NOTES AND CORRESPONDENCE

A New FSU Winds Climatology

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(Manuscript received 21 November 2003, in final form 13 February 2005)

ABSTRACT

A new objective time series of in situ–based monthly surface winds has been developed as a replacement for the subjective tropical Pacific Florida State University (FSU) winds. The new time series begins in January 1978, and it is ongoing. The objective method distinguishes between observations from volunteer observing ships (VOSs) and buoys, allowing different weights for these different types of observations. An objective method is used to determine these weights and accounts for the differences in error characteristics and in spatial/temporal sampling. A comparison is made between the objective and subjective products, as well as scatterometer winds averaged monthly on the same grid. The scatterometer fields are a good proxy for truth. These three sets of fields have similar magnitudes, directions, and derivative fields. Both in situ wind products underestimate convergence about the intertropical convergence zone; however, the objective FSU product is a much better match to the scatterometer observations. Furthermore, the objective winds have smaller month-to-month variation than the subjective winds. Composites of ENSO phases are also examined and show minor differences between the subjective and objective wind products. The strengths and weaknesses of the objective and subjective winds are discussed.

1. Introduction

Fields of surface winds and fluxes are used in a wide range of applications including El Niño–Southern Oscillation (ENSO) forecasts and impacts, as well as ocean and atmospheric variability on a wide range of spatial and temporal scales. In situ observations have been used to develop many surface wind products (e.g., Hellerman and Rosenstien 1983; da Silva et al. 1994; Servain et al. 1996; Stricherz et al. 1997). For more recent time periods, surface winds have also been determined from satellite observations: Special Sensor Microwave Imager (SSM/I; Atlas et al. 1996), altimeters (Chelton and Wentz 1986), and scatterometers (Polito et al. 1997; Bentamy et al. 1998; Kutsuwada 1998; Chin et al. 1998; Kelly et al. 1999; Pegion et al. 2000). Surface flux fields are usually developed from atmospheric general circulation models such as the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalyses (Kalnay et al. 1996; Kanamitsu et al. 2002). The advantages of the GCM fields are greater temporal resolution than most in situ fields, longer time series than satellite-derived fields, and the addition of upper-air fields. However, reanalysis data are noted to have a poor handling of the wind field in equatorial regions (Putman et al. 2000), as well as large biases in heat fluxes (Smith et al. 2001; Bony et al. 1997). For applications that require accurate surface fluxes and/or winds, and do not require better than monthly temporal resolution, a research quality climatology based on in situ observations is preferred.

An objective technique is used to create a new monthly climatology for surface fluxes and related fields for the tropical Pacific Ocean. The wind (pseudostress) products are improved in comparison to our previous product: the subjectively analyzed FSU winds (Smith et al. 2004). Fields of turbulent surface fluxes and the variables needed to calculate these fluxes are also generated. The new objective method is an extension of a technique used to create daily fields of scatterometer vector wind observations obtained from a polar-orbiting satellite (Pegion et al. 2000). The prob-

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lems related to gridding monthly ship data are analogous to those of gridding daily scatterometer observations. In both cases, there are large gaps in the observational coverage, observational errors, and uncertainty that should be considered. Furthermore, observational tracks (e.g., ship tracks or satellite tracks) from different times intersect, often with substantial changes in the wind pattern occurring between the observations. Simple averaging would result in spurious wind curl and divergence, which generates spurious Rossby and Kelvin waves when these fields are used to force ocean models.

Despite the above problems, in situ observations have 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). The fields were first used to study equatorial Kelvin waves and then as forcing for studies in the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE). There are several reasons for developing our new product. First, the gridding technique developed for scatterometer observations (Pegion et al. 2000) deals with the above problems more effectively than the previous techniques. Second, the approach requires much fewer man-hours per field. Lastly, specific shortcomings of the traditional products have been identified. For example, ocean models forced with the old subjective Florida State University (FSU) winds tend to produce realistic sea surface height anomalies; however, they do not produce realistic temperature anomalies (A. Busalacchi 2000, personal communication). Preliminary tests with the new wind product produced improved modeled ocean currents (Z. Yu 2002, personal communication).

Our new objective technique is adapted from a technique for gridding observations from a single polar-orbiting satellite (Pegion et al. 2000). The new objective technique treats various types of data sources [i.e., buoys and volunteer observing ships (VOSs)] as independent (detailed in section 3). These new fields will be shown to have great improvements over the subjective FSU winds. The objective fields have already become a standard of comparison for tropical Pacific Ocean winds. Both in situ products are examined in section 4. Particularly significant differences are found in fields of spatial derivatives (section 4) and month-to-month variability (section 4a). The accuracy of both in situ products are demonstrated in comparison to buoy and scatterometer observations (section 4b). One of the great advantages of the in situ products is that they can be extended much further back in time than is possible with buoy or scatterometer observations. Consequently, it is possible to use composites of the in situ products to examine ENSO-related variability in surface winds (section 4c). Both the strengths and weaknesses of these two in situ products are examined with the goal of aiding the many researchers that use these products in climatological applications.

2. Data

The new objective method produces fields of stress, latent heat flux, sensible heat flux, pseudostress (the product of the scalar and vector mean wind), scalar mean wind speed, air temperature, and atmospheric specific humidity. Only the pseudostress fields and the related data will be discussed herein.

The in situ observations used in creating the new research-quality fields are from two sources. Fields for 1997 and earlier are developed from the International Comprehensive Ocean–Atmosphere Dataset (ICOADS; Woodruff et al. 1987), while in situ data for post-ICOADS years are from the National Climatic Data Center (NCDC) technical document on marine surface observations (TD-1129; NCDC 2003). Quick-look products (produced when a month's data become available) are from NCEP (1997). Research quality products were produced when the TD-1129 became available in the summer of the following year.

There are practical differences between the three above datasets. The TD-1129 product includes late data and has slightly better quality control than the Global Telecommunications System (GTS). In the tropical Pacific Ocean, the difference in the number of points per 2° bin is almost always ± 5 observations. There is little change in the number of points; however, in the Southern Hemisphere these changes could halve or double the number of observations per bin. The ICOADS data have historical data and much more detailed quality control and quality assessment, requiring little additional quality control by our analyst prior to producing the gridded fields.

The Tropical Atmosphere Ocean array (TAO)/Triangle Trans-Ocean Buoy Network (TRITON) observations that are provided through the NCEP real-time marine observations and data from TD-1129 have biases in the times of day at which the observations are reported. The TAO/TRITON buoy arrays (McPhaden et al. 1998) are extracted from the above datasets and replaced with daily average observations provided by the Pacific Marine Environmental Laboratory (PMEL) for the research and quick-look products. This correction was developed in 1996 for the subjective FSU winds (Smith et al. 2004) and will not be further discussed herein.

a. Quality control

In situ datasets are plagued with seemingly large errors, many of which are associated with incorrect records of ship locations. There are also errors related to instrument malfunctions or misuse. We remove the worst of these data through a comparison to climatological values. We accept all values within 3.5 standard deviations from the monthly mean, where the mean and standard deviation for each month are calculated from the da Silva climatology (da Silva et al. 1994). Because of the da Silva climatology's limited variability in parts of the globe, we also prescribe minimum standard deviations for each variable. Plots of the rejected observations clearly show ship tracks of bad data. Only a small fraction (<5%) of open ocean data are rejected.

A second level of quality control is applied with a tool developed to display the monthly mean gridded observations for visual inspection. An analyst edits these in situ fields to remove erroneous or nonrepresentative data that were not removed by the comparison to climatology. A common example of nonrepresentative observations comes from ships encountering atypical severe weather in sparsely sampled areas. These checks result in much more appropriate data for our objective method. This approach is necessary for in situ data and greatly reduces the amount of smoothing that would otherwise be required.

b. Biases and uncertainties in in situ observations

Anemometer observations from ships are assumed to correspond to a 20-m observation height, and they are height adjusted (with atmospheric stratification calculated from observations) to the standard height (10 m). The impact of the height adjustment is substantial, particularly for TAO buoys that have ~4 m anemometer heights. The choice of flux model (Bourassa et al. 1999) used in the height adjustment has little impact on the value of this adjustment. An adjustment (Lindau 1995) is also applied to Beaufort (visually estimated) winds to remove wind speed–dependent biases and rescale the wind speeds to a 10-m reference height.

As a result of a critical oversight in the information recorded in the dataset used to create the quick-look product, these bias adjustments are dependent on the dataset used to make the gridded product. NCEP's real-time marine observations do not contain information on the method of taking the wind observations: anemometer-based or a visual estimate. Consequently, we treat all ship observations from that dataset as being from the same height, which was determined to best match the research-quality fields when this height was set at 17.7 m. These changes in reference height cause some of the differences between the quick-look and research-quality products; however, in most cases the changes in sampling (either due to exclusion of late data from NCEP's dataset or due to NCDC's and ICOADS's superior quality control in the datasets used for the research quality products) are the dominant source of differences in the two products.

c. Comparison data

Satellite vector winds are obtained from the National Aeronautics and Space Administration (NASA) Scatterometer (NSCAT) and the SeaWinds scatterometer on QuikSCAT (QSCAT). Data from the European Remote Sensing System satellites (*ERS-1/2*) would be useful for times when NSCAT and SeaWinds data were not available but were not used in this comparison. Scatterometer winds are calibrated to a 10-m height. They contain speed and direction, whereas other satellite instruments (e.g., SSMI and altimeters) determine only wind speed. The monthly pseudostress fields based on in situ data are compared to monthly averages of daily fields based on NSCAT and QSCAT observations. Observational uncertainty in scatterometer observations (Bourassa et al. 1997; Freilich and Dunbar 1999; Bourassa et al. 2003) is small relative to uncertainty in VOS observations. The scatterometer coverage and spatial sampling are also superior to VOS observations: in one day, SeaWinds makes approximately the annual number of VOS wind observations. Compared to SeaWinds, NSCAT took approximately half the number of observations per unit time, which still provided far better sampling than VOS observations. These characteristics of scatterometer observations make scatterometer-based wind fields an ideal standard of comparison for the time periods when these observations are available.

The NCEP Reanalysis 2 (NCEPR2) provides a comparison to a Numerical Weather Prediction (NWP) product that attempts to assimilate VOS data as well as a wide range of other available data in a self-consistent manner. The usefulness of such products is limited by several factors including the accuracy of the physical assumptions within the model and the ability of the model to assimilate data. The NWP parameterizations for planetary boundary layers are typically relatively poor, contributing to substantial differences between model products and surface data (Curry et al. 2004). It has been often stated that a large fraction of open ocean surface data is rejected during the assimilation process. These problems presumably contribute to substantial errors in NWP surface fields. Extreme problems can be seen in comparisons of high-quality satellite data to NWP output (Hilburn et al. 2003).

The TAO/TRITON buoys in the equatorial Pacific Ocean represent the highest-quality (and reasonably long term) in situ observations within the region of interest. These observations are used to construct the objective product: they are not an independent validation. However, the objective FSU winds must be shown to be consistent with these isolated high-quality observations.

d. Pseudostress

Although in situ and satellite observations are recorded as winds, gridded fields of pseudostresses are produced because the FSU winds have been intended for ocean modeling: the fields were first used to study equatorial Kelvin waves, then as forcing for studies in the TOGA COARE. Ocean circulation is largely driven by wind stress and the curl of wind stress. 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

$$\tau_x = \rho\, C_D\, \Psi_x \quad \text{and} \quad \tau_y = \rho\, C_D\, \Psi_y, \tag{1}$$

where ρ is the density of air, and C_D is the drag coefficient. The choice of drag coefficient is highly contentious and dependent on application. While producing the subjective FSU winds, it was found that pseudostress fields were far less controversial and readily accepted. The zonal (Ψ_x) and meridional (Ψ_y) components of the pseudostress are defined as

$$\Psi_x = uw \quad \text{and} \quad \Psi_y = \upsilon w, \tag{2}$$

where w is the scalar mean wind speed, and u and υ are the mean zonal and meridional components of the wind vector, respectively.

3. Methodology

A variational method is employed to objectively grid in situ (VOS and buoy) observations. This objective method is employed iteratively with subjective editing in the data, to remove the relatively large inconsistencies between the input data and the solution fields. These inconsistencies are due to erroneous data (usually ship position) as well as poor sampling. The variational method employed is direct minimization, which employs a cost function (section 3b) based on several weighted constraints. Three types of constraints are applied to each vector variable: misfits to each type of observation, a smoothing term, and a misfit of curl. The second and third terms are applied to differences between the solution field and a background field. The first two types of constraints are applied to scalar terms. The influence of the background field, relative to the observations, is controlled by the ratios of the weights for misfits to observations to the weights on the other constraints.

a. Background fields

The background fields are overly smooth monthly fields based on the observations. The smoothing function is an isotropic Gaussian filter in space. The radius of the Gaussian function is equal to the $\sqrt{Rr}$, where r is the radius of the search area, which is a minimum of 6°. The other distance scale, R, is dependent on the sampling and uncertainty characteristics: R = 16 500 km for the research quality fields, and R = 8800 km for the quick-look product. There are many areas where the noise in the observations is not adequately reduced because the minimum averaging area has an insufficient number of observations. Observations from only the month being examined are used in the construction of the background field. A practical number for this minimum is 100 observations: the resulting fields have been found to have little sensitivity to <30% changes in the number of observations. The smaller value of R for the quick-look product is probably due to larger values of r needed to reach the minimum number of observations. In regions of insufficient observations (Fig. 1), the area of the averaging is increased until there is a sufficient number or until the search radius becomes too large (8°). In practice, there are locations were there are routinely less than 100 observations within the averaging domain. In these locations, the average in the background field was determined with the available data. This simple blending technique has unrealistic features if the sampling characteristics of buoys are too different from those of ships. Therefore, buoy data are combined into daily averages and weighted evenly with data from other platforms to create the background field.

The background fields have been found to be more effective than using a long-term mean of monthly winds (e.g., the da Silva or FSU climatologies), particularly during strong ENSO events where the long-term mean is a poor estimate. This approach reduces random errors (Pierson 1990) through averaging and removes large biases that would otherwise occur in El Niño or La Niña years.

The data in the background are further constrained to reduce the occurrences of blending from greatly differing wind regimes. For monthly averages, such errors are typically related to blending across land. Therefore, only those observations that have a "line of sight" unblocked by land (based on a 0.5° land mask) are considered in the averaging. This procedure has been particularly effective in preventing unrepresentative strong winds in the Caribbean Sea from influencing weak winds in the eastern Pacific.

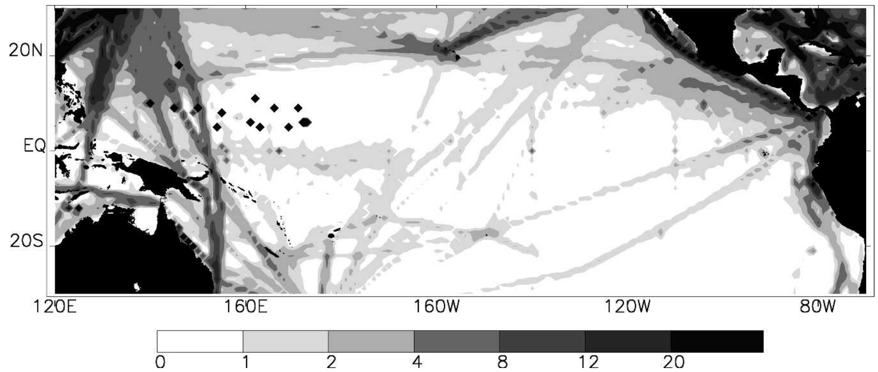

FIG. 1. Number of VOS observations, in 2° × 2° bins, in Aug averaged from 1988 to 1997.

Prior to 1978, there are areas within our Pacific region where the sampling is insufficient to create a data-based background field. The Pacific objective FSU winds can be extended further back in time if the technique for creating the background field is modified for that time period. One such possibility is adding information based on the 1978–2002 climatology, modified by the phase (and possibly strength) of the ENSO cycle. Composites of the ENSO phases are discussed in section 4c.

b. The variational method

The variational method utilizes several constraints to maximize similarity to observations, minimize nongeophysical features in the spatial derivatives (e.g., the observational patterns), and accomplishes these goals with the minimum necessary smoothing. Previous works (Legler et al. 1989; Meyers et al. 1994; Siefridt et al. 1998; Pegion et al. 2000) have shown that three constraints can be coupled to construct physically sound wind fields. Each of these constraints is multiplied by a weight. In previous studies, these weights have been determined through subjective observations (Legler et al. 1989), less subjectively through a sensitivity study (Meyers et al. 1994), or objectively with cross validation (Pegion et al. 2000). We continue to apply cross validation to determine the weights.

The functional (f) for a vector variable (e.g., pseudostress) is

$$
\begin{aligned}
f = \sum_{i,j}^{I,J} \Big\{ & \beta_a \sigma_{o1}^{-2}[(\Psi_x - \Psi_{x_{o1}})^2 - (\Psi_y - \Psi_{y_{o1}})^2] \\
& + \beta_b \sigma_{o2}^{-2}[(\Psi_x - \Psi_{x_{o2}})^2 - (\Psi_y - \Psi_{y_{o2}})^2] \\
& + \beta_c L^4[\nabla^2(\Psi_x - \Psi_{x_{bg}})^2] + \beta_c L^4[\nabla^2(\Psi_y - \Psi_{y_{bg}})^2] \\
& + \beta_d L^2[\hat{\mathbf{k}} \cdot \nabla \times (\boldsymbol{\Psi} - \boldsymbol{\Psi}_{bg})^2] \Big\}, \qquad (3)
\end{aligned}
$$

where the betas are weights, the *i, j* subscripts for geographical position have been dropped (the βs and L are the only terms that do not vary spatially), the unsubscripted pseudostress (Ψ_x, Ψ_y) is the solution field, the o subscript indicates monthly averaged observations ("o1" for ships and "o2" for buoys), the subscript bg indicates the background field, and L is a grid-spacing-dependent nondimensional scale that make the weights approximately independent of grid spacing. The function is kept dimensionally sound by scaling each term by estimates of the variability (i.e., uncertainty squared, σ^2) in the observations or background used in that term. For the first release of this product, the local uncertainty in observations has been estimated from the daily variability in the NCEP–NCAR reanalysis (Kalnay et al. 1996), determined for each month averaged over the period of the reanalysis (i.e., an average for each January, February, and so on). The uncertainties for the Laplacian and curl terms are treated as a global average, and they are combined with the weights (β_b, β_c, and β_d). This approach considers sampling variability but does not consider observational uncertainty (random errors in observations) and representativeness (differences in space and time from the center of the grid cell). These considerations are being developed and are anticipated in the next release. The consideration of local uncertainty in observations (and in the other terms in the next release) is also useful in reducing spatial variability in the functional's weights.

c. Objectively determined weights

The weights for each type of observations are determined independently through cross validation (Pegion et al. 2000). These weights combine the considerations of observational uncertainty and data coverage, which differ for each type of platform; therefore, the weights are not expected to be equal. The weights are also highly dependent on the quality of the background field

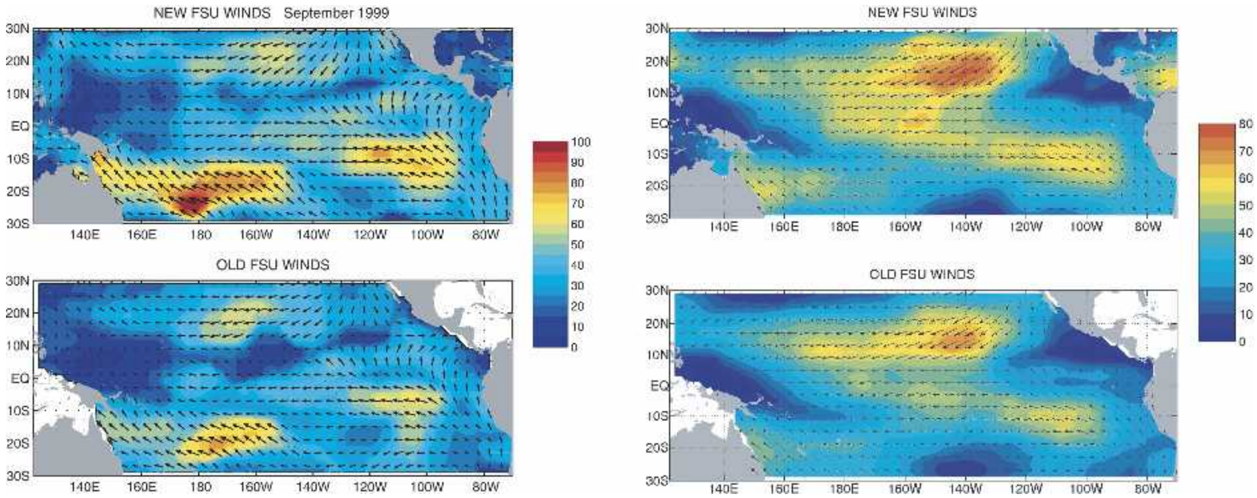

FIG. 2. The (top) new objective FSU winds are compared to (bottom) the subjective FSU winds for (left) monthly and (right) annual averages of pseudostress ($m^2\ s^{-2}$). The monthly fields are from Sep 1999, and the annual averages are from 1999.

(section 3a). Our original technique based on Pegion et al. (2000) determined the background fields from bin averages (a uniformly weighted filter) rather than a Gaussian filter: the objectively determined weights for the penalty term and misfit to curl were reduced by a factor of 50 when the Gaussian filter was applied. The increased weights for observations close to the point of interest increase the accuracy of the background field. It is the ratios of the weights that are important rather than the individual values; therefore, one of the functional's weights can be prescribed. The most difficult weight to determine (because of limited spatial coverage) is the misfit-to-buoy wind components. After the weights were determined, they were rescaled to set the weight for misfit of VOS wind components (β_a) to unity. The other weights are $\beta_b = 20$ (buoy observations), $\beta_c = 0.6$ (smoothing), and $\beta_d = 2.0$ (misfit to curl). These weights are largely independent of season. The approximately regular pattern and quality of TAO buoy observations leads to relatively high weight for buoy observations. This weight also insures that the new FSU winds will be an excellent match to the height-adjusted buoy observations.

4. Results

The new objective FSU winds are compared to the subjective FSU winds for monthly (Fig. 2a) and annual (Fig. 2b) averages. The new and old FSU winds (adjusted to 10 m) have similar patterns and magnitudes. Examinations of the other months and years indicate that neither product has substantially stronger maxima or minima in speed. A key difference is seen in the divergence and curl fields (Fig. 3), where the new FSU winds typically have weaker maxima and show a clearer spatial pattern in curl and divergence. These differences are particularly noticeable at and around the equatorial cold tongue. The above differences have little to do with changes in the grid spacing: the subjective Pacific FSU winds had $2° \times 2°$ grid spacing, interpolated from an analysis based on 2° latitudinal bins and 10° longitudinal bins, whereas the new FSU winds are analyzed from $2° \times 2°$ bins. One area where the grid spacing in the objective product has resulted in improved resolution is the South Pacific convergence zone (SPCZ). The binning over 10° longitude in the subjective product smoothed the SPCZ. The intertropical convergence zone (ITCZ) has relatively little meridional variability; consequently, it was less adversely influenced by the binning in the subjective product.

a. Changes in temporal variability

The patterns of large-scale year-to-year variability for a single month within each year (e.g., July; Fig. 4) in the objective FSU winds are similar to the patterns in the subjective product. However, the small-scale spatial/temporal variability is greatly reduced in the new product. Recall that the background field used in the objective method is based solely on the observations. Therefore, the lack of small-scale temporal variability is not due to the imposition of a prescribed background climatology. One cause for the greater variability in the old product could be differing smoothing; however, the binning on larger spatial scales and the relatively weak convergence zones in the old product suggest that there is greater smoothing in the subjective product. Conse-

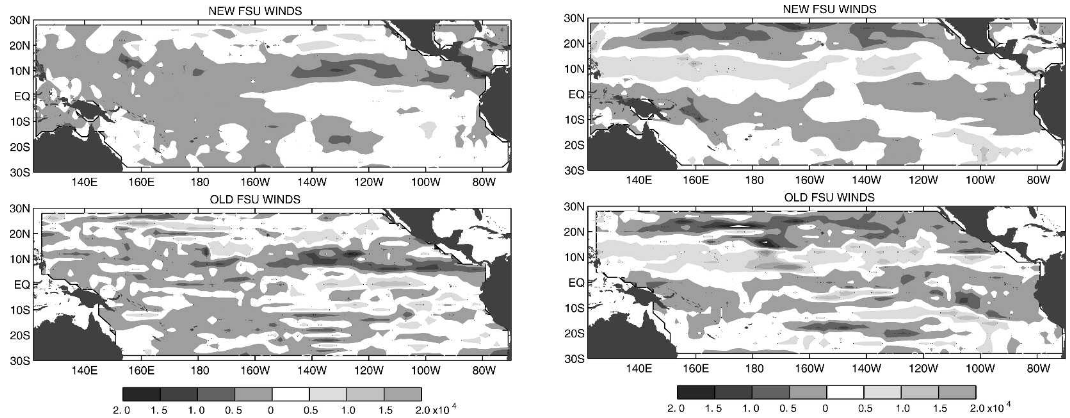

FIG. 3. (left) Divergence and (right) curl fields from Nov 1987: (top) new FSU winds and (bottom) subjective winds.

quently, the larger small-scale variability in the old product is probably due to changes in analysts and human variability in subjective analysis.

The month-to-month variability in the subjective FSU winds has been a matter of concern, prompting some investigators to apply 1–2–1 temporal filters (A. Kaplan 2002, personal communication). The scale of month-to-month variability can be seen (Figs. 5 and 6) in root-mean-square (rms) differences between adjacent months, averaged for each grid point from 1978 to 1997. Similar results are found in the standard deviations of the wind fields for each month, when they are subset by ENSO phases.

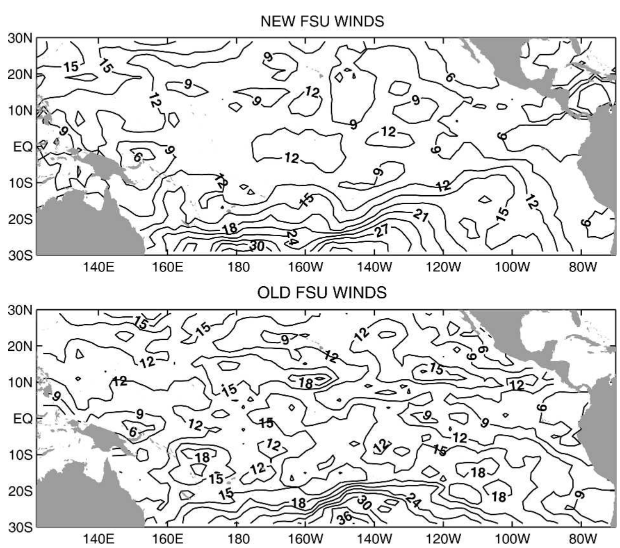

FIG. 4. The patterns of large-scale year-to-year standard deviations in zonal pseudostress, for Jul from 1978 to 1999, in the (a) objective and (b) subjective FSU winds. The general pattern is similar in both products; however, there is much more noise in the subjective product.

The rms differences in the magnitude of month-to-month vector differences is a diagnostic that combines speed and directional differences into a single statistic. Comparison of the objective FSU winds to the NCEPR2 shows remarkably similar patterns (Fig. 6). The differences in magnitude are partially due to differences in grid spacing.

b. *Comparison to satellite vector winds*

The time series of FSU winds have also been compared (Fig. 7, left) to in situ observations from the TAO buoys and satellite winds from two scatterometers: NSCAT on the Advanced Earth Observing Satellite *ADEOS-1* and SeaWinds on QSCAT. In the largest data void (19°S, 254°E), which is typical of two other data voids that were examined, the FSU wind products are compared with scatterometer data (Fig. 7, right). The fit to the vector components within these regions is similar to the fits in areas of much better coverage. The subjective FSU winds have occasional relatively large departures from the other products and observations and have the earlier-mentioned large month-to-month variability. The objective FSU winds are similar to monthly averaged TAO buoys (which are included in the objective product; Fig. 7 left) and to monthly averaged NSCAT and QSCAT winds (which are not included in the objective product), while being slightly better matches to the QSCAT winds. The departure from the TAO observations is due to input from nearby ship data and spatial smoothing. This smoothing combined with the pattern of winds causes the largest departures to occur in the meridional wind component.

The objective in situ product has been compared to monthly averages of scatterometer (NSCAT and QSCAT) pseudostress analyzed on the same grid as the

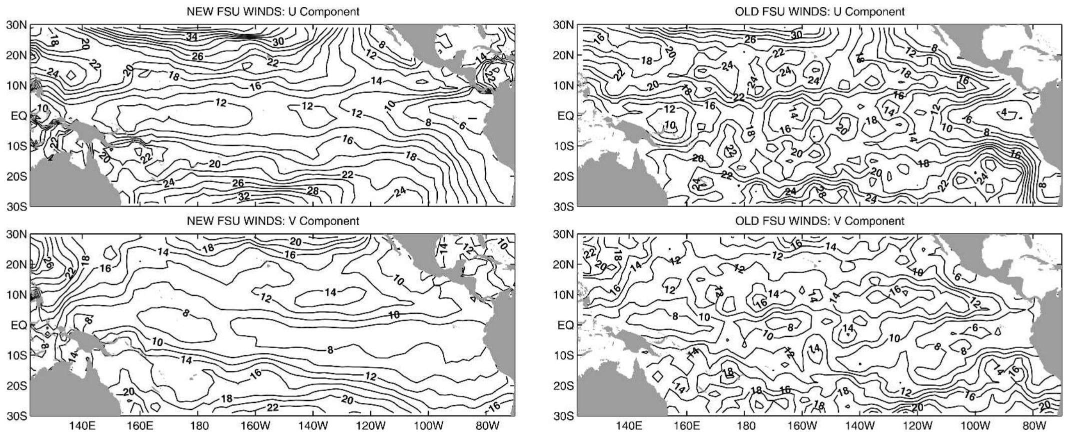

FIG. 5. Rms month-to-month differences of (top) zonal and (bottom) meridional pseudostress components ($m^2 s^{-2}$), averaged from 1978 to 1999. (left) The new objective FSU winds have more month-to-month consistency than (right) old subjective FSU winds. The lack of month-to-month consistency was a major issue for some users of the subjective product.

new FSU winds. The scatterometer observations are gridded with the same objective technique used herein, except that the uncertainty estimates consider observational error and representativeness, there is no manual quality control of the scatterometer data, and the length scale for spatial smoothing is approximately one-tenth of the scale for in situ data. The scatterometer observation density is sufficient to produce much finer spatial resolution for monthly time scales: scatterometer winds are the best available standard of comparison. The comparison times are October 1996 through June 1997 for NSCAT and August 1999 through December 2003 for QSCAT. The comparison to scatterometer data includes mean differences (biases) as well as standard deviations, which are more indicative of seemingly random differences.

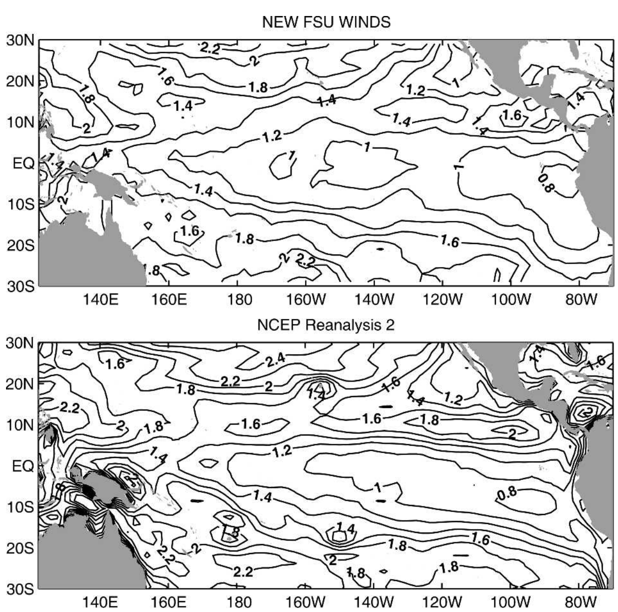

FIG. 6. The internal consistency can also be examined with rms values of the magnitude of month-to-month vector pseudostress differences ($m^2 s^{-2}$). This approach considers a combination of both vector components (i.e., both speed and direction). The month-to-month variability is similar in (top) the new FSU winds and in (bottom) the NCEPR2.

The comparisons of mean differences (Fig. 8) between the scatterometer and FSU wind products have similar spatial patterns; however, the differences between the scatterometer and subjective FSU pseudostress are much greater than for the objective pseudostress. The clearest pattern occurs in the meridional wind comparisons and is related to an underestimation of the FSU products' convergence about the ITCZ. The zonal differences are partially due to the scatterometer measuring current relative winds, while the in situ winds are earth relative. The magnitude and direction of speed biases (Fig. 8, top) near the equator are consistent with the South Equatorial Current (SEC; Kelly et al. 2001). The biases near the SEC are also partially due to the broad spatial smoothing used to create the background field for the objective product. The speed biases to the north of the North Equatorial Counter Current (NECC; 7° or 8°N) are greater than the observed and modeled currents. This region has very sparse coverage, and the information that propagates into this region is a relatively poor match to local conditions. For a strong majority of locations, the magnitude of the bias in stress components is <0.006 N m^{-2}.

Greater differences between the subjective and objective FSU winds are seen in standard deviations of differences with scatterometer winds (Fig. 9). These

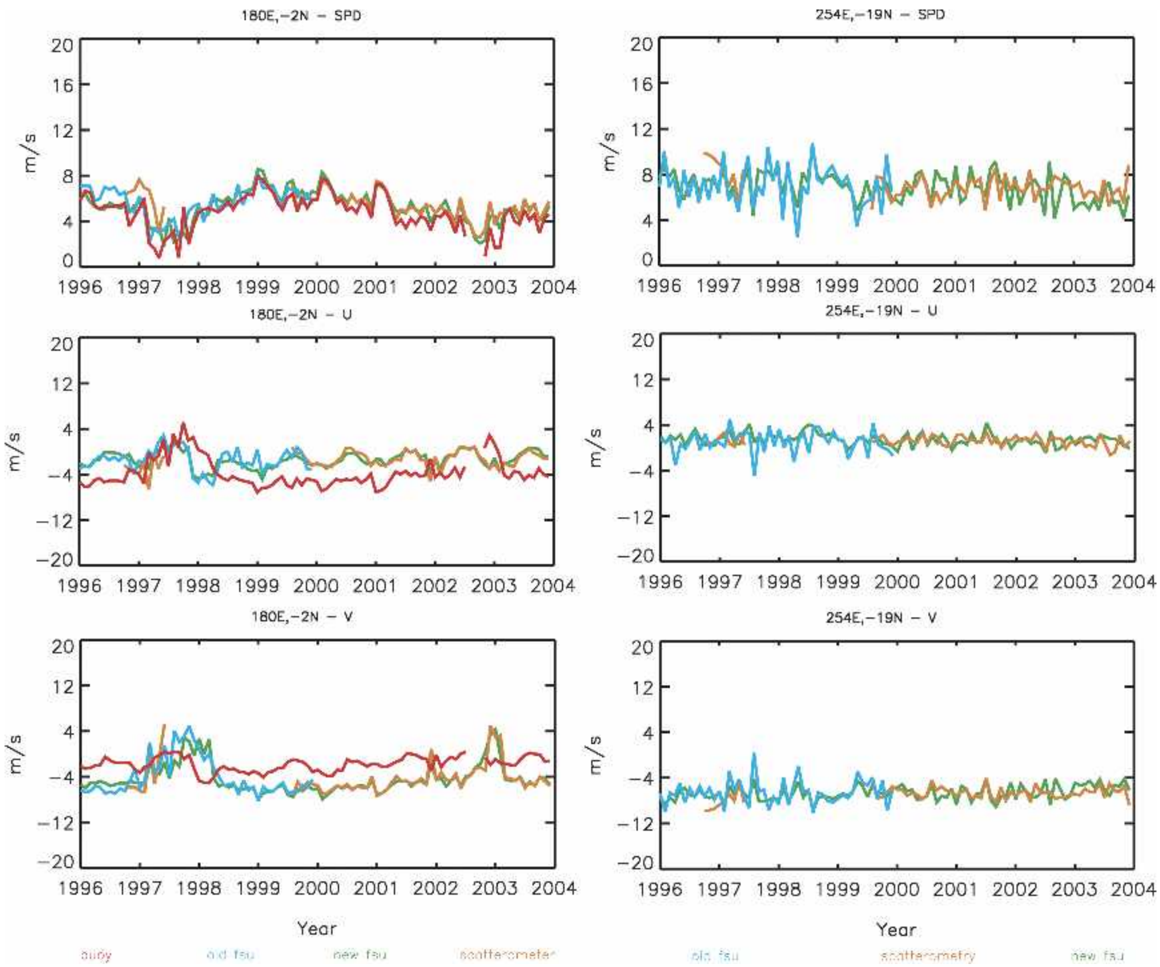

FIG. 7. Comparison between the TAO buoy winds (m s^{-1}; red) (left) at 2°S, 180° and (right) in a large data void at 19°S, 254°E. The lines show subjective FSU winds (blue; not produced after Dec 1999), objective FSU winds (green), and NSCAT and QSCAT winds (yellow), for (top) wind speed, (middle) zonal component, and (bottom) meridional component.

standard deviations are much greater in the comparisons with the subjective product. The subjective FSU product has local maximums around the ITCZ and the SPCZ. The subjective product's shortcomings related to the SPCZ are likely due to the use of 10° longitudinal bins in the hand analysis. The objective product also has remarkably improved accuracy in the western Pacific Ocean. Presumably the good quality of the objective FSU winds extends as far back as there are adequate in situ observations. Degradation in quality with time can be examined in future studies if in situ data from the scatterometer time period can be subsampled to simulate coverage during earlier times.

Statistics on scalar averages of speed are used to examine the dependence on data density. The dependence of accuracy on proximity to observations (Tables 1 and 2) indicates mixed results and again must be interpreted with caution because of the physical differences between in situ and scatterometer measurements. There is no clear dependence on the number of in situ observations within a bin, provided that there are observations in the bins. The large biases in cases 2 and 4 relative to case 3 suggest that greater smoothing would reduce the global bias statistics. However, doing so globally would also increase the error characteristics for spatial derivatives in regions where these derivatives are large, which are very important for ocean forcing.

Monthly averaged ship and buoy winds have relatively large differences from the mean scatterometer wind speeds averaged in identical bins. The monthly 2° × 2° ship or buoy observations minus scatterometer observations have a standard deviation ~3.9 m s^{-1} over the domain. These values are much greater than similar statistics for the objective and subjective gridded products. This result indicates that the gridding procedures not only fill gaps in the in situ observations, but also

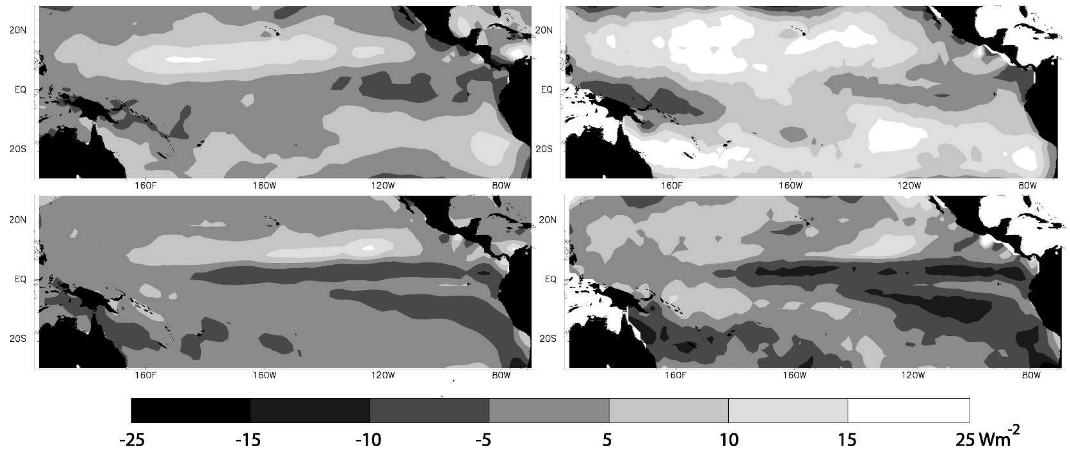

FIG. 8. Mean monthly differences of FSU and scatterometer pseudostress components (FSU minus scatterometer): (top) zonal pseudostress and (bottom) meridional pseudostress. (left) The new objective FSU winds are much more similar to the scatterometer winds than (right) the old subjective FSU winds. The meridional differences indicate that neither the subjective or objective FSU winds capture the strong meridional convergence about the ITCZ. The patterns in the zonal winds are related to the currents. Scatterometer winds are current relative, whereas the FSU winds are earth relative.

greatly improve the accuracy even where there were observations.

c. Comparison of ENSO-related variability

The temporal averages of the new objective FSU winds have small but physically significantly differences from the old subjective FSU winds (Fig. 10). The La Niña fields are relatively noisy because of the smaller sample size. The number of samples (years) in each composite are 3 for La Niña, 14 for neutral, and 5 for El Niño, where the ENSO phase is determined with the Japan Meteorological Agency (JMA) definition (Japan Meteorological Agency 1991; Hanley et al. 2003). The JMA definition is based on sea surface temperatures within the region 4°S–4°N, 150°–90°W. The clearest example of such differences between the subjective and objective ENSO patterns is the band of low pseudostress magnitudes that extends to the southeast from the equatorial central Pacific Ocean. Both products show this band; however, this band has slightly larger values of pseudostress in the objective product, and it is more spatially consistent along the band. This spatial consistency is apparent in composites of each ENSO

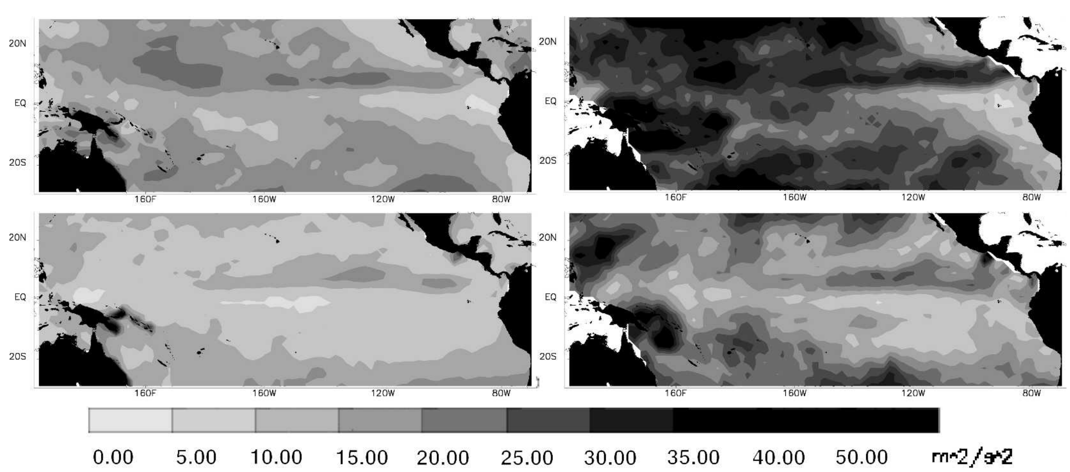

FIG. 9. Same as in Fig. 8, but for standard deviations of monthly differences. The meridional standard deviations have a local maximum about the ITCZ and in the area of the SPCZ. The VOS observation pattern is easily identifiable in the subjective FSU winds.

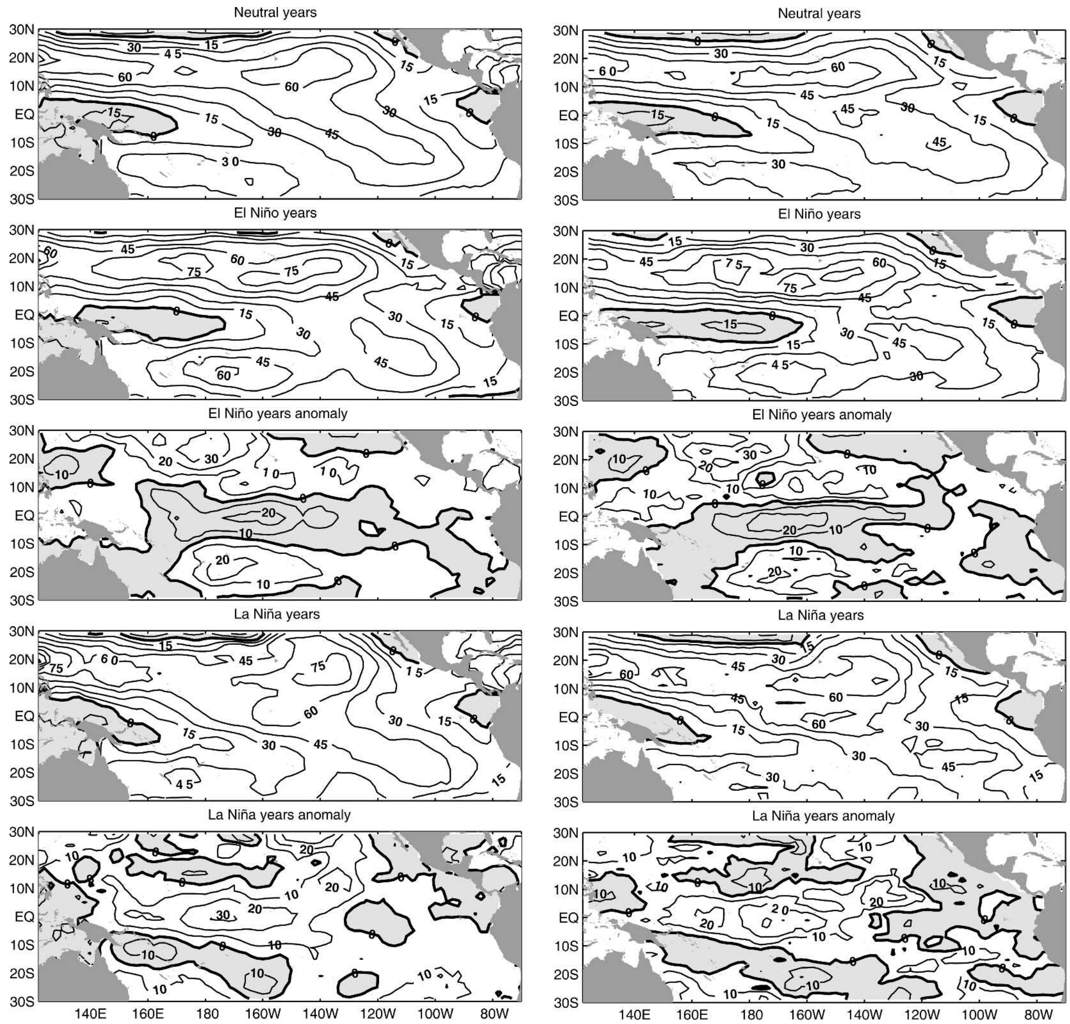

FIG. 10. Comparison of (left) the new objective and (right) old subjective Dec composites of zonal pseudostress ($m^2 s^{-2}$), as a function of ENSO phase, for 1978–99. The zero contour is darkened, distinguishing between easterly and westerly flow.

phase. The greatest differences in this feature occur near the equator, where the objective product has substantially greater pseudostress magnitudes. The composite anomalies are much noisier in the subjective FSU winds, particularly off the coast of Chile in La Niña years. The fields for El Niño years are more similar than for La Niña years; however, the objective fields have greater magnitudes south of the equator.

5. Conclusions

The fields produced by this objective technique are superior in quality to previous subjectively derived fields: accuracy is improved, and spurious forcing related to noise in the observational pattern should be greatly reduced. The research dataset consists of 26 yr (1978–2003) of monthly $2° \times 2°$ fields. It will soon be extended as far back in time as is practical. The subjective FSU winds are no longer being produced in favor of this objective product. The large month-to-month and year-to-year variability seen in the subjective product is greatly reduced in this objective product. The larger variability in the subjective product appears to be spurious and due to inconsistencies in the subjective analysis.

The objective winds have a better match to TAO buoy observations (which are included in both analyses) and scatterometer observations (which are independent of both analyses). The objective product has much better zonal resolution than the subjective product, resulting in better estimates of convergence of zonal winds (particularly in the SPCZ). Shortcomings

TABLE 1. Comparison between gridded in situ ship winds and gridded scatterometer wind speeds (FSU minus scatterometer), for various conditions on proximity and observation density. All points in the gridded product are considered for the entire period with scatterometer observations. Nine cases are examined: 1) no observations in the bin and less than 30 observations in neighboring bins, 2) no observations in the bin and at least 30 observations in neighboring bins, 3) no observations in the bin and less than 30 observations within two bins, 4) no observations in the bin and at least 30 observations within two bins, 5) 1–4 observations in the bin, 6) 5–9 observations within the bin, 7) 10–15 observations in the bin, 8) 17–24 observations in the bin, and 9) >24 observations in the bin. No cell had sufficient ship observations for cases 7–9.

Condition	No. of occurrences	FSU2 bias ($m\ s^{-1}$)	FSU1 bias ($m\ s^{-1}$)	FSU2 std dev ($m\ s^{-1}$)	FSU1 std dev ($m\ s^{-1}$)
Case 1	2597	−1.17	−0.93	1.72	2.04
Case 2	309	−1.33	−1.31	1.62	2.01
Case 3	564	−0.85	−0.85	1.78	2.30
Case 4	2342	−1.27	−1.00	1.68	1.97
Case 5	2874	−1.18	−1.00	1.82	2.01
Case 6	21 960	−1.16	−1.16	1.50	2.07

are also evident in comparison to scatterometer observations. Neither version of the FSU winds shows the tight ITCZ seen in scatterometer fields, and both fail to show the observed strong changes in wind speed and direction near coastlines. The otherwise excellent match during the modern period indicates that the quality of the new objective fields is excellent when and where there is sufficient observational density. For the period examined, the accuracy in spatial data voids is similar to the accuracy in well-sampled regions. The data density for the Pacific region appears to be sufficient for at least the period including and after 1978. Comparisons to scatterometer wind fields indicate that the bias in the objective product's wind fields is usually $<0.005\ N\ m^{-2}$ and that standard deviations of difference with the scatterometer winds are more geographically consistent and are typically in the range of 0.005 to $0.015\ N\ m^{-2}$. Furthermore, the wind patterns for ENSO phases are more spatially consistent (less noisy) in the new objective FSU winds than in the old subjective FSU winds.

TABLE 2. Comparison between gridded in situ buoy winds and gridded scatterometer wind speeds, for various conditions on proximity and observation density. Cases and comparison data are the same as in Table 1.

Condition	No. of occurrences	FSU2 bias ($m\ s^{-1}$)	FSU1 bias ($m\ s^{-1}$)	FSU2 rms diff ($m\ s^{-1}$)	FSU1 rms diff ($m\ s^{-1}$)
Case 1	16 269	−1.07	−1.10	1.53	2.08
Case 2	5195	−1.32	−1.13	1.63	2.02
Case 3	11 453	−1.01	−1.10	1.50	2.12
Case 4	10 011	−1.27	−1.12	1.61	2.00
Case 5	0	—	—	—	—
Case 6	0	—	—	—	—
Case 7	0	—	—	—	—
Case 8	209	−1.01	−1.33	1.52	2.03
Case 9	6276	−1.26	−1.16	1.57	2.03

Further modifications to the FSU winds are being developed. We are working on quality-assurance procedures that will allow us to produce $1° \times 1°$ products with better representation of coastal winds. Such a product is nearing completion for the Indian Ocean. We anticipate routinely producing $1° \times 1°$ products in 2005. We also expect to produce equatorial Pacific fields for years prior to 1978. We are also working toward gridded fields for the North Pacific Ocean and the tropical and North Atlantic Oceans. The production of gridded flux products is progressing well, as is the development of fields of uncertainty in all our gridded products.

Acknowledgments. We thank Robert Banks, Jen Braxton, Stacey Campbell, Josh Grant, Yan Gu, David Legler, Wendy Shi, and Jiraporn Whalley for their contributions to the development process. Support for the development of these flux fields and the related science came from NSF, and support for production came from NOAA OGP. Support for the scatterometer research came from the NASA/OSU SeaWinds project and the NASA OVWST project. The Ku-2001 scatterometer data were provided by Frank Wentz and Deborah Smith at Remote Sensing Systems. COAPS receives base funding from NOAA OGP and the Secretary of Navy Grant from ONR to James J. O'Brien.

REFERENCES

Atlas, R., R. N. Hoffman, S. C. Bloom, J. C. Jusem, and J. Ardizzone, 1996: A multiyear global surface wind velocity dataset using SSM/I wind observations. *Bull. Amer. Meteor. Soc.,* **77,** 869–882.

Bentamy, A., N. Grima, and Y. Quilfen, 1998: Validation of the gridded weekly and monthly wind fields calculated from ERS-1 scatterometer wind observations. *Global Atmos. Ocean Syst.,* **6,** 373–396.

Bony, S., Y. Sud, K. M. Lau, J. Susskind, and S. Saha, 1997: Comparison and satellite assessment of NASA/DAO and NCEP–NCAR reanalyses over tropical ocean: Atmospheric hydrology and radiation. *J. Climate,* **10,** 1441–1462.

Bourassa, M. A., M. H. Freilich, D. M. Legler, W. T. Liu, and J. J. O'Brien, 1997: Wind observations from new satellite and research vessels agree. *Eos, Trans. Amer. Geophys. Union,* **78,** 597–602.

——, D. G. Vincent, and W. L. Wood, 1999: A flux parameterization including the effects of capillary waves and sea state. *J. Atmos. Sci.,* **56,** 1123–1139.

——, D. M. Legler, J. J. O'Brien, and S. R. Smith, 2003: SeaWinds validation with research vessels. *J. Geophys. Res.,* **108,** 3039, doi:10.1029/2001JC001081.

Chelton, D. B., and F. J. Wentz, 1986: Further development of an improved altimeter wind speed algorithm. *J. Geophys. Res.,* **91,** 14 250–14 260.

Chin, T. M., R. F. Milliff, and W. G. Large, 1998: Basin-scale, high-wavenumber sea surface wind fields from a multiresolution analysis of scatterometer data. *J. Atmos. Oceanic Technol.,* **15,** 741–763.

Curry, J. A., and Coauthors, 2004: SEAFLUX. *Bull. Amer. Meteor. Soc.,* **85,** 409–424.

da Silva, A., A. C. Young, and S. Levitus, 1994: *Algorithms and Procedures.* Vol. 1, *Atlas of Surface Marine Data 1994,* NOAA Atlas NESDIS 6, 83 pp.

Freilich, M. H., and R. S. Dunbar, 1999: The accuracy of the NSCAT 1 vector winds: Comparisons with National Data Buoy Center buoys. *J. Geophys. Res.,* **104,** 11 231–11 246.

Hanley, D. E., M. A. Bourassa, J. J. O'Brien, S. R. Smith, and E. R. Spade, 2003: A quantitative evaluation of ENSO indices. *J. Climate,* **16,** 1249–1258.

Hellerman, S., and M. Rosenstien, 1983: Normal monthly wind stress over the world ocean with error estimates. *J. Phys. Oceanogr.,* **13,** 1093–1104.

Hilburn, K. A., M. A. Bourassa, and J. J. O'Brien, 2003: Scatterometer-derived research-quality surface pressure fields for the Southern Ocean. *J. Geophys. Res.,* **108,** 3244, doi:10.1029/2003JC001772.

Japan Meteorological Agency, 1991: Climate charts of sea surface temperatures of the western North Pacific and the Global Ocean. Tech. Rep., Marine Department, Japan Meteorological Agency, 51 pp.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kanamitsu, M., W. Ebisuzaki, J. Woollen, S.-K. Yang, J. J. Hnilo, M. Fiorino, and G. L. Potter, 2002: NCEP–DOE AMIP-II Reanalysis (R-2). *Bull. Amer. Meteor. Soc.,* **83,** 1631–1643.

Kelly, K. A., S. Dickinson, and Z.-J. Yu, 1999: NSCAT tropical wind stress maps: Implications for improving ocean modeling. *J. Geophys. Res.,* **104,** 11 291–11 310.

——, ——, M. J. McPhaden, and G. C. Johnson, 2001: Ocean currents evident in satellite wind data. *Geophys. Res. Lett.,* **28,** 2469–2472.

Kutsuwada, K., 1998: Impact of wind/wind-stress field in the North Pacific constructed by ADEOS/NSCAT data. *J. Oceanogr.,* **54,** 443–456.

Legler, D. M., I. M. Navon, and J. J. O'Brien, 1989: Objective analysis of pseudostress over the Indian Ocean using a direct-minimization approach. *Mon. Wea. Rev.,* **117,** 709–720.

——, J. N. Stricherz, and J. J. O'Brien, 1997: *Indian Ocean.* Vol. 3, *TOGA Pseudo-Stress Atlas 1985–1994,* COAPS Rep. 97-3, 175 pp. [Available from COAPS, The Florida State University, Tallahassee, FL 32306.]

Lindau, R., 1995: A new Beaufort equivalent scale. *Proc. Int. COADS Winds Workshop*, Kiel, Germany, Institut für Meereskunde Kiel and NOAA, 232–252.

McPhaden, M. J., and Coauthors, 1998: The Tropical Ocean-Global Atmosphere (TOGA) observing system: A decade of progress. *J. Geophys. Res.,* **103,** 14 169–14 240.

Meyers, S. D., C. S. Jones, D. M. Legler, and J. J. O'Brien, 1994: The sensitivity of parametric variations in direct minimization techniques. *Mon. Wea. Rev.,* **122,** 1632–1639.

NCDC, 2003: Data documentation for Data Set 1129: Marine data. Tech. Doc. TD-1129, 31 pp. [Available from NCDC, 151 Patton Ave., Asheville, NC 28801-5001.]

NCEP, 1997: NCEP real-time marine observations. [Available from Diane Stokes, W/NP24, Room 807, 4700 Silver Hill Road, Washington, DC 20233-9910.]

Pegion, P. J., M. A. Bourassa, D. M. Legler, and J. J. O'Brien, 2000: Objectively derived daily "winds" from satellite scatterometer data. *Mon. Wea. Rev.,* **128,** 3150–3168.

Pierson, W. J., Jr., 1990: Examples of, reasons for and consequences of poor quality of wind data for the marine boundary layer: Implications for remote sensing. *J. Geophys. Res.,* **95,** 13 313–13 340.

Polito, P. S., W. T. Liu, and W. Tang, 1997: Correlation-based interpolation of NSCAT wind data. *Proc. Scatterometer Symp.,* Maui, HI, NASA, 30–32. [Available from Scatterometer Projects Office, Jet Propulsion Lab., Pasadena, CA 91109.]

Putman, W. M., D. M. Legler, and J. J. O'Brien, 2000: Interannual variability of synthesized FSU and NCEP reanalysis pseudostress products over the Pacific Ocean. *J. Climate,* **13,** 3003–3016.

Servain, J., J. N. Stricherz, and D. M. Legler, 1996: *Tropical Atlantic.* Vol. 1, *TOGA Pseudo-Stress Atlas 1985–1994,* Centre ORSTOM, 158 pp.

Siefridt, L., B. Barnier, D. M. Legler, and J. J. O'Brien, 1998: 5-day average winds over the North-West Atlantic from ERS1 using a variational analysis. *Global Atmos. Ocean Syst.,* **5,** 317–344.

Smith, S. R., D. M. Legler, and K. V. Verzone, 2001: Quantifying uncertainties in NCEP reanalyses using high-quality research vessel observations. *J. Climate,* **14,** 4062–4072.

——, J. Servain, D. M. Legler, J. N. Stricherz, M. A. Bourassa, and J. J. O'Brien, 2004: In situ–based pseudo–wind stress products for the tropical oceans. *Bull. Amer. Meteor. Soc.,* **85,** 979–994.

Stricherz, J. N., D. M. Legler, and J. J. O'Brien, 1997: *Tropical Pacific Ocean*. Vol. 2, *TOGA Pseudo-Stress Atlas 1985–1994,* COAPS Rep. 97-2, 177 pp. [Available from COAPS, The Florida State University, Tallahassee, FL 32306.]

Woodruff, S. D., R. J. Slutz, R. L. Jenne, and P. M. Steurer, 1987: A comprehensive ocean–atmosphere data set. *Bull. Amer. Meteor. Soc.,* **68,** 1239–1250.