Assessment of Sea Surface Wind from NWP Reanalyses and Satellites in the Southern Ocean

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ABSTRACT

Reanalysis projects and satellite data analysis have provided surface wind over the global ocean. To assess how well one can reconstruct the variations of surface wind in the data-sparse Southern Ocean, sea surface wind speed data from 1) the National Centers for Environmental Prediction–Department of Energy reanalysis (NCEP–DOE), 2) the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim), 3) National Climate Data Center (NCDC) blended sea winds, and 4) cross-calibrated multiplatform (CCMP) ocean surface velocity are evaluated. First, the accuracy of sea surface wind speed is validated with quality-controlled in situ measurements from research vessels. The results show that the CCMP value is closer to the ship observations than other products, whereas the NCEP–DOE value has the largest systematic positive bias. All four products show large positive biases under weak wind regimes, good agreement with the ship observations under moderate wind regimes, and large negative biases under high wind regimes. Second, the consistency and discrepancy of sea surface wind speed across different products is examined. The intercomparisons suggest that these products show encouraging agreement in the spatial distribution of the annual-mean sea surface wind speed. The largest across-data scatter is found in the central Indian sector of the Antarctic Circumpolar Current, which is comparable to its respective interannual variability. The monthly-mean correlations between pairs of products are high. However, differing from the decadal trends of NCEP–DOE, NCDC, and CCMP that show an increase of sea surface wind speed in the Antarctic Circumpolar region, ERA-Interim has an opposite sign there.

1. Introduction

Sea surface wind drives a wide range of ocean movement, from individual storm surges to a complete current system. Near-inertial oscillations observed in the mixed layer induced by sea surface wind play an important role in transferring momentum from the atmosphere to the ocean (D’Asaro 1985; Alford 2001). Sea surface wind also regulates interactions between the atmosphere and the ocean through modulating air–sea exchanges of heat, moisture, and gases (Curry et al. 2004). Therefore, accurate sea surface wind is needed for various applications.

This is particularly true in the convectively active Southern Ocean (i.e., the Southern Ocean hosts the climatologically strongest sea surface wind in the world), which drives the deep and vigorous Antarctic Circumpolar Current eastward around the Antarctic continent (Rintoul et al. 2001). These winds push the surface waters away from the Antarctic continent through Ekman transport, creating a massive divergence-driven upwelling south of the current and strongly tilting the isopycnal surfaces along the path of the Antarctic Circumpolar Current.

The numerical weather prediction (NWP) reanalyses and satellite-derived products are the major data sources of sea surface wind at various spatial and temporal scales. The NWP reanalyses can provide sea surface wind continuously in space and time (i.e., 3 or 6 h) over the global ocean. However, the primary problem of the NWP reanalyses is that they are more dependent on physical
parameterizations used in the particular atmospheric model (Curry et al. 2004). Satellite-derived products can provide sea surface wind at high spatial resolution, but the swath sampling of satellite tracks tends to limit coverage over the global ocean at high frequency (i.e., 3 or 6 h).

Some validation studies have been carried out by comparing NWP reanalysis and satellite-based sea surface wind with in situ observations using buoys and research vessels (Smith et al. 2001; Renfrew et al. 2002; Ladd and Bond 2002; Parekh et al. 2007; Atlas et al. 2011). These studies are primarily conducted for tropical, subtropical, and northern midlatitude oceans. However, the accuracy of NWP reanalysis and satellite-based sea surface wind in the data-sparse Southern Ocean is not well documented in previous studies, although slight progress is being made (Atlas et al. 2011).

In this study, we use in situ measurements from selected research vessels that at the Research Vessel Surface Meteorology Data Center achieved the ability to evaluate the accuracy of the NWP reanalysis and satellite-based sea surface wind speed (SSWS) in the Southern Ocean. Also, a preliminary intercomparison of the consistency and discrepancy between the NWP reanalysis and satellite-based SSWS is conducted for the Southern Ocean.

2. Data and method

a. NWP reanalysis and satellite-based sea surface wind

Four sea surface wind products that include the Southern Ocean are analyzed in this study. A brief description of each product is given below. The National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF) NWP reanalyses use improved forecast model and data assimilation systems, which are kept unchanged over the reanalysis period to produce a consistent climate record without discontinuities due to changes in forecast models and data assimilation techniques, although the observation network itself can change (Kanamitsu et al. 2002; Dee et al. 2011). The NCEP–Department of Energy (DOE) reanalysis provides data at a spatial resolution of T62 (~1.9°) from 1979 to the present. The ECMWF Interim Re-Analysis (ERA-Interim) is the latest ECMWF global reanalysis, providing data at a spatial resolution of 1.5° from 1979 to the present. The temporal resolution is four times daily for both NCEP–DOE and ERA-Interim.

The National Climate Data Center (NCDC) blended sea surface wind (Zhang et al. 2006) uses a spatial temporally weighted interpolation method to combine satellite wind products obtained from the Remote Sensing System (RSS), including three microwave radiometer sensors (the Special Sensor Microwave Imager, the Tropical Rainfall Measuring Mission Microwave Imager, and the Advanced Microwave Scanning Radiometer for Earth Observing System) and one scatterometer (QuikSCAT). The wind direction information is obtained from the NCEP–DOE reanalysis. The NCDC blended sea surface wind provides data on a global 0.25° grid from July 1987 to the present. By contrast, the cross-calibrated multiplatform (CCMP) ocean surface velocity uses a variational analysis method to combine not only the satellite wind products obtained from RSS but also in situ data from ships and buoys archived at the National Center for Atmospheric Research (NCAR). Moreover, the CCMP uses the 40-yr ECMWF Re-Analysis (ERA-40) and operational analysis as the background winds (first guess as a prior estimate for the variational analysis; Atlas et al. 2011). The CCMP product also provides sea surface wind on a global 0.25° grid from July 1987 to December 2009. The four-times daily data are available for both the NCDC and CCMP. Given that the NCDC and CCMP are primarily dependent on satellite data, hereafter we refer to them as satellite-based products.

b. Ship observations

Near–sea surface wind speed observations are obtained from the Research Vessel Surface Meteorology Data Center (RVSMDC), which collects, quality controls, archives, and distributes surface meteorological data from research vessels (http://coaps.fsu.edu/RVSMDC/html/data.shtml). The data include observations made by a nearly continuous automated recording system and ship bridge crews. The World Ocean Circulation Experiment (WOCE) was carried out over the global ocean between 1990 and 1998. Both automated and visual quality-control procedures were used for the WOCE cruises, and quality-control flags were added in the data (Smith et al. 1996). Moreover, problems in computing true winds (defined as a vector wind with a speed referenced to the fixed earth and a direction referenced to true north) from an automated system were identified and corrected (Smith et al. 1999). The Shipboard Automated Meteorological and Oceanographic System (SAMOS) initiative is complementary to the Voluntary Observing Ship project, which collects surface marine meteorological and oceanographic data at 1-min intervals from 2005 to the present. The quality-control flags were added in the data based on the automated quality control (Briggs et al. 2011). In this study, only the ship observations believed to be realistic and flagged with good quality are used.
The domain selected for this study encompasses all the oceans south of 35°S since our focus is the Southern Ocean. In this study, a total of 10 cruises are selected from WOCE and SAMOS cruises for the period 1992–2009, including research vessels (R/Vs) Knorr, Roger Revelle, Ronald Brown, Thompson, Lawrence M. Gould, Polarstern, Franklin, Aurora Australis, Discovery, and Vidal Gormaz (see Table 1). For research cruises having both port and starboard winds (i.e., Lawrence M. Gould and Aurora Australis), only wind speed where the difference between the port and starboard wind speed is less than 0.1 m s\(^{-1}\) and the corresponding wind direction difference is less than 10° is used in this study. As a result, about 11.4% of the data are used for these two cruises. Figure 1 gives the locations of wind speed measurements for each individual research cruise south of 35°S. It shows extensive wind speed samplings in the Southern Ocean.

c. Method

The ship observations used to evaluate the NWP reanalysis and satellite-based SSWS were measured at different anemometer heights, ranging from ~10 to ~37 m. To facilitate direct comparisons, shipboard wind measurements must be adjusted to a reference height of 10 m.

![Figure 1](https://example.com/figure1.png)

**FIG. 1.** Locations of in situ measurements for each research vessel south of 35°S.
Here, we assume that the atmospheric conditions are neutrally stable, since not all the meteorological and oceanic observations (i.e., sea temperature) are synchronous. The following equation for the modified log wind profile is used:

\[ ku/u* = \ln(z/z_0) \]  
\[ z_0 = \alpha_z u^2/g, \]

where \( u \) is the wind speed at a height of \( z \), \( k \) is the von Kármán constant (0.4), \( \alpha_z \) is the Charnock parameter (0.016), \( u_\alpha \) is the friction velocity, \( z_0 \) is the roughness height, and \( g \) is the gravitational acceleration. Then the adjusted wind speed at 10 m \( (u_{10}) \) can be obtained using

\[ u_{10} = (u_\alpha/k) \ln(10/z_0). \]

Similar methods to adjust wind have been used in previous studies (Liu and Tang 1996; Mears et al. 2001).

In this study, comparison of the ship observations and the particular product (NCEP–DOE, ERA-Interim, NCDC, and CCMP) requires each ship value to be matched with a product value in both space and time. Only the sea surface wind speed from the particular product and from the ship observations falling within 10 min of one another are used. We extract the sea surface wind speed from the particular product that has the smallest distance relative to the ship observations (i.e., falling within the half-grid spacing scale of the particular product). As a result, the total number of matchups is 37,084 for 1992–2009 (note there is no matchup in 1999–2003 and 2007 based on the criteria used here).

3. Results

a. Comparisons between NWP and satellite wind speeds and ship measurements

The overall bias and root-mean-square error (RMSE) of the NCEP–DOE SSWS are 1.37 and 3.60 m s\(^{-1}\), respectively (note that the bias and RMSE are calculated based on the difference between the particular product and ship observations). By contrast, Smith et al. (2001) reported a negative bias (−1.0 m s\(^{-1}\)) when comparing the NCEP–NCAR reanalysis wind speed with a few WOCE ship observations in the southern Atlantic and the ocean connecting south of southeastern Australia and Antarctica for 1990–95. As shown in Table 1, the NCEP–DOE SSWS is larger than the ship measured for each individual vessel, ranging from 0.61 to 2.40 m s\(^{-1}\). Figure 2a shows the averaged NCEP–DOE SSWS biases for each individual year. The NCEP–DOE SSWS has systematic positive biases for each year. We also calculate the averaged NCEP–DOE SSWS biases for each individual month of 1992–2009. As shown in Fig. 3a, the NCEP–DOE SSWS also has persistent positive biases for each month, with the largest bias in June. Additionally, the percentage of SSWS under wind conditions exceeding 10 m s\(^{-1}\) is ~51% for NCEP–DOE, which is significantly more than that of ship observations (~38%). This further supports that in the Southern Ocean the sea surface wind speed of NCEP–DOE is larger than those of ship observations, which leads to the above large positive bias.

On average, the ERA-Interim SSWS has the mean bias and RMSE of 0.06 and 1.96 m s\(^{-1}\), respectively, which are much smaller than those of NCEP–DOE. Moreover, the bias and RMSE of the ERA-Interim for each individual vessel are much smaller than those of NCEP–DOE (i.e., the biases of the ERA-Interim are primarily within ±0.5 m s\(^{-1}\)). For each individual year, the ERA-Interim SSWS has small biases relative to ship observations, except 2004. For each individual month, the bias of the ERA-Interim SSWS mainly falls within ±0.5 m s\(^{-1}\) (Fig. 3b). In aggregate, the NCDC SSWS yields a mean bias of 0.04 m s\(^{-1}\) and an RMSE of 2.18 m s\(^{-1}\). In general, the magnitude of the biases (including each individual vessel) of the NCDC SSWS is smaller than the NCEP–DOE and larger than or comparable to the ERA-Interim. The NCDC SSWS shows a large positive bias in 2008 and moderate biases in some years (Fig. 2c). The NCDC SSWS also exhibits large positive biases in June and July relative to the other months (Fig. 3c).

Aggregately, the CCMP SSWS gives a bias and RMSE of 0.04 and 1.81 m s\(^{-1}\), respectively. By contrast, Atlas et al. (2011) reported a negative bias (−0.3 m s\(^{-1}\)) when evaluating the CCMP wind speed for the global ocean using the conventional wind speed obtained from NCAR. For CCMP, both the bias for each individual vessel (Table 1) and yearly averaged bias (Fig. 2d) fall within ±0.5 m s\(^{-1}\). The monthly averaged biases are also small, although moderate positive biases are observed in June and July, which is also a feature in the NCDC. Overall, CCMP SSWS has the smallest bias and RMSE as compared to the NCEP–DOE, ERA-Interim, and NCDC SSWS. In addition, the correlation coefficient between the CCMP and ship-measured sea surface wind speed is 0.89, which is relatively higher than 0.66 (NCEP–DOE), 0.87 (ERA-Interim), and 0.83 (NCDC).

We examine the dependence of the biases of the sea surface wind speed of the four products on ship observations. Figure 4 shows the scatterplot of the SSWS biases for NCEP–DOE, ERA-Interim, NCDC, and
CCMP versus the ship-measured wind speed. It appears that the SSWS biases of the four products have a statistically significant dependence on the ship-measured wind speed in the Southern Ocean. That is, all four products overestimate (underestimate) ship observed wind speed for low (high) wind ranges.

We further calculate the averaged SSWS biases for NCEP–DOE, ERA-Interim, NCDC, and CCMP as a function of each 1.0 m s\(^{-1}\) bin of the ship-measured wind speed. As shown in Fig. 5, in general, all four products show a similar pattern. That is, the SSWS bias is positive and large under weak wind conditions (<4 m s\(^{-1}\)) and gradually reduced when associated with increasing observed wind speed. Here we define the point of the transition of the SSWS bias from positive to negative as the critical wind speed. NCEP–DOE shows that the critical wind speed occurred at 16–17 m s\(^{-1}\), which is larger than for ERA-Interim, NCDC, and CCMP (10–11 m s\(^{-1}\)). Note that the SSWS biases tend to decrease when the wind speed exceeds ~20–22 m s\(^{-1}\) (which is particularly true for the ERA-Interim and NCDC) and then increase remarkably for wind speed exceeding ~25 m s\(^{-1}\). The SSWS bias of the limited matchups for the wind speed beyond ~25 m s\(^{-1}\) is ~3.65 m s\(^{-1}\) for NCEP–DOE, ~5.25 m s\(^{-1}\) for ERA-Interim, ~4.57 m s\(^{-1}\) for NCDC, and ~3.30 m s\(^{-1}\) for CCMP, suggesting that

![Fig. 2. Averaged SSWS biases for each individual year during 1992–2009: (a) NCEP–DOE, (b) ERA-Interim, (c) NCDC, and (d) CCMP. The value in the parentheses is the number of matchups for each year.](image-url)
all four products are most likely to underestimate wind speed under high wind conditions.

b. Intercomparison of NWP and satellite wind speeds

Here we conduct preliminary intercomparisons of the consistency and discrepancy between the NWP reanalysis and satellite-based sea surface wind speed for the Southern Ocean from the climatological and interannual-to-decadal variability perspective. Such intercomparisons are useful for identifying geophysical regimes linked to the identified differences, which may need further investigation. The same “ice mask” for all four products is generated based on their sea ice cover or missing values. The monthly-mean sea surface wind speed is generated using four-times daily data from the four products for the period 1989–2009.

The annual-mean SSWS averaged over the Southern Ocean for 1989–2009 varies from 9.67 (CCMP) to 10.70 m s\(^{-1}\) (NCEP–DOE), with an average of 9.99 m s\(^{-1}\). Encouragingly, the spatial distribution of the SSWS shows qualitative agreement for all four products (Figs. 6a–d). Despite some differences in magnitude, the strongest SSWS are located in a zonal belt between 45° and 60°S (Antarctic Circumpolar Current). Within the Antarctic Circumpolar Current, the SSWS in the Indian Ocean sector is larger than that in the Pacific and Atlantic sectors. Compared to other products, NCEP–DOE has larger SSWS values in the Antarctic Circumpolar region and the difference can be as large as ~2.2 m s\(^{-1}\). This is consistent with the validation using the ship observations. As demonstrated by the spatial distribution of the across-data standard deviation (Fig. 6e; based on
the difference between the climatology for each product and the average of the climatology of the four products), the largest SSWS discrepancy among the four products is found in the Antarctic Circumpolar Current, where the value exceeds $1 \text{ m s}^{-1}$.

Based on the monthly-mean correlations of the SSWS between pairs of products (here CCMP is used as the reference), it appears that none of the four products are outliers and their correlations are high (Fig. 7). The correlations between the NCEP–DOE and CCMP SSWS are high (>0.8) for the Southern Ocean, except for some areas in the Atlantic and Indian sectors of the Antarctic Circumpolar Current, where the correlations drop to 0.65–0.75. The spatial pattern of the correlations between ERA-Interim and CCMP is similar to that between NCEP–DOE and CCMP. The two satellite-based products (NCDC and CCMP) have the highest correlations (>0.9) for the Southern Ocean.

Trend analysis for the monthly anomalies of the SSWS (the departure from the monthly mean for each product) is performed for 1989–2009 using the linear least squares fit regression. The spatial distribution of the SSWS trends is shown in Fig. 8. NCEP–DOE, NCDC, and CCMP, which are similar, exhibit a strengthening of the SSWS in much of the Southern Ocean, with statistically significant increasing trends in much of the Antarctic Circumpolar Current. By contrast, the ERA-Interim exhibits a weakening of the SSWS in large parts of the Antarctic Circumpolar Current, with pronounced decreasing trends in the southern Atlantic and between the eastern Indian and western Pacific sectors of the Antarctic.

4. Discussion and conclusions

In this study, we evaluate the performance of two NWP reanalyses (NCEP–DOE and ERA-Interim) and two satellite-based (NCDC and CCMP) sea surface wind speeds in the Southern Ocean.

For the accuracy comparison, these products are validated against in situ measurements from 10 WOCE and SAMOS cruises (37,084 matchups). Our analysis shows
that all four products overestimate the wind speed under weak wind conditions (<4 m s\(^{-1}\)). The large positive SSWS bias gradually decreases with increasing ship-measured wind speed and then turns negative and gradually increases after a critical wind speed, indicating that different products tend to have a better agreement with the observations under moderate wind conditions. All four products underestimate the wind speed under

![Fig. 5. Averaged SSWS biases for each 1.0 m s\(^{-1}\) bin of ship-measured wind speed: (a) NCEP–DOE, (b) ERA-Interim, (c) NCDC, and (d) CCMP.](image)

![Fig. 6. Spatial distribution of the annual-mean SSWS (m s\(^{-1}\)) during 1989–2009 for (a) NCEP–DOE, (b) ERA-Interim, (c) NCDC, and (d) CCMP, and (e) the standard deviation of the annual-mean SSWS (m s\(^{-1}\)) across the four wind products.](image)
high wind conditions (>25 m s^-1), although more observations are needed to further confirm this. Additionally, NCEP–DOE and NCDC (CCMP) show large (moderate) biases in June as compared to other months. We notice the bias of sea surface wind speed tends to be large under weak wind conditions. Here we further calculate the percentage of the number of sea surface wind speed as less than 4 m s^-1 for each individual month of 1992–2009 for the ship observations and the four products. For the ship observations, 39% of SSWS in June is under weak wind conditions, which is much greater than those of other months. By contrast, for NCEP–DOE, NCDC, and CCMP, only 7%, 6%, and 24% of SSWS, respectively, are found in June under weak wind conditions. Thus, the large biases in June are largely because of the discrepancy of the portion of data falling into weak wind conditions.

Overall, the NCEP–DOE SSWS has the largest bias (positive) and RMSE in the Southern Ocean, whereas the other three products have smaller biases and RMSEs. CCMP seems to have more accurate sea surface wind speed relative to the other products (Table 1; Fig. 5). NCEP–DOE uses ship wind speed and direction received at the NCEP as long as they are put onto the Global Telecommunication System (GTS) in a timely manner (W. Ebisuzaki 2013, personal communication). In addition to what the ECMWF received from the GTS, ERA-Interim also assimilates ship winds from other sources, including the International Comprehensive Ocean–Atmosphere Dataset, the U.S. Navy, and NCEP (A. Simmons 2013, personal communication). This in part explains why ERA-Interim SSWS has smaller bias relative to NCEP–DOE. As mentioned previously, CCMP also uses in situ data from ships and buoys archived at NCAR and ERA-40 and ECMWF operational analysis (as first-guess background winds). Thus, it is not that surprising that CCMP SSWS shows a better agreement with the ship observations relative to the other three products. According to our validation results, the CCMP in particular may provide a sea surface wind speed to within ~2 m s^-1 for all wind regimes, except wind speed exceeding 25 m s^-1 (Fig. 5), when in situ data and ECMWF reanalysis/analysis are used. Regarding the WOCE and SAMOS ship observations (obtained from the RVSMDC) used in this study, the RVSMDC does not presently submit data to the GTS, but this does not necessarily mean that data from the individual vessels were not on the GTS. However, the
WOCE and SAMOS data from the RVSMDC have higher quality control and much higher temporal sampling than any data found on the GTS for a given vessel (S. Smith 2013, personal communication).

Confirming the difference between the simple height adjustment (assuming neutrally stable atmospheric conditions) and more complicated height adjustment has minor impacts on our results. We also adjust shipboard wind measurements to a reference height of 10 m using a combination of the Coupled Ocean–Atmosphere Response Experiment (COARE) bulk flux algorithm 3.0 (Fairall et al. 2003) and the atmospheric profile from the ERA-Interim (e.g., air temperature and humidity, sea surface temperature, and pressure). The bias analysis between the NWP and satellite-based SSWS and ship observations shown in Figs. 2 and 3 is then repeated for the more complicated adjustment. It appears that the variations of the biases for both the simple and more complicated adjustments are in good agreement (Fig. 2 vs Fig. 9 and Fig. 3 vs Fig. 10). Furthermore, we repeat the accuracy comparison for the SSWS from the particular product and the ship observations falling within 1 min of one another. The results are similar to those of the 10-min time window.

For the regional intercomparison, the spatial variations of the annual-mean SSWS for these products are quite similar, although NCEP–DOE has much larger SSWS in the Southern Ocean than the other three products, which is consistent with the validation against the ship observations. The largest across-data scatter is found in the Antarctic Circumpolar Current, which is as large as their corresponding interannual variability. The four products have decadal trends of different signs. NCEP–DOE, NCDC, and CCMP show an increase of SSWS in much of the Antarctic Circumpolar Current, while the opposite is the case for ERA-Interim. It is not clear what contributes to the different sign in ERA-Interim (i.e., assimilated wind, model physics).

Accurate knowledge of air–sea flux in the convectively active Southern Ocean is extremely important for understanding and simulating variations in the coupled ocean–atmosphere system and feedbacks (Curry et al.)

Fig. 9. Averaged SSWS biases for each individual year during 1992–2009 calculated from a combination of the COARE bulk flux algorithm 3.0 and the atmospheric profile from the ERA-Interim: (a) NCEP–DOE, (b) ERA-Interim, (c) NCDC, and (d) CCMP.
Sea surface wind speed is an essential parameter for calculating not only the wind stress but also the turbulent heat fluxes. Bourassa et al. (2013) suggest that although specific air–sea flux accuracy requirements for climate research vary depending on the application, in general fluxes would better represent high-latitude processes if wind stresses achieved 0.01 N m\(^{-2}\) accuracy at high wind speed and if heat fluxes achieved 10 W m\(^{-2}\) accuracy. Our validation results indicate that the accuracy of sea surface wind speed for the NWP re-analyses and satellite-based products analyzed here cannot meet the flux accuracy requirements under weak and high wind conditions. Ongoing in situ monitoring from ships and buoys in the Southern Ocean, particularly in the Antarctic Circumpolar Current region (where the largest across-data scatter is found and has sea surface winds exceeding 20 m s\(^{-1}\) ), are needed to better understand the reasons leading to the discrepancies among these sea surface wind products and to reduce the uncertainty, since a range of climate applications in the Southern Ocean require the accurate sea surface wind.

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FIG. 10. As in Fig. 9, but for averaged SSWS biases for each individual month.


