Unusual Mortality of Krill (Crustacea: Euphausiacea) in Bahía de La Paz, Gulf of California[1]

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Abstract: Surface aggregations and beach strandings of a species of krill, *Nematoscelis difficilis* Hansen, were observed in June 2003 at locations along the shore of Bahía de La Paz in the Gulf of California. For 10 days before the krill die-off, a steady wind blew from the south at speeds between 4 and 5 m/sec. For that period, satellite images showed water temperatures between 18 and 22 °C along this coast, which is low compared with typical seasonal water temperatures of 26 to 28 °C for June. Phytoplankton biomass, determined by pigment concentration and cell counts, was the highest in the area in June. The diatom *Chaetoceros debilis* represented more than 96% of the phytoplankton community. Nutrients were in relatively higher concentrations. These data suggest that upwelling conditions occurred and the diatom bloom was in its final phase. Based on this limited data set, we present a hypothetical scenario describing the sea-surface aggregations and beach strandings of *N. difficilis*.

The euphausiid or krill species *Nematoscelis difficilis* Hansen is distributed in the northern Pacific Ocean in the transitional zone (30–45° N) of the North Pacific Drift and California Current (Brinton 1962). Vertical distribution of *N. difficilis* is typically between 100 and 200 m (Brinton 1967). In the Gulf of California and along the Pacific coast of the Baja California Peninsula, it is present in many locations and seems to be a conspicuous component of the zooplankton fauna (Boden et al. 1955, Gómez-Gutierrez 1992, De Silva-Dávila et al. 2002). In Bahía de La Paz, a large bay in the southwestern part of the Gulf of California, *N. difficilis* has been recorded for several years but only in deep zones and at low densities. Aggregations described for other krill species, such as *Nyctyphanes simplex* (Gendron 1992) and *Nyctyphanes australis* (O'Brien et al. 1986), have not been recorded for *Nematoscelis difficilis*. In June 2003, several surface aggregations of *N. difficilis* were observed, lasting for several days. Because this euphausiid inhabits deep waters (Brinton 1967), these aggregations near and on the beach made us suspect a relatively rare event. We describe this event here and, supported by a small data set of physical, chemical, and biological observations, speculate about the causes of this phenomenon.

MATERIALS AND METHODS

Euphausiid surface aggregations were observed in June 2003 in Bahía de La Paz (~24.5° N, 110.5° W) at several locations (Figure 1). Organisms were in bands about 100 m wide and 1,000 m long, separated 300–400 m from each other. These bands covered approximately 60 km^2 on the southern and eastern coast of the bay as well

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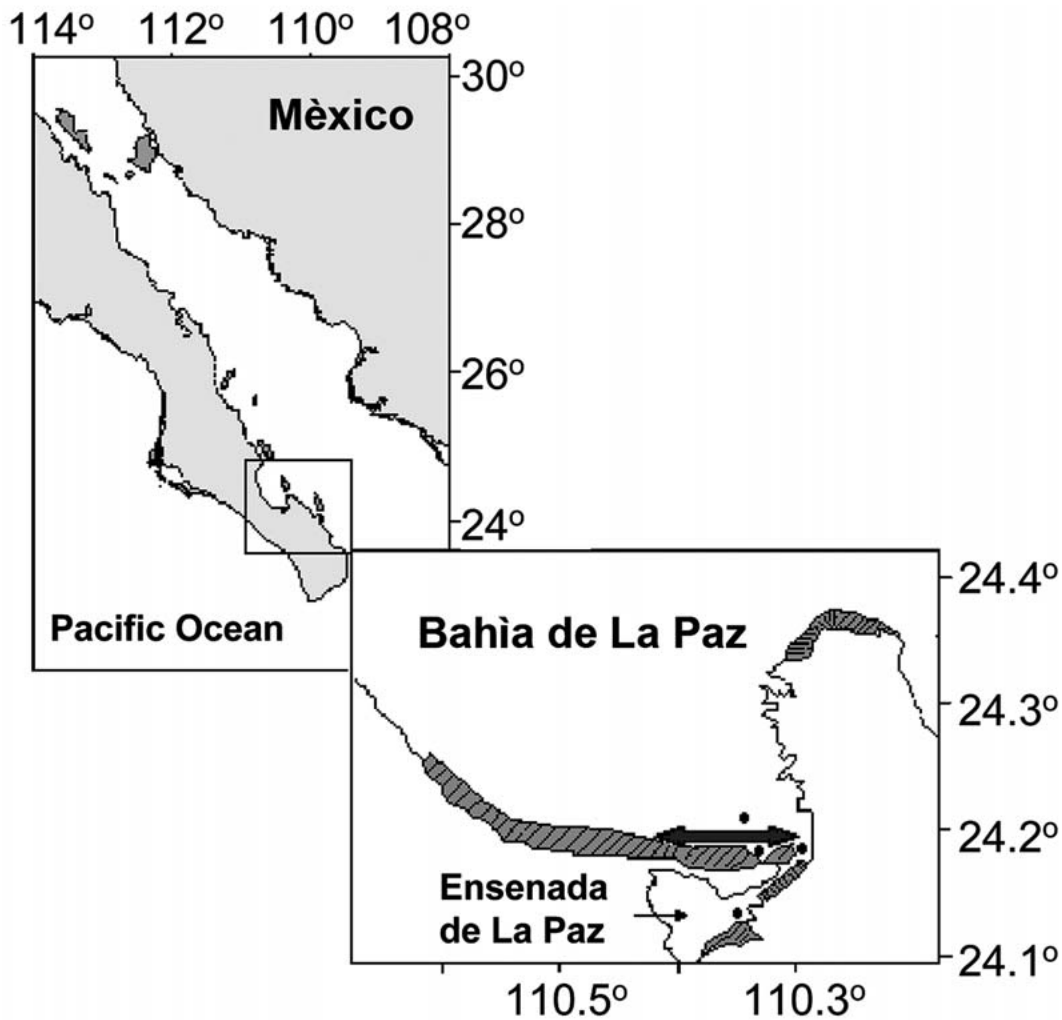

FIGURE 1. Location of the study area, where an unusual mortality of krill *Nematoscelis difficilis* occurred in June 2003.

as 15 km^2 on the southern part of the Ensenada de La Paz, the lagoon located at the southern end of the Bahía de La Paz (Figure 1). Samples were collected in 1-liter plastic bottles directly from the aggregations and fixed with 10% buffered formalin. Water samples were taken with Van Dorn bottles to determine nutrient concentrations (NH_4, NO_3, PO_4, SiO_4), pigments, and abundance of phytoplankton and planktonic species. Also, two samples of phytoplankton were fixed and preserved with Lugol for identification and cell counts. Cell counts were made in 5-ml settling chambers using a phase-contrast inverted microscope (Hasle 1978). Phytoplankton abundance was estimated at the same time as identification of species using sedimentation chambers in an inverted microscope (Zeiss). Sea-surface temperature was measured with a bucket thermometer (Kahlsico International Corp., El Cajon, California). Nutrients were measured according to Strickland and Parson (1972). Chlorophyll was identified with HPLC (high-peformance liquid chromatography) (Vidussi et al. 1996). Identification and assessment of abundance of chlorophyll pigments were performed as described in Bustillos-Guzmán et al. (1995). Meteorological data were obtained from the CIBNOR meteorological station located 200 m from the southwestern shore of the Ensenada de La Paz.

RESULTS AND DISCUSSION

Nematoscelis difficilis aggregations, composed of dead (95%) and live (5%) organisms on the sea surface and forming rows several hundred meters long, lasted several days. Density of krill was about 300–320 specimens per liter. This pattern may be a consequence of vortices, called Langmuir Circulation, set up by a continuous wind in relatively calm seas. On the beaches, several slightly elevated bands linked to tide levels and small ponds with dead krill were also present.

Of seven euphausiid species previously reported in the Bahía de La Paz, *Nyctiphanes simplex* is the most abundant, followed by *N. difficilis* and *Euphausia distinguenda*. *Nematoscelis difficilis* usually occurs in deeper waters between 100 and 200 m and is considered a transitional oceanic species with a composition of a maximum of 1.4% larvae (all stages) and over 98% adults (De Silva-Dávila 1997).

On this occasion, our samples showed only one krill species, *N. difficilis*, with less than 2% larvae. Krill containing parasitoid ciliates, as described by Gómez-Gutiérrez et al. (2003), was not present. This krill occurred in the southernmost, shallow part of the bay, including the Ensenada de La Paz, an unusual situation. Here, the sea-surface temperature ranged from 18 to 18.5 °C. This is a low temperature compared with typical seasonal temperatures of 26 to 28 °C for this month (De Silva-Dávila et al. 2002, Reyes-Salinas et al. 2003). Satellite images show a temperature range from 18 to 22 °C along the Bahía de La Paz when krill mortality occurred (Figure 2). During summer 1981, similar low temperatures (~18 °C) were recorded in this area (Granados-Guzmán and Álvarez-Borrego 1983), and this was attributed to upwelling waters from the Gulf of California. Before the appearance of surface aggregations of krill in 2003, winds were blowing from the south at speeds as high as 4 to 5 m/sec for 10 consecutive days (Figure 3). The wind direction, duration, and intensity could create conditions for mixing shallow water with deeper layers, thereby decreasing surface temperatures (Gómez-Gutiérrez et al. 1999). Seawater was brownish from high phytoplankton density and pigmentation. Phytoplankton density in the samples ranged from 1.24 to 1.35×10^6 cells liter^{-1}. High chlorophyll *a* (557.0 mg m^{-3}) and fucoxanthin (228.2 mg m^{-3}) content was present, together with other minor pigments (Table 1). Jones et al. (1982) described a red tide of *Gyrodinium aureolum* in western Scotland that reached a biomass as high as 2,200 mg m^{-3}. Fucoxanthin is a pigment characteristic of diatoms (Liaeen-Jensen 1985). The biomass and species composition confirmed that the phytoplankton bloom was largely diatoms, particularly *Chaetoceros debilis*, representing >96% of the phytoplankton community, with densities $>1 \times 10^6$ cells liter^{-1} (Table 2). This is the highest concentration recorded in this area, even when compared with values obtained during other algal blooms (Gárate-Lizárraga et al. 2001, 2003, 2004). Zooplankton in net and bottle samples was very scarce, suggesting low grazing activity. These features suggest that a diatom bloom was occurring during the occurrence of the krill mortality. However, nutrient concentrations (Table 1) were similar or at relatively higher concentrations than those previously reported for the area (Reyes-Salinas 1999, Cervantes-Duarte et al. 2001, Gárate-Lizárraga et al. 2004). It is probable that fertilization occurred before the krill die-off, and species with high nutrient affinity, such as diatoms (Smayda 1997), had exhausted the nutrients. Therefore, the die-off occurred during the final stage of the bloom. Although, we did not measure oxygen concentration, it is plausible that under the conditions described here hypoxic or anoxic conditions below the euphotic zone can occur from oxidation of organic matter, as suggested by Lechuga-Devéze et al. (2001).

A scenario of the physical, chemical, and

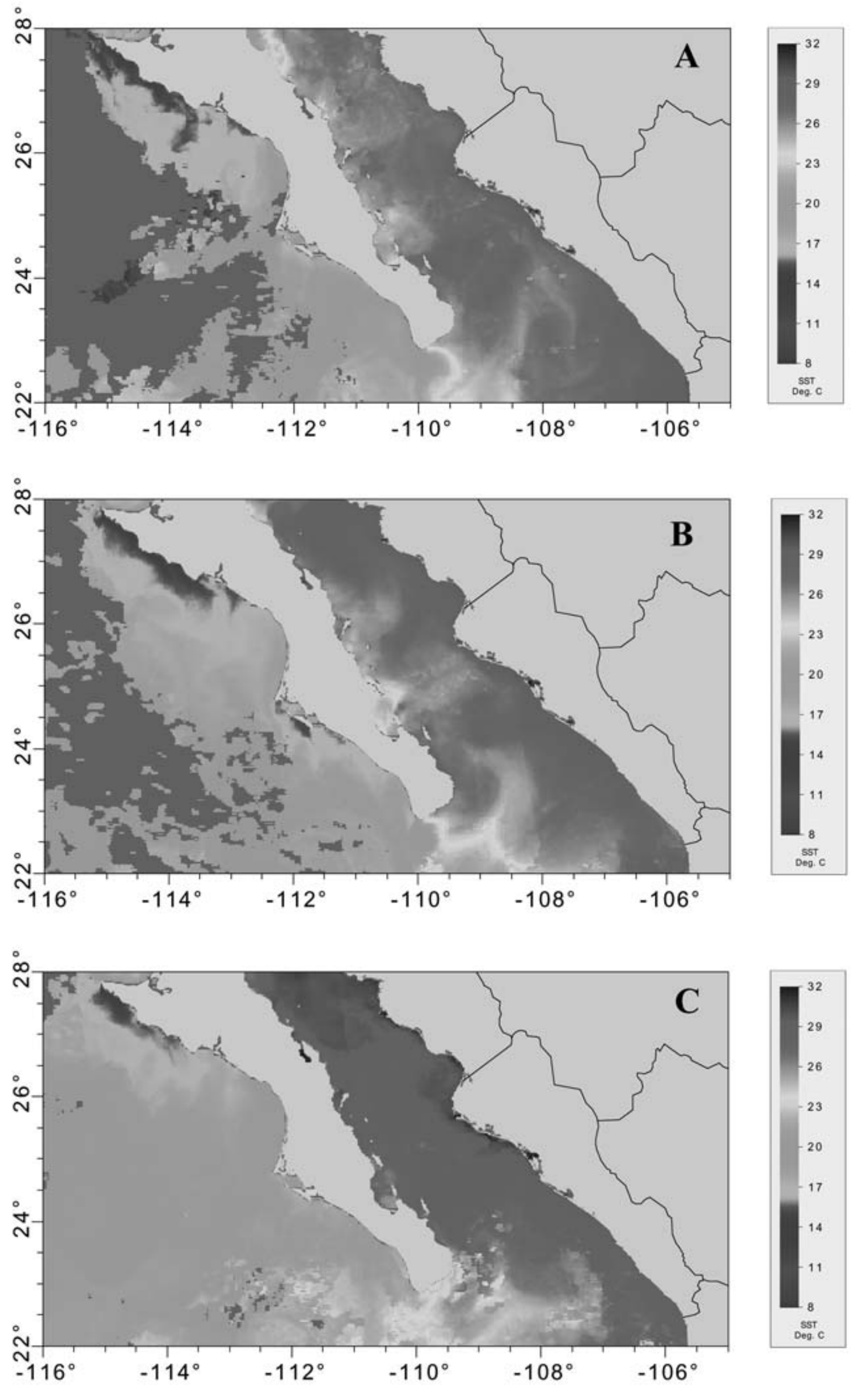

FIGURE 2. Sea WiFS images showing temperature variations in Bahía de La Paz in 2003: (*A*) 23–30 May composite image, (*B*) 5–12 June composite image, and (*C*) 23–30 June composite image. Sea-surface temperature maps were obtained from the CoastWatch program (National Oceanic and Atmospheric Administration).

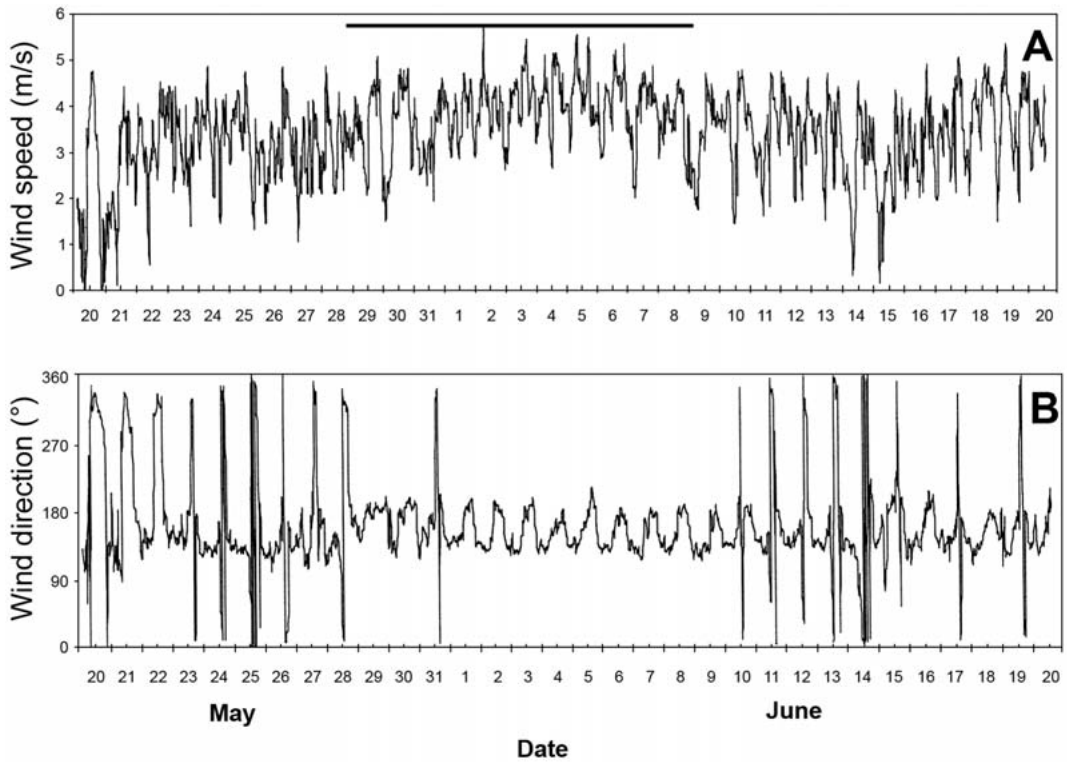

FIGURE 3. Speed (*A*) and direction (*B*) of the winds from 20 May to 20 June 2003 in the Bahía de La Paz. Bold horizontal line shows the 10-day period before *N. difficilis* mortality. Wind direction is given in degrees.

TABLE 1

Photosynthetic Pigment and Nutrient Concentrations during the Unusual Mortality of *Nematoscelis difficilis* in 2003 in Bahía de La Paz, Gulf of California

Pigments (mg m^{-3})				Nutrients (μM)			
Chlorophyll *a*	Fucoxanthin	Peridinin	Chlorophyll *b*	NH_4	NO_3	PO_4	SiO_4
557.0	228.2	1.54	18.6	7.35	4.48	1.36	4.58

biological characteristics and circumstances related to the mortality of this krill is summarized as follows. Prolonged winds from the south (Figure 3) provoked fertilization of the euphotic zone by resuspension of nutrients from the shallow areas and upwelling of nutrient-rich waters from below the thermocline. This promoted a massive increase of phytoplankton. Phytoplankton production led to a decline of available nutrients. A decoupling of primary production and zooplankton grazing may have occurred, as suggested by the low density of zooplankton. As the organic matter produced at the surface sank below the compensation depth (Sverdrup 1953), depletion of the oxygen in the water column and the bottom occurred. Organisms inhabiting euphotic and bottom

TABLE 2

Phytoplankton Species Recorded during the Bloom of June 2003 in Bahía de La Paz, Gulf of California

Species	Sample A (cells liter^{-1})	Sample B (cells liter^{-1})
Diatoms		
Asteromphalus heptactis (Brébisson) Ralfs	200	0
Azpeitia nodulifera (A. Schmidt) G. Fryxell & P. Sims	200	0
Chaetoceros debilis Cleve	1,300,000	1,196,000
Cocconeis scutellum Ehrenberg	0	400
Leptocilyndrus danicus (Cleve)	1,200	1,800
Lyrella lyra (C. G. Ehrenberg) N. I. Karayeva	0	400
Planktoniella sol (Wallich) Schütt	200	0
Rhizosolenia debyana H. Peragallo	400	0
R. imbricata Brightwell	800	0
Thalassionema frauenfeldii (Grunow) Hallegraeff	2,400	4,000
T. nitzschioides (Grunow) Mereschkowsky	24,800	32,400
Dinoflagellates		
Ceratium furca (Ehrenberg) Claparède & Lachmann	1,000	200
Gonyaulax polygramma Stein	1,200	0
Gymnodinium catenatum Graham	1,200	800
Phytoflagellates	16,200	8,400
Total phytoplankton abundance	1,349,800	1,244,400

zones, as is the case for *N. difficilis*, were forced to migrate to more-oxygenated surface waters. Surface currents carried the organisms to the shallow parts of the bay and lagoon. Once the organisms were at the surface, wave action deposited the flotsam on the beach. In another report, *Nyctiphanes simplex* was the dominant species during a massive mortality event near Guaymas, Sonora, México (Montemayor-López and Cisneros-Mata 1999). Those authors suggested that the massive die-off of that species was related to the 1997/1998 El Niño. In Chilean coasts, stranding of krill species *Euphausia mucronata* is apparently common and associated with upwelling conditions (Melo 2003). In our study, we hypothesize that mortality of *N. difficilis* was related to cooling of seawater affected by unusual meteorological conditions, including generation of cold-water upwelling. Monitoring programs directed toward harmful algal blooms or detection of zooplankton aggregations will probably provide more observations of plankton blooms in this area and their ecological consequences. This will lead to a better understanding of phytoplankton blooms and zooplankton swarming under various conditions and of the mechanisms that trigger and sustain a particular bloom.

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