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Accuracy of 10 m winds from satellites and NWP products near land-sea boundaries

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[1] Through a comprehensive analysis, reliability of 10 m wind speeds is presented near the land-sea boundaries over the global ocean. Winds from three numerical weather prediction (NWP) centers and two satellite-based products are analyzed. NWP products are 1.875° × 1.875° National Center Environmental Prediction reanalyses, 1.125° × 1.125° European Centre for Medium-Range Weather Forecasts 40-year Reanalysis (ERA-40), and 1.0° × 1.0° Navy Operational Global Atmospheric Prediction System (NOGAPS) operational product. These are compared to much finer resolution (0.25° × 0.25°) satellite winds, Quick Scatterometer (QSCAT) and Special Sensor Microwave/Imager. Large biases (e.g., >3 m s^{-1}) may exist in NWP products near the land-sea boundaries, because wind speeds from the uniformly gridded global fields are generally at a spatial scale too coarse to appropriately define the contrast between water and land grid points. This so-called land contamination of ocean-only winds varies, and typically depends on the extent of the land-sea mask. A creeping sea-fill methodology is introduced to reduce errors in winds. It is based on the elimination of land-corrupted NWP grid points and replacement by adjacent, purely over-ocean values. In comparison to winds from many moored buoys, the methodology diminishes RMS errors (from >4 m s^{-1} to <1 m s^{-1}) for NOGAPS and ERA-40. The creeping sea-fill is not advised for NCEP winds which have low contrast between land and sea points, thereby resulting in little impact from the land contamination.

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1. Introduction

[2] Accurate determination of winds at the air-sea interface (e.g., at 10 m) is essential near the land-sea boundaries for a variety of reasons. For example, coastal ocean upwelling related processes generally depend largely on the magnitude of the surface winds [*Capet et al.*, 2004]. Decisions regarding hurricane evacuation also rely upon accurate estimates of near-surface wind speed, which affect storm intensification in coastal regions [*Elsner and Kara*, 1999]. Reliable wind speeds over the sea and land are required to properly compute momentum transfer [*Grachev and Fairall*, 2001] and heat exchanges through sensible and latent heat fluxes [*Mahrt et al.*, 1998] near the coastal boundaries. Similarly, an ocean model requires sea-only atmospheric forcing with no contamination from land values to properly simulate upper ocean variables near the coastal boundaries [*Kara et al.*, 2007a].

[3] Despite its importance, knowledge of near-surface wind speed near land-sea boundaries is limited by insufficient spatial and temporal coverage of measurements over many regions of the global ocean. Numerical weather prediction (NWP) centers are commonly used sources for obtaining global coverage of wind speeds. These systems include NOGAPS, ERA-40, and NCEP (Table 1). They provide high spatial (global) and temporal resolution (6 hour) archived wind speed values. However, such fields are distributed at selected subsampled grid resolutions which are unique to each NWP center. For example, NCEP has a grid of 1.875° × 1.875°, the coarsest grid in comparison to NOGAPS and ERA-40.

[4] Serious problems may arise when using near-surface wind speeds from these coarse resolution NWP products for applications near the land-sea boundaries. In general, the gridded products may have only one wind speed value near the coast, and it may not be clear if this value is representative of land, ocean or a weighted average of both. This single wind speed value can be influenced by both land and sea effects. In other words, there is land (sea) contamination over the sea (land) grid points near the coastal regions. Thus a gridded product may not be able provide correct winds over the land and sea. For example, low wind speeds (1 m s^{-1}) over land could dominate the contamination in the grid box, resulting in low speed over the ocean part of the grid. Wind speeds over the ocean could be 3–4 m s^{-1}. If applied to estimate the typical length of wave breaking fronts per unit area, proportional

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Table 1. Abbreviations and Grid Resolutions for Wind Products[a] Used Throughout the Text[b]

Acronym	Name of the product	Grid resolution
QSCAT	Quick Scatterometer	0.250° × 0.250°
SSM/I	Special Sensor Microwave/Imager	0.250° × 0.250°
NOGAPS	Navy Operational Global Atmospheric Prediction System	1.000° × 1.000°
ERA-40	European Centre for Medium-Range Weather Forecasts	1.125° × 1.125°
NCEP	National Centers for Environmental Prediction	1.875° × 1.875°

[a]While ERA-40 and NCEP are reanalysis products, NOGAPS is not. Note that NCEP has two different reanalyses, and the one we use here is the second reanalysis. Details of each product can be found in *Liu* [2002] (QSCAT), *Meissner et al.* [2001] (SSM/I), *Rosmond et al.* [2002] (NOGAPS), *Kållberg et al.* [2004] (ERA-40), and *Kanamitsu et al.* [2002] (NCEP).

[b]Winds for NWP products are obtained from the National Center for Atmospheric Research (NCAR) data support section (http://dss.ucar.edu/datasets/), and monthly means are constructed using 6 hourly data during 2000–2001. Twice-daily QSCAT wind measurements were obtained from Remote Sensor Systems (RSS), http://www.remss.com, and rain-free winds were formed. SSM/I winds are directly used from RSS.

to the cube of wind speed [*Melville and Matusov*, 2001], the actual extent of wave breaking would be 27–64 times greater than estimated using the erroneous low winds. The underestimate or overestimate in wind speed may also result in serious errors in computing the magnitude of wind stress, which is the primary driving mechanism for upwelling circulations along the coastal boundaries [*Enriquez and Friehe*, 1995].

[5] We investigate the accuracy of winds from not only NWP centers (i.e., NOGAPS, ERA-40, and NCEP) but also satellites (SSM/I and QSCAT) at various coastal boundaries. In particular, bringing the application of land-sea masks from NWP products in determining the preciseness of coastal winds is something that has not been revealed for the global ocean. Our goal is not to determine which product is the most reliable near the land-sea boundaries but to demonstrate the strength and weakness of each product.

[6] A methodology is then applied for reducing the land contamination from NWP winds over the sea over various regions of the global ocean. Regarding this matter, we answer many potential questions as follows: (1) Does the technique work for different NWP products? Multiple NWP products are used in the analysis, including the most commonly used global ones from NCEP, ECMWF, and NOGAPS. The paper identifies different errors and demonstrates differences in effectiveness for these products, showing that the applicability is not limited to a single source of atmospheric forcing. (2) Is the technique validated extensively? Satellite products (QSCAT and SSM/I) are processed to check the validity of the approach. They are used as a spatial representation of truth for evaluation of NWP products. We demonstrate the robustness of the technique when applied to these products. (3) Is this correction likely to reduce wind product errors in a region of interest to any reader? In addition to satellite-based winds, all NWP products are also validated against winds from not only one buoy but also those located at various regions of the global ocean, demonstrating geographic robustness. (4) What are the shortcomings of this approach? We discuss reasons of why winds from a particular product may not be sufficiently accurate to be used without an adjustment in offshore applications near the land-sea boundaries.

2. Land-Sea Masks

[7] The ocean and land areas in NWP products (NOGAPS, ERA-40, and NCEP) are defined by a land-sea mask. The mask determines whether a particular grid point is land or sea. If the total fraction of a grid cell that is land exceeds 50%, then the grid point is classified as a land point, otherwise it is classified as a sea point. The land-sea masks in these three NWP products are represented as values 0 (for sea) and 1 (for land).

[8] Land-sea mask values from the coarsest resolution NCEP grid (Table 1) are interpolated to a finer resolution grid, 1/12° × 1/12° cos(latitude), using bilinear interpolation, to demonstrate the extent of land contamination over sea points (Figure 1). Bilinear interpolation is preferred as will be described in section 4. For example, a contour value of 0.6 in the land-sea mask implies that wind speed is 60% contaminated by land values over the ocean grid point. Land-sea masks are zoomed at various subregions to show the extent of the land contamination.

[9] Land contamination over the ocean can be serious, reaching 100% right next to the boundaries in all subregions (Figure 1). This simply implies that wind over the sea is not quite correct. In reality, surface wind strength often increases significantly when passing from land to open sea because of the reduced drag friction over water [*Stull*, 1988]. In addition, narrow topographic features at the coast may funnel winds offshore, so that on average, winds may tend to be stronger over water than land. The grid resolution of the NWP product may not represent such features properly. As expected, the contamination from land decreases systematically as one proceeds farther away from the coast to the interior of the ocean. There is no land contamination in the white regions.

[10] A coastal ocean-only application in a region unduly influenced by land-based atmospheric values (e.g., wind speed) will likely produce inaccurate nearshore predictions. Thus one needs to identify where land values are improperly mapped into sea regions. For instance, NCEP has no sea grid points over inlets in the eastern Gulf of Alaska, so land values completely dominate these sea grid points. Serious land contamination also occurs in the Indonesian and Japan/East Seas, which in Figure 1 is seen to have sea regions that exceed 90% dependence on land values.

3. Wind Errors Near the Land-Sea Boundaries

[11] The preceding section gave an overview of possible land contamination problems arising from inaccurate representation of coastal boundaries due to the land-sea mask from NCEP only. Here, we extend the investigation to other NWP products (NOGAPS and ERA-40), and examine land contamination over ocean points for 10 m wind speed, in detail.

3.1. Data Products

[12] We form monthly mean winds for each product (Table 1). Satellite-based products (QSCAT and SSM/I) have much finer resolution than global NWP products;

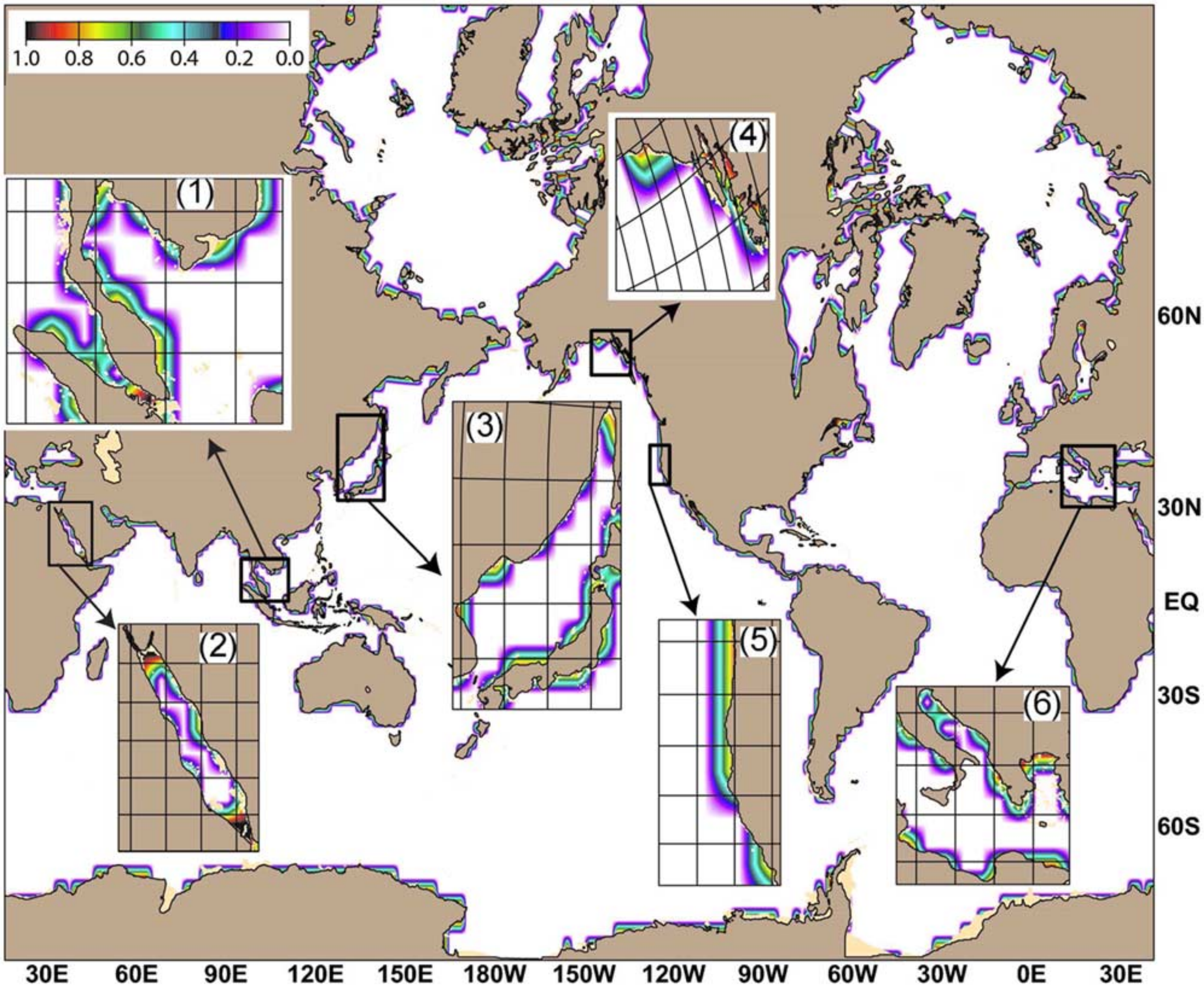


Figure 1. NCEP land-sea mask interpolated to 1/12° × 1/12° cos(latitude) grid (≈7 km at midlatitudes) over the global ocean. Six zoom plots are provided to better show land-sea mask values in those particular regions: (1) Indonesian Sea, (2) Red Sea, (3) Japan/East Sea, (4) northeastern Pacific Ocean, (5) west coast of U.S., and (6) eastern Mediterranean Sea. The color bar demonstrates land contamination (0 for no contamination and 1 for 100% land contamination). On the basis of this particular example, if near-surface atmospheric variables (e.g., 10 m wind speed) were needed for ocean-only applications in regions contaminated by land values, one would not be able to extrapolate accurate values from an NWP product (e.g., NCEP).

therefore, they will be used for assessing the accuracy of wind speed values near the coastal boundaries along with winds from many moored buoys. A scatterometer measures the strength of signals returned from each location at several angles. These backscatters are used to determine the wind direction and equivalent neutral wind speed [*Liu*, 2002].

[13] We formed monthly mean QSCAT winds using twice daily satellite measurements. In our processing, first, we form monthly averages on the 0.25° × 0.25° grid using a cutoff of 20 rain-free observations per month. Thus days with any rain are removed. We then determine a 25-point (1.25° square) observation-weighted average at each 0.25° cell using a cutoff of 100 rain-free observations per month. These numbers are chosen subjectively on the basis of some tests. Both QSCAT and SSM/I provide equivalent neutral wind speeds [*Meissner et al.*, 2001] at a height of 10 m, while 10 m wind speeds from NOGAPS, ERA-40 and NCEP include effects of air-sea stability. For comparison purposes, QSCAT and SSM/I winds are converted to stability-dependent 10 m winds using 6 hourly atmospheric variables from ERA-40 (not shown). Differences between equivalent neutral winds and stability-dependent winds are generally small (very rarely >0.3 m s^{-1}) over most of the global ocean on monthly time scales.

[14] The time period of 2000 and 2001 is used for our investigation because it is a common time period covered by all products. Winds from the ERA-40 reanalysis are not available beyond mid-2002, and QSCAT starts on July 1999. In addition, winds from QSCAT are not assimilated into NWP products in 2000 and 2001, so they will be used for validating NWP products along with those from buoys.

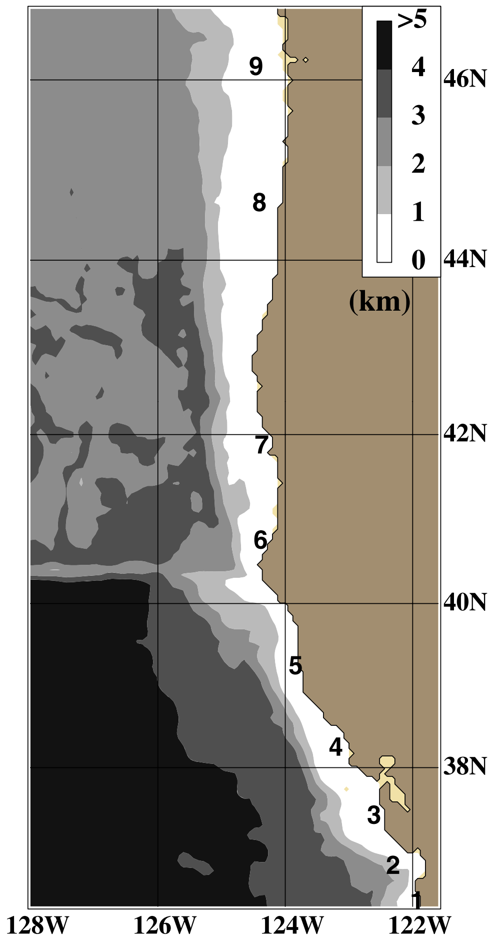


Figure 2. Bottom topography in kilometers at the U.S. west coast and surrounding regions. The numbers (from 1 through 8) in the map show locations of moored buoys which will later be used for evaluating wind speed of the satellite-based and NWP products.

In the case of all NWP products, monthly winds were formed from 6 hourly outputs.

3.2. Wind Speed Accuracy Near the U.S. West Coast

[15] Accuracy of winds from NWP and satellite-based products are first examined along the U.S. west coast (Figure 2). This region is chosen because there are irregularities in the coastline, and the complex adjacent topography interacts. There are also numerous buoys measuring wind speed in the region, which is helpful for validating wind speeds from the satellite-based and NWP products.

[16] Figure 3a shows land-sea masks during February of 2001. The land-sea masks for NWP and satellite-based products have different meanings because QSCAT and SSM/I do not have any measurements over the land. Unlike the land-sea masks of NWP products examined in section 2, we describe the satellite-based daily mask as 1.0 for data void areas and 0.0 for regions with valid QSCAT and SSM/I winds. On a month by month basis the mask could vary depending on the number of satellite measurements. In summary, a land-sea mask value of 1.0 for satellite winds indicates that there are no valid measurements in that region, specifically very near the coastal boundaries. SSM/I land-sea mask is directly obtained from RSS, and winds very near the coast are typically masked because of their uncertainties.

[17] As expected, the largest land contamination is seen in NCEP because of its relatively coarse resolution in comparison to NOGAPS and ERA-40 (Figure 3a). However, the contamination does not necessarily mean that winds from NCEP near the coast boundary will be much different than those from ERA-40 and NOGAPS. For example, it is possible that NCEP winds over the land near the coastal boundary may be more representative of sea conditions than winds from NOGAPS and NCEP, yielding more accurate winds over the sea. We will later demonstrate that this is the case along the U.S. west coast and regions at high latitudes. The NOGAPS land-sea mask has the least contamination in comparison to other NWP products, but is still limited by its $1^\circ \times 1^\circ$ resolution (Figure 3a).

[18] Coarse resolution NOGAPS, ERA-40, and NCEP winds are quite different from the much finer satellite-based QSCAT and SSM/I winds near the land-sea boundary (Figure 3b). Wind speed differences from QSCAT are almost zero for SSM/I (i.e., QSCAT-SSM/I $\approx$ 0) almost everywhere, but not for the NWP products (Figure 3c). QSCAT and SSM/I winds exist only over the sea, so there is no comparison very near the land-sea boundaries. When winds are obtained from the NWP products, e.g., in the case of ERA-40, the consequences from land contamination are severe because winds over the land are very weak ($<$4 m s^{-1}) in comparison to those over the sea, and the same is also true for NOGAPS (Figure 3d). In the color bar, blue (red) denotes winds stronger (weaker) than QSCAT winds. NCEP winds over the land just near the coastal boundary are weak as well but they are larger than those from NOGAPS and ERA-40. If one were to eliminate wind speed bias from NCEP with respect to QSCAT winds in the interior of the ocean (i.e., add 1 to 1.5 m s^{-1} to NCEP winds) to make it roughly agree with NOGAPS and ERA-40, then errors near the land-sea boundary would then be larger (e.g., $>$3 m s^{-1}) but still reduced by weak winds over land. Some differences in NWP winds are expected in the interior, which is not our focus here, because the models from NWP centers have different spatial resolutions, boundary layer parameterizations, and data assimilation methods. Thus NWP products have their unique limitations in producing atmospheric variables at the sea surface.

4. Creeping Sea-Fill Methodology

[19] Here, a method is introduced to improve accuracy of winds over the sea near the land-sea boundaries for use in offshore applications, and it is applied to the U.S. west coast (Figure 3e). The creeping sea-fill technique is one of the interpolation techniques designed for irregularly spaced data [*Burrough and McDonnell*, 1998]. The methodology makes use of only over-sea values of any given scalar atmospheric variable (e.g., wind speed) and replaces the value associated with each land-masked point by one using only nearby sea values.

[20] The creep-fill scheme makes multiple passes through the array over the grid. Before the initial pass, all land (sea) points are designated unfilled (filled). During each pass, a

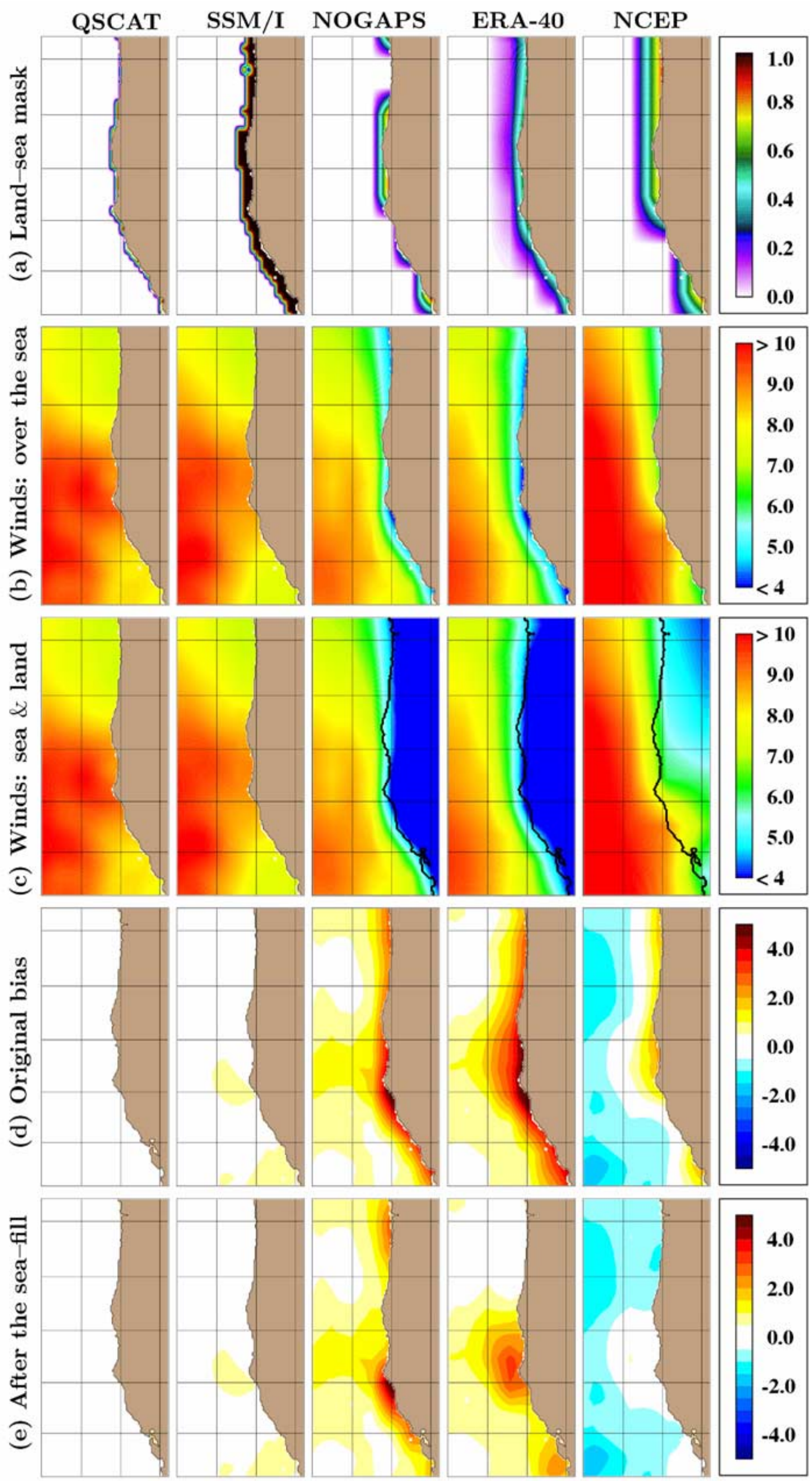


Figure 3. (a) The land-sea masks in the U.S. west coast region. (b) Monthly mean 10 m wind speeds during February 2001. (c) The same as Figure 3b but winds from NWPs are also shown over the land. (d) Differences in wind speed with respect to QSCAT (i.e., QSCAT-SSM/I, QSCAT-NOGAPS, QSCAT-ERA-40, and QSCAT-NCEP, respectively). (e) The same as Figure 3c but differences calculated after applying creeping sea-fill.

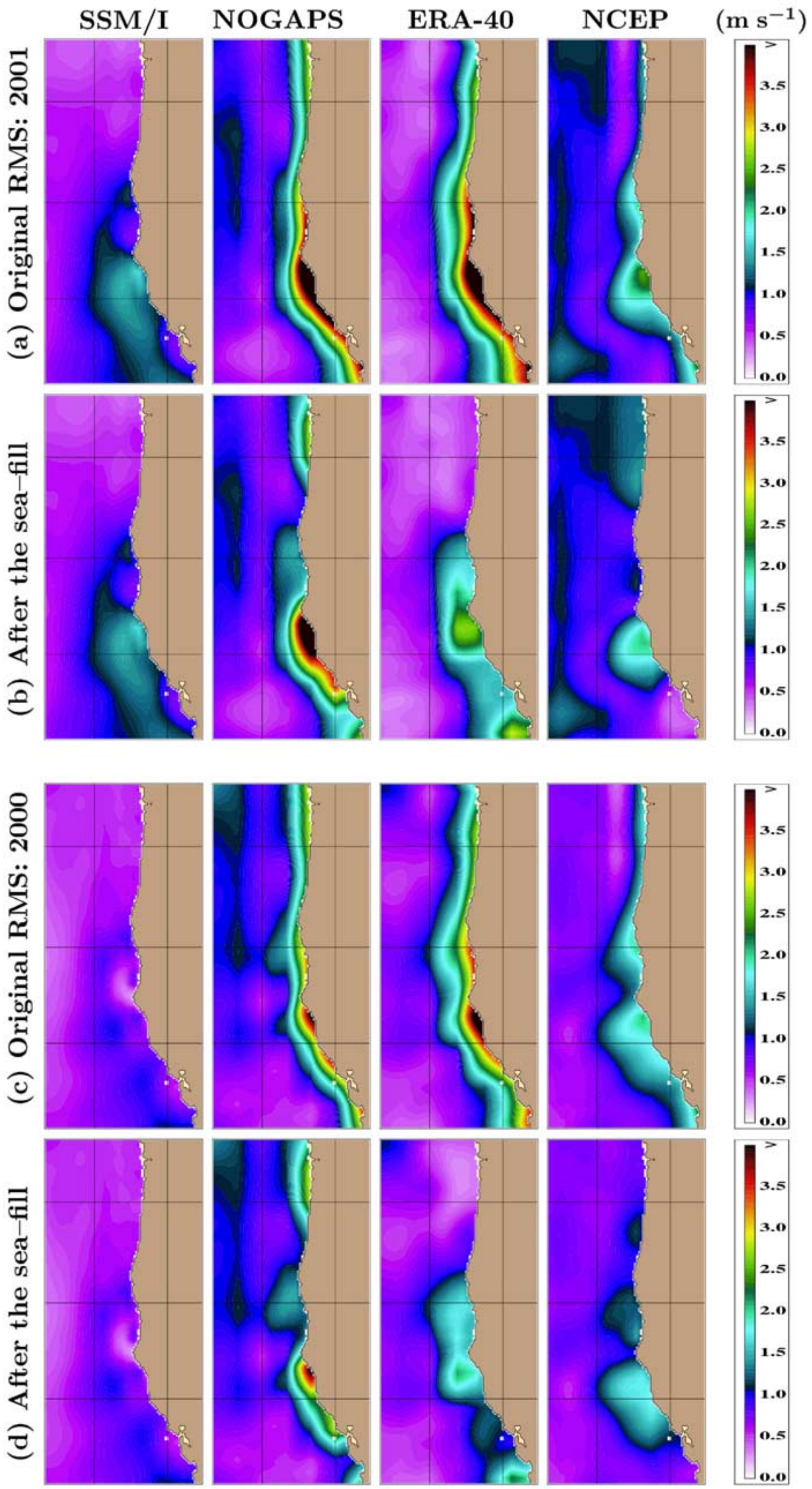


Figure 4. RMS wind speed errors with respect to QSCAT calculated over the seasonal cycle for the (a) standard NWP products in 2001, (b) sea-filled NWP products in 2001, (c) standard NWP products in 2000, and (d) sea-filled NWP products in 2000.

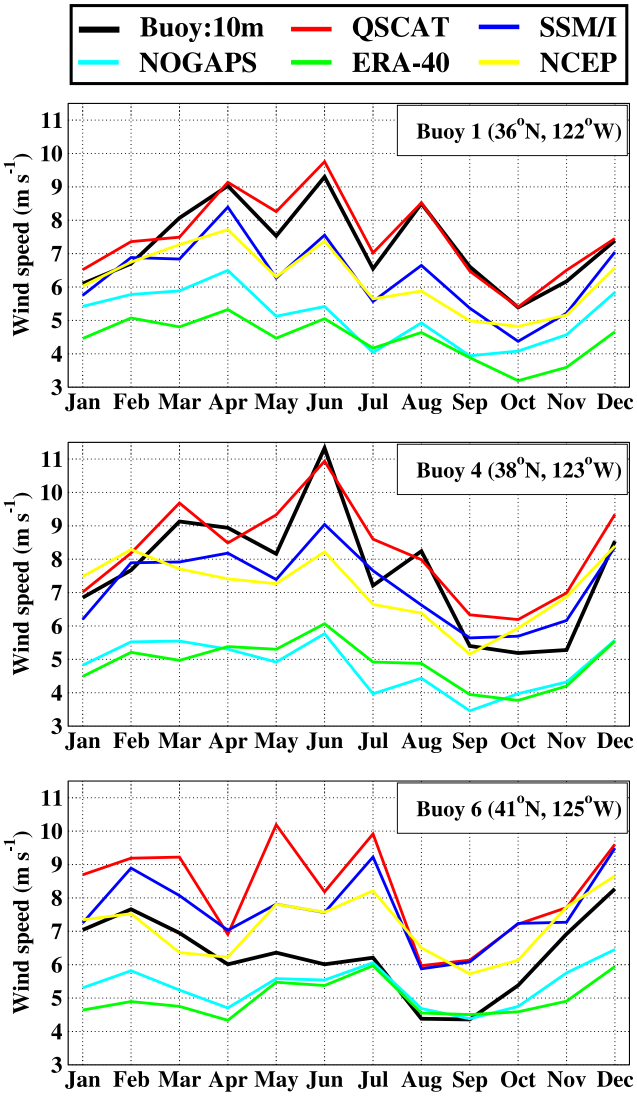


Figure 5. Wind speed at 10 m above the sea surface from NWP and satellite-based products in 2001. Monthly means from buoys were formed when daily winds were available for at least 20 days. Three coastal buoy locations are marked as 1, 4, and 6 in 2001 (Figure 2). NDBC station IDs are 46028, 46013, and 46022, respectively. Approximate deployment locations for these buoys are (35.7°N, 121.9°W), (38.2°N, 123.3°W), and (40.7°N, 124.5°W), which are used for extracting winds from satellite-based and NWP products. For ease of notation, nearest integer values of average latitude and longitude are used for each buoy in the text and figures.

weighted mean is calculated over the neighbors of each unfilled point. The unfilled neighbor has a zero weight. Diagonally adjacent filled neighbors are assigned to a weight of one, and horizontally or vertically adjacent neighbors are assigned a weight of two. The target point is filled if the weights sum to at least three. This is a "creep-fill" because each pass through the array only provides values near to the filled-unfilled boundary from the previous pass. Gaps are usually filled using data from nearby observations, and the technique does not use values from both sides of an isthmus. For example, if the purpose is to fill wind speeds at the grid points near Central America, then gaps are filled with data either from the Atlantic or Pacific Oceans. The atmospheric arrays are creep-filled on the original atmospheric grid and are best interpolated to finer oceanic grids using bilinear interpolation. We tested a few other interpolation schemes (such as cubic splines) but none yielded results as good as the bilinear interpolation (not shown).

[21] The creeping sea-fill is also applied at each 6 hourly time interval for each NWP product, and then monthly mean of sea-filled winds are formed. It is clearly evident that most of the errors in winds (Figure 3d) are greatly reduced after using the nearby sea values (Figure 3e) in February of 2001. Wind errors are calculated with respect to QSCAT, whose accuracy itself will be discussed below. We examine whether or not the creeping sea-fill also reduces errors in winds near the land-sea boundaries during other time periods. Thus we compute RMS errors with respect to QSCAT for each product over the seasonal cycle based on the 12 monthly mean wind speeds to determine overall performance of the methodology. Spatial variation of RMS wind differences clearly demonstrate that errors in wind speeds from NWP products are reduced after applying the creeping sea-fill not only in 2001 (Figures 4a and 4b) but also in the earlier year, 2000 (Figures 4c and 4d).

[22] Previously, we have shown that the fine resolution QSCAT and SSM/I winds agree quite well with each other, but they are both much stronger than NWP winds near the land-sea boundary (Figure 3b). However, this statement, regarding the NWP wind being too weak, is with respect to those from the satellite-based QSCAT and SSM/I winds. Thus, one might ask, "are these satellite-based winds sufficiently accurate to support this conclusion?" We answer this question by validating wind speeds from all products against those processed from moored buoys of the National Data Buoy Center (NDBC) available online (http://www.ndbc.noaa.gov).

[23] Three NDBC buoys near the California U.S. coast are selected to examine differences in monthly mean wind speeds among all data products (Figure 5). These buoys are chosen because they are relatively close to the coast and cover a broad range of water depths (Figure 2). In particular, buoys marked 1, 4, and 6 are located ≈102, 89 and 31 km away from the coast, respectively. Water depths at these buoy locations are ≈1112, 123, and 509 m. The water depths at the last two are relatively shallow.

[24] There are several issues complicating the comparisons for wind speed between the buoys and other products. For example, comparisons can be made using the collocated wind vectors, but our main focus here is on monthly means. In addition, wind speed from NDBC buoys are averaged over an eight-minute period. The average wind speed is the simple scalar average of the wind speed observations, which may estimate higher wind speeds than if a true vector average were used [e.g., *Dickinson et al.*, 2001]. However, on the basis of some tests (not shown), this effect is generally negligible (0.2 m s^{-1}) on monthly time scales and these locations. There are also some effects of ocean currents on satellite-based winds [*Kelly et al.*, 2001]. Similarly, waves can also have some impact on buoy winds [*Kara et al.*, 2007b]. Ocean currents and waves are not

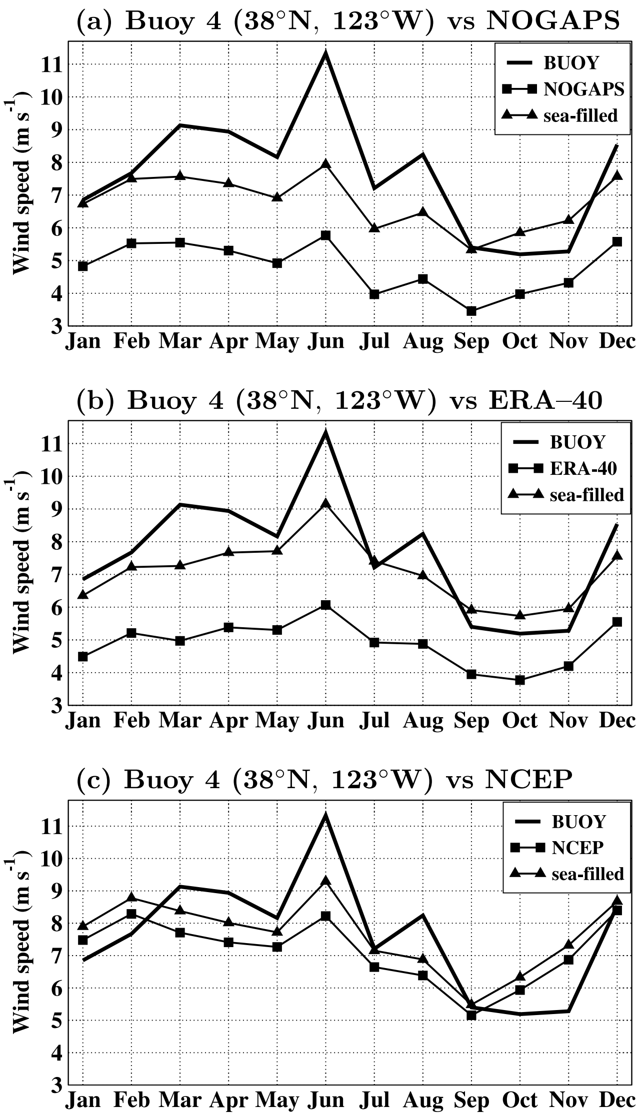


Figure 6. Comparisons of monthly time series of wind speed at 10 m above the sea surface from an NDBC buoy located at (38°N, 123°W) versus that from three NWP products: (a) NOGAPS, (b) ERA-40, and (b) NCEP. All are in 2001. Time series for NWP products are shown for both standard and sea-filled wind speeds. NDBC station for the buoy is 46013, and water depth at which the buoy is located is ≈123 m, as mentioned earlier.

measured by NDBC buoys regularly, so they will not be considered. However, implications of neglecting currents and waves in determining buoys wind speeds will be mentioned later.

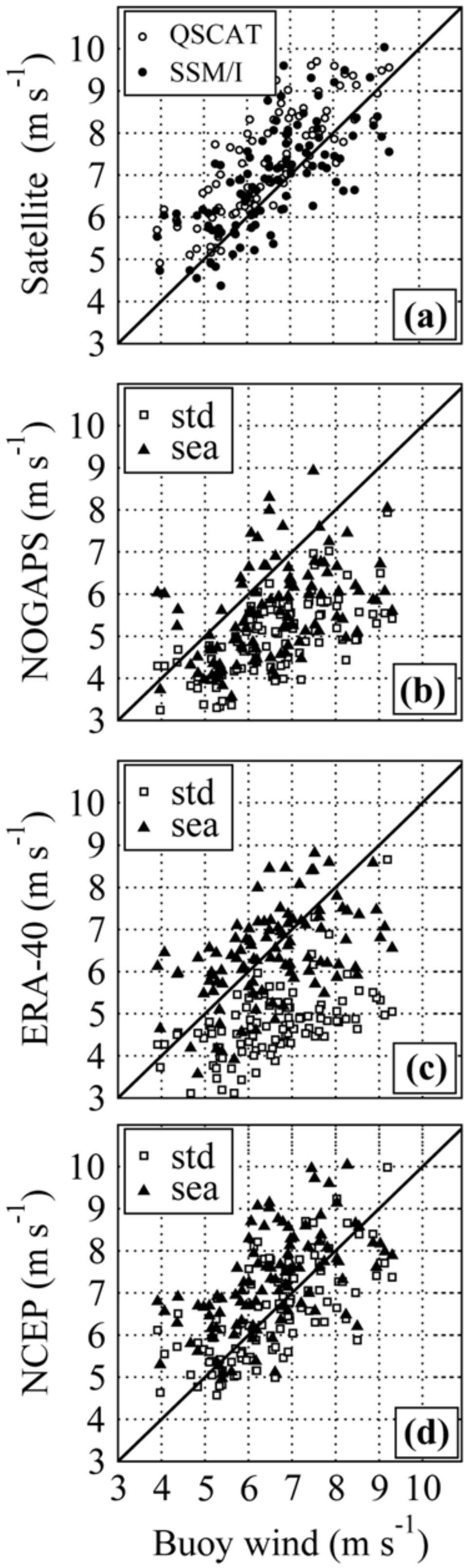
[25] To make the direct comparisons between buoy and satellite-based winds, the traditional method is to convert buoy wind speed measurements from their observation height (typically 4 m) to 10 m above the sea level. Since NWP winds take atmospheric stability into account, satellite-based winds were converted to 10 m as explained earlier. Buoy winds are adjusted to 10 m using both the COARE 3.0 [*Fairall et al.*, 2003] and Bourassa-Vincent-Wood (BVW) [*Bourassa et al.*, 1999] algorithms which have the option of stability-dependent winds taking the air-sea stratification into account. The conversion to 10 m buoy winds was made using daily averaged sea surface temperature, air temperature and relative humidity from the buoy measurements. Both COARE and BVW gave almost identical results with an RMS wind speed difference of <0.2 m s^{-1}, demonstrating the robustness and accuracy of the conversion. Monthly mean wind speeds from NDBC buoys were then formed from daily values (Figure 5).

[26] The most striking feature evident from Figure 5 is that wind speeds from NOGAPS and ERA-40 are consistently too weak in comparison to those from QSCAT. The differences can be as large as 4 m s^{-1} at buoy 1 and even >5 m s^{-1} at buoy 4 during summer, clear indications of land contamination in winds from ERA-40 and NOGAPS. This is confirmed by examining the spatial variations of winds over land from both products, which are generally <2 m s^{-1}. Winds from NCEP are stronger than those from ERA-40 and NOGAPS and are relatively close to those from buoys. However, as explained earlier, NCEP winds are already relatively strong even in the interior (Figure 3). While QSCAT agrees with buoys 1 and 4 very well, the agreement is not quite as good for SSM/I. These differences are due in part to differences in overpass time and in part to local biases in SSM/I retrievals related to marine aerosols.

[27] Buoy 6 is the closest to the land-sea boundary (31 km away from the coast) in comparison to buoys 1 and 4. QSCAT and SSM/I winds do not agree with buoy winds at this particular location. This may indicate land contamination in the satellite products. Not surprisingly, the QSCAT footprint is an ellipse approximately 25-km in azimuth by 37-km in the range. The scatterometer land-sea mask extends 35 km from the coast. This allows winds to be accurately measured from space relatively near the coastal regions, but contamination can be a problem where the footprint includes land areas. For example, the backscatter from land is usually much greater than from water. If the main antenna pattern from the satellite overlaps land, then higher backscatter from land may lead to overestimation of winds. Also note that the scatterometer measures winds relative to the ocean surface, while winds from NDBC buoys are measured by an anemometer at a constant location. The scatterometer observations are all seaward of the buoy observations, which may result in biased representation. Because the ocean current effect is not directly taken into account in buoy winds, this may introduce additional minor errors into the comparisons. However, averaging the buoy winds over a day or a month will generally remove any ocean current effects that cause the buoy to move, therefore the in situ mean winds are affected only slightly by the surface currents [e.g., *Quilfen et al.*, 2001].

[28] Performance of the creeping sea-fill is further evaluated at a buoy location, (38°N, 123°W) numbered as 4 in Figure 2, in 2001. The accuracy of winds from ERA-40 is significantly improved after the sea-fill (Figure 6). For example, the sea-filled winds are ≈3 m s^{-1} stronger than the original winds, bringing them closer to buoy measurements. Annual mean wind speed for the original winds from ERA-40 is 4.9 m s^{-1} but 7.1 m s^{-1} for the sea-filled winds, in closer agreement with the buoy annual mean wind value of 7.7 m s^{-1}). The annual mean of NCEP winds shows

similar agreement with buoy winds after the creeping sea-fill. The original NCEP wind did not show a serious effect from land contamination because its winds over the land were not very different than those over the sea near the land-sea boundary, as discussed before (Figure 3c).



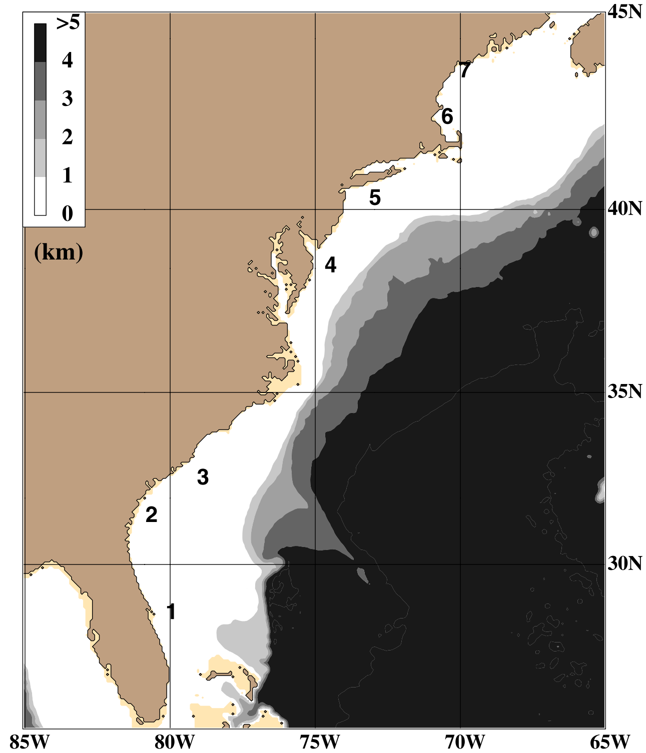


Figure 8. Bottom depth in kilometers at the U.S. coast and surrounding regions. The numbers (from 1 through 7) in the map show locations of moored buoys which will later be used for evaluating wind speed among the satellite-based and NWP products.

[29] Finally, overall performance of the creeping sea-fill is examined at all 9 buoy locations along the U.S. west coast. Scatter diagrams of 10 m wind speeds for buoy versus each product are presented (Figure 7). Winds from NWP products are clearly much weaker than those from buoys, although this is not the case for satellite-based products. For the standard (sea-filled) NOGAPS and ERA-40 products, mean biases are 1.6 (0.9) m s^{-1}, and 1.9 (0.2) m s^{-1}. Thus, after applying the creeping sea-fill, there is a closer agreement between NWP and buoy winds. Mean satellite product biases, i.e., buoy-QSCAT and buoy-SSM/I are -0.9 m s^{-1} and -0.3 m s^{-1}. Similarly, RMS differences for the original (sea-filled) NOGAPS, and ERA-40 winds with respect to buoy are 1.9 m s^{-1} (1.5 m s^{-1}) and 2.2 m s^{-1} (1.2 m s^{-1}). RMS difference for buoy versus QSCAT and buoy versus SSM/I winds are 1.3 m s^{-1} and 1.1 m s^{-1}, respectively. On the basis of these values, the creeping sea reduces RMS

Figure 7. Scatter plots of 10 m wind speeds between buoy versus (a) satellite-based QSCAT and SSM/I, (b) NOGAPS, (c) ERA-40, and (d) NCEP. (a–d) std (sea) refers to standard (sea-filled) winds from NWP products. Results are based on monthly winds from 9 buoys (see Figure 2) at the U.S. west coast in 2001. Each buoy has 12 monthly mean wind time series so there are 9 × 12 = 108 monthly mean winds. A few buoys had data voids in a few months. Thus, we use a total of 103 monthly mean wind speeds in the analysis.

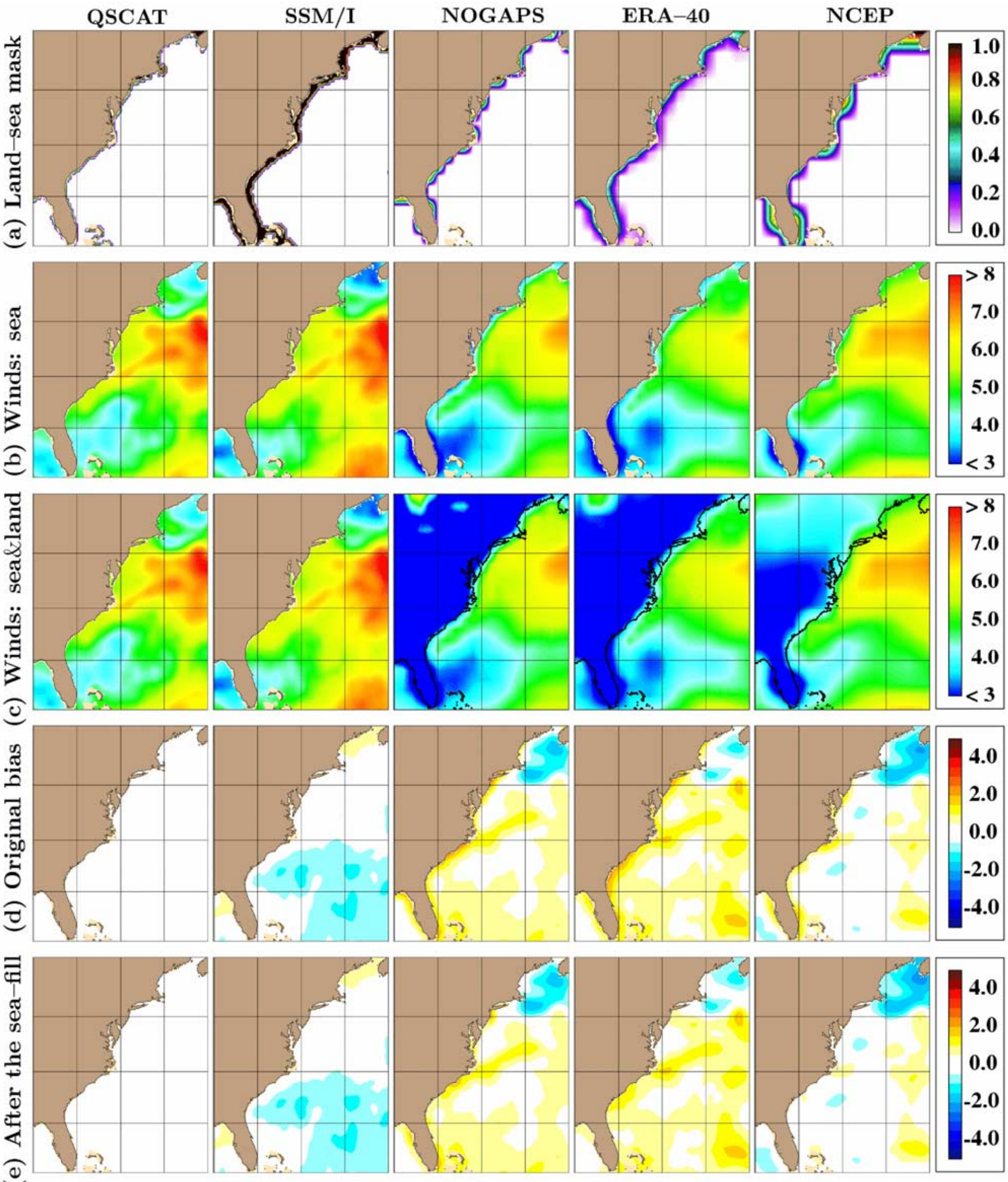


Figure 9. The same as Figure 3 but for the U.S. east coast. QSCAT and SSM/I have no wind values on land, so the creeping sea-fill is not applied as mentioned in the text. However, their plots are repeated in Figures 9b–e to allow for easy comparisons with NWP products.

difference in winds 25% for the original NOGAPS winds and 80% for the original ERA-40 winds.

[30] One weakness of the creeping sea-fill is that it assumes that winds from NWP products over sea are more representative of sea conditions than those over land. For some cases, land values are a better indicator of sea winds, so that application of sea-fill methodology causes NWP winds to diverge from buoy winds, while the original winds have already better agreement with buoys. This is not the deficiency of the methodology. For example, in the case of

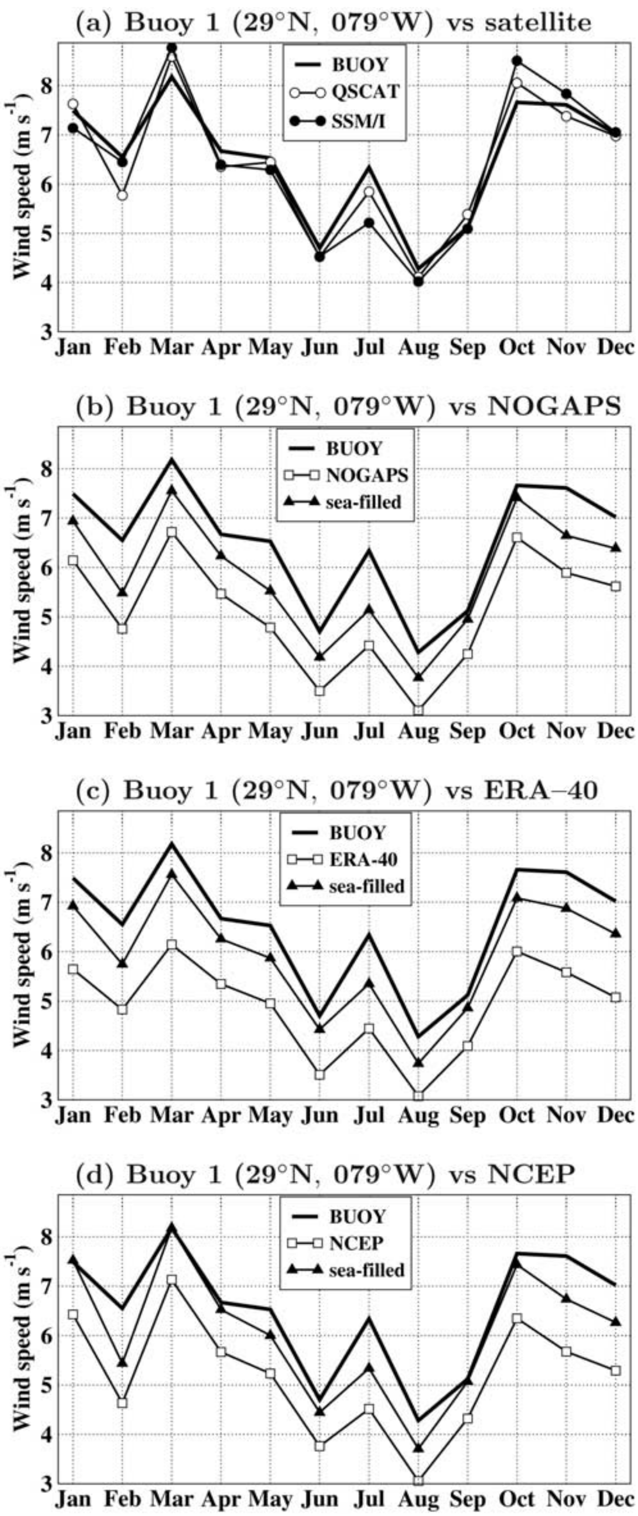


Figure 10. Comparisons of monthly time series of wind speed at 10 m above the sea surface from an NDBC buoy located at (29°N, 079°W) versus that from (a) satellite-based QSCAT and SSM/I, (b) NOGAPS, (c) ERA-40, and (d) NCEP. All are in 2001. Time series for NWP products are shown for both standard and sea-filled wind speeds. NDBC station for the buoy is 41010 (28.9°N, 78.5°W). Water depth where the buoy is located is ≈840 m.

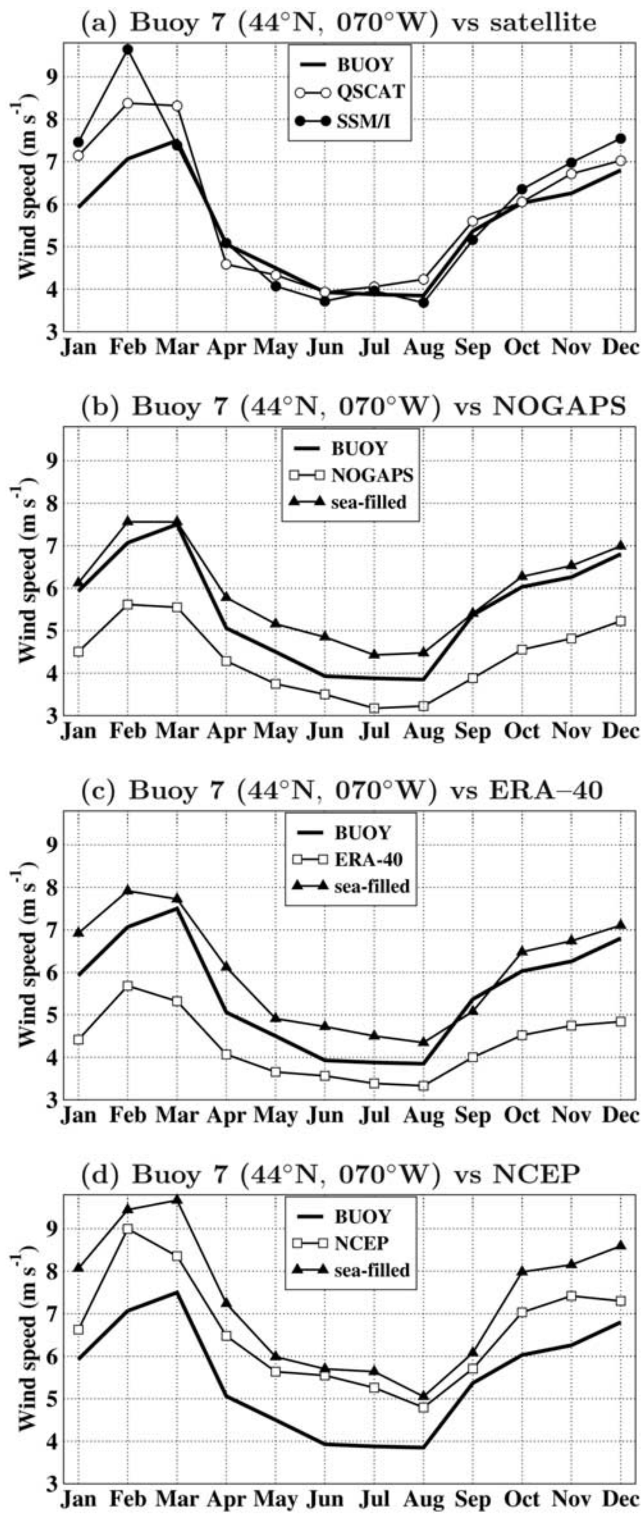


Figure 11. Comparisons of monthly time series of wind speed at 10 m above the sea surface from an NDBC buoy located at (44°N, 070°W) versus that from (a) satellite-based QSCAT and SSM/I, (b) NOGAPS, (c) ERA-40, and (d) NCEP. All are in 2001. Time series for NWP products are shown for both standard and sea-filled wind speeds. NDBC station for the buoy is 44007 (43.6°N, 70.1°W). Water depth where the buoy is located is ≈19 m.

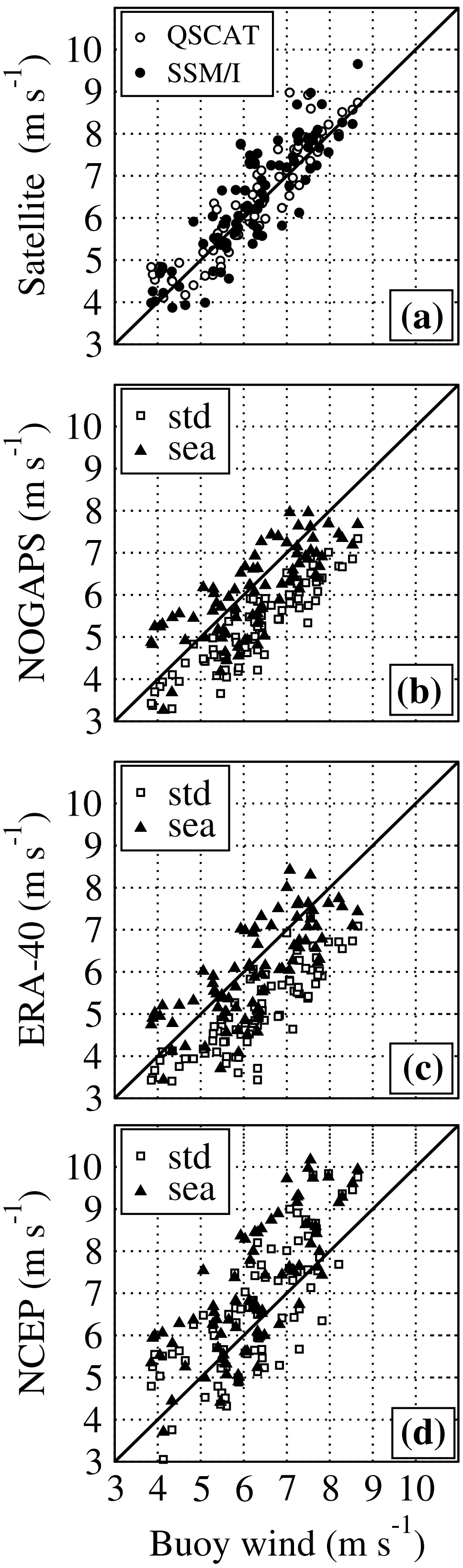


Figure 12. The same as Figure 7 but for the U.S. east coast in 2001. Results are based on monthly winds from 7 buoys (see Figure 8). Each buoy has 12 monthly mean winds in 2001, so there are 7 × 12 = 84 monthly mean winds. A few buoys had data voids in a few months. Thus, we use a total of 81 monthly mean wind speeds in the analysis.

NCEP, this is definitely the case, i.e., stronger winds from the interior ocean are interpolated to the coastal regions. In other words, land contamination improves the accuracy of NCEP product over the sea near the coast by weakening the generally excessive winds in the ocean interior.

5. Wind Speed Accuracy at Other Land-Sea Boundaries

[31] In this section, we investigate whether or not wind speed errors, noted along the U.S. west coast (section 3.2) are similarly found in other coastal locations. Two regions are chosen below because they include buoys where winds can be validated.

5.1. U.S. East Coast

[32] As evident from Figure 8, the shape of the coastline does not have a significant impact on the ability of the QSCAT footprint to make measurements as evident from the QSCAT land-sea mask values being close zero near the coastal boundary (Figure 9a). Winds in the interior ocean are generally in good agreement for all products in August of 2001 (Figure 9b).

[33] Compared with the U.S. west coast, NWP winds over the water near the land-sea boundaries of the east coast have much less contamination from land values (Figure 9c). Coastal winds from NWPs are still weaker than QSCAT winds, but mean differences with respect to QSCAT are smaller, typically <2 m s^{-1} (Figure 9d). The creeping sea-fill eliminates most of the bias with respect to QSCAT along the majority of the coastline (Figure 9e). The NCEP sea-filled winds are almost the same as QSCAT winds near the land-sea boundary, except at the northern boundary where the winds in the interior ocean are already very strong.

[34] Time series of 10 m wind speeds from the NWP and satellite-based products are compared to those from a buoy in 2001 (Figure 10). The buoy is located at the southern part of the east coast, marked as 1 in Figure 8. Both QSCAT and SSM/I winds agree with buoy winds very well at this particular location with almost no mean bias in all months

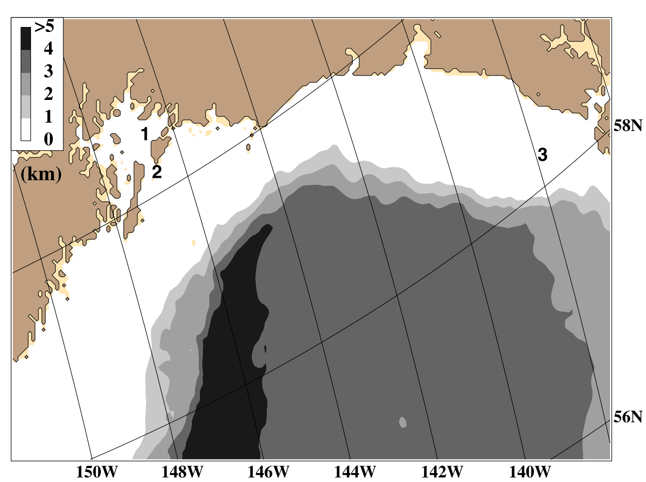


Figure 13. Bottom depth in kilometers along the Alaskan coast and surrounding regions. The numbers (from 1 through 3) in the map show locations of moored buoys.

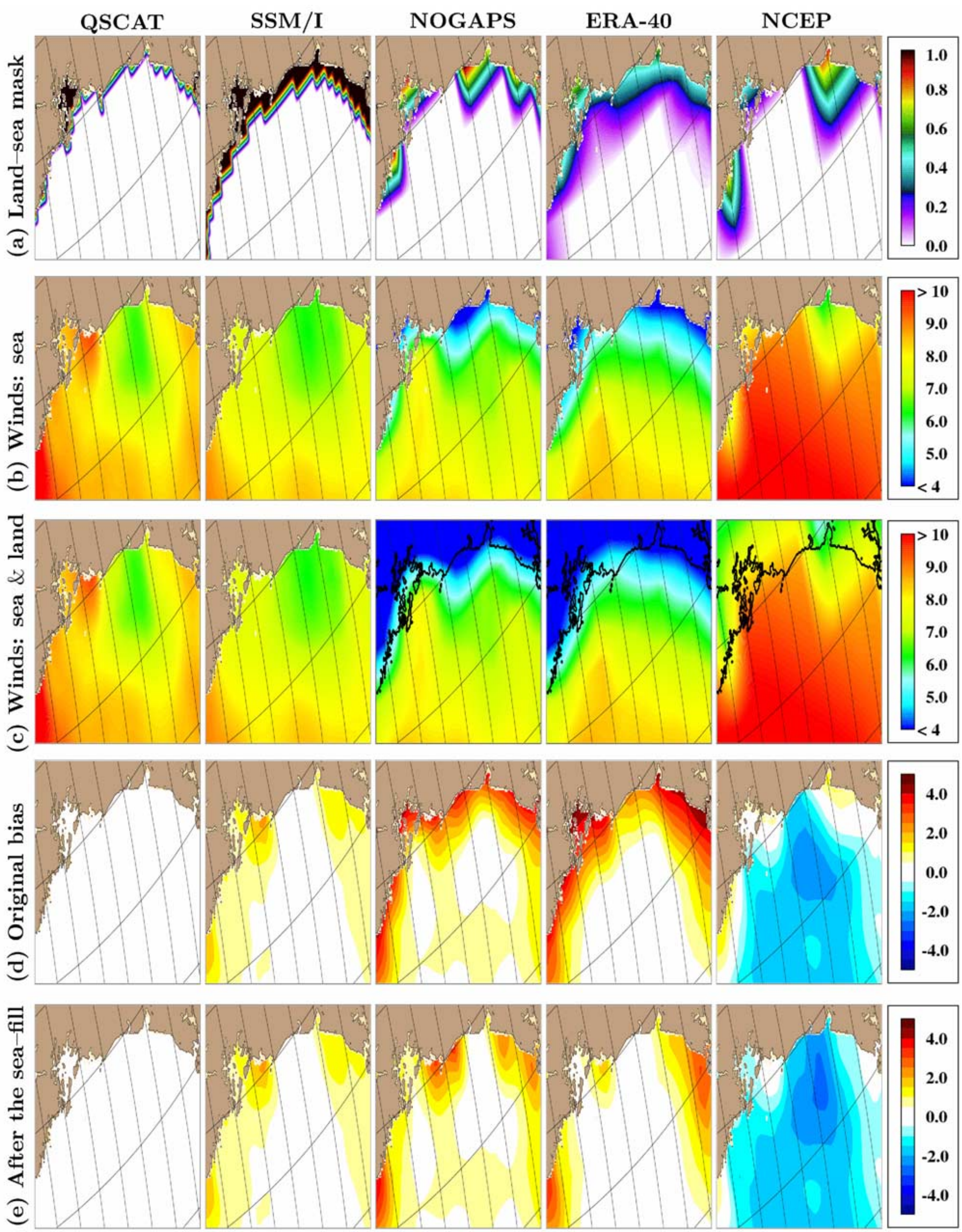


Figure 14. The same as Figure 3 but for the Alaskan coast.

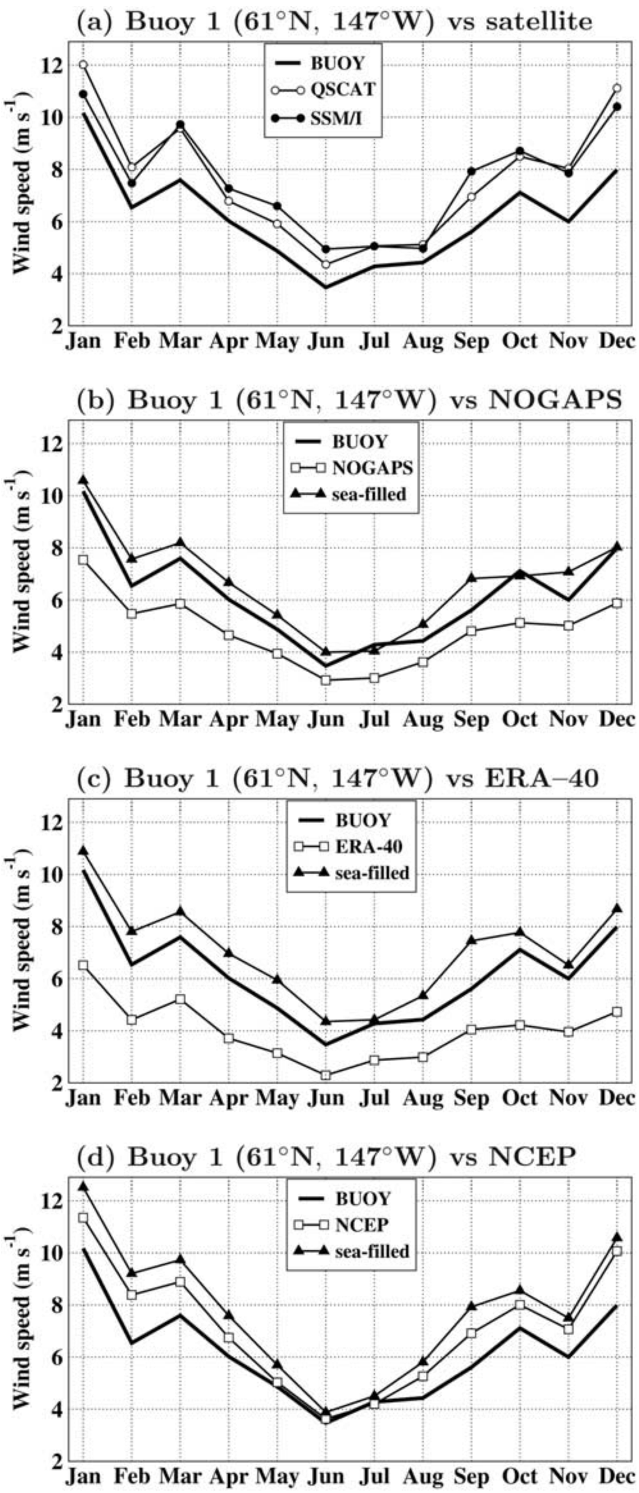


Figure 15. Comparisons of monthly time series of wind speed at 10 m above the sea surface from an NDBC buoy located at (61°N, 147°W) versus that from (a) satellite-based QSCAT and SSM/I, (b) NOGAPS, (c) ERA-40, and (d) NCEP. All are in 2001. Time series for NWP products are shown for both standard and sea-filled wind speeds. NDBC station for the buoy is 46060 (60.6°N, 146.8°W). Water depth at the buoy is location is ≈457 m.

(Figure 10a). The land contamination of wind speed from all NWP products appear to be the same and is typically reduced by ≈1 m s^{-1} after the sea-fill is applied (Figures 10b–10d). Figure 11 presents similar analyses at another buoy location, (44°N, 070°W), marked as 7 in Figure 8. Note that the sea-filled NOGAPS and ERA-40 winds at this particular location became stronger by ≈0.5 m s^{-1} than the buoy winds from April to September.

[35] Using the time series of wind speed from all 7 buoys shown in Figure 8, scatter diagrams of buoy versus satellite and NWP-based winds are produced (Figure 12). Missing winds in some months from the buoys are not considered in the analysis, resulting in 81-month-long time series. There is almost no bias (−0.2 m s^{-1}) between buoy and satellite-based products (i.e., buoy-QSCAT and buoy-SSM/I). RMS differences are also small, with values of 0.6 m s^{-1} and 0.7 m s^{-1}. For the ERA-40 winds, a mean bias (RMS) of 1.2 m s^{-1} (1.4 m s^{-1}) is reduced to 0.1 m s^{-1} (0.8 m s^{-1}) after the sea-fill. Although there is a remarkable improvement for the ERA-40 winds, the bias is slightly increased for the sea-filled NCEP winds, as in the U.S. west coast region. Mean bias of standard (sea-filled) winds with respect to buoy winds (NCEP-buoy) is 0.3 m s^{-1} (0.9 m s^{-1}), clearly indicating that the success of the creeping sea-fill also depends on the accuracy of the original winds over the sea points used for the interpolation.

5.2. The Alaskan Coast

[36] Wind speed variability near the Alaskan coast is of particularly interest because of the irregular coastline surrounding Prince William Sound north of 60°N where two NBDC buoys are also located (Figure 13). A striking feature of this small inland region is that even QSCAT does not have wind measurements there in February of 2001, so its land-sea mask values are always 1 (Figure 14a). In this case, QSCAT values from the nearest sea grid are filled into that region.

[37] Wind speeds from QSCAT, SSM/I, NOGAPS and ERA-40 in the sea interior are similar, and the main differences arise near the land-sea boundaries (Figure 14b). Once again, NCEP winds over the land are relatively stronger than those from NOGAPS and ERA-40, and the low NCEP wind contrast between land and sea reduces the impact of land contamination (Figure 14c). Similar characteristics were already noted in the U.S. east and west coast regions (Figures 3b and 9b). The creeping sea-fill is again useful for the NOGAPS and ERA-40 winds, which is further evident from time series of wind speed at a buoy location (Figure 15).

[38] RMS wind speed difference values with respect to QSCAT clearly reveal the significant land contamination for NOGAPS and ERA-40 but not for NCEP during 2000 and 2001 (Figure 16). Winds from ERA-40 agree with those from QSCAT well in the interior, with RMS values <0.5 m s^{-1}, and this agreement results in wind speed improvements near the coastal boundary when the creeping sea-fill is applied. In particular, the creeping sea-fill remarkably reduces RMS values from >3 m s^{-1} to <1 m s^{-1} for NOGAPS and ERA-40.

5.3. Some Limitations of the Creeping Sea-Fill

[39] As discussed in the preceding sections, the success of the creeping sea-fill greatly depends on the accuracy of the winds in the interior, which are interpolated toward coastal

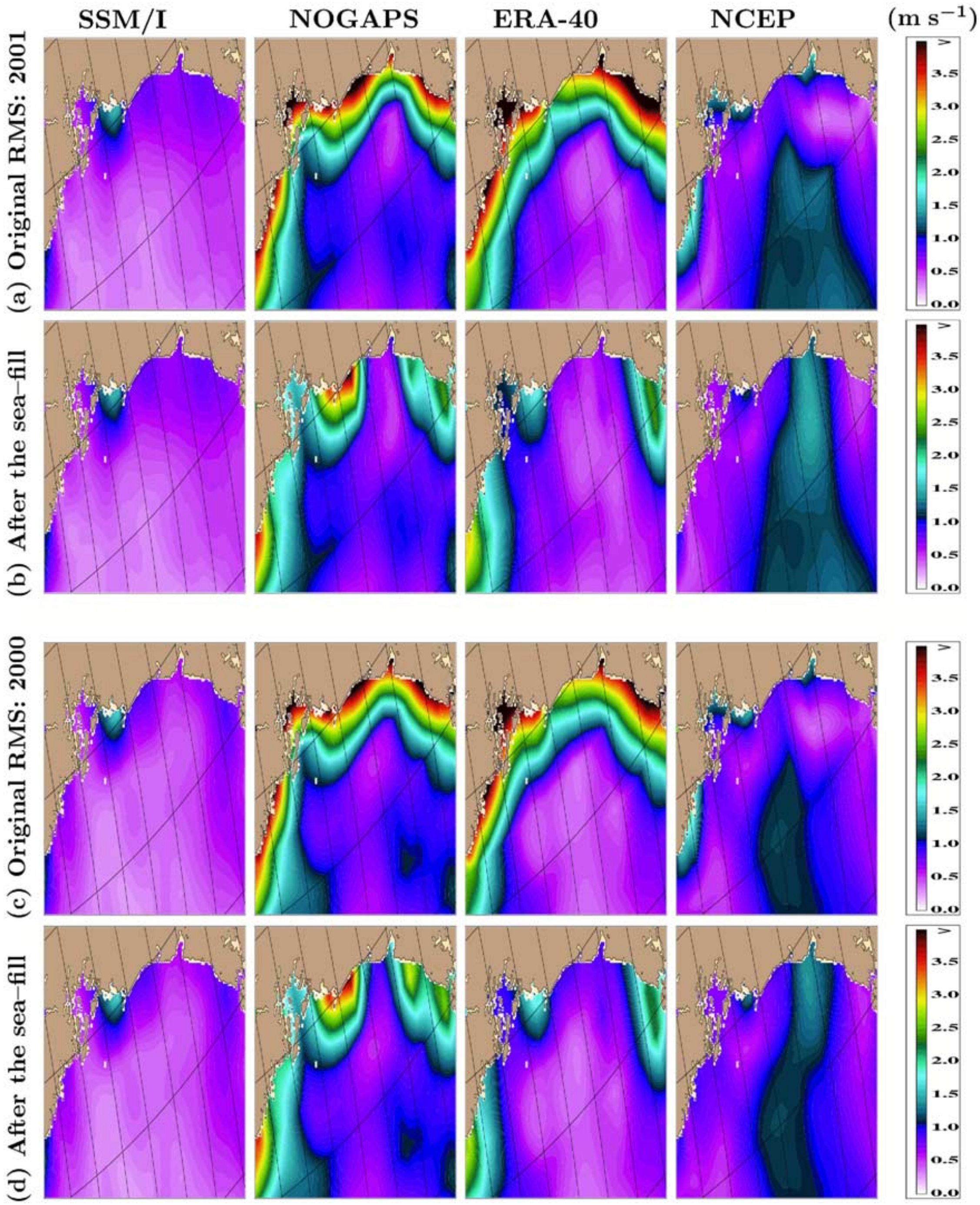


Figure 16. RMS wind speed errors with respect to QSCAT calculated over the seasonal cycle for the (a) standard NWP products in 2001, (b) sea-filled NWP products in 2001, (c) standard NWP products in 2000, and (d) sea-filled NWP products in 2000.

boundaries. There are also other limitations at fine length scales. Some examples are provided here. The underestimation or overestimation in wind strength of the creeping sea-fill algorithm with NWPs may be considered to be consistent with the development of a stable atmospheric marine boundary layer in spring and summer months along the U.S. west coast [e.g., *Rogerson*, 1998]. In addition, hydraulic jumps associated with coastal orography strongly influence buoy wind speeds, raising them above NWP products or even satellite estimates outside the coastal rind. Marine atmospheric boundary layer dynamics similar to those on the U.S. west coast are also present in several other coastal upwelling areas such as Morocco and the western Sahara, Peru, and Namibia [*Winant et al.*, 1988], suggesting that NWP products may also underestimate wind stress in these areas when extrapolated using the creeping sea-fill methodology.

[40] On the other hand, one should note that resolution of NWP products is generally too coarse to be related to such small-scale processes, such as hydraulic jumps. In this paper

we provide enough detail for a reader with knowledge of a particular coastal region to decide if the creeping sea-fill technique is likely to be useful. This paper has not investigated mechanisms for why ocean interior and coastal winds might differ. That would certainly be a topic for a further study with the availability of much finer (e.g., 3 km) global NWP products since the results would change locally.

[41] This study does not present any correction for wind direction. From an ocean model point of the view, the ocean mixed layer is very strongly dependent on wind speed, and is only indirectly affected by wind direction. Ocean models are typically forced by vector wind stress, and their currents are very sensitive to the wind stress curl. An advantage of NWP products is that they provide a dynamically consistent wind stress curl (even when the curl itself is in error). It would be better to correct vector winds (speed and direction), but this is very difficult to do in a manner that gives a reasonable curl. By correcting wind speed, and therefore wind stress magnitude, we do change the curl but not typically by a large amount. Thus, a shortcoming of the creeping sea-fill technique is that if the NWP wind direction is in error near the coast then this will not be corrected by changing its speed.

[42] One final note is that the wind at sea points near coast should feel the influence from land, for an example, in a sea breeze event. For this reason, one may also think that the approach of the creeping sea-fill artificially isolates the wind at sea from the wind from land, and it might miss the information passed from the land. However, NWP products rarely capture sea breeze unless the resolution is increased. Only diurnal variability shown in the model can appear after the creeping sea-fill.

6. Summary and Conclusions

[43] Surface wind speeds at 10 m above the sea surface from NWP products (NOGAPS, ERA-40 and NCEP) are quite accurate, having remarkable agreements ($\approx$0.5 m s^{-1} mean bias) in comparison to satellite-based QSCAT and SSM/I measurements in the interior of the ocean. However, winds can be quite inaccurate over the sea near the land-sea boundaries. This is a consequence of including winds over land at ocean points due to coarse resolution atmospheric model grids from NWP centers. For example, typical mean wind speeds over the land can be as weak as 2 m s^{-1} but those over the water are often much stronger (e.g., >6 m^{-1}) at the U.S. west coast. Because there is no distinct transition along the coastal boundary, winds over the water are contaminated by those over the land, depending on the extent of the land-sea mask, i.e., and related grid resolution of the NWP product.

[44] Special action needs be taken to ensure that wind speed over land from NWP products does not contaminate wind speed over sea, allowing these products to be used more safely for offshore applications near coastal boundaries. A viable method, the creeping sea-fill, is therefore introduced. This methodology significantly improves accuracy of winds near the coastal boundaries as demonstrated at various regions of the global ocean. This is particularly true for NOGAPS and ERA-40. However, two factors render the creeping sea-fill ineffective for NCEP winds near the land-sea boundaries. First, NCEP winds tend to be too strong over open water points, so contamination with weaker land values actually reduces nearshore values to more reasonable speeds. Second, wind speed tends to be lower over land than water, so that relatively high NCEP wind speeds over land are more reasonable for estimates of wind speeds over water areas.

[45] Overall, the success of the creeping sea-fill methodology mainly depends on (1) the accuracy of the NWP winds in the interior and (2) the assumption that actual interior winds near the coast are representative of actual coastal winds. If we look at fine enough scales, coastal winds are often different from interior winds but in this study we are concerned with the scales resolved by global NWP products. At this scale, we have demonstrated that interior winds are typically superior to the NWP's local near-coast solutions. On the other hand, there is clearly a ceiling on the representativeness of this approach where (2) fails. We are currently exploring a linear regression analysis between NWP and satellite winds. This approach certainly helps with (1) by improving the accuracy of the winds in the interior. It also helps with (2) in regions where the satellite (e.g., QSCAT) winds are available close to the coast.

[46] Errors similar to those noted in wind speeds from NWP products also exist in other atmospheric variables, such as near-surface air temperature, air specific humidity, surface heat fluxes, etc. Using such variables for ocean-only applications (e.g., for forcing an ocean model) requires similar corrections based on the creeping sea-fill technique. For example, atmospheric forcing variables for the HYbrid Coordinate Ocean Model (HYCOM) are typically obtained from ECMWF or NOGAPS, and the creeping sea-fill methodology is applied to scalar forcing variables before using then in model simulations.

[47] Improving the accuracy of wind speeds near coastal boundaries from global NWP products is essential for fine resolution studies. This would also help better understanding the influence of near surface oceanic processes on the atmosphere or vice versa near the land-sea boundaries. In addition to the creeping sea-fill, another direct solution to reduce land contamination is that NWP products could provide wind speeds gridded using only the ocean and land values, separately. While not discussed here, wind direction also requires additional corrections.

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