A COMPARISON OF VARIOUS EQUATORIAL PACIFIC SURFACE WIND PRODUCTS

G. Peng1, 2, H.-M. Zhang2, H.P. Frank3, J.-R. Bidlot4, M. Higaki5, and W. Hankins1, 2

1 STG, Inc, Asheville, NC, USA; 2 NOAA/NESDIS/NCDC, Asheville, NC, USA
3 DWD, Offenbach, Germany; 4 ECMWF, Reading, UK; 5 JMA, Tokyo, Japan

ABSTRACT

Daily 2009 surface winds from five model, remotely-sensed, and reanalysis wind products are compared with measurements from three fixed mooring buoys located in the west equatorial Pacific (0°N, 165°E), the central equatorial Pacific (0°N, 170°W), and the eastern-central equatorial Pacific Ocean (0°N, 140°W). The cross-correlation coefficients between these five wind products and the buoy winds are all statistically significant at the 95% confidence level, ranging from 0.77 to 0.97 for the zonal winds and 0.45 to 0.93 for the meridional winds. However, a systematic positive/negative bias was found in wind directions in all wind products at the central/eastern central Pacific Ocean, which could have an impact on local wind stress curl field in the region.

Index Terms—Winds, Statistical analysis, Model verification and validation, Remote sensing, Reanalysis

1. INTRODUCTION

Recognizing that accurate global high-resolution surface winds and related momentum flux or surface stress are crucial for improving Numerical Weather Prediction (NWP) and climate forecast skills and driving ocean general circulation models [1-3], the World Climate Research Program (WCRP) Working Groups on Numerical Experimentation, the Surface Fluxes, Observation & Assimilation Panel, and the Ocean Observation Panel have initiated the Surface Fluxes Analysis (SURFA) project. A collocated in situ and NWP model data repository center (www.ncdc.noaa.gov/thredds/surfa.html) has been established at the National Climatic Data Center (NCDC), which is also one of the data centers for the National Oceanic and Atmospheric Administration (NOAA)’s satellite, global coupled model, and other climate data. A pre-defined model grid for all NWP models has been agreed upon, which minimizes the effort and potential errors of collocating data from different data grids. As a first step in evaluating the performance of the global NWP forecast winds, we will compare short-range forecast winds from three global high-resolution NWP models with high quality in situ observations at three locations along the Equator in the Pacific Ocean. NCDC blended ocean surface winds and surface winds from the newly available Climate Forecast System Reanalysis (CFSR) generated at the National Centers for Environmental Prediction (NCEP) are also included in the comparison. Most of previous satellite, model, and in situ wind comparisons have been focused on the absolute speed as most of remotely sensed measurements are wind speed only. Satellite wind vector measurements, however, have been proven to be useful in identifying directional errors and therefore improving buoy measurements [4]. The objective of SURFA is to uncover temporal and spatial biases in the NWP forecast winds with high quality in situ reference observational data to improve NWP surface flux or stress products. Since zonal and meridional (u, v) components of the winds, rather than wind speeds, are NWP forecast variables and the inputs for computing surface wind stresses and the stress curl, the focus here will be to identify any bias in u and v of those wind products against point observations as a baseline before we move on to examine spatial bias in NWP forecast winds using the NCDC remotely-sensed and/or NCEP/CFSR wind products.

2. DATA OUTLINE

Wind data products used in this study consist of three categories: 1) observed winds, both in situ and remotely-sensed; 2) NWP short-range forecast winds; and 3) reanalysis winds.

2.1. In situ winds from OceanSITES

The high quality in situ reference observations are wind measurements from oceanSITES. OceanSITES is a global network of open-ocean sustained time series sites, called ocean reference stations including four Tropical Atmosphere Ocean (TAO) moorings, which are an integral part of the Global Ocean Observation System. Daily winds from year 2009 for three out of four oceanSITES/TAO mooring sites along the equatorial Pacific Ocean are used (osTAO winds hereafter): the west equatorial Pacific (0°N, 165°E), the central equatorial Pacific (0°N, 170°W), and the eastern-central equatorial Pacific Ocean (0°N, 140°W). The equatorial Pacific Ocean was selected as the starting point due to its known importance in weather/climate events. Year 2009 was chosen as the result of most complete whole year wind records for both model and in situ datasets when
we started the analysis. Unfortunately, the winds from year 2009 for the eastern equatorial Pacific Ocean (0°N, 110°W) are not included as less than two months of data are available. The buoy winds are measured at the height of 4 m with an accuracy of about 0.3 m/s for wind speed and about 1.0° for wind direction [5]. In this study, those 4-m buoy winds are logarithmically adjusted to the 10-m height based on [6] with a typical oceanic value of 1.52 x10^-4 m for the roughness length.

2.2. Blended remotely-sensed surface winds

The blended remotely-sensed surface winds are high-resolution ocean surface winds [7]. The 6-hourly gridded winds are on a global 0.25° x 0.25° grid over ice-free oceans (65oS – 65°N) (blended winds hereafter). Swath wind speeds, retrieved by the Remote Sensing System (RSS) from satellite measurements of AMSR-E, SSM/I F13, TMI, and QuickSCAT, are used in constructing the 2009 blended wind speed fields; wind directions from NCEP/DOE (Department of Energy) reanalysis II are used in the decomposition of east-west and south-north winds. The blended winds are the neutral winds at the height of 10 m.

2.3. NWP Winds from the national operational centers

The NWP winds are short-range forecast 10-m surface winds (NWP winds hereafter) from the three participating national operational NWP Centers: the European Centre for Medium-Range Weather Forecasts (ECMWF), the German Weather Service “Deutscher Wetterdienst” (DWD), and Japan Meteorological Agency (JMA). All NWP winds had been interpolated on the same global 0.25° x 0.25° grid by the NWP Centers. All forecasts started at 12 UTC. Thus, the forecast winds at 12-, 15-, 18-, 21, 24-, 30-, and 33-hours correspond to winds at 00, 03, 06, 09, 12, 15, 18, and 21 UTC of the following day.

2.4. Winds from the NCEP/CFSR

The winds from the latest reanalysis produced by NCEP, referred to as CFSR, are also included in the comparison (CFSR winds hereafter). A number of improvements from its predecessors are associated with this reanalysis product including a 6-hourly coupling between atmosphere and ocean, an interactive sea-ice model, and higher spatial and temporal model outputs [8]. The CFSR winds are 10-m winds on the T382 grid with a grid spacing of about 0.31° x 0.31° in the tropics.

3. RESULTS

3.1. Annual means, bias, and standard deviations

The bias is defined as the mean of residual which is the difference between winds from each product and the osTAO winds. The bias measures the shift in the 2009 annual mean of winds for each wind product from that of the osTAO winds. The standard deviation of each wind product is the square root of its variance.

The time series of daily osTAO winds are displayed in Fig. 1. The largest fluctuation of zonal winds occurs at 165°E which shifts from easterly in the first part of 2009 to westerly in the latter part of 2009 with a mean of -1.6 m/s and a standard deviation of 4.2 m/s, which is the largest among all three locations. The zonal winds from other two locations are mostly easterly with means of -5.28 and -5.98 m/s, respectively. The meridional winds at the three locations fluctuate around zero with mostly northerly winds at 170°W. The means of the meridional winds are -0.49, 1.36, and 0.53 m/s, respectively.

Figure 1: Time series of 2009 osTAO zonal winds (left panels) and meridional winds (right panels) at the west equatorial Pacific (0°N, 165°E, top panels), the central equatorial Pacific (0°N, 170°W, middle panels), and the eastern-central equatorial Pacific (0°N, 140°W).

The 2009 means of almost all other zonal winds (Fig.2) are quite close to that of the osTAO zonal winds with a mean bias less than 0.5 m/s. The exceptions are the ECMWF and JMA winds at 165°E with a mean bias of -1.1 m/s, and the CFSR winds at 170°W and 140°W, with biases of 0.57 and 0.74 m/s (Fig. 2). On the other hand, the bias for the meridional winds at 165°E is relatively small compared to other two sites – less than 0.5 m/s in magnitude. The means of the meridional winds at 170°W/140°W are systematically lower/higher than that of osTAO winds, resulted a systematic negative/positive bias. The magnitude of the bias of most meridional winds is larger than 0.5 m/s, with that of the DWD meridional winds at 140°W just below at 0.42 m/s.

The blended winds tend to have larger standard deviations for both wind components than any other winds. They are very close to that of the osTAO winds for the zonal winds, although still on the higher side for the meridional winds. While NWP models do not generally predict winds of extreme values, the blended winds could have extreme wind
values as a result of isolated pixel(s) of high wind values. The impact of isolated high wind pixel(s) could be minimized by applying either more vigorous quality control or stronger filtering techniques.

3.2. Root-Mean-Square (RMS) errors and cross-correlation coefficients

The RMS error is defined as the square root of the variance of the residuals. The RMS errors are being widely used in the evaluation of data products as a measure of accuracy. The RMS errors for the CFSR winds are overall smaller than all other wind products; the exception is the zonal winds at 140°W (Fig. 2). The results are mixed for others.

The cross-correlation is a standard method of estimating the degree to which two series are correlated. The maximum cross-correlation coefficients between all wind products and the osTAO winds occur at the zero lag, implying no systematic phase shift in the wind products. The cross-correlation coefficients between the CFSR winds and osTAO winds are the highest, ranging from 0.94 to 0.97 for the zonal winds and 0.89 to 0.93 for the meridional winds (Fig. 2). The blended winds have comparable or slightly higher values of cross-correlation coefficients for the zonal components than the NWP zonal winds, but the results are mixed for the meridional winds. Among the NWP winds, the ECMWF winds have the highest cross-correlation coefficients; the JMA winds come close second; and the DWD winds rank next. All values of the cross-correlation coefficients are statistically significant at the 95% confidence level.

3.3. Time series of wind direction residual

Fig. 3 shows the time series of wind direction residuals (difference between wind directions of a wind product and the osTAO winds). The weak winds (wind speed <3 m/s) are not included due to the large uncertainty associated with the resultant wind direction. The range of the means of the wind direction residuals at 165°E is from 1.5 to 11.63 degrees, with very large RMS errors, ranging from 63 to 81 degrees (Table 1). The averaged value of means and RMS errors are 7.9 and 61.3 degrees, respectively. As the temporal distribution of the wind direction residuals is quite random, there is no indication of a systematic bias in wind directions by any wind product at this location.

![Figure 2: From left to right: 2009 means (m/s), biases (m/s), standard deviations (m/s), root-mean-square (RMS) errors (m/s), and the maximum cross-correlation coefficients of winds. The top panels are for zonal winds and bottom panels are for meridional winds. The biases, the RMS errors, and the cross-correlations are computed using the 2009 osTAO winds as the reference.](image)

![Figure 3: Time series of 2009 wind direction residuals (difference from osTAO) at 165°E (top panels), 170°W (middle panels), and 140°W (bottom panels). Weak winds (wind speed <3 m/s) are not included. On the left three panels: red for the blended winds and blue for the CFSR winds. On the right three panels: blue for the ECMWF winds, green for the DWD winds, and red for the JMA winds.](image)

Although the RMS errors in wind direction at 170°W and 140°W are smaller than that at 165°E, comparing 20 and 14 degrees to 61 degree, there is visually a positive/negative bias for all wind products at 170°W/140°W, respectively (Fig. 3). With mean wind directions of 166 and 175 degrees for the osTAO winds at 170°W and 140°W, respectively, a

<table>
<thead>
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<th>170°W</th>
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<td>20.00</td>
<td>-6.48</td>
<td>13.95</td>
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Table 1: The means and RMS errors of wind direction residuals
positive bias of about 11.85 degrees will reduce the meridional winds at 170°W and a negative bias of about -6.48 degrees will increase the meridional winds at 140°W, which contributes to the negative/positive bias we have seen in the biases and RMS errors of the meridional winds at 170°W/140°W.

4. SUMMARY AND DISCUSSION

Daily 2009 surface winds from five model, remotely-sensed, and reanalysis wind products are compared with the measurements from three TAO buoys located at the west (165°E), the central (170°W), and the eastern-central (140°W) equatorial Pacific Ocean.

Our results have shown that the cross-correlations between various wind products and the buoy winds are all above 95% significant level, ranging from 0.77 to 0.97 for the zonal winds and 0.45 to 0.93 for the meridional winds. The cross-correlations between the CFSR winds and the buoy winds are consistently higher than others, with overall smallest root-mean-square (RMS) errors, for both zonal and meridional winds. On the other hand, the cross-correlation coefficients between the DWD winds and the buoy winds are mostly lower than others.

All the wind products restrain their winds (analysis or reanalysis) by either buoy or satellite data to a certain degree. The CFSR and ECMWF models assimilate both remotely-sensed data as well as in situ measurements, although assimilation schemes may differ. The DWD model assimilates buoy winds and satellite scatterometer winds since July 2009. The JMA model only assimilates satellite scatterometer data. The blended winds are based on the remotely-sensed wind speed with wind directions from the NCEP/DOC reanalysis II, which also assimilates both remote-sensed data and in situ data. This may contribute to the fact that overall characteristics of all wind products examined here are fairly similar and correlations are high.

Previous examination of tropical Pacific surface wind analyses had shown that the agreement between the winds from three analyses (U.S National Meteorological Center, the U.K. Meteorological Office, and ECMWF) and the TAO buoy data is relatively poor with a bias as large as 3.1 m/s [9]. At that time, the TAO buoy data were not included in any of the meteorological analyses. Since then, the quality of the TAO buoy and availability satellite data have been improved; So does the quality of the models which are now assimilating either one or both types of those observational data. Therefore, it is not surprising that all five wind products examined here compare well with each other and correlate well with the osTAO winds, especially for the zonal winds, with the CFSR winds being closely fitted to the osTAO winds. The bias for all wind products is now less than 1.1 m/s. The performance of these three NWP forecasts is also quite close, particularly so between the ECMWF and JMA winds.

However, our analysis has also revealed that all the 2009 meridional winds have a systematic negative/positive bias at 170°W/140°W, respectively. This bias is associated with a consistent positive/negative bias in wind directions at the location, which could potentially have implication in local wind stress curl field. This directional bias does not appear to be related to the known alignment error associated with the instruments for the TAO buoy winds that described in [5]. As there is no visible directional bias at the west equatorial Pacific Ocean, it could not be completely categorized as something unique at the Equator.

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5. REFERENCES