

# IN SITU-BASED PSEUDO-WIND STRESS PRODUCTS FOR THE TROPICAL OCEANS

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These widely used products, derived from surface-based observations, are an excellent resource for ENSO forecasting and ocean-atmosphere research.

**M**any studies of oceanography and ocean-atmosphere interaction require high-quality wind-forcing fields. In the mid-1970s, The Florida State University (FSU) developed subjective analyses of the monthly mean winds over the tropical Pacific using in situ ship and buoy observations. The product became known as the “FSU winds.” Methods for producing tropical ocean wind fields have evolved into modern objective analyses. A historical retrospective of FSU-style wind analyses for three tropical ocean basins (Pacific, Indian, and Atlantic) is presented along with a brief introduction

to current techniques. The development of each product is described, and examples of the scientific application of these in situ-based wind fields are provided.

Upper-ocean circulation is primarily driven by the wind stress and the curl of the wind stress; however, direct measurements of the wind stress are very difficult to obtain (Bourassa et al. 1999; Curry et al. 2004). Wind stress calculations require one to determine a representative drag coefficient, the choice of which is often contentious (Bourassa et al. 1999); therefore, the FSU-style “wind” products described herein provide fields of pseudostress. Pseudostress is defined as the wind components multiplied by the wind magnitude and is proportional to surface stress. Wind stress can be obtained by multiplying the pseudostress components by an air density and a drag coefficient. Using pseudostress removes some nonlinearities involved in averaging stress: those related directly to averaging wind vectors. However, it does not deal with variability in the drag coefficient related to atmospheric stratification, wind speed, and wave dependence in the drag coefficient (Bourassa 2004). These biases and random errors are probably less than 10% for a monthly average provided that a reasonable wind speed dependency is applied. In the early days of the FSU winds, ocean models had relatively coarse resolution and

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therefore required unrealistically large frictional dissipation. Consequently, wind forcing (via the drag coefficient) was increased to result in physically reasonable magnitudes for major ocean currents. By not specifying a drag coefficient in the FSU-type pseudostress products, each user can choose a coefficient that best suits their model and application.

The monthly FSU pseudostress fields for the tropical Pacific (30°N–30°S, 120°E–70°W) originated as a research dataset for testing hypotheses related to the formation of El Niño events (e.g., Busalacchi and O'Brien 1981; Inoue and O'Brien 1984, 1986). The strong 1982/83 El Niño focused the scientific community on the importance of interannual variations in the earth's climate and raised the need for pseudostress fields to be produced on an operational basis. Operational FSU pseudostress products include "quick look" fields produced each month using the previous month's ship and buoy data and a "research" product that is created for the previous year using an enhanced dataset that includes delayed ship and buoy reports. The quick-look Pacific FSU pseudostress fields are widely used to force ENSO forecast models. Interest in air–sea interaction has expanded to other ocean basins; therefore, FSU also produces quick-look and research fields for the tropical Indian Ocean (25°N–30°S, 30°–120°E) and distributes tropical Atlantic Ocean (30°N–20°S, 60°W–15°E) fields produced by J. Servain at the French Institut de Recherche pour le Développement [IRD; formerly Institut Français de Recherche Scientifique pour le Développement en Coopération (ORSTOM)].

The FSU Pacific and Indian Ocean and the IRD Atlantic Ocean pseudostress fields are all based solely on in situ ship and buoy data; however, the analysis methods differ and are continually evolving. In 2001, the methodology for the FSU Pacific analyses was switched from a subjective process to an objective process (Bourassa et al. 2004, manuscript submitted to *J. Climate*, hereafter BOSR). The new objective process is briefly described; however, this paper focuses on the history of older pseudostress products and provides a context to how the products evolved into the fields being produced today. Each product was motivated by scientific problems, and the scientific need for in situ–based pseudostress fields continues to the present day.

The article begins with an overview of modern-day wind stress products (see section titled "Modern-day wind stress"). The overview sets the stage for a historical discussion of the FSU Pacific and Indian Ocean winds and the IRD Atlantic Ocean winds (see section titled "Historical perspective"). The section titled

"Analysis methodology" provides brief descriptions of the analysis methodology for each historical product and the new objective Pacific FSU winds. Timelines for the historical and current products are also provided. "Subjective versus objective FSU Pacific products" provides a brief comparison of the subjective and objective FSU Pacific wind products. Several past and present applications of the FSU and IRD pseudostress products are introduced in "Application of in situ products." Product availability is provided in "Conclusions."

**MODERN-DAY WIND STRESS.** The ability to measure winds over the sea surface and estimate the near-surface wind stress has evolved greatly since the inception of the FSU-type pseudostress products. Satellites, high-speed computers, and detailed physical models currently allow estimation of the wind stress in ways not even conceived in the 1970s. Modern wind and wind stress products vary in spatial and temporal coverage; thus, individual products are not suitable for all research applications. Satellite products take advantage of high spatial coverage but are limited by short time series. In situ–based products have the advantage of long time series but are limited by poor spatial distribution of their input data.

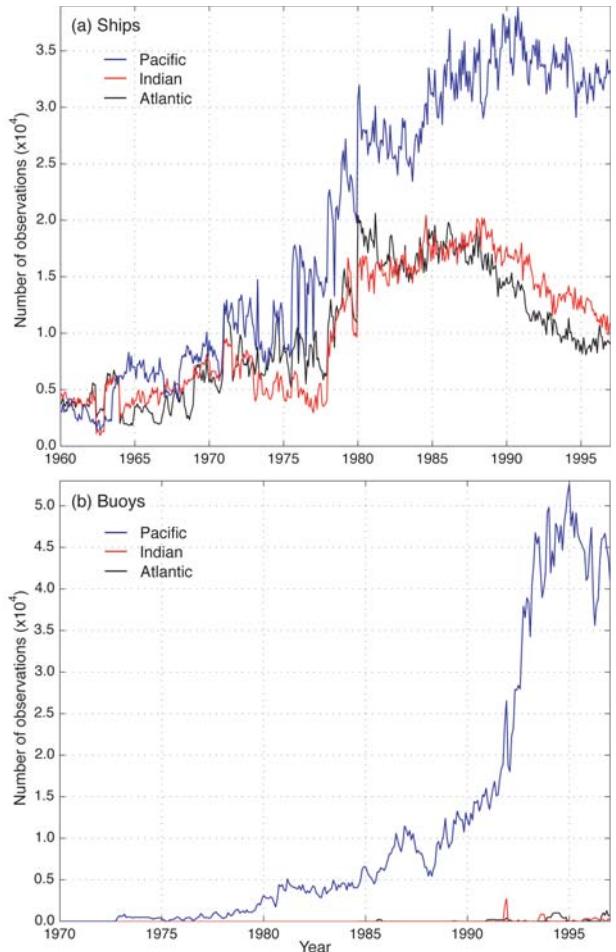
Satellites provide a platform to indirectly measure surface vector winds (BOSR) and stress (Weissman and Graber 1999; Verschell et al. 1999) with scatterometers [e.g., National Aeronautics and Space Administration (NASA) Scatterometer (NSCAT), Sea Winds]. The individual swaths of data collected by scatterometers can be objectively gridded to produce global (over water) fields of wind, pseudostress, or stress at time intervals as short as 1 day (Pegion et al. 2000). Recent scatterometers provide 90% spatial coverage of the world's oceans every day. Alternative approaches blend directions from numerical weather analyses with scalar winds from satellites (Atlas et al. 1996; Chin et al. 1998; Grassl et al. 2000; Sun et al. 2002). The improvements in spatial coverage and the ability to create fields on time scales much shorter than monthly allow scatterometer-derived fields to resolve features (e.g., tropical cyclones, fronts) not well-represented by in situ products. These instruments have existed for a little over a decade (with considerably poorer coverage in the first half of the decade), limiting their application to interannual or interdecadal climate studies.

Longer temporal coverage (up to 50 yr) can be obtained from wind stress fields derived by global numerical assimilation systems. In particular, the re-analysis products produced by the European Centre

for Medium-Range Weather Forecasts (ECMWF; Josey et al. 2002) and the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR; Kalnay et al. 1996; Kanamitsu et al. 2002) can provide monthly, daily, or even 6-hourly wind stress fields for the global oceans. Reanalysis surface wind stress fields are produced by a fixed data assimilation system that ingests surface marine (however, a large fraction are rejected), upper-air, and often satellite observations (for years when they are available) and includes a surface flux parameterization scheme. Comparisons (e.g., Smith et al. 2001; Putman et al. 2000; Josey et al. 2002) have noted some reanalysis (primarily the first NCEP–NCAR reanalysis) wind fields to be weaker than in situ observations over many parts of the global oceans. Furthermore, the accuracy of synoptic-scale variability has been demonstrated to be extremely poor in data-sparse regions (Hilburn et al. 2003).

In situ ship and buoy observations continue to provide a valuable resource for producing near-surface wind stress fields. Limitations on in situ-derived wind stress products are related to the availability of ship and buoy observations in space and time. Temporally, the number of ship observations increased substantially from 1960 through the late 1980s in the tropical Pacific, Indian, and Atlantic Oceans, with a steady decline in numbers occurring in subsequent years (Fig. 1a). The number of buoy measurements has also increased rapidly since 1980 in the Pacific Ocean (Fig. 1b). Large spatial gaps in shipboard data coverage exist on average in the central and southeastern tropical Pacific (Fig. 2a). The gaps in shipboard coverage are largely offset between 10°N and 10°S by the Tropical Atmosphere Ocean (TAO)/Triangle Trans-Ocean Buoy Network (TRITON) buoy array (Fig. 2b; McPhaden et al. 1998); however, data from the southeastern tropical Pacific remains sparse. The tropical Atlantic (Fig. 3a) and Indian (Fig. 3b) Oceans have more spatially uniform coverage by ships, although data are lacking in the central Indian Ocean south of 10°S. Until recently, buoy observations were mostly nonexistent in the tropical Indian and Atlantic basins. The recent installation of the Pilot Research Moored Array in the Tropical Atlantic (PIRATA; Servain et al. 1998) will increase buoy observations in the tropical Atlantic.

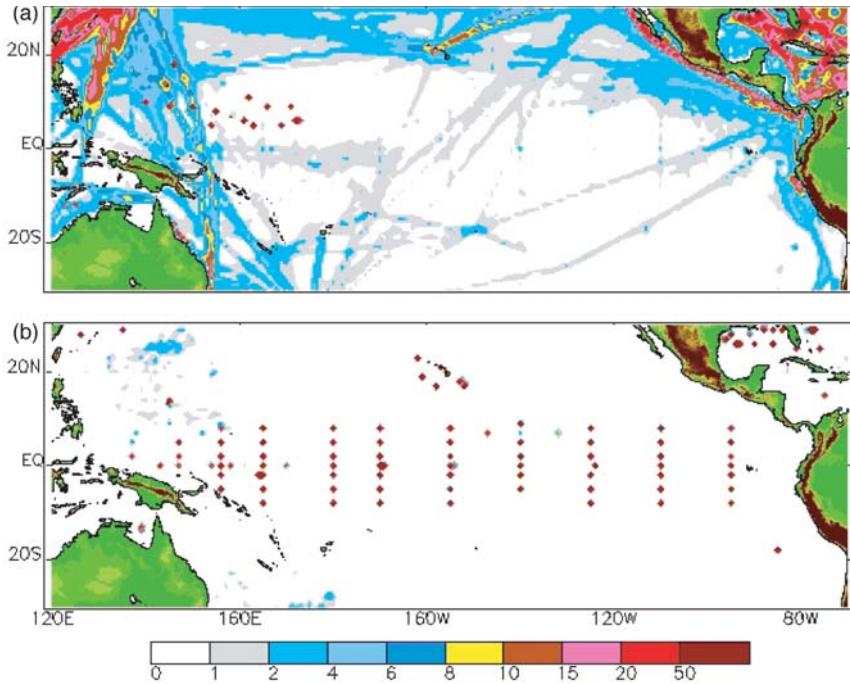
As we move into a new era of observing winds and deriving wind stress over the global oceans, it is important to document past achievements. The historical pseudostress products provide a valuable resource for operational and research applications, and a need for continuous, consistent, high-quality wind stress



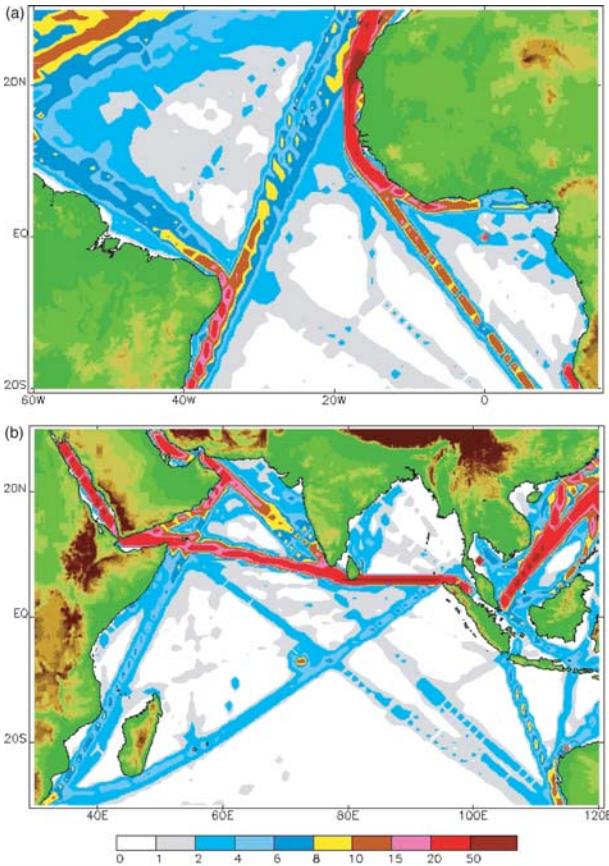
**FIG. 1.** Total number of (a) ship and (b) buoy pseudostress values available each month in the tropical Pacific (blue), Indian (red), and Atlantic (black) Oceans. The counts are from COADS (Woodruff et al. 1987) and represent an upper bound on data availability.

products has been expressed by the scientific community (e.g., Taylor 2000). One strength of the in situ products is their ability to place satellite wind stress products in the correct historical context. In time, when sufficient satellite data are available, it may be possible to reconstruct historical wind stress fields by combining the long temporal record of in situ products with the improved spatial coverage of satellite products (e.g., Shriver and O'Brien 1995; Meyers et al. 1999).

**HISTORICAL PERSPECTIVE.** The history of in situ tropical pseudostress fields at FSU began in the mid-1970s when FSU was focusing on producing subjective wind fields for the tropical Pacific to drive early ocean models. In the 1980s, FSU began collaborating with IRD, which produces the Atlantic Ocean pseudostress products, and started production of an in situ product for the tropical Indian Ocean. In 2001,



**FIG. 2.** Mean number of (a) ship and (b) buoy pseudostress values per month for the tropical Pacific Ocean. Averages based on COADS data for the period Jan 1988 through Dec 1997. Means were calculated in  $1^\circ$  bins, then were contoured with magnitudes shown in the color bar.



**FIG. 3.** Mean number of ship pseudostress values per month for the tropical (a) Atlantic and (b) Indian Oceans. Averages based on COADS data for the period Jan 1988 through Dec 1997. Means were calculated in  $1^\circ$  bins, then were contoured with magnitudes shown in the color bar.

an objective method was implemented for the FSU Pacific winds. The Pacific, Indian, and Atlantic Ocean pseudostress each have an interesting history driven by scientific problems specific to each ocean basin.

*Pacific Ocean.* In the mid-1970s, several researchers suggested that equatorial oceanic Kelvin waves were responsible for initiating El Niño events (e.g., Wyrtki 1975; Hurlburt et al. 1976; McCreary 1976). Since oceanographers had no way to observe Kelvin waves at the time, forcing fields were developed in an attempt to model this phenomena. Researchers at FSU began producing suitable forcing fields by subjectively analyzing monthly tropical

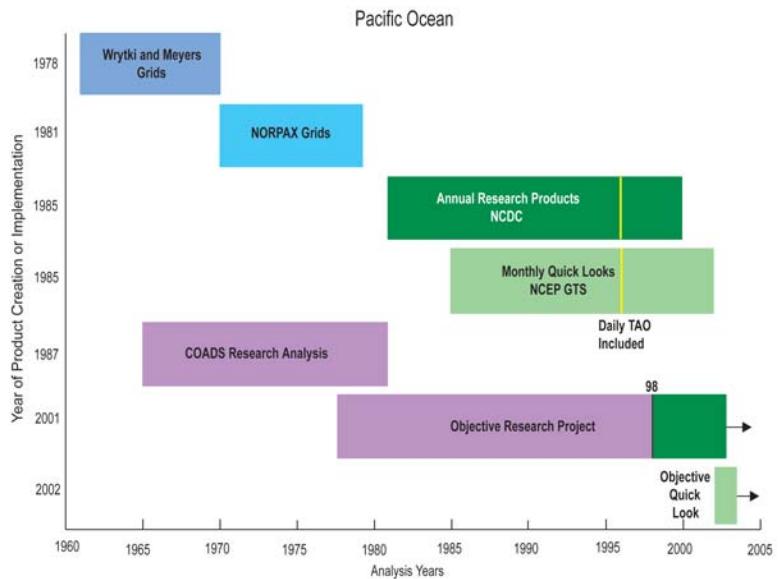
Pacific ship wind data, developed by Wyrtki and Meyers (1975a,b), onto a  $2^\circ \times 2^\circ$  grid for 1961–70 (O’Brien and Goldenberg 1982). These subjective analyses were used to force simulations of El Niño events, and the model simulations successfully showed the role of Kelvin waves in the development of the 1963, 1965, and 1968 El Niño events (Busalacchi and O’Brien 1981). The subjective analyses for 1961–70 became the prototype for all future subjective analyses completed for the tropical Pacific by FSU (Fig. 4).

The second set of FSU pseudostress fields was produced using Pacific Ocean wind data for the 1970s collected by the Scripps Institution of Oceanography during the North Pacific Experiment (Fig. 4). S. Pazan provided FSU with the data binned on the  $2^\circ \times 10^\circ$  grid previously used by Wyrtki and Meyers (1975a,b). The data were subjectively analyzed, and an atlas of the resulting pseudostress fields was published (Legler and O’Brien 1985). Prior to the release

of the atlas, these fields were used to drive an FSU Pacific Ocean model that simulated the occurrence, timing, and relative amplitude of the 1972 and 1976 El Niño events (Busalacchi et al. 1983).

The original FSU pseudostress products for the 1960s and 1970s were produced to conduct research on El Niño events that had already occurred; however, the strong El Niño event of 1982/83 focused research attention on the need to predict future El Niño events. As part of early prediction efforts, the United States Tropical Ocean Global Atmosphere (TOGA) Project Office funded FSU to prepare quick-look pseudostress fields on a monthly basis and to run an experimental El Niño forecast model (Inoue and O'Brien 1984, 1986). Quick-look fields were initiated around 1985 and based on monthly summary data collected from the Global Telecommunication System (GTS) by the National Centers for Environmental Prediction (NCEP 1997; Fig. 4). Pseudostress fields for 1981–85 were needed to run the model; therefore, individual marine reports from the National Climatic Data Center (NCDC) were obtained and analyzed. NCDC TD-1129 data (NCDC 1998) were obtained for subsequent years to produce the research product through 1999 (Fig. 4).

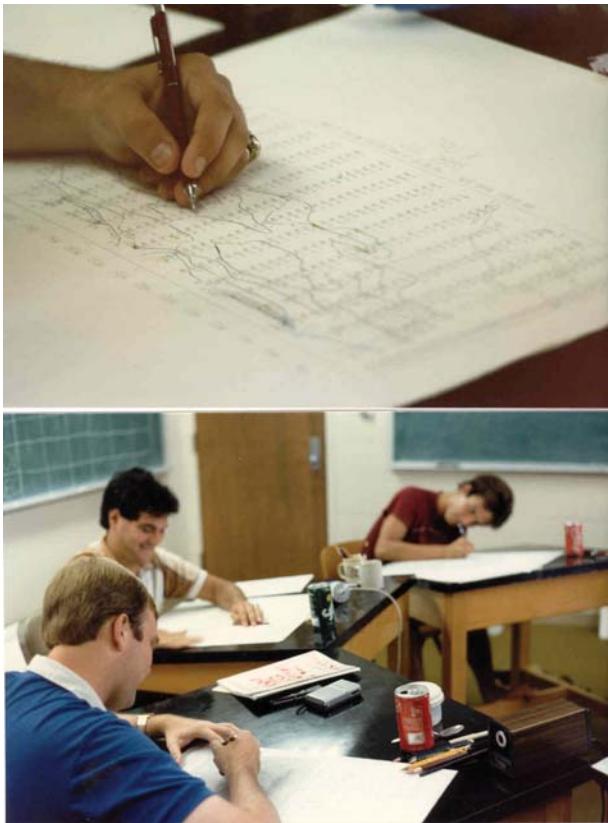
The initiation of quick-look fields and El Niño forecast model runs revealed a need for a homogeneous research-quality product. In the mid-1980s, a research pseudostress product for 1965–80 was produced using the Comprehensive Ocean–Atmosphere Data Set (COADS; Woodruff et al. 1987; Fig. 4). COADS was chosen because it provided the most complete international set of individual ship and buoy observations available at the time. COADS data include many ship and buoy reports never transmitted via GTS, and all COADS data are subject to data quality control. Subjective monthly analysis of 15 yr of COADS data was quite an undertaking. The project was best described as a “synoptic lab full of meteorology students drawing and high school students digitizing maps” (D. Legler 2001, personal communication; Fig. 5). The result at the time was a two-decade (1965–85) record of the Pacific pseudostress based on COADS and NCDC input data (Stricherz et al. 1992).



**FIG. 4. Timeline for FSU Pacific Ocean pseudostress products. The approximate creation year and time range covered by each monthly product are on the ordinate and abscissa, respectively. A yellow line marks when the subjective analyses began using daily average TAO values. Bar colors differentiate the data sources used for each product. Note that the base data for the objective research product changed from COADS to NCDC at the start of 1998.**

From 1985 through 1999, both the monthly quick-look and research-quality tropical Pacific products (e.g., Stricherz et al. 1997) were subjectively analyzed using GTS ship and buoy observations from NCEP (quick look) and NCDC (research product). In the mid-1980s observations from the TOGA–TAO moored buoy array (McPhaden et al. 1998) were incorporated into both the quick-look and research FSU winds. At first, hourly TAO values were ingested directly from the GTS data provided by NCEP or NCDC. In 1996, these TAO data were replaced with daily averages obtained from the Pacific Marine Environmental Laboratory (PMEL) archive. FSU obtained daily averages in near-real time for the quick-look fields and downloaded updated TAO averages for the research products. The 1996 substitution was done to remove a temporal sampling bias in the GTS data caused by irregular satellite passes over the TAO array. All daily average TAO buoy data were also height adjusted to the FSU pseudostress field height of 20 m (not done prior to 1996) using a bulk flux model (Bourassa et al. 1999). Aside from these changes involving the TAO data, the subjective analysis technique remained fairly constant from 1985 to 1999.

The complete subjective FSU research product currently distributed for the Pacific covers 39 yr:



**FIG. 5. (bottom) Students working hard on 1965–80 subjective analyses for the Pacific Ocean (circa 1985). (top) A close-up of the old-fashioned process.**

1961–99. This final subjective product is based on data from Wyrтки and Meyers (1961–64), COADS (1965–80), and NCDC (1981–99). The era of subjective analysis for the Pacific FSU winds ended in March 2002. The new objective technique [see subsection titled “Objective Pacific Ocean” (BOSR)] was implemented operationally beginning with the 2000 research product and the 2002 quick-look fields (Fig. 4).

*Atlantic Ocean.* The history of the Atlantic wind product started in the early 1980s with the joint French–American oceanic experiment Français Océan Climat Atlantique Equatorial (FOCAL)–Seasonal Response of the Equatorial Atlantic (SEQUAL). FOCAL-SEQUAL operated in the tropical Atlantic in 1982–84 with several numerical experiments and more than 12 oceanic cruises. The study of the seasonal variability of the coupled ocean–atmosphere system in the tropical Atlantic basin was one of the main objectives of the experiment.

FOCAL-SEQUAL provided a unique dataset that stimulated interest to study the climatic background of the tropical Atlantic at seasonal and interannual

time scales. A monthly climatic reference based on available historical data was needed. For two variables, sea surface temperature (SST) and vector wind at the sea surface, the only long-term historical data source was provided by the observation network of merchant ships. In the early 1980s, the only SST and wind monthly product based on merchant ship observations was the Hastenrath and Lamb (1977) climatic atlas. Although their atlas provided interannual monthly time series (1911–72) on a 5° latitude × 5° longitude grid, such a course grid was not adequate for a systematic study of most problems for the equatorial Atlantic.

The limitations of Hastenrath and Lamb (1977) prompted what is now the IRD to develop a new SST and wind product. The Atlantic product was originally produced from individual merchant ship observations (TDF-11 world dataset) and later using marine data provided by NCDC (Fig. 6). Blending both objective and subjective methods, the IRD first produced an SST and pseudostress monthly atlas (means and anomalies) for the years 1964–79 (Picaut et al. 1985). The fields were produced on a 2° latitude × 2° longitude grid from 30°N to 20°S and from 60°W to the African coast. The time (beginning in 1964) and space (latitudes north of 20°S) restrictions were due to limitations in the data availability before 1964 and poor data density in the Southern Hemisphere. A series of studies of the SST and wind variability on seasonal and interannual time scales using the 1964–79 database have been published (e.g., Picaut et al. 1984; Servain et al. 1985; Servain and Legler 1986). The studies demonstrated that the interannual variability of the air–sea coupled system in the tropical Atlantic was not negligible, as was commonly believed before the 1960s.

The SST and pseudostress processing underwent many improvements in the years following the first atlas publication (Picaut et al. 1985). The subjective method was partially automated and made more objective (Servain et al. 1987). The system changed from processing many years of data acquired at different times, as was the case for the early processing of the 1964–79 data (Picaut et al. 1985) and the 1980–84 data (Servain et al. 1987), to a monthly processing similar to the FSU quick-look fields. During an intermediate 2-yr period, 1985 and 1986, the data were processed annually with a 6-month delay from the NCDC (Fig. 6). In 1987 (Fig. 6), routine production of quick-look monthly SST and pseudostress fields began for the tropical Atlantic (Servain 1990). Monthly quick looks were made possible through a collaborative effort with FSU whereby the raw GTS

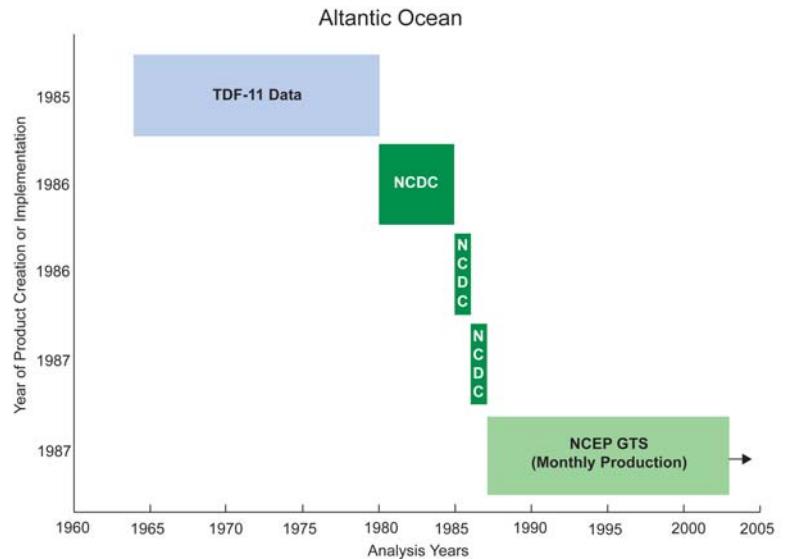
data for the Atlantic basin were obtained from NCEP, examined for statistical outliers, and finally provided to IRD. The ongoing procedure for quick-look Atlantic Ocean pseudostress has remained essentially the same since 1987.

**Indian Ocean.** The need for a monthly Indian Ocean wind product comparable to the Pacific FSU winds became evident in the mid-1980s through several scientific initiatives. Hypotheses were proposed that linked the Indian Ocean/Indonesian region to the Pacific warm pool and ENSO variability (e.g., Barnett 1984). At the same time, models designed to simulate seasonal circulations of the Indian Ocean (e.g., Luther and O'Brien 1985) were typically forced using climatological wind fields. The mid-1980s was also the period of scientific planning for the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS) that focused on the physical and biological aspects of the Indian Ocean. These programs required higher-resolution and routinely available surface stress and wind speed fields to explore the circulation and coastal upwelling characteristics of the Indian Ocean (e.g., McCreary et al. 1993). To meet the growing need for new Indian Ocean wind products, FSU developed a monthly research pseudostress product for the period 1976–88 (Fig. 7). The FSU Indian Ocean product was later extended for the TOGA project (Legler et al. 1997).

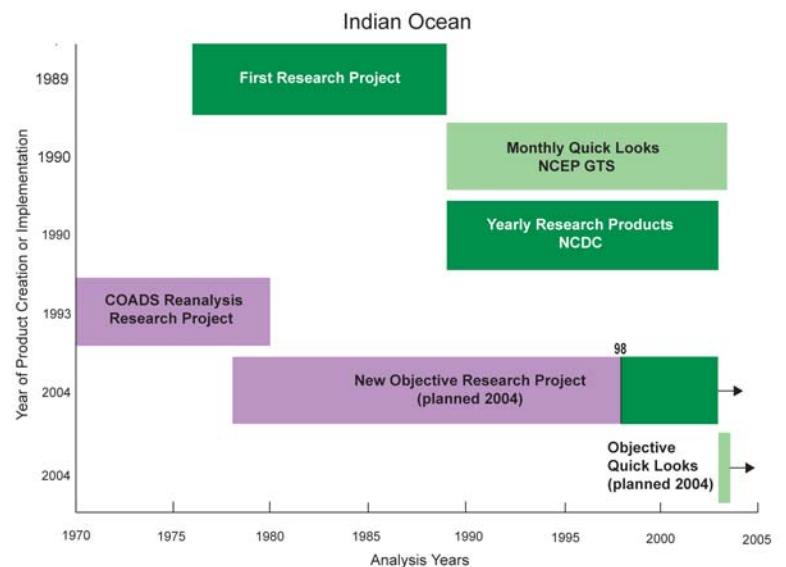
The observational coverage of surface winds over the Indian Ocean (Fig. 3b) was more uniform than that of the tropical Pacific (Fig. 2), more easily allowing an objective approach to be applied. The advent of efficient numerical algorithms suitable for large-scale variational problems allowed the objective mapping of wind observations to be accomplished using multivariate direct minimization. This approach (Legler et al. 1989) minimized a set of constraints expressed as misfits

between the solution and input data. Follow-on studies made the selection of tuning parameters more objective (e.g., Meyers et al. 1994) and increased the robustness of the approach to consider a full suite of meteorological variables and resulting turbulent air-sea fluxes (e.g., Jones et al. 1995).

Monthly mean quick-look and research pseudostress fields for the Indian Ocean have been



**FIG. 6.** Timeline for IRD Atlantic Ocean pseudostress products. The approximate creation year and time range covered by each monthly product are on the ordinate and abscissa, respectively. Bar colors differentiate the data sources used for each product.



**FIG. 7.** Timeline for FSU Indian Ocean pseudostress products. The approximate creation year and time range covered by each monthly product are on the ordinate and abscissa, respectively. Bar colors differentiate the data sources used for each product.

produced on the same operational schedule as the Pacific winds since 1990. In 1993 (Fig. 7), the time series of research data was extended back to 1970 using COADS data (1970–79; Stricherz et al. 1993). Plans are underway to replace the objective method of Legler et al. (1989) with the new FSU objective method (BOSR) in 2004 (Fig. 7).

**ANALYSIS METHODOLOGY.** The history of the FSU and IRD pseudostress fields resulted in different analysis methods for each product. Although the products are all based on in situ ship and buoy data, differing temporal and spatial characteristics of the data lead to unique analysis methods for each basin. The historical FSU Pacific fields result from a subjective analysis, while the FSU Indian, IRD Atlantic, and new objective FSU Pacific products are predominantly objective analyses with some subjective quality control of the input data.

*Subjective Pacific Ocean.* An identical subjective analysis method was used for the historical Pacific quick-look and research-quality pseudostress fields; only the input data differed. Individual wind vector data in the tropical Pacific, 30°N to 30°S, 120°E to 70°W, were extracted from the NCEP GTS and NCDC data for the quick-look and research products, respectively. As noted above, the typical number of observations in the tropical Pacific has varied since 1960 (Fig. 1), and the spatial coverage is unevenly distributed (Fig 2). Prior to the installation of the TAO/TRITON array of moored buoys (McPhaden et al. 1998) beginning in the mid-1980s, data coverage was poor along the equator. Data coverage in the Southern Hemisphere continues to be sparse, especially in the eastern part of the basin.

A series of simple outlier tests were applied to the wind vectors. First, any individual report of wind speed exceeding  $40 \text{ m s}^{-1}$  was deleted. Vector components of the pseudostress were obtained for the remaining wind observations. The pseudostress vector components were sorted into  $2^\circ$  latitude  $\times$   $10^\circ$  longitude bins, and a second crude statistical test removed outliers in each bin. For bins with 3 to 10 observations the minimum and maximum of the signed pseudostress components were removed. For bins with greater than 10 reports, the minimum and maximum 10% of the data were removed for each pseudostress component. Components were treated independently during these tests. Averages were computed using the remaining components in each bin and a three-standard-deviation test was used to eliminate any remaining outliers. The resulting sca-

lar fields were then subjectively analyzed and checked by trained meteorologists.

The subjective analysis began with the analyst drawing a streamline field to fit the bin-average pseudostress vectors. The streamlines allowed the analyst to determine which bin-averaged pseudostress values did not agree with the large-scale flow pattern. Using the streamlines as a guide, the analyst contoured the magnitude of the  $u$  and  $v$  components of the pseudostress (Fig. 5), with less influence from the suspect bin averages. The contoured pseudostress component fields were digitized, resulting in a  $2^\circ \times 2^\circ$  grid of pseudostress vectors. The first gridded field was compared to the original streamline analysis, and the analyst made necessary adjustments to individual vectors, using a graphical editor, to bring the final pseudostress field into agreement with the streamline analysis.

*Atlantic Ocean.* Pseudostress (and SST) fields for the tropical Atlantic are produced using a combination of subjective and objective methods. The analyses are based on the NCDC marine observation and real-time GTS data for the historical and recent years, respectively (Fig. 6). Vector winds are extracted for the region 30°N to 20°S, 60°W to the African coast. Data coverage is excellent north of the equator (Fig. 3a), and spatial gaps south of the equator are small compared to the Pacific (Fig. 2a). The focus herein is pseudostress; therefore, only the wind analysis methods are described.

Picaut et al. (1985) and Servain et al. (1987) provide details of the method used to eliminate wind outliers. Briefly, the method begins by sorting the wind data into  $2^\circ$  latitude  $\times$   $5^\circ$  longitude bins and removing any wind greater than  $25 \text{ m s}^{-1}$ . Bins with only one wind observation are ignored. The method applied to the 1964–79 database (Picaut et al. 1985) used a visual inspection to determine the wind vector quality when two to seven wind observations occurred in a bin. For bins with eight or more observations, a Gaussian distribution was assumed, and excessive departures from the mean were eliminated (Servain et al. 1987). Pseudostress averages for each bin are created using data not eliminated by these tests.

An objective method based on progressive distance influence (Cressman 1959) is used to create a  $2^\circ \times 2^\circ$  pseudostress field from the  $2^\circ \times 5^\circ$  averages (Servain et al. 1985). In large regions of missing data, some bins are filled with pseudostress values that are subjectively determined using surrounding data, climatological means, and the previous month's anomaly. This subjective "seeding" avoids having more than two suc-

cessive bins without data. No more than a total of 2% of the grid cells are seeded to allow the objective system to converge on a solution field (Servain et al. 1985).

The second version of the data processing, initiated in 1986, reinforces the automation of the methodology to reduce the calculation time while assuring good reliability of the final product. The previous visual validation test of the wind stress vectors is replaced by an entirely automatic method based on an adaptation of the homogeneity test already in use for the treatment of the SST. This method (Servain et al. 1987) depends on the local variances of both the magnitude and the direction of the wind stress, not only in each of the  $2^\circ \times 5^\circ$  analyzed bins, but also in all the surrounding bins. The time saving from the automation allows the maximum number of observations used in the test to be raised from 8 to 15. A verification of the coherence of the two methods was undertaken using the original data for the year 1979 (Servain et al. 1987). The final pseudostress resulting from the new method is slightly different in magnitude (but not in direction) from the Picaut et al. (1985) values (Servain et al. 1990). These results prompted IRD to apply the new treatment to all winds from 1964; thus, the available 1964–2001 pseudostress dataset has been reanalyzed using the automated homogeneity test. The only other changes in the process since 1986 are related to changes in the way IRD received the raw data (from delayed annual to near-real time monthly delivery).

The method of processing described above is antiquated in many aspects, so the IRD recently modified the method (while keeping the same philosophy in the sequential analysis) to one in which the subjective part is now entirely interactive (D. Corre and J. Servain 2003, unpublished manuscript). The new method became fully operational at the beginning of 2002.

**Indian Ocean.** The tropical Indian Ocean pseudostress fields are created using an objective technique combined with limited subjective editing of the input data. As with subjective FSU Pacific winds, the quick-look product is produced with real-time GTS data from NCEP (NCEP 1997) while the more complete TD-1129 data (NCDC 1998) are used to create the research product (Fig. 7). Individual wind vector data are extracted for the tropical Indian Ocean,  $25^\circ\text{N}$  to  $30^\circ\text{S}$ ,  $30^\circ$  to  $120^\circ\text{E}$  (Fig. 3b), and the same objective method is used for the quick-look and research products.

Once data are extracted, simple statistical tests remove outliers. Any individual wind speed exceeding

$40 \text{ m s}^{-1}$  is deleted, and vector components of the pseudostress are obtained for the remaining wind observations. Vector component pairs are objectively filtered by comparing both the  $u$ - and  $v$ -component values to basin averages calculated for each month. Upper and lower limits for each component are set to be the basin average  $\pm 30$  times the average value. Whenever either component falls outside this range, both components are deleted. Less than 1% of all reports are removed by the objective filter (Legler et al. 1997).

The remaining pseudostress components are averaged in  $1^\circ$  bins before a final objective screening is applied individually to each bin-average value. In bins with greater than five observations per month, individual observations are removed when either component is greater than  $\pm 3.9$  standard deviations from the bin-average value. This second screening typically removes less than 1% of the pseudostress vectors. The remaining observations are again averaged onto a  $1^\circ$  grid, with empty bins occurring primarily in areas outside of the shipping lanes (Fig. 3b).

A variational objective analysis (direct minimization) is performed on the new binned data using the  $1^\circ$  gridded data as a first guess (Legler et al. 1989). The cost function, which is to be minimized, consists of five constraints, each expressing a lack of fit to prescribed conditions. These constraints include a proximity to the input data, a penalty function for each vector component, and agreement of kinematic variables to expected climatological patterns. The penalty terms and constraints on the curl of the pseudostress improve the characteristics of the wind field and allow for connectivity between the zonal and meridional pseudostress. At times, a few bad observations will not be eliminated by the objective filtering, resulting in errors in the objectively derived pseudostress fields. When this occurs, an analyst removes the problem from the input data and the objective procedure is rerun. The resulting final fields are produced on a  $1^\circ$  grid (whereas Pacific and Atlantic analyses are on  $2^\circ$  grids), which better resolves key circulation features (e.g., Somali jet).

**Objective Pacific Ocean.** Building upon the objective technique of Legler et al. (1989), a new variational method is now employed to objectively grid in situ (ship and buoy) observations for the tropical Pacific Ocean (BOSR). The new objective research product was produced from an updated version of COADS for 1978–97 and NCDC TD-1129 for 1998–2002 (Fig. 4). Quick-look fields continue to be produced using GTS data obtained monthly from NCEP. All the new ob-

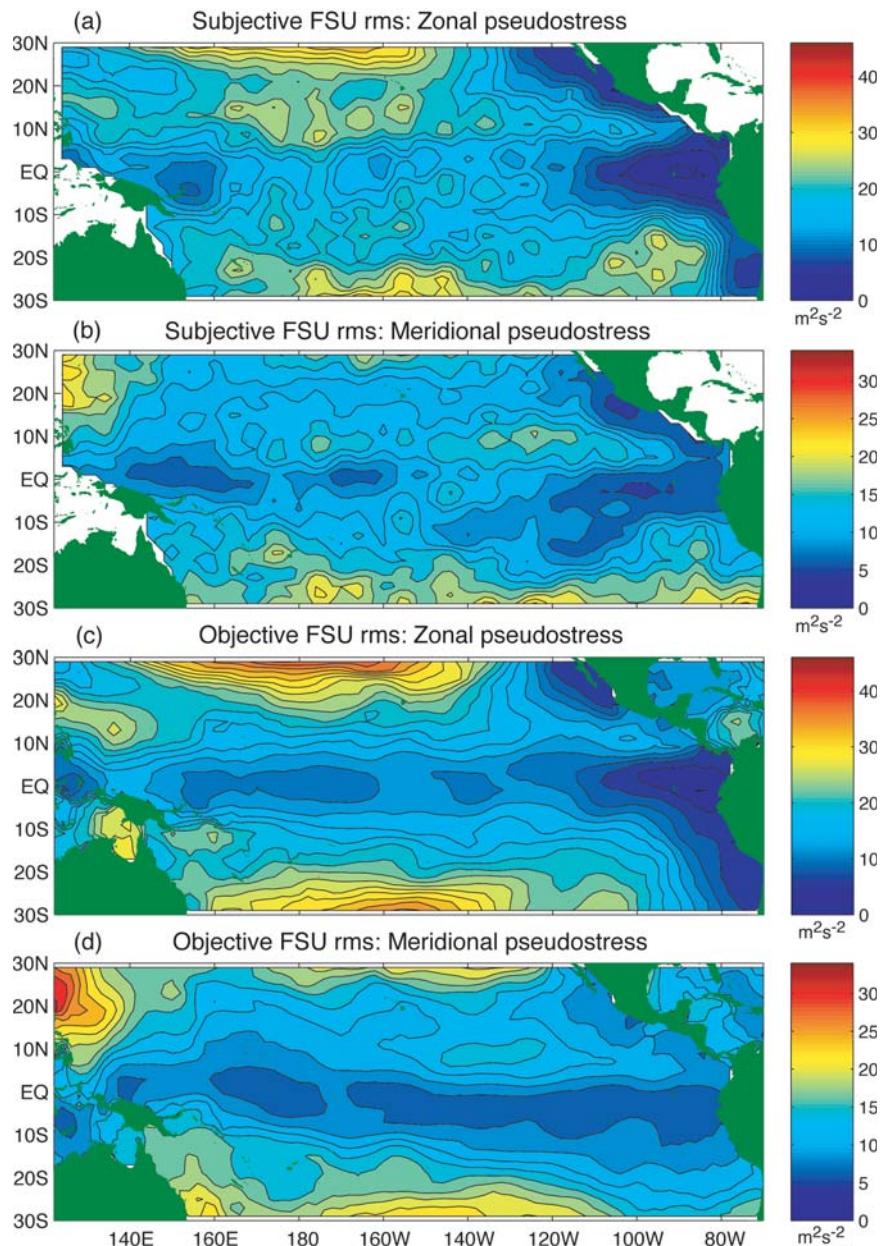
jective fields are produced on a  $2^\circ$  grid for the region  $30^\circ\text{N}$  to  $30^\circ\text{S}$ ,  $122^\circ\text{E}$  to  $70^\circ\text{W}$ .

The objective method is employed iteratively with subjective editing of the input data to remove the relatively large inconsistencies between the input data and the solution fields. These inconsistencies are primarily due to erroneous data (usually ship position) and poor sampling. The chosen variational method, direct minimization, employs a cost function 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 misfit of curl. The second and third constraints 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.

The background fields are smoothed monthly fields based on the observations. These background fields have been found to be more effective than using a long-term mean of monthly winds [e.g., the daSilva et al. (1994) or FSU climatologies], particularly during strong ENSO events where the long-term mean is a poor estimate.

The constraints used in the variational method maximize the 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 the three constraints can be coupled to construct physically sound wind fields. Each constraint 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). The new Pacific wind method continues to apply cross validation to determine the weights.



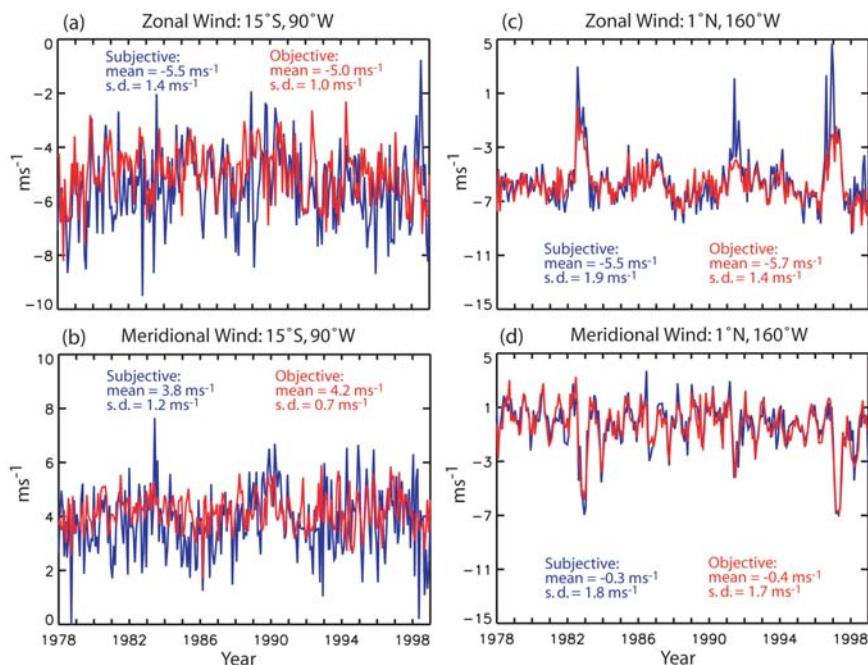
**FIG. 8.** Rms month-to-month differences, averaged for each grid point from 1978 to 1999, for (a) zonal and (b) meridional subjective FSU pseudostress. The rms for the (c) zonal and (d) meridional objective FSU pseudostress show more month-to-month consistency than the subjective product.

**SUBJECTIVE VERSUS OBJECTIVE FSU PACIFIC PRODUCTS.** The recent change to an objective approach for the FSU Pacific pseudostress fields removes some known shortcomings of the subjective method while continuing the history of producing a product that is well suited for ENSO studies. One concern with the subjective FSU winds was the high degree of month-to-month variability (Figs. 8a,b), which had prompted some users to apply a 1-2-1 temporal filter to the product (A. Kaplan 2002, personal communication). The overall month-to-month variability has been reduced, and the variability is more spatially consistent using the new objective method (Figs. 8c,d).

Comparing wind component time series at individual grid points reveals some of the similarities and differences between the subjective and objective FSU Pacific winds. Overall, the differences were largest in the data-sparse regions (e.g., the region south of 10°S and east of 160°W). For example, large differences occur between individual monthly wind values at 15°S, 90°W (Figs. 9a,b); however, the multiyear patterns are consistent between the products. In data-sparse regions, the distribution of the component winds is much tighter (reduced standard deviation), especially for the meridional component, in the objective FSU product. In data-rich regions along the equator and in the northwest tropical Pacific (region north of the equator and west of 160°E), the wind component time series are very similar. At 1°N, 160°W both products show clear signals of the 1982 and 1997 El Niño events (Figs. 9c,d). It is noteworthy that the new FSU winds reduce the month-to-month peaks in the zonal wind component during the El Niño events, which results in the new product downplaying the magnitude of the weak 1991/92 El Niño. The authors believe that the subjective analysts, knowing that an El Niño had occurred prior to completing the subjective research product, may have overemphasized the zonal winds during these events.

Isolating the cause for the differences between the subjective and objective FSU wind products is problematic. Users must consider that the objective research product is based on different input data than the subjective winds for the period 1978–97 (Fig. 4), with the updated COADS data providing additional delayed ship and buoy reports and more quality control than the NCDC dataset. Quality processing of the input data by FSU is limited to basic range checks and statistical trimming for the subjective product (see section titled “Subjective Pacific Ocean”), while the objective method employs more advanced trimming, height adjustments, and bias corrections (BOSR). Finally, the products are analyzed on substantially different grids: 2° latitude × 10° longitude for the subjective and 2° latitude × 2° longitude for the objective. Clearly, there are multiple sources for differences between the two FSU Pacific wind products.

One operational advantage of FSU’s objective Pacific analysis that cannot be overlooked is that the quick-look products are now available within a few days after the start of the month, as opposed to 2 weeks with the old subjective method. Faster production allows wider use of the FSU products in operational ENSO forecast models. Additional comparisons of the new objective versus the old subjective FSU winds can be found in BOSR.



**FIG. 9.** Time series of monthly (a), (c) zonal and (b), (d) meridional wind components from 2° bins at 15°S, 90°W and 1°N, 160°W. Winds from the subjective vs the objective FSU Pacific product are marked in blue and red, respectively. The overall mean and std dev (s.d.) are provided for each time series.

## APPLICATION OF IN SITU PRODUCTS.

FSU and IRD tropical pseudostress products have been and still are widely utilized by the atmospheric and oceanic communities. The quick-look products were developed primarily for seasonal to interannual forecasting applications. As noted above, quick looks are based on GTS ship and buoy observations collected by NCEP in real time and are subject to the reporting limitations of any real-time GTS product. Many vessels report data months after it is collected, and these do not appear in the NCEP GTS record used for quick-look fields. The delayed reports are contained in the yearly TD-1129 data obtained from NCDC to produce the research products for the Pacific and Indian Oceans. In any given month, the NCDC data can contain up to 25% more data than the GTS data received from NCEP. Internal (unpublished) reviews of the quick-look versus research products at FSU have shown that the increased data volume results in improved fields for research applications (D. Legler 2003, unpublished manuscript). Additionally, acquiring updated daily averages of the TAO observations, which include any corrections applied by PMEL, also improves the research product for the Pacific. In general, the research product would be the preferred pseudostress product, unless one is involved in forecasting activities.

Tracking published applications of the subjective Pacific pseudostress products is very difficult. The product was originally referenced with Goldenberg and O'Brien (1981) but soon became generically cited as the "FSU winds" without any formal manuscript reference. The authors suggest that the present manuscript be used for future citations of the subjective FSU Pacific winds. A reference search of American Meteorological Society (AMS) publications for the period 1997–2002 locates 29 manuscripts citing Goldenberg and O'Brien (1981), and a reference list maintained at the Center for Ocean–Atmospheric Prediction Studies (COAPS) contains 63 manuscripts published between 1981 and 1997 that cited the FSU Pacific product. Major topics of the 63 papers include physical oceanography (19), ENSO modeling (16), and coupled, general circulation, or ocean modeling (12). Modeling applications include one of the first coupled models developed for ENSO prediction (Cane et al. 1986; Zebiak and Cane 1987). Through the years, this coupled model was improved and continued to use the FSU pseudostress to initialize the ocean (e.g., Chen et al. 1997). FSU Pacific pseudostresses are also used in ENSO hindcast models (e.g., Schopf and Loughe 1995) and hybrid coupled ocean–atmosphere models (e.g., Barnett et al. 1993; Syu and Neelin 2000).

Other topics included ENSO physics, atmospheric physics, and trends and variability in the tropical Pacific.

Several comparisons of the subjective Pacific winds to other products have been completed. Hundermark et al. (1999) found the ECMWF operational wind stress to be weaker than the FSU product prior to the assimilation of the TAO buoy observations into the ECMWF. ECMWF was also shown to have wind stress curl features related to topography (e.g., around the Hawaiian Islands) not present in the FSU product because of the  $2^\circ$  latitude  $\times$   $10^\circ$  longitude averaging used by FSU. Putman et al. (2000) compared the FSU pseudostress to the first NCEP–NCAR and ECMWF reanalysis fields. Good agreement was found between the divergence for the FSU and ECMWF reanalysis, with each showing a marked ITCZ. In contrast, the ITCZ was poorly defined in the NCEP reanalysis divergence fields (Fig. 1 in Putman et al. 2000). In addition, Putman et al. (2000) found the FSU and ECMWF reanalysis to better resolve the strength and duration of anomalous wind events associated with El Niño. Pegion et al. (2000) compared the Pacific FSU wind product to a pseudostress product computed from the NSCAT winds. Large-scale features were found to be similar between the NSCAT and FSU products; however, the NSCAT fields provided finer spatial detail including tropical cyclones and topographic wind features. Overall, comparisons between the subjective FSU product, ECMWF, and NSCAT were favorable, and these products were found to better represent tropical wind stress than the first NCEP–NCAR reanalysis.

The operational objective Pacific FSU pseudostress fields continue to be used by U.S. government agencies [e.g., NCEP, National Oceanic and Atmospheric Administration/Atlantic Oceanographic and Meteorological Laboratory (NOAA/AOML), NASA Jet Propulsion Laboratory (JPL)] and universities (e.g., Columbia University; New York University; University of California, Los Angeles; University of California, San Diego; FSU). International users include ECMWF, the Royal Netherlands Meteorological Institute, Commonwealth Scientific and Industrial Research Organisation (CSIRO; Australia), and the Shanghai Typhoon Institute. The quick-look Pacific fields are also reproduced on a monthly basis in the *Climate Diagnostics Bulletin* distributed by NOAA.

The FSU Indian Ocean winds are also applied to numerous research topics and are generally referenced with Legler et al. (1989). A search using the Web of Science located 60 manuscripts published

between 1989 and 2003 that refer to Legler et al. (1989). A sampling of the papers address topics from physical oceanography (e.g., Han et al. 1999), the Indian monsoon (e.g., Schott and McCreary 2001), Indian Ocean variability (e.g., Schiller and Godfrey 2003), ocean modeling (e.g., Jensen 1993), numerical data assimilation (e.g., Meyers et al. 1994; Smedstad and O'Brien 1991), and marine biology (e.g., Brock and McClain 1992).

Finally, the IRD Atlantic fields are used to describe the seasonal and interannual variability in the tropical Atlantic. The IRD pseudostress and SST products were often used to analyze specific climatic events (e.g., Servain and Séva 1987; Delécluse et al. 1994), process studies (e.g., Binet and Servain 1993; Servain et al. 2000; Servain and Arnault 1995), and relationships with other domains or climatic indices (e.g., Déqué and Servain 1989; Servain 1991; Mélice and Servain 2002). Furthermore, the IRD tropical Atlantic wind database served to force several oceanic numerical experiments (e.g., Picaut et al. 1984; Reverdin and du Penhoat 1987; Merle and Morlière 1988; Morlière et al. 1989a,b; Servain and Arnault 1995; Huang and Shukla 1997).

**CONCLUSIONS.** Through the years, the tropical pseudostress products from FSU and IRD have provided an excellent resource for both oceanographers and meteorologists. The products have been shown to be effective for a wide range of applications, the results of which have improved our understanding of atmosphere–ocean interactions in the Tropics. Continued improvement in operational models and numerical techniques (e.g., ENSO forecasting) has paved the way for a new generation of objective in situ pseudostress analyses. The new IRD method has eliminated the subjective portion of the analysis in 2002 while the new objective FSU technique has re-

placed the subjective Pacific analysis and will be applied to the Indian Ocean in 2004.

In an era of satellites and models, it is necessary to emphasize the importance of continuing historical in situ wind products. The in situ fields produced by FSU and IRD provide a homogeneous dataset that extends back to the 1960s in the Pacific. Although satellites can provide excellent spatial coverage for the modern day, to date they are unable to reproduce the historical record. In addition, continued in situ analyses provide a reliable source of comparison data that can place new satellite products in a historical context. Finally, in situ products provide a key resource to identify biases in model-derived wind stress fields.

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## DATA ACCESS

All FSU and IRD pseudostress products continue to be freely available to the scientific community. Pseudostress products for all three tropical ocean basins are available online at [www.coaps.fsu.edu/RVSMDC/SAC/](http://www.coaps.fsu.edu/RVSMDC/SAC/) and via anonymous FTP at [ftp.coaps.fsu.edu/pub/wind/](ftp://ftp.coaps.fsu.edu/pub/wind/). Both the old subjective and new objective FSU Pacific products are available. The most up-to-date Atlantic SST and pseudostress data can be obtained at [www.funcceme.br/demet/monitoramento.asp](http://www.funcceme.br/demet/monitoramento.asp). Data are available primarily as ASCII files, although COAPS periodically combines multiple years of data into single netCDF files.

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