JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, D16109, doi:10.1029/2008JD011696, 2009

Comparisons of monthly mean 10 m wind speeds from satellites and NWP products over the global ocean

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Received 31 December 2008; revised 15 June 2009; accepted 19 June 2009; published 27 August 2009.

[1] The accuracy of wind speed at 10 m above the sea surface from two satellite and three numerical weather prediction (NWP) products is investigated over the global ocean. Rain-free equivalent neutral winds from the Quick Scatterometer (QuikSCAT) are converted to stability-dependent winds to be consistent with those from NWP products and are taken as truth in comparisons to winds from other products. Quantitative statistical analyses presented at each grid point over the global ocean reveal that monthly winds from NWP products have almost perfect skill relative to those from QuikSCAT winds during the 3-year common period (September 1999 to August 2002). Exceptions occur in tropical regions and high southern latitudes. Wind speeds adjusted to 10 m at many moored buoys located in different regions of the global ocean further confirm the accuracy of monthly NWP winds, giving RMS difference of 1.0 m s^{-1} based on 1281 monthlong time series. The satellite-based QuikSCAT winds agree with buoy winds relatively better than NWP products. While there is good agreement among wind products on monthly timescales, large differences (>3 m s^{-1} and more) in NWP winds are found in comparison to QuikSCAT winds on shorter time intervals at high latitudes. Daily means of sensible and latent heat fluxes based on NWP winds can therefore differ as much as 100 W m^{-2} in comparison to those based on QuikSCAT winds. In general, NWP wind-based sensible and latent heat fluxes are more similar to their QuikSCAT wind-based counterparts in tropical regions and midlatitudes.

Citation: Wallcraft, A. J., A. B. Kara, C. N. Barron, E. J. Metzger, R. L. Pauley, and M. A. Bourassa (2009), Comparisons of monthly mean 10 m wind speeds from satellites and NWP products over the global ocean, *J. Geophys. Res.*, *114*, D16109, doi:10.1029/2008JD011696.

1. Introduction

[2] Wind speed above the sea surface (typically at 10 m) is one of the most important variables for oceanic applications. For example, it is essential for determining heat and momentum fluxes (i.e., sensible and latent heat fluxes and wind stress magnitude) from bulk parameterizations [*Large and Pond*, 1981; *Fairall et al.*, 2003]. Tropical storm or hurricane intensification is also related to variations of wind speed [*Swanson*, 2007; *Gierach et al.*, 2007]. Wave height and the wind stress drag coefficient are typically formulated as a function of wind speed [*Johnson et al.*, 1998; *Bourassa et al.*, 1999; *Hwang et al.*, 1998]. Storm surge is greatly influenced by wind speed [*Morey et al.*, 2006]. Wind speed also plays an important role in various other aspects of the sea surface, such as atmospheric stability [*Kara et al.*, 2008a], radiative reflection and emission properties [e.g., *Watts et al.*, 1996]. There is, therefore, a need for accurate surface wind speeds for these various applications.

[3] Satellites and numerical weather prediction (NWP) centers are the major data sources of over-water winds at various spatial and temporal scales. Such well-known and commonly used wind products are listed in Table 1, along with their abbreviations which will be used throughout the text. Each wind product in Table 1 has its own advantages and disadvantages. For example, while satellites can provide wind measurements at high spatial resolution, their orbital patterns may limit coverage over the global ocean for a given day. In particular, QuikSCAT (hereinafter referred to as QSCAT) wind measurements are from a scatterometer, which is an active microwave sensor that samples ≈90% of the ice-free ocean in one day, with an average of at most two observations per 25 × 25 km^2 grid cell each day. Rain complicates determining winds from QSCAT because rainfall affects the small-scale surface roughness, the attenuation and the scattering of the radar signal in the atmosphere, thereby reducing the accuracy of measurements [e.g., *Portabella and Stoffelen*, 2001; *Draper and Long*, 2003; *Weissman et al.*, 2003]. The SSM/I sensor consists of seven separate total-power radiometers sharing a common

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0148-0227/09/2008JD011696$09.00

Table 1. Wind Products Over the Global Ocean, Including Their Abbreviations and Original Grid Resolutions[a]

Acronym	Name of the Product	Grid Resolution
QSCAT	SeaWinds instrument on the Quick Scatterometer	$0.250° \times 0.250°$
SSM/I	Special Sensor Microwave/Imager	$0.250° \times 0.250°$
NOGAPS	Navy Operational Global Atmospheric Prediction System	$1.000° \times 1.000°$
ERA-40	European Centre for Medium-Range Weather Forecasts	$1.125° \times 1.125°$
NCEP	National Centers for Environmental Prediction	$1.875° \times 1.875°$

[a]Twice-daily QSCAT wind measurements were obtained from Remote Sensing Systems (RSS), http://www.remss.com, and rain-free winds were formed. QSCAT winds were obtained using the Ku-2001 model function, which differs from the QSCAT-1 model function applied at the Jet Propulsion Laboratory (JPL). The Ku-band scatterometer data processing typically uses microwave radiometer measurements for rain flagging and sea ice detection [e.g., *Hilburn et al.*, 2006]. Monthly SSM/I winds are directly used from RSS. ERA-40 and NCEP re-analysis products are obtained from the National Center for Atmospheric Research (NCAR) data support section (http://dss.ucar.edu/datasets/), and NOGAPS winds are from the US GODAE server (www.usgodae.org). Monthly means for NWP products are constructed based on 6-hourly winds.

feedhorn, and measurement details can be found in the study by *Wentz* [1997]. The 1400 km swath and the orbit inclination of 98.8° provide complete coverage of the Earth in 2 to 3 days, except for two small circular holes of 2.4° centered on the North and South poles. Differences in the responses of radiometers and scatterometers to the wind vector are discussed in the study by *Weissman et al.* [2002a], concluding that both instruments respond to short sea surface waves of very similar wavelengths and give similar sensitivities to the wind vector.

[4] Unlike the satellites, winds from NWP products are continuous in time and space over the global ocean. They typically provide higher frequency outputs at 3- or 6-hour time intervals, with coarser grid resolutions than satellite-based products. Higher spatial and temporal resolution can only be obtained by relying heavily on the underlying atmospheric model to fill in observation gaps. NWP products generally use wind measurements from satellites for assimilation, and because atmospheric models have different physics, inputs, and boundary layer parameterizations, differences in their outputs are expected.

[5] There are various studies evaluating winds from QSCAT and SSM/I with those from moored buoys and ECMWF and NCEP products [*Meissner et al.*, 2001; *Ebuchi et al.*, 2002; *Freilich and Vanhoff*, 2006; *Ruti et al.*, 2008]. Specifically, comparisons between scatterometer and reanalysis products include studies of high wind events and cyclones [e.g., *Perrie et al.*, 2008; *Patoux et al.*, 2008], consistency between small-scale winds and sea surface temperatures [*Haack et al.*, 2008; *Song et al.*, 2009], and large-scale differences [*Kara et al.*, 2008b; *Risien and Chelton*, 2008]. Some studies only compared QSCAT winds with buoy winds [e.g., *Pickett et al.*, 2003; *Satheesan et al.*, 2007]. Such evaluation studies are typically based on collocated wind measurements, where satellite winds are available within a given temporal and spatial window. However, the accuracy of gridded satellite-based winds in relation to NWP products is something that also deserves particular attention at times when direct measurements are not available in some locations over the global ocean. This topic is also one of the focuses of this study.

[6] It has also been demonstrated that the SeaWinds scatterometer on the QSCAT satellite generally provides accurate winds in the absence of rain [e.g., *Stiles and Yueh*, 2002; *Hoffman et al.*, 2004]. In addition, *Pickett et al.* [2003] and *Satheesan et al.* [2007] discussed possible effects of including/excluding rain contamination in evaluating satellite winds, specifically QSCAT, in comparison to buoy winds. In this paper, unlike previous studies we investigate the impacts of rain contamination on monthly mean wind speeds after the air-sea stability corrections are applied over the global ocean. We also outline the procedure for applying the air-sea stability corrections to the neutral QSCAT winds to be consistent with NWP winds which already include the impacts of air-sea stratification.

[7] The main objective of this paper is to quantify differences among satellite- and NWP model-based monthly wind products. Within a quantitative framework, statistical error and skill analysis will be performed for winds from QSCAT, SSM/I and several NWP products over the global ocean. We will answer various questions as follows: (1) Are there similar accuracies in winds from the satellite and NWP fields over the global ocean? (2) Do satellite products give higher correlation and skill than do any of the NWP products? (3) Does having high temporal resolution (e.g., 6-hourly) winds from NWP products provide a greater advantage for forcing ocean models?

2. Wind Data Sets

[8] Five products are used to examine wind speeds at 10 m above the sea surface over the global ocean. A brief description of each is given in Table 1. There are two satellite-based products (QSCAT and SSM/I) and three NWP products (NOGAPS, ERA-40 and NCEP). Details of the above mentioned data sources can be found in the studies by *Liu* [2002] (QSCAT), *Meissner et al.* [2001] (SSM/I), *Rosmond et al.* [2002] (NOGAPS), *Uppala et al.* [2005] (ERA-40), and *Kanamitsu et al.* [2002] (NCEP). NCEP has two different re-analyses, and the one used here is the 2nd re-analysis (i.e., NCEP2).

[9] Temporal resolution for the winds is roughly twice daily for QSCAT and SSM/I and 6 hourly for NWP products except for NOGAPS which is 3 hourly. The satellite-based products have relatively finer spatial resolution than the NWP products, but include data voids. All these NWP products assimilate SSM/I data. NOGAPS did not assimilate QSCAT in the study period.

[10] Monthly means of 10 m wind speeds are created for each product as explained below. For evaluation purposes, the winds from all products are interpolated to a common grid of $0.25° \times 0.25°$. QSCAT (SSM/I) winds are available starting from July 1999 (January 1988) onward. However, winds from the ERA-40 re-analysis are not available beyond September 2002. In evaluating wind products, we choose a

common time period of 3 years from September 1999 through August 2002 for all products. QSCAT winds were processed using a 25-point observation filter to remove scales below 1.25°. This is also due to the fact that we will later apply air-sea stability correction to the QSCAT product using a coarse resolution NWP product (ERA-40). Note that there are no QSCAT wind measurements above ice. Therefore, in our analyses regions where ice is present (e.g., very high northern and southern latitudes) are masked. The ice-free regions over the global ocean are determined from monthly ice-land masks [*Reynolds et al.*, 2002].

[11] Winds from QSCAT and SSM/I are calibrated to equivalent neutral wind speeds at 10 m above the ocean surface, for example, effects of air-sea stability on the shape of the wind profile are ignored [e.g., *Meissner et al.*, 2001]. In contrast, 10 m winds from NOGAPS, ERA-40 and NCEP include effects of air-sea stability. For comparisons between satellite-based and NWP products, equivalent neutral wind speeds from QSCAT are converted to stability-dependent 10 m winds using 6-hourly atmospheric variables from ERA-40 (not shown). In tests, the use of another NWP product in the conversion process did not affect the results. Thus, for QSCAT, we first produce stability-dependent wind speeds and then form monthly means. Typically, differences between equivalent neutral winds and stability-dependent winds are very small (within ±0.2 m s^{-1}) over most of the global ocean on monthly timescales [*Kara et al.*, 2008a].

[12] Monthly means of equivalent neutral winds for SSM/I are directly obtained from http://www.remss.com and therefore have not been corrected. The SSM/I geophysical data set consists of data derived from observations collected by SSM/I instruments carried onboard the Defense Meteorological Satellite Program (DMSP) series of polar orbiting satellites (F11 and F13 are used here). A land-sea mask was already applied to SSM/I winds to remove unrealistic values near the coastal regions. A monthly value of 0.2 m s^{-1} is added to SSM/I winds to approximately account for air−sea stability [*Meissner et al.*, 2001].

[13] There are also a few basic differences in the way that winds from QSCAT and SSM/I are measured. For example, while QSCAT measures the backscatter from capillary and ultragravity waves, SSM/I winds are determined by the radiometer measuring polarization mixing and sea foam emission. The physics that influences the radiometrically determined winds is also dependent on stress; thus it is assumed that both types of sensors respond to stress rather than wind. Hence they are calibrated to equivalent neutral winds at a height of 10 m. QSCAT provides wind vectors, whereas SSM/I gives only wind speeds. Vector winds are much more useful for meteorology (wind divergence) and oceanography (curl of the stress). QSCAT works well through clouds, and radiometers can see through clouds as well, but cannot get winds when there is rain. QSCAT uses information from one frequency and multiple looks at the same location, whereas SSM/I senses multiple frequencies in one look.

3. Evaluation Procedure

[14] As a first step, mean winds from QSCAT are taken as a reference product, and compared with SSM/I, NOGAPS, ERA-40 and NCEP, separately. Various statistical metrics are used: mean error (ME), root-mean-square (RMS) wind speed difference, correlation coefficient (R) and nondimensional skill score (SS), all of which are described below.

[15] Let X_i (i = 1, 2, ⋯, n) be the set of n = 12 monthly mean reference QSCAT winds at the ith grid point over the global ocean, and let Y_i (i = 1, 2, ⋯, 12) be the set of corresponding winds from any one of the other products (i.e., SSM/I, NOGAPS, ERA-40 and NCEP) at the same grid location. Also, let $\overline{X}(\overline{Y})$ and σ_X (σ_Y) be the mean and standard deviations of the winds from QSCAT (other product), respectively. Following *Murphy* [1995], the statistical relationships in wind speed time series between QSCAT and any one of the other products at a given grid point are expressed as follows:

$$\mathrm{ME} = \overline{Y} - \overline{X}, \tag{1}$$

$$\mathrm{RMS} = \left[\frac{1}{n}\sum_{i=1}^{n}(Y_i - X_i)^2\right]^{1/2}, \tag{2}$$

$$R = \frac{1}{n}\sum_{i=1}^{n}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)/(\sigma_X\sigma_Y), \tag{3}$$

$$\mathrm{SS} = R^2 - \underbrace{[R - (\sigma_Y/\sigma_X)]^2}_{B_{\mathrm{cond}}} - \underbrace{\left[\left(\overline{Y} - \overline{X}\right)/\sigma_X\right]^2}_{B_{\mathrm{uncond}}}. \tag{4}$$

ME is the mean bias relative to QSCAT, RMS (root-mean-square) wind difference is an absolute measure of the distance between the two time series, and the R value is the linear correlation between the wind speed time series.

[16] The nondimensional SS given in equation (4) is the fraction of variance explained by any given wind product minus two dimensionless biases (conditional bias, B_{cond}, and unconditional bias, B_{uncond}) as explained in the study by *Murphy* [1988]. These two nondimensional biases are not taken into account in the correlation coefficient, equation (3). B_{uncond}, also known as systematic bias, is a measure of the difference between the means of wind speed time series (e.g., QSCAT versus SSM/I, QSCAT versus ERA-40, etc). B_{cond} is a measure of the relative amplitude of the variability in the wind speed time series, which is due to differences in standard deviations of the time series. A skill value of 1 indicates perfect relationship with QSCAT winds, and a negative skill value explains poor agreement with QSCAT winds.

4. Rain Effects on Monthly Mean QuikSCAT Winds

[17] There are earlier studies presenting the effects of rain on ku-band scatterometer winds [e.g., *Stiles and Yueh*, 2002; *Weissman et al.*, 2002b; *Tournadre and Quilfen*, 2003; *Hoffman et al.*, 2004]. Unlike these studies, our approach in determining the impact of rain contamination is based on monthly mean gridded QSCAT fields which involve the daily effects of air-sea stability. The stability corrections on QSCAT fields are necessary because winds from NWP

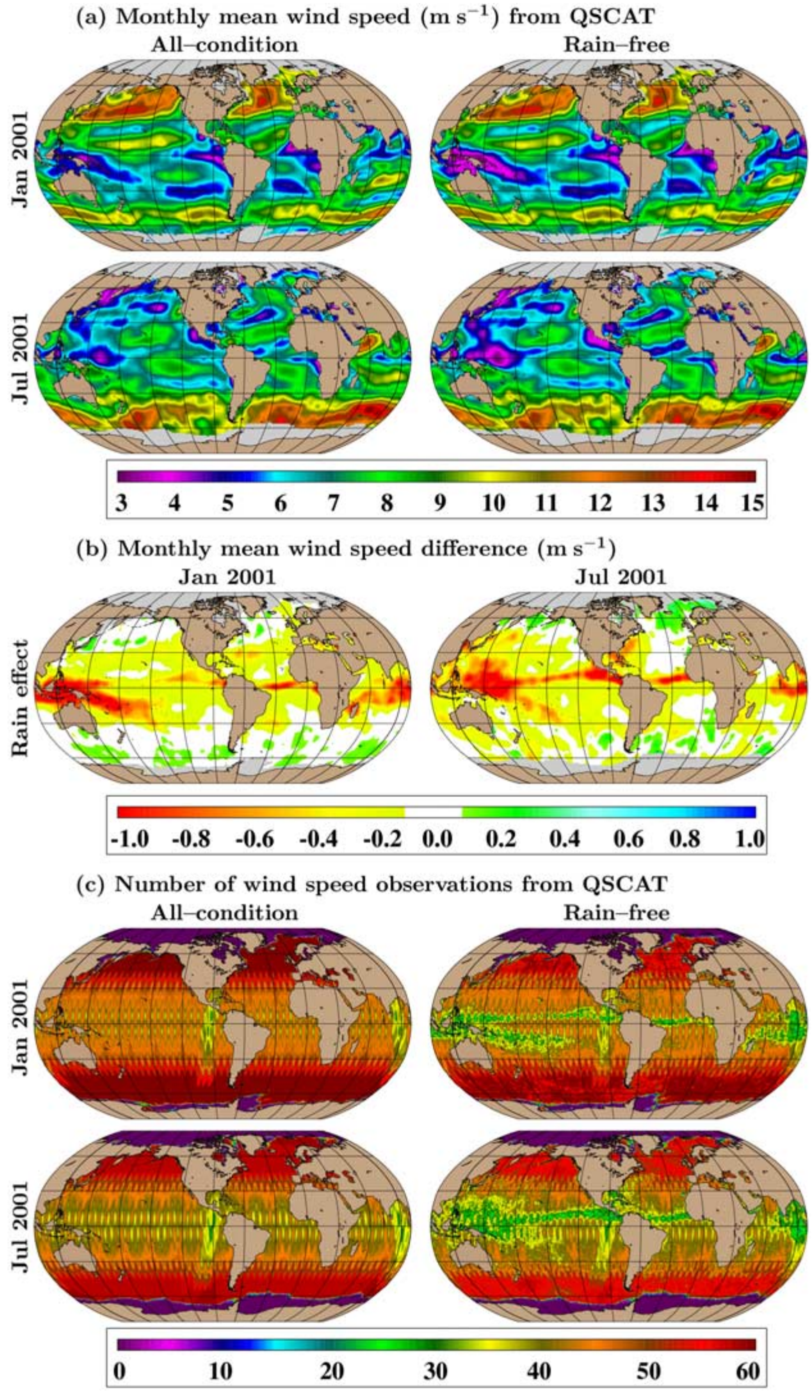

Figure 1. (a) $0.25^\circ \times 0.25^\circ$ resolution 10 m winds constructed from the QSCAT in January and July of 2001 when using (left) all-condition winds (rain-contaminated and rain-free) and (right) rain-free winds. (b) Differences in Figure 1a when subtracting the all-condition winds from the rain-free winds. Negative difference values in the color palette are shown in red. (c) Number of wind measurements used for forming monthly mean winds in Figure 1a for each month.

products already include effects of air-sea stratification, Thus, in this section, we further evaluate the impact of rain contamination on monthly mean wind speeds before performing any validations among the wind products.

[18] Twice-daily measurements from QSCAT are obtained from http://www.remss.com. These include zonal and meridional wind components gridded to a resolution of $0.25^\circ \times 0.25^\circ$. We produce monthly means of 10 m equivalent neutral wind speed averages for all months (September 1999 to August 2002). QSCAT winds are examined in two ways. (1) the rain-contaminated winds and (2) the rain-free winds. In (1) we include all winds (i.e., rain-contaminated and rain-free), hereinafter will be referred to as all-condition winds.

[19] There are more than 20 rain-free observations per month (per 0.25° × 0.25° bin) at many locations over the global ocean, as will be discussed later. In our initial processing, monthly averages are formed on the 0.25° × 0.25° grid using a cutoff of 20 rain-free observations per month. From this we form a 25-point (1.25° × 1.25° square) observation-weighted average at each 0.25° cell using a cutoff of 100 rain-free observations per month, which is found to be a sufficient number for the averaging based on various tests and diminishes the number of data voids. Finally, we fill in all remaining data voids (land- and rain-contaminated cells) using a creep-fill interpolation to reduce land contamination near land-sea boundaries as described in the studies by *Kara et al.* [2007, 2008b]. These steps result in a data set on a 0.25° grid with a similar resolution to ERA-40 (1.125° × 1.125°), which is used for the atmospheric stability corrections. The all-condition averaged winds are calculated the same way, using the same 20 observation cutoff but now with fewer initial data voids over the ocean.

[20] The impact of rain contamination in forming wind speed is examined over the global ocean in two selected months in 2001 (Figure 1). The rain-free winds are generally weaker than all-condition winds except at high latitudes during January and July of 2001 (Figure 1a). The rain-free and all-condition winds are nearly equal in the southern hemisphere. Differences on monthly timescales between all-condition winds and rain-free winds can exceed 1 m s^{-1} in tropical regions (Figure 1b), including the western tropical Pacific, tropical Atlantic and northern Indian Oceans. Rain contamination is clearly evident from the number of observations available for forming the monthly mean (Figure 1c).

[21] Some of the spatial patterns existing in the number of observation maps are due to satellite track artifacts. This is one reason for applying the 25-point smoothing mentioned earlier, which reduces variations due to sampling issues. For example, suppose one uses at least 20 observations in forming the monthly mean. This works better if 20 or more measurements are well distributed throughout the month. However, wind measurements could all be from the first 10 days of that particular month, i.e., a skewed distribution.

[22] At midlatitudes, the effect of rain is to increase estimated winds ≈0.4 m s^{-1} or less during the time periods examined here. In contrast, at high latitudes the presence of rain can slightly decrease estimates of wind speeds. For example, though small, rain-contaminated wind estimates can be ≈0.3 m s^{-1} weaker than rain-free winds in some regions of high northern and southern latitudes. These regionally differing impacts of rain can be anticipated from the study of *Draper and Long* [2003], combined with knowledge of the local wind and rain climatologies.

[23] The global area-weighted average of wind speed difference is −0.34 m s^{-1} during January 2001 and −0.33 m s^{-1} in July 2001. Thus, globally, rain-free winds are weaker by ≈0.3 m s^{-1}. Similarly, standard deviations of global differences for these two specific months are relatively higher with values of 0.95 m s^{-1} and 0.83 m s^{-1}, respectively. While rain-contaminated winds are artificially strong (biased high) under typical conditions (low wind speeds), we should emphasize that rain-contaminated winds are typically biased low in very strong winds such as those found in well developed hurricanes. However, in many cases a bigger influence for the underestimation could be the small spatial scale of the strong winds relative to the spatial scale of the footprint.

5. Evaluations of Wind Products

5.1. Spatial Variations of Wind Speed

[24] Spatial variability of wind speeds from QSCAT, SSM/I, NOGAPS, ERA-40 and NCEP are shown in February of 2001 (Figure 2), along with differences from QSCAT for each product. The wind speed field for QSCAT in Figure 2a is constructed using twice-daily scatterometer measurements with 25-point smoothing as described earlier.

[25] Within the latitudes spanning the Arctic and Antarctic, no ice mask is applied in order to show the extent of wind measurements from QSCAT (i.e., zero for ice-covered regions). Relatively fewer measurements (e.g., 30–40) are evident at low to mid-latitudes due to (1) the observation pattern and (2) increased likelihood of rain contamination. Overall, the rain-contaminated observations show spatially coherent patterns distinct from the observational pattern (see Figure 2b).

[26] Spatial variability of wind speeds from all products generally show similar features in February of 2001 (Figure 2c). For example, strong winds (>10 m s^{-1}) are found in high northern and southern latitudes. All the NWP products (NOGAPS, ERA-40 and NCEP) along with QSCAT and SSM/I have similar low wind speeds (4 m s^{-1}) in the tropical regions, including the eastern equatorial Pacific, tropical Atlantic and tropical Indian Oceans. In general, all products demonstrate similar magnitudes and patterns over the global ocean.

[27] Figure 2d shows biases relative to QSCAT. Specifically, NOGAPS and ERA-40 are weaker than QSCAT nearly everywhere over the global ocean, at least in this particular month of February 2001. Winds can be weaker by 2 m s^{-1} in specific locations (such as gap flows, current regions) or more at high northern latitudes. NCEP tends to give stronger winds than QSCAT almost everywhere, and by 2 m s^{-1} or more at high southern latitudes.

5.2. QSCAT Versus NWP Winds Over the Global Ocean

[28] Evaluating all wind products in a given single month based on a specific statistical metric (i.e., mean error), as in February of 2001 above, cannot provide sufficient information about overall accuracy of winds from NWP products relative to those from QSCAT. Thus, for a more comprehensive examination, we extend the evaluation procedure to the time period of September 1999 to August 2002, an interval which is common for all products, using all statistical metrics described in section 3.

[29] Mean wind speed bias calculated with respect to QSCAT reveals that NOGAPS (NCEP) has the weakest (strongest) winds over the common time period from September 1999 through August 2002 (Figure 3a). The ice-land mask is a function of the ice analysis and thus varies monthly from September 1999 through August 2002. Therefore each individual monthly ice-land mask described in section 2 is used in computing each statistical field, while the overall maximum ice extent over the three years is used when presenting results.

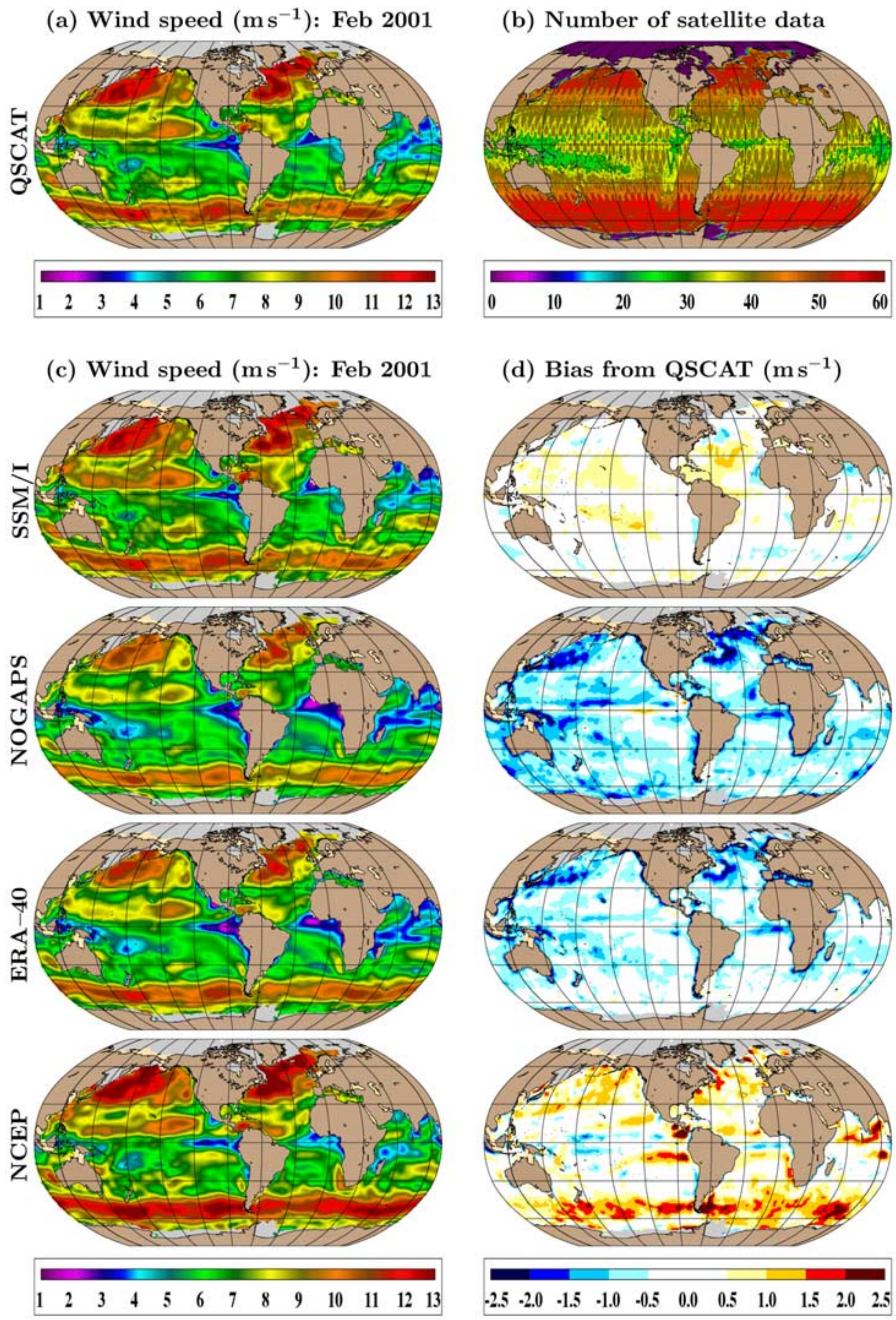

Figure 2. (a) Monthly mean rain-free winds at 10 m from QSCAT over the ice-free regions in February 2001; (b) number of rain-free wind observations used for forming winds in Figure 2a; (c) mean wind speeds from SSM/I, NOGAPS, ERA-40, and NCEP from top to bottom; and (d) difference in mean wind speed with respect to QSCAT for all products in Figure 2c, i.e., SSM/I-QSCAT, NOGAPS-QSCAT, etc. All are gridded to a resolution of $0.25^\circ \times 0.25^\circ$.

[30] Mean biases between QSCAT and SSM/I are within ± 0.5 m s^{-1} over the global ocean. RMS monthly wind differences relative to QSCAT also indicate better agreement for SSM/I winds than for any of the NWP products (Figure 3b). Among the NWP products, RMS values are lowest for ERA-40. Winds from all NWP products have RMS values of >1 m s^{-1} near the western boundary currents, including the Gulf Stream and the Kuroshio current systems. In the case of NCEP, RMS wind differences near the boundary currents are not as large as those for ERA-40 and NOGAPS. However, NCEP has consistently large errors in the high southern latitudes, where the agreement is relatively good for ERA-40 winds.

[31] Using the bias and RMS values, we determine the NWP product yielding lowest values in comparison to QSCAT wind at each grid point. SSM/I winds are not

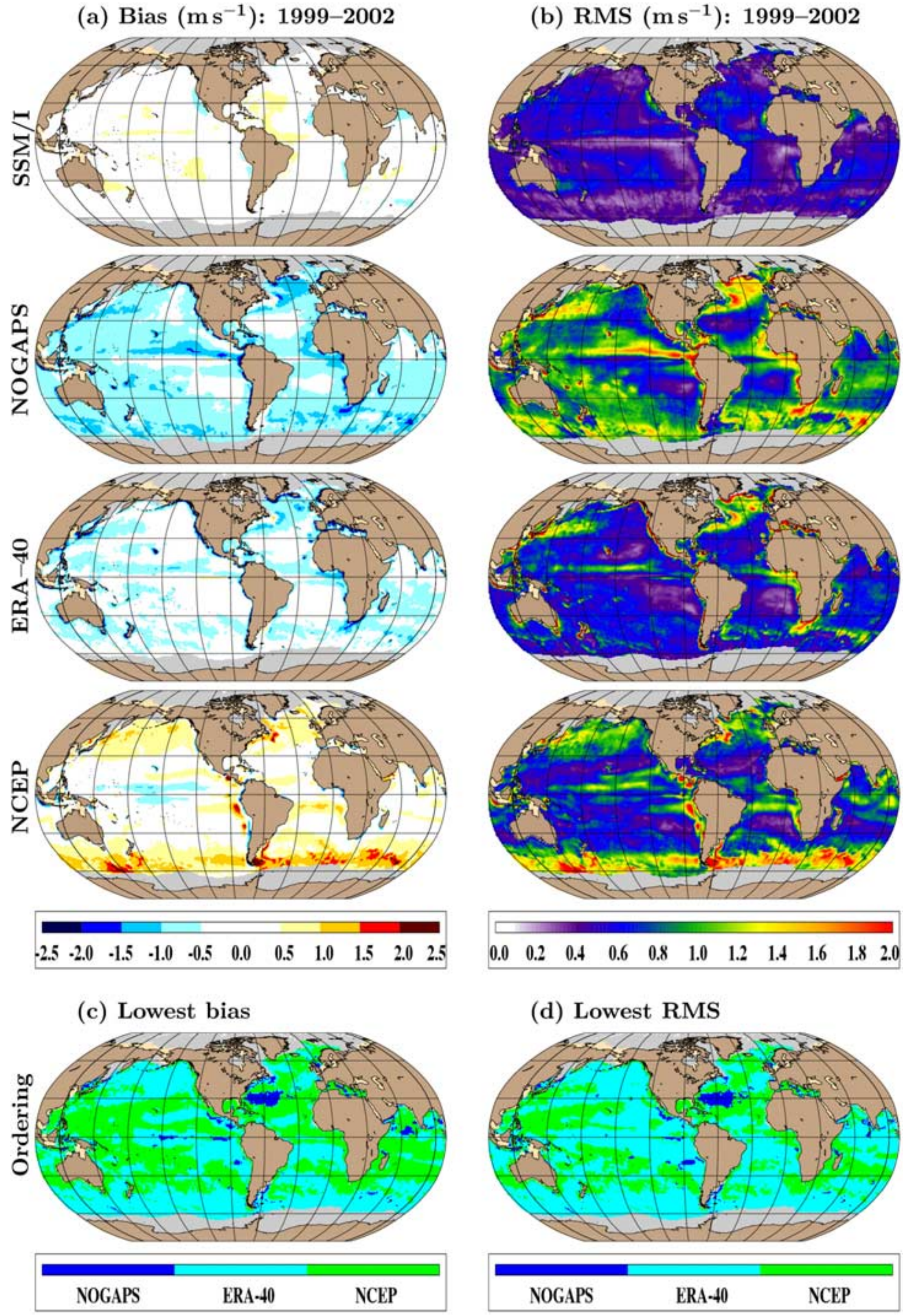

Figure 3. Spatial maps of mean (a) bias and (b) RMS difference in wind speed between QSCAT and other products from September 1999 through August 2002. The bias in Figure 3a was computed by subtracting QSCAT from other products, SSM/I-QSCAT, NOGAPS-QSCAT, etc. Also shown are NWP products giving (c) lowest bias and (d) lowest RMS with respect to QSCAT winds.

considered in this analysis, although they are generally superior to NWP products for estimating monthly wind speed over most of the global ocean. In the analysis, bias and RMS values given for NWP products, shown in Figures 3a and 3b, are ordered from the smallest to the largest. We then plot the color representing the NWP product associated with the smallest one at each grid point and produce global maps (Figures 3c and 3d). It should be noted that biases are ranked in terms of their absolute values.

[32] Results reveal that winds from ERA-40 or NCEP re-analyses tend to be closest to those from QSCAT over most of the global ocean, showing better agreement than the operational winds from NOGAPS. In fact, the percentage area of the global ocean mean, where the bias is the smallest, is 44% for ERA-40 and 52% for NCEP (Figure 3c). In the case of RMS wind speed difference with respect to QSCAT winds, ERA-40 (NCEP) winds result in the lowest values over 58% (37%) of the global ocean (Figure 3d).

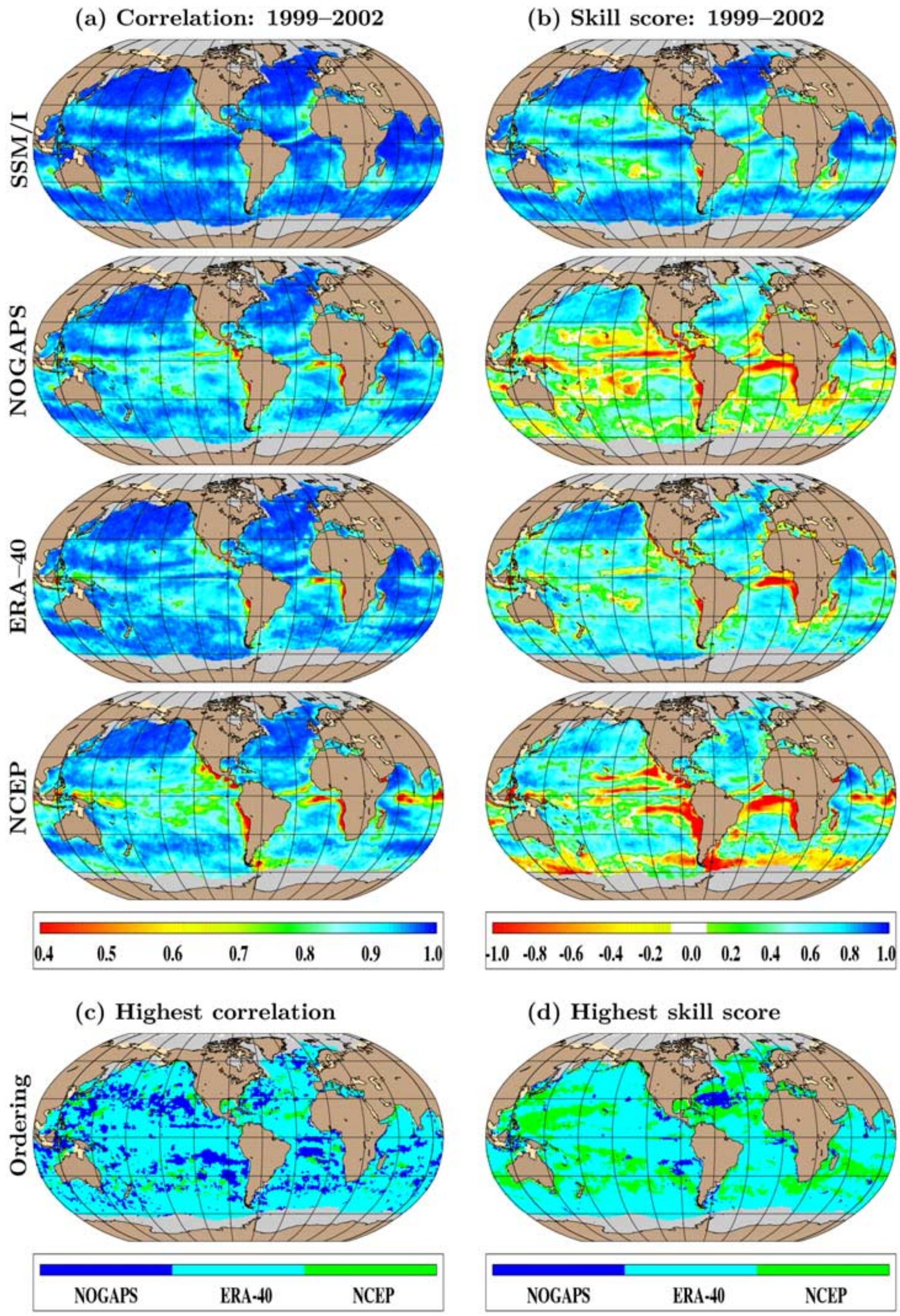

Figure 4. The same as Figure 3 but for (a) correlation coefficient and (b) nondimensional skill score. (c and d) NWP products giving highest correlation and highest skill in comparison to QSCAT winds. Negative skill values (red color tones) indicate poor agreement.

[33] We now examine correlation and skill of winds from all NWP products and SSM/I in comparison to those from QSCAT from September 1999 through August 2002. Correlation coefficients are generally >0.8 over the global ocean (Figure 4a). For 36 monthly mean wind speed time series at a given grid point, an absolute R value of at least 0.45 is needed if one uses zero correlation as the demarcation point for significance at 95% confidence interval. Thus there is a strong linear relationship between QSCAT and other products. Although correlations are high, the nondimensional skill, involving RMS and nondimensional biases (see section 3), reveals poor agreement between QSCAT and NWP products in some regions (Figure 4b). For example, skill values are negative for NOGAPS in the eastern equatorial Pacific Ocean and a majority of the equatorial Atlantic Ocean. Similarly, poor agreement between NCEP and QSCAT winds is evident in the same regions and even extending to some other locations at southern latitudes and the tropical Indian Ocean.

[34] Similar to the mean bias and RMS, we also order correlation and skill values from the smallest to the largest to find the NWP product giving closest agreement to the

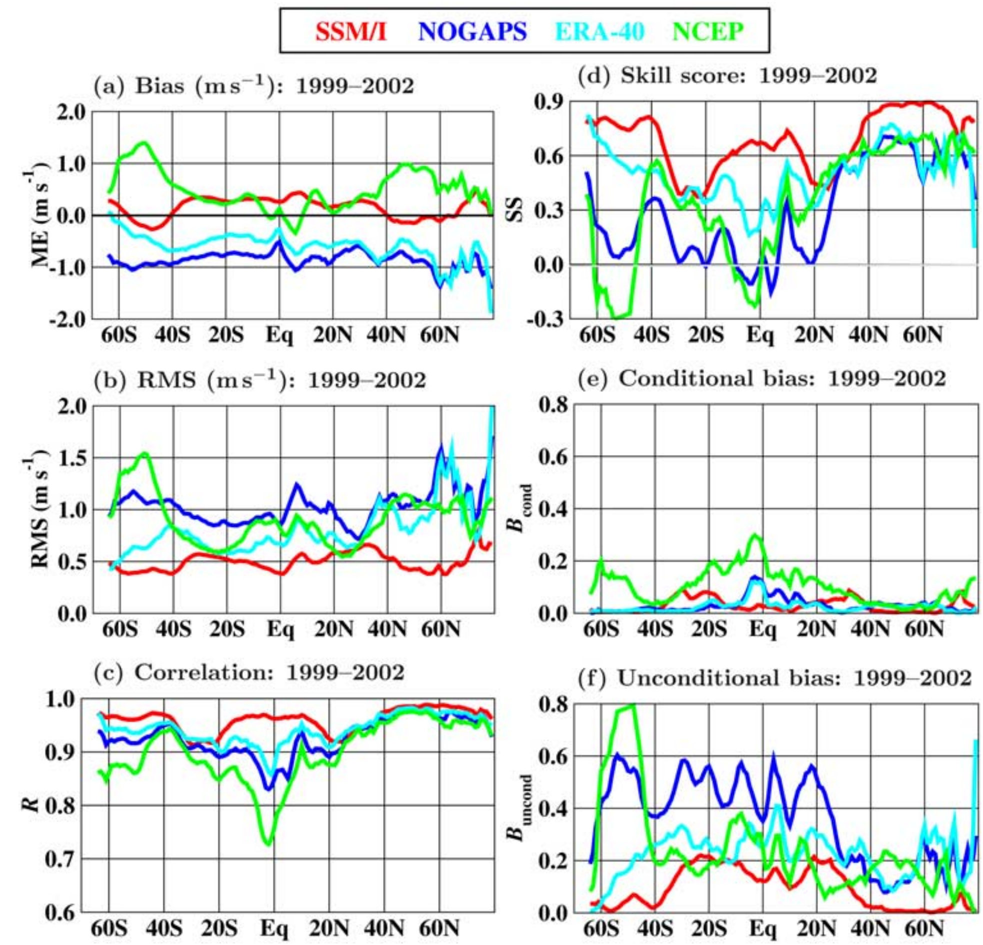

Figure 5. Zonal averages of statistical metrics shown in Figures 3 and 4. Zonal averages for conditional and unconditional biases used for calculating nondimensional skill score are also given. Zonal averaging was performed at each 0.25° latitude belt.

QSCAT winds. ERA-40 winds give the highest correlations, with 70% of the global ocean, followed by NOGAPS 23% (Figure 4c). However, differences in correlations for the NWP products are not statistically significant, that is, there are negligible differences in ordering values. Skill score provides more insight to performance of NWP winds, as Figure 4b shows more regional differences among values. Highest skill scores are evident from ERA-40 over most of the global ocean (66%), and with NCEP winds preferred over only 28% (Figure 4d).

[35] To examine regional differences in wind products, zonal averages of the statistical metrics (bias, RMS, correlation and skill score) shown in Figures 3a, 3b, 4a, and 4b are computed (Figure 5). Zonally averaged wind biases from NOGAPS and ERA-40 (NCEP) are nearly always negative (positive), indicating weaker (stronger) winds than QSCAT, but regional variations of RMS values for all NWP products are generally similar (Figures 5a and 5b). NCEP winds typically have the low correlations ranging between 0.7 and 0.9 in comparison to other products, which is one of the factors leading to negative skill in the tropical regions (Figures 5c and 5d) Conditional and unconditional biases are also plotted on the same *y* scale. They demonstrate that the unconditional bias is the main contributor to low skills between NWP products and QSCAT winds, that is, the biases are due mainly to differences in the means rather than standard deviations (Figures 5e and 5f).

5.3. Comparisons at Buoy Locations

[36] In addition to global analysis of differences in wind products relative to QSCAT winds, further evaluations are performed against winds from many individual moored buoys located in tropical Atlantic and Pacific as well as coastal North America (Figure 6). This comparison allows one to examine accuracy of not only the NWP model–based products of NOGAPS, ERA-40 and NCEP but also the satellite-based QSCAT and SSM/I winds.

[37] Wind speed measurements from buoys are obtained from three sources as follows: (1) the Tropical Atmosphere-Ocean (TAO)/TRITON array [*McPhaden et al.*, 1998], (2) the Pilot Research Array (PIRATA) [*Servain et al.*, 1998], and (3) the National Data Buoy Center (NDBC) database, which is available from the National Oceanographic Data Center (NODC) (http://www.nodc.noaa.gov/BUOY/buoy.html).

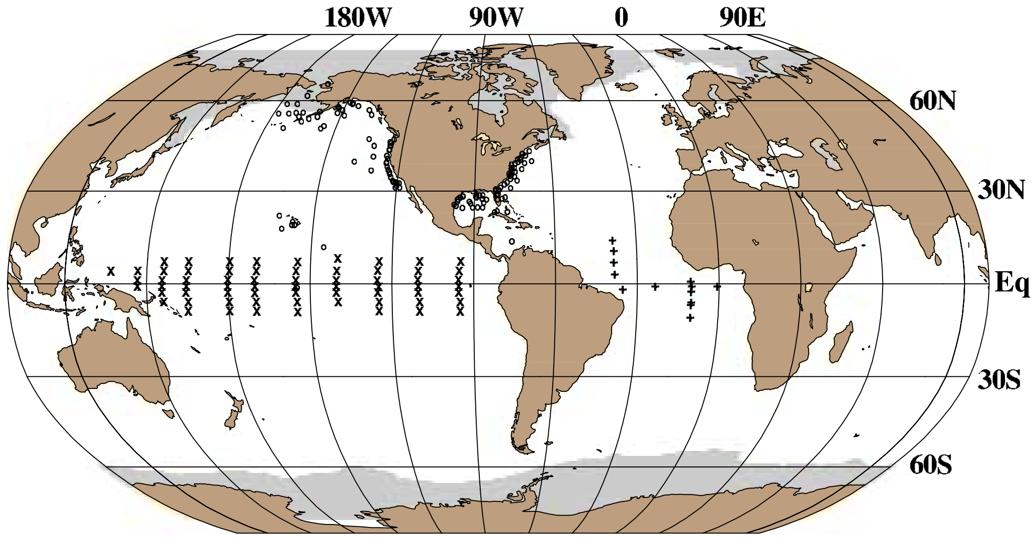

Figure 6. Locations of TAO (x), PIRATA (+) and NDBC (o) used in the analyses in this paper.

[38] There are 78 TAO, 117 NDBC and 13 PIRATA buoys used in this study over the time period. The heights of sensors measuring winds and other near-surface atmospheric variables (e.g., air temperature, sea surface temperature, relative humidity) at buoy locations vary. For example, buoy winds are typically measured at a height of 4 m, requiring an adjustment to be consistent with 10 m winds represented by satellite-based and NWP products. Measurements of near-surface atmospheric variables from buoys are used for adjusting winds to 10 m from their original heights.

[39] At all buoy locations, we first adjust hourly wind speeds to 10 m using Coupled Ocean-Atmosphere Response Experiment (COARE) and Bourassa-Vincent-Wood (BVW) models. These air-sea flux algorithms are described in the studies by *Fairall et al.* [2003] and *Bourassa et al.* [1999]. We examined a total of 7594 monthly mean winds from all NDBC, TAO and PIRATA buoys. Both algorithms provided similar results, indicating the robustness and accuracy of the adjustment process. The mean bias between the two is 0.01 m s^{-1}. The adjustment to 10 m buoy winds is made only when all necessary near-surface atmospheric variables are available from the buoy measurements; otherwise, that specific record is skipped. Details of buoy data and the adjustment to 10 m winds are further provided in the study by *Kara et al.* [2008a]. After adjusting winds to 10 m, monthly means were formed.

[40] Scatterplots of 10 m monthly mean wind speeds are produced between the buoys and each wind product (Figure 7). There are 584 monthly wind values from NDBC buoys, 606 from TAO buoys, and 91 from PIRATA buoys in 2001. The most obvious feature of these plots is that NCEP winds typically overestimate wind speed at all locations. Table 2 reveals positive and relatively high skill score values for all products in comparison to buoy winds. The agreement between the pairs of QSCAT versus buoy and SSM/I versus buoy is quite remarkable, with skill values of 0.80 and 0.78 and RMS values of 0.73 m s^{-1} and 0.81 m s^{-1}, respectively. Wind speeds from NWP products also agree well with the buoy observations, but skill and correlation values are slightly lower than for the satellite-based products.

[41] Another feature evident from Table 2 is that QSCAT winds are stronger than buoy winds. This is consistent with earlier studies which are based on collocated measurements although our evaluation statistics are based on monthly winds at TAO, NDBC and PIRATA locations during different time periods. For example, *Satheesan et al.* [2007] analyzed the performance of QSCAT winds using in situ data from moored buoys over the Indian Ocean, and demonstrated that QSCAT overestimates the winds by 0.37 m s^{-1}. They also found a high correlation value of 0.87 (versus 0.92 in our study). Similarly, *Pickett et al.* [2003] pointed to the existence of stronger QSCAT winds in comparison to buoy winds with RMS differences of 1 m s^{-1} near the U.S. west coast.

6. Impact of Winds on Surface Heat Fluxes

[42] As discussed in section 5, there can be quite large differences in various monthly wind products, although the agreement between NWP products and QSCAT is generally quite good, with high skill values over a majority of the global ocean. Since the earlier analysis is based on monthly averages only, one might wonder how results would change on shorter timescales, which is the major focus of this section. In particular, on a given day we will first investigate differences in winds between NWP products and QSCAT. We will then explore differences in the resulting sensible heat and latent heat fluxes when using winds from each particular product over the global ocean.

[43] An example of variations on shorter timescales (Figure 8) shows daily means of wind speeds at 10 m, sensible and latent heat fluxes along with differences with respect to the fields from QSCAT over the global ocean on 1 February 2002. Computations of the fluxes will be described below in detail. For QSCAT we form daily winds only in grid cells for which at least 2 over passes exist in one day (Figure 8a). For NWP products, daily winds are computed based on 6-hourly values for ECMWF and NCEP and 3-hourly values for NOGAPS. Spatial patterns of winds from all NWP products reveal distinct similarities with

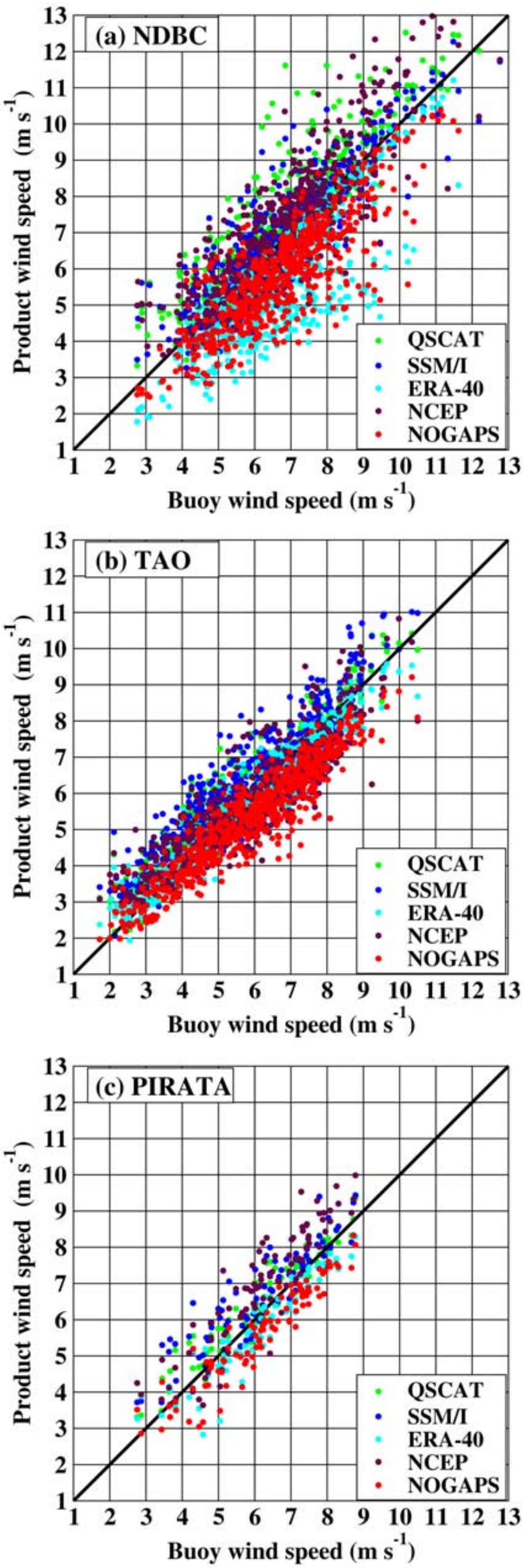

Figure 7. Scatterplots of monthly mean wind speeds at 10 m above the sea surface obtained from buoys versus those from various products. Results are shown at (a) NDBC, (b) TAO, and (c) PIRATA buoys in 2001.

those from QSCAT over the majority of the global ocean. Wind speeds from NWP products generally reveal good agreement with those from QSCAT in the tropical regions and midlatitudes on this particular day. Strong winds (>20 m s^{-1}) at high northern latitudes are evident from all products. However, differences in winds are evident especially in high southern regions and the North Atlantic Ocean, as will be shown later.

[44] Given those differences in winds from satellite- and NWP-based products, we also compare sensible and latent heat fluxes (Figures 8b and 8c). Computations are based on the COARE (v3.0) algorithm [*Fairall et al.*, 2003], where the bulk parameterizations calculate exchange coefficients for sensible and latent heat fluxes using wind speed, air-sea temperature and specific humidity differences [e.g., *Kara et al.*, 2005]. For consistency, all of these 6-hourly surface fields are taken from ERA-40. Thus, in forming sensible and latent heat fluxes, the only changing variable is the wind speed from each of the products. The resulting sensible heat fields from QSCAT winds qualitatively generally agree with those from NWP winds, with positive sensible heat fluxes mostly confined to high southern latitudes and the western North Atlantic in all products (Figure 8b). The latent heat fluxes from all NWP products and QSCAT reveal similar patterns but few regions of positive values (Figure 8c). Similar to sensible heat fluxes, the largest magnitude for the latent heat fluxes are seen in the North Atlantic Ocean where winds are strongest (as already shown in Figure 8a) and air-sea temperature differences are greatest.

[45] Differences in wind speeds, sensible and latent heat fluxes are formed for NWP products to examine where in the global ocean NOGAPS, ERA-40 and NCEP fields result in large biases in comparison to those from QSCAT (Figures 8d–8f). In summary, Figure 8d is based on winds from Figure 8a. For example, QSCAT winds are subtracted from NOGAPS winds to find the mean bias at each grid point on 1 February 2002. Similarly, in Figure 8e sensible heat flux computed using QSCAT winds is subtracted from the flux computed using NOGAPS winds. In all difference plots, red denotes regions where results from NWP products are smaller than those from QSCAT fields, and white indicates the close agreement.

[46] The resulting differences can be quite large for all variables in some regions of the global ocean. In particular, NWP winds are much weaker (5 m s^{-1} or more) than QSCAT winds in the North Atlantic where a low is located, and rain may exist that was not sufficiently removed (Figure 8d). NOGAPS and ERA-40 winds tend to be somewhat weaker than QSCAT in the high southern latitudes, while NCEP winds are typically much stronger. In fact, NCEP winds are mostly stronger than QSCAT winds in all regions other than the North Atlantic Ocean. There are also some biases in the regions where the Kuroshio and Gulf Stream current systems are located. These biases are likely due to (1) differences between earth-relative and surface-relative winds, and (2) differences in spatial resolution. The most striking feature of differences in sensible heat fluxes is that using the different NWP products results in almost no bias relative to QSCAT over most of the global ocean (Figure 8e). The largest differences are in the North Atlantic Ocean, as expected from large differences in wind speed.

Table 2. Evaluation of Monthly Mean of 10 m Wind Speeds at the NDBC, TAO, and PIRATA Buoy Locations in 2001[a]

2001	Bias (m s^{-1})	RMS (m s^{-1})	σ_{BUOY} (m s^{-1})	$\sigma_{PRODUCT}$ (m s^{-1})	R	SS
Buoy versus QSCAT	0.33	0.73	1.72	1.69	0.92	0.80
Buoy versus SSM/I	0.30	0.81	1.72	1.61	0.90	0.78
Buoy versus NOGAPS	−0.72	1.08	1.72	1.49	0.88	0.60
Buoy versus ERA-40	−0.61	1.07	1.72	1.60	0.86	0.61
Buoy versus NCEP	0.15	0.97	1.72	1.77	0.86	0.70

[a]Statistics are based on 1281 monthly mean winds obtained from all 137 buoys (i.e., NDBC, TAO, PIRATA). σ_{BUOY} denotes standard deviation of buoy winds in 2001. $\sigma_{PRODUCT}$ denotes standard deviation of winds from various products, i.e., QSCAT, SSM/I, ERA-40, NCEP, and NOGAPS. Differences in wind speed are computed with respect to buoy values (e.g., QSCAT-buoy, SSM/I-buoy, NOGAPS-buoy, etc.).

The color palette does not convey these large differences, but in fact differences for sensible heat fluxes are >100 W s^{-2} in this region. Differences in latent heat fluxes are larger than those in sensible heat fluxes (Figure 8f) because of larger latent heat flux magnitudes. Note that it is the magnitude of negative fluxes that are being overestimated or underestimated. In general, NOGAPS and ERA-40 tend to underestimate latent heat fluxes by 20–40 W m^{-2}, while overestimation is common from NCEP fluxes in comparison to QSCAT.

7. Conclusions

[47] Through quantitative analyses and various statistical metrics we examine accuracy of winds at 10 m above the sea surface over the global ocean. Our major goal is to quantify differences among fields commonly derived from operational, re-analysis products and satellite products. This is done using globally available winds from the three NWP products (NOGAPS, ERA-40 and NCEP) and two satellite products (QSCAT and SSM/I). Considering the QSCAT winds as a reference, we first evaluate winds from NWP products and SSM/I globally. Comparisons are then performed for all wind products at moored buoy locations.

[48] Before performing any evaluations, rain contamination in QSCAT winds is quantified. It is demonstrated that the rain-free winds are generally 0.5–1 m s^{-1} weaker than the rain-contaminated ones over the majority of tropical regions, while differences are small in most other regions. The outcome of removing the rain effect is to reduce winds by ≈0.2 m s^{-1}, with significant regional variations. The impact of rain on wind speeds can change regionally from one month to another. Thus not accounting for rain contamination in satellite-based winds can alter accuracy of satellite-based winds and can be misleading for the evaluations of NWP model-based wind products.

[49] Monthly winds from all NWP products demonstrate nearly similar skill in comparison to those from QSCAT. In fact, the skill score approaches perfection (close to 1) over the majority of the global ocean. However, winds from NOGAPS and NCEP typically have no skill in the tropical regions and in high southern latitudes. There are high correlations between winds from each one of NWP products and those from QSCAT. RMS differences for monthly wind speed differences of NWP products are typically <1 m s^{-1} over most of the global ocean, and this is also confirmed by independent buoy analysis. NCEP is found to be the only wind product with typically relatively large RMS wind speed differences of >1 m s^{-1} in the high southern latitudes.

[50] Of the NWP products examined here, NOGAPS and ERA-40 tend to underestimate wind speed, while NCEP tends to overestimate it. All three demonstrate significant regional variability in these tendencies. In comparison to NWP products, winds from satellites provide relatively higher accuracies. Despite these positive characteristics, the incomplete daily coverage by the satellites makes them insufficient as a stand-alone source for atmospheric forcing for ocean mixed layer models, requiring high temporal resolution (e.g., 3 hourly). The NWP products offer gap-free wind fields at higher temporal resolution, maintaining consistent representations of not only wind speed but also other atmospheric fields needed to compute surface heat and momentum fluxes which are needed for ocean model predictions.

[51] In addition to the monthly mean analysis, in this study we also examine differences among wind products on shorter timescales. For this purpose, daily winds are formed based on two satellite passes. Similarly, daily winds from NWP products are constructed based on 3- and 6-hourly values. Comparisons to the satellite (QSCAT) track passes reveal that NWP winds can be quite different from satellite winds, especially at the North Atlantic Ocean and high southern latitudes. Typically, in the former (latter) location, NWP winds are too strong (weak) by 5 m s^{-1} (2 m s^{-1}). The resulting sensible and latent heat fluxes based on winds from NWP products can have errors as large as 100 W m^{-2} with even larger errors in the case of latent heat flux in the North Atlantic. The comparisons are of practical use because daily winds from satellites have insufficient temporal sampling for some applications (e.g., diurnal variability, wind power distribution, surface fluxes associated with episodic forcing), making the improved sampling from NWP products desirable for those applications. However, the NWP data are only useful for these applications if the regional biases can be removed.

[52] Finally, since a lot of ocean modeling work is done for historical time periods for which NWP re-analyses are the best available drivers, we think that some mention of the ongoing improvements in NWP might be appropriate. For example, most operational global NWP models now have higher resolution and assimilate QSCAT, and all probably would give better results for current times than for this historical period. Most NWP models also either are now or soon will be assimilating ASCAT winds from the METOP-A satellite, which should provide additional coverage and benefits. Therefore continuous evaluations of winds, as presented in this study, are helpful for many types of applications. In particular, winds, either individually or in combination from various products, are used to force ocean models. Errors and biases in these products need to be understood since they will negatively impact the simulated ocean response. This understanding can also lead to strat-

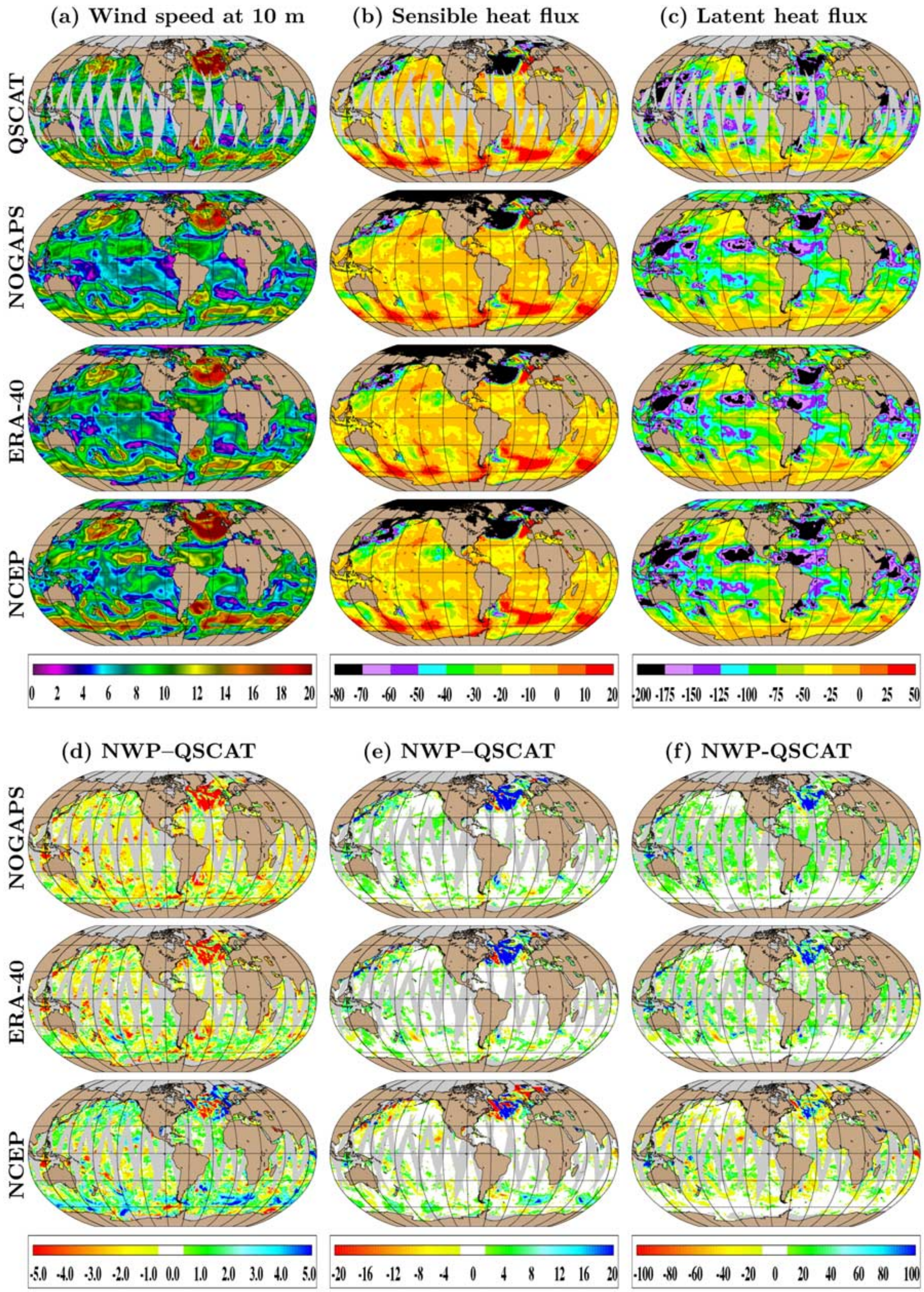

Figure 8. Spatial variations of the variables from QSCAT and NWP products on 1 February 2002: (a) wind speed (m s^{-1}), (b) sensible heat flux (W m^{-2}), and (c) latent heat flux (W m^{-2}). (d, e, and f) Differences for NWP products with respect to QSCAT.

egies that blend two or more of these products to produce improved forcing fields.

[53] **Acknowledgments.** The two anonymous reviewers are greatly acknowledged for their constructive comments, which improved the quality of the article. This work is funded by the Office of Naval Research (ONR) under the 6.1 project, Global Remote Littoral Forcing via Deep Water Pathways, and the 6.2 project, HYbrid Coordinate Ocean Model and Advanced Data Assimilation. QSCAT and SSM/I wind measurements are produced by Remote Sensing Systems and sponsored by the NASA Ocean Vector Winds Science Team. The article is contribution NRL/JA/7320/08/8220 and has been approved for public release.

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