately $10^3-10^4$ times the vertical $A_{nm}$, this vertical mixing has the potential to drive mixing orders of magnitude higher than by molecular diffusion. The vertical root-mean-square porewater velocities were all $\leq 0.0025$ cm s$^{-1}$, or 3 orders of magnitude less than the upper velocity limit (2 cm s$^{-1}$) for intergranular laminar flow (Muskat 1949). Thus, wave-induced dispersion results from laminar flow. The Reynolds number associated with vertical flow through porous media can be calculated as:
where \( \rho \) is the porewater density, \( w_{\text{rms-pw}} \) is the vertical root-mean-square porewater velocity (m s\(^{-1}\)), \( L_{\text{characteristic}} \) is the characteristic length of flow (m), and \( \mu \) is the dynamic viscosity (N s m\(^{-1}\)). Since \( \rho_{\text{pw}}/\rho \) is equal to \( 1/\nu \), where \( \nu \) is the kinematic viscosity (m\(^2\) s\(^{-1}\)), the Reynolds number expression can be further simplified to

\[
R_e = \frac{(\rho_{\text{pw}})(w_{\text{rms-pw}})(L_{\text{characteristic}})}{\mu}
\]

(3.29)

where \( L_{\text{characteristic}} \) in the case of flow by macrodispersion is approximated by mean pore size or grain size, while in the case of flow by megadispersion may be as high as the step-length, or \( 2A_{\text{rms-pw}} \) (Cherry and Freeze 1979). Using the largest values of \( A_{\text{rms-pw}} \) and \( w_{\text{rms-pw}} \) obtained during either a strong N-NE swell (at station C, 10/8/92), or from estimates of the vigorous Kona waves (at station E, 2/24/92), along with their respective mean grain sizes (i.e., for the macroscopic flow case), and \( \mu = 1.05 \times 10^{-6} \) m\(^2\) s\(^{-1}\) (Vogel 1981), results in \( R_e \) values of 0.04-0.22 for flow by macroscopic dispersion, and 4-8 for flow by megadispersion. Thus wave-induced flow by either mechanism is well under the upper limit of \( R_e \) equal to 10 for laminar flow (Bear 1972).

**Porewater Residence Time**

The very low residence times (RT) for porewater within the upper 10 cm of the framework demonstrates the highly dynamic nature of wave-impacted carbonate sediments. While the more gentle N-NE swell driven waves induced a range of mean RT\(_{\text{upper 10-cm}}\) of 4-34 h, and the more vigorous N-NE swells reduced the RT\(_{\text{upper 10-cm}}\) range to 1-8 h, the very low RT\(_{\text{upper 10-cm}}\) during the Kona swell indicates that the upper 10 cm-porewater at station E renews itself in only 0.3 h (18 minutes). In almost all wave conditions the RT\(_{\text{upper 10-cm}}\) at the fore reef was much greater, with a range of 6 to 34 h, which surely would allow the more complete remineralization of POM/DOM within the interstices by the resident microbial assemblages. The long RT\(_{\text{upper 10-cm}}\) at station A thus
provides confirmation of the hypothesized physical forcing discussed in Chapter 2, which results in the observed low fore-reef RIW nutrient levels and restricted inorganic N:P.

Because of the normally-prevalent trade-driven swell direction, the fore-reef OSW is probably more well-mixed with the surrounding more oligotrophic Kaneohe Bay waters than that at the mid- to back-reef. The dissolved O_2, POM/DOM, and inorganic nutrients will be more completely consumed within the upper 10 cm of fore-reef pore space over the 6-34 hour RT_{upper-10 cm}. The RIW silica at the fore-reef, for instance, increases to a higher concentration by 10 cm sediment depth than at any other station, consistent with the more complete mineralization of a more diatomaceous, more oceanic source, and the less intense organic matter mixing at a shallower depth within the fore-reef framework. Consequently, there is relatively little NH_4 and O_2 around to allow nitrification to regenerate as much NO_3 and NO_2 as observed in RIW of the mid- to back-reef. Microaerophilic N_2O production may occur from the relative stagnation within the fore-reef framework, possibly leading to a loss of fixed-N from the fore-reef framework. Anaerobic denitrification of the relatively low levels of N_2O results in further loss of even more N as N_2 from the fore-reef RIW, resulting in the observed low RIW TIN:P at station A (Fig. 1.3).

Because of the elevated residence times of porewater at the fore- and, to a lesser extent, back-reef, organic substrates are mineralized more completely at a shallower sediment depth than in the mid-reef sediments. At the fore-reef, steep vertical gradients in phosphate, ammonium, and silica are maintained near the sediment-seawater interface, but the mean RIW concentrations of these nutrients do not develop to the high levels observed at 1-2 m sediment depth within the mid-reef framework. It is therefore likely that similarly steep gradients of other RIW components and properties (i.e., O_2, CH_4, pH), may also be present at the fore- and back-reef. However, nitrate-plus-nitrite gradients increased progressively away from the fore-reef, again implying that the development of such gradients depends on the physical stability of the sedimentary habitat and the interplay of nitrifying- and denitrifying-communities. The sharp nitrate-plus-nitrite gradients observed at the back-reef (station E) during the Kona-driven wave events
were consistent with an enhanced "over-production" of NO$_3$+NO$_2$ by the nitrifiers in excess of what could be utilized by the denitrifiers, driven by the increased ventilation (O$_2$ supply) and DOM/POM flux through the permeable back-reef sediments. The ability of the anaerobic denitrifying bacteria to balance the over-production of NO$_3$+NO$_2$ was restricted until the back-reef sedimentary habitat could become more anaerobic, which apparently took several days (i.e., 2/24/92-2/29/92). The Kona wind condition certainly introduced the high variability of the nitrate-plus-nitrite gradient values at the back-reef.

In the rare absence of wave-action, fluxes may be controlled by molecular diffusion. The resulting cross-reef distribution of flux magnitudes would then follow the same trend as the interfacial gradients, with enhanced flux at the fore- and back-reef (e.g., compare Figs. 3.40 and 3.42). The fluxes by gradient-driven molecular diffusion of phosphate, ammonium, and silica were usually highest at the fore- and back-reef, areas where steep interfacial gradients were common. NO$_3$+NO$_2$ molecular fluxes would increase progressively away from the fore-reef, as does their respective gradients. The very low-to sub-μmolar m$^{-2}$ d$^{-1}$ fluxes of any nutrient by molecular diffusion, along with the unlikelihood of periods of no wave-action over the reef, indicate that molecular diffusion is a negligible component in supplying nutrients to benthic reef autotrophs in the long (i.e., yearly) term. However, the hydraulic heads were monitored during one quiescent period at station E, scan # 2, 11/20/92 (Fig. 3.35). This yielded the lowest wave-energy yet recorded for Checker Reef (Appendix 1), and resulted in an A$_{rms-pw}$ of only 7 mm at 2 m framework depth (not shown). Assuming a single dominant frequency of 0.25 Hz (40 s period), this relatively small vertical motion resulted in a D$_{macro}$ of only 0.35 x 10$^{-5}$ cm$^2$ s$^{-1}$ and a D$_{mega}$ of 6 x 10$^{-5}$ cm$^2$ s$^{-1}$. The low A$_{rms-ref}$ of only 1.18 cm during this scan (Appendix 1) resulted in a D$_{macro}$ of 0.6 x 10$^{-5}$ cm$^2$ s$^{-1}$ and a D$_{mega}$ of 10 x 10$^{-5}$ cm$^2$ s$^{-1}$. Typical free solution molecular diffusion coefficients were ≤2 x 10$^{-5}$ cm$^2$ s$^{-1}$. After correcting for the formation resistivity typical of sands and sediment porosity ($\phi$ = 0.5), the effective bulk sediment molecular diffusion coefficient was ≤0.25 x 10$^{-5}$ cm$^2$ s$^{-1}$. The values used in the calculation of fluxes by macroscopic dispersion and megadispersion were based on the results of the cross-reef assessments and were 6-8 fold higher than the above reference values (e.g., see Footnote "a" in Figs. 3.7 and 3.11).
However, the former were probably more accurate since the higher frequency-components clearly shown in Figure 3.35 were not included in the above dispersion coefficient calculations. Still, the contribution by molecular flux clearly became more significant for Checker Reef during the much calmer periods of wave action; thus the sum of the dispersion and diffusion coefficients would have to be used for accurate computations of fluxes across the sediment-seawater interface.

**Variation in $D_{\text{macro}}$ and $D_{\text{mega}}$**

That the $D_{\text{mega}}$ values were over 1-3 orders of magnitude larger than those of $D_{\text{macro}}$, and over 5 orders of magnitude higher than typical molecular diffusion coefficients, were consistent with the impact of waves on a porous carbonate framework. During the cross-reef assessments of the N-NE swells of 10/8/92 and 10/27/92, the $D_{\text{mega}}$ values were always 2-3 orders of magnitude greater than those for $D_{\text{macro}}$ because of the large differences in step-lengths. The $D_{\text{macro}}$ values at station A, D, and E during these N-NE swells were approximately the same as molecular diffusion coefficients ($1-5 \times 10^{-5}$ cm$^2$ s$^{-1}$), with station C about 5 time higher. From these types of results Van der Loeff (1981) discarded wave-action as a significant mechanism for solute flux, since the $D_{\text{macro}}$ expression assumed that the dominant paths of wave-impacted porewater was constrained by an average pore space no larger than the mean sediment grain size. The water within the framework has been now quite well documented to move up and down vigorously, as observed by Tribble (1990) using piezometers, and in partial coherence and phase with passing waves. This motion of water must physically spread in the vertical any solute concentration gradient, thus inducing upward flux in the presence of a positive (downward increasing) concentration gradient. The much larger calculated $D_{\text{mega}}$ values for the N-NE swells of 10/8/92 and 10/27/92 would obviously drive much higher nutrient fluxes. The even more intense Kona wind-driven waves induced tremendously vigorous mixing at the back-reef, primarily because of the four-fold higher $D_{\text{mega}}$ values.

The high values for $D_{\text{mega}}$ were corroborated by estimates of porewater residence time from salinity perturbations, dissolved $^{222}\text{Rn}$ concentrations and hydrological
measurements (Tribble 1990). All of the measurements agreed fairly well to a mean porewater residence time of 1.9 days at 1 m framework depth. Tribble's (1990) salinity determinations were conducted after a heavy rainfall on the bay. Sea conditions were too rough to sample Checker Reef porewaters until after most of the rain event, so the porewater had been diluted by the time of sampling. The wave and wind conditions were still vigorous during the sampling period, and the OSW had already regained its normal salinity values. The rate (from an exponential recovery curve) at which the porewater regained its normal salinity value was used by Tribble (1990) to estimate the intensity of the mixing over the upper meter of framework. Salinity was assumed to be a conservative tracer of mixing, and the more freshwater-diluted was only slightly less saline than typical seawater. As mentioned in the Introduction of this chapter, one can take Tribble's modelled fluxes and his 0-1 m concentration gradients to arrive at an effective dispersion coefficient ($\sim 27000 \times 10^{-5} \text{cm}^2 \text{s}^{-1}$) approximately the same as the $D_{meg}$ values listed in Tables 3.1 and 3.2. As described in the Results section and shown in Figures 3.42 and 3.44, flux estimates from Tribble (1990) and megadispersion agreed very well for $\text{PO}_4$, $\text{NH}_4$, and $\text{Si}$. The lack of $\text{NO}_3^-+\text{NO}_2^-$ at 1 m framework depth was likely the result of consumption by denitrifiers, and the more appropriate gradient documented in the present study for the sediment-seawater interface resulted in much higher $\text{NO}_3^-+\text{NO}_2^-$ fluxes. While the cross-reef distribution of flux estimates from Tribble (1990) and megadispersion differ, this is more a reflection of the high variability introduced on the present data set by the episodic yet vigorous Kona wind condition during the determination of gradients during February 1992. Tribble's (1990) multi-method flux determinations essentially used the mean 0-1 m concentration gradient, but probably his more extensive sampling time series dampened the variability introduced by an occasional Kona condition on the normal pattern of moderate-strong trade winds. Nevertheless, the wave-induced flux of conservative chemical species such as salt ions or $^{222}\text{Rn}$ is apparently well described by the megadispersion mixing model. The agreement between Tribble's (1990) inferred mixing and that by megadispersion is a remarkable indication of the stability of wave-driven nutrient fluxes at Checker Reef. This agreement provides broad support for the conclusion that wave-induced vertical exchange is the primary mechanism driving framework fluxes at Checker Reef.
Benthic Chamber Design and Measured Fluxes

The nutrient fluxes due to molecular diffusion were but a small fraction of the fluxes estimated with the benthic chambers or with the hydrological models (Figure 3.44). This result was expected since the framework porewaters were demonstrated by this study and others to be hydraulically-responsive to wave movement. In the future any hydraulically-conducive sediment subjected to what seems even a modest degree of wave-action should be carefully examined for wave-induced dispersion, even by crude visual determinations. For example, Capone et al. (1992) attempted to estimate NH$_4$ flux from reef sediments from the interfacial gradients and bulk molecular diffusion coefficients, even though one of their reef sites was located in only 2 m deep water and likely subject to some degree of wave-action. Flux models based on molecular diffusion are not appropriate in estimating flux from hydraulically-conducive sediments impacted by any degree of wave action.

Flux estimates from the benthic chambers were usually higher than the macroscopic dispersion fluxes and always lower than megadispersion fluxes (Figure 3.44), but within reported ranges of other chamber-derived fluxes from shallow water sedimentary environments (e.g., see Hopkinson, 1987, and references listed therein). Hansen et al. (1987) found chamber flux rates and variabilities at Davies Reef, Great Barrier Reef, Australia to be similar to those at Checker Reef in their work ($290 \pm 30$ $\mu$mol PO$_4$ m$^{-2}$ d$^{-1}$, $130 \pm 10$ $\mu$mol NO$_3$+NO$_2$ m$^{-2}$ d$^{-1}$, $250 \pm 230$ $\mu$mol NH$_4$ m$^{-2}$ d$^{-1}$, and $1390 \pm 750$ $\mu$mol m$^{-2}$ d$^{-1}$). However, Hines (1985) also had a difficult time demonstrating any flux of either PO$_4$ or NH$_4$ using benthic chambers on the shallow water sediments surrounding Bermuda. Williams et al. (1985a,b) found highly variable sedimentary NH$_4$ and NO$_3$+NO$_2$ fluxes at a wave-impacted back-reef of Teague Bay, St. Croix, U.S.V.I. Their NH$_4$ fluxes were predominantly positive, with a mean of 71 $\mu$mol m$^{-2}$ d$^{-1}$, which compares favorably with the range of mean NH$_4$ fluxes measured by benthic chambers at Checker Reef (-15 to 318 $\mu$mol m$^{-2}$ d$^{-1}$). Their NO$_3$+NO$_2$ fluxes were even more variable, with a mean around -5 $\mu$mol m$^{-2}$ d$^{-1}$, which compares favorably
with the station C mean NO$_3^-$+NO$_2^-$ flux of -6 $\mu$mol m$^{-2}$ d$^{-1}$. The energetic wave action and sediments at station C were similar to the site wave-impacted and "turbulent" site chosen by Williams et al. (1985a,b). In contrast, the much greater NO$_3^-$+NO$_2^-$ chamber-derived fluxes at the more-protected stations D and E (320 and 180 $\mu$mol m$^{-2}$ d$^{-1}$) are consistent with the greater previously-discussed physical stability of the sedimentary habitat at this site. This stability is necessary for the development of sharp NO$_3^-$+NO$_2^-$ gradients which enhance sedimentary fluxes.

Both the megadispersion model and Tribble’s methods are based essentially on the flux of conservative tracers, either the motion of water (hydrology) or the flux of dissolved salts. Essential nutrients may be agitated to flux by wave-induced hydraulic head variations, but do they actually flux out to the surrounding benthic biota or are they consumed by framework microbial assemblages? The benthic chamber-based fluxes suggest that only about 10% of the wave-driven flux of PO$_4^-$, NH$_4^+$, and Si is actually getting out to the overlying water column. Compared to free-living assemblages, the communities inhabiting the coral surface microlayer and associated sediments have been shown to have 1-50 times the growth rate (Paul et al. 1986), and enhanced metabolic rates (Hines 1985; Schiller and Herndl 1989; Capone et al. 1992).

Before comparisons are made, however, one should consider whether the benthic chambers used in this study actually measure the diffusive or dispersive fluxes for which they were designed. The use of stirred benthic chambers has become the standard tool for measuring diffusive solute transfer, and the design of the chambers in this study was very similar to that employed by many others in terms of enclosed volume and covered sediment area (see review by Malan and McLachlan 1991). The covering of the chambers with the opaque, aluminized "Airplane" tape, the large tape-coated skirt surrounding the base of the chamber, and the dusk-to-dawn duration of the chamber experiments certainly inhibited extensive autotrophic growth and nutrient drawdown. Alternatively, the large area covered by the chamber-skirt may have interfered with wave-induced dispersion and flux. In future research, chambers of various dimensions should be examined in a
systematic manner for differences in flux determinations, perhaps in a wave-tank with a deep sandy bottom.

Previous research has demonstrated that excessive stirring can drastically influence flux rates (Boynton et al. 1981; Callender and Hammond 1982; Huettel and Gust 1992a,b). The use of the "jet" stirrer (bilge pump; Figure 3.11) set-up in the benthic chambers of this study produces a slow, circular flow within the inverted benthic chambers which seemed to mix completely within 5 min (see Methods section). This flow may force a higher pressure at the chamber's internal wall, since centrifugal forces could drive the water down toward the circumference of the chamber (Prandtl and Tietjens 1957). Lower pressure in the center may induce a secondary circulation pattern, drawing water being forced down the walls up though the center. However, it was necessary to stir the benthic chambers to prevent the development of a stagnant boundary layer at the sediment-seawater interface, which would allow the formation of a concentration gradient that could retard the actual upward flux. The stirring rate for the chambers employed in this study was kept at a minimum to avoid possible disturbance of the enclosed sediment.

Bioturbation by benthic animals can form a major component of chemical flux, and can enhance porewater exchange with OSW through irrigation, burrowing, and sediment mixing (Aller 1988; Kristensen 1988; Huettel 1990; Pelegri et al. 1994). If stirring within the chamber actually pushed water down into the sediment, it may ventilate portions of the upper sediment with $O_2$. The sudden shift in oxygen and hydrogen sulfide concentrations may change the behavioral patterns of the bioturbating fauna, most of which are sensitive the $O_2/H_2S$ level in the inhabited part of the upper sediments (Reise 1985). A bottom dweller may even abandon its normal ventilation and irrigation activities if enough oxygen is pumped down into its burrow tube (Huettel and Gust 1992a). This new microzonation may then influence the activities of meiofauna, benthic macroalgae, and bacteria, thus disturbing the activities of the communities producing the remineralized nutrients the chamber was attempting to collect.
Another concern with using the benthic chambers, however, involves the possibility of "washout" of the enclosed volume by the pressure gradients induced by a unidirectional flow over an object protruding from the sediment. Huettel and Gust (1992 a,b) have measured an enhanced mixing of porewaters induced from the lateral flow of water over objects placed on a sediment bed in a flume. In one experiment, bell jars resting over a large sandy sediment were subjected to various intensities of lateral flow, up to current velocities of 10 cm s⁻¹. The jars were 25 cm in diameter and were stirred in a circular fashion with a magnetic stir bar, and pressure ports in the flume allowed the monitoring of differential pressure between the inside and outside of the jars. When a chamber was subjected to currents of 10 cm s⁻¹, pressure transducers located on the outside and inside of the chamber detected a lower pressure inside the bell than outside, due to the local flow acceleration around and over the jar (Figure 3.44 A). When subject to flow velocities of around 10 cm s⁻¹, considerable "washout" of the enclosed volume of dyed-waters could be observed. Lateral currents with velocities from approximately 1-10 cm s⁻¹ can certainly be expected to pass over Checker Reef (Bathen 1968; Atkinson 1987). Ignoring the likelihood of oscillatory flow over a wave-impacted reef flat for the moment, the effect of a 10 cm s⁻¹ lateral current on the chambers used for Checker Reef should not produce significant "washout" of their enclosed volume. Figure 3.44 B shows a cross-section of a typical benthic chamber used on Checker Reef. The prominent peripheral skirt (15 cm wide) surrounding the base of the chamber and the cylindrical flange, which penetrates 7.5 cm into the sediment, should interfere and decouple flow from the enclosed volume, according to the conclusions of Huettel and Gust (1992a). Wave-driven oscillatory flow should tend to cancel out temporarily-induced and localized pressure gradients around a benthic chamber, due to flow reversal. These concerns can be carefully examined in the future by measuring the pressure outside (i.e., a reference pressure) and inside the chambers with the transducers, after placement on Checker Reef during periods of high- and low- wave action. The flexible tube(s) from the pressure transducer(s) could be attached to various ports drilled into the chamber wall so as to be specific heights above the sediment-seawater interface enclosed by the chamber, and/or specific distances from the chamber wall into the chamber volume.
The high variability in the benthic chamber-derived fluxes may also have been the result of mechanical disturbance of the chambers by wave action. The chambers were usually in less than 1 m of water and had to be heavily weighted to avoid wave-induced movement of the chambers. It is possible however, that the weights were insufficient to hold the chambers firmly in the sediment during periods of heavy reef wave action. Most benthic chamber flux studies by others usually operate in much deeper water, which permits withdrawal of samples using SCUBA with minimal mechanical disturbance of the chambers. Sampling the Checker Reef domes with syringes in the shallow water at night during periods of wave-activity was difficult and tedious, and the chambers were occasionally kicked, which may have promoted nutrient efflux from disturbance of the sediments enclosed by the chambers. Disturbance of the sediments was possible even during periods of low wave-activity, visible light and sufficient chamber weights, simply by the action of walking very close to the chambers which may have sent shock-waves through the sediments surrounding the chambers and porewater into the chamber volumes. Since the domes were thoroughly opaque to light, and were deployed only from dusk-to-dawn experiments, it is unlikely that photosynthetically-enhanced nutrient uptake influenced the high variability in observed flux.

Each benthic chamber should be viewed as an individual experiment on sedimentary nutrient flux, since the chambers were placed in slightly different areas close to the station well points during each separate experiment. The relatively uniform, fine-grained sediments of station E usually resulted in good penetration of the flange. However, the sediments at stations C and D were characterized by coral rubble, which could interfere with penetration of the equatorial flange on the chamber, thus preventing a good seal of the dome to the sediment. Earlier versions of the chambers attached the equatorial flanges in a stressed state, which occasionally resulted in cracks after use in the field. Later versions attached the curved flanges in a heat-induced pre-formed state which increased their strength and reliability in penetrating into the sediment. The ability of the plexiglass surfaces to adsorb nutrients was not examined. However, the domes were scrupulously cleaned before and after each field experiment. Future versions of the chambers could employ teflon-coating of the chamber internal walls, and the use of a
teflon-coated stainless steel flange, in order to avoid any harmful toxic effects of the plexiglass or plexiglass glues on the enclosed microbial communities, no matter how minimal. Optimally, the flange should be detachable from the chamber to facilitate penetration into the sediment, and its upper edge should protrude several centimeters above the sediment-seawater interface. The chamber could then be routinely attached and sealed to the flange with a large O-ring and plastic wing-nuts. Theoretically, these sturdy, durable flanges could be left in place in the reef sediment, open to the elements, but allowing preservation of the sedimentary structure and accompanying microbial habitat within and around its circumference. Re-cleaned chambers could therefore be returned to the same site and disturbance of the sediment by their emplacement would be greatly reduced. Reproducibility and reliability of chamber-derived fluxes would likely be significantly enhanced.

The chamber-derived flux values were so tremendously variable that probably vast improvements are needed in chamber design and theory. Malan and McLachlan (1991) were able to demonstrate enhanced O₂ consumption within cylindrical chambers which were not stirred but had instead a flexible polyethylene/nylon membrane which deformed under wave action. They thought this would help mimic pressure differential due to wave action, and render a more realistic assessment of sedimentary flux. The flexible membrane then acts like a piston pump, which is essentially the effect that wave action exerts on RIW mixing through megadispersion. Their research did, however, suggest that multiple, small volume enclosures may render better accuracy and confidence in chamber-based flux determinations than do larger chambers.

The relative flux values can now be compared to the removal rates of nutrients by benthic reef communities measured by Atkinson (1987) and other investigators. The gross productivity (or uptake) of most reef communities is around 500 mmol C m⁻² d⁻¹ (Kinsey 1985). Because most reef benthic autotrophs have a C:N:P of around 500:30:1, the actual nutrient need for the community to sustain itself is at most only 1 mmol P m⁻² d⁻¹ and 30 mmol N m⁻² d⁻¹ (Atkinson and Smith 1983). Given that a standing stock of a typical reef flat is around 25,000 mmol C m⁻², the gross productivity per unit biomass
is only 2% d⁻¹ (Lewis 1977; Atkinson 1988). Most reef algae have a specific growth rate near 2% d⁻¹, and do not necessarily need to quickly recycle N and P. The removal rate of PO₄ passing over a reef flat is typically only 1 mmol P m⁻² d⁻¹ (Atkinson 1987; Atkinson and Smith 1987). Therefore reef autotrophs may be supplied with most of their nutrients from the waters flowing over, and not necessarily through, the framework.

An upper boundary on nutrient uptake by reef autotrophs can be set by using the bulk OSW nutrient concentrations described in Chapter 2, and the more recent work on mass transfer limited rate constants for nutrient uptake into a reef community subjected to horizontal advection (Bilger and Atkinson 1992, and in press; Atkinson and Bilger 1992). The apparent first order rate constants for PO₄ and NH₄ removal by a living coral/coral rubble assemblage were determined by the drawdown in concentrations of added nutrients in a flume at current speeds from 4 to 39 cm s⁻¹. The community within the flume did not have a substantial coral sediment component, and is probably representative of a net autotrophic reef system. The Checker Reef flat is a net heterotrophic system (Tribble 1990), so the flume community uptake rates, if applied to Checker Reef, set the maximum rate of nutrient uptake by benthic autotrophs at the reef flat surface. Nevertheless the horizontal current velocities used in the flume studies were typical of what is usually observed on the Checker Reef flat (Morrissey 1985) and in Kaneohe Bay in general (5-15 cm s⁻¹; Bathen 1968). At current velocities around 10 cm s⁻¹ typical first order rate constants obtained for phosphate uptake (S₀) were about 20 x 10⁻⁶ m s⁻¹, while those for ammonium uptake were 100 x 10⁻⁶ m s⁻¹. The rate constants for different nutrients scale approximately as their free solution molecular diffusion coefficients (Atkinson, personal commun), so the rate constant for nitrate plus nitrite uptake and silica uptake are probably around 10 x 10⁻⁶ m s⁻¹ (see legends in Tables 3.3-3.6). Multiplying these rate constants times the mean OSW concentrations at Checker Reef for February, 1992 (Figure 2.7) yields uptake rates by benthic reef autotrophs of approximately 170-260 μmoles PO₄ m⁻² d⁻¹, 170-290 μmoles NO₃+NO₂ m⁻² d⁻¹, 2500-3500 μmoles NH₄ m⁻² d⁻¹, and 3600-5800 μmoles Si m⁻² d⁻¹.
It is interesting to compare these uptake rates to the various mean flux rate estimates, as shown in Figure 3.45. The flux estimates by molecular diffusion, macroscopic dispersion and megadispersion are means of all sampling dates (Tables 3.3-3.14). In this figure the log of the negative benthic chamber fluxes (Tables 3.15-3.18) are indicated to be off-scale by an arrowhead. As shown previously (Figure 3.42), flux estimates by megadispersion were well-matched by multi-approach estimates of Tribble (1990), and rigorously confirms that interstitial mixing is controlled by megadispersion.

However, it also can be seen that uptake by benthic reef autotrophs is approximately matched by fluxes from megadispersion and Tribble's (1990) estimates. If reef plants are receiving adequate nutrients from the water column then where are the wave-driven nutrient fluxes being consumed? Perhaps the projected high fluxes by wave-induced megadispersion are actually occurring and contributing to the productivity of the benthic reef plants. This wave-associated production of reef benthic plants and their associated community may occur during times of intense wave-pumping and megadispersion, but may also result in the convective transport of the "excess" production and biomass as detritus. The wave-forcing may drive higher gross community productivity, yet this productivity was not properly assessed, perhaps because of the more dangerous conditions and sampling difficulties imposed when conducting productivity measurements on a reef flat subject to intense wave-action and storms. Because of the methodological difficulties with the benthic chambers, neither possibility can yet be disregarded.

If the benthic chamber-derived fluxes are accurate, then this implies that most (~90%) of the framework nutrient flux is consumed in the upper 5-10 cm of sediment before it ever escapes to the overlying waters and autotrophs. This would imply that the gross community productivity of the framework microbial communities in this shallow sedimentary layer is almost as great as that of the surface community (i.e., 500 mmol m⁻² d⁻¹). As previously mentioned, the communities inhabiting the coral surface microlayer and associated sediments have been shown to have 1-50 times the growth rate (Paul et al. 1986), and enhanced metabolic rates, compared to free-living assemblages
(Hines 1985; Schiller and Herndl 1989; Capone et al. 1992). Carbonate sediments are unusual microbial habitats compared to typical sediments in that light is not as readily occluded with sediment depth, and is transmitted at certain wavelengths through the visually "opaque" carbonate sediments (R. Johnstone, personal commun. to F. Sansone). Sediment disturbance and resuspension by wave-action could further enhance light-penetration. Thus, enhanced autotrophic growth and nutrient uptake is possible by interstitial algae, and this consumption before reaching the sediment seawater interface would explain the low observed flux determinations by the benthic chambers.

Finally, megadispersion can "spread" porewater nutrients down into the sediment as well as up into the overlying water column. In this context it is interesting to compare the observed decreases in nitrate plus nitrite porewater concentrations below their typical concentration peaks (Figure 2.9) to known removal mechanisms by denitrification. Negative NO$_3^-+$NO$_2^-$ gradients (i.e., concentrations decreasing downward) occurred below 5-10 cm depth, and were as high as 0.5 $\mu$M cm$^{-1}$ at station E. NO$_3^-+$NO$_2^-$ consumption rates can be estimated by multiplying these negative gradients by the mean megadispersion coefficients observed for each station during Trade- and Kona-driven conditions (Tables 3.1 and 3.2). Therefore, within the upper 10-50 cm the NO$_3^-+$NO$_2^-$ consumption rate was 20-60 $\mu$moles N m$^{-2}$ d$^{-1}$ at station A, 780-2900 $\mu$moles N m$^{-2}$ d$^{-1}$ at station C, and 1100-1600 $\mu$moles N m$^{-2}$ d$^{-1}$. At station E the sharp decrease in NO$_3^-+$NO$_2^-$ concentrations below 5 cm sediment depth resulted in a removal rate as high as 42000 $\mu$moles N m$^{-2}$ d$^{-1}$, which decreases to around 1000 $\mu$moles N m$^{-2}$ d$^{-1}$ by 50-100 cm sediment depth.

These denitrification rates are well matched to the estimates of Tribble et al. (1989) which averaged about 1310 $\mu$moles m$^{-2}$ d$^{-1}$, and ranged from 60 to 9800 $\mu$moles m$^{-2}$ d$^{-1}$. Acetylene blockage incubation experiments conducted by Seitzinger and D'Elia (1985) at Abrahams Bay, Bahamas yielded denitrification rates of 1200 $\mu$moles m$^{-2}$ d$^{-1}$. Denitrification rates within coral reef sands have been reported by Corredor and Capone (1985) to be 2420-4860 $\mu$moles m$^{-2}$ d$^{-1}$. Smith (1984) has reviewed data from three "whole-system" studies with denitrification rates around 60-1890 $\mu$moles m$^{-2}$ d$^{-1}$. The loss
of fixed nitrogen in the sediments is probably equaled by nitrogen fixation (Tribble et al. 1988), as many studies report N-fixation rates of approximately 1310 µmoles m⁻² d⁻¹ in reefs (Wiebe et al. 1975; Hanson and Gundersen 1977; Wilkinson et al. 1984). The wave-induced N removal rates seem to be reasonably well matched by measured denitrification rates. Mixing by wave-induced megadispersion again seems to be well-matched by expected metabolism rates, and the model is again confirmed.

**Conclusions**

Waves with frequencies around 0.6-1.1 Hz are efficiently and coherently driven through the porous Checker Reef framework. Their origin derives from strong trade winds blowing far to the NE of the Hawaiian Islands. Occasionally, vigorous Kona winds will drive waves onto the back of Checker Reef, essentially "back-flushing" nutrients out through the more hydraulically-conducive back-reef sediments. Wave-energy and $A_{rms}$ dissipate in a regular, easily understood cross-reef pattern in accordance with the degree of frictional interaction of the waves with the reef flat. The pressure transducers were sensitive indicators of porewater movement, and demonstrate the possibility that wave-driven framework nutrient fluxes may theoretically exceed that provided by onflowing surface seawater. New benthic chamber designs are recommended to address this paradox of having too much nutrient supply possible for the gross productivity measured for reef flats. Mixing of OSW and RIW is controlled by megadispersion, which in turn controls metabolic rates within the framework. Thus, physical forcing, rather than biological mechanisms, appears to control reef growth and metabolism.
Table 3.1. Cross-reef wave parameters during two N-NE swells at Checker Reef, and the calculated coefficients of macroscopic dispersion ($D_{\text{macro}}$) and megadispersion ($D_{\text{mega}}$) projected to the sediment-seawater interface. Water depth (d), wave-period ($T_{\text{ref}}$), -length ($\lambda_{\text{ref}}$), -number ($A_{\text{ref}}$), -total spectral energy ($E_{\text{ref}}$), root-mean-square wave amplitude ($A_{\text{rms-ref}}$), the porewater root-mean-square wave amplitude at 5 cm sediment depth ($A_{\text{rms-pw-5 cm}}$), and the porewater root-mean-square vertical velocity in the upper 10 cm sediment depth ($w_{\text{rms-pw}}$), were derived from spectral analyses.

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<tr>
<td>$\lambda_{\text{ref}}$ (m)</td>
<td>24.9 16.4 26.2 32.1</td>
<td>15.7 14.6 15.9 21.3</td>
</tr>
<tr>
<td>$A_{\text{ref}}$ (m$^4$)</td>
<td>0.40 0.43 0.39 0.29</td>
<td>0.25 0.38 0.24 0.20</td>
</tr>
<tr>
<td>$E_{\text{ref}}$ (J m$^2$)</td>
<td>19.9 32.2 70.6 51.9</td>
<td>3.2 7.2 14.4 9.8</td>
</tr>
<tr>
<td>$A_{\text{rms-ref}}$ (cm)</td>
<td>7.2 8.4 5.7 4.4</td>
<td>3.1 3.8 2.7 1.8</td>
</tr>
<tr>
<td>$A_{\text{rms-pw-5 cm}}$ (cm)</td>
<td>4.2 5.2 8.2 6.7</td>
<td>1.6 2.4 3.1 2.5</td>
</tr>
<tr>
<td>$w_{\text{rms-pw}}$ (m d$^{-1}$)</td>
<td>0.91 1.14 2.17 0.29</td>
<td>0.22 0.46 0.50 0.07</td>
</tr>
<tr>
<td>$R_{\text{T upper 10-cm}}$ (h)</td>
<td>2.6 2.1 1.1 8.3</td>
<td>10.9 5.2 4.83 34.3</td>
</tr>
<tr>
<td>$D_{\text{macro}}$ ($10^5$ cm$^2$ s$^{-1}$)</td>
<td>4.3 4.5 24.1 5.3</td>
<td>1.0 1.8 5.5 1.3</td>
</tr>
<tr>
<td>$D_{\text{mega}}$ ($10^5$ cm$^2$ s$^{-1}$)</td>
<td>882 1372 4119 450</td>
<td>81 255 359 43</td>
</tr>
</tbody>
</table>

- $a$ Wavelength calculated by shallow-water approximation.
- $b$ $A_{\text{rms-pw-5 cm}}$ is the $A_{\text{rms-pw}}$ at 5 cm sediment depth, and was extrapolated from $A_{\text{rms-ref}}$ and the $A_{\text{rms-pw}}$ at sediment depths of either 0.5 m (station A only) or 1 m (all other stations).
- $c$ $A_{\text{rms}}$, $w_{\text{rms-pw}}$, $D_{\text{macro}}$, and $D_{\text{mega}}$ calculated assuming sediment porosity of 0.5, and a hydraulic conductivity of 15 m d$^{-1}$ at station A, 68 m d$^{-1}$ at station C, 51 m d$^{-1}$ at station D, and 54 m d$^{-1}$ at station E.
- $d$ $D_{\text{macro}}$ calculated assuming mean grain was 1.59 mm for station A, 0.96 mm for station C, 0.34 mm for station D, and 0.41 mm for station E.
Table 3.2  Cross-reef wave parameters during the Kona wind-event at Checker Reef, 2/24/92, and comparison of the coefficients of macroscopic dispersion (D_{macro}) and megadispersion (D_{mega}), which were both projected to the sediment-seawater interface. Surface wave-period (T) was assumed to be 10 s at all stations. Water depth (d), surface wave-length (λ), -number (Λ), -total spectral energy (E) were all based on visual observations.

<table>
<thead>
<tr>
<th>Checker Reef Station</th>
<th>E</th>
<th>D</th>
<th>C</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>d (m)</td>
<td>0.42</td>
<td>0.42</td>
<td>0.40</td>
<td>0.70</td>
</tr>
<tr>
<td>T_{ref} (s)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>λ_{ref} (m)</td>
<td>20.3</td>
<td>20.3</td>
<td>19.8</td>
<td>26.2</td>
</tr>
<tr>
<td>Λ_{ref} (m^{-1})</td>
<td>0.31</td>
<td>0.31</td>
<td>0.32</td>
<td>0.24</td>
</tr>
<tr>
<td>E_{ref} (J m^{-2})</td>
<td>14.1</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>A_{rms-ref} (cm)</td>
<td>5.3</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>A_{rms-pw-5 cm} (cm)</td>
<td>4.2</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>w_{rms-pw} (m d^{-1})</td>
<td>8.7</td>
<td>5.5</td>
<td>3.8</td>
<td>0.4</td>
</tr>
<tr>
<td>R_{T upper 10 cm} (h)</td>
<td>0.3</td>
<td>0.4</td>
<td>0.6</td>
<td>5.9</td>
</tr>
<tr>
<td>D_{micro} (x 10^{-5} cm^2 s^{-1})</td>
<td>82.4</td>
<td>43.0</td>
<td>85.5</td>
<td>14.2</td>
</tr>
<tr>
<td>D_{mega} (x 10^{-5} cm^2 s^{-1})</td>
<td>30610</td>
<td>8660</td>
<td>3044</td>
<td>304</td>
</tr>
</tbody>
</table>

*a Wavelength calculated by shallow-water approximation.
*b A_{rms-pw-5 cm} is the root-mean-square porewater wave amplitude at 5 cm sediment depth. A_{rms-pw-5 cm} was estimated as 20% of the root-mean-square surface wave-amplitude (A_{rms-surf}). A_{rms-surf} was estimated as 0.71 times the visually-estimated significant surface wave-amplitude according to Longuet-Higgins (1952).
*c A_{max}, w_{rms-pw}, D_{macro}, and D_{mega} calculated assuming sediment porosity of 0.5, and a hydraulic conductivity of 15 m d^{-1} at station A, 68 m d^{-1} at station C, 51 m d^{-1} at station D, and 54 m d^{-1} at station E.
*d D_{macro} calculated assuming mean grain was 1.59 mm for station A, 0.96 mm for station C, 0.34 mm for station D, and 0.41 mm for station E.
Table 3.3  Cross reef variation in flux by molecular diffusion of inorganic phosphate (μmoles m⁻² d⁻¹) for Checker Reef, Oahu. Positive flux is upward, out of the sediments into the overlying water. Flux was calculated by Equation 3.5, using a φ equal to 0.5, a Dₕ for HPO₄²⁻ at 25°C of 0.73 x 10⁻⁵ cm² s⁻¹, and the $\partial C_p/\partial z$ listed in Appendix 4.

<table>
<thead>
<tr>
<th>Date</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
<th>Station A</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/31/91</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.13</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/22/91</td>
<td>n.d.</td>
<td>0.01</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>12/5/91</td>
<td>n.d.</td>
<td>0.01</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/1/92</td>
<td>0.10</td>
<td>0.04</td>
<td>0.06</td>
<td>0.20</td>
</tr>
<tr>
<td>2/6/92</td>
<td>0.09</td>
<td>0.05</td>
<td>0.0</td>
<td>0.13</td>
</tr>
<tr>
<td>2/19/92</td>
<td>n.d.</td>
<td>0.02</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/22/92</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.14</td>
</tr>
<tr>
<td>2/24/92</td>
<td>0.07</td>
<td>0.02</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>2/29/92</td>
<td>0.02</td>
<td>0.04</td>
<td>0.13</td>
<td>0.17</td>
</tr>
<tr>
<td>6/12/92</td>
<td>n.d.</td>
<td>0.03</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>7/2/92</td>
<td>n.d.</td>
<td>0.03</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>10/2/92</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.06</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/20/92</td>
<td>0.05</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

2/92 Mean 0.07 0.04 0.09 0.15
± s.d. 0.04 0.01 0.03 0.04

All station-data mean 0.07 0.03 0.09 0.15
± s.d. 0.03 0.01 0.03 0.04

* n.d. = Not determined.
*b s.d. = Standard deviation.
c Station A was sampled only during February, 1992.
Table 3.4  Cross reef variation in flux by molecular diffusion of dissolved nitrate plus nitrite (μmoles m⁻² d⁻¹) for Checker Reef, Oahu. Positive flux is upward, out of the sediments into the overlying water. Flux was calculated by Equation 3.5, using a φ equal to 0.5, a $D_o$ for $\text{NO}_3^- + \text{NO}_2^-$ at 25°C of $0.1905 \times 10^{-5}$ cm²s⁻¹, and the $\partial C_p/\partial z$ listed in Appendix 5.

<table>
<thead>
<tr>
<th>Date</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
<th>Station A</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/31/91</td>
<td>n.d.*</td>
<td>n.d.</td>
<td>0.17</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/22/91</td>
<td>n.d.</td>
<td>0.03</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>12/5/91</td>
<td>n.d.</td>
<td>0.04</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/1/92</td>
<td>0.03</td>
<td>0.06</td>
<td>0.11</td>
<td>0.02</td>
</tr>
<tr>
<td>2/6/92</td>
<td>0.02</td>
<td>0.18</td>
<td>0.15</td>
<td>0.02</td>
</tr>
<tr>
<td>2/19/92</td>
<td>n.d.</td>
<td>0.13</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/22/92</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>-0.02</td>
</tr>
<tr>
<td>2/24/92</td>
<td>0.33</td>
<td>0.09</td>
<td>0.14</td>
<td>0.21</td>
</tr>
<tr>
<td>2/29/92</td>
<td>0.21</td>
<td>0.13</td>
<td>0.08</td>
<td>0</td>
</tr>
<tr>
<td>10/2/92</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.06</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/20/92</td>
<td>0.07</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/92 Mean</td>
<td>0.15</td>
<td>0.12</td>
<td>0.12</td>
<td>0.01</td>
</tr>
<tr>
<td>± s.d.</td>
<td>0.15</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
</tr>
</tbody>
</table>

All station-data mean 0.13 0.09 0.13 0
± s.d. 0.13 0.05 0.04 0.01

* n.d. = Not determined.
* s.d. = Standard deviation.
* Station A was sampled only during February, 1992.
Table 3.5  Cross reef variation in flux by molecular diffusion of ammonium (μmoles m⁻² d⁻¹) for Checker Reef, Oahu. Flux was calculated by Equation 3.5, using a $\phi$ equal to 0.5, a $D_0$ for NH₄ at 25°C of $1.98 \times 10^{-5} \text{cm}^2\text{s}^{-1}$, and the $\partial C_r/\partial z$ listed in Appendix 6.

<table>
<thead>
<tr>
<th>Date</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
<th>Station A</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/31/91</td>
<td>n.d.</td>
<td>n.d.</td>
<td>1.49</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/22/91</td>
<td>n.d.</td>
<td>0.01</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>12/5/91</td>
<td>n.d.</td>
<td>0.03</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/1/92</td>
<td>2.00</td>
<td>3.63</td>
<td>0.06</td>
<td>2.00</td>
</tr>
<tr>
<td>2/6/92</td>
<td>1.91</td>
<td>0.26</td>
<td>0.13</td>
<td>0.99</td>
</tr>
<tr>
<td>2/19/92</td>
<td>n.d.</td>
<td>-0.11</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/22/92</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>2.16</td>
</tr>
<tr>
<td>2/24/92</td>
<td>1.88</td>
<td>-0.08</td>
<td>0.25</td>
<td>1.35</td>
</tr>
<tr>
<td>2/29/92</td>
<td>0.82</td>
<td>4.91</td>
<td>0.64</td>
<td>2.82</td>
</tr>
<tr>
<td>10/2/92</td>
<td>n.d.</td>
<td>n.d.</td>
<td>-0.23</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/20/92</td>
<td>2.36</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/92 Mean</td>
<td>1.65</td>
<td>1.72</td>
<td>0.27</td>
<td>1.86</td>
</tr>
<tr>
<td>± s.d.</td>
<td>0.56</td>
<td>2.37</td>
<td>0.26</td>
<td>0.72</td>
</tr>
<tr>
<td>All station-data mean</td>
<td>1.79</td>
<td>1.23</td>
<td>0.17</td>
<td>1.86(^c)</td>
</tr>
<tr>
<td>± s.d.</td>
<td>0.58</td>
<td>2.11</td>
<td>0.31</td>
<td>0.72(^c)</td>
</tr>
</tbody>
</table>

\(^a\) n.d. = Not determined.
\(^b\) s.d. = Standard deviation.
\(^c\) Station A sampled only during February, 1992.
Table 3.6  Cross reef variation in flux by molecular diffusion of dissolved silica ($\mu$moles m$^{-2}$ d$^{-1}$) for Checker Reef, Oahu. Flux was calculated by Equation 3.5, using a $\phi$ equal to 0.5, a $D_o$ for Si at 25°C of $0.3 \times 10^{-5}$ cm$^2$s$^{-1}$, and the $\partial C_p/\partial z$ listed in Appendix 7.

<table>
<thead>
<tr>
<th>Date</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
<th>Station A</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/31/91</td>
<td>n.d.$^a$</td>
<td>n.d.</td>
<td>0.72</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/22/91</td>
<td>n.d.</td>
<td>0.08</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>12/5/91</td>
<td>n.d.</td>
<td>-0.21</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/1/92</td>
<td>1.19</td>
<td>0.66</td>
<td>0.18</td>
<td>1.94</td>
</tr>
<tr>
<td>2/6/92</td>
<td>1.06</td>
<td>0.16</td>
<td>0.33</td>
<td>1.19</td>
</tr>
<tr>
<td>2/19/92</td>
<td>n.d.</td>
<td>0.14</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/22/92</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>1.74</td>
</tr>
<tr>
<td>2/24/92</td>
<td>1.30</td>
<td>-0.08</td>
<td>0.32</td>
<td>1.11</td>
</tr>
<tr>
<td>2/29/92</td>
<td>0.36</td>
<td>0.28</td>
<td>0.43</td>
<td>1.68</td>
</tr>
<tr>
<td>10/2/92</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.17</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/20/92</td>
<td>0.35</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

2/92 Mean  
$\pm$ s.d.$^b$  
0.98 | 0.23 | 0.31 | 1.53 
0.42 | 0.27 | 0.10 | 0.36 

All station-
data mean  
$\pm$ s.d.$^c$  
0.85 | 0.15 | 0.36 | 1.53 
0.46 | 0.28 | 0.20 | 0.36 

$^a$ n.d. = Not determined.  
$^b$ s.d. = Standard deviation.  
$^c$ Station A was sampled only during February, 1992.
Table 3.7  Cross reef variation in the flux of dissolved inorganic phosphate (μmoles m⁻² d⁻¹) by wave-induced macroscopic dispersion at Checker Reef, Oahu. Flux was calculated by Equation 3.1, using a φ equal to 0.5, the $\partial C/\partial z$ values listed in Appendix 4, and a $D_{\text{macro}}$ value for wave conditions characterized as either of small or large amplitude, and coming from either the N.E. or S.W. direction.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wave Amplitude</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
<th>Station A</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/31/91</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>1.95</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/22/91</td>
<td>Large/N.E.</td>
<td>n.d.</td>
<td>0.11</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/1/92</td>
<td>Large/N.E.</td>
<td>0.44</td>
<td>0.54</td>
<td>3.87</td>
<td>2.99</td>
</tr>
<tr>
<td>2/6/92</td>
<td>Large/N.E.</td>
<td>1.09</td>
<td>0.62</td>
<td>5.32</td>
<td>1.95</td>
</tr>
<tr>
<td>2/19/92</td>
<td>Large/S.W.</td>
<td>n.d.</td>
<td>2.92</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/22/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.51</td>
</tr>
<tr>
<td>2/24/92</td>
<td>Large/S.W.</td>
<td>15.60</td>
<td>2.65</td>
<td>20.68</td>
<td>3.25</td>
</tr>
<tr>
<td>2/29/92</td>
<td>Large/N.E.</td>
<td>0.24</td>
<td>0.47</td>
<td>8.54</td>
<td>2.46</td>
</tr>
<tr>
<td>6/12/92</td>
<td>Large/N.E.</td>
<td>n.d.</td>
<td>0.35</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>10/2/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.97</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/20/92</td>
<td>Small/N.E.</td>
<td>0.12</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

- **2/92 Mean**: 4.34 1.44 9.60 1.98
- ± s.d.: 7.50 1.23 7.64 1.07

- **All station-data mean**: 3.50 0.88 6.89 1.98
- ± s.d.: 6.77 1.10 7.26 1.07

- The $D_{\text{macro}}$ used when waves were of small amplitude and from the N.E. direction was $1.3 \times 10^{-5}$ cm² s⁻¹ at station A, $5.5 \times 10^{-5}$ cm² s⁻¹ at station C, $1.8 \times 10^{-5}$ cm² s⁻¹ at station D, and $1.0 \times 10^{-5}$ cm² s⁻¹ at station E.
- The $D_{\text{macro}}$ used when waves were of large amplitude and from the N.E. direction was $5.3 \times 10^{-5}$ cm² s⁻¹ at station A, $24.1 \times 10^{-5}$ cm² s⁻¹ at station C, $4.5 \times 10^{-5}$ cm² s⁻¹ at station D, and $4.3 \times 10^{-5}$ cm² s⁻¹ at station E.
- The $D_{\text{macro}}$ used when waves were of large amplitude and from the S.W. direction was $14.2 \times 10^{-5}$ cm² s⁻¹ at station A, $85.5 \times 10^{-5}$ cm² s⁻¹ at station C, $43.0 \times 10^{-5}$ cm² s⁻¹ at station D, and $82.4 \times 10^{-5}$ cm² s⁻¹ at station E.
- s.d. = Standard deviation.
- Station A was sampled only during February, 1992.
Table 3.8 Cross reef variation in the flux of dissolved nitrate plus nitrite (μmoles m⁻² d⁻¹) by wave-induced macroscopic dispersion at Checker Reef, Oahu. Flux was calculated by Equation 3.1, using a φ equal to 0.5, the ∂C/∂z values listed in Appendix 5, and a $D_{\text{macro}}$ value for wave conditions characterized as either of small or large amplitude, and coming from either the N.E. or S.W. direction.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wave Amplitude /Direction</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
<th>Station A</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/31/91</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>10.0</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/22/91</td>
<td>Large/N.E.</td>
<td>1.5</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>12/5/91</td>
<td>Large/N.E.</td>
<td>1.9</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/1/92</td>
<td>Large/N.E.</td>
<td>1.2</td>
<td>3.0</td>
<td>28.5</td>
<td>1.2</td>
</tr>
<tr>
<td>2/6/92</td>
<td>Large/N.E.</td>
<td>1.1</td>
<td>8.3</td>
<td>37.2</td>
<td>1.0</td>
</tr>
<tr>
<td>2/19/92</td>
<td>Large/S.W.</td>
<td>n.d.</td>
<td>61.1</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/22/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>-0.3</td>
</tr>
<tr>
<td>2/24/92</td>
<td>Large/S.W.</td>
<td>285.3</td>
<td>38.6</td>
<td>123.0</td>
<td>3.6</td>
</tr>
<tr>
<td>2/29/92</td>
<td>Large/N.E.</td>
<td>9.7</td>
<td>6.0</td>
<td>19.4</td>
<td>0.4</td>
</tr>
<tr>
<td>10/2/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>3.8</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/92 Mean</td>
<td></td>
<td>73.3</td>
<td>23.4</td>
<td>52.0</td>
<td>1.2</td>
</tr>
<tr>
<td>± s.d.</td>
<td></td>
<td>140.7</td>
<td>25.5</td>
<td>47.9</td>
<td>1.5</td>
</tr>
<tr>
<td>All station-data mean</td>
<td></td>
<td>59.8</td>
<td>17.2</td>
<td>37.0</td>
<td>1.2</td>
</tr>
<tr>
<td>± s.d.</td>
<td></td>
<td>126.1</td>
<td>23.3</td>
<td>43.8</td>
<td>1.5</td>
</tr>
</tbody>
</table>

a The $D_{\text{macro}}$ used when waves were of small amplitude and from the N.E. direction was $1.3 \times 10^5$ cm² s⁻¹ at station A, $5.5 \times 10^3$ cm² s⁻¹ at station C, $1.0 \times 10^5$ cm² s⁻¹ at station D, and $1.0 \times 10^5$ cm² s⁻¹ at station E.

b n.d. = Not determined.

c The $D_{\text{macro}}$ used when waves were of large amplitude and from the N.E. direction was $5.3 \times 10^5$ cm² s⁻¹ at station A, $24.1 \times 10^3$ cm² s⁻¹ at station C, $4.5 \times 10^5$ cm² s⁻¹ at station D, and $4.3 \times 10^5$ cm² s⁻¹ at station E.

d The $D_{\text{macro}}$ used when waves were of large amplitude and from the S.W. direction was $14.2 \times 10^5$ cm² s⁻¹ at station A, $85.5 \times 10^3$ cm² s⁻¹ at station C, $43.0 \times 10^5$ cm² s⁻¹ at station D, and $82.4 \times 10^5$ cm² s⁻¹ at station E.

e s.d. = Standard deviation.

Station A was sampled only during February, 1992.
Table 3.9  Cross reef variation in the flux of dissolved ammonium (μmoles m$^{-2}$ d$^{-1}$) by wave-induced macroscopic dispersion at Checker Reef, Oahu. Flux was calculated by Equation 3.1, using a $\phi$ equal to 0.5, the $\partial C/\partial z$ values listed in Appendix 6, and a $D_{\text{macro}}$ value for wave conditions characterized as either of small or large amplitude, and coming from either the N.E. or S.W. direction.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wave Amplitude /Direction</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
<th>Station A</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/31/91</td>
<td>Small/N.E.$^a$</td>
<td>n.d.$^b$</td>
<td>n.d.</td>
<td>8.2</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/22/91</td>
<td>Large/N.E.$^c$</td>
<td>n.d.</td>
<td>0</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>12/5/91</td>
<td>Large/N.E.</td>
<td>n.d.</td>
<td>0.1</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/1/92</td>
<td>Large/N.E.</td>
<td>3.7</td>
<td>15.8</td>
<td>1.5</td>
<td>10.8</td>
</tr>
<tr>
<td>2/6/92</td>
<td>Large/N.E.</td>
<td>3.5</td>
<td>1.2</td>
<td>3.1</td>
<td>5.3</td>
</tr>
<tr>
<td>2/19/92</td>
<td>Large/S.W.$^d$</td>
<td>n.d.</td>
<td>-4.7</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/22/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>2.8</td>
</tr>
<tr>
<td>2/24/92</td>
<td>Large/S.W.</td>
<td>156.4</td>
<td>-3.3</td>
<td>21.4</td>
<td>22.3</td>
</tr>
<tr>
<td>2/29/92</td>
<td>Large/N.E.</td>
<td>1.5</td>
<td>22.3</td>
<td>15.7</td>
<td>15.1</td>
</tr>
<tr>
<td>10/2/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>-0.8</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

| 2/92 Mean  | 41.3                      | 6.3       | 10.4      | 8.5       |
| ± s.d.$^e$ | 76.7                      | 12.1      | 9.7       | 5.5       |

All station-data mean 33.5 4.5 8.2 8.5$^f$
± s.d. 68.7 10.3 8.7 5.5$^f$

$^a$ The $D_{\text{macro}}$ used when waves were of small amplitude and from the N.E. direction was $1.3 \times 10^{-5}$ cm$^2$ s$^{-1}$ at station A, $5.5 \times 10^{-5}$ cm$^2$ s$^{-1}$ at station C, $1.8 \times 10^{-5}$ cm$^2$ s$^{-1}$ at station D, and $1.0 \times 10^{-5}$ cm$^2$ s$^{-1}$ at station E.

$^b$ n.d. = Not determined.

$^c$ The $D_{\text{macro}}$ used when waves were of large amplitude and from N.E. direction was $5.3 \times 10^{-5}$ cm$^2$ s$^{-1}$ at station A, $24.1 \times 10^{-5}$ cm$^2$ s$^{-1}$ at station D, and $1.0 \times 10^{-5}$ cm$^2$ s$^{-1}$ at station E.

$^d$ The $D_{\text{macro}}$ used when waves were of large amplitude and from the S.W. direction was $14.2 \times 10^{-5}$ cm$^2$ s$^{-1}$ at station A, $85.3 \times 10^{-5}$ cm$^2$ s$^{-1}$ at station C, $43.0 \times 10^{-5}$ cm$^2$ s$^{-1}$ at station D, and $82.4 \times 10^{-5}$ cm$^2$ s$^{-1}$ at station E.

$^e$ s.d. = Standard deviation.

$^f$ Station A was sampled only during February, 1992.
Table 3.10  Cross reef variation in the flux of dissolved silica (μmoles m$^{-2}$ d$^{-1}$) by wave-induced macroscopic dispersion at Checker Reef, Oahu. Flux was calculated by Equation 3.1, using a $\phi$ equal to 0.5, the $\partial C/\partial z$ values listed in Appendix 7, and a $D_{macro}$ value for wave conditions characterized as either of small or large amplitude, and coming from either the N.E. or S.W. direction.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wind/Wave Conditions</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
<th>Station A</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/22/91</td>
<td>Large/N.E.$^c$</td>
<td>n.d.</td>
<td>2</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/1/92</td>
<td>Large/N.E.</td>
<td>34</td>
<td>20</td>
<td>29</td>
<td>68</td>
</tr>
<tr>
<td>2/6/92</td>
<td>Large/N.E.</td>
<td>31</td>
<td>4</td>
<td>53</td>
<td>77</td>
</tr>
<tr>
<td>2/19/92</td>
<td>Large/S.W.$^d$</td>
<td>n.d.</td>
<td>41</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/22/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>15</td>
</tr>
<tr>
<td>2/24/92</td>
<td>Large/S.W.</td>
<td>717</td>
<td>-24</td>
<td>185</td>
<td>121</td>
</tr>
<tr>
<td>2/29/92</td>
<td>Large/N.E.</td>
<td>11</td>
<td>9</td>
<td>70</td>
<td>59</td>
</tr>
<tr>
<td>10/2/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>6</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/92 Mean</td>
<td></td>
<td>198</td>
<td>10</td>
<td>84</td>
<td>68</td>
</tr>
<tr>
<td>± s.d.$^e$</td>
<td></td>
<td>350</td>
<td>24</td>
<td>69</td>
<td>38</td>
</tr>
<tr>
<td>All station-data mean</td>
<td></td>
<td>159</td>
<td>6</td>
<td>61</td>
<td>68$^f$</td>
</tr>
<tr>
<td>± s.d.</td>
<td></td>
<td>312</td>
<td>20</td>
<td>64</td>
<td>38$^f$</td>
</tr>
</tbody>
</table>

$^a$ The $D_{macro}$ used when waves were of small amplitude and from the N.E. direction was $1.3 \times 10^5$ cm$^2$ s$^{-1}$ at station A, $5.5 \times 10^4$ cm$^2$ s$^{-1}$ at station C, $1.8 \times 10^5$ cm$^2$ s$^{-1}$ at station D, and $1.0 \times 10^5$ cm$^2$ s$^{-1}$ at station E.

$^b$ n.d. = Not determined.

$^c$ The $D_{macro}$ used when waves were of large amplitude and from the N.E. direction was $5.3 \times 10^5$ cm$^2$ s$^{-1}$ at station A, $24.1 \times 10^5$ cm$^2$ s$^{-1}$ at station C, $4.5 \times 10^5$ cm$^2$ s$^{-1}$ at station D, and $4.3 \times 10^5$ cm$^2$ s$^{-1}$ at station E.

$^d$ The $D_{macro}$ used when waves were of large amplitude and from the S.W. direction was $14.2 \times 10^5$ cm$^2$ s$^{-1}$ at station A, $85.5 \times 10^5$ cm$^2$ s$^{-1}$ at station C, $43.0 \times 10^5$ cm$^2$ s$^{-1}$ at station D, and $82.4 \times 10^5$ cm$^2$ s$^{-1}$ at station E.

$^e$ s.d. = Standard deviation.

$^f$ Station A was sampled only during February, 1992.
Table 3.11  Cross reef variation in the flux of dissolved inorganic phosphate (μmoles m⁻² d⁻¹) by wave-induced megadispersion at Checker Reef, Oahu. Flux was calculated by Equation 3.1, using a φ equal to 0.5, the \( \delta C/\delta z \) values listed in Appendix 4, and a \( D_{\text{mega}} \) value for wave conditions characterized as either of small or large amplitude, and from either the N.E. or S.W. direction.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wave Amplitude /Direction</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
<th>Station A</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/31/91</td>
<td>Small/N.E. (^a)</td>
<td>n.d.</td>
<td>n.d.</td>
<td>120</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/22/91</td>
<td>Large/S.W. (^c)</td>
<td>n.d.</td>
<td>30</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/1/92</td>
<td>Large/N.E.</td>
<td>250</td>
<td>160</td>
<td>650</td>
<td>250</td>
</tr>
<tr>
<td>2/6/92</td>
<td>Large/N.E.</td>
<td>230</td>
<td>190</td>
<td>900</td>
<td>150</td>
</tr>
<tr>
<td>2/19/92</td>
<td>Large/S.W. (^d)</td>
<td>n.d.</td>
<td>570</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/22/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>20</td>
</tr>
<tr>
<td>2/24/92</td>
<td>Large/S.W.</td>
<td>5630</td>
<td>570</td>
<td>740</td>
<td>70</td>
</tr>
<tr>
<td>2/29/92</td>
<td>Large/N.E.</td>
<td>50</td>
<td>140</td>
<td>1450</td>
<td>210</td>
</tr>
<tr>
<td>6/12/92</td>
<td>Large/N.E.</td>
<td>n.d.</td>
<td>60</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>10/2/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>70</td>
<td>n.d.</td>
<td></td>
</tr>
</tbody>
</table>

2/92 Mean ± s.d.\(^e\)  
1540 ± 2730
330 ± 220
930 ± 360
140 ± 100

All station-data mean ± s.d.\(^f\)  
1230 ± 2460
200 ± 220
650 ± 520
140 ± 100

\( a \) The \( D_{\text{mega}} \) used when waves were of small amplitude and from the N.E. direction was 43 x 10⁻⁵ cm² s⁻¹ at station A, 359 x 10⁻⁵ cm² s⁻¹ at station C, 255 x 10⁻⁵ cm² s⁻¹ at station D, and 81 x 10⁻⁵ cm² s⁻¹ at station E.

\( b \) n.d. = Not determined.

\( c \) The \( D_{\text{mega}} \) used when waves were of large amplitude and from the N.E. direction was 450 x 10⁻⁵ cm² s⁻¹ at station A, 4119 x 10⁻⁵ cm² s⁻¹ at station C, 1372 x 10⁻⁵ cm² s⁻¹ was at station D, and 882 x 10⁻⁵ cm² s⁻¹ at station E.

\( d \) The \( D_{\text{mega}} \) used when waves were of large amplitude and from the S.W. direction was 304 x 10⁻⁵ cm² s⁻¹ at station A, 3044 x 10⁻⁵ cm² s⁻¹ at station C, 8660 x 10⁻⁵ cm² s⁻¹ at station D, and 30610 x 10⁻⁵ cm² s⁻¹ at station E.

\( e \) Standard deviation.

\( f \) Station A was sampled only during February, 1992.
Table 3.12  Cross reef variation in the flux of dissolved nitrate plus nitrite (μmoles m⁻² d⁻¹) by wave-induced megadispersion at Checker Reef, Oahu. Flux was calculated by Equation 3.1, using a φ equal to 0.5, the $\partial C/\partial z$ values listed in Appendix 5, and a $D_{\text{mega}}$ value for wave conditions characterized as either of small or large amplitude, and coming from either the N.E. or S.W. direction.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wave Amplitude</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
<th>Station A</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/1/92</td>
<td>Large/N.E.</td>
<td>250</td>
<td>920</td>
<td>4850</td>
<td>110</td>
</tr>
<tr>
<td>2/6/92</td>
<td>Large/N.E.</td>
<td>230</td>
<td>2550</td>
<td>6360</td>
<td>70</td>
</tr>
<tr>
<td>2/19/92</td>
<td>Large/S.W.</td>
<td>n.d.</td>
<td>12280</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/22/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>-10</td>
</tr>
<tr>
<td>2/24/92</td>
<td>Large/S.W.</td>
<td>106330</td>
<td>7810</td>
<td>4370</td>
<td>70</td>
</tr>
<tr>
<td>2/29/92</td>
<td>Large/N.E.</td>
<td>2000</td>
<td>1840</td>
<td>3320</td>
<td>40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>2/92 Mean</th>
<th>± s.d.</th>
<th>All station-data mean</th>
<th>± s.d.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>27200</td>
<td>52760</td>
<td>21770</td>
<td>47270</td>
</tr>
<tr>
<td></td>
<td>± s.d.¹</td>
<td>± s.d.</td>
<td>± s.d.</td>
<td>± s.d.</td>
</tr>
<tr>
<td></td>
<td>5080</td>
<td>4830</td>
<td>5080</td>
<td>4530</td>
</tr>
<tr>
<td></td>
<td>4720</td>
<td>1260</td>
<td>3650</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>40</td>
<td>60</td>
<td>40</td>
</tr>
</tbody>
</table>

¹ The $D_{\text{mega}}$ used when waves were of small amplitude and from the N.E. direction was \(43 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\) at station A, \(359 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\) at station C, \(255 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\) at station D, and \(81 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\) at station E.

² n.d. = Not determined.

³ The $D_{\text{mega}}$ used when waves were of large amplitude and from the N.E. direction was \(450 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\) at station A, \(4119 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\) at station C, \(1372 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\) at station D, and \(882 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\) at station E.

⁴ The $D_{\text{mega}}$ used when waves were of large amplitude and from the S.W. direction was \(304 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\) at station A, \(3044 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\) at station C, \(8660 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\) at station D, and \(30610 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\) at station E.

⁵ s.d. = Standard deviation.

⁶ Station A was sampled only during February, 1992.
Table 3.13 Cross reef variation in the flux of ammonium (μmoles m$^2$ d$^{-1}$) by wave-induced megadispersion at Checker Reef, Oahu. Flux was calculated by Equation 3.1, using a $\phi$ equal to 0.5, the $\partial C/\partial z$ values listed in Appendix 6, and a $D_{\text{mega}}$ value for wave conditions characterized as either of small or large amplitude, and coming from either the N.E. or S.W. direction.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wave Amplitude /Direction</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
<th>Station A</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/22/91</td>
<td>Large/N.E.$^c$</td>
<td>n.d.</td>
<td>20</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/1/92</td>
<td>Large/N.E.</td>
<td>1790</td>
<td>4830</td>
<td>240</td>
<td>910</td>
</tr>
<tr>
<td>2/6/92</td>
<td>Large/N.E.</td>
<td>1690</td>
<td>360</td>
<td>470</td>
<td>450</td>
</tr>
<tr>
<td>2/19/92</td>
<td>Large/S.W.$^d$</td>
<td>n.d.</td>
<td>-770</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/22/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>70</td>
</tr>
<tr>
<td>2/24/92</td>
<td>Large/S.W.</td>
<td>58010</td>
<td>-670</td>
<td>760</td>
<td>460</td>
</tr>
<tr>
<td>2/29/92</td>
<td>Large/N.E.</td>
<td>740</td>
<td>6800</td>
<td>2640</td>
<td>1290</td>
</tr>
<tr>
<td>2/92 Mean</td>
<td></td>
<td>15560</td>
<td>2110</td>
<td>1030</td>
<td>640</td>
</tr>
<tr>
<td>± s.d.$^e$</td>
<td></td>
<td>28310</td>
<td>3480</td>
<td>1100</td>
<td>470</td>
</tr>
<tr>
<td>All station-data mean</td>
<td></td>
<td>12490</td>
<td>1520</td>
<td>640</td>
<td>640$^f$</td>
</tr>
<tr>
<td>± s.d.</td>
<td></td>
<td>25460</td>
<td>3020</td>
<td>1120</td>
<td>470$^f$</td>
</tr>
</tbody>
</table>

$^a$ The $D_{\text{mega}}$ used when waves were of small amplitude and from the N.E. direction was $43 \times 10^5$ cm$^2$ s$^{-1}$ at station A, $359 \times 10^5$ cm$^2$ s$^{-1}$ at station C, $255 \times 10^5$ cm$^2$ s$^{-1}$ at station D, and $81 \times 10^5$ cm$^2$ s$^{-1}$ at station E.

$^b$ n.d. = Not determined.

$^c$ The $D_{\text{mega}}$ used when waves were of large amplitude and from the N.E. direction was $450 \times 10^5$ cm$^2$ s$^{-1}$ at station A, $4119 \times 10^5$ cm$^2$ s$^{-1}$ at station C, $1372 \times 10^5$ cm$^2$ s$^{-1}$ at station D, and $82 \times 10^5$ cm$^2$ s$^{-1}$ at station E.

$^d$ The $D_{\text{mega}}$ used when waves were of large amplitude and from the S.W. direction was $304 \times 10^5$ cm$^2$ s$^{-1}$ at station A, $3044 \times 10^5$ cm$^2$ s$^{-1}$ at station C, $8660 \times 10^5$ cm$^2$ s$^{-1}$ at station D, and $30610 \times 10^5$ cm$^2$ s$^{-1}$ at station E.

$^e$ s.d. = Standard deviation.

$^f$ Station A was sampled only during February, 1992.
Table 3.14  Cross reef variation in the flux of dissolved silica (μmoles m⁻² d⁻¹) by wave-induced megadispersion at Checker Reef, Oahu. Flux was calculated by Equation 3.1, using a $\phi$ equal to 0.5, the $\partial C/\partial z$ values listed in Appendix 7, and a $D_{\text{mega}}$ value for wave conditions characterized as either of small or large amplitude, and coming from either the N.E. or S.W. direction.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wave Amplitude</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
<th>Station A</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/22/91</td>
<td>Large/N.E.</td>
<td>180</td>
<td>n.d.</td>
<td>3360</td>
<td>2790</td>
</tr>
<tr>
<td>12/5/91</td>
<td>Large/N.E.</td>
<td>-1060</td>
<td>n.d.</td>
<td>6200</td>
<td>1700</td>
</tr>
<tr>
<td>2/1/92</td>
<td>Large/N.E.</td>
<td>6970</td>
<td>3240</td>
<td>2790</td>
<td></td>
</tr>
<tr>
<td>2/6/92</td>
<td>Large/N.E.</td>
<td>5740</td>
<td>820</td>
<td>1700</td>
<td></td>
</tr>
<tr>
<td>2/19/92</td>
<td>Large/S.W.</td>
<td>4470</td>
<td>n.d.</td>
<td>n.d.</td>
<td></td>
</tr>
<tr>
<td>2/22/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>230</td>
<td></td>
</tr>
<tr>
<td>2/24/92</td>
<td>Large/S.W.</td>
<td>-2560</td>
<td>5370</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>2/29/92</td>
<td>Large/N.E.</td>
<td>2160</td>
<td>1370</td>
<td>2420</td>
<td></td>
</tr>
<tr>
<td>2/92</td>
<td>Mean</td>
<td>70170</td>
<td>1470</td>
<td>5770</td>
<td>1780</td>
</tr>
<tr>
<td>± s.d.</td>
<td>130450</td>
<td>2680</td>
<td>1980</td>
<td>1130</td>
<td></td>
</tr>
</tbody>
</table>

| All station-data mean | 56180 | 1250 | 4600 | 1780 |
| ± s.d.           | 117230| 2460 | 2440 | 1130 |

* The $D_{\text{mega}}$ used when waves were of small amplitude and from the N.E. direction was $43 \times 10^5$ cm² s⁻¹ at station A, $359 \times 10^5$ cm² s⁻¹ at station C, $255 \times 10^5$ cm² s⁻¹ at station D, and $81 \times 10^5$ cm² s⁻¹ at station E.

b n.d. = Not determined.

e The $D_{\text{mega}}$ used when waves were of large amplitude and from the N.E. direction was $450 \times 10^5$ cm² s⁻¹ at station A, $4119 \times 10^5$ cm² s⁻¹ at station C, $1372 \times 10^5$ cm² s⁻¹ at station D, and $882 \times 10^5$ cm² s⁻¹ at station E.

d The $D_{\text{mega}}$ used when waves were of large amplitude and from the S.W. direction was $304 \times 10^5$ cm² s⁻¹ at station A, $3044 \times 10^5$ cm² s⁻¹ at station C, $8660 \times 10^5$ cm² s⁻¹ at station D, and $30610 \times 10^5$ cm² s⁻¹ at station E.

* s.d. = Standard deviation.

f Station A was sampled only during February, 1992.
Table 3.15 Dissolved inorganic phosphate flux (μmoles m$^{-2}$ d$^{-1}$) as measured with either one, two, or three open-bottomed benthic chambers on sand patches of Checker Reef, Oahu.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wave Amplitude /Direction</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/8-9/91*</td>
<td>Small/S.W.</td>
<td>72 ± 2</td>
<td>37 ± 4</td>
<td>n.d. b</td>
</tr>
<tr>
<td>7/2/92c</td>
<td>Small/N.E.</td>
<td>82</td>
<td>18</td>
<td>n.d.</td>
</tr>
<tr>
<td>7/16-17/92a</td>
<td>Small/N.E.</td>
<td>413 ± 7</td>
<td>11 ± 3</td>
<td>n.d.</td>
</tr>
<tr>
<td></td>
<td>134 ± 87</td>
<td></td>
<td>4 ± &lt;1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-6</td>
</tr>
<tr>
<td>10/10-11/92c</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>11/4-5/92a</td>
<td>Large/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>-3 ± 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4 ± 1</td>
</tr>
<tr>
<td></td>
<td>62 ± 6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean fluxes$^d$</td>
<td></td>
<td>90 ± 170</td>
<td>17 ± 12</td>
<td>&lt; 1 ± 6</td>
</tr>
<tr>
<td>$n^e$</td>
<td></td>
<td>7</td>
<td>4</td>
<td>7</td>
</tr>
</tbody>
</table>

* Standard deviation based on error of differences between rates (slopes) of phosphate accumulation over time in open-bottomed chambers and rates of accumulation in the closed-bottomed control chambers.

b n.d. = not determined.

c Two point determinations; no standard deviation calculated from accumulation rate differences.

d Mean fluxes based on all determinations.

e $n =$ number of determinations.
Table 3.16  Dissolved nitrate plus nitrite flux (μmoles m⁻² d⁻¹) as measured with either one, two, or three open-bottomed benthic chambers on sand patches of Checker Reef, Oahu.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wave Amplitude</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/8-9/91</td>
<td>Small/S.W.</td>
<td>378 ± 36</td>
<td>1233 ± 1406</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/4-5/92</td>
<td>Large/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>- 10 ± 14</td>
</tr>
</tbody>
</table>

Mean fluxes^d 274 ± 183 1233 ± 1406 -6 ± 28

n 3 1 7

---

^a Standard error based on error of differences between rates (slopes) of nitrate plus nitrite accumulation over time in open-bottomed chambers and rates of accumulation in the closed-bottomed control chambers.

^b n.d. = not determined.

^c Two point determinations; no standard error calculated from accumulation rate differences.

^d Mean fluxes based on all determinations; n = number of determinations.
Table 3.17  Dissolved ammonium flux (μmoles m⁻² d⁻¹) as measured with either one, two, or three open-bottomed benthic chambers on sand patches of Checker Reef, Oahu.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wave Amplitude /Direction</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/8-9/91</td>
<td>Small/S.W.</td>
<td>47 ± 50</td>
<td>318 ± &lt;1</td>
<td>n.d. b</td>
</tr>
<tr>
<td>10/2-3/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-34</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-41</td>
</tr>
<tr>
<td>11/4-5/92</td>
<td>Large/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>298 ± 1736</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>89 ± 12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>43 ± 38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean fluxes</td>
<td></td>
<td>180 ± 233</td>
<td>318 ± &lt;1</td>
<td>- 15 ± 249</td>
</tr>
<tr>
<td>n</td>
<td>3</td>
<td>1</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

a Standard error based on error of differences between rates (slopes) of ammonium accumulation over time in open-chambers and rates of accumulation in the closed-bottomed control chambers.
b n.d. = not determined.
c Two point determinations; no standard error calculated from accumulation rate differences.
d Mean fluxes based on all determinations; n = number of determinations.
Table 3.18  Dissolved silica flux (μmoles m$^{-2}$ d$^{-1}$) as measured with either one, two, or three open-bottomed benthic chambers on sand patches of Checker Reef, Oahu.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wave Amplitude</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/8-9/91$^b$</td>
<td>Small/S.W.</td>
<td>685 ± 764</td>
<td>1015 ± 166</td>
<td>n.d.$^b$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>182</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>179</td>
</tr>
<tr>
<td>10/10-11/92$^c$</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>464</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1684</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>54 ± 26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-492 ± 326</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mean fluxes$^d$ -553 ± 1270  1015 ± 166  303 ± 682
n  3  1  7

$^a$ Standard error based on error of differences between rates (slopes) of silica accumulation over time in open-chambers and rates of accumulation in the closed-bottomed control chambers.

$^b$ n.d. = not determined.

$^c$ Two point determinations; no standard error calculated from accumulation rate differences.

$^d$ Mean fluxes based on all determinations; n = number of determinations.
Figure 3.1. Idealized depiction of a windward reef showing some of the hydraulic heads and possible porewater flow and mixing processes. K represents hydraulic conductivity (from Buddemeier and Oberdorfer 1989).
Figure 3.2. Hypothesized RIW flow patterns within Checker Reef. RIW flow is indicated by single-arrow lines; wave-induced advective OSW/RIW-mixing is indicated by double-arrow lines. Curved lines indicate hypothesized hydrostatic isobars. (from Sansone et al., 1989).
Figure 3.3. Qualitative depiction of water particle orbits, orbital velocities and stream lines in a (A) deep water wave, (B) shallow water wave over an impermeable bottom, and (C) shallow water wave over a porous sedimentary bed. $\Theta$ indicates wave phase. Adapted from McLellan (1977).
Figure 3.4. Idealized shallow-water wave form passing over a permeable sedimentary bed, where $d$ is the still water depth, $A$ is the wave amplitude, and $h$ is the thickness of a uniform sand bed overlying impermeable bedrock (from Phillips 1991). Vertical scale of shallow water waves is exaggerated approximately $10^2$-$10^4$ times the horizontal scale, depending upon the wavelength.
Figure 3.5. Comparison of the range and mean values of predicted coefficients of macroscopic dispersion versus megadispersion induced by N-NE trade wind-driven waves on Checker Reef, during high and low tide.
Figure 3.6. Comparison of the range and mean values of predicted coefficients of macroscopic dispersion versus megadispersion induced by S-SW Kona wind-driven waves on Checker Reef, during high and low tide.
Figure 3.7. Pressure sensor array connected to a large well point at Checker Reef sampling at 1 and 2 m (not to scale). Pressure transducers were fastened to an acrylic plate, which was held to bottom with lead weights (not shown). Pressure transducers (PT#1-3) were connected either to a sealevel reference tube (PT#1) held in place with rubber bands, or to a well point sampling tube (PT#2, PT#3).
Figure 3.8. Comparison of output of pressure transducer # 1 to that of # 2 (□) and # 3 (+) at station A, 9/28/92. The coefficient of determination \( (r^2) \) of PT # 1 vs. # 2, and # 1 vs. # 3 were both \( = 0.95 \).
Figure 3.9. Representative section of the variation with time of the wave-induced pressures occurring at 37 cm above the sediment-seawater interface, and at 100 cm and 200 cm below the interface, at station D, 10/8/92.
Figure 3.10. Variance-preserving spectral variance (cm$^2$) vs. frequency (Hz) and period (s) of mean-detrended reference sea level waveform (solid line), with 95% confidence intervals (dashed lines) at station A, 10/8/92.
Figure 3.11. Benthic chambers used for direct flux determinations. The "skirt" is a 15-20 cm wide circular ring of solid plexiglass, attached directly to dome, and overlaid with a 20 cm wide flexible plastic ring. The dome and skirt were covered with plasticized aluminum tape (not shown). Inset shows N-S orientation of benthic chambers, one of which is a sealed-bottom control chamber.
Figure 3.12. (Opposite page) Section of cross-reef pressure scan, 10/8/92, stations A and C, at 1 scan s\(^{-1}\). Pressure head variations were mean-detrended and shown at reference level ("Ref."; solid line) and at sediment depths of either 0.5 m (dotted line) and 1 m (dashed line) for Station A, or 1 m (dashed line) and 2 m (dotted line) for station C. Positive ($A_{\text{ms-ref}}$) and negative root-mean-square amplitude are shown by horizontal lines, and twice the $A_{\text{ms-ref}}$ is the root-mean-square reference wave height ($H_{\text{ms-ref}}$).
Figure 3.13. (Opposite page) Section of cross-reef pressure scan, 10/8/92, stations D and E, at 1 scan s$^{-1}$. Pressure head variations were mean-detrended, and shown at reference level ("Ref."); solid line) and at sediment depths of 1 m (dashed line) and 2 m (dotted line). Positive ($A_{\text{rms-ref}}$) and negative root-mean-square amplitude is plotted as horizontal lines, and twice the $A_{\text{rms-ref}}$ is the root-mean-square reference wave height ($H_{\text{rms-ref}}$).
Figure 3.14. (Opposite page) Section of cross-reef pressure scan, 10/27/92, stations A and C, at 1 scan s⁻¹. Pressure head variations were mean-detrended and shown at reference level ("Ref."; solid line) and at sediment depths of either 0.5 m (dotted line) and 1 m (dashed line) for Station A, or 1 m (dashed line) and 2 m (dotted line) for station C. Positive (A\textsubscript{rms-ref}) and negative root-mean-square amplitude are shown by horizontal lines, and twice the A\textsubscript{rms-ref} is the root-mean-square reference wave height (H\textsubscript{rms-ref}).
Figure 3.15. (Opposite page) Section of cross-reef pressure scan, 10/27/92, stations D and E, at 1 scan s⁻¹. Pressure head variations were mean-detrended and shown at reference level ("Ref."; solid line) and at sediment depths of 1 m (dashed line) and 2 m (dotted line). Positive ($A_{\text{rms-ref}}$) and negative root-mean-square amplitude is plotted as horizontal lines, and twice the $A_{\text{rms-ref}}$ is the root-mean-square reference wave height ($H_{\text{rms-ref}}$).
Figure 3.16. Root-mean-square amplitude ($A_{rms}$) of pressure fluctuations at the mean reference level (0.4 m above the sediment-seawater interface) and within the framework during the two cross-reef assessments. Stations identified by letters.
Figure 3.17. (Opposite page) Spectral analysis of mean-detrended pressure variations, 10/8/92, station A, at the reference level (Ref.) and at sediment depths of 0.5 m and 1 m, when monitored at 1 scan s⁻¹. Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 0.5 m-spectrum (Ref./0.5 m) or between the 0.5 m-spectrum and 1 m-spectrum (0.5 m/1 m).
Figure 3.18. (Opposite page) Spectral analysis of mean-detrended pressure variations, 10/8/92, station C, at reference level (Ref.) and at sediment depths of 1 m and 2 m, when monitored at 1 scan s⁻¹. Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 1 m-spectrum (Ref./1 m) or between the 1 m-spectrum and 2 m-spectrum (1 m/2 m).
Station C  10/8/92

Variance (cm$^2$)

Coherence

Phase (degrees)

Frequency (Hz)
Figure 3.19. (Opposite page) Spectral analysis of mean-detrended pressure variations, 10/8/92, station D at reference level (Ref.) and at sediment depths of 1 m and 2 m, when monitored at 1 scan s\(^{-1}\). Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 1 m-spectrum (Ref./1 m) or between the 1 m-spectrum and 2 m-spectrum (1 m/2 m).
Station D 10/8/92

Period (sec)

Variance (cm²)

Coherence

Phase (degrees)

Frequency (Hz)
Figure 3.20. (Opposite page) Spectral analysis of mean-detrended pressure variations, 10/8/92, station E, at reference sea level (Ref.) and at sediment depths of 1 m and 2 m, when monitored at 1 scan s⁻¹. Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 1 m-spectrum (Ref./1 m) or between the 1 m-spectrum and 2-m spectrum (1 m/2 m).
Station E 10/8/92

- Variance (cm$^2$)
- Coherence
- Phase (degrees)

Frequency (Hz)
Figure 3.21. (Opposite page) Spectral analysis of mean-detrended pressure variations, 10/27/92, station A, at reference sea level (Ref.) and at sediment depths of 0.5 m and 1 m, when monitored at 1 scan s$^{-1}$. Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 0.5 m-spectrum (Ref./0.5 m) or between the 0.5 m-spectrum and 1 m-spectrum (0.5 m/1 m).
Station A 10/27/92

Period (sec)

Variance (cm²)

Coherence

Phase (degrees)

Frequency (Hz)
Figure 3.22. (Opposite page) Spectral analysis of mean-detrended pressure variations, 10/27/92, station C, at reference level (Ref.) and at sediment depths of 1 m and 2 m, when monitored at 1 scan s⁻¹. Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 1 m-spectrum (Ref./1 m) or between the 1 m-spectrum and 2 m-spectrum (1 m/2 m).
Station C 10/27/92

Variance (cm²)

Coherence

Phase (degrees)

Period (sec)

Frequency (Hz)
Figure 3.23. (Opposite page) Spectral analysis of mean-detrended pressure variations, 10/27/92, station D, at reference level (Ref.) and at sediment depths of 1 m and 2 m, when monitored at 1 scan s$^{-1}$. Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 1 m-spectrum (Ref./1 m) or between the 1 m-spectrum and 2 m-spectrum (1 m/2 m).
Figure 3.24. (Opposite page) Spectral analysis of mean-detrended pressure variations, 10/27/92, station E, at reference level (Ref.) and at sediment depths of 1 m and 2 m, when monitored at 1 scan s⁻¹. Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 1 m-spectrum (Ref./1 m) or between the 1 m-spectrum and 2 m-spectrum (1 m/2 m).
Figure 3.25. Variation of waveform energy with reef location at the reference level (Ref.; ■), and at sediment depths of 0.5 m (Station A only; X), 1 m (▲), and 2 m (□) during cross-reef pressure scans of 10/8/92 and 10/27/94.
Figure 3.26. Variation of waveform energy with distance above and below the sediment-seawater interface at stations A-E (identified by station letter) during cross-reef pressure scans of 10/8/92 and 10/27/94.
Figure 3.27. (Opposite page) Spectral analysis of mean-detrended pressure variations, 9/28/92, station A (Scan 3) at the reference level (Ref.), and at sediment depths of 0.5 m and 1 m, when monitored at 1 scan s⁻¹. Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 0.5 m-spectrum (Ref./0.5 m) or between the 0.5 m-spectrum and 1 m-spectrum (0.5 m/1 m).
Figure 3.28. (Opposite page) Spectral analysis of mean-detrended pressure variations 9/28/92, station A (Scan 4) at reference sea level (Ref.) and at sediment depths of 0.1 m and 0.25 m, when monitored at 1 scan s⁻¹. Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 0.1 m-spectrum (Ref./0.1 m) or between the 0.1 m-spectra and 0.25 m-spectrum (0.1 m/0.25 m).
Station A 9/28/92
Scan 4

Period (sec)

Variance (cm²)

Coherence

Phase (degrees)

Frequency (Hz)
Figure 3.29. (Opposite page) Spectral analysis of mean-detrended pressure variations of 10/22/92, station A (Scan 2) at reference level (Ref.) and at sediment depths of 0.5 and 1 m, when monitored at 1 scan s⁻¹. Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 0.5 m-spectrum (Ref./0.5 m) or between the 0.5 m-spectrum and 1 m-spectrum (0.5 m/1 m).
Station A 10/22/92

Period (sec)

Variance (cm^2)

Coherence

Phase (degrees)

Frequency (Hz)
Figure 3.30. (Opposite page) Spectral analysis of mean-detrended pressure variations of 10/10-11/92, station C, from 19:05 (Scan # 2), 10/10/92 to 06:08, 10/11/92 at reference level (Ref.) and at sediment depths of 1 m and 2 m, when monitored at 1 scan min⁻¹. Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 1 m-spectrum (Ref./1 m) or between the 1 m-spectra and 2 m-spectrum (1 m/2 m).
Station C 19:05 10/10/92
-06:08 10/11/92

Variance (cm²)

Coherence

Phase (degrees)

Frequency (Hz)
Figure 3.31. (Opposite page) Spectral analysis of mean-detrended pressure variations of 10/11/92, station C, beginning 07:14 (Scan # 3) at the reference level (Ref.) and at sediment depths of 1 m and 2 m when monitored at 1 scan s\(^{-1}\). Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 1 m-spectrum (Ref./1 m) or between the 1 m-spectrum and 2 m-spectrum (1 m/2 m).
Figure 3.32. (Opposite page) Spectral analysis of mean-detrended pressure variations of 11/4/92, station C, beginning 16:55 (Scan # 1) at the reference level (Ref.) and sediment depths of 1 m and 2 m when monitored at 1 scan s⁻¹. Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 100-cm-spectrum (Ref./1 m) or between the 1 m-spectrum and 2 m-spectrum (1 m/2 m).
Figure 3.33. (Opposite page) Spectral analysis of mean-detrended pressure variations of 11/4/92, station C, beginning 19:39 (Scan # 3) at the reference level (Ref.) and at sediment depths of 1 m and 2 m when monitored at 1 scan s⁻¹. Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 1 m-spectrum (Ref./1 m) or between the 1 m-spectrum and 2 m-spectrum (1 m/2 m).
Station C 19:39 11/4/92

Variance (cm²)

Coherence

Phase (degrees)

Frequency (Hz)
Figure 3.34. (Opposite page) Spectral analysis of mean-detrended pressure variations of 11/5/92, station C, beginning 03:18 (Scan # 4) at the reference level (Ref.) and at sediment depths of 1 m and 2 m. Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 1 m spectrum (Ref./1 m) or between the 1 m-spectra and 2 m-spectra (1 m/2 m).
Station C 03:18 11/5/92

Variance (cm²)

Coherence

Phase (degrees)

Frequency (Hz)
Figure 3.35. (Opposite page) Spectral analysis of mean-detrended pressure variations of 11/20/92, station E, beginning 15:52 (Scan # 1) at the reference level (Ref.) and at 1 m and 2 m when monitored at 1 scan s⁻¹. Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 1 m-spectrum (Ref./1 m) or between the 1 m-spectrum and 2 m-spectrum (1 m/2 m).
Figure 3.36. (Opposite page) Spectral analysis of mean-detrended pressure variations of 11/21/92, station E, beginning 03:08 (Scan # 3) at the reference level (Ref.) and at sediment depths of 1 m and 2 m when monitored at 1 scan s⁻¹. Cross spectral coherence and phase functions are shown as either between the reference level-spectrum and the 1 m-spectrum (Ref./1 m) or between the 1 m-spectrum and 2 m-spectrum (1 m/2 m).
Station E 03:08 11/21/92

**Variance (cm²)**
- 1 m
- 2 m

**Coherence**
- Ref./1 m
- 1 m/2 m

**Phase (degrees)**
- Ref./1 m
- 1 m/2 m

**Period (sec)**
Figure 3.37. Variation of waveform energy with distance above, and below, the sediment-seawater interface at: (1) station E, 11/20-21/92, from 15:52 to 16:22 (■) and from 03:08 to 03:35 (□); (2) station C, 10/10-11/92, from 19:05 to 07:00 at 1 scan min⁻¹ (+), and from 07:00 to 07:07 at 1 scan s⁻¹ (○); at 1 scan s⁻¹, 11/4/92, from 16:55 to 17:05 (□) and from 19:39 to 19:45 (△), and on 11/5/92 from 03:18 to 03:24 (■); (3) station A, 9/28/92 (□) and 10/22/92 (■). The 9/28/92 profile is a composite of two separate scans, such that the reference sea level energy shown is the mean of the two scans and whose individual scan reference energies shown by vertical bars.
Figure 3.38. Variation with reef location of (1) root-mean-square vertical porewater velocity ($w_{rms-pw}$) at 5 cm sediment depth, and (2) porewater residence time ($R_{T,upper\,10\,cm}$) within the upper 10 cm of sediment for 2/24/92 (▲), 10/8/92 (■), and 10/27/92 (□). Values for 2/24/92 were based on visual estimates of wave-conditions listed in Table 3.2, while those for 10/8/92 and 10/27/92 were based on pressure transducer measurements and spectral analyses of wave conditions listed in Table 3.1.
Figure 3.39. Variation with reef location of (1) macroscopic dispersion coefficient ($D_{\text{macro}}$) and (2) megadispersion coefficient ($D_{\text{meg}}$) for 2/24/92, 10/8/92, and 10/27/92. Values for 2/24/92 were based on visual estimates of wave-conditions (Table 3.2), while those for 10/8/92 and 10/27/92 were based on pressure transducer measurements and spectral analyses of wave conditions (Table 3.1).
Figure 3.40. Mean nutrient gradients at the sediment-seawater interface at Checker Reef for February 1992, with respective ± standard deviations shown as vertical bars.
Figure 3.41. Variation of mean fluxes of \( \text{PO}_4 \) (●), \( \text{NO}_3 + \text{NO}_2 \) (+), \( \text{NH}_4 \) (▲), and \( \text{Si} \) (□) due to either molecular diffusion (\( \text{Flux}_{\text{molec}} \)) and macroscopic dispersion (\( \text{Flux}_{\text{macro}} \)) with reef location (stations A-E identified by letters) during February, 1992.
Figure 3.42. Variation of mean fluxes of $\text{PO}_4$ (■), $\text{NO}_3^+\text{NO}_2^+$ (+), $\text{NH}_4$ (▲), and Si (□) from megadispersion during February, 1992 ($\text{Flux}_{\text{mega}}$) or Tribble (1990; $\text{Flux}_{\text{Tribble}}$) with reef location (stations A-E identified by letters). The very low and negative $\text{NO}_3^+\text{NO}_2^+$ fluxes of Tribble (1990) are plotted, but on this scale they are indistinguishable from the abscissa.
Figure 3.43. (Opposite page) Diffusive flux experiment at station D, February 8-9, 1991 showing accumulation of PO₄, NO₃ + NO₂, NH₄, and Si. Open benthic chamber (■) and linear regression of concentration variation with elapsed time (thin line); closed bottom control dome (□) and linear regression of concentration variation with elapsed time (thin line).
Figure 3.44. A. Centerline transect of the washout pattern produced by a bell jar resting on a large sediment core in a recirculating flume (Adapted from Huettel and Gust 1992a). B. Centerline transect of a typical benthic chamber used on Checker Reef, showing a 7.5 cm deep circular flange and 15 cm wide peripheral skirt. The bell jar with stirrer bar rotating at 12 rpm was exposed to a flow of 10 cm s⁻¹. "p" indicates pressure transducer ports. The benthic chambers were stirred with bilge pump (not shown). Arrows indicate streamlines of fluid movement.
Figure 3.45. Comparison of the log of nutrient uptake by mass transfer (*) "Uptake") to the log of nutrient fluxes by molecular diffusion (○; "molec."), macroscopic dispersion (□; "macro."), megadispersion (╳; "mega."), benthic chamber determinations (*; "b.c.") and Tribble's (1990) estimates (+; "Trib.").
Chapter 4. CONCLUSIONS AND RECOMMENDATIONS

The gain in vertical resolution of the concentrations of framework interstitial constituents by the use of the small well points was clearly useful in revealing the dynamic character of microbial activities in the upper meter. The small well points, originally suggested by Tribble (1990), are inexpensive, can be quickly constructed, and are easy to sample. Nevertheless, it should be cautioned that reef systems are well known for their patchy distribution of chemical and biological processes. A single well point only characterizes the chemical environment of a single depth at a fixed point. The resulting chemical depth profiles assume that similar sedimentary characteristics exist in the area defined by a total, single-station, well point array. It would be useful in future research of the upper porewater to use a single well point sampler with multiple ports opening out to regular depths over the upper meter of the framework. Future research objectives may also include metal and sulfur ion speciation, which may preclude the use of corrodible stainless steel for construction. Instead, there are on the market sturdy plastic well point samplers typically employed in terrestrial hydrology. Small, simple plastic well point samplers similar in design to the small well point samplers employed in this study could be immediately useful in an examination of metal/ion speciation. Examination of the cross-reef RIW distribution of redox-sensitive species and/or free metals may be a useful first step in examining these concerns.

Similar small well points optimally should eventually be driven into the outside flanks of Checker Reef and the inner flanks of the "blue-hole" pools to examine the magnitude of flank fluxes. The blue-holes may behave somewhat like lakes, forming a thermal inversion layer which allows the buildup of out-fluxing, wave-driven metabolic endproducts such as CH₄ (F. Sansone, personal comm.).

This study has confirmed most, if not all, of the original hypotheses posed in the first chapter of this work. Hypotheses number 1-3 and 6 (see page 9) have been
confirmed, though it is unlikely that hypotheses 4 and 5 are possible. Wave-driven mixing and concomitant fluxes were shown to be a function of wave direction and type, the relative water depth, and the particular location on the reef. The opportunity to sample the reef porewaters during an intense, Kona wind-driven S-SW swell documented chemical variability not usually seen at Checker Reef. The Kona swell induced "back-flushing" of an area of the reef that normally receives relatively little advective pumping, and the stratification of the microbial communities within back-reef sediments appeared to be perturbed by the increased ventilation. The change in the swell direction most likely resulted in enhanced organic matter and oxygen throughput to the back reef, which induced a rapid response among the framework microbial community, as evidenced by the development of the sharp NO$_3$+NO$_2$ peak.

Checker Reef porewaters should be sampled more often during Kona wind events to further substantiate these observations. Since the upper reef RIW chemistry has now been shown to vary dramatically over the course of only a few days, a future research objective would be to intensively sample the RIW of the upper meter during the onset of both the N-NE swells and, if possible, during the onset of a Kona swell. If enough field participants are available, the entire upper meter RIW should be sampled every few hours, possibly in a truly-synoptic manner. It would take two people to sample all the well point samplers at a single reef site, so eight participants would be required. A small floating tub, with a centerboard and one small anchor, could be used to sample at each site without using a boat. It is important to examine the reef synoptically, since wave-driven dispersion is influenced by tidal water levels. The quasi-synoptic sampling performed 10/8/92 and 10/27/92 took some 4 hours to complete with considerable tide change.

The diagenetic reactions within the upper 1 m of the framework seem to be easily understood when the influence by wave-action is precisely recorded and spectrally analyzed. Wave-induced macroscopic dispersion and megadispersion, when combined with more-finely resolved chemical gradients, results in fluxes far in excess of molecular diffusion. During some very quiescent, calm periods on the reef, however, molecular
diffusion may make a small, but significant, contribution to chemical flux. The upper 3-5 m of the framework was dominated for the most part by wave-induced porewater motion, and chemical fluxes were controlled by mixing.

A far more precise method of examining the pressure field synoptically should now be attempted since the transducers have passed their initial field tests. This would involve connecting of the relatively inexpensive transducers to all the well point-samplers. Signals and power could be provided with long cables back to the field boat, which could contain long-life high capacity batteries such as car batteries. Alternatively, the batteries could be left in water-tight cases at each station and the pressure signals transmitted at separate frequencies to an antennae or the field boat, which would send the individual signals from each transducer to the data logger. A way to down-load the logged signals in real time to a small lap top should also be attempted to better resolve the importance of longer-period, higher-frequency wave components in framework mixing. Using better batteries, much longer cables and/or telemetry would also allow the field boat and hands to "batten-down" during more vigorous wave action and/or storms, and extend our understanding of these more energetic mixing events.

The contributions of wave-induced dispersion to providing nutrients for benthic autotrophs is still uncertain. The potential surely exists for waves to drive substantial fluxes in the low mmol m\(^{-2}\) d\(^{-1}\) range which, according to the work of Atkinson (1987), may be in excess of what autotrophic reef communities need to sustain themselves. However, assimilation and growth as a response to the more intense wave-drive fluxes could also be accompanied with the production of detritus and the advective export of biomass and detritus from the reef. There is a significant macroalgal detrital export from Checker Reef, 9.9 g C m\(^{-2}\) y\(^{-1}\) during times of storm activity (Morrissey 1985), though usually the reef exports only around 0.7 g C m\(^{-2}\) y\(^{-1}\). It is possible that megadispersion is occurring in small, highly porous patches of the reef flat. This would result in enhanced but highly localized fluxes which are quickly mixed with the bulk OSW. However, the close agreement between the fluxes by megadispersion and the multi-method flux determinations by Tribble (1990) confirm that fluxes and mixing within the
reef framework is controlled by megadispersion. Furthermore, the close agreement of wave-induced denitrification with the work of many others further substantiate the physical control of nutrient turnover and metabolism by wave-induced megadispersion. Rather than refuting the predicted flux rates by megadispersion by the lack of an observable increase in OSW nutrients that should result if these fluxes are occurring, the lack of such an increase simply highlights the need to future examine what is likely a very productive interstitial algal community within the upper 5-10 cm of the framework.

These possibilities will need to be examined by employing a perhaps better empirical method of measuring and verifying the tremendous potential of wave-driven nutrient fluxes. As suggested in Chapter 3, the use of more-or-less permanently-emplaced chamber "flanges" driven into the framework, along with detachable chambers, has the potential to vastly improve chamber-based flux determinations. It is probably unlikely that anyone will develop an ideal chamber that is inexpensive, simple to construct, easy to operate under a variety of conditions, capable of mimicking environmental conditions, and acceptable to all researchers. However, with regard to the chambers used in this study, mundane matters such as simply providing a better seal of the enclosed volume over the sediment and wiring the bilge-pump power source back to the field boat could greatly improve reliability and increase confidence in the chamber measurements. One of the main disadvantages of using in situ chambers to measure metabolism or flux of dissolved species across the benthic boundary layer is the possible interference of hydrodynamic processes by the chamber (Huettel and Gust 1992 a,b). It is very difficult to replicate the effects of wave flow on sedimentary fluxes with benthic chambers. The use of collapsible bag-chambers (Anderson et al. 1986; Dryssen 1986) at least replicates somewhat the pressure distribution felt across the area of sediment covered by passing waves. While the design and dimensions of the chambers utilized for the Checker Reef studies were like many others, Malan and McLachlan (1992) achieved some success in demonstrating 70% greater flux using cylindrical benthic-chambers with a flexible membrane stretched across the upper end than when using solid-top chambers, and they attributed this enhanced flux to wave action. Any new chambers should have a flexible wall and a radically flatter aspect to prevent localized pressure gradients from developing.
from lateral flow and possibly interfering with flux determinations. Any new chamber-derived flux determinations should also be initiated at the much more homogeneously composed sand patch (SP, Fig. 2.1) area of Checker Reef. The sand patch area is as wave-impacted as any other representative area of the mid-reef, yet its uniform sandy composition would obviate any concerns about a good-seal at the flange, even if using the current chamber design. The determination of low, sub-mmol m⁻² d⁻¹ flux values at the sand patch would be a useful corroboration of the similar fluxes determined at the more rocky well point reef sites. Alternatively, high chamber-derived nutrient fluxes from the sand patch would help corroborate the high fluxes predicted by the megadispersion model. In addition, a flexible wall may help to replicate wave action within any chambers to be constructed for future research of wave-induced fluxes.

A more sensitive resolution of the time-varying amplitude of hydraulic head variation should in the future be determined by complex demodulation (Bloomfield 1976). Complex demodulation extracts approximations of a time series which has a perturbed periodic component, or a slowly changing amplitude and phase, by elimination of secondary harmonics and irrelevant fine structure. The dominant frequencies are determined by further, more detailed spectral analysis of representative time series, usually by increasing the section length (i.e., from m = 64, to m = 128 or 256). The detrended time series for the surface waveform is multiplied by its complex demodulate using the dominant radian frequency, and smoothed by a moving average. The absolute value of the real portion of the smoothed, demodulated time series is then the dominant mean wave amplitude, and the wave height should be twice these amplitudes. I have had some success in explorations of a few trial demodulations of the pressure transducer time series. Complex demodulation could provide a more accurate model of wave-driven diffusion in future assessments. Ultimately, the real time assessment of wave-energy, spectral density, and cross-spectral phase and coherence relationships could be accomplished with a preprogrammed lap-top computer.

Finally, a longer pressure transducer reference tube should be used in future reef studies to obviate the previously discussed possible interference of wave action at station
A by the coral heads, although it would not accurately measure the amount of wave-energy impacting sediments within similar "sand-patch pockets" located throughout the fore-reef area (e.g., see Fig. 2.1). Certainly a detailed depth profile of wave-induced pressure variations over the water column from the pocket depth on up could be attempted, and may answer whether there is significant sheltering of wave-action by the coral heads surrounding the pockets. If so, an additional "reference" transducer could be utilized to measure wave-energy and head-variations above the pocket, as well as the original reference set-up with the reference tube port much closer to the sediment-seawater interface.

This research demonstrates the likelihood that similar hydraulic activity can be expected in other wave-impacted porous sediments, such as found on carbonate platforms. Sandy coasts would also experience elevated porewater movement, yet it is uncertain whether the more homogeneously-packed sediments would allow such great vertical wave amplitude as was observed in this study. Finely packed oolitic banks, such as the extensive ones found near the Bahamas, may also be another interesting area to examine wave-induced mixing and chemical flux, since little is understood on the origins of these formations, or how they sustain their structure. It is very likely that wave-induced circulation extends deep into porous and hydraulically-conducive formations. For instance, Monterey Canyon, California is the site of an underwater cold "seep" wherein cracked hydrocarbons and other organics have been observed to actively extrude from the sediments (D. Stakes, personal commun.). A vent faunal community has developed around this seep, yet very little is known on the origin or physical forces responsible for the seep fluxes. Tides may be dispersing sedimentary organics out through the flanks of the canyon. A natural extension of the research described in this dissertation would be to drive well point samplers into the Monterey Canyon flanks, and sample both for dissolved organics and inorganics, as well as to monitor the hydraulic head over an interval of time long enough to resolve tidal periods accurately. Benthic chambers with flexible walls could be left over a representative number of seeps, and samples could be withdrawn over the period of hydraulic head monitoring, and the concentrations could be related by correlation to the spectra derived from the hydraulic head analyses.
In conclusion, the use of pressure transducers offer many exciting possibilities for the examination of similar wave-driven processes in other environments. The wave-induced porewater motion was extensive to relatively great sedimentary depths in Checker Reef. The resolution of the actual ecological impact of the high fluxes predicted by the dispersion models must be examined in future research.
Appendix 1. Wave parameter summary from single-site hydraulic head determinations. Water depth (d), reference wave-period ($T_{ref}$), wavelength ($\lambda_{ref}$), wave number ($A_{ref}$), reference root-mean-square wave amplitude ($A_{rms-ref}$), and total spectral energy ($E_{ref}$) were all derived from spectral analyses.

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<td></td>
<td></td>
<td>4.9</td>
<td>8.0</td>
<td>0.79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.6</td>
<td>4.2</td>
<td>1.51</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.95</td>
<td>4.6</td>
<td>14.0</td>
<td>0.45</td>
<td>6.08</td>
<td>37.22</td>
</tr>
</tbody>
</table>
Appendix 2. Results of linear regression of the decrease in the root-mean-square wave amplitude ($A_{rms}$-Dec.) with framework depth (f.d.). The inverse of regression slopes (Dec.) are in units of (cm-$A_{rms}$/m), and the constant (or y-intercept) indicates the extrapolated framework depth (m-f.d.) where $A_{rms}$ equal zero. Regressions assumed that the $A_{rms}$ at the sediment/seawater interface was equal to the reference $A_{rms}$ (e.g., framework depth = 0 m).

<table>
<thead>
<tr>
<th>Station/ Date and (Scan No.)</th>
<th>$A_{rms}$-Dec. (cm-$A_{rms}$/m)</th>
<th>Framework depth of zero $A_{rms}$ (m)</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A  9/28/92 (3)</td>
<td>-0.65 ± 0.31</td>
<td>2.7 ± 0.3</td>
<td>0.82</td>
</tr>
<tr>
<td>A  9/28/92 (4)</td>
<td>-1.32 ± 0.19</td>
<td>1.5 ± 0.0</td>
<td>0.98</td>
</tr>
<tr>
<td>A 10/8/92 (2)</td>
<td>-1.60 ± 1.18</td>
<td>4.5 ± 0.4</td>
<td>0.65</td>
</tr>
<tr>
<td>A 10/22/92 (2)</td>
<td>-0.93 ± 0.46</td>
<td>3.0 ± 0.3</td>
<td>0.80</td>
</tr>
<tr>
<td>A 10/27/92 (1)</td>
<td>-1.35 ± 0.82</td>
<td>2.3 ± 0.4</td>
<td>0.73</td>
</tr>
<tr>
<td>mean ± s.d.*</td>
<td>-1.17 ± 0.38</td>
<td>2.8 ± 1.1</td>
<td>0.80 ± 0.10</td>
</tr>
<tr>
<td>C 10/8/92 (4)</td>
<td>-1.98 ± 0.63</td>
<td>4.5 ± 0.4</td>
<td>0.91</td>
</tr>
<tr>
<td>C 10/10/92 (2)</td>
<td>-0.76 ± 0.26</td>
<td>4.1 ± 0.5</td>
<td>0.89</td>
</tr>
<tr>
<td>C 10/10/92 (3)</td>
<td>-0.62 ± 0.08</td>
<td>3.5 ± 0.2</td>
<td>0.98</td>
</tr>
<tr>
<td>C 11/4/92 (1)</td>
<td>-0.53 ± 0.74</td>
<td>6.1 ± 0.4</td>
<td>0.92</td>
</tr>
<tr>
<td>C 11/4/92 (3)</td>
<td>-0.74 ± 0.17</td>
<td>5.5 ± 0.3</td>
<td>0.95</td>
</tr>
<tr>
<td>C 11/5/92 (4)</td>
<td>-1.27 ± 0.07</td>
<td>4.4 ± 0.1</td>
<td>1.00</td>
</tr>
<tr>
<td>mean ± s.d.*</td>
<td>-0.98 ± 0.55</td>
<td>4.7 ± 1.0</td>
<td>0.94 ± 0.04</td>
</tr>
<tr>
<td>D 10/8/92 (5)</td>
<td>-1.36 ± 0.05</td>
<td>4.1 ± 0.1</td>
<td>1.00</td>
</tr>
<tr>
<td>D 10/27/92 (3)</td>
<td>-0.93 ± 0.20</td>
<td>2.8 ± 0.3</td>
<td>0.96</td>
</tr>
<tr>
<td>mean*</td>
<td>-1.14</td>
<td>3.4</td>
<td>0.98</td>
</tr>
<tr>
<td>E 10/8/92 (6)</td>
<td>-1.22 ± 0.05</td>
<td>3.7 ± 0.1</td>
<td>1.00</td>
</tr>
<tr>
<td>E 10/27/92 (4)</td>
<td>-0.49 ± 0.20</td>
<td>3.6 ± 0.5</td>
<td>0.86</td>
</tr>
<tr>
<td>E 11/20/92 (1)</td>
<td>-0.20 ± 0.03</td>
<td>5.0 ± 0.3</td>
<td>0.96</td>
</tr>
<tr>
<td>E 11/20/92 (3)</td>
<td>-0.01 ± 0.00</td>
<td>4.3 ± 0.0</td>
<td>1.00</td>
</tr>
<tr>
<td>mean ± s.d.*</td>
<td>-0.48 ± 0.53</td>
<td>4.1 ± 0.6</td>
<td>0.96 ± 0.07</td>
</tr>
</tbody>
</table>

* s.d. = Standard deviation of mean values.

* Only two values available, so no standard deviation calculated.
Appendix 3. Results of linear regression equations of the dissipation in the wave energy (E-Diss.) with framework depth. The inverse of the regression slopes are in units of \( \text{J m}^{-2}/\text{m} \), and the constant (or y-intercept, ± s.d.) indicates the extrapolated framework depth (m) where energy is zero. Regressions assumed that the energy at the sediment/seawater interface was equal to the reference energy (framework depth \( = 0 \text{ m} \)).

<table>
<thead>
<tr>
<th>Station/ Date and (Scan No.)</th>
<th>E-Diss. of zero energy (J m(^{-2}/\text{m}))</th>
<th>Framework depth (m)</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 9/28/92 (3)</td>
<td>-2.00 ± 0.96</td>
<td>1.6 ± 0.3</td>
<td>0.81</td>
</tr>
<tr>
<td>A 9/28/92 (4)</td>
<td>-4.76 ± 0.91</td>
<td>0.8 ± 0.0</td>
<td>0.97</td>
</tr>
<tr>
<td>A 10/8/92 (2)</td>
<td>-20.00 ± 12.00</td>
<td>2.5 ± 0.4</td>
<td>0.66</td>
</tr>
<tr>
<td>A 10/22/92 (2)</td>
<td>-4.54 ± 2.27</td>
<td>1.7 ± 0.3</td>
<td>0.79</td>
</tr>
<tr>
<td>A 10/27/92 (1)</td>
<td>-7.14 ± 4.08</td>
<td>1.4 ± 0.4</td>
<td>0.74</td>
</tr>
<tr>
<td><strong>mean ± s.d.(^a)</strong></td>
<td>-7.67 ± 7.12</td>
<td>1.6 ± 0.6</td>
<td>0.79 ± 0.11</td>
</tr>
<tr>
<td>C 10/8/92 (4)</td>
<td>-25.00 ± 6.25</td>
<td>3.0 ± 0.4</td>
<td>0.93</td>
</tr>
<tr>
<td>C 10/10/92 (2)</td>
<td>-3.22 ± 0.93</td>
<td>2.8 ± 0.4</td>
<td>0.92</td>
</tr>
<tr>
<td>C 10/10/92 (3)</td>
<td>-2.12 ± 0.04</td>
<td>2.4 ± 0.0</td>
<td>1.00</td>
</tr>
<tr>
<td>C 11/4/92 (1)</td>
<td>-2.78 ± 0.69</td>
<td>3.8 ± 0.3</td>
<td>0.94</td>
</tr>
<tr>
<td>C 11/4/92 (3)</td>
<td>-4.76 ± 0.91</td>
<td>3.4 ± 0.3</td>
<td>0.97</td>
</tr>
<tr>
<td>C 11/5/92 (4)</td>
<td>-11.10 ± 0.29</td>
<td>2.8 ± 0.0</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>mean ± s.d.(^a)</strong></td>
<td>-8.16 ± 8.87</td>
<td>3.0 ± 0.5</td>
<td>0.96 ± 0.03</td>
</tr>
<tr>
<td>D 10/8/92 (5)</td>
<td>-12.50 ± 1.56</td>
<td>2.6 ± 0.2</td>
<td>0.98</td>
</tr>
<tr>
<td>D 10/27/92 (3)</td>
<td>-3.57 ± 1.27</td>
<td>1.9 ± 0.5</td>
<td>0.90</td>
</tr>
<tr>
<td><strong>mean(^b)</strong></td>
<td>-8.03</td>
<td>2.2</td>
<td>0.94</td>
</tr>
<tr>
<td>E 10/8/92 (6)</td>
<td>-8.33 ± 0.69</td>
<td>2.5 ± 0.1</td>
<td>1.00</td>
</tr>
<tr>
<td>E 10/27/92 (4)</td>
<td>-1.39 ± 0.62</td>
<td>2.3 ± 0.6</td>
<td>0.83</td>
</tr>
<tr>
<td>E 11/20/92 (1)</td>
<td>-0.46 ± 0.06</td>
<td>3.2 ± 0.2</td>
<td>0.98</td>
</tr>
<tr>
<td>E 11/20/92 (3)</td>
<td>-14.28 ± 2.04</td>
<td>2.7 ± 0.1</td>
<td>0.99</td>
</tr>
<tr>
<td><strong>mean ± s.d.(^a)</strong></td>
<td>-6.11 ± 6.47</td>
<td>2.7 ± 0.4</td>
<td>0.95 ± 0.08</td>
</tr>
</tbody>
</table>

\(^a\) s.d. = Standard deviation of mean values.

\(^b\) Only two values available, so no standard deviation calculated.
Appendix 4. Phosphate gradients ($\mu$M cm$^{-1}$) estimated for the sediment-seawater interface of Checker Reef. Gradients are calculated as the difference between the RIW nutrient concentration from either 5 cm (if available) or 10 cm sediment depth minus the OSW nutrient concentration, divided by the depth interval. Wind-driven wave conditions are characterized as either of small or large amplitude, and coming more or less from the N.E. or S.W. direction.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wave Amplitude</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
<th>Station A</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/31/91</td>
<td>Small/N.E.</td>
<td>n.d.$^a$</td>
<td>n.d.</td>
<td>0.08</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/22/91</td>
<td>Large/N.E.</td>
<td>n.d.</td>
<td>0.01</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>12/5/91</td>
<td>Large/N.E.</td>
<td>n.d.</td>
<td>0.01</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/1/92</td>
<td>Large/N.E.</td>
<td>0.07</td>
<td>0.03$^b$</td>
<td>0.04</td>
<td>0.13</td>
</tr>
<tr>
<td>2/6/92</td>
<td>Large/N.E.</td>
<td>0.06</td>
<td>0.03$^b$</td>
<td>0.05</td>
<td>0.08</td>
</tr>
<tr>
<td>2/19/92</td>
<td>Large/S.W.</td>
<td>n.d.</td>
<td>0.02$^b$</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/22/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.09</td>
</tr>
<tr>
<td>2/24/92</td>
<td>Large/S.W.</td>
<td>0.04$^b$</td>
<td>0.01$^b$</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>2/29/92</td>
<td>Large/N.E.</td>
<td>0.01</td>
<td>0.02$^b$</td>
<td>0.08</td>
<td>0.11</td>
</tr>
<tr>
<td>6/12/92</td>
<td>Large/N.E.</td>
<td>n.d.</td>
<td>0.02</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>7/2/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>0.02</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>10/2/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.04</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/20/92</td>
<td>Small/N.E.</td>
<td>0.03</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/92 Mean</td>
<td></td>
<td>0.04</td>
<td>0.02</td>
<td>0.06</td>
<td>0.09</td>
</tr>
<tr>
<td>± s.d.$^c$</td>
<td></td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>All station-</td>
<td></td>
<td>0.04</td>
<td>0.02</td>
<td>0.06</td>
<td>0.09$^d$</td>
</tr>
<tr>
<td>data mean</td>
<td></td>
<td>± s.d.</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
</tr>
</tbody>
</table>

$^a$ Not determined.

$^b$ Gradients determined using 5-cm porewater.

$^c$ Standard deviation.

$^d$ Station A was sampled only during February, 1992.
Appendix 5. Nitrate plus nitrite gradients (μM cm⁻¹) estimated for the sediment-seawater interface of Checker Reef. Gradients are calculated as the difference between the RIW nutrient concentration from either 5 cm (if available) or 10 cm sediment depth minus the OSW nutrient concentration, divided by the depth interval. Wind-driven wave conditions are characterized as either of small or large amplitude, and coming more or less from the N.E. or S.W. direction.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wave Amplitude /Direction</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
<th>Station A</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/31/91</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td></td>
<td>0.42</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/22/91</td>
<td>Large/S.W.</td>
<td>n.d.</td>
<td>0.08</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/1/92</td>
<td>Large/N.E.</td>
<td>0.06</td>
<td>0.15</td>
<td>0.27</td>
<td>0.06</td>
</tr>
<tr>
<td>2/6/92</td>
<td>Large/N.E.</td>
<td>0.06</td>
<td>0.43</td>
<td>0.36</td>
<td>0.04</td>
</tr>
<tr>
<td>2/19/92</td>
<td>Large/S.W.</td>
<td>n.d.</td>
<td>0.33</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/22/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>-0.06</td>
</tr>
<tr>
<td>2/24/92</td>
<td>Large/S.W.</td>
<td>0.80</td>
<td>0.21</td>
<td>0.33</td>
<td>0.05</td>
</tr>
<tr>
<td>2/29/92</td>
<td>Large/N.E.</td>
<td>0.52</td>
<td>0.31</td>
<td>0.19</td>
<td>0.02</td>
</tr>
<tr>
<td>10/2/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.16</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/20/92</td>
<td>Small/N.E.</td>
<td>0.18</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/92 Mean</td>
<td></td>
<td>0.36</td>
<td>0.29</td>
<td>0.29</td>
<td>0.02</td>
</tr>
<tr>
<td>± s.d.¹</td>
<td></td>
<td>0.36</td>
<td>0.11</td>
<td>0.08</td>
<td>0.05</td>
</tr>
</tbody>
</table>

All station-data mean
|                       | 0.33   | 0.23   | 0.29   | 0.02²   |
| ± s.d.²              | 0.33   | 0.13   | 0.10   | 0.05²   |

¹ Not determined.
² Gradients determined using 5 cm-porewater.
³ Standard deviation.
⁴ Station A was sampled only during February, 1992.
Appendix 6. Ammonium gradients (µM cm⁻¹) estimated for the sediment-seawater interface of Checker Reef. Gradients are calculated as the difference between the RIW nutrient concentration from 10 cm sediment depth minus the OSW nutrient concentration, divided by the depth interval. Wind-driven wave conditions are characterized as either of small or large amplitude, and coming more or less from the N.E. or S.W. direction.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wave Amplitude /Direction</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
<th>Station A</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/31/91</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.35</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/22/91</td>
<td>Large/N.E.</td>
<td>n.d.</td>
<td>&lt;0.01</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>12/5/91</td>
<td>Large/N.E.</td>
<td>n.d.</td>
<td>&lt;0.01</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/1/92</td>
<td>Large/N.E.</td>
<td>0.47</td>
<td>0.85ᵇ</td>
<td>0.01</td>
<td>0.47</td>
</tr>
<tr>
<td>2/6/92</td>
<td>Large/N.E.</td>
<td>0.45</td>
<td>0.06ᵇ</td>
<td>0.03</td>
<td>0.23</td>
</tr>
<tr>
<td>2/19/92</td>
<td>Large/S.W.</td>
<td>n.d.</td>
<td>-0.03ᵇ</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/22/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.50</td>
</tr>
<tr>
<td>2/24/92</td>
<td>Large/S.W.</td>
<td>0.44ᵇ</td>
<td>-0.02ᵇ</td>
<td>0.06</td>
<td>0.32</td>
</tr>
<tr>
<td>2/29/92</td>
<td>Large/N.E.</td>
<td>0.19</td>
<td>1.15ᵇ</td>
<td>0.15</td>
<td>0.66</td>
</tr>
<tr>
<td>10/2/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>-0.05</td>
<td>n.d.</td>
</tr>
<tr>
<td>11/20/92</td>
<td>Small/N.E.</td>
<td>0.55</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

|        | 2/92 Mean ± s.d.ᵇ        | 0.39      | 0.40      | 0.06      | 0.44      |
|        | All station-data mean ± s.d. | 0.42      | 0.29      | 0.09      | 0.44ᵇ     |

* Not determined.
ᵇ Gradients determined using 5-cm porewater.
ᶜ Standard deviation.
ᵈ Station A was sampled only during February, 1992.
Appendix 7. Silica gradients (μM cm⁻¹) estimated for the sediment-seawater interface of Checker Reef. Gradients are calculated as the difference between the RIW nutrient concentration from 10 cm sediment depth minus the OSW nutrient concentration, divided by the depth interval. Wind-driven wave conditions are characterized as either of small or large amplitude, and coming more or less from the N.E. or S.W. direction.

<table>
<thead>
<tr>
<th>Date</th>
<th>Wave Amplitude /Direction</th>
<th>Station E</th>
<th>Station D</th>
<th>Station C</th>
<th>Station A</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/5/91</td>
<td>Large/N.E.</td>
<td>n.d.</td>
<td>-0.33</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/1/92</td>
<td>Large/N.E.</td>
<td>1.83</td>
<td>1.02</td>
<td>0.28</td>
<td>3.00</td>
</tr>
<tr>
<td>2/6/92</td>
<td>Large/N.E.</td>
<td>1.63</td>
<td>0.25</td>
<td>0.51</td>
<td>1.83</td>
</tr>
<tr>
<td>2/19/92</td>
<td>Large/S.W.</td>
<td>n.d.</td>
<td>0.22</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2/22/92</td>
<td>Small/N.E.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>2.69</td>
</tr>
<tr>
<td>2/24/92</td>
<td>Large/S.W.</td>
<td>2.01&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-0.13&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.50</td>
<td>1.72</td>
</tr>
<tr>
<td>2/29/92</td>
<td>Large/N.E.</td>
<td>0.56</td>
<td>0.43&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.67</td>
<td>2.60</td>
</tr>
<tr>
<td>11/20/92</td>
<td>Small/N.E.</td>
<td>0.54</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

2/92 Mean: 1.51 0.36 0.49 2.37
± s.d.<sup>c</sup> 0.65 0.42 0.16 0.56

All station-data mean: 1.32 0.22 0.55 2.37<sup>d</sup>
± s.d. 0.71 1.14 0.31 0.56<sup>d</sup>

<sup>a</sup> Not determined.
<sup>b</sup> Gradients determined using 5-cm porewater.
<sup>c</sup> Standard deviation.
<sup>d</sup> Station A was sampled only during February, 1992.
LITERATURE CITED


Rayleigh, L. (1880) On the resultant of a large number of vibrations of the same pitch and arbitrary phase. Phil. Mag. 10: 73-86.


