4.9 **ASSIMILATION OF SCATTEROMETER AND IN SITU WINDS FOR REGULARLY GRIDDED PRODUCTS**

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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; daSilva 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) reanalysis (Kalnay et al. 1996). The advantages of the GCM fields are greater temporal resolution than 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). For applications that require accurate surface fluxes and/or winds, and don't require better than monthly temporal resolution, the in-situ products are preferred.

An objective technique is used to create a new monthly climatology for surface fluxes and related fields. The wind (pseudostress) products are improvements over our previous product: the subjectively analyzed FSU winds. Fields of turbulent surfaces 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 grid scatterometer vector wind observations obtained a polar-orbiting satellite (Pegion et al. 2000). The problems related to gridding daily ship data are analogous to those of gridding daily scatterometer observations. In both cases, there are large gaps in the observational coverage and observational errors and uncertainty should be considered. Furthermore, observational 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 these 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 gridding technique developed for scatterometer observations (Pegion et al. 2000) deals with these problems more effectively the previous techniques.

Our previous objective technique (Pegion et al. 2000) considered observations from only one type of platform. The new objective technique treats various types of data sources (volunteer observing ships, buoys, and scatterometers) as independent. Two products are produced: one based solely on in-situ observations, and another that also includes scatterometer observations. Comparisons are made between the new FSU fields (based on volunteer observing ships and buoy observations), the old subjective FSU fields, individual TAO buoys, the NCEP reanalysis, and fields based solely on the SeaWinds scatterometer observations.

2. DATA

The new objective method produces fields of stress, latent heat flux, sensible heat flux, pseudostress (the product of the scalar and vector wind), scalar wind speed, air temperature and atmospheric specific humidity. Winds, atmospheric temperature, and humidity correspond to a height of 10m. Calculation of the fluxes also requires sea surface temperature (SST)

The in-situ observations used in creating the new fields are from two sources. Fields for 1997 and earlier are developed from the Comprehensive Ocean-Atmosphere Data Set (COADS; Woodruff et al. 1987). In-situ data sets for post-COADS times are created from the National Climatic Data Center (NCDC) TD-1129 Marine Surface Observations (NCDC 1998). Quick-look products are created from the NCEP Real-time Marine

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Observations (NCEP 1997). Research quality products are produced when the TD-1129 becomes available in the summer of the following year.

In-situ data sets are plagued with seemingly large errors associated with incorrect records of the ships location. There are also errors related to instrument malfunctions or misuse. We remove the worst of these problems 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 daSilva climatology. Due to the daSilva 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.

A tool has been developed to display the monthly mean gridded observations for visual inspection. An analyst edits the in-situ fields to remove erroneous or non-representative data that were not removed by the comparison to climatology. These checks result in much more accurate data for our objective method. This approach is necessary for in-situ data, and greatly reduces the need for smoothing.

The satellite winds come from the NASA Scatterometer (NSCAT) and the SeaWinds scatterometer on QuikSCAT. Data from the European Remote Sensing System Satellites (ERS-1/2) would be useful for times when NSCAT and SeaWinds data were not available. We anticipate making use of this data set in the future. Scatterometer winds contain speed and direction, whereas other satellite instruments (e.g., SSMI and altimeters) determine only wind speed. It is likely that this information could be used to improve the scalar surface turbulent fluxes (sensible and latent heat fluxes), which depend on the scalar wind speed; however for monthly fields these observations will have little impact on stresses and pseudostresses.

2.1 *Pseudostress*

Although in-situ and satellite observations are recorded as winds, gridded fields of pseudo-stresses are produced because the product is intended for ocean modeling. 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:

$$\tau_x = \rho\, C_D\, P_x \text{ and } \tau_y = \rho\, C_D\, P_y\,, \qquad (1)$$

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

$$P_x = u\,w \text{ and } P_y = v\,w, \qquad (2)$$

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

3. METHODOLOGY

Weights are applied to each constraint in the cost function. 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 relative to 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 ratio of the weight for misfit to observations to the weights on the other constraints.

3.1 *Background fields*

When scatterometer data are not available, the background fields are monthly 12° moving averages. There are areas where a 12° area has an insufficient number of observations. In these cases, the area of the averaging is increased until there is a sufficient number (200). These background fields have been tested with in-situ data from 2000. This approach has been found to be more effective than using a long-term mean of monthly winds (e.g., the daSilva climatology). This approach reduces random errors (Pierson 1990) through averaging, and removes large biases that would occur in El-Niño or La-Niña years.

When scatterometer data are available, the background is calculated as an average of the daily NSCAT fields (Pegion et al. 2000) or six hourly SeaWinds fields. These scatterometer fields are publicly available through the COAPS website (http://coaps.fsu.edu/). This approach greatly reduces any signature of the observational pattern in the background field.

Scatterometer winds are surface-relative, whereas in-situ observations are closer to earth-relative winds. These differences can be important in areas of strong winds. For calculations of turbulent surface fluxes, the surface-relative winds are idea. Therefore, the in situ observations are modified by surface currents obtained through a combination of altimetry and scatterometry (Lagerloef et al. 1999). Earth-relative winds can easily be recovered by adding these currents to the surface-relative winds.

3.2 *The Variational Method*

The variational method utilizes several constraints to maximize similarity to observations, minimize non-geophysical 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

$$f = \sum_{i,j}^{I,J} \Big\{ \beta_a \sigma_{P_{o1}}^{-2} \left[\left(P_x - P_{x_{o1}}\right)^2 - \left(P_y - P_{y_{o1}}\right)^2 \right] +$$
$$\beta_b \;\; \sigma_{P_{o2}}^{-2} \left[\left(P_x - P_{x2}\right)^2 - \left(P_y - P_{y2}\right)^2 \right] +$$
$$\beta_c \;\; \sigma_{P_{o3}}^{-2} \left[\left(P_x - P_{x3}\right)^2 - \left(P_y - P_{y3}\right)^2 \right] +$$
$$\beta_d \, L^4 \left\{ \left[\nabla^2 \left(P_x - P_{x_{bg}}\right)^2 \right] + \left[\nabla^2 \left(P_y - P_{y_{bg}}\right)^2 \right] \right\} +$$
$$\beta_e \, L^2 \left[\hat{k} \bullet \nabla \times \left(\vec{P} - \vec{P}_{bg}\right)^2 \right] \qquad (3)$$

where the betas are weights, the i,j subscripts for geographical position have been dropped, the unsubscripted pseudostress (P_x,P_y) is the solution field, the 'o' subscript indicates observations ('o1' for ships, 'o2' for buoys, and 'o3' for the scatterometer), the subscript 'bg' indicate the background field, σ is an uncertainty (considering sampling error, observational uncertainty, and representiveness), and L is a length scale that makes the terms dimensionally consistent. The scalar terms in the functional have a similar form, except that there is no misfit to the background curl, and the scalar wind speed is the only term with scatterometer observations.

The solution fields for fluxes are determined from a bulk flux algorithm (Bourassa et al. 1999). Without the flux terms, the weights related to one variable could be determined independently from the weights for other variables. The flux terms link together the other terms, which improves the accuracy of relatively sparsely observed fields, at the expense of the better sampled fields.

This approach also allows the weights for each type of observation to be determined independently. These weights combine the considerations of uncertainty and coverage. These considerations differ for each type of platform; therefore, the weights are not expected to be equal. For example, in the equatorial Pacific, with hourly observations from the TAO/TRITON buoy array, the weight for buoy winds is 350 times greater than the weight for VOS winds.

4. RESULTS

The new objective FSU winds are compared to buoy winds, the subjective FSU winds, and gridded scatterometer winds (Fig.1) for one TAO buoy at 2°N 110°W. In this example, scatterometer data are not used, and the weight of buoy data is 50 times the weight of ship data (β_b/β_a=50). In March, the new winds differ from the subjective FSU winds and buoy winds due to removal of suspect buoy observations. Otherwise, the objective winds track the buoy better than the subjective winds. There are no buoy observations from September, during which time the objective winds are a close match to the subjective winds.

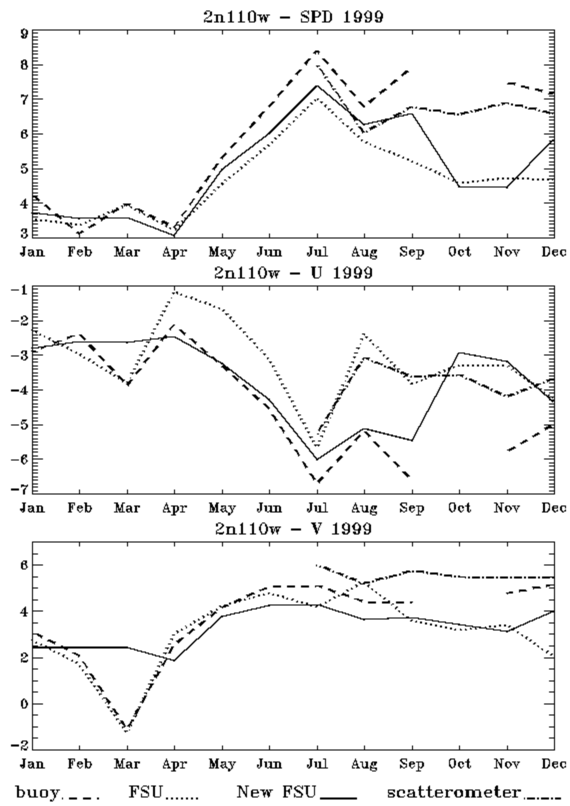

Fig. 1. Comparison of the new objective FSU winds to TAO buoy winds (2N 110W), the subjective FSU winds, and gridded scatterometer winds. The panels show the wind speed (ms-1), zonal wind component, and meridional wind component.

4.1 COMPARISON OF GRIDDED FIELDS

The magnitude and general characteristics of the two sets of wind fields are similar; however, there are persistent substantial differences between the objective and subjective FSU winds (Fig. 2). The South Pacific Convergence Zone (SPCZ) and Inter-Tropical Convergence Zone (ITCZ) both have much stronger convergence in the new objective fields. These differences could explain shortcomings of the old FSU winds in forcing surface and subsurface SST anomalies. It has been speculated that the strength of the ITCZ and SPCZ influences the magnitude of currents and hence temperature advection. Preliminary tests with a beta-release of the objective winds indicate much stronger and more accurate currents are produced when an ocean is forced with the new FSU winds.

5. CONCLUSIONS

The fields produced by this technique should be of superior quality to previous fields: accuracy should be improved, and spurious forcing related to the observational pattern should be greatly reduced. A 30 year time series of equatorial (±30°) Pacific winds has been processed and released. Flux fields for this product are anticipated during winter of 2001/2002. In January of 2002, production of the old subjective FSU winds will cease, and that product be replaced with this objective technique. We will process these wind and fluxes as far back in time as the data set allows.

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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. Metoer. Soc*., **77**, 869-882.

Bentamy, A., B., H. 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.

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

Chelton, D. B., and F. J. Wentz, 1986: Further development of an improved altimeter wind speed algorithm, *J. Geophys. Res.,* **91**, 14250-14260.

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.

daSilva, A., A. C.Young, and S. Levitus, 1994: Atlas of surface marine data 1994, volume 1: Algorithms and procedures. Tech. Rep. 6, U.S. Department of Commerce, NOAA, NESDIS.

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

Kalnay, E., M. and others, 1996: The NCEP/NCAR 40-year reanalysis project, *Bull. Amer. Meteor. Soc.,* **77**, 437-77,471.

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.

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

Lagerloerf, G. S. E., G. Mitchum, R. Lukas and P. Niiler, 1999: Tropical Pacific near-surface currents estimated from altimeter, wind, and difter data, *J. Geophys. Res*., **104**, 23,313-23,326.

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.

Legler, D. M., J. N. Stricherz, and J. J. O'Brien, 1997: TOGA pseudostress atlas 1985-1994: III Indian Ocean, *COAPS Rep.* 97-3, 175 p. [Available from COAPS, The Florida State University, Tallahassee, FL 32306].

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, 1998: Data Documentation for Data Set TD-1129. Available from: NCDC, 151 Patton Ave., Asheville, NC, 28801-5001, USA, 33pp.

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.

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

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**, 13313-13340.

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*, in press.

Servain, J., J. N. Stricherz, and D. M. Legler, 1996: TOGA pseudo-stress atlas 1985-1994. vol. I: Tropical Atlantic. *Centre ORSTOM*, Plouzané, France, 158 pp.

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

Stricherz, J. N., D. M. Legler, and J. J. O'Brien, 1997: TOGA pseudo-Stress atlas 1985-1994: II Tropical Pacific Ocean. *COAPS Rep. 97-2*, 177 p. [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.

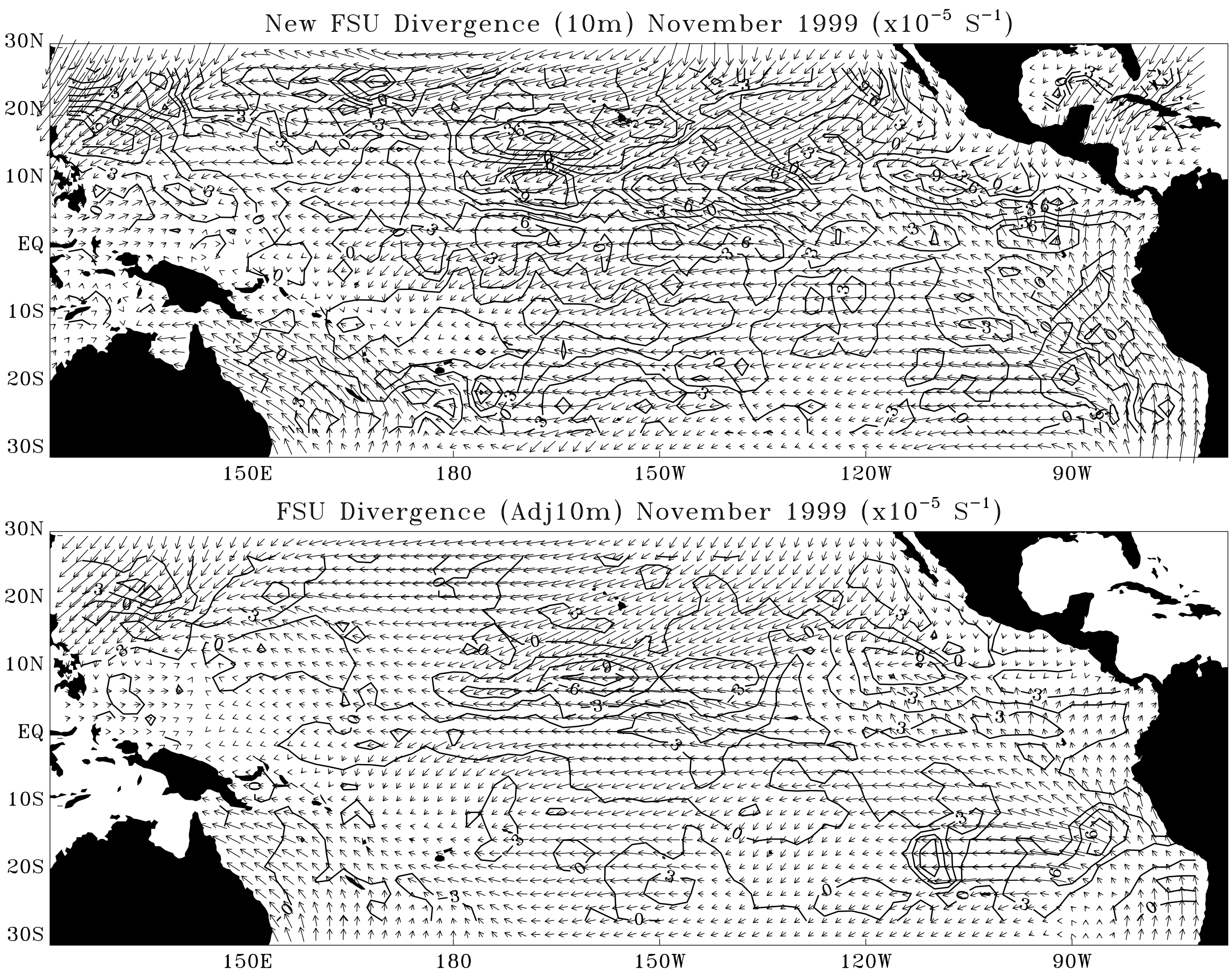

Fig. 2. Objective (top) and subjective (old) FSU pseudostress and divergence for November 1999. Note the stronger convergence zones (ITCZ and SPCZ) in the new product.