AN ASSESSMENT OF DIURNAL AND SEASONAL CLOUD COVER CHANGES OVER THE HAWAIIAN ISLANDS USING TERRA AND AQUA MODIS

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ABSTRACT

Knowledge of cloud cover patterns is important in effective management of natural resources, climate change studies, and remote sensing applications. The objective of this study was to develop a comprehensive understanding of the spatial, seasonal, and diurnal patterns in cloud cover frequency over the Hawaiian Islands using high resolution image data (every 6 hours at 1 km) from the National Aeronautics and Space Administration’s Moderate Resolution Imaging Spectroradiometer (MODIS) sensors aboard the Terra and Aqua satellite platforms. The Terra and Aqua MODIS cloud mask products, which provide the likelihood that clouds obscure a given 1 km pixel, were obtained for the entire MODIS time series (10+ years) over the main Hawaiian Islands. Monthly statistics were generated from the daily cloud mask data, including mean cloud cover frequency at the four overpass times of ~11am, 2pm, 11pm, and 2am. The derived monthly statistics showed several significant trends that were consistent with generally known rainfall patterns. First, cloud cover frequency increased with height above the lifting condensation level (roughly 600 m) until the trade wind inversion (mean elevation 2100-2200 m), above which it was generally clear. Second, cloud cover frequency was higher on the windward (northeastern) sides of mountains than on the leeward (southwestern sides) of the mountains on all of the main Hawaiian Islands. Third, irrespective of season, mean cloud cover frequency was higher in the afternoon than in the morning and higher in the daytime than in the nighttime. Lastly, the dry season months (May – Oct) were less cloudy than the wet season months (Nov – Apr), and this pattern was stronger at nighttime than during the daytime. The derived statistics also revealed a unique and unexpected trend of anomalously low cloud cover in December and January over the Hawaiian Islands. The monthly time series produced in this thesis is the first high spatial resolution
cloud cover dataset in Hawai‘i and is expected to be a useful resource in a variety of applications, including the management of energy and fresh water resources.
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INTRODUCTION

Knowledge of cloud cover frequency is essential for climate science and remote sensing applications. Clouds have a strong but variable impact on the earth’s energy budget; clouds could potentially intensify or mitigate the effects of increased CO₂ in the atmosphere (Wylie et. al 2005, Pincus et al. 2012). Clouds reflect incoming radiation and reduce ambient temperature, thereby reducing the evapotranspiration (ET) demand of plants (Ackerman et al. 1998). With regard to ET estimation, cloud cover frequency can be used to estimate daily solar radiation in the absence of ground data (Running et al. 1989). A comprehensive analysis of cloud frequency patterns using high resolution data is necessary for the determination of parameters related to the earth/atmosphere energy balance, such as net solar radiation. Additionally, clouds represent contamination in the field of remote sensing; retrieval of surface parameters are impeded by cloud cover. Consequently, knowledge of cloud cover frequency is essential to the production of high-quality remote sensing products. Knowledge of cloud patterns enables understanding of the degree and frequency of cloud contamination of remotely sensed parameters such as land surface temperature and leaf area index (LAI).

To date, there has not been a comprehensive spatial and temporal analysis of cloud cover over the Hawaiian Islands using high spatial resolution data. This was due to a lack of high resolution remotely sensed cloud cover data with a long data record. The Moderate-Resolution Imaging Spectroradiometer (MODIS) instruments aboard the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) Terra and Aqua have the high spatial and temporal resolution necessary to examine spatial patterns in cloud cover in detail.
Shortly after MODIS cloud cover data became available, Yang et al. (2008a, b) investigated cloud cover frequencies in Hawai`i. These studies were, however, limited in scope due to the insufficient length of the MODIS data record at the time and maturity of the cloud cover algorithm. Yang et al. (2008a) used daytime cloud mask data from Terra and Aqua MODIS from June-August of 2004 and 2005 to determine cloud cover frequency over the Hawaiian Islands. Yang et al. (2008b) used what appears to be the same set of cloud cover data. Analysis of seasonal and diurnal trends in cloud cover frequency was not possible as the data are from only the summer months and only from the daytime MODIS overpasses.

The objective of this study was to derive a comprehensive understanding of cloud cover frequencies over the Hawaiian Islands, which has never before been accomplished. Specifically, this study aimed to determine how spatial patterns of cloudiness change diurnally and seasonally over the Hawaiian Islands using high resolution 1 km cloud cover data generated from the Terra and Aqua MODIS satellite sensors. At the commencement of this study, the MODIS data record had surpassed 10 years, providing an opportunity to determine general seasonal and diurnal trends in cloud cover frequency.

**Hypotheses**

In Hawai`i, May-October is the ‘dry season’ and that November – April is the ‘wet season’. Based on these rainfall patterns, we hypothesized that the cloud cover frequency in the dry season would be lower than cloud cover frequency in the wet season.

In the tropics in general, maximum precipitation tends to occur in the late afternoon/early evening over land (Kikuchi and Wang 2008). In Hawai`i, however, there is a well-documented nighttime rainfall maximum that occurs late at night and
in the early morning hours (Leopold 1949, Smolarkiewicz et al. 1988, Chu and Feng 1995, 2001, Austin 1996, Wang and Chen 1998, Li and Chen 1999, Feng and Chen 2001, Frye and Chen 2001, Yang and Chen, 2003). The precise timing of this rainfall maximum, however, varies greatly based on local geography and topography. Based on this knowledge we might expect it be more cloudy at night than in the afternoon in general. However, due to the large spatial and temporal variability in the timing of the nighttime rainfall maximum, no explicit hypothesis was made regarding diurnal variation in cloud cover.

**MATERIALS AND METHODS**

**Description of Study Area**

The State of Hawai‘i is situated nearly in the middle of the Pacific Ocean (18-22°N; 154-161°W). The Hawaiian Islands were formed by volcanic eruptions, which continue today on the island of Hawai‘i.

The State of Hawai‘i encompasses nearly the entire Hawaiian Island chain consisting of 8 large islands and 124 small islands, atolls and shoals. The island of Hawai‘i, known as the Big Island, is the largest of the Hawaiian Islands at 10430 km² in area (Figure 1d). The Big Island consists of five separate shield volcanoes, three of which are considered active (Mauna Loa, Mauna Kea, Kohala, Hualalai, and Kilauea) (Figure 1d). Snow falls on the high summits of Mauna Loa and Mauna Kea during some winter months. Maui consists of two shield volcanoes separated by a central isthmus (Figure 1c). The West Maui Mountains are older and highly eroded and East Maui is dominated by the younger, larger volcano Haleakalā (Figure 1c). Kaho‘olawe lies 11 km southwest of East Maui. Northwest of Maui is Moloka‘i, which was formed from the coalescence of two volcanoes, the East Molokai‘i volcano and the West Moloka‘i volcano (Figure 1c). Directly west of Maui is Lana‘i. O‘ahu, the most
populous of the Hawaiian Islands, has two parallel mountain ranges, the Koʻolau and Waiʻanae Mountains, remnants of two shield volcanoes (Figure 1b). Kauaʻi is the oldest of the Hawaiian Islands. The second highest point on the island, Waialeale reaches 1569 m and is one of the rainiest spots on earth, averaging more than 9990 mm of rain a year from the time period spanning 1950 to the present (Giambelluca et al. 2013, Figure 1a). Niʻihau lies in Kauaʻi’s rain shadow, 30 km to southwest.

Hawaiʻi’s climate is considered to be tropical; however topography causes great variation in local climate. Hawaiʻi has both some of the rainiest and driest places on earth; Big Bog on the windward slope of Haleakalā, Maui averages 10271mm of rainfall, while the summit of Mauna Kea averages only 204mm of rain (Giambelluca et al. 2013). The Hawaiian Islands receive the most precipitation during the winter months; generally November to April is considered the ‘rainy season’ (Giambelluca et al. 1986, 2013). Winter is cooler than summer, with highs of 26–28°C in the wet season (Sanderson 1993). The dry season (May through October) is generally hotter, with highs of 29–32°C (Sanderson 1993).

The trade winds, easterly surface winds that are found in the tropics, blow persistently from the ENE direction in Hawaiʻi (Giambelluca and Schroeder 1998, Giambelluca et al. 2013). These winds result in orographic clouds and rain on the windward (northeast) slopes of mountains. The leeward (southwest) sides of mountains are then generally drier. Another climate feature in Hawaiʻi is the trade wind inversion (TWI). This shallow layer of air, generally 2200 m above sea level over the islands, prevents air from moving up windward mountain slopes and instead diverts it around the mountains (Giambelluca and Schroeder 1998, Giambelluca et al. 2013). This results in very low precipitation and cloud cover at elevations above 2200 m.
MODIS Cloud Mask Product

There are two MODIS sensors, one on each of NASA’s Terra and Aqua satellites. Aqua and Terra are both polar orbiting sun-synchronous satellites with an altitude of 705 km (Platnick et al. 2003). The MODIS swath is 2330 km and its repeat cycle is 16 days. The sensors have two overpasses each per day, one at night and one during the day. The MODIS instrument has a spatial resolution of 250 m in bands 1-2, 500 m in bands 3-7, and 1000 m in bands 8-36 and acquires data continuously, providing global coverage every 1-2 days.

The Terra and Aqua MODIS Level 2 cloud mask products (MOD35 and MYD35, respectively) were used in this study. The cloud mask provides the likelihood that clouds obscure a particular 1 km (at nadir) pixel at the instant the image was acquired (Ackerman et al. 1998, Platnick et al. 2003, Ackerman et al. 2008, Frey et al. 2008). The detection of cloud is based on the contrast between the cloud and the background environment (e.g. land surface or atmosphere) in a given 1 km (at nadir) pixel (Ackerman 2008, Frey et al. 2008), for which a combination of spectral threshold tests are employed using as many as 14 of the 36 MODIS spectral bands (Ackerman et al. 1998, Platnick et al. 2003, Frey et al. 2008). The particular series of spectral threshold tests applied to the field of view is determined by the surface type (land, water, snow/ice, desert, and coastline) and the solar illumination (day vs. night) (Ackerman et al. 1998, Frey et al. 2008). Each individual test returns a confidence level from 1 (high confidence that pixel is clear) to 0 (high confidence of cloud) (Ackerman et al. 1998, Frey et al. 2008). The tests are grouped by type in order to maximize the independence of the spectral threshold tests, then the final cloud mask confidence (Q) is calculated as the product of the minimum confidences for each group (Ackerman et al. 1998, Ackerman et al. 2002, Frey et al. 2008). The four confidence levels of the cloud mask are as follows: confident clear (Q > 0.99),
probably clear (Q > 0.95), uncertain/probably cloudy (Q > 0.66), and cloudy (Q ≤ 0.66) (Frey et al. 2008, Ackerman et al. 2002). The cloud mask algorithm is clear-sky conservative in that if a pixel fails any single test, the pixel is defined as cloud contaminated (Ackerman et al. 2006, Frey et al. 2008). In addition to the cloud mask scientific data set, the MODIS cloud mask product also has a cloud mask product quality assurance (QA) scientific dataset. The QA flags indicate the quality of various parameters in the cloud mask scientific dataset.

A preliminary comparison of the MODIS cloud mask with ground-based combination Microcompulse Lidar/Millimeter Wavelength Cloud Radar (MPL/MMCR) indicated that the MODIS cloud detection algorithm agreed with MPL/MMCR 86% of the time when it was clear or probably clear, and 92% of the time when a cloud was present (Ackerman et al. 2002). A more in-depth study of MODIS cloud mask performance compared MODIS cloud mask data to Program Active Remotely Sensed Cloud (ARSCL) product that combines MPL and MMCR at the same DOE ARM Southern Great Plains site indicated that agreement between MODIS and ARSCL was approximately 83% (Ackerman et al. 2008).

**Data Collection and Processing**

The cloud mask products (MOD35 and MYD35) over the major Hawaiian Islands (Top: 22.503, Left: -160.5, Bottom: 18.75, Right: -154.497) were obtained from NASA’s Level 1 and Atmosphere Archive and Distribution System (LAADS) (http://ladsweb.nascom.nasa.gov/). Eleven years of data were obtained from Terra MODIS (2001-2011) and nine years of data were obtained from Aqua MODIS (2003 – 2011). The mean daytime and nighttime overpass times were 11:10 and 22:40, respectively, for Terra MODIS and 13:50 and 02:20, respectively, for Aqua MODIS.
The cloud mask images were reprojected onto a 1km (0.083º) geographic coordinate grid on the NAD83 datum and subset to cover the major Hawaiian Islands (Top: 22.503, Left: -160.5, Bottom: 18.75, Right: -154.497) using MODIS Reprojection Tool Swath (https://lpdaac.usgs.gov/tools/modis_reprojection_tool_swath).

The reprojected and subset cloud mask data were then coded into the binary indicator of cloudy (1) or clear (0) from the four confidence levels. The binary encoding algorithm was created based off the suggestions in the MODIS User’s Guide for isolating cloudy scenes (Strabala 2005, Ackerman et al. 2002) since the MODIS cloud mask product is clear-sky conservative, minimizing false clear, determining cloudiness requires extensive processing (Ackerman et al. 2002, Ackerman 2008).

Two different encoding methods were devised to determine cloud cover frequencies, one for daytime scenes and the other for nighttime scenes (Table 1). For the daytime images, pixels designated as ‘confident cloudy’ or ‘probably cloudy’ by the MODIS cloud mask were considered ‘cloudy’, and pixels designated as ‘confident clear’ or ‘probably clear’ by the MODIS cloud mask were considered ‘clear’. Areas flagged as sunglint regions by the MODIS cloud mask algorithm were not included. If the QA flags indicated that there was low confidence in the cloud mask, the pixels were not included. The nighttime algorithm was altered from the daytime algorithm to remedy the problem of systematic overclouding over the land (http://modis-atmos.gsfc.nasa.gov/MOD35_L2/qa.html, Yang et al. 2008a, b). In the nighttime algorithm, pixels designated as ‘confident cloudy’ were considered ‘cloudy’ and pixels designated as ‘probably cloudy’, ‘confident clear’ or ‘probably clear’ by the MODIS cloud mask were considered ‘clear’. Additionally, if the surface temperature test was the only test performed, the pixel was considered ‘clear’.
Our modifications to the algorithm minimized the false cloud detection at elevations between coastal lowlands and 2000 m (Frey, personal comm.). Specifically, the nighttime MODIS cloud mask product falsely detected clouds at elevations between coastal lowlands and 2000 m. This was the result of the surface temperature test that compares gridded surface air temperatures from Global Data Assimilation System (GDAS) to observed 11µm brightness temperatures at elevations up to 2000 m (Frey et al. 2008). Due to the large variations in surface temperature in mountainous areas, the test does not necessarily perform well in these regions. We consulted with the MODIS cloud mask team to determine the best way to reduce the overclouding issues. The aforementioned algorithm changes resulted in a reduction of false cloud detection over land at elevations from sea level to 2000 m (Figure 2).

Monthly statistics including mean cloud cover frequency at each of the four overpass times were generated from the daily MOD35 and MYD35 binary cloudiness time series. For each month, daily cloud cover scenes were processed into a monthly cloud cover frequency for each year in the time series (2011, 2010, etc.). The means of these monthly frequencies (11 years for Terra MODIS and 9 years for Aqua MODIS) were then calculated. The resulting time series was one cloud cover frequency map for each month for all four overpass times. This resulted in 48 monthly cloud cover frequency maps. The daytime and nighttime algorithms both calculated monthly statistics including mean cloud cover frequency, standard deviation, minimum cloud cover frequency, and maximum cloud cover frequency at each pixel.

**Data Analysis**

Description of spatial and diurnal patterns of cloudiness was accomplished qualitatively and therefore did not require explicit statistical analysis.
In order to address the specific hypothesis that cloud cover frequency is lower in the dry season (May – Oct) than in the wet season (Nov – Apr), a one-way Analysis of Variance (ANOVA) was performed. Additionally, one-tailed, two-sample student’s t-tests were performed to determine whether the difference between dry and wet season varied with overpass time. All statistics were performed using Minitab statistical software (Minitab Inc., State College, Pennsylvania, USA).

RESULTS

Mean Annual Cloud Cover Maps

Derived mean cloud cover statistics show some spatial trends that are independent of season and time of day. Cloud cover frequency increases with height above the lifting condensation level (roughly 600 m) until the trade wind inversion (mean elevation 2100-2200 m) (Figs. 3-6). The smallest cloud cover frequency (the highest frequency of clear sky) was observed over the high elevation areas (above the inversion layer) on the islands of Maui and Hawai’i (Figures 3, 4).

Annual mean cloud cover frequency (Figs. 3-6) show that cloud cover frequency is generally higher on the windward side of the mountains than the leeward side for all islands. This pattern seems especially distinct at the nighttime overpasses but also is present at the daytime overpasses.

Figure 3 shows the annual mean cloud cover frequency for the island of Hawai’i at all four MODIS overpass times. On the island of Hawai’i, cloud cover frequency is lowest above Mauna Loa (elevation 4169m) and Mauna Kea (elevation 4205m) (Juvik and Juvik 1998). A distinct reduction in cloud cover frequency over the summits of Mauna Loa and Mauna Kea at all overpass times is observed. Since the island of Hawai’i is built from five separate shield volcanoes that overlap,
discerning leeward and windward sides of each volcano is not possible. In general,
the leeward side of the overlapping volcanos Mauna Loa and Mauna Kea in the center
of the island had lower cloud cover frequency than the windward side of the
volcanos. This pattern was more pronounced at the nighttime overpasses but is also
discernible at the daytime overpasses. Increased cloud cover frequencies seen at the
summit of Mauna Loa at nighttime is likely false cloud detection due to snow cover
during the winter.

Figure 4 shows the annual mean cloud cover frequency for Maui and Kalawao
counties at all four overpass times. The massive East Maui Volcano (Haleakalā)
reaches 3055m (Juvik and Juvik 1998). There is reduced cloud cover around the
summit of Haleakalā at all overpass times. Cloud cover frequency is higher on the
windward (northeastern) side of the East Maui Volcano than on the leeward
(southwestern) side of the volcano. This pattern is more distinct at the nighttime
overpasses than at the daytime overpasses. The West Maui Volcano also shows
higher cloud cover frequency on the windward of the volcano than the windward
side. The West Maui Volcano has a peak elevation of 1764m, which is lower than the
average elevation of the trade wind inversion (Juvik and Juvik 1998). As such, there
is no reduced cloud cover over the summit of the West Maui Volcano. The island of
Molokai shows lower cloud cover frequency on the leeward side than the windward
side of the island as well. As with the other islands, the pattern is more pronounced
at the nighttime overpasses than at the daytime overpasses.

Figure 5 shows the annual mean cloud cover frequency over the island of
O’ahu (Honolulu County) at all four overpass times. The leeward side of the Ko’olau
mountain range has lower cloud cover frequency than the windward side of the
mountains at the nighttime overpass times. During the daytime overpasses there is
not a pronounced difference in cloud cover frequency between the leeward and windward sides of the mountains.

Figure 6 shows the annual mean cloud cover frequency over Kaua‘i County at all four overpass times. Kaua‘i is characterized by a central mountain mass that includes Kaua‘i’s highest peak, Kawaihina and Mount Waialeale (Juvik and Juvik 1998). The leeward side of the central mountains has a lower cloud cover frequency than the windward side of the central mountains at all overpass times. The pattern is more pronounced at the nighttime overpasses than at the daytime overpasses.

**Diurnal Patterns**

A time series of 1 km monthly mean cloud cover frequency for each overpass time are presented in Figures 7-10. These maps display both spatial and monthly trends in cloud cover.

The time series of mean monthly cloud cover across the state shows some diurnal patterns that hold true across all months, regardless of season (Figure 11). Comparing cloud cover frequencies for the Terra MODIS daytime overpass and Aqua MODIS daytime overpass shows that cloud cover frequency is generally higher in the afternoon (13:50) than in the morning (11:10) irrespective of season. The mean cloud cover frequencies for the morning (11:10) and afternoon (13:50) overpasses were 0.5884 and 0.7054, respectively (Table 9). By looking at the monthly cloud cover frequency time series for the Terra MODIS daytime overpass vs. the Aqua MODIS daytime overpass (Figure 7 vs. Figure 8), it is evident that cloud cover frequency is higher in the afternoon than in the morning for every month of the year.

Mean cloud cover frequency is generally similar at the two Terra MODIS and Aqua MODIS nighttime overpass times (22:40 and 02:20, respectively) regardless of season (Figure 11). The mean cloud cover frequencies for the 22:40 overpass and
the 02:20 overpass were 0.3684 and 0.3907, respectively. Visual comparison of the monthly cloud cover frequency time series for the Terra MODIS and Aqua MODIS nighttime overpasses (Figure 9 vs. Figure 10) confirms that the two overpass times are very similar for each month.

The time series of mean monthly cloud cover across the state also shows that there is lower cloud cover frequency at the nighttime overpasses than during the daytime overpasses (11:10 and 13:50) during all months of the year (Figure 11). The mean cloud cover frequencies for the two daytime overpasses vs. the two nighttime overpasses were 0.6469 and 0.3907, respectively (Table 11). A visual comparison of Figures 7 and 8 (11:10 and 13:50, respectively) to Figures 9 and 10 (22:40 and 02:20, respectively) confirms that the two daytime overpasses are cloudier than the nighttime overpasses for every month of the year.

**Seasonal Patterns**

In general, the dry season months (May – Oct) appear to have lower cloud cover frequency than the wet season months (Nov – Apr) in both the daytime and the nighttime (Figure 8). The mean cloud cover frequencies for the dry season months and wet season months were 0.4928 and 0.5315, respectively (Table 3).

A difference was found in seasonal cloud cover frequency patterns that relates to overpass time. Figure 8 shows that the dry season months generally have lower cloud cover frequencies than the wet season months at the nighttime overpass times (22:40 and 02:20). For the daytime overpasses (11:10 and 13:50), the dry season months appear to have lower cloud cover frequency than the wet season months except for December and January, which display the lowest cloud cover frequencies out of all the months of the year.
Plotting the mean cloud cover frequencies in the dry season vs. the wet season separately for each overpass time indicates differences in seasonal patterns in cloud cover frequency based on overpass time. Figure 12 shows that for both the Terra MODIS and Aqua MODIS daytime overpasses (11:10 and 13:50, respectively), cloud cover frequency is similar between the dry and wet season, and in fact appears to be lower during the wet season than the dry season. The mean cloud cover frequencies at the Terra MODIS daytime overpass for the dry season months and wet season months were 0.6160 and 0.5607, respectively (Table 5). The mean cloud cover frequencies at the Aqua MODIS daytime overpass (13:50) for the dry season and wet season were 0.7167 and 0.6940, respectively.

For both the Terra MODIS and Aqua MODIS nighttime overpasses (22:40 and 02:20, respectively), cloud cover frequency is lower during the dry season months than during the wet season months (Figure 12). For the Terra MODIS nighttime overpass (22:40) the mean cloud cover frequencies for the dry season months vs. wet season months were 0.3051 and 0.4317, respectively (Table 7). For the Aqua MODIS nighttime overpass (02:20) the mean cloud cover frequencies for the dry season months vs. wet season months were 0.3182 and 0.4631, respectively (Table 8).

**Statistical Analysis**

In order to quantify the difference in cloud cover frequency between the dry season and wet season, a limited statistical analysis was performed. A one-way Analysis of Variance (ANOVA) was performed to determine the effect of season (dry vs. wet) on mean cloud cover frequency (Table 2). The results show that season (dry vs. wet) has a significant effect on mean cloud cover frequency ($p = 0.016$).
Even though cloud cover frequency is generally lower during the dry season than wet season, further exploration showed that this seasonal effect appears to be true only at some overpass times. In order to quantify the differences in seasonality based on overpass time, 1-tailed, two-sample t-tests were performed for dry season vs. wet season for each overpass time. Table 4 displays the results for the 1-tailed t-tests for all four overpass times.

At the Terra MODIS daytime overpass (11:10), mean cloud cover frequency during the wet season was not significantly different from mean cloud cover frequency during the dry season months ($p = 0.914$) (Table 4). At the Aqua MODIS daytime overpass (13:50), mean cloud cover frequency during the wet season months is not significantly different from mean cloud cover frequency during the dry season months ($p = 0.765$) (Table 4).

At the Terra MODIS nighttime overpass (22:40), the dry season months had significantly lower mean cloud cover frequency than the wet season months ($p = 0.003$) (Table 4). Similarly, at the Aqua MODIS nighttime overpass (02:20), the dry season months had significantly lower mean cloud cover frequency than the wet season months ($p = 0.001$) (Table 4).

These results support the assertions made from the qualitative analysis of seasonal patterns in the cloud cover frequency data. During the morning, wet season months and dry season months do not appear to differ in mean cloud cover frequency (Table 5). Similarly, the wet season months and dry season months do not appear to differ in mean cloud cover frequency in the afternoon (Table 6). At nighttime, the dry season months have lower cloud cover frequency than the wet season months as expected for both the Terra MODIS nighttime overpass (Table 7) and the Aqua MODIS nighttime overpass (Table 8).
DISCUSSION

December/January Anomaly

Examining the monthly time series of cloud cover revealed an anomaly in the months of January/December for all 4 overpass times. While December and January are the months in the middle of the wet season, they have lower cloud cover frequency than expected at all four overpass times (Figure 11). For Terra and Aqua MODIS daytime overpasses (11:10 and 13:50, respectively), December and January represent the lowest cloud cover frequency across the islands for the entire year (Figures 7, 8). For the Terra and Aqua MODIS nighttime overpasses (22:40 and 02:20, respectively), cloud cover frequency in December and January is lower than the other wet season months (Figures 9, 10). This anomaly does not appear to correspond to seasonal changes in rainfall. A winter maximum of rainfall has been recorded in dry areas of the islands, however the reduced cloud cover in December/January seems to occur in both wet and dry areas of the islands (Giambelluca et al. 1986). While the causes of the low cloud cover frequency in December and January are unknown, it is an important finding. December and January, particularly during the daytime, are the time of year when obtaining cloud free observations would be most likely.

Correspondence with Seasonal Rainfall Patterns

The general patterns in cloud cover frequency over the Hawaiian Islands correspond with known rainfall patterns over the state. Rainfall patterns in Hawai‘i are very spatially and seasonally diverse; however a leeward/windward rainfall gradient is well-documented on the Hawaiian Islands (Giambelluca et al. 2013). Orographic lifting and east-northeast trade winds combine to produce orographic clouds and rain on the windward slopes of mountains, while the trade wind inversion produces very dry zones above the summits of high mountains (Giambelluca et al.
Generally, high mean rainfall is found on windward slopes of mountains and low rainfall is found on leeward sides of mountains and on the upper slopes of high mountains (Giambelluca et al. 2013). The lowest observed mean rainfall across the state is on the summits of the high mountains Haleakalā, Mauna Kea, and Mauna Loa (Giambelluca et al. 2013). This leeward/windward gradient in rainfall corresponds to the observed cloud cover frequency patterns. The annual mean cloud cover frequency results for all the main Hawaiian Islands show higher cloud cover frequency on the windward (northeastern) sides of mountains and lower cloud cover frequency on the leeward (southwestern) sides of the mountains. Additionally, the areas of lowest cloud cover were above the trade wind inversion at the summits of Haleakalā, Mauna Loa, and Mauna Kea. Overall, the leeward/windward and elevational gradients in cloud cover parallel the observed rainfall patterns.

A unique rainfall pattern exists on the North and South Kona districts of the Island of Hawai‘i (Giambelluca et al. 2013). While the leeward sides of mountains are generally dry, the Kona districts of Hawai‘i have a narrow belt of high rainfall due to unique airflow patterns in the region (Figure 13, Giambelluca et al. 2013). In addition to the persistent rainfall, this area also has more rain in the summer than other seasons and has an afternoon rainfall peak (Giambelluca et al. 2013). Annual mean cloud cover frequency is also increased in the North and South Kona regions; however this increased cloud cover seems to be most distinct at the daytime MODIS overpasses (Figure 3a, 3b). Additionally, the highest cloud cover in this region is observed in the afternoon, which is in accordance with the observed afternoon rainfall maximum in the area (Figure 3b).

With regard to seasonal rainfall patterns, cloud cover frequency generally corresponds to the expected dry season/wet season designations. The dry season months of May through October generally have lower rainfall than the wet season
months of November through April. Statistical tests of cloud cover frequency between the dry season and wet season only show a significant difference at the nighttime overpass times. At the Terra and Aqua MODIS nighttime overpasses (22:40 and 02:20, respectively), the dry season has significantly lower mean cloud cover frequency than mean cloud cover frequency in the wet season months. At the Terra and Aqua MODIS daytime overpasses (11:10 and 13:50, respectively), mean cloud cover frequency does not differ between the dry and wet season.

Diurnal patterns in rainfall vary across the Hawaiian Islands; however a higher chance of rain is generally found at night and in the early morning (generally between 20:00 to 08:00) than during the late morning and afternoon (Leopold 1949, Smolarkiewicz et al. 1988, Chu and Feng 1995, 2001, Austin 1996, Wang and Chen 1998, Li and Chen 1999, Feng and Chen 2001, Frye and Chen 2001, Yang and Chen, 2003). Based on this knowledge we might expect higher cloud cover frequency at the nighttime overpass times than during the daytime overpass times, and higher cloud cover frequency in the morning than in the afternoon. The results of the MODIS cloud cover frequency analysis do not support this prediction, as there was lower cloud cover at the Terra and Aqua MODIS nighttime overpasses (22:40 and 02:20, respectively) than during the Terra and Aqua MODIS daytime overpasses (11:10 and 13:50, respectively). Additionally, the overpass time with the highest cloud cover frequency was the Aqua MODIS daytime (afternoon) overpass at 13:50. This discrepancy could be due to insufficient temporal resolution to detect the nocturnal maximum in rainfall, or perhaps high nocturnal rainfall does not correspond to high nocturnal cloud cover frequency due to physical factors such as cloud type. Additionally, the inability to detect the nocturnal maximum in rainfall might be due to algorithm differences between the daytime and nighttime MODIS data.
Possible Data Limitations

The Terra MODIS and Aqua MODIS cloud mask algorithms are essentially the same (Ackerman et al. 2008). Results between the two satellites are offset by 2% globally, however it is difficult to assess whether these differences are due to variances in instrument performance or reflect real diurnal variation in cloud amount (Ackerman et al. 2008). For the purposes of this study, it was assumed that the accuracy of the Terra and Aqua MODIS cloud mask product were equivalent.

As mentioned previously, adjustments for nighttime data were made to the algorithm that translated MODIS cloud cover designations into binary cloudy/clear. These adjustments were to reduce well-documented errors in the MODIS cloud mask product over the Hawaiian Islands. Specifically, the nighttime surface temperature test performed by the MODIS cloud mask algorithm caused false cloud detection over coastal lowlands up to 2000 m over the Hawaiian Islands. The changes to the nighttime algorithm reduced the false overclouding as a result of the surface temperature test. However, there is a possibility that the algorithm changes made to reduce false cloud detection could also reduce detection of real clouds. As a result, there could be a small bias in the nighttime cloud cover frequency data towards lower-than-actual cloud cover frequency.

One of the drawbacks of using MODIS data to determine cloud cover frequency is that high temporal resolution is sacrificed in favor of high spatial resolution. The data is therefore temporally limited – a MODIS sensor only passes over the Hawaiian Islands four times per day. While MODIS cloud mask data is able to illuminate spatial patterns of cloud cover in detail, it is difficult to discern the diurnal cloud cover cycle using only four data points per day. A study currently being performed at the University of Hawai‘i is merging the MODIS-derived cloud cover frequency data presented here with data from the Geostationary Satellite system.
(GOES). GOES is operated by the National Environmental Satellite, Data, and Information Service (NESDIS) and is used for weather forecasting and meteorology research. Between the two GOES Satellites cloud cover data over the Hawaiian Islands is acquired every 15 minutes at a 4 km spatial resolution. By fusing MODIS and GOES together, a cloud cover frequency time series with both high spatial and temporal resolution can be derived. Examining this merged dataset would allow for a more complete picture of the diurnal cycle in cloud cover frequency and illuminate the relationship between nighttime cloud cover frequency and the nocturnal maximum in rainfall.

**CONCLUSIONS**

This study showed that cloud cover frequency statistics derived from MODIS 1 km cloud cover data have the ability to determine spatial, diurnal, and seasonal patterns in cloud cover in detail. The key findings of this study are as follows:

- Cloud cover frequency generally increases with elevation until roughly 2000 m, above which it is usually clear.
- The lowest cloud cover frequencies were observed over the high elevation areas (above the trade wind inversion layer) on the islands of Maui and Hawai‘i.
- Cloud cover frequency systematically varied in relation to the facings of slopes; cloud cover frequency was higher on the windward (northeastern) sides of the mountains than on the leeward (southwestern) sides of the mountains.
- The dry season months (May – Oct) have lower cloud cover frequency than the wet season months (Nov – Apr) when data from all four overpass times is pooled together.
• When all four overpass times are examined separately, cloud cover frequency is lower during the dry season and the wet season at the two nighttime overpasses (22:40 and 02:20).

• Cloud cover frequency is not significantly different between the dry season and wet season at the two daytime overpasses (11:10 and 13:50).

• Cloud cover frequency is generally higher in the afternoon (13:50) than in the morning (11:10) irrespective of season.

• Mean cloud cover frequency is at the two nighttime overpasses (22:40 and 02:20) regardless of season.

• There is lower cloud cover frequency at the nighttime overpasses than during the daytime overpasses (11:10 and 13:50) during all months of the year.

• The months of January and December have lower cloud cover frequencies than expected based on the knowledge that these two months are both in the wet season. This anomaly does not appear to correspond to seasonal changes in rainfall.
Table 1. Daytime and nighttime cloudiness designations for derivation of monthly statistics

<table>
<thead>
<tr>
<th>DAYTIME ALGORITHM</th>
<th>NIGHTTIME ALGORITHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOD35/MYD35 Cloud Mask Product</td>
<td>Derived cloud frequencies</td>
</tr>
<tr>
<td>Confident cloudy</td>
<td>Cloudy (1)</td>
</tr>
<tr>
<td>Probably Cloudy</td>
<td>Cloudy (1)</td>
</tr>
<tr>
<td>Probably Clear</td>
<td>Clear (0)</td>
</tr>
<tr>
<td>Confident Clear</td>
<td>Clear (0)</td>
</tr>
</tbody>
</table>

Table 2. Results of One-Way Analysis of Variance (ANOVA) to determine the effect of season (dry vs. wet) on cloud cover frequency.

<table>
<thead>
<tr>
<th>Variable</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Season</td>
<td>1</td>
<td>0.1799</td>
<td>0.1799</td>
<td>5.89</td>
<td><strong>0.016</strong></td>
</tr>
<tr>
<td>Error</td>
<td>478</td>
<td>14.6128</td>
<td>0.306</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>479</td>
<td>14.7927</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Comparison of mean cloud cover frequencies for the dry vs. wet season. All four overpass times are pooled.

<table>
<thead>
<tr>
<th>Season</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Season</td>
<td>240</td>
<td>0.4928</td>
<td>0.1962</td>
</tr>
<tr>
<td>Wet Season</td>
<td>240</td>
<td>0.5315</td>
<td>0.1504</td>
</tr>
</tbody>
</table>
Table 4. One tailed two-sample t-test results and CI for dry season (May – Oct) vs. wet season (Nov – Apr) at all four overpasses:

<table>
<thead>
<tr>
<th></th>
<th>95% Upper Bound for Difference</th>
<th>T-value</th>
<th>p-value</th>
<th>DF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terra MODIS Daytime (11:10) Dry vs. wet season</td>
<td>0.1253</td>
<td>1.59</td>
<td>0.914</td>
<td>5</td>
</tr>
<tr>
<td>Aqua MODIS Daytime (13:50) Dry vs. wet season</td>
<td>0.0814</td>
<td>0.78</td>
<td>0.765</td>
<td>5</td>
</tr>
<tr>
<td>Terra MODIS Nighttime (22:40): Dry vs. wet season</td>
<td>-0.0634</td>
<td>-3.67</td>
<td>0.003</td>
<td>9</td>
</tr>
<tr>
<td>Aqua MODIS Nighttime (02:20): Dry vs. wet season</td>
<td>-0.1449</td>
<td>-4.58</td>
<td>0.001</td>
<td>9</td>
</tr>
</tbody>
</table>

*bolded values indicate significance at the $\alpha = 0.05$ level

Table 5. Dry season (May – Oct) vs. wet season (Nov – Apr) at the Terra MODIS Daytime (11:10) overpass.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terra MODIS Daytime (11:10) Dry Season</td>
<td>6</td>
<td>0.6160</td>
<td>0.0217</td>
<td>0.0089</td>
</tr>
<tr>
<td>Terra MODIS Daytime (13:50) Wet Season</td>
<td>6</td>
<td>0.5607</td>
<td>0.0822</td>
<td>0.034</td>
</tr>
</tbody>
</table>

Table 6. Dry season (May – Oct) vs. wet season (Nov – Apr) at the Aqua MODIS Daytime (13:50) overpass.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aqua MODIS Daytime (13:50) Dry Season</td>
<td>6</td>
<td>0.7167</td>
<td>0.0192</td>
<td>0.0077</td>
</tr>
<tr>
<td>Aqua MODIS Daytime (13:50) Wet Season</td>
<td>6</td>
<td>0.6940</td>
<td>0.0688</td>
<td>0.028</td>
</tr>
</tbody>
</table>
Table 7. Dry season (May – Oct) vs. wet season (Nov – Apr) at the Terra MODIS Nighttime (22:40) overpass.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terra MODIS Nighttime (22:40) Dry Season</td>
<td>6</td>
<td>0.3051</td>
<td>0.0644</td>
<td>0.026</td>
</tr>
<tr>
<td>Terra MODIS Nighttime (22:40) Wet Season</td>
<td>6</td>
<td>0.4317</td>
<td>0.0547</td>
<td>0.022</td>
</tr>
</tbody>
</table>

Table 8. Dry season (May – Oct) vs. wet season (Nov – Apr) at the Aqua MODIS Nighttime (02:20) overpass.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aqua MODIS Nighttime (02:20) Dry Season</td>
<td>6</td>
<td>0.3182</td>
<td>0.0573</td>
<td>0.023</td>
</tr>
<tr>
<td>Aqua MODIS Nighttime (02:20) Wet Season</td>
<td>6</td>
<td>0.4631</td>
<td>0.0522</td>
<td>0.021</td>
</tr>
</tbody>
</table>
Table 9. Mean cloud cover frequency and standard deviation at the Terra MODIS (11:10) and and Aqua MODIS (13:50) daytime overpasses

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terra MODIS Daytime</td>
<td>12</td>
<td>0.5884</td>
<td>0.0642</td>
<td>0.019</td>
</tr>
<tr>
<td>Aqua MODIS Daytime</td>
<td>12</td>
<td>0.7054</td>
<td>0.0495</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Table 10. Mean cloud cover frequency and standard deviation at the Terra MODIS (22:40) and and Aqua MODIS (02:20) nighttime overpasses

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terra MODIS Nighttime</td>
<td>12</td>
<td>0.3684</td>
<td>0.0872</td>
<td>0.025</td>
</tr>
<tr>
<td>Aqua MODIS Nighttime</td>
<td>12</td>
<td>0.3907</td>
<td>0.0920</td>
<td>0.027</td>
</tr>
</tbody>
</table>

Table 11. Daytime vs. nighttime cloud cover frequency for combined Terra and Aqua MODIS data (Terra MODIS Daytime (11:10) + Aqua MODIS Daytime (13:50)) vs. (Terra MODIS Nighttime (22:40) + Aqua MODIS Nighttime (02:20))

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined Terra and Aqua MODIS Daytime</td>
<td>24</td>
<td>0.6469</td>
<td>0.0820</td>
<td>0.017</td>
</tr>
<tr>
<td>Combined Terra and Aqua MODIS Nighttime</td>
<td>24</td>
<td>0.3796</td>
<td>0.0884</td>
<td>0.018</td>
</tr>
</tbody>
</table>
Figure 1. Major geologic, geographic, and political features in the four counties in the State of Hawai‘i. Major mountain summits and major cities are labeled. (a) Kaua‘i county, (b) Honolulu County, (c) Maui County, and (d) Hawai‘i County
Figure 2. Improvements to nighttime MODIS cloud mask algorithm. (a) mean cloud cover in January from the nighttime Aqua MODIS overpass before nighttime improvements to algorithm, and (b) mean cloud cover in January from the nighttime Aqua MODIS overpass after nighttime improvements to the algorithm.
Figure 3. Annual mean cloud cover at all four MODIS overpass times over Hawai‘i county. Red represents 100% clear sky, blue represents 100% cloud cover, and green represents 50% cloud/50% clear. (a) 11:10 Terra MODIS overpass, (b) 13:50 Aqua MODIS Overpass, (c) 22:40 Terra MODIS overpass, (d) 02:20 Aqua MODIS overpass.
Figure 4. Annual mean cloud cover at all four MODIS overpass times over Maui County. Red represents 100% clear sky, blue represents 100% cloud cover, and green represents 50% cloud/50% clear. (a) 11:10 Terra MODIS overpass, (b) 13:50 Aqua MODIS Overpass, (c) 22:40 Terra MODIS overpass, (d) 02:20 Aqua MODIS overpass
Figure 5. Annual mean cloud cover at all four MODIS overpass times over Honolulu County. Red represents 100% clear sky, blue represents 100% cloud cover, and green represents 50% cloud/50% clear. (a) 11:10 Terra MODIS overpass, (b) 13:50 Aqua MODIS Overpass, (c) 22:40 Terra MODIS overpass, (d) 02:20 Aqua MODIS overpass.
Figure 6. Annual mean cloud cover at all four MODIS overpass times over Kaua‘i county. Red represents 100% clear sky, blue represents 100% cloud cover, and green represents 50% cloud/50% clear. (a) 11:10 Terra MODIS overpass, (b) 13:50 Aqua MODIS Overpass, (c) 22:40 Terra MODIS overpass, (d) 02:20 Aqua MODIS overpass
Figure 7. Mean cloud cover frequency over the Hawaiian Islands for the years of 2001-2011 from the Terra MODIS daytime overpass (average overpass time 11:10).
Figure 8. Mean cloud cover frequency over the Hawaiian Islands for the years of 2003-2011 from the Aqua MODIS daytime overpass (average overpass time 13:50).
Figure 9. Mean cloud cover frequency over the Hawaiian Islands for the years of 2001-2011 from the Terra MODIS nighttime overpass (average overpass time 22:40).
Figure 10. Mean cloud cover frequency over the Hawaiian Islands for the years of 2003-2011 from the Aqua MODIS nighttime overpass (average overpass time 02:20).
Figure 11. Monthly time-series of mean cloud cover frequencies over the main Hawaiian Islands at all four MODIS Overpass times.
Figure 12. Interaction plot displaying the interaction between overpass time and season on mean cloud cover frequency.
Figure 13. Narrow band of increased rainfall in the North and South Kona regions (Giambelluca et al. 2013).
Works Cited


