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OBJECTIVELY-DERIVED DAILY "WINDS" FROM SATELLITE SCATTEROMETER DATA

By

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products are similar but the NSCAT product has finer detail such as the flow off of Central America and the cross equatorial flow in the eastern Pacific.

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ABSTRACT

An objective technique is used to create regularly gridded daily “wind” fields from NASA scatterometer (NSCAT) observations for the Pacific Ocean north of 40°S. The objective technique is a combination of direct-minimization, and cross validation with multigridding. The fields are created from the minimization of a cost function. The cost function is developed to maximize information from the observational data and minimize smoothing. Three constraints are in the cost function: a misfit to observations, a smoothing term and a misfit of vorticity. The second and third terms are relative to a background field. The influence of the background field is controlled by weights on the smoothing constraints. Weights are objectively derived by the method of cross validation. Cross validation is a process that removes observations from the input to the cost function and determines tuning parameters (weights) by the insensitivity of the removed observations to the output field. This method is highly computational; thus the technique of multigridding is incorporated into cross validation. Multigridding solves for the weights by cross validation on a coarse grid. Then these weights are used to determine pseudostress on the original fine grid. This allows for the practical application of cross validation with only modest computational resources required.

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Daily pseudostress fields are generated on a 1° by 1° resolution grid for the NSCAT period. These objectively derived fields are compared to independent data sources (NCEP and FSU Winds). The kinetic energy of the NSCAT fields exceeds that of the independent NCEP reanalysis and is similar to observations. Pseudostresses for the equatorial cold tongue region (15°S-15°N, 180°-90°W) are extracted from the objectively derived NSCAT fields and a CEOF analysis is performed. The analysis shows a large amount of variability in intra-seasonal time-scales for the Southern Hemisphere tradewinds. This variability is supported by in-situ observations.

1. INTRODUCTION

The NASA scatterometer (NSCAT; Naderi et al. 1991) operated for only 9.5 months, but provided unprecedented amounts of high quality wind data over the oceans. NSCAT was an active microwave radar mounted on a polar orbiting satellite that retrieved high-resolution surface (10m) wind vectors. Wind speed and direction were measured for ~77% of the ice-free oceans each day. This high spatial coverage was made possible by two sets of antennae, one on each side of the satellite relative to the forward motion, which allowed for two swaths of ocean to be observed simultaneously. Accuracy and spatial coverage of these observations were unprecedented (Caruso et al. 1997; Bourassa et al. 1997; Freilich and Dunbar 1999). Despite the high quality and excellent coverage that NSCAT data provided, the data contain spatial gaps that need to be filled before these observations can be easily utilized for forcing ocean models or for studies of atmospheric variability. For these purposes, serially complete daily pseudostress fields based purely on NSCAT data are desirable. This study details a new approach to produce these fields.

Other wind products over the ocean are available; however they are not based on NSCAT data. Ships and buoys collect an order of magnitude less observations than NSCAT did. Furthermore, most of these observations were taken in shipping lanes, leaving large portions of the ocean unobserved. Also, ship observations have large errors (Pierson 1990) in speed and direction. Nevertheless, in-situ observations have

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demonstrated value in producing monthly products, such as the specialized tropical wind products (Servain et al. 1996; Stricherz et al. 1997; Legler et al. 1997)

Surface winds are also available from atmospheric general circulation models such as the National Center for Environmental Prediction (NCEP) reanalysis (Kalnay et al. 1996). The reanalysis data have a much coarser spatial resolution than NSCAT data and are noted to have a poor handling of the wind field in equatorial regions (Putman et al. 1998).

Other remote sensing devices have retrieved surface winds over the ocean. SSM/I (Atlas et al. 1996) and altimeters (Chelton and Wentz 1986) can only measure wind speed. The European Space Agency's European Remote Sensing (ERS-1/2) satellite scatterometers measured both speed and direction, but the rate at which data can be collected is less than half of NSCAT. The dearth of data collected by ERS-1/2 is due to the relatively narrow single swath of ocean that is observed (unlike NSCAT, which measured two swaths). However, some products are available (Bentamy et al. 1996; Siefridt et al. 1998)

NSCAT data are an improvement on all of the previously mentioned sources of wind vector data, but gaps between the observational swaths limit the usefulness. Several techniques have been attempted to fill in these gaps. Tang and Liu (1996) used ECMWF winds to fill the gaps, and applied objective interpolation. The need for non-NSCAT data was eliminated in various interpolation approaches (Paulo et al. 1997; IFREMER/CERSAT 1998; Cheng et al. 1998). Interpolation schemes such as these suffered from the obvious appearance of the satellite tracks in spatial derivative fields (i.e. vorticity and divergence). Alternative approaches use weighted spatial and/or temporal averages (Bourassa et al. 1998; Kutsuwada 1998; Bourassa et al. 1999; Kelly et al. 1999). These approaches suffer from excessive smoothing and reduction of kinetic energy in the wind field due to the averaging. Another approach (Chin et al. 1998), which removes satellite tracks, applied
from excessive smoothing and reduction of kinetic energy in the wind field due to the averaging. Another approach (Chin et al. 1998), which removes satellite tracks, applied
wavelet-based multi-resolution analysis to a combination of NSCAT, ERS-2, and NCEP

winds. The averaging and wavelet-based techniques reduce the problems with the satellite tracks; however, they have excessive smoothing. The new technique discussed in this paper is effective in removing the satellite tracks signature with a minimal amount of smoothing.

The method for filling the observational gaps used herein is direct-minimization. This approach applies several constraints to maximize similarity to observations and minimize non-geophysical features in the spatial derivatives, particularly the satellite tracks in the curl field. Previous works (Legler et al. 1989; Meyers et al. 1994; Siefridt et al. 1998) have shown that three constraints can be coupled to construct smooth wind fields: a misfit to observation, a Laplacian smoothing term and a kinematic constraint. The smoothing and kinematic constraints are relative to a background field that has no missing data. Each quadratic term is multiplied by a weight. In previous studies, these weights have been determined through subjective observations (Legler 1989), or less subjectively through a sensitivity study (Meyers et al. 1994). Here, a technique (cross validation) is applied to objectively determine these weights.

The NSCAT data and a gridded NSCAT product are detailed in section 2. The methodology of direct-minimization and cross validation is described in section 3. Spatial dependence of the weights is investigated in section 4 and is shown to be minimal. Weights are determined by cross validation and are used to create 1° resolution daily pseudostress fields for the Pacific Ocean from 40°S to 60°N and 105°E to 65°W.

The objectively derived daily NSCAT pseudostress fields are compared (section 4) to the FSU Winds (Stricherz 1997) and the NCEP Reanalysis (Kalnay 1996). Pseudostress data from the region around the equatorial cold tongue in the eastern Pacific Ocean are extracted for a Complex Empirical Orthogonal Function analysis (CEOF; Section 2). The first four CEOF modes, which contain 43.3% of the total variance, are statistically
extracted for a Complex Empirical Orthogonal Function analysis (CEOF; Section 2). The first four CEOF modes, which contain 43.3% of the total variance, are statistically
significant. Mode 1 represents the seasonal cycle of the tradewinds. Modes 2 and 4 show

synoptic variability in the western portion of the region and around the gulf of Tehuanepec. The third mode is representative of the south Pacific convergent zone (SPCZ).

2. DATA

The Pacific Ocean from 40° S to 60° N and from 105° E to 65° W was chosen as the region to generate objectively derived NSCAT daily pseudostress fields. NSCAT data began on September 15, 1996, and ended on June 29, 1997, with the demise of the ADEOS satellite. These nine and a half months are referred to as the NSCAT period.

Although NSCAT backscatter is interpreted as winds, pseudostresses are chosen rather than winds because the resulting gridded NSCAT data product is intended for ocean modeling. The ocean circulation is primarily driven by the wind stress along the equator and in coastal regions, and by the curl of the wind stress elsewhere. Wind stress is extremely difficult to measure, but can be approximated by a bulk aerodynamic approach. This approach defines the zonal (τ_x) and meridional (τ_y) components of the wind stress as:

$$\tau_x = \rho C_D u \text{ , and}$$

$$\tau_y = \rho C_D v , \qquad (1)$$

where ρ is the density of air and C_D is the drag coefficient. The zonal (u) and meridional (v) components of the pseudostress are defined as:

$$u = Uu' \text{, and}$$

$$v = Uv' , \qquad (2)$$

$$v = Uv' , \qquad (2)$$

where U is the wind speed; u' and v' are the zonal and meridional components of the wind vector.

2.1 NSCAT Observations

A scatterometer is an active radar that emits a beam of microwave radiation directed towards the sea-surface. The scatterometer measures backscatter, which is the amount of microwave energy that returns to the satellite from the sea surface. The amount of backscatter is dependent on the roughness of the sea surface, which can be related empirically to wind speed. Direction is determined by multiple scans of the same spot on the sea surface from different angles. Three scatterometer antennae on each side of the satellite point in different directions. The motion of the satellite allows the same spot to be viewed from three different angles over a relatively short period of time.

NSCAT observations had a spatial resolution of approximately 25 km. The scatterometer measured a swath of ocean on each side of the satellite parallel to its motion. Each swath was 600 km wide and there was a 400 km 'Nader gap' between the swaths (Fig. 1). Wind speed and direction was measured at this high resolution for ~77 % of the world's ice free oceans in 24 hours, resulting in roughly 260,000 observations per day.

NSCAT derived wind vectors had unprecedented accuracy for satellite wind vector observations. A wide range of in-situ observations was used to validate NSCAT wind vectors. Buoys (Graber 1996; Atlas et al. 1999), research vessels (Bourassa et al. 1997), quality controlled buoys (Freilich and Dunbar 1999), and volunteer observing ships (Atlas et al. 1999) show that NSCAT observations are highly accurate. The accuracy in speed is ~1.2 ms^{-1} (Freilich and Dunbar 1999). The accuracy in direction is 13° for correctly chosen ambiguities (Bourassa et al. 1997) with ~90% correct selection of ambiguities (Gonzales and Long 1999).

and Long 1999).

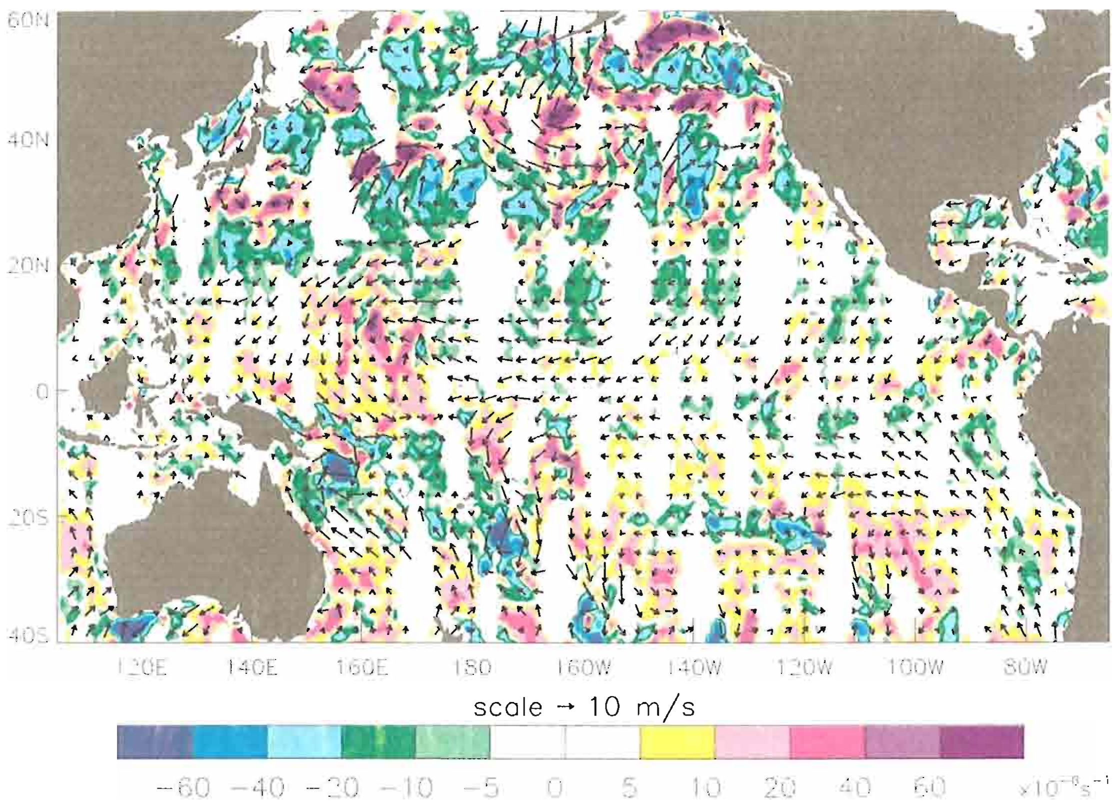

Figure1: 24 hours of NSCAT observations, for the Pacific Ocean basin north of 40°S, from March 16, 1997. Observations are binned onto a 1° by 1° grid. Vorticity is contoured, and wind vectors are plotted every 3° by 3° for clarity. Gaps in the daily coverage are clearly seen.

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2.2 Background Field

The COAPS/NSCAT gridded winds (Bourassa et al. 1999) are used as the background fields for direct-minimization because this data set consists of purely NSCAT winds. This data set is an eight-day weighted temporal average of NSCAT wind vectors on a 1° by 1° grid. Wind vectors for each grid cell are averaged with more weight placed on the days closer to the day of interest.

3 METHODOLOGY

Daily 1° resolution NSCAT pseudostress fields are generated using a technique that involves direct-minimization of a cost function. Development of the cost function is described in section 3.1. Associated with each term in the cost function is a weight, which is objectively derived through the method of cross validation (section 3.2). Cross validation is highly computational, therefore the technique of multigridding (section 3.3) is implemented to reduce computation time.

3.1 Direct-Minimization

Direct-minimization requires the creation of a cost function to be minimized. The cost function herein utilizes the information from the observations while forcing the solution field to be smooth with respect to the background field. Previous work (Legler et al. 1989; Meyers et al. 1994; Siefridt et al. 1998) showed that three constraints are necessary for a vector field. These constraints are: a misfit to observations, a Laplacian smoothing term or penalty function, and a kinematic constraint (misfit of the curl of the pseudostress). The cost function (f) developed to find the solution vector pseudostress (u, v) is:

$$f=\sum_{i,j}^{I,J}\Big\{\ln(1+N_{i,j})\left[\left(u_{i,j}-u_{o_{i,j}}\right)^2+\left(v_{i,j}-v_{o_{i,j}}\right)^2\right]$$

$$+\beta_a L^4\left[\left(\nabla^2\left(u_{i,j}-u_{bg_{i,j}}\right)\right)^2+\left(\nabla^2\left(v_{i,j}-v_{bg_{i,j}}\right)\right)^2\right]$$

$$+\beta_a L^2\left[\left(\hat{i}\bullet\nabla\left(u_{i,j}-u_{bg_{i,j}}\right)\right)^2+\left(\nabla\left(v_{i,j}-v_{bg_{i,j}}\right)\right)^2\right] \quad (2)$$

$$+\beta_b L^2\left[\hat{k}\bullet\nabla\times\left(\vec{u}_{i,j}-\vec{u}_{bg_{i,j}}\right)\right]^2\Big\}; \tag{3}$$

where i and j are indices for the longitude and latitude, and I and J are the number of longitudinal and latitudinal grid points. The subscript 'o' indicates NSCAT observations and the subscript 'bg' is the background field of pseudostress (COAPS/NSCAT gridded winds), $\vec{u}$ is the vector pseudostress. The pseudostress components without a subscript are the solution. The second and third terms are scaled by a length scale L, which is chosen to be the distance between grid points at the equator. $N_{i,j}$ is the number of observations at each grid point and is used to emphasize the mean of the observations in cells with multiple observations. Grid points that have no NSCAT observations have the first term of the cost function set to zero by $N_{i,j}$. The two weights (β_a and β_b) govern the contribution of the smoothing terms to the cost function. The Laplacian and curl terms link the value at one grid point to surrounding grid points to ensure spatial continuity of the field.

This equation is solved for a minimum in the cost function (f). The minimization of this non-linear least squares equation is accomplished iteratively through conjugate minimization (Shanno 1979). NSCAT observations binned on to a 1° grid with the COAPS/NSCAT data filled in at missing points are used as a first guess to the minimization technique.

Before the cost function can be minimized, the two free weights must be determined. Such weights have been determined subjectively in previous studies (Legler et al. 1989; Jones et al. 1995) or with guidance from a sensitivity analysis (Meyers et al. 1994). This study uses an objective technique of cross validation to determine the weights.

3.2 Cross Validation

The objective calculation of the weights for direct-minimization is done by cross

The objective calculation of the weights for direct-minimization is done by cross validation. Generalized cross validation (GCV; Wahba and Wendelberger 1980) is not a new technique in other scientific fields; however GCV has only recently been used in meteorological applications. One application of GCV in meteorology is to measure the uncertainty and quality in a forecasting algorithm (Elsner and Schmertmann 1994). In another study, Michaelsen (1987) masked (removed) observations from the forecasting algorithm and determined the importance an observation has in the forecast. A second application for GCV is for fitting a surface of some unknown order to available data. This second application of GCV is used in determining the weights for direct-minimization.

The method of GCV finds the weights for direct-minimization by removing observations from the calculation of the cost function and comparing this result to the case when no observations are masked. The differences of these two cases are minimized in a least squares sense. Weights are determined by repeating this process for each data point.

The cross validation functional (F)

$$F(\beta) = \sum_{k}^{K} \left(f_k(\beta) - \tilde{f}(\beta) \right)^2, \tag{4}$$

is designed to minimize the difference between the cost function (eq. 3) without data exclusion ($\tilde{f}$) and the cost function with data exclusion (f_k). The number, K, is the number of masked subsets, and β is the vector of weights. This approach finds weights, which optimize f, and for which small variations in the weights have little impact on the fields.

GCV requires that each masked data value be independent from other data values. Due to the high spatial correlation of meteorological parameters, bins of data are removed to create sets of independent observations that can be masked for cross validation. GCV also requires massive amounts of calculations and the removal of bins of data reduces the number of removal steps needed.

number of removal steps needed.

The weights associated with a minimum in F are determined through conjugate minimization. Direct-minimization requires positive values for the weights; however, the conjugate gradient method allows solutions to range from $-\infty$ to ∞. The natural log of the weights is utilized to meet these requirements. The derivative of the functional with respect to the natural log of the weights is:

$$\frac{dF}{d\ln(\beta)} \cong 2\sum_{k}^{K}\left[\left(f_k - \tilde{f}\right)\left(\frac{\Delta f_k}{\Delta\ln(\beta)} - \frac{\Delta\tilde{f}}{\Delta\ln(\beta)}\right)\right]. \tag{5}$$

The first constraint in $\tilde{f}$ (the cost function) is dependent on the number of grid points with observations, the value of f_k changes when regions are masked. A correction is needed to scale the first constraint in f_k; otherwise f_k will be biased low compared to $\tilde{f}$. This scaling is:

$$r = \frac{\tilde{N}}{N_k}. \tag{6}$$

$\tilde{N}$ is the number of grid points with observations in $\tilde{f}$, and N_k is the number of grid points with observations in f_k. Scaling by this ratio reduces a bias in the gradient used to find the weights. The weights are found by setting the equations equal to zero and solving this non-linear least squares problem using an iterative method. This approach requires a first guess.

Selection of Masked Subset

Cross validation requires the removal of independent observations; otherwise the information associated with the masked observation is never fully removed from the calculation. Subsets of data are excluded due to the fact that meteorological variables are closely correlated in space. The subsets need to be large enough so the center point of the calculation. Subsets of data are excluded due to the fact that meteorological variables are closely correlated in space. The subsets need to be large enough so the center point of the

subset is independent from the points that remain for cross validation. A 12° latitude by 12° longitude mask is expected to be more than large enough (Chelton and Wentz 1986).

The size of the study area and the size of the mask limit the maximum number of masked regions. In practice, these masked regions must cover a wide range of wind regimes in the study area. This is necessary because even though the weights are assumed to be spatially independent, different wind patterns and different vorticity fields need to be examined to determine the best weight for the entire region. For this study area, the uncertainty in the weights decreases as the number of excluded regions increases. Sixteen masked regions provide reasonable coverage over the study region, while calculating optimal weights with substantially fewer regions (e.g. 12) results in the weights varying more than an order of magnitude. There are 14,321 points where the functional is calculated and only about 2,200 points have observations masked. With fewer masked regions, there are large areas of observations that are not considered in the cross validation. These areas tend to occur in the tropics due to the constraint that each masked region needs to have observations in 90% of the grid boxes. The geometry of the satellite orbit results in relatively few locations in the tropics where there are such 12° by 12° bins.

3.3 Multigridding

Cross validation requires about 15 hours of CPU time on a SGI Origin 2000 with 200 MHz processors to determine the optimal weights for one daily pseudostress field. An increase in efficiency is needed to make cross validation practical. The weights that are determined by cross validation are expected to be independent of space. This suggests that the weights found for a coarse grid will be valid for a finer grid. A coarse grid has fewer points for calculations, allowing much faster results. The technique of Multigridding (Brandt 1982) calculates the optimal weights through cross validation on a coarse grid, then

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uses these optimal weights as the initial guess on the fine (1°by 1°) grid, and one iteration step on the fine grid adequately tunes the weights.

The method of multigridding is valid only if the solutions from two different grid resolutions are within an order of magnitude (Brandt 1982). This requirement is validated with calculations of optimal weights on a 1°, 2°, 3°, and 6° grids for several test cases, one test case is presented in table 2. The optimal weights vary within an order of magnitude; therefore multigridding is a valid technique for this study.

Selection of the coarse grid

The size of the masked subset regions dictates the resolution of the coarse grid. The masked region size must be an even integer multiple of the coarse grid resolution. A 1° by 1° fine grid is used here, and the masked regions are 12° by 12° squares. This geometry allows for 2°, 3°, and 6° coarse resolutions. Weights calculated on the 6° grid have variability much larger than the weights from the finer grids and was determined to be unstable. The 2° and 3° grids are stable and the 3° grid is chosen for minimization of computer time use, resulting in approximately a factor of nine reduction in processing time.

Table 1: Weights (β_a, β_b) for one day are calculated by cross validation for different grid resolutions. The change in the weights for the different grid resolution is less than an order of magnitude, thus allowing for the conclusion that the multigridding technique is valid for this application of cross validation.

resolution	β_a	β_b
1 °	0.00528	0.00772
2°	0.00613	0.00896
3°	0.00904	0.01034
6°	0.00228	0.00221

4 RESULTS

4.1 Verification of optimal weights

Visual inspection of the output fields provides a preliminary verification that cross validation chooses the optimal weights correctly. Fields constructed with weights that are too low have vorticity fields that show satellite tracks. Conversely, weights that are too high result in fields with too much smoothing, and details that are in the observations are lost. The effectiveness in which NSCAT observations are preserved is shown quantitatively in the comparison of the average kinetic energy of the 1° by 1° binned swath data (observations), output, and background fields. Kinetic energy is defined as $0.5mU^2$, where m is mass and U is speed. The density of the surface air has a negligible amount of variability compared to the variability of wind, thus mass is neglected in this comparison, and specific kinetic energy is represented by the square of the wind speed (which is equal to the magnitude of the pseudostress). The average kinetic energy for one day (May 15, 1997) in the study region (40°S-60°N, 105°E-65°W) is 22.1 m^2s^{-2} for NSCAT observation, 21.5 m^2s^{-2} for the resultant field, and 17.6 m^2s^{-2} for the background field. Since little kinetic energy is lost in the resultant field compared to the observations, it is clear that the weights for the smoothing terms in the cost function are not too high. Furthermore, the vorticity field does not show the satellite tracks which are apparent in the first guess field.

Furthermore, the vorticity field does not show the satellite tracks which are apparent in the
first guess field.

Spatial independence of optimal weights

Cross validation assumes that the weights are independent of space and magnitude of the pseudostress. Spatial independence is tested by calculating optimal weights for two smaller regions of the Pacific Ocean. One sub-region is the mid-latitude north Pacific (30°N -60°N, 125°E- 105°W). This region is characterized by strong winds and high vorticity. The other sub-region is the equatorial western Pacific (20°S - 20°N, 115°E - 165°E) and is selected because it has low wind speeds. The difference in the weights between these two sub-regions and the weights for the entire Pacific Ocean are small (Table 2). Pseudostress fields created from these different sets of weights show little sensitivity to the weights. The change in the output field due to the different weights is typically less 4.7 m^2s^{-2} (0.5 ms^{-1}), which is near the uncertainty of the binned NSCAT observations, and verifies that the weights are nearly independent of space and magnitude.

Time dependence of optimal weights

Weights are calculated for every fifth day of the NSCAT period to reduce computer time. The timeseries of the weights shows no trend or pattern (Fig. 2). Therefore, an average value for each weight ($\beta_a = 3.12\times10^{-3}, \beta_b = 3.11\times10^{-3}$) is selected. The selected weights are used in the direct minimization to generate the daily pseudostress fields.

The impact of the difference between average weights and determined weights on the pseudostress fields is examined. Case I compares the pseudostress field for a day when the optimal weights are high (β_a = 7.02×10^{-3}, β_b = 1.12×10^{-2}) to the output from the average weights. Case II compares the pseudostress field for a day when the calculated weights are low (β_a = 2.8×10^{-4}, β_b = 2.5×10^{-4}) to the output from the average weights. Both cases show little sensitivity of the output field to the changes in weights. The RMS difference for case I are 2.45 m^2s^{-2} (0.16 ms^{-1}) for the u component and 2.08 m^2s^{-2} (0.15

Both cases show little sensitivity of the output field to the changes in weights. The RMS
difference for case I are 2.45 m^2s^{-2} (0.16 ms^{-1}) for the u component and 2.08 m^2s^{-2} (0.15

ms^{-1}) for the v component. Case II has RMS differences of 6.19 m^2s^{-2} (0.55 ms^{-1}) and 5.9

Table 2. Weights (β_a, β_b) are calculated by cross validation for two sub-regions (midlatitude and tropical) and the whole study region (Pacific Ocean) for two different dates. The small differences show that the weights are nearly independent of space and pseudostress magnitude.

	Weights (1/ 5/97)	Weights (6/14/97)
Midlatitude	$1.18 \times 10^{-4}; 7.29 \times 10^{-4}$	$3.18 \times 10^{-3}; 3.98 \times 10^{-3}$
Tropical	$9.27 \times 10^{-5}; 8.61 \times 10^{-4}$	$1.37 \times 10^{-4}; 9.73 \times 10^{-4}$
Pacific Ocean	$3.22 \times 10^{-3}; 8.61 \times 10^{-4}$	$2.01 \times 10^{-4}; 1.36 \times 10^{-3}$

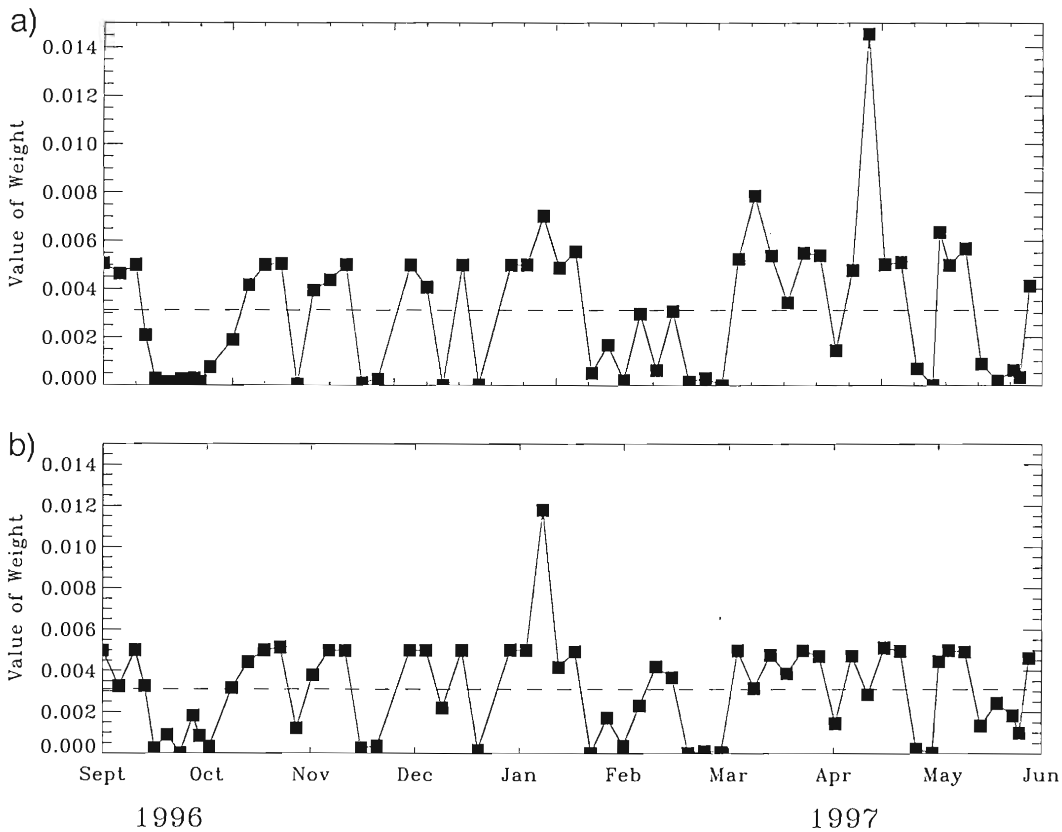

Figure 2: Time series of the weights for (a) the smoothing of the pseudostress, and (b) misfit of the curl of the pseudostress constraints determined by cross validation. Weights are valid for the entire Pacific Ocean study region and are calculated roughly every five days (indicated by squares). No pattern or trend is apparent, and the average values (dashed lines) are used for the entire NSCAT period.

period.

m^2s^{-2} (0.56 ms^{-1}) for the u and v components respectively. Since the resulting output fields for case I and II show little difference from the output field produced by using the average weights, the average weights can be used to generate the pseudostress fields through direct-minimization for the entire NSCAT period.

4.2 CEOF Analysis

The two average weights are applied to the direct minimization cost function and daily, 1° resolution pseudostress fields are constructed. These daily fields are publicly available (at http://www.coaps.fsu.edu/scatterometery). They cover the Pacific Ocean between 40°S and 60°N for the entire NSCAT period.

A complex empirical orthogonal function analysis (CEOF; Horel 1984; Putman et al. 1998) of the daily pseudostress fields is performed for the equatorial cold tongue region (15°S - 15°N, 90°W - 180°W). Briefly, a CEOF analysis calculates eigenvalues and eigenvectors from a covariance matrix. The equation:

$$S_N = \sum_{n=1}^{nt} \vec{u}(n) E_N^*(n) \qquad (7)$$

calculates the N^{th} spatial function (S) from the data, where nt is the length of the time record, $\vec{u}$ is the pseudostress field, and E^* is the complex conjugate eigenvector. The temporal mean zonal and meridional pseudostresses(Fig. 3) are removed prior to the analysis. The CEOF results in 276 spatial functions and eigenvectors (principal components). Each principal component represents a certain percentage of the variance (in both space and time) given by the eigenvalues. The eigenvector (time series) has both an amplitude and rotation angle. The amplitude multiplied by the spatial function gives the spatio-temporal variability of the principal component, and the rotation angle represents the counterclockwise rotation of each vector in the spatial function. The original data set can be reproduced by calculating the sum of the product of every eigenvector and spatial function.

counterclockwise rotation of each vector in the spatial function. The original data set can be reproduced by calculating the sum of the product of every eigenvector and spatial function.

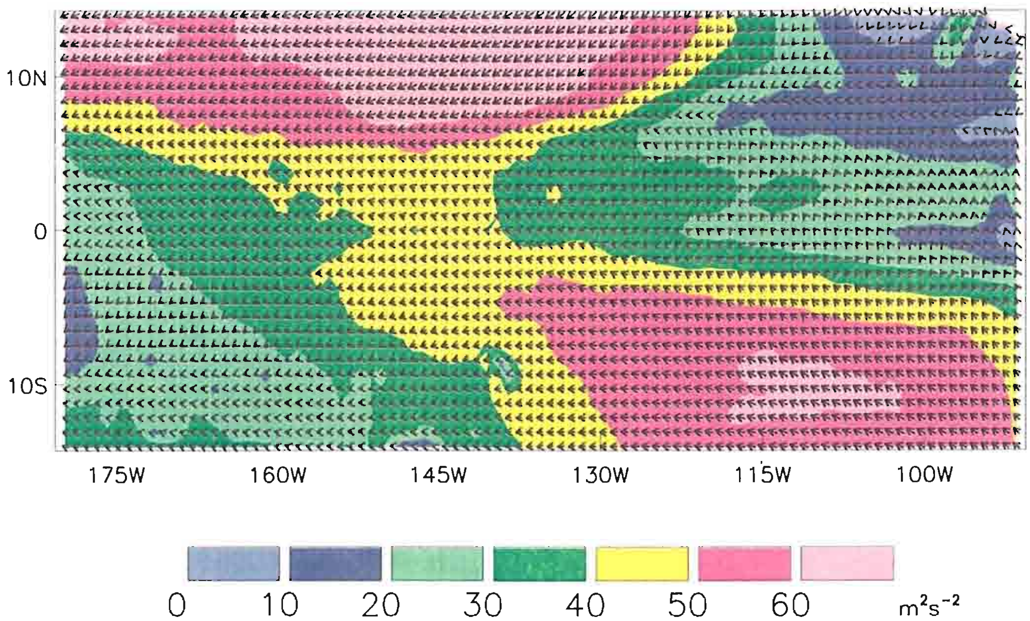

Figure 3: Mean pseudostress of the equatorial cold tongue region from the objectively derived NSCAT pesudostress fields. This mean is removed prior to the CEOF analysis. The Northeast and Southeast trade winds are apparent, as well as the gap flow through the Sierra Madres (upper right hand corner).

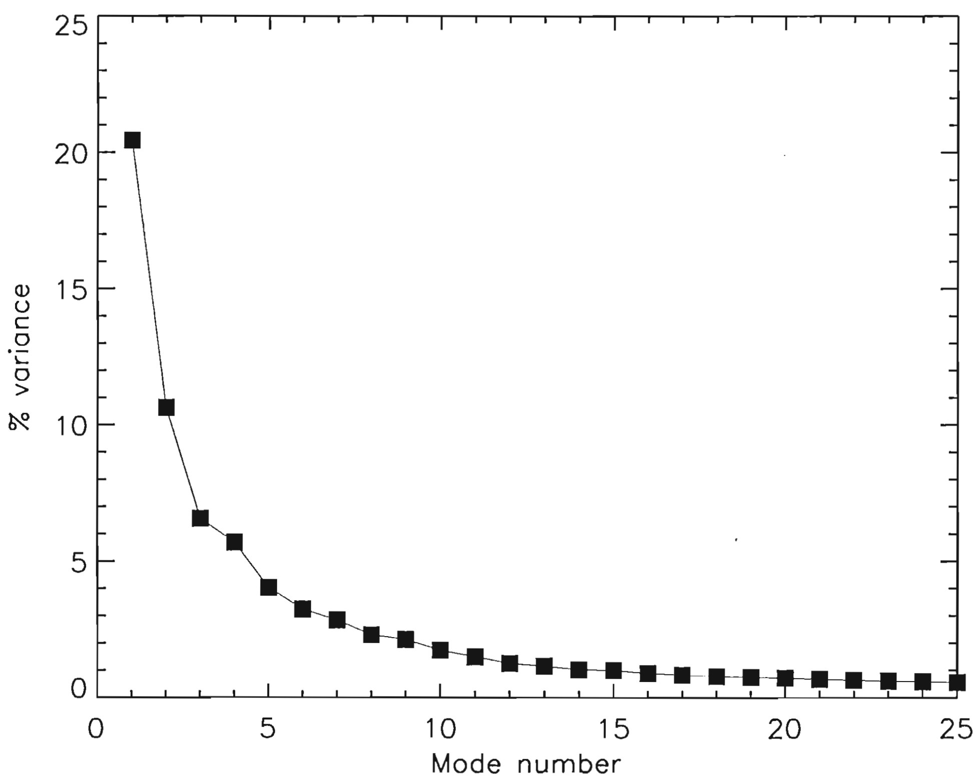

Figure 4: A Scree diagram showing the percent variance associated with the first 25 modes of the CEOF analysis. The first four modes are statistically significant.

A scree test (Wilks, 1995) is used to determine which principal components are statistically significant. The first four modes, which contain 43% of the variance, are statistically significant (Fig. 4).

Principal Component 1

The first mode (Fig. 5) represents 20.44% of the variance. The principal component has most of the variance associated with the Northern Hemisphere trade winds and a lesser amount with the Southern Hemisphere tradewinds. A rotation of the spatial function by 180° increases the Northern Hemisphere trades and decreases the Southern Hemisphere trades.

The time series of the rotation angle (Fig. 5 c) shows the seasonal change in the strength of the tradewinds. The amplitude (Fig. 5 b) also has a strong seasonal signal, with maximums in the winter and summer and minimums and the fall and spring which is expected for equatorial winds, and supported by the FSU winds climatology (Stricherz et al. 1997). Spectral analysis of the amplitude (Fig. 6 a) shows energy in periods greater than 50 days and at time scales near 20 days. A rotary spectrum (Fig. 7a; O'Brien and Pillsbury 1974) shows a clockwise rotation of the tradewinds (negative period) on an annual time scale.

Principal Component 2

The second mode (Fig. 8) represents 10.63% of the variance. This mode's variance is associated with the western portion of the northeast and southeast trades. In the fall, the spatial function is rotated by 90° and anomalous convergence occurs along the equator. The spring has a rotation angle around 270°, with anomalous divergence occurring along the equator. The winter months are a transition time, when the angle rotates from 90° through 180° to near 270°.

A spectral analysis of the time series of the amplitude (Fig. 6 b) shows a signal at a
180° to near 270°.

A spectral analysis of the time series of the amplitude (Fig. 6 b) shows a signal at a
period 20.6 days, and a synoptic signal. TAO buoy observations for the same time period

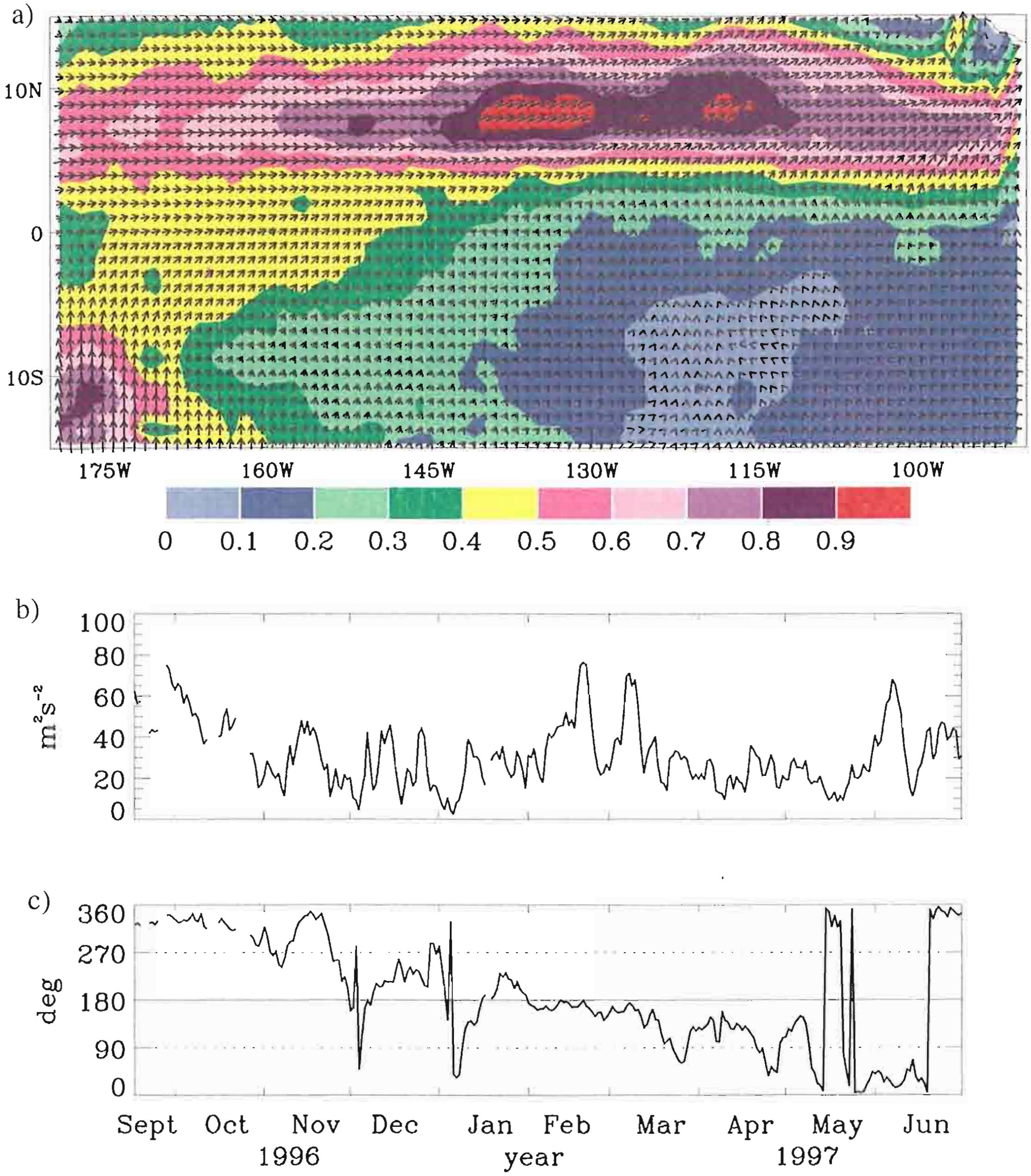

Figure 5: Principal component 1 contains 20.44% of the variance. The spatial function (a) multiplied by the amplitude of the eigenvector (b) gives the magnitude of the pseudostress. Rotation angle (c) is a counterclockwise rotation of the spatial function vectors. Gaps in the time series indicate days that were excluded from the CEOF analysis due to missing data.

function vectors. Gaps in the time series indicate days that were excluded from the CEOF analysis due to missing data.

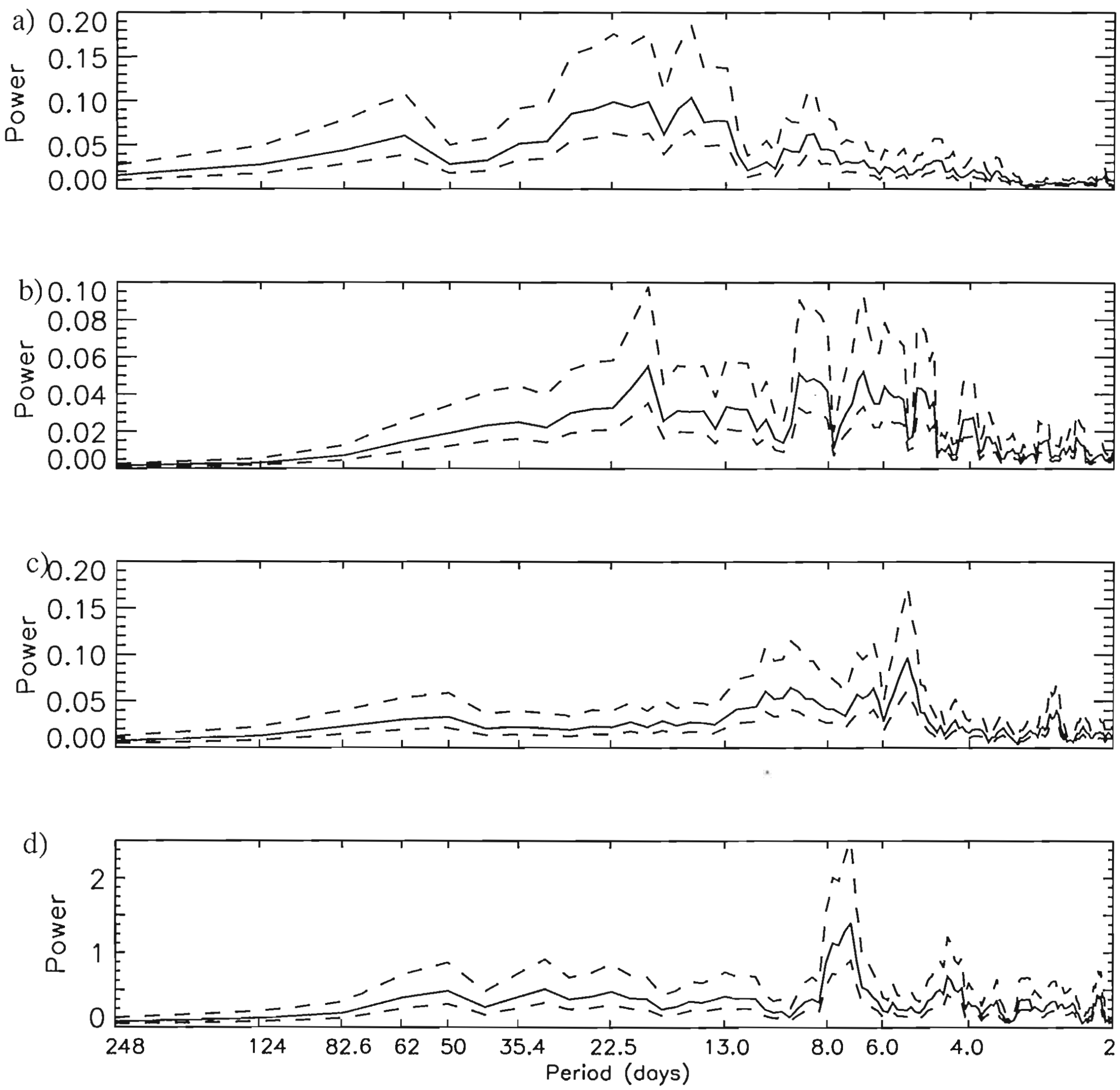

Figure 6: Spectral analysis of the eigenvector amplitude for principal components: 1 (a), 2 (b), 3 (c), and 4 (d). Power is plotted against period in days in an area preserving plot. Dashed lines are the 95% (upper) and 5% (lower) confidence limits. Spectrum is smoothed using a 5 point running mean. The time period analyzed is Oct. 25, 1996 - June 29, 1997. Data before Oct. 25 had numerours preserving plot. Dashed lines are the 95% (upper) and 5% (lower) confidence limits. Spectrum is smoothed using a 5 point running mean. The time period analyzed is Oct. 25, 1996 - June 29, 1997. Data before Oct. 25 had numerours missing days and are omitted from the spectral analysis. One other missing day (Jan. 16) in the time series is linearly interpolated.

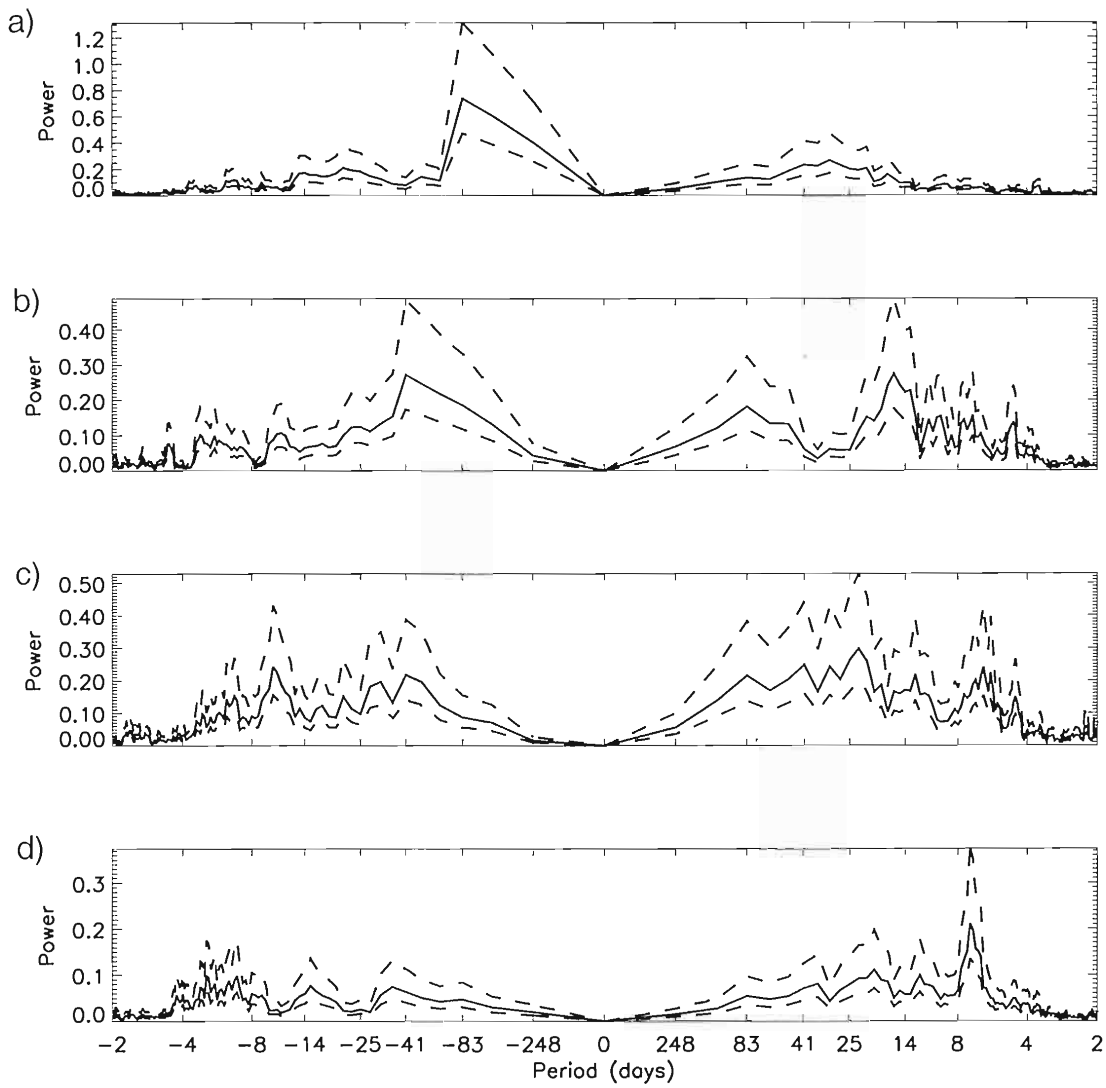

Figure 7: Rotary spectra for the complex eigenvectors of principal compents: 1 (a), 2(b), 3 (c), and 4 (d). Power is plotted against rotation period in days on an area preserving plot. Confidence limits (dashed lines) are same as Figure 6. Positive (negative) periods indicate counterclockwise (clockwise) rotation.
1 (a), 2(b), 3 (c), and 4 (d). Power is plotted against rotation period in days on an area preserving plot. Confidence limits (dashed lines) are same as Figure 6. Positive (negative) periods indicate counterclockwise (clockwise) rotation.

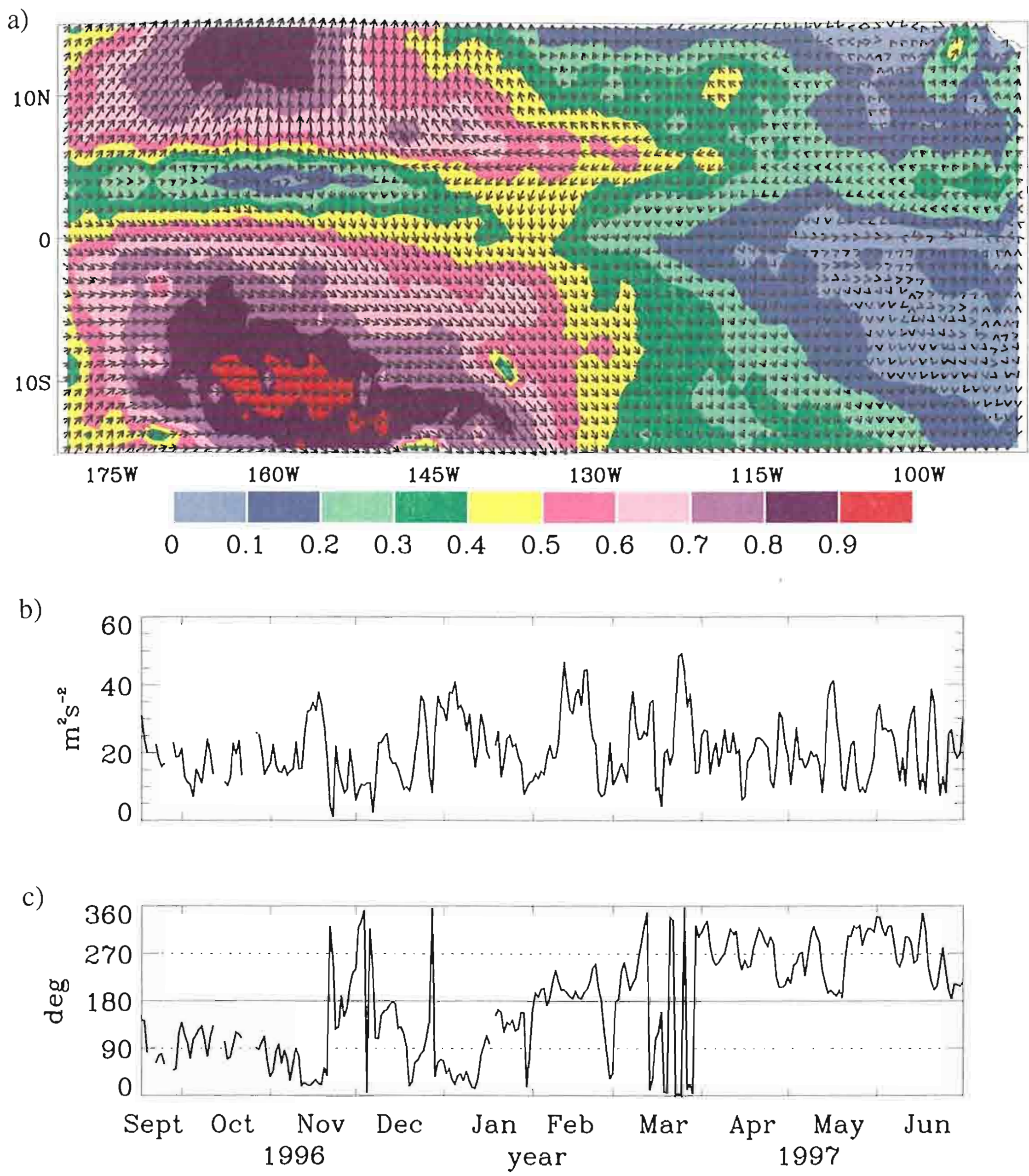

Figure 8: Same as Figure 5 except for the second principal component. (a) spatial function, (b) eigenvector amplitude, (c) and counterclockwise rotation angle. This principal component represents 10.63% of the variance.

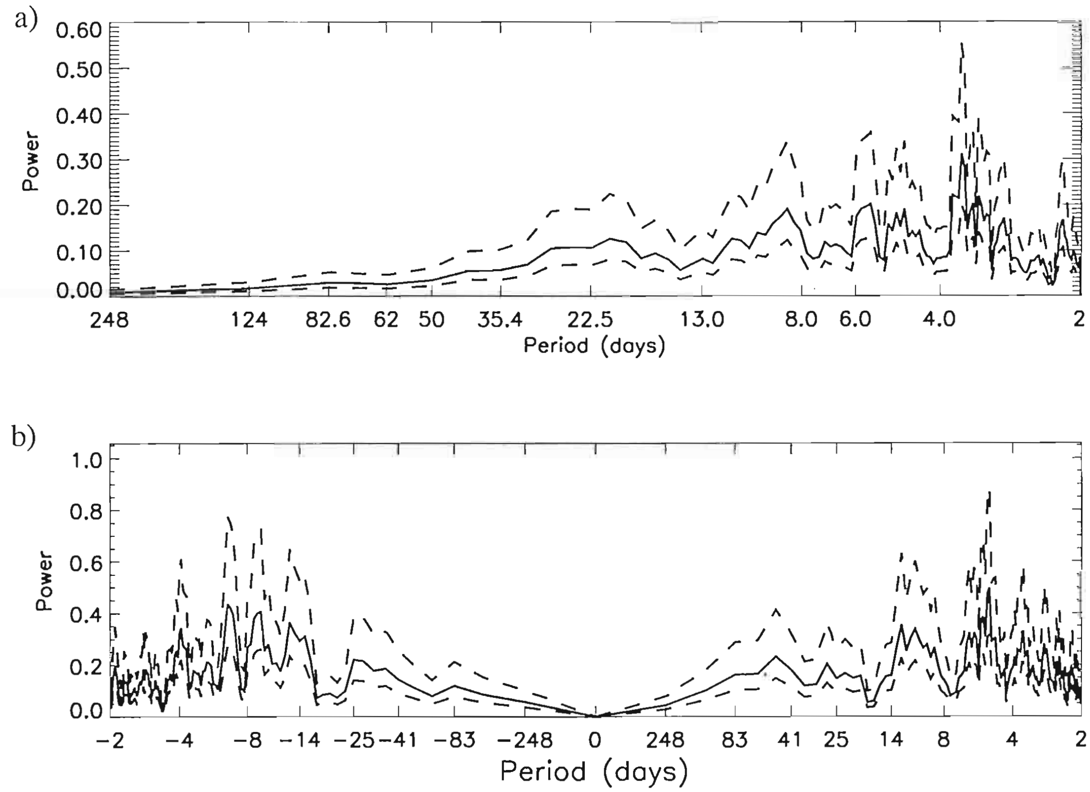

Figure 9: Spectral analysis (via a Fast Fourier Transform) of TAO buoy data located at 8S, 170W. Pseudostress magnitude (a), and rotary wind spectra (b). The time period analyzed is the same as figure 6 (10/25/96 - 6/29/97). Missing days are linearly interpolated. A period near 20 days (a) matched the result of the spectral analysis of the second principal component's eigenvector (Figure 6 b), and a counter- clockwise rotation (postive period) of around 60 days (b) matched the second principal component's rotary spectrum (Figure 7 b). Confidence limits (dashed lines) are same as in Figure 6.

as in Figure 6.

at 8°S and 170°W also show a period near 20 days in the magnitude of the pseudostress (Fig. 9 a). The rotary spectrum of the complex eigenvector (Fig. 7 b) shows a counterclockwise rotation with a period between 40 and 80 days, and a counterclockwise rotation of 80 days and about 14 days. The rotary spectrum of the TAO buoy (Fig. 9 b) has similar results. Supporting the conclusion that the 20 day signal is geophysical in origin, rather than an artifact of the orbital pattern of the satellite.

Waves in the SST field for the tropical eastern Pacific with 20 to 30 day periods were found by Legeckis (1977) and Philander et al. (1985). Also, a mixed Rossby-gravity wave with a period of 20 days that caused an oscillation in the meridional current was noted by Halpern et al. (1988). These oscillations may be related to the 20 day period in the eigenvector amplitude.

Principal Component 3

The third mode (Fig. 10) represents 6.56% of the variance. The variance is associated with the South Pacific Convergent Zone, and the extreme western and eastern portions of the northeast trades. Late November, early December, early February, and the middle of May through the end of the NSCAT period have a rotation angle of 0°. This rotation angle indicates anomalous convergence from 0°N, 180°W to 10°S, 160°W and anomalous convergence from 10°N to 15°N, and 140°W to 110°W. March and April have the spatial function rotated by 180°. This springtime pattern has anomalous divergence in the southwestern portion of the equatorial cold tongue region and divergence north of the equator. Anomalous convergence in the area of the SPCZ is strongest in the fall, early winter, and June. There is anomalous divergence in this area in the late winter and spring.

The time series of the amplitude vector show three peaks, one in early December (rotation of 0°), one in mid March (rotation of 180°), and the last in early June (rotation near 0°). A spectral analysis of the amplitude time series (Fig. 6 c)shows a signal at a
(rotation of 0°), one in mid March (rotation of 180°), and the last in early June (rotation near 0°). A spectral analysis of the amplitude time series (Fig. 6 c)shows a signal at a

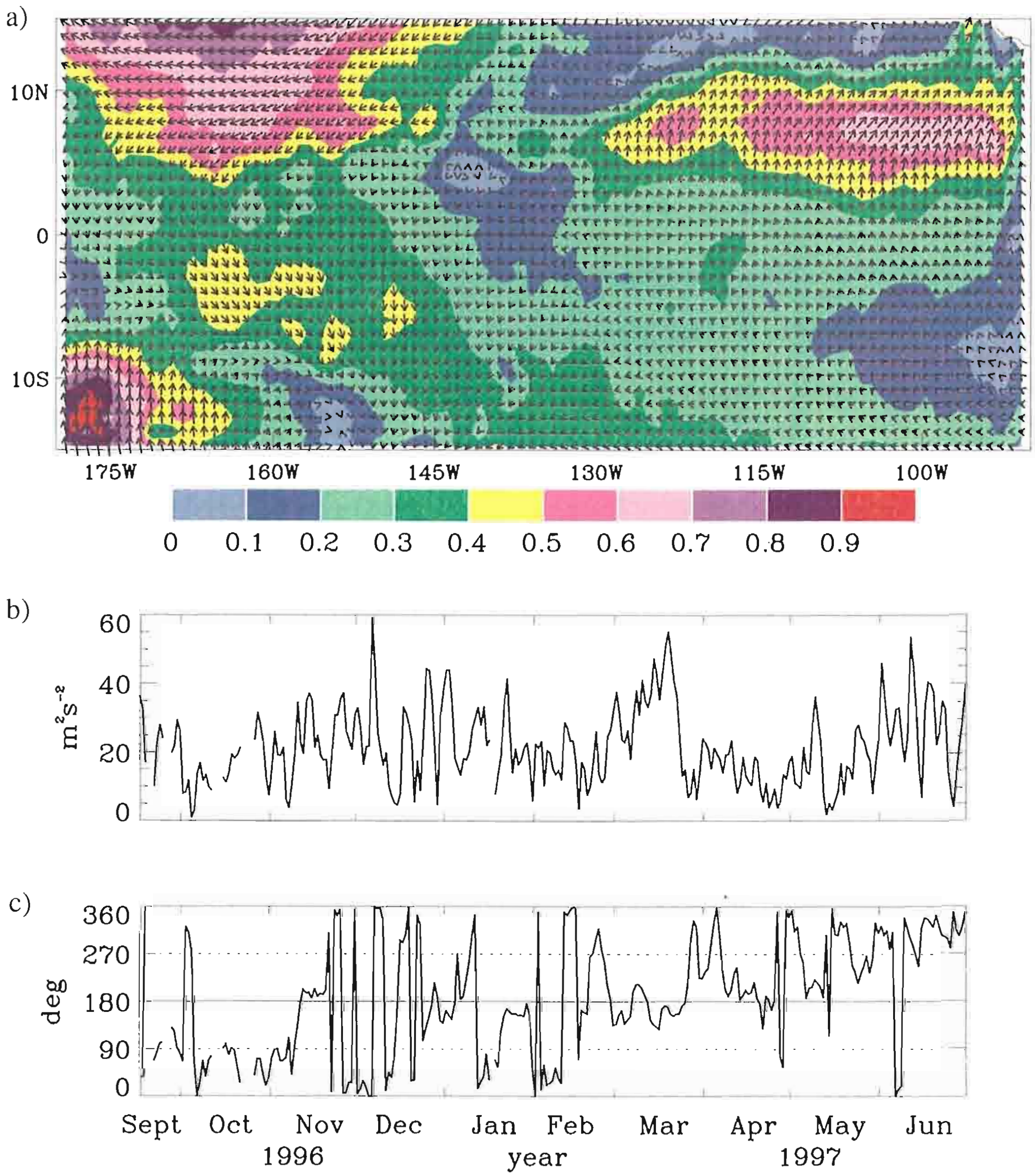

Figure 10: Same as Figure 5 except for the third principal component. (a) spatial function, (b) eigenvector amplitude, and (c) counterclockwise rotation angle. This principal component respresents 6.56% of the variance.

principal component respresents 6.56% of the variance.

period of 50 days. The 50 day period may be associated with the Madden-Julian oscillation (Madden and Julian 1971; Lau and Chan 1988)

Principal Component 4

The fourth mode (Fig. 11) represents 5.69% of the variance. A large portion of the variance in this mode is associated with the eastern portion of the northeasterly trades, the gap flow through the Sierra Madres (Bourassa et al 1999), and the central portion of the southeast trades. With a rotation of 0°, the spatial function has an anomalous convergent zone running from 150°W to 110°W centered near 8°N. A rotation angle between 90° and 200° of the spatial function results in an anomalous divergent zone for this area. The peak of the amplitude (Fig. 11 b) in December is associated with strong convergence at 8°N and divergence along the equator. The peaks in March and June are associated with divergence in the area of the ITCZ (Rasmusson and Carpenter, 1982) and convergence on the equator.

Spectral analysis of the magnitude shows variability on the order of 50 days, 30 days, and near 7 days. TAO buoy data from 5°S and 135°W shows a similar signal between 30 to 50 days and at 7 days for the NSCAT period (Fig. 12 a). Rotary spectral analysis (Fig. 7 d) shows counter-clockwise rotations between 40 and 80 days that correspond to the TAO buoy data (Fig. 12 b). The TAO buoys confirm that for this study the periodic changes in pseudostress are not a satellite sampling problem, but that they occur in nature.

4.3 Comparison to FSU Winds

Monthly means of the objectively derived NSCAT pseudostresses are validated with the FSU winds (Stricherz et al. 1997), which use in-situ data to derive monthly pseudostress fields for the equatorial Pacific Ocean. NSCAT wind and pseudostress vectors are calibrated to a height of 10 m. Pseudostresses can be height adjusted, assuming neutral stability, using a log wind profile, to the 20 m height of the FSU winds. This doubling of

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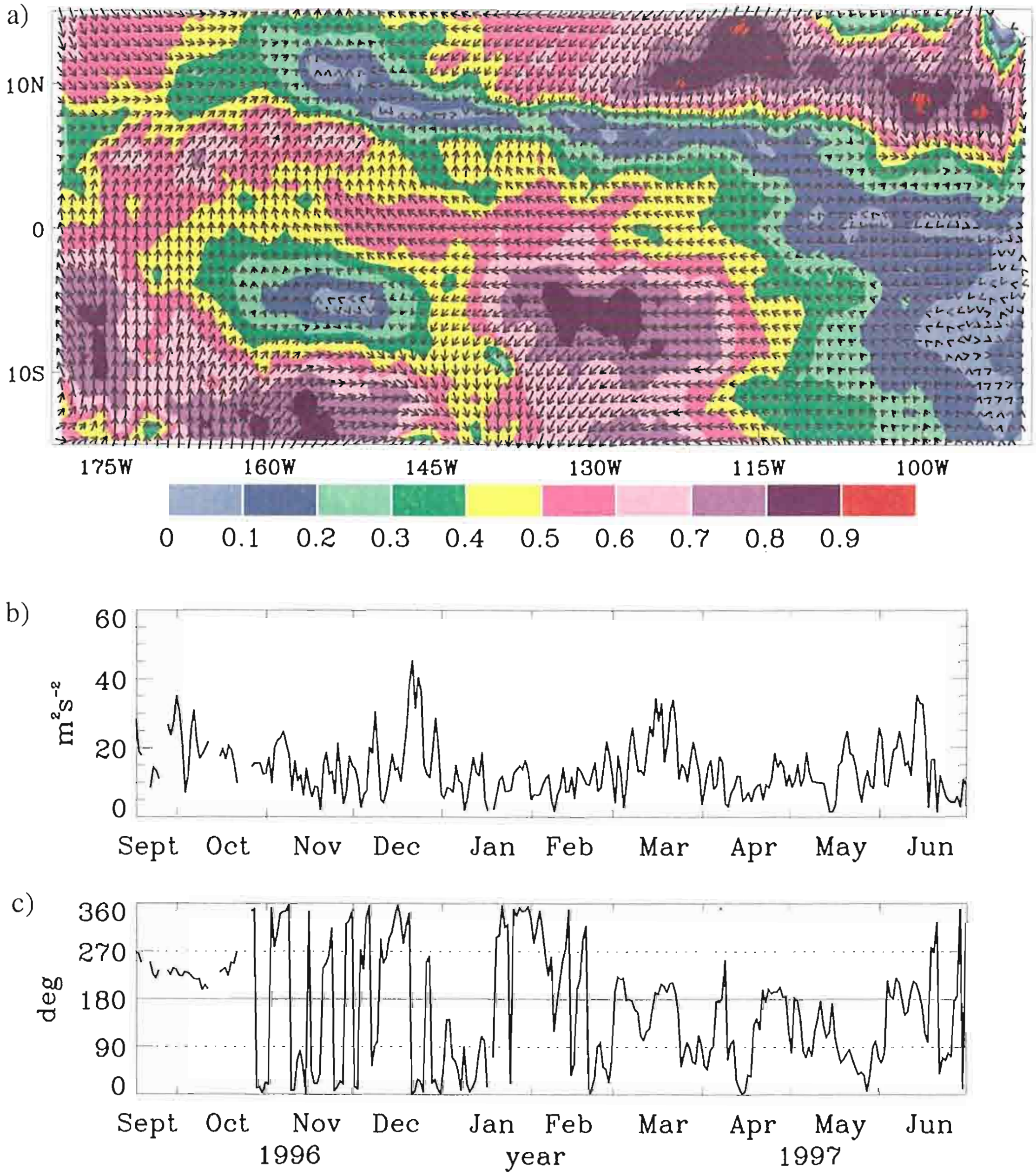

Figure 11: Same as Figure 5 except for the fourth principal component. (a) spatial function, (b) eigenvector amplitude, and (c) counterclockwise rotation angle. This principal component represents 5.69% of the variance.

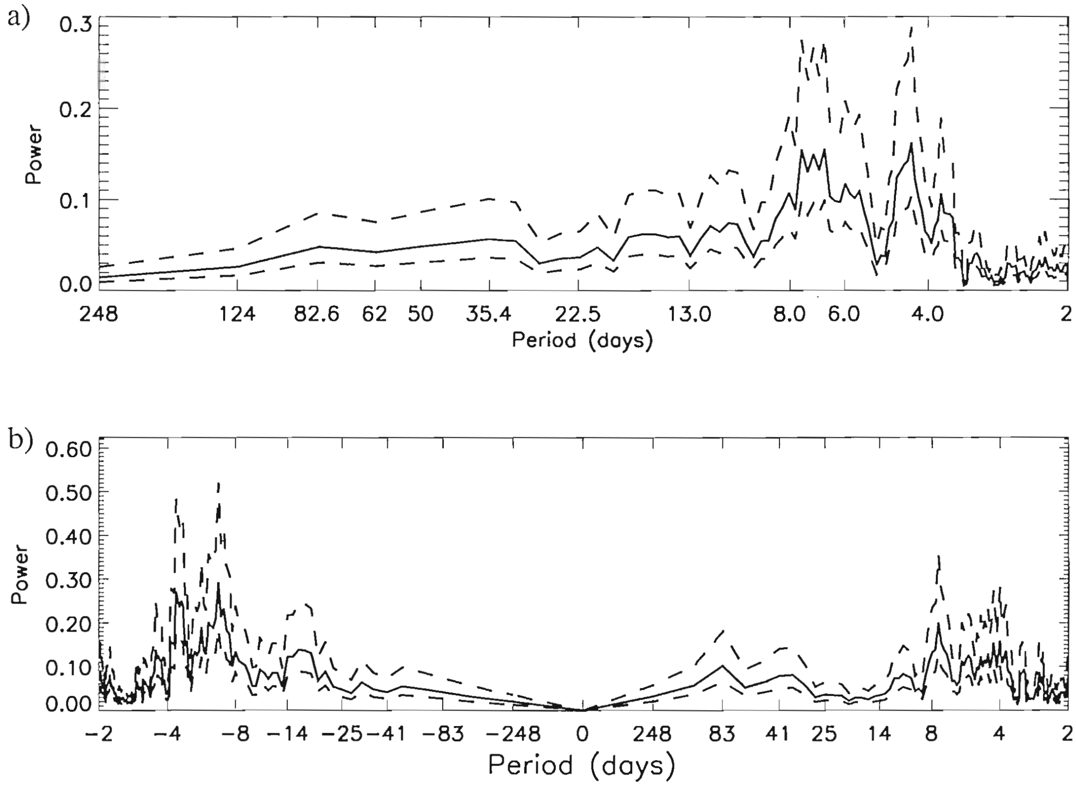

Figure 12: Same as Figure 9, except for TAO buoy located at 5S, 125W. Magnitude of pseudostress (a) shows a period near 7 days and a period between 30 and 50 days that are similar to the periods of the fourth principal component's eigenvector (Figure 6 d). Rotary wind spectrum (b) shows a signal near 40 - 80 days with a counterclockwise rotation, which is also found in the fourth principal component's rotary spectum (Figure 7 d). Confidence limits (dashed lines) are same as in Figure 6.

height results in a ~13% increase of NSCAT pseudostresses. When this adjustment is made, the two data sets show many of the same large-scale features that are similar in magnitude. The NSCAT pseudostress has greater spatial detail, such as the gap flow through the Sierra Madres (Fig. 13), and tropical cyclones in the western Pacific, which are not in the FSU wind analysis (Fig. 14).

4.4 Comparison to NCEP reanalysis

The NSCAT derived pseudostresses are converted to wind vectors and compared to the NCEP reanalysis. Wind patterns and magnitudes (Fig. 15) are generally similar in both products. The tropical eastern Pacific is one area where there is a substantial difference between the two products. In this area, the NSCAT derived field has stronger trade winds. The eastern Pacific is a region where NCEP is known to underestimate the trade winds (Putman et al. 1998). Another difference is the amount of detail resolved by the two products. The NCEP reanalysis product is on a gaussian grid (approximately 2° by 2°), while the NSCAT derived fields are gridded at an 1° by 1° resolution. This coarser resolution combined with the fact that the NCEP reanalysis is determined from modeled data is apparent in the smoother vorticity field (Fig. 15).

The average specific kinetic energy of the NSCAT derived field is compared to NCEP and to NSCAT observations (Table 3). NCEP has average specific kinetic energy that is lower (~12%) than the NSCAT derived field, which is slightly lower (~1.5%) than that of the NSCAT observations. A source for the difference in the kinetic energy is the weaker trade winds analyzed by NCEP. Furthermore, the higher kinetic energy in the derived NSCAT fields are supported by the kinetic energy in the NSCAT observations.

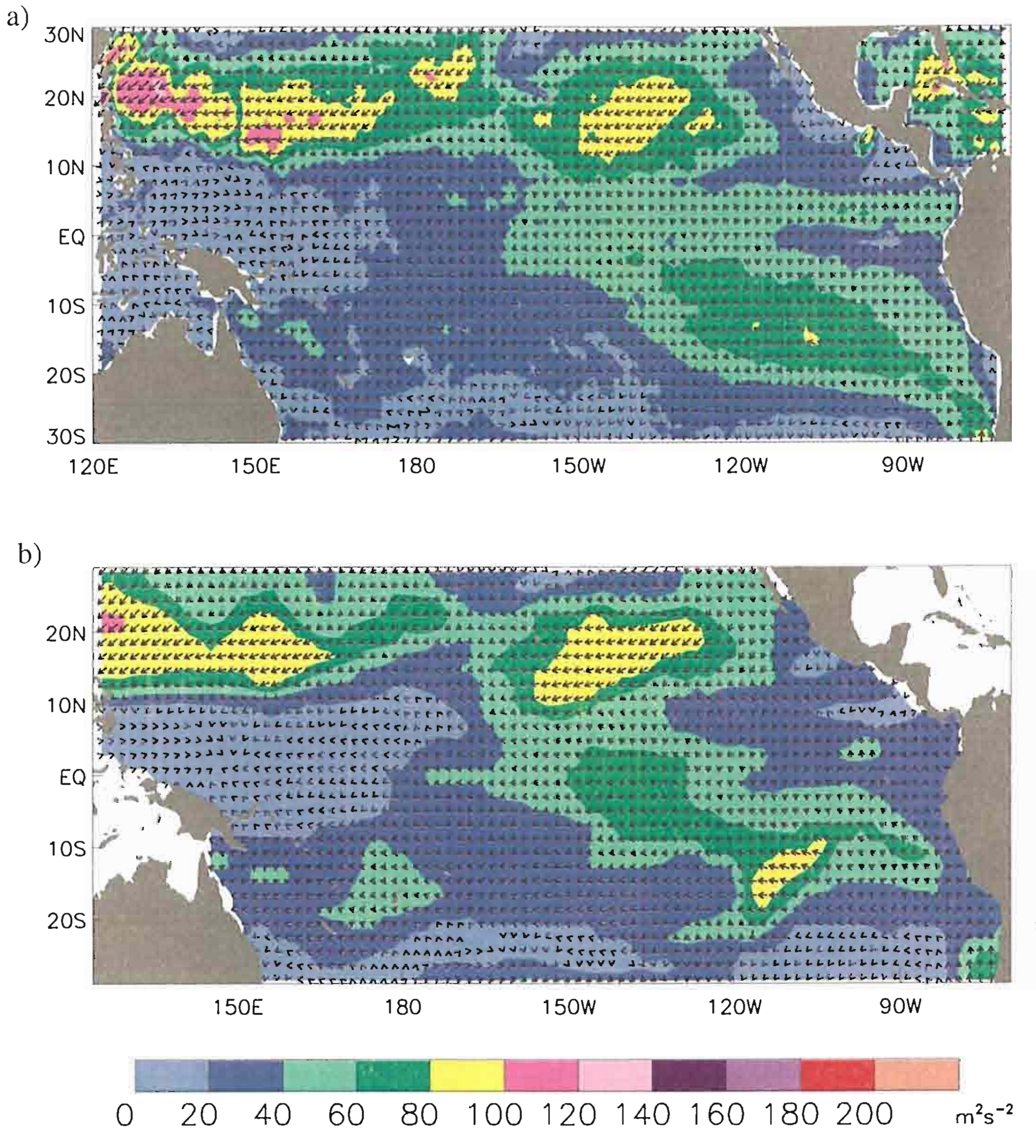

Figure 13: November 1996 mean pseudostress for the (a) objectively derived NSCAT field (1° by 1° resolution) adjusted to a height of 20, vectors are plotted every 2° by 2° for clarity, and (b) FSU winds monthly pseudostress (2° by 2° resolution). Magnitude of the pseudostress is contoured and direction is indicated by vectors. Magnitudes of the two products are similiar but the NSCAT product has finer detail such as the flow off Central America and the cross equatorial flow in the eastern Pacific.

has finer detail such as the flow off Central America and the cross equatorial flow in the eastern Pacific.

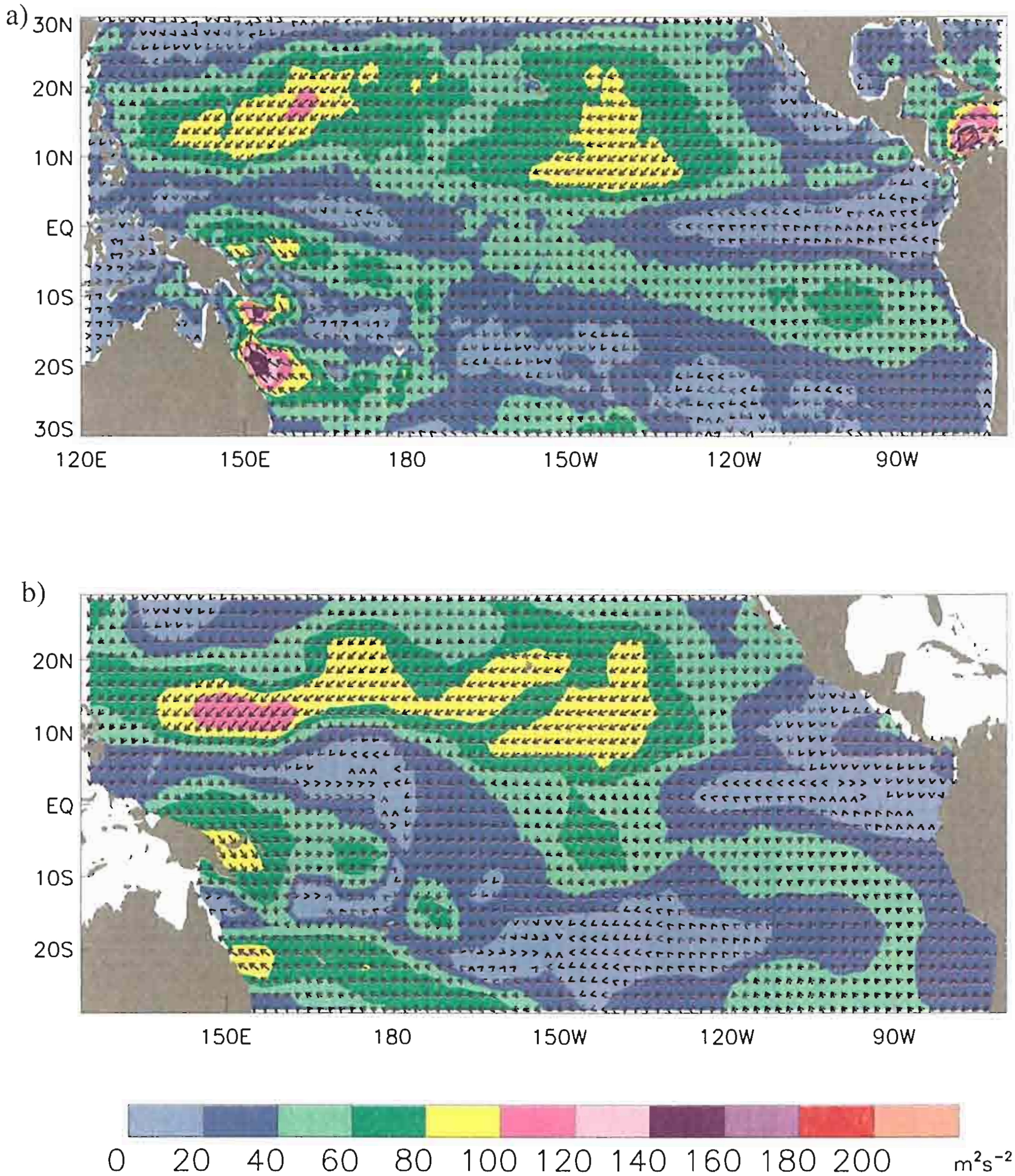

Figure 14: Same as Fiugre 13 except for March 1997. NSCAT product (a) shows high values of pseudostress off of the coast of Australia which are missing in the FSU wind analysis (b).

high values of pseudostress off of the coast of Australia which are missing in the FSU wind analysis (b).

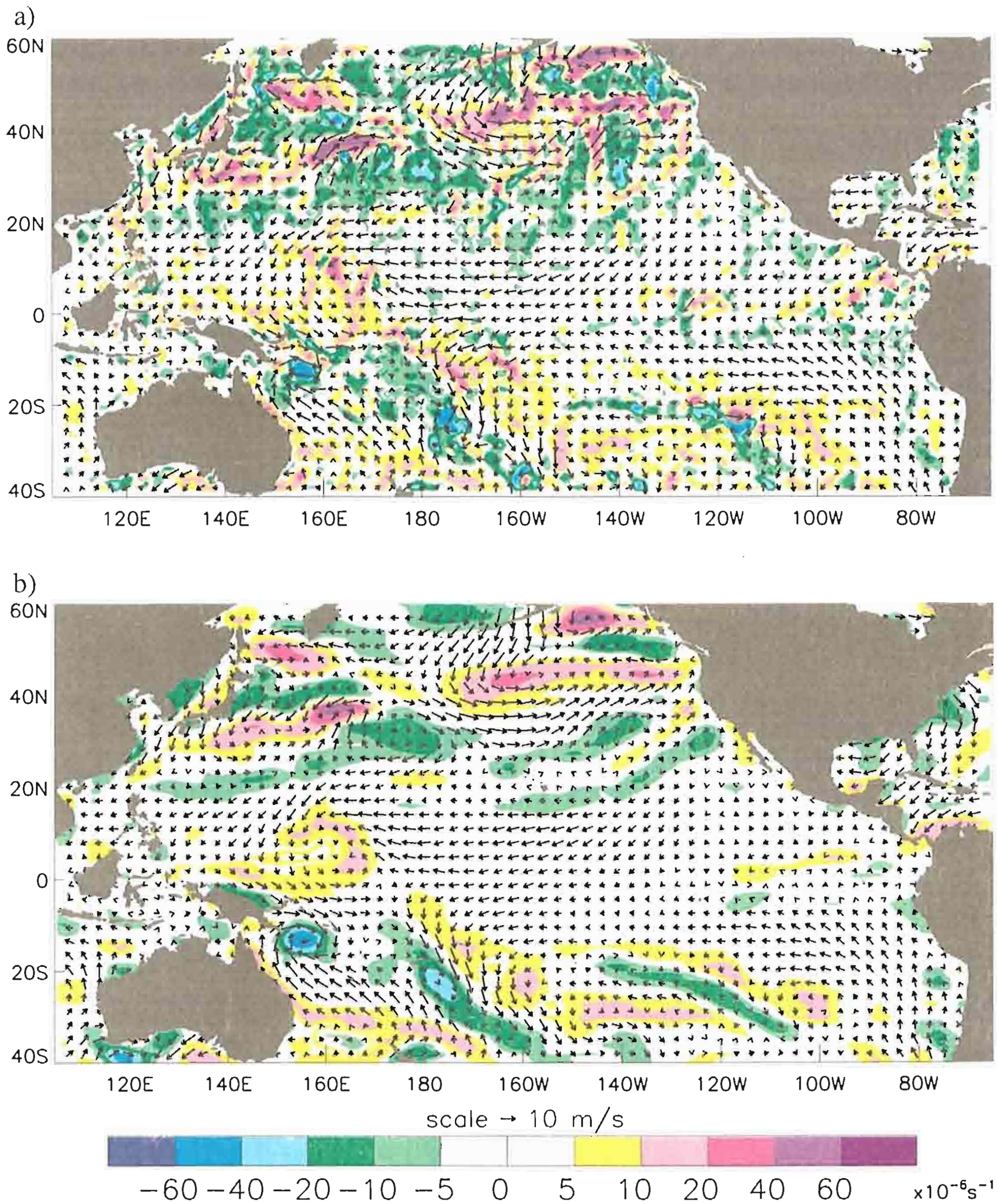

Figure 15: Winds from (a) objectively derived NSCAT pseudostresses and (b) NCEP reanalysis for March 16, 1997. NCEP wind components are interpolated onto a 1° by 1° grid and vorticity is contoured. Wind vectors are plotted every 3° by 3° for clarity. The NSCAT product has stronger winds near the coast of Central America and shows more detail than NCEP.

1° grid and vorticity is contoured. Wind vectors are plotted every 3° by 3° for clarity. The NSCAT product has stronger winds near the coast of Central America and shows more detail than NCEP.

Table 3. Average specific kinetic energy for the Pacific basin expressed as the average magnitude of the pseudsostress (m^2s^{-2}). The kinetic energy of the derived NSCAT field is close in magnitude to the observations and higher than the kinetic energy for NCEP.

	January 25, 1997	March 16, 1997	June 25, 1997
Derived NSCAT field	28.5	23.3	23.3
NSCAT Observations	29.9	24.2	23.1
NCEP Reanalysis	25.3	20.7	19.8

5. CONCLUSION

An objective technique is used to produce daily pseudostress fields based purely on NSCAT observations. Three weighted constraints specify the conditions for which the pseudostress fields are optimized. The constraints are: a misfit to observations, a Laplacian smoothing, and a kinematic constraint (the curl of the pseudostress). These weights are objectively determined through cross validation, which is a computationally expensive technique. The number of computations is further increased by the large size of the study region, 14,321 ocean grid points. A reduction in the number of calculations is necessary for practical application of cross validation. This reduction is achieved through the technique of multigridding (i.e., initially performing calculations on a coarser grid). The near independence of the weights on spatial resolution (up to at least 6°) demonstrates the validity of multigridding applied to cross validation.

This new gridded product is an improvement on the COAPS/NSCAT temporally averaged winds and other gridded NSCAT products due to the reduction of temporal smoothing and better removal of the satellite tracks from the curl field. These daily fields have kinetic energy similar to the NCEP reanalysis daily winds and the NSCAT observations. Similarly, monthly averages of these winds have patterns that are similar to FSU winds. After a height adjustment (from 10 m to 20 m) the objective product also has magnitudes similar to FSU winds.

magnitudes similar to FSU winds.

The high spatial and temporal resolution of the daily pseudostress fields allows for detailed analyses of wind patterns in sparsely observed regions. A CEOF analysis of the equatorial cold tongue region shows that there is a strong seasonal component to the trade winds in the first principal component. In the second principal component, there is a 20 day oscillation in the magnitude of the pseudostress, which is also found in TAO buoy wind observations. This periodicity could be associated with a mixed Rossby gravity wave in the area. The third principal component shows fluctuations in the magnitude of the pseudostress that are related to the SPCZ. Synoptic variability associated with the gap flow through the Sierra Madres is evident in the fourth principal component.

The objective techniques of direct-minimization and cross validation can be applied to any set of observations that have incomplete spatial coverage. The SeaWinds scatterometer recently launched on the QuikScat satellite will provide a new generation of scatterometer data to which this technique can be applied. The utilization of cross validation to determine the weights removes the subjective judgement of the researcher, and allows for the proper amount of information from the observations to go into the final product.

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BIOGRAPHICAL SKETCH

Degrees

M.S. anticipated December 1999, Meteorology, Florida State University, Tallahassee, FL. Thesis title: "Objectively-Derived Daily "Wind" Fields from Satellite Scatterometer Data."

B.S. May 1996, Atmospheric Science, State University of New York at Stony Brook, Stony Brook, NY.

Experience

Florida State University. Center for Ocean-Atmospheric Prediction Studies (COAPS). Graduate student research. Research involved assimilating NSCAT observations into daily gridded fields by an objective method. The resulting field was compared to independent data and an complex empirical orthogonal function (CEOF) analysis was performed on a subset of the data.

Brookhaven National Laboratory. Upton, NY. Summer Intern 1996. Issued weather forecasts for the lab, kept a log of meteorological data, and calibrated instruments.

Course work

Numerical weather prediction. Statistical weather prediction. Remote sensing. Cloud Physics. Radar Meteorology. Time series analysis. Synoptic, dynamical, and physical meteorology. Ocean physics. Air-sea interactions. Modern physics. Thermodynamic Physics. Radar Meteorology. Time series analysis. Synoptic, dynamical, and physical meteorology. Ocean physics. Air-sea interactions. Modern physics. Thermodynamic and statistical physics. Chemistry. Partial differential equations.

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