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Evaluation of reanalysis and satellite-based sea surface winds using *in situ* measurements from Chinese Antarctic Expeditions

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Abstract Sea surface winds from reanalysis (NCEP-2 and ERA-40 datasets) and satellite-based products (QuikSCAT and NCDC blended sea winds) are evaluated using *in situ* ship measurements from the Chinese National Antarctic Research Expeditions (CHINAREs) from 1989 through 2006, with emphasis on the Southern Ocean (south of 45°S). Compared with ship observations, the reanalysis winds have a positive mean bias (0.32 m·s^{-1} for NCEP-2 and 0.13 m·s^{-1} for ERA-40), and this bias is more pronounced in the Southern Ocean (0.57 m·s^{-1} and 0.45 m·s^{-1}, respectively). However, mean biases are negative in the tropics and subtropics. The satellite-based winds also show positive mean biases, larger than those of the reanalysis data. All four wind products overestimate ship wind speed for weak winds (<4 m·s^{-1}) but underestimate for strong winds (>10 m·s^{-1}). Differences between the reanalysis and satellite winds are examined to identify regions with large discrepancies.

Keywords **Sea surface winds, NCEP-2, ERA-40, QuikSCAT, NCDC blended sea winds, Southern Ocean**

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1 Introduction

Sea surface wind is important for the exchange of heat, moisture, and momentum between atmosphere and ocean[1], and it provides the most important forcing of ocean circulation. Ocean winds of consistent high quality and high spatial and temporal resolution are needed for operational prediction and climate research. The development of numerical weather prediction (NWP) models and satellite remote sensing techniques makes it possible to obtain high-resolution (e.g., 25 km) and real-time global wind products effectively. Together with routine wind observations, these allow more comprehensive understanding of ocean dynamics. The radiometer and scatterometer are two effective means for measuring sea surface winds, and the latter can even obtain wind vectors. However, single-satellite application is limited because of its spatial and temporal coverage. Thus, some studies[2-3] blend winds from multiple satellites to produce winds with greater spatial and temporal coverage.

Both model and satellite-based winds need as many observations as possible. However, observation data are very sparse in some regions, especially in the Southern Ocean. Thus, it is necessary and important to evaluate the quality of wind products using all available *in situ* data, especially in data-sparse regions. Validation studies have been conducted mainly in the tropical, subtropical and northern mid-latitude oceans, using buoy and ship observations[4-9]. But the Southern Ocean has not been well documented.

In this study, we use wind observation data of the CHINAREs from 1989 to 2006 to evaluate wind products of NCEP-2 and ERA-40 reanalyses, two satellite-based wind products of NCDC blended sea winds, and sea winds from the QuikSCAT satellite. We focus on evaluating these wind products over the Southern Ocean (south of 45°S), using those over the tropics and subtropics as reference. Finally, we analyze differences between the two reanalysis winds and NCDC blended sea winds.

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2 Data

2.1 Reanalysis and satellite data

NCEP-2[10] is an updated version of the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis dataset (NCEP-1). The new version improves the forecast model and data assimilation system. NCEP-2[11] is a 6-hourly (00, 06, 12, 18 UTC) global reanalysis series from 1979 to present, with T62 horizontal resolution (~1.9°) and 28 sigma levels in the vertical. The data can be downloaded from the Earth System Research Laboratory of NOAA (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.gaussian.html). ERA-40[12] is a reanalysis dataset from 1957 to 2002 provided by the European Center for Medium-Range Weather Forecasts (ECMWF). ERA-40 has 6-hourly (00, 06, 12, 18 UTC) time resolution, 2.5°×2.5° horizontal resolution, and 60 levels in the vertical. The data can be obtained from the website (http://data-portal.ecmwf.int/data/d/era40_daily).

The NCDC blended sea winds[2] have provided blended sea surface (10 m) winds since 1987 on a global 0.25° grid, at the same 6-hourly timescale as NCEP-2. The NCDC product has used spatiotemporal weighted interpolation to composite multiple satellite wind products, including SSM/I F13, SSM/I F14, SSM/I F15, TMI, QuikSCAT and AMSR-E after 2002. Its wind direction is obtained by interpolating NCEP-2 wind directions onto the blended wind speed grid. QuikSCAT[13] was launched by the National Aeronautics and Space Administration (NASA) in June 1999 to replace the NASA Scatterometer (NSCAT). Spatial and temporal resolution is the same as that of NCDC, and can be obtained from the Remote Sensing System (RSS). QuikSCAT wind speed is one of the data resources of NCDC.

2.2 CHINARE observations

CHINARE has carried out more than 20 meteorological and oceanic expeditions to the Antarctic since 1984. We collected wind observations from the 6th, 7th, 8th, 9th, 11th, 13th, 14th, 15th, 18th, 19th, 21st and 22nd CHINAREs over the period 1984–2006. Figure 1 shows that observation locations were mainly in the eastern and southeastern Indian Ocean, western Pacific Ocean and much of the Southern Ocean. Especially during the 6th, 9th, 14th, 18th, 19th and 21st CHINAREs, the ship cruised Antarctic circumpolar regions. CHINARE sea surface temperature (SST) measurements were used to evaluate the satellite SST products[14].

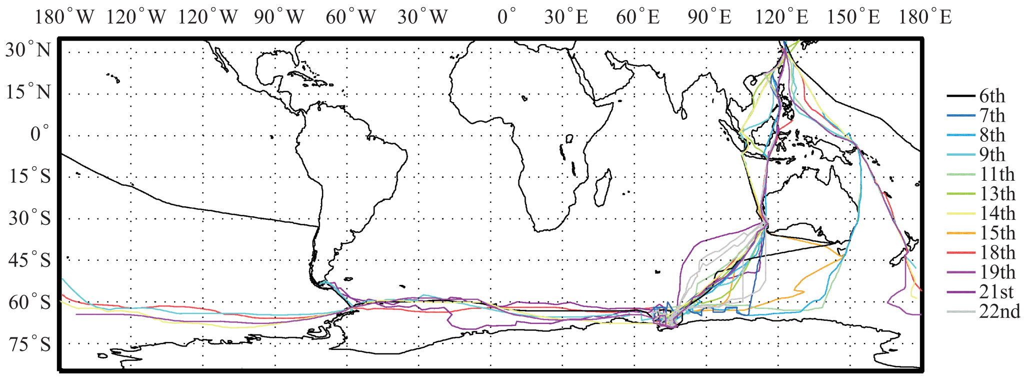

Figure 1 Locations of ship measurements for each CHINARE cruise

In the earlier expeditions (before the 18th), wind was measured by anemometers at 6-hourly times identical to those of the reanalysis. Afterward, a Vaisala MILOS 500 automatic weather station was used, with temporal resolution 10 min. The instruments were fixed on the top deck, 28 m above the sea surface. Precision of measured wind speed is 0.2 m·s^{-1} for both instruments. The cruises usually start in November and end in April, corresponding to the Southern Hemisphere summer.

3 Method

To do the comparisons, we first adjusted the observational winds to those at a standard 10-meter height, defined as “adjusted” winds. Because the meteorological and oceanic observations were not synchronous, atmospheric conditions were assumed neutrally stable and the following formulas were used.

$$\mathrm{k}u/u^{*}=\ln(z/z_0), \quad (1)$$

$$z_0=\alpha_c u^2/g, \quad (2)$$

where u is wind speed at height z; k and α_c are the Karman constant (0.4) and Charnock parameter (0.016); u^* and z_0 are the friction velocity and roughness height. Then, the 10-m adjusted wind speed is obtained using the following.

$$u_{10}=(u^{*}/\mathrm{k})\ln(10/z_0) \quad (3)$$

Similar methods have been used in previous studies, and the difference is negligible when taking into account of the atmospheric stability relative to the neutral conditions[5,15].

In this study, we compared the ship-measured adjusted wind speed with simultaneous NCEP-2, ERA-40 and NCDC winds within a 100-km search radius. There were

3 198, 1 440 and 3 404 collocations, respectively. The QuikSCAT wind speed was compared within ±6 h and a 100-km search radius, giving 913 collocations.

4 Results

4.1 Comparison between reanalysis and satellite-based winds and observations

4.1.1 Assessment of CHINARE ship observations

Before evaluating the wind speed products in the Southern Ocean, it is important to assess the quality of the ship data. We focused on the tropics and subtropics (north of 45°S), because earlier evaluation studies mainly treated these regions. On average, NCEP-2 minus ship winds gave a mean bias −0.08 m·s^{-1} and root mean square error (RMSE) 2.72 m·s^{-1} (1 254 matchups). ERA-40 had mean bias and RMSE −0.54 m·s^{-1} and 2.39 m·s^{-1}, respectively (464 matchups). QuikSCAT had mean bias and RMSE 0.87 m·s^{-1} and 2.58 m·s^{-1} (303 matchups), and NCDC 0.38 m·s^{-1} and 2.57 m·s^{-1} (1 335 matchups), respectively (Table 1). Smith et al.[4] evaluated NCEP-1 reanalysis wind speed with World Ocean Circulation Experiment (WOCE) ship observations, finding mean bias and RMSE ranges from −1.4 m·s^{-1} to −0.1 m·s^{-1} and 2.0 m·s^{-1} to 3.9 m·s^{-1}, respectively, which are consistent with our results. Parekh et al.[9] evaluated ERA-40 wind speed using buoy data in the Indian Ocean; mean bias and RMSE were −0.01 m·s^{-1} and 2.59 m·s^{-1}, also comparable to the present study. Our results are larger than those of Ebuchi et al.[6], who evaluated QuikSCAT winds using ocean buoy data. Their mean bias and RMSE were −0.02 m·s^{-1} and 1.01 m·s^{-1}. However, general consistency with the previous evaluation studies gives confidence in the CHINARE observations.

Table 1 Statistics of the comparison of four wind speeds with ship observations

Ship wind speed	NCEP-2			ERA-40			QuikSCAT			NCDC		
	Bias /(m·s^{-1})	RMSE/ (m·s^{-1})	No. of Match-up	Bias /(m·s^{-1})	RMSE/ (m·s^{-1})	No. of Match-up	Bias /(m·s^{-1})	RMSE/ (m·s^{-1})	No. of Match-up	Bias /(m·s^{-1})	RMSE/ (m·s^{-1})	No. of Match-up
all	0.32	2.82	3 198	0.13	2.53	1 440	0.61	2.82	913	0.43	2.64	3 404
0−4 m·s^{-1}	1.76	2.23	992	1.77	2.11	437	2.71	2.02	255	1.88	2.28	968
4−10 m·s^{-1}	-0.13	2.78	1 782	-0.34	2.35	803	0.29	2.49	471	0.16	2.51	1 901
>10 m·s^{-1}	-1.21	2.79	424	-1.60	2.11	200	-1.44	2.67	187	-1.22	2.41	535
North of 45°S	-0.08	2.72	1 254	-0.54	2.39	464	0.87	2.58	303	0.38	2.57	1 335
0−4 m·s^{-1}	1.51	2.15	336	1.35	2.20	113	2.76	1.77	88	2.11	2.25	314
4−10 m·s^{-1}	-0.44	2.61	773	-1.04	2.13	300	0.63	2.28	160	0.12	2.38	836
>10 m·s^{-1}	-1.85	2.74	145	-1.81	1.96	51	-1.47	2.31	55	-1.40	2.21	185
South of 45°S	0.57	2.85	1 944	0.45	2.53	976	0.49	2.92	610	0.47	2.69	2 069
0−4 m·s^{-1}	1.89	2.26	656	1.92	2.06	324	2.68	2.15	167	1.77	2.29	654
4−10 m·s^{-1}	0.11	2.89	1 009	0.09	2.37	503	0.12	2.58	311	0.19	2.61	1 065
>10 m·s^{-1}	-0.88	2.76	279	-1.53	2.16	149	-1.43	2.82	132	-1.13	2.50	350

4.1.2 Comparison in the Southern Ocean

In the Southern Ocean, compared with the ship observations, NCEP-2 winds had overall bias and RMSE 0.57 m·s^{-1} and 2.85 m·s^{-1}, respectively (1 944 matchups). The NCEP-2 winds were stronger than ship winds, contrary to the result north of 45°S. In aggregate, ERA-40 had a mean bias 0.45 m·s^{-1} and RMSE 2.53 m·s^{-1} (976 matchups). The bias was much larger than that north of 45°S, but smaller than that of NCEP-2. The mean bias and RMSE for QuikSCAT were 0.49 m·s^{-1} and 2.92 m·s^{-1}, respectively. NCDC had mean bias and RMSE 0.47 m·s^{-1} and 2.69 m·s^{-1} in the Southern Ocean. The NCDC blended sea winds were generated using several satellite remote-sensing winds, including QuikSCAT. As a composite wind product, the results were consistent with those of QuikSCAT. However, the NCDC product has higher spatial and temporal coverage relative to that of a single satellite product, enabling broader application and prospects. Correlation coefficients between NCEP-2, ERA-40, QuikSCAT and NCDC were 0.71, 0.75, 0.70 and 0.75, respectively.

We examined dependence of mean biases of the four wind products to ship data. Figure 2 shows the scatter plot of mean biases for NCEP-2, ERA-40, QuikSCAT and NCDC versus ship observations. It appears that the biases have a dependence on the ship observations. That is, the wind products overestimate ship wind speeds for weak winds (<4 m·s^{-1}) but underestimate for strong winds (> 10 m·s^{-1}). The dependence on ship observations appears closer north of 45°S than in the Southern Ocean (Figure 2).

We further calculated average biases and RMSEs for NCEP-2, ERA-40, QuikSCAT and NCDC, dividing the ship-measured wind speed into three ranges. Those are weak (<4 m·s^{-1}), moderate (4–10 m·s^{-1}) and strong (>

10 m·s^{-1}). As shown in Table 1, all four wind products had similar patterns. The mean bias is positive and large under weak winds, negative under strong winds, and smaller under moderate winds. This further proves that the four wind products overestimate ship wind speed under weak winds but underestimate it under strong winds. Comparing with the Southern Ocean, the mean bias is more negative north of 45°S for NCEP-2 under strong winds. However, mean biases and RMSEs are comparable for NCDC and QuikSCAT with different wind ranges.

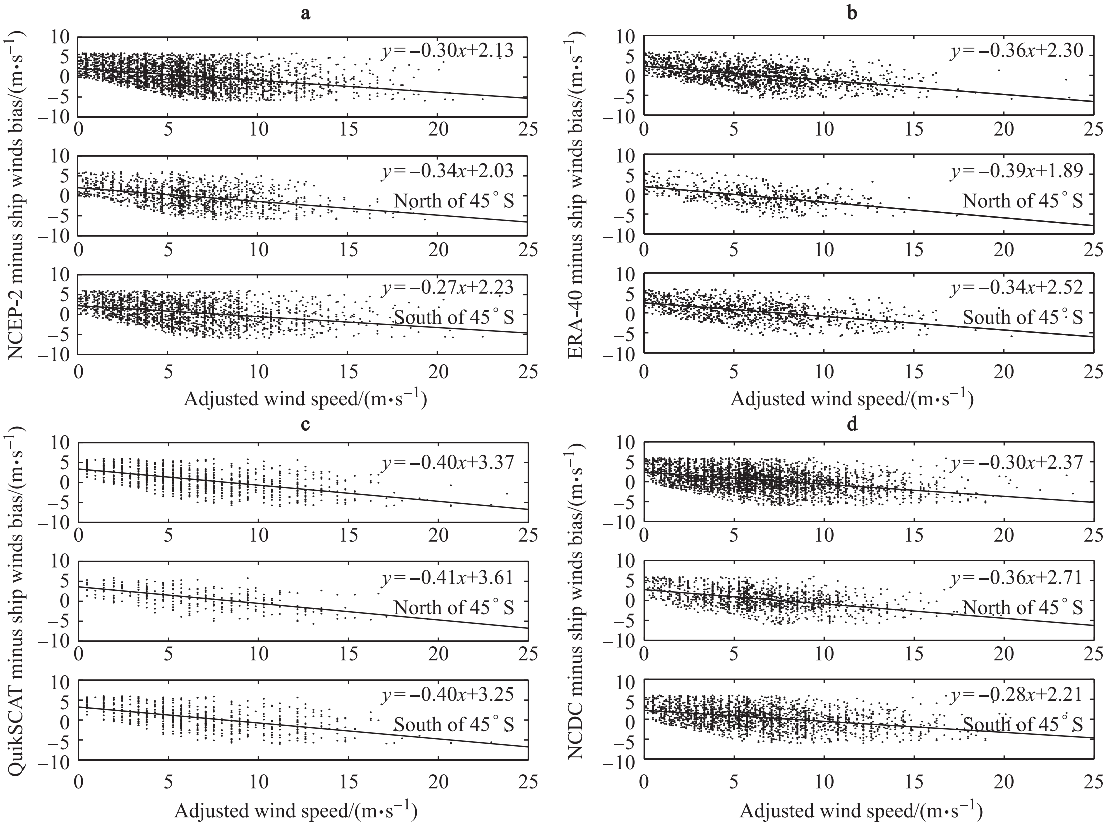

Figure 2 Scatter plots of four wind products against ship wind speed: (**a**) NCEP-2, (**b**) ERA-40, (**c**) QuikSCAT, and (**d**) NCDC. The solid line is the linear regression.

4.2 Comparisons between NCEP-2/ERA-40 and NCDC

Preliminary comparisons of consistency between reanalysis and satellite-based wind speed products were conducted for the Southern Ocean in summer 2001/2002 (December to February during the 18th CHINARE). These comparisons are necessary to identify geophysical regions with potentially large discrepancies. The three datasets were interpolated onto the same 1°×1° latitude-longitude grid using Cressman Interpolation because they had differing spatial resolutions.

Overall, the difference between NCEP-2 and NCDC wind speed was 0.35 m·s^{-1}, with RMSE 1.25 m·s^{-1}. Overall NCEP-2 winds were larger than those of NCDC in the Southern Ocean (with mean bias and RMSE 0.99 m·s^{-1} and 1.45 m·s^{-1}, respectively), but smaller across the central tropics (mean bias and RMSE −0.33 m·s^{-1} and 1.01 m·s^{-1}). Figure 3a reveals that the NCEP-2 winds were generally stronger than NCDC winds, except in the tropics. The positive biases were nearly consistent in the Southern Ocean, except in regions surrounding the Antarctic continent (regions south of 70°S).

The difference between ERA-40 and NCDC was −0.93 m·s^{-1}, with RMSE 1.31 m·s^{-1}. Mean bias and RMSE were −0.46 m·s^{-1} and 1.47 m·s^{-1} in the Southern Ocean, and −1.00 m·s^{-1} and 0.88 m·s^{-1} in the central tropics. Although there were many regions with positive biases, overall bias was still negative in the Southern Ocean because the ERA-40 winds were much weaker than NCDC around the Antarctic continent (Figure 3b). The NCEP-2 and ERA-40 winds were both weaker than NCDC sea winds around that continent.

5 Conclusions

In this study, we have evaluated two reanalysis winds and two satellite-based wind products using CHINARE observations, comparing the tropics and subtropics with the Southern Ocean.

Our result shows that NCEP-2 wind speed had a positive mean bias (0.32 m·s^{-1}) relative to ship observations. This bias was greater in the Southern Ocean (0.57 m·s^{-1}), contrary to the result north of 45°S (−0.08 m·s^{-1}). In aggre

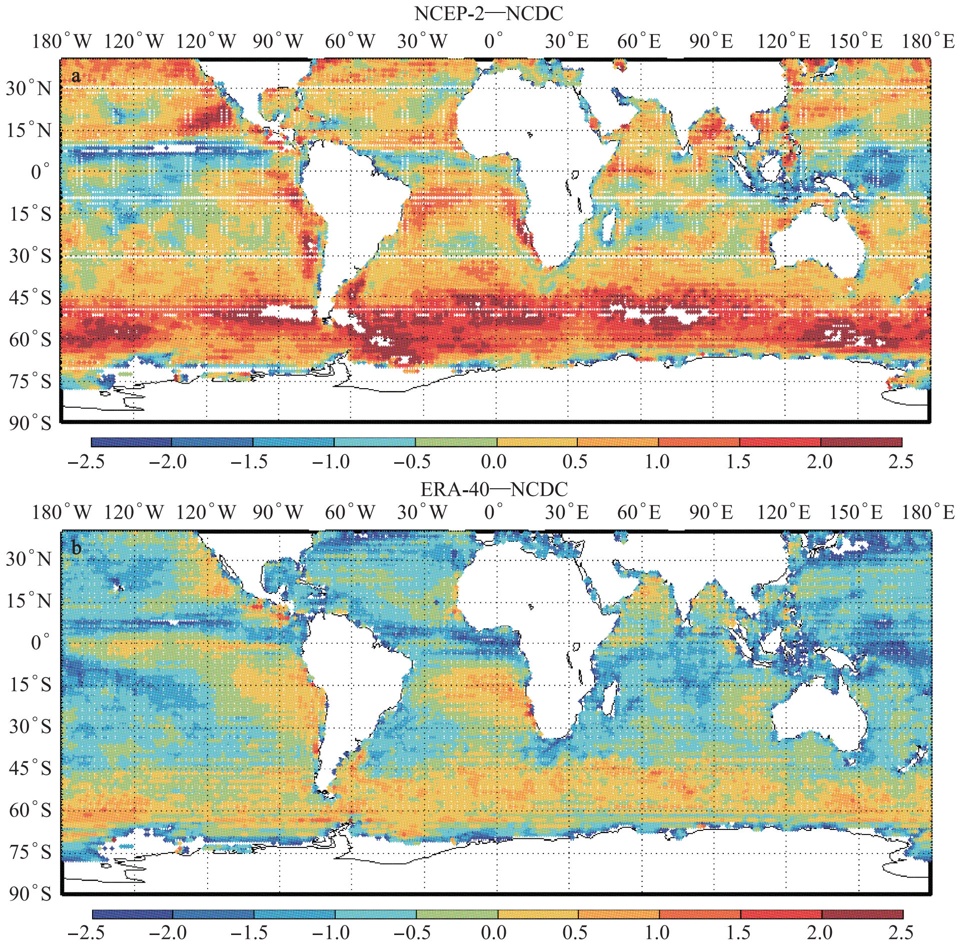

Figure 3 Spatial distributions of the difference between (**a**) NCEP-2 and NCDC, and (**b**) between ERA-40 and NCDC in summer (December–February) 2001/2002.

gate, ERA-40 had a positive mean bias 0.13 m·s^{-1}. Similar to NCEP-2, ERA-40 winds had an aggregate positive bias (0.45 m·s^{-1}) in the Southern Ocean, but a more pronounced negative mean bias (−0.54 m·s^{-1}) north of 45°S. QuikSCAT and NCDC winds both had positive mean biases (0.61 m·s^{-1} and 0.43 m·s^{-1}), larger than those of the reanalysis data. The mean biases for the two satellite products in the Southern Ocean were consistent with those in the tropics and subtropics. Therefore, the NCDC winds have broader application prospects because of their greater spatial and temporal coverage. All four wind products overestimated the ship wind speed for weak winds (<4 m·s^{-1}), but underestimated for strong winds (>10 m·s^{-1}). Mean biases were smaller for moderate winds (4–10 m·s^{-1}). Both the reanalysis and satellite-based winds gave a better result for moderate winds. Compared to the result of the Southern Ocean, mean bias was more negative north of 45°S for NCEP-2 under strong winds, but mean biases and RMSEs were comparable for NCDC and QuikSCAT for different wind ranges. The dependence of all wind products on ship observations appeared closer north of 45°S than in the Southern Ocean.

We presented a preliminary comparison between the reanalysis and NCDC winds. Compared with NCDC, the NCEP-2 wind speed was generally stronger in the Southern Ocean but smaller in the central tropics. Overall, ERA-40 had weaker winds than NCDC in the Southern Ocean but smaller in the central tropics. Both NCEP-2 and ERA-40 wind speeds were weaker than those of NCDC near the Antarctic mainland. Further investigations are needed to confirm these differences and identify their sources. This is important for improving accuracy of the reanalysis data and satellite remote-sensing wind products in the future.

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