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Resolving the Diurnal and Synoptic Variance of Scatterometer Vector Wind Observations

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RESOLVING THE DIURNAL AND SYNOPTIC VARIANCE OF
SCATTEROMETER VECTOR WIND OBSERVATIONS

By

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ABSTRACT

Scatterometer observations of vector winds are used to examine the amplitudes of synoptic and diurnal cycles. Scatterometers have the advantage of providing global coverage over water; however, irregular temporal sampling complicates the analyses. A least squares technique is used in determination of the amplitudes and phases of the diurnal and synoptic cycles on spatial scales of 5°, 15°, and 30°. In open ocean areas and regions with sufficient open water, the magnitudes of the diurnal and synoptic cycles are 1.0 ms$^{-1}$ and 3.5 ms$^{-1}$, respectively. Diurnal amplitudes are highest in the polar regions and close to land surfaces due to sea breeze effects. The fraction of variance explained by the diurnal cycle is greatest near the equator. Synoptic amplitudes are consistently larger downwind of land from storm tracks and in the southern polar region as the time analyzed is during the southern winter season.
CHAPTER 1
INTRODUCTION

Near-surface ocean waters are greatly influenced by the wind at the ocean-atmosphere interface. The wind transfers momentum and energy to the surface waters and then gives rise to ocean currents and the fluctuating motions of waves [Pond and Pickard, 1983]. The wind varies on many time scales (e.g., annual, seasonal, synoptic and diurnal cycles), and these cycles are quite different from each other in magnitude, temporal scales, and in their impact on the ocean surface. It is of great importance to study these cycles to obtain a greater understanding of the wind’s influences on ocean transport. Scatterometers are not commonly utilized for studies that determine the smaller temporal cycles of the wind [Chelton and Wentz, 1986; Schlax et al., 2001]; however, they can be instrumental in resolving these cycles, which is particularly useful where there are limited sources of observations over the global oceans. Buoy observations are limited to a small fraction of the global ocean surfaces; whereas, scatterometers have the capability of obtaining wind observations globally over the ocean. The observations from two scatterometers are combined herein to examine synoptic and diurnal cycles.

Many diurnal and semidiurnal studies have been performed over several oceanic regions of the world. During the GARP [Global Atmospheric Research Program] Atlantic Tropical Experiment (GATE), ships released soundings every six hours to study the diurnal and semidiurnal variations of the wind from the surface to the upper atmosphere [Pedder, 1978]. Pedder [1978] found that the diurnal and semidiurnal components of the wind reinforced each other during the morning. This reinforcement produced a principle maximum in the eastward wind component at approximately 1030 local time. The meridional component exhibited
similar diurnal variability, but the semidiurnal ranges were much smaller than the diurnal ranges [Pedder, 1978].

Hourly data from the Tropical Atmosphere-Ocean (TAO) moored buoy array were utilized to examine the zonal and meridional winds [Deser and Smith, 1997]. The meridional wind spectra showed peaks at the diurnal and synoptic time periods. Alternatively, the zonal wind spectra exhibited a peak at time scales longer than a week and at the semidiurnal frequency; no peak was consistently seen at the diurnal frequency. The semidiurnal variations accounted for 68% of the mean daily variance of the zonal wind component, whereas; the diurnal variations accounted for 82% of the mean daily variance in the meridional component. The mean daily variations are defined as the percent variance explained by the diurnal and semidiurnal harmonics of the mean daily march of the zonal or meridional wind component [Deser and Smith, 1997].

A recent study [Gille et al., 2003] used scatterometer data to examine the diurnal cycle of the wind near coastlines. Utilizing knowledge of the phase of the sea breeze present along many of the world’s coastlines, Gille et al. [2003] tested the National Aeronautics and Space Administration (NASA) Quick Scatterometer (QuikSCAT or QSCAT) scatterometer’s ability to resolve the well-known diurnal cycle associated with the sea breeze [Davis et al., 1890]. Statistically significant diurnal variability of the wind was found to occur along most coastlines equatorward of 50° and in the easterly trade winds. The appropriate diurnal reversal of the wind direction associated with the sea breeze was also observed.

It is plausible that scatterometers can also be used in analyses similar to those previously discussed to resolve the synoptic and diurnal cycles of the wind over the global oceans. Data from QSCAT and Japan’s Advanced Earth Observing Satellite 2 (ADEOS 2, renamed Midori 2) are utilized for a period of approximately six months (section 2.3) to examine the synoptic and diurnal cycles of the wind as well as spatial variability.

There has been some uncertainty as to whether scatterometer coverage is capable of resolving these scales. Preliminary examples, based on a regular sampling period and utilizing buoy and European Centre for Medium Range Weather Forecasts (ECMWF) data, help to illustrate one aspect of this problem. The National Data Buoy Center (NDBC) hourly buoy wind data (detailed in section 2.1) and the ECMWF six hourly wind data (section 2.2) were sampled at constant sampling intervals, enabling a Fast Fourier Transform (FFT) to be used in analyzing the
wind rotary spectra. Three datasets of 64 days (April 10, 2003 – June 12, 2003; June 13, 2003 – August 15, 2003; and August 16, 2003 – October 18, 2003) were specifically chosen to minimize any possible error that could be made by leakage from the FFT [Cochran et al., 1967]. The ECMWF data (section 2.2) only covers the first period of 64 days. Data were taken from the buoy datasets at 1, 3, 6, and 12 hourly sampling intervals, whereas samples from the ECMWF datasets were only taken every 6 and 12 hours. All output from the FFT were smoothed with a Hanning filter (five passes). The rotary spectra of the wind (Figure 1) are shown for time intervals 1, 3, 6, and 12 hours for the Alaskan buoy and the 6 and 12 time intervals for the ECMWF data related to that location. Figure 2 shows the rotary spectra of the wind at the 1, 3, 6, and 12 hour for the Hawaiian buoy and the 6 and 12 hour intervals for the ECMWF data related to that location.

**Figure 1 – Alaskan Rotary Wind Spectra:** Rotary wind spectra for the period of April 10, 2003 – June 12, 2003 for the Alaskan buoy (a and b) for the time intervals of 1, 3, 6, and 12 hours and the ECMWF data corresponding to the Alaskan buoy region (c and d) for the 6 and 12 hourly time intervals. The counter-clockwise variances are represented by a and c and the clockwise variances are shown in b and d.
Figure 2 – Hawaiian Rotary Wind Spectra: Rotary wind spectra for the period of April 10, 2003 – June 12, 2003 for the Hawaiian buoy (a and b) for the time intervals of 1, 3, 6, and 12 hours and the ECMWF data corresponding to the Hawaiian buoy region (c and d) for the 6 and 12 hourly time intervals. The counter-clockwise variances are represented by a and c and the clockwise variances are shown in b and d.

Figures 1a and b show either relatively small diurnal variance or little difference from similar frequencies. The 1, 3, and 6 hour sampling intervals have very similar spectra in the diurnal and synoptic ranges for both the positive and negative frequencies. The spectra for the 12 hour sampling interval have relatively large differences between the periods of one to two days. The problem with a 12 hour sampling interval is that there are no samples of the component of the diurnal cycle that is one quarter of a cycle out of phase with the sampling time. Six hour sampling interval is much more effective than the 12 hour sampling interval for examining variability on the daily scale. Previous studies have also shown that diurnal variations are not well sampled by twice-daily observations [Gille et al., 2003].

The ECMWF-based spectra (Figure 1b and c) have smaller variances due to the much larger spatial/temporal scales (and hence, smoothing) to which it applies. The large peaks in Figures 1
and 2 (a and b) at the smaller periods are due to the variability of small spatial scale winds with time periods of several hours. There is a small peak at a period of 24 hours, which is due to either an artifact of modeled physics or a relatively strong reduction of the non-diurnal signal. The ECMWF spectrum also has a very weak peak for synoptic variability.

In each figure (1a and c and 2a and c), there are noticeable differences in every spectrum for each period from 15 – 64 days. These differences are due to varying characteristics of each subsample and large uncertainty in the spectral decomposition of amplitudes for low frequency variability. No substantial diurnal peaks were observed in the spectra (Figure 2a and b) in contrast to earlier tropical studies [Pedder, 1978; Deser and Smith, 1997]. There is higher variance in the counter-clockwise component in the larger time scales, which depicts that the larger scaled features of the wind have a more dominant effect on the counter-clockwise rotating component of the wind. Otherwise, the counter-clockwise and clockwise components of the wind correlate well and show similar diurnal effects and synoptic effects from the period of four to ten days.

In order to provide a better comparison to the earlier studies, an examination of the individual zonal and meridional spectra for the Hawaiian buoy at all the three 64 day periods was performed. In all but one case (the second 64 day period from June 13, 2003 – August 15, 2003), there were no substantial peaks in the spectra at the diurnal frequency for the zonal wind component, but there was a slight peak in the spectra at or around the diurnal frequency for the meridional wind component. Although expected, the diurnal peak cannot be shown in equatorial buoy data for the periods used in this study due to observational gaps in the data available from the equatorial region.

The above examples indicate that, for most domains, one scatterometer would not sample frequently enough to accurately represent the spectrum of the wind on the scales of interest, particularly the diurnal cycle. A 6-hour sampling interval was seen to have enhanced accuracy in comparison to the 12-hour sampling interval; that is, the six hour spectra differs little from the more finely sampled spectra. This study will use observations from both QSCAT and Midori 2 to resolve the diurnal and synoptic scale cycles.

Employing both scatterometers, the diurnal and synoptic scale cycles and variability are determined with high accuracy. The highest variances in the zonal and meridional components are mainly observed in poorly sampled regions of the globe; and thus, these areas will be ignored.
in this study. It is shown that the large-scale features can be determined unexpectedly well in comparison to what the preliminary analysis showed. The scatterometers’ observations prove to be a useful tool for the diurnal and synoptic scale resolution as well as in variability analyses for most areas of the globe.
Buoy data and the ECMWF operational analyses were utilized in preliminary examples to examine the temporal variability of the data using a constant sampling interval. These preliminary analyses depicted the specific limitations that the scatterometer datasets would have within this analysis. The scatterometer data are described in section 2.3.

**Buoy Data**

The buoy data were obtained from the NDBC. The NDBC buoys 46001 and 51002 are moored in the Gulf of Alaska (56.30°N, 148.17°W) and southwest of Hawaii (17.14°N, 157.79°W), respectively. These buoys were chosen due to their latitude and distance from land (88 and 215 nautical miles), respectively. SeaWinds scatterometer observations are masked within 30 miles of land; thus, if the buoys were located within this region, it could not be closely co-located to scatterometer observations. Furthermore, the diurnal cycle observed by near-coastal buoys could include strong land/sea breezes, which are not representative of the open ocean.
ECMWF Operational Data

The operational data came from the ECMWF Tropical Ocean and Global Atmosphere (TOGA) Global Advanced Operational Surface Analysis. The high-resolution surface data from the ECMWF operational model are on a Gaussian grid with a resolution of 1.125 degrees. This data set contained the zonal and meridional components of the wind at 10 m. Data are available from January 1985 to June 2003. Modeled data were output at 0, 6, 12, and 18Z and have global coverage. Only the period overlapping SeaWinds on Midori 2 were considered. Since the operational ECMWF analysis outputs data every 1.125° of latitude and longitude, data were chosen based on the two closest corresponding locations of both the Alaskan and Hawaiian buoys.

Scatterometer Data

Ocean vector wind observations were obtained from the SeaWinds instruments on QSCAT and Midori 2. QSCAT was launched on June 19, 1999, as a “quick recovery” mission to fill the gap between the loss of NASA Scatterometer (NSCAT) and the launch of Midori 2 [Bourassa et al., 2003b], and is currently functional. Midori 2 was launched on December 14, 2002 and lost power on October 25, 2003 due to an unknown anomaly. Each satellite provides twice-daily coverage (globally averaged), which is lessened at the equator and enhanced at the poles. The latitudinal dependence is thoroughly described by Schlax et al. [2001]. Both satellites have an eight-day repeat cycle, resulting in temporally irregular sampling. Resolution of a diurnal cycle requires more than two sampling times; thus, both satellites’ observations are necessary for most latitudes. Due to the catastrophic failure of Midori 2, only approximately 6 months of data are available for this application. Observations are combined from both satellites from all oceanic regions.

Scatterometers are unique in terms of their accuracy in remotely observing surface wind speed and direction. Microwaves are scattered by capillary and ultra gravity waves (short water waves), which respond quickly to changes in the wind. The backscatter cross section, which is the fraction of transmitted energy that returns to the satellite, is a function of wind speed and
direction relative to the orientation of the scatterometer [Wentz and Smith, 1999]. The wind direction is then found by determining the angle that is most likely to match the observed backscatters [Bourassa et al., 2003a]. The SeaWinds instrument has two conically rotating beams at fixed incidence angles (46.25° and 54°), resulting in a very wide (1800 km) swath for which only one of the beams reaches in the outer seven cells of the swath. The inner and outer beams have radii of 707 km and 900 km, respectively. Individual footprints are binned into 25 x 25 km cells with up to 76 cells across a swath [Bourassa et al., 2003b]. There is decreased accuracy near nadir and near the edges of the swath [Bourassa et al., 2003a].

For this analysis, the QSCAT dataset is the Ku-2001 product obtained from Remote Sensing Systems (RSS). Ku-2001 is an improved geophysical model function. The Ku-2001 product more accurately represents the wind direction dependence on σ₀ at low winds and has a flatter σ₀ versus wind speed response at high winds [Wentz et al., 2001]. Midori 2 observations were obtained from JPL’s Level 2B (L2B) product. For both scatterometers, only the wind speed and direction selected by the data providers were used. The scatterometer winds are calibrated to equivalent neutral winds at a height of 10m above the local mean water surface [Cardone et al., 1996; Bourassa et al., 2003a]. The differences between equivalent neutral winds and winds measured by anemometers after adjustment to a height of 10m are a function of atmospheric stratification and are almost always less than 0.5 ms⁻¹ [Bourassa et al., 2003a].

Rain is another variable that decreases the accuracy of the observed winds. Rain influences radar returns through three processes: backscatter off of the rain, attenuation of the signal passing through the rain [Weissman et al., 2002], and modification of the surface shape by raindrop impacts [Bliven et al., 1993; Sobieski et al., 1995; 1999]. Observations that were believed to be taken during periods of rain incidences were flagged and removed from the datasets, making sampling even less regular. Each satellite’s products are passed through a different flagging algorithm. QSCAT data utilize the Ku-2001 rain-flagging algorithm, which combines four different flags. To produce a single flag for rain, the four rain flags are as follows:

1) Ku-2001 ‘quality of retrieval’ flag (iclass) = 0 (no retrieval),
2) Ku-2001 scatterometer-based flag (rflag_scat) = 1,
3) Ku-2001 fit to GMF flag (sos_all) > 1.9, and
4) Ku-2001 radiometer-based (rad_rain) flag > 0.15 and difference in temporal co-location < 30 minutes.
These four flags are combined as suggested by RSS with the exception of flag 1, which in this form is more similar to the flags of the Jet Propulsion Laboratory (JPL) [Bourassa et al., 2003b]. The Midori 2 observations utilize an Empirical Normalized Objective Function (ENOF) flag to eliminate rain-contaminated data. The ENOF is based on variability in the normalized radar cross sections within a wind cell and is calculated relative to the value consistent with the selected wind vector [Mears et al., 2000].
CHAPTER 3

METHODOLOGY

In general, a 12-hour sampling interval cannot be used to accurately determine both components of a diurnal cycle. Accuracy is somewhat decreased when resolving the synoptic scale. A 6-hour sampling interval is more effective for resolving both synoptic and diurnal cycles. For a satellite-based investigation of the diurnal cycle, it is therefore necessary to utilize data from at least two wide swath scatterometers. With two scatterometers, it is possible to obtain four or more observations per day in a 25 x 25 km domain for dry weather conditions. Rain-flagged observations (approximately 7% of observations) are removed from the dataset. Different spatial domain sizes are utilized in the analyses to vary the number of rain-free observations. Large domains can have data from several swaths, thereby, benefiting from an increased diversity of sampling times. Three different domain sizes are utilized in this study: 5° x 5°, 15° x 15°, and 30° x 30° domains. Data are obtained corresponding to the same 6-week time periods utilized in the buoy and ECMWF analyses (section 1) for global oceanic regions.

If the phase of the diurnal cycle is best described relative to any fixed time relative to the solar cycle, then there is a longitudinally dependent change in phase of time across the domains. The change in longitude and local time is accounted for by adjusting scatterometer observation times for longitudinal differences. The scatterometer data are sorted into spatial and temporal (30 minutes) domains, and then the means of the zonal and meridional components of the wind are calculated for each domain. A least squares regression technique is used to evaluate the
amplitudes and phases of the data. In the least squares method below, $z_j$ represents the $j^{th}$ observed zonal ($u$) and meridional ($v$) components of the wind in the form of:

$$z_j = u_j + iv_j,$$

where $i$ is the imaginary number (square root of $-1$). The cyclic variability at frequency $f$ is modeled as

$$z(t_j) = a \cos(2\pi ft_j) + b \sin(2\pi ft_j) + i[c \cos(2\pi ft_j) + d \sin(2\pi ft_j)],$$

where $z(t_j)$ represents the modeled fit to the unknown zonal ($a$ and $b$) and meridional ($c$ and $d$) wind components at time $t$. The least squares method minimizes a function ($F$) describing the square of the magnitude of the differences between modeled ($z(t_j)$) and observed ($z_j$) wind observations. The asterisks in (3) indicates a complex conjugate.

$$F(a, b, c, d) = \sum_{j=1}^{N} \left \{ [z(t_j) - z_j] [z^*(t_j) - z_j^*] \right \} = \sum_{j=1}^{N} [x^2 + y^2]$$

$$x = a \cos(2\pi ft_j) + b \sin(2\pi ft_j) - u_j$$

$$y = i[c \cos(2\pi ft_j) + d \sin(2\pi ft_j) - v_j]$$

where $N$ is the number of observations.

The best fit amplitude values $a$, $b$, $c$, and $d$ correspond to the minimum of $F$. These are found when the partial derivatives of $F$, with respect to the unknown amplitudes, are zero. For example

$$\frac{\partial F}{\partial a} = \sum_{j=1}^{N} \frac{2x}{\partial a} x = 0.$$

This approach results in one equation for each amplitude (the following examples are for amplitude $a$).

$$\sum_{j=1}^{N} [a \cos(2\pi ft_j) + b \sin(2\pi ft_j) - u_j] \cos(2\pi ft_j) = 0.$$

Equations (5 – 6) demonstrate how the matrices (9 – 11) are derived.

Expanding (6) results in

$$\sum_{j=1}^{N} [a \cos^2(2\pi ft_j) + b \sin(2\pi ft_j) \cos(2\pi ft_j)] = \sum_{j=1}^{N} u_j \cos(2\pi ft_j)$$

Equation (7) and the three analogous equations can be written as a matrix equation. Three matrices are developed to solve for the unknown amplitudes. The three matrices are defined as
follows (8); matrix $\mathbf{M}$ represents the left-hand side of equation (7) excluding the amplitudes; matrix $\mathbf{F}$ is the forcing matrix, which is the right-hand side of equation (7) and lastly, matrix $\mathbf{A}$ is the amplitude matrix.

$$\mathbf{F} = \mathbf{MA}$$  \hspace{1cm} (8)

$$\mathbf{M} = \begin{bmatrix}
\sum_{j=1}^{N} \cos^2(ct_j) & \sum_{j=1}^{N} \cos(ct_j) \sin(ct_j) & 0 & 0 \\
\sum_{j=1}^{N} \cos(ct_j) \sin(ct_j) & \sum_{j=1}^{N} \sin^2(ct_j) & 0 & 0 \\
0 & 0 & \sum_{j=1}^{N} \cos^2(ct_j) & \sum_{j=1}^{N} \cos(ct_j) \sin(ct_j) \\
0 & 0 & \sum_{j=1}^{N} \cos(ct_j) \sin(ct_j) & \sum_{j=1}^{N} \sin^2(ct_j)
\end{bmatrix}$$  \hspace{1cm} (9)

The constant $2\pi f$ is represented by $c$ in (9).

$$\mathbf{F} = \begin{bmatrix}
\sum_{j=1}^{N} (u_j \cos(2\pi ft_j)) \\
\sum_{j=1}^{N} (u_j \sin(2\pi ft_j)) \\
\sum_{j=1}^{N} (v_j \cos(2\pi ft_j)) \\
\sum_{j=1}^{N} (v_j \sin(2\pi ft_j))
\end{bmatrix}$$  \hspace{1cm} (10)

$$\mathbf{A} = \begin{bmatrix}
a \\
b \\
c \\
d
\end{bmatrix}$$  \hspace{1cm} (11)

Equation (8) is manipulated to determine the amplitudes.

$$\mathbf{A} = \mathbf{M}^{-1}\mathbf{F}$$  \hspace{1cm} (12)

The amplitudes (13) and phases (14) are determined through the least squares technique:

$$\text{amp} = \sqrt{a^2 + b^2}$$  \hspace{1cm} (13)

$$\text{phase} = \arctan\left(\frac{-b}{a}\right).$$  \hspace{1cm} (14)

Similar equations can be used to solve for the meridional amplitude and phase.
Diurnal scale features are determined using a period of 24 hours, whereas; synoptic scale features are evaluated using an average of the synoptic time period (four to eight days) of six days (144 hours).
CHAPTER 4

RESULTS

Resolution of the Diurnal Cycle

Although an FFT was not useful for scatterometers observations, the least squares regression technique can accommodate irregular sampling intervals well. Utilizing the same 64-day periods as used in the preliminary analyses, the zonal and meridional diurnal and synoptic amplitudes and phases of the wind were calculated over the globe for three latitude/longitude domain sizes of 30° x 30°, 15° x 15°, and 5° x 5°.

The amplitude of the diurnal cycle (Figures 3, 4, and 5) is relatively small near the equator and increases towards the poles. Amplitudes are larger in the 15° x 15° and 5° x 5° domains than the 30° x 30° domains; however, the 30° x 30° domains clearly depict the increase in amplitude in the mid-latitudes. The high amplitudes around the southern polar regions (Figure 5) are a result of the large diurnal changes in the sea/ice temperature difference. Other areas of high diurnal amplitudes are located in oceanic regions close to land, which can be associated with the daily sea breeze cycle as Gille et al. [2003] observed. Some major atmospheric features that have an influence on the diurnal cycle of the winds can be identified in the 5° x 5° plots (Figure 5), such as the ITCZ (convection effects the diurnal cycle) and the Somali Jet near Africa (again associated with convective effects).
Figure 3 – Diurnal Amplitudes (30° Domain): The zonal (a, c, and e) and meridional (b, d, and f) diurnal amplitudes of the winds over water for the 30° by 30° domains during the time periods of: April 10, 2003 – June 12, 2003 (a and b), June 13, 2003 – August 15, 2003 (c and d), and August 16, 2003 – October 18, 2003 (e and f).
Figure 4 – Diurnal Amplitudes (15° Domain): The zonal (a, c, and e) and meridional (b, d, and f) diurnal amplitudes of the winds over water for the 15° by 15° domains during the time periods of: April 10, 2003 – June 12, 2003 (a and b), June 13, 2003 – August 15, 2003 (c and d), and August 16, 2003 – October 18, 2003 (e and f).
Figure 5 – Diurnal Amplitudes (5° Domain): The zonal (a, c, and e) and meridional (b, d, and f) diurnal amplitudes of the winds over water for the 5° by 5° domains during the time periods of: April 10, 2003 – June 12, 2003 (a and b), June 13, 2003 – August 15, 2003 (c and d), and August 16, 2003 – October 18, 2003 (e and f). White areas indicate areas where the scatterometers are unable to take observations (land or ice).
Scatterometers cannot estimate winds over land or ice. Examination of time series for regions containing too much land or ice indicate that some of the high amplitudes depicted in the 15° x 15° and 5° x 5° domain plots (Figures 4 and 5) are a result of under sampling. Due to systematic orbit-related day-to-day changes in coverage, regions containing ice or land are sampled on some days, but not on others, resulting in a poor sampling of diurnal variability.

Figure 6 – Expanded Diurnal Amplitude Analysis: The mean diurnal amplitudes of the zonal (a) and meridional (b) wind components for the domain of 0° - 30°N and 210°E - 240°E, during June 13 – August 15, 2003. The colored circles represent the zonal and meridional means from each spatial/temporal domain. The bottom figure (c) depicts the amplitudes and phases of the zonal and meridional anomaly components (represented by the ellipse) with the LT time displayed.

An example of good sampling for a region with a large amplitude is shown in Figure (6). The zonal (Figure 6a) and meridional (Figure 6b) amplitudes, calculated from the least squares technique, are shown with the mean zonal and meridional wind observations from the scatterometers. The high variability seen in this domain (for the time interval of June 13 – August 15, 2003) is due to topography varying the winds near Hawaii rather than inconsistent
sampling issues. The cosine waves (Figures 6a and b) indicate the amplitude of the diurnal cycle, as resolved from the least squares technique. The meridional wind component has a larger diurnal amplitude than the zonal component; which can also be seen in the ellipse displayed in Figure (6c). This is consistent with the conclusions Deser and Smith [1997] made using the TAO buoy array. The larger diurnal meridional component is also seen in the ellipse (Figure 6c). The ellipse (Figure 6c) also shows the shift in the wind direction at six hour intervals. The wind makes a 180° shift every 12 hours in this region of the world during this time period.

**Evaluated Diurnal Variance**

The least squares technique is employed using times from 2 to 1536 hours (64 days) to approximate the full spectrum of the wind. The resulting spectra (Figures 7 and 8) are compared to the preliminary analyses based on hourly buoy data. The scatterometer spectra are quite similar to the buoy spectra, especially in the large time scales, the synoptic range, and the diurnal range. Both the buoy and scatterometer spectra are plotted using a variance preserving technique (15) for visual comparison of the variances in the wind based on each spectra.

\[
\sigma_p^2 = \int_\infty^\infty a f d \ln(f) \tag{15}
\]

The spectra (Figures 7 and 8) determined through the least squares technique are very similar to the spectra from the Alaskan buoy analysis (section 1). In all four figures, the least squares technique produces spectra with similar magnitudes as that found from the preliminary analysis (the blue dashed line in Figures 7 and 8) for the portion of the spectra that is related to this study. Both techniques produce similar synoptic and diurnal peaks, but the 5° x 5° (Figure 8) domain tends to slightly overestimate the spectra at the diurnal frequency. This overestimation is occurring due to the sampling of the winds is very fine in the 5° x 5° domain in comparison to the other two domain sizes. The smaller spatial scales in these winds affect the resulting spectra. The spectra for the 30° x 30° domain are also similar to the buoy spectra; however, the amplitudes decrease with the larger domain size. These results strongly indicate that the longitude time correction used throughout this analysis is accurately adjusting the local times. Overall, the examination of Figures (7 and 8) show that the least squares analysis can
produce results similar to surface observations passed through an FFT. Scatterometer observations can be used to resolve diurnal cycles in the open ocean.

**Figure 7 – Alaskan 15° Domain Comparison:** The spectrum of the zonal (a) and meridional (b) components of the wind during April 10, 2003 – June 12, 2003 for the 15° domain. The examined domain represents the location of 210 - 225°E and 45 - 60°N (corresponding to the region surrounding the Alaskan buoy). The dashed line represents the respective wind component from hourly buoy observations.

**Figure 8 – Alaskan 5° Domain Comparison:** The spectrum of the zonal (a) and meridional (b) components of the wind during April 10, 2003 – June 12, 2003 for the 5° domain. The examined domain represents the location of 210 - 215°E and 55 - 60°N (corresponds to the region surrounding the Alaskan buoy). The dashed line represents the respective wind component from the preliminary analysis.

The small-scale variability (Figures 7 and 8) does not match the buoy resolved small-scale variability well, as was expected due to the mismatch in spatial scales of the observations, and smoothing implicit in the least squares technique. Thus, these small-scale variances will not be examined in any further detail.
Figure 9 – Diurnal Variability (5° Domain): The fraction of variance associated with the diurnal cycle of the zonal (a, c, and e) and meridional (b, d, and f) wind component over the ocean during the three time intervals for the 5° x 5° domain. The white areas depict regions near land or ice where the scatterometer cannot take observations. The time series variance associated with the diurnal cycle is equal to the square of the amplitude of the diurnal signal. The fraction of the variance explained by the diurnal cycle (Figure 9) is determined by taking a ratio of the diurnal amplitude squared to the variance of the
The greatest fractions of variance associated with the diurnal cycle are found largely in the tropics and near polar ice. The tropics have a relatively large variance associated with the diurnal cycle because light winds are being impacted by daytime heating and changes in cloud coverage, along with limited synoptic variances. High variances seen in the polar areas are probably due to the large diurnal temperature changes. The highest variabilities are in the northern hemisphere which are also due to land and ocean temperature cycles. The meridional wind component consistently has higher variabilities.

Calculated Synoptic Amplitudes and Variance

The zonal and meridional amplitudes of the synoptic cycle (Figure 10) are found using a frequency of $144^{-1}$ hours (six day period). The amplitudes are consistently lower around the location of the equator, which is due to little intrusion of mid-latitude synoptic systems. The synoptic amplitudes are larger in oceanic regions downwind of land (over western boundary currents) and storm tracks locations. Very high synoptic amplitudes are shown in the southern polar region, which is due to the fact that the hemisphere is entering the winter season, and synoptic scaled features have larger effects during the winter. The synoptic amplitudes are approximately three times higher than the diurnal amplitudes.

Employing the same technique as used for the diurnal variability evaluation, the fraction of variability explained by synoptic scale variance is estimated. This analysis then shows the regions in which the synoptic cycles account for a greater fraction of the local variability (Figure 11). The greatest synoptic scale variances (Figures 11) are located around land masses (Figures 11 a, c, and d). These areas of high variabilities are associated with storm tracks downwind of land. The increased variances seen around the polar regions are a result of under sampling intervals due to the swaths’ locations to over land. Outside the tropics, the synoptic cycle of the zonal wind component usually has a larger contribution to the total variance than the diurnal cycle or meridional component. The synoptic variability is on average 10% in comparison to 1% of the variability being associated with the diurnal cycle.
Figure 10 – Synoptic Amplitudes (5° Domain): The zonal (a, c, and e) and meridional (b, d, and f) synoptic amplitudes of the winds over the ocean for the 5° x 5° domains during the three time intervals, respectively. The white areas depict regions of land or ice where the scatterometer cannot take observations.
Figure 11 – Synoptic Variability (5° Domain): The fraction of variance explained by the synoptic cycle of the zonal (a, c, and e) and meridional (b, d, and f) wind components over the ocean during the three time intervals, respectively, for the 5° x 5° domain. The white areas depict regions of land or ice where the scatterometer cannot take observations.
In conclusion, it has been determined that scatterometers are very effective in resolving forcings such as the diurnal and synoptic cycles of the surface wind over water, provided the observations are combined for a sufficiently large area. The scatterometers resolved the synoptic and diurnal cycles similarly to those seen in hourly buoy observations. This result gives confidence for such studies in other regions of the globe. It is consistent that the meridional component has, on average, the higher diurnal variability for all time periods, which is consistent with the findings of Deser and Smith [1997].

The scatterometer data prove to also be highly effective in determining the variability of the synoptic features of the wind. The synoptic variance is larger in mid-latitudes and close to land. The synoptic variance is greater for the meridional wind component rather than the zonal component. The synoptic amplitudes are approximately three times larger than the diurnal amplitudes over the open ocean, but similar in magnitude for regions close to land. Overall, the scatterometers have proved to be an extremely effective tool in the examination of the diurnal and synoptic scale features of the wind.
REFERENCES


BIOGRAPHICAL SKETCH

I was born in Atlanta, Georgia on April 5, 1980. As a HOPE scholarship recipient, I attended the Georgia Institute of Technology in the Fall of 1998. In May 2002, I received my Bachelors degree in Earth and Atmospheric Sciences from the Georgia Institute of Technology. While attending Georgia Tech, I was employed by Drs. Doug Davis and Gao Chen in which I co-authored the publication listed below. In the Fall of 2002, I came to the Florida State University to obtain my Masters in Meteorology. I am a current member of the American Meteorological Society and the Chi Epsilon Pi Meteorology Honors Fraternity.

Publications: