A Near-Real-Time Version of the Cross-Calibrated Multiplatform (CCMP) Ocean Surface Wind Velocity Data Set

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Abstract The Cross-Calibrated Multiplatform (CCMP) ocean surface wind data set was originally developed by Atlas and coworkers to blend cross-calibrated satellite winds, in situ data, and wind analyses from numerical weather prediction. CCMP uses a variational analysis method to smoothly blend these data sources into a gap-free gridded wind estimate every 6 hr. CCMP version 2.0 is currently produced by Remote Sensing Systems using consistently cross-calibrated satellite winds, in situ data from moored buoys, and background winds from the ERA-Interim reanalysis. The reanalysis fields are only available after a delay of several months, making it impossible to produce CCMP 2.0 in near real time. Measurements from in situ sources such as moored buoys are also often delayed. To overcome these obstacles and produce a near-real-time (NRT) version of CCMP (CCMP-NRT), two changes are made to the input data sets: The background winds are now the operational 0.25-degree NCEP analysis winds, and no in situ data are used. This allows CCMP-NRT to be routinely processed with a latency of less than 48 hr. An intercomparison of the CCMP-NRT results with CCMP 2.0, and independent measurements from moored buoys shows that CCMP-NRT provides a modest improvement over the background wind from NCEP in regions where satellite data are available. Analysis shows that the inclusion of in situ measurement in CCMP improves the agreement with these measurements, artificially reducing estimates of the error.

Plain Language Summary Satellites that orbit the Earth estimate winds over the ocean by evaluating the roughness the ocean surface. These satellites make their measurements at different time of the day, and there are spatial gaps between the satellite measurements. These characteristics make the data hard to use. The Cross-Calibrated Multiplatform (CCMP) vector wind analysis uses a mathematical technique that combines satellite measurements, in situ measurements, and a background wind field into complete maps of ocean winds every 6 hr. This paper describes a new version of CCMP that can be constructed only a few days after the satellite measurement are made, opening up near-real-time applications for these data.

1. Introduction

The Cross-Calibrated Multiplatform (CCMP) vector wind analysis uses a variational method to blend information from satellite wind retrievals, in situ wind measurements, and a background wind field from a numerical weather analysis to produce a gap-free estimate of vector winds over the world's oceans. CCMP Version 1.1 was originally developed in the late 2000s using a combination of the ERA-40 reanalysis and the European Center for Medium Range Weather Forecasting operational analysis as the background wind vector field and a variety of satellite wind speed/vector data sets (Atlas et al., 2011). CCMP Version 2.0 is an upgraded version that uses accurately intercalibrated winds from Remote Sensing Systems (Wentz, 2013, 2015) and exclusively uses a background field from the ERA-Interim reanalysis (Dee et al., 2011) and included several newer satellites that were not used for V1.1. These two changes leads to an improvement in long-term stability, though significant problems remain even in the improved product (McGregor et al., 2017).

One of the major drawbacks of CCMP 2.0 is its reliance on reanalysis output, which is typically produced after a latency period of several months, making it impossible to process CCMP 2.0 in near real...
real time. There is also a shorter latency period for the moored buoy data and certain sources of satellite data.

McGregor et al. (2017) noted several additional drawbacks associated with the use of buoy data in the CCMP analysis. First, it is difficult to evaluate the accuracy of CCMP because the most common source of validation data, measurements from anemometers mounted on moored buoys, are assimilated into the baseline CCMP 2.0 data product. In the immediate vicinity of the buoys, the analysis is strongly influenced by the buoy data, and the resulting winds are closer to the buoy winds than they would have been had the buoys not been included. Therefore, a naïve analysis using moored buoys as validation truth would result in an estimated accuracy that is better than the true value for regions far from buoys. Second, the wind field curl and divergence in CCMP V2.0 is distorted in places near the buoy locations and at the edges of the satellite swaths due to a mismatch between buoy, satellite, and reanalysis winds. The distortion of the curl can lead to erroneous results if the CCMP wind field is used to force an ocean model (McGregor et al., 2017).

In this work, we describe two new versions of the CCMP data set that do not include any in situ data. The main focus is a near-real-time (NRT) version that uses the operational analysis from the National Center for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS) for the background wind field and excludes in situ data. We call the version CCMP-NRT. We also present a version of CCMP 2.0 that uses ERA-Interim as the background but also excludes in situ measurements. This version is called CCMP-NO-BUOY. The purpose of this second version is to be able to separate the effects of not using buoy data from the effects of changing the background field from ERA-Interim to the NCEP GDAS. This version can also be used to estimate the errors in CCMP V2.0 by comparison to the moored buoys and may be an improvement for some applications in the vicinity of moored buoys. For both versions, the CCMP analysis system is unchanged from what is described by Atlas et al. (2011) and summarized in Section 2 below.

2. The CCMP Analysis

The CCMP combines satellite and in situ measurements with a background field derived from operation analyses or reanalysis to produce a gap-free near-global oceanic vector wind map every 6 hr using a variational approach (Atlas et al., 2011). Relative to the satellite data, the method fills in the gaps between satellite swaths, adds direction information to satellite measurements of scalar wind speed, and adjusts the measurements to correspond to a single synoptic time over the entire gridded data set. This makes the data set much easier to use than the raw satellite data in a variety of oceanographic and meteorological applications. The variational analysis method (VAM) used is tuned so that CCMP wind speeds directly reflect observations close to the analysis time and smoothly merges these data-rich areas into the background when no close observations are available. Typically, CCMP is more closely aligned with actual wind measurements than the background analyses, which both assimilate similar satellite or moored buoy measurements along with other measurements (e.g., pressure and temperature) that affect the analyzed state of the surface winds.

The CCMP VAM functions by minimizing a cost function \( J \) (Atlas et al., 2011),

\[
J = \lambda_{\text{CONV}}J_{\text{CONV}} + \lambda_{\text{SCAT}}J_{\text{SCAT}} + \lambda_{\text{SPD}}J_{\text{SPD}} + \lambda_{\text{VWM}}J_{\text{VWM}} + \lambda_{\text{LAP}}J_{\text{LAP}} + \lambda_{\text{DIV}}J_{\text{DIV}} + \lambda_{\text{VOR}}J_{\text{VOR}} + \lambda_{\text{DYN}}J_{\text{DYN}}.
\]

The cost function includes a number of terms that reflect the misfit of the analysis from different types of observations (CONV = conventional [buoys], SCAT = satellite scatterometer, and SPD = satellite wind speed), the background (VWM = vector wind magnitude), a priori smoothing constraints (LAP = Laplacian of wind components, DIV = divergence, and VOR = vorticity), and a dynamic constraint (DYN) that limits the time rate of change of the wind field. The CCMP analysis is the final result of a multi-stage procedure that allows for both adaptive quality control and analysis at a cascade of increasingly finer length scales for computational efficiency. The \( \lambda \)s are weights that control the influence each type of constraint has on the final results. The method is described in considerable detail in Atlas et al. (2011). Examples of a 6-hourly global wind field for the background field, the CCMP-NRT analysis, and the difference of CCMP-NRT and NCEP for \( U, V \), and wind speed are shown in Figures 1b–1j. The largest increments are associated with extratropical cyclones. Figure 1a shows the number of satellite observations analyzed at each grid point for this analysis.
3. Input Data Sets

In this section, we describe the input data sets that are included in the versions of the CCMP analyses evaluated in this work.

3.1. Satellite Wind Retrievals

We use two types of satellite wind retrievals in CCMP, imaging radiometers and scatterometers. Imaging radiometers retrieve near-surface wind speed (but generally not direction) over the ice-free oceans by evaluating changes in microwave radiance caused by changes in the emission and scattering properties of the ocean surface as wind increases (Draper et al., 2015; Meissner & Wentz, 2012; Wentz, 1997). These measurements start in late 1987 with the flight of the first Special Sensor Microwave/Imager (SSM/I) instrument on the Defense Meteorological Satellite Program (DMSP) F08 satellite (Goodberlet et al., 1989). This is the first of a series of similar radiometers on DMSP platforms, culminating with the Special Sensor Microwave Imager Sounder (SSMIS) on the DMSP F19 satellite. The lowest frequency on these radiometers is 19.35 GHz, limiting their ability to retrieve wind speed in moderate to heavy rain. There have been several other radiometers with lower frequency channels. Two satellites with 10.65 GHz channels are the Tropical Rainfall Measuring Mission Microwave Imager (Simpson et al., 1996) and the Global Precipitation Mission Microwave Imager (Draper et al., 2015). The Advanced Microwave Scanning Radiometer (AMSR;
Satellites included in CCMP 2.0 and CCMP-NO-BUOY as a function of time. Imaging radiometers are shown in blue, and scatterometers are shown in green. The names for satellites that were operational in early 2018 are shown in red. CCMP-NRT does not begin until January 2015 (vertical purple line) when the 0.25-degree NCEP analysis becomes available.

Kawanishi et al. (2003) has operated with a 6.9 GHz channel on three satellites, AMSR-2 on the Japan Aerospace Exploration Agency’s (JAXA) GCOM-W1 spacecraft, AMSR-E on NASA’s Earth Observation System (EOS) Aqua spacecraft, and AMSR on JAXA’s ADEOS-II spacecraft. The Coriolis radiometer on the U.S. Defense Department’s WindSat platform (Gaiser et al., 2004) also has a 6.9 GHz channel. The lower-frequency channels (both 10.65 and 6.9 GHz) may allow for more accurate retrievals in the presence of rain at the expense of somewhat reduced spatial resolution (Meissner & Wentz, 2009).

Scatterometers retrieve both wind speed and direction from a radar signal backscattered from the ocean surface. Here, we use scatterometer retrievals from NASA’s QuikSCAT mission (Wu et al., 1994) and from the Advanced Scatterometer (ASCAT) on EUMETSAT’s MetOp-A mission (Figa-Saldaña et al., 2002). Other scatterometer data are available but have not been precisely intercalibrated with the measurements listed above and thus are not ready to be included in CCMP. Figure 2 shows a plot of the mission lifetimes for all satellite instruments included in CCMP V2.0 and the versions described here. In all cases, we are using the most recent versions of the satellite data produced at Remote Sensing Systems. These retrievals have been intercalibrated to produce consistent wind retrievals (Draper et al., 2015; Ricciardulli & Wentz, 2015; Wentz, 2013, 2015). Note that WindSat is capable of retrieving wind direction in addition to wind speed because of the addition of fully polarimetric channels at low frequency. WindSat wind direction retrievals are not used in our analysis because the uncertainty of the direction retrieval depends strongly on wind speed. We have not yet developed a method to account for this dependence for CCMP. In all cases, the satellite data are quality controlled to remove the effects of rain on wind retrievals.

### 3.2. Background Wind Fields

CCMP operates by adjusting a background surface wind field to match the assimilated observations, subject to the constraints imposed by a cost function. The background field is important because it provides direction information in regions without closely collocated measurements with direction information, that is, scatterometers and moored buoys. Because of the way the cost function is currently configured, the influence of the measured winds does not typically extend further than about 100 km from the measured location. The background field is the only source of information in regions far from collocated measurements, and CCMP is equal to the background estimate in these regions. In previous work, the dependence of the final results on the background field has not been rigorously explored. In this work, we take the first step by comparing results for two different choices of the background field. CCMP 2.0 and CCMP-NO-BUOY use the 6-hourly wind analysis from the ERA-Interim reanalysis (Dee et al., 2011; Simmons et al., 2011) as the background. ERA-Interim starts in 1979 and continues to the present. The horizontal resolution of ERA-Interim is approximately 80 km but is interpolated to a 0.25-degree grid (~28 km at the equator) using bilinear interpolation. Because we wanted CCMP-NRT to be updated in near real time, we use the output from a global numerical weather prediction system, the NCEP Global Data Assimilation System (GDAS) analysis. This product is available at 0.25-degree resolution with a delay of only a few hours. Since 14 January 2015, the spatial resolution of this model is considerably higher than ERA-Interim, which may allow it to more precisely resolve small features in the wind field. An example of the global NCEP wind analysis is shown in Figures 1b–1d.

### 3.3. Moored Buoys

Vector wind measurements from moored buoys are also used in CCMP V2.0, but not in CCMP-NO-BUOY and CCMP-NRT. In all cases, buoys form a comparison and validation data source. We use tropical moored buoys operated by the TAO (McPhaden, 1995), TRITON (Kuroda & Amitani, 2001), PIRATA (Servain et al., 1998), and RAMA (McPhaden et al., 2009) projects, as well as buoys operated by the National Data Buoy Center (Gilhousen, 1987) and the Canadian Marine Environmental Data Section. These buoys provide hourly measurements of vector winds averaged over a short (2 to 10 min) period near the observation time. We routinely download and archive these data from the National Data Buoy Center and from the Marine
Environmental Data Section. We perform several additional quality control steps to flag and remove observations that are obviously erroneous or mislocated. We also convert the buoy wind measurements to 10-m neutral stability (NS) winds using the procedure described in Liu and Tang (1996). Ideally, all data sources would be converted to NS winds due to the way the satellite sensors are calibrated. Because the satellite sensors respond to the ocean surface and the ocean surface responds to the atmospheric stress on the ocean, buoy data are corrected for stability effects before they are used to calibrate the satellite sensors. Consequently, the satellite wind data observations are NS winds. In CCMP, the background winds should also be NS winds but are not, likely leading to inconsistencies in regions of anomalous stability. The buoy winds are converted to NS winds if possible, as described here. The Liu and Tang method requires both the sea surface temperature (SST) and the air temperature ($T_{AIR}$) above the surface to assess the near-surface stability. Since these measurements are not always available from the buoy record, we performed the adjustment using values of SST and air temperature from the ERA-Interim background field. A comparison of a similar adjustments made using buoy-measured values for SST and $T_{AIR}$ show substantial differences for individual measurements but almost no difference for mean and standard deviation of the buoy-CCMP statistics evaluated over monthly or longer time periods. Figure 3 shows a map of buoy locations with valid data for an example month, December 2016. The tropical Pacific and Indian oceans show fairly good coverage, as do the coastal regions surrounding North America. Huge regions of the oceans elsewhere have no moored buoy observations and thus would be unaffected by their removal from the CCMP analysis.

4. Analysis

Our analysis of the results covers three broad areas: (a) changes in the product caused by removing the moored buoy measurements; (b) change caused by using a different background field; and (c) an evaluation of all three products by comparing CCMP winds with moored buoys.

4.1. Impact of Removing Buoys

A comparison of CCMP-NO-BUOY with CCMP 2.0 shows the impacts of not using buoys without the complicating effects of also changing the background field. Figures 4a–4c show this on a single CCMP analysis on the zonal wind ($U$), the meridional wind ($V$), and the wind speed ($W$). The largest effects, up to about 1.0 m/s, are in the regions that directly surround buoy locations in the tropics and surrounding North America. The effects are larger on the individual wind components than on the wind speed, suggesting that some of the difference is in wind direction. The sign of the effect can be either positive or negative for both the wind components and for the wind speed. There are also differences far from the location of any buoy: In this example, differences can be seen in the Southern Pacific, west of Patagonia, in the southern Indian Ocean, in the Bering Sea, and in the North Atlantic southwest of Iceland. These differences occur because a different number of iterations were performed in the two versions before the analysis met the convergence criteria in the CCMP system. Differences in the number of iterations were caused by inclusion of the buoys, but the effects are manifested more generally because the convergence to an exact minimum of the cost function is never achieved. These differences vary with time substantially and randomly both in sign and magnitude (not shown).

The second row of Figure 4 (d–f) shows monthly mean values for the CCMP-NO-BUOY and CCMP 2.0 differences for $U$, $V$, and $W$ for a typical month. The magnitude of the monthly mean differences is considerably smaller than the individual time step differences because part of the difference has been reduced by the averaging procedure. Despite this reduction, there are still discernable differences near the buoys, indicating that the presence of the buoys has a long-term effect on the CCMP analysis. This is because the buoys tend to be biased relative to the satellite measurements and/or the background field (Carvalho et al., 2014; Mears et al., 2001; Satheesan et al., 2007). The third row of Figure 4 (g–i) shows maps of the standard deviation over a typical month. The standard deviation of the changes is small away from the buoy locations and is typically between 0.5 and 1.0 m/s near buoy locations.

The inconsistency between buoy and other winds has an important effect on spatial derivatives in the CCMP analysis. Figure 5 illustrates this point by showing the annual mean of the wind stress curl in the tropical Pacific for CCMP 2.0, CCMP NO BUOY, and the ERA-Interim background field for 2016. The CCMP curl field shows obvious artifacts at buoy locations, as was first shown in McGregor et al., (2017). As expected, these artifacts are no longer present when the buoys are removed from the analysis. In regions more
distant from the buoy locations, the two CCMP versions are very similar. Relative to the background, both versions show an intensification of features near the equator in the eastern part of the region shown, so the removal of the buoy information does not substantially affect the impact of the CCMP analysis. It is likely that some of the difference between the CCMP and ERA-Interim curl fields is due to the influence of surface currents that are implicitly included in CCMP via the satellite winds, which are relative to the ocean surface.

The elimination of buoy measurements has little effect on long-term trends in the CCMP analysis. Maps of 1988–2016 trends from CCMP 2.0 and CCMP-NO-BUOY are shown in Figure 6. In the CCMP 2.0 trend map, the trends appear to be reduced near some buoy locations. This is most noticeable in the Tropical Pacific, where a pattern caused by the TAO buoys can be seen. This makes sense if the overall trends are a result of increases in data coverage combined with the NWP analysis low bias because at the buoy locations there has always been good data coverage. A fainter version of the tropical array mooring pattern can also be seen in the CCMP-NO-BUOY map. This is likely because the buoy data are assimilated into the ERA-Interim background field.

Figure 3. Map of buoy locations with any valid wind data during the month of December 2016.

Figure 4. Comparison of CCMP-NO-BUOY with CCMP 2.0. The top row (a–c) shows a typical differences CCMP NO BUOY minus CCMP 2.0 for a single synoptic map (1 February 2016, 00Z) for zonal wind $U$, meridional wind $V$, and wind speed $W$. The middle row (d–f) shows the monthly averages mean differences for $U$, $V$, and $W$ for an example month, January 2016. The bottom row (g–i) shows the monthly standard deviation of the difference for $U$, $V$, and $W$. 
4.2. Impact of Changing the Background Field

A comparison of CCMP-NO-BUOY with CCMP-NRT allows investigation of the more profound effects of changing the background field on the CCMP analysis. Figures 7a–7c show maps of differences between CCMP-NO-BUOY and CCMP-NRT for zonal wind (U), the meridional wind (V), and the wind speed (W) for an example time step. The differences are often greater than 0.5 m/s except in regions where satellite direction data are available from ASCAT. These areas can be seen as diagonal swaths of low difference in the Atlantic and Western Pacific. The differences tend to be smaller for W, suggesting that much of the difference in the wind components is due to direction differences. The differences often are large near frontal boundaries, indicating that they may arise from differences in locations of synoptic weather in the two products. When averaged over 1 month, the differences are much reduced, as shown in Figures 7d–7f.

Some of the largest remaining differences occur near the equator, where rain often results in missing or compromised data for the satellite winds. Figures 7g–7i show monthly standard deviation for U, V, and W. The standard deviation values are smaller for W, again suggesting that direction differences are an important contributor to the differences in wind components. The standard deviations are larger in the northern hemisphere mid-latitudes because these plots were made for January 2016 during the northern hemisphere winter.

When there is no satellite data available, the differences between the CCMP-NO-BUOY and CCMP-NRT products are large and are
approximately equal to the differences in the background field. Figures 8a and 8b show the monthly mean difference and standard deviation in wind speed when satellite data are present (SAT), and Figures 8c and 8d show the corresponding maps when satellite data are not available (NO‐SAT). The monthly mean wind speed difference is close to zero with satellite data, which is expected because the CCMP wind speed is very close to the satellite values when satellite data are present. Without satellite data, the differences between the corresponding background fields remain. Maps corresponding to those shown in Figure 8, but for zonal and meridional wind, are shown in Supporting Information Figures S1 and S2.

4.3. Comparison With Buoy Measurements

Ocean winds are measured by in situ instruments mounted on a variety of platforms, including moored oceanographic buoys, drifting buoys, fixed platforms, commercial vessels, research vessels, and military vessels. Of these, moored buoys are both highly reliable and are mostly located in the open ocean far enough from land so that satellite measurements are not compromised by land contamination. These features make them suitable for validation of both satellite‐derived and CCMP winds. The main drawback is that both the CCMP 2.0 winds, and, to a lesser degree, the NWP‐derived background wind fields are not completely independent of the buoy measurements. Measurements from moored buoys are included in the CCMP 2.0 analysis. In addition, buoy measurements are often assimilated into the NWP systems used to produce ERA‐Interim reanalysis and the NCEP operational global analysis that we use as background fields.

Because CCMP 2.0 closely fits the buoy winds, buoy‐CCMP 2.0 comparison statistics are unrealistically good and not representative of the quality of the CCMP analysis far from the buoys. CCMP‐NO‐BUOY allows us to more reliably evaluate the quality of the CCMP analyses. Note that the buoys have an unknown influence on the background fields and thus still have an influence on CCMP‐NO‐BUOY. We suspect that this influence is much smaller than the more direct effect on CCMP 2.0 but may be spread over a greater distance depending on the details of the assimilation methods used by the NWP analyses. This smaller influence may be the
cause of the faint vertical structures in the lower panel of Figure 6, which shows the long-term trends in the tropics for CCMP-NO-BUOY. It appears that near the locations of the TAO moorings, the long-term trends are slightly reduced compared to other nearby regions. This can only be via the influence of the buoy measurements on the ERA-Interim background winds. However, this effect appears to be several times smaller than the direct effect on CCMP 2.0 for long-term trends.

To investigate the quality of the CCMP analysis and the effect of the direct inclusion of the buoy measurements, we study buoy-CCMP differences for all collocations within 30 min. Since the buoy measurements are almost always made each hour in our buoy data set, this automatically chooses the closest buoy measurement in time. The CCMP value for the one-fourth-degree grid cell that contains the buoy location is used for the comparison. Since we also want to investigate the quality of the CCMP-NRT analysis, we focus our study on the period of 16 January 2015 to 30 December 2017 where both CCMP-NRT and CCMP 2.0 are available. This resulted in 405,394 collocations, of which 273,287 had retrievals from at least one satellite at the buoy location.

In Figure 9, we show histograms of differences of the gridded products from the buoy NS winds for the zonal and meridional components U and V, wind speed W, and wind direction. Statistical parameters from these comparisons are summarized in Table 1. The top row (a–d) shows the histograms for all collocations, the middle row (e–h) shows the histograms for collocations where at least one satellite observation was included in the CCMP analysis at the buoy location (SAT), and the bottom row (i–l) shows the cases without satellite observations in the grid cell (NO-SAT). In all cases, for all four parameters, the agreement between CCMP 2.0 and buoys is substantially better than any of the other wind products. This is not surprising since the CCMP analysis is “pulled” toward the buoy measurements. Considering the wind components for ALL collocations, CCMP-NRT agree slightly better with buoys than CCMP-NO-BUOY. This appears to be due to the better agreement between the NCEP analysis and buoys than the ERA-Interim reanalysis and buoys. CCMP-NO-BUOY shows a small but clear improvement when compared to its background field, ERA-Interim, while the performance of CCMP-NRT is almost identical to the NCEP analysis. Most of the improvement in CCMP-NO-BUOY relative to ERA-Interim occurs for cases where satellite retrievals are present. It is interesting to note that the background fields agree better with buoys for cases when satellite data are present than for cases when no satellite data are available. The assimilation of the satellite winds (or other information from instruments operating on the same satellite platforms) improves the quality of the NWP analyses of surface winds (Cucurull & Anthes, 2014; Kazumori et al., 2016; Laloyaux et al., 2016).

The results are different in some respects for wind speed. Again, CCMP 2.0 shows the best agreement. The background fields are biased low by almost 0.5 m/s compared to the buoys. This bias is almost
completely removed in both CCMP versions for cases where satellite data are present. Even in cases where there are no satellite data at the buoy location, the CCMP analyses show smaller bias that the background fields. We speculate that this is due to cases, such as in regions of convective rain or near the edge of the satellite swath, where there are nearby satellite observations even when the satellite data are missing at the buoy location, and the beneficial effect of the satellite data affects the grid cell containing the buoy.

Figure 9. Histograms of the difference between gridded products (different versions of CCMP, the NCEP 0.25-degree analysis, and the ERA-Interim reanalysis) and moored buoys for zonal wind U (first column), meridional wind V (second column), wind speed (third column), and wind direction (fourth column). The histograms include all buoy-gridded product matchups from February 2015 to December 2017 where the time difference between the buoy measurement and the gridded product is less than 30 min. The top row (a–d) shows results for all gridded data, the middle row (e–h) shows data from buoy matchups where at least one satellite is analyzed by the CCMP VAM at the buoy location. The bottom row (i–l) shows buoy matchups where no satellite data are included in CCMP at the buoy location. In the legend, CCMP-NB stands for CCMP NO-BUOY.

Table 1
Mean and Standard Deviation (σ) of Between Gridded Products and Moored Buoys

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<th>Data subset</th>
<th>Comparison data set</th>
<th>U wind (m/s) Mean</th>
<th>U wind (m/s) σ</th>
<th>V wind (m/s) Mean</th>
<th>V wind (m/s) σ</th>
<th>Wind speed (m/s) Mean</th>
<th>Wind speed (m/s) σ</th>
<th>Direction (degrees) Mean</th>
<th>Direction (degrees) σ</th>
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<td>0.082</td>
<td>1.313</td>
<td>0.111</td>
<td>1.351</td>
<td>−0.402</td>
<td>1.144</td>
<td>−2.14</td>
<td>22.4</td>
</tr>
<tr>
<td>No satellite data</td>
<td>CCMP 2.0</td>
<td>0.030</td>
<td>1.534</td>
<td>0.067</td>
<td>1.572</td>
<td>−0.203</td>
<td>1.229</td>
<td>−1.17</td>
<td>28.6</td>
</tr>
<tr>
<td></td>
<td>CCMP NB</td>
<td>0.091</td>
<td>2.023</td>
<td>0.107</td>
<td>2.040</td>
<td>−0.282</td>
<td>1.635</td>
<td>−2.75</td>
<td>32.9</td>
</tr>
<tr>
<td></td>
<td>CCMP RT</td>
<td>−0.102</td>
<td>1.824</td>
<td>0.054</td>
<td>1.931</td>
<td>−0.199</td>
<td>1.518</td>
<td>−1.66</td>
<td>32.0</td>
</tr>
<tr>
<td></td>
<td>ERA-I</td>
<td>0.166</td>
<td>2.025</td>
<td>0.113</td>
<td>2.059</td>
<td>−0.595</td>
<td>1.734</td>
<td>−2.91</td>
<td>32.9</td>
</tr>
<tr>
<td></td>
<td>NCEP</td>
<td>−0.079</td>
<td>1.806</td>
<td>0.052</td>
<td>1.904</td>
<td>−0.496</td>
<td>1.535</td>
<td>−1.81</td>
<td>31.9</td>
</tr>
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</table>
It may appear paradoxical that the wind speeds are clearly biased for the background fields, but the background wind components are unbiased. This is due to the correlation of wind component errors with the wind component itself (i.e., a multiplicative error). Figure 10 shows mean differences between buoy and gridded values of zonal wind ($U$) as a function of the mean of the two wind components. As can be seen in Figure 10, the mean differences between the buoys and the weather models (d and e) are fairly strongly correlated with the value of $U$, indicating that the analysis absolute value of $U$ tends to be too small, consistent with a multiplicative error, while the CCMP and buoy differences (a–c) show little or no correlation for wind speeds less than 10 m/s, even for versions of CCMP that do not include the buoys in their analysis. For positive values of $U$ (winds blowing toward the East), CCMP-NO-BUOY and CCMP-NRT tend to be larger than buoy measurements for $U$ greater than about 12 m/s. For negative values of $U$ (blowing toward the west), CCMP-NO-BUOY and CCMP-NRT tend to have smaller absolute magnitude than the buoys, though the size of the effect is smaller than that for positive $U$.

The last column in Figure 9 shows histograms of wind direction differences. Again, CCMP 2.0 shows the best performance. The two CCMP versions without buoys show performance very close to background fields for both the SAT and NO_SAT cases, indicating the CCMP processing does not significantly improve the direction information. Note that the performance of both CCMP and the background analyses is dramatically better when satellite data are present, again illustrating that data from satellites improve the quality of the NWP products substantially.

In Figures 11 and 12, we show maps of the mean zonal wind and mean wind speed differences (CCMP-NRT and buoy) for individual buoys. Each colored circle corresponds to a buoy, and a buoy is only shown if there are more than 1,000 buoy and CCMP colocations over the 3-year study period. For cases where satellite data are present (Figure 11a), the individual buoy biases in zonal wind are generally smaller (RMS average = 0.297 m/s) than for cases where satellite data are not available (RMS average = 0.419 m/s; Figure 10c). For wind speed, the presence of the satellite data does not improve the RMS average substantially (Figures 12a and 12c). We also investigated the impact on meridional winds, but because the mean currents in the tropical Pacific are mostly zonal, the effect was not as large.

In the satellite-data-present case, we note a pattern in the biases in the Tropical Pacific, with CCMP zonal wind tending to be larger than buoys near the Equator, and less than buoys north of the Equator. A similar pattern was noted for CCMP 2.0 in McGregor et al. (2017). At least part of this pattern is due to the large-velocity ocean surface currents in the Tropical Pacific. Satellites retrieve the wind relative to the ocean surface, while the buoy winds and the NWP analyses are relative to the fixed Earth. Thus, as currently configured, CCMP mixes two different types of winds. In most locations, the typical velocity of the ocean surface is too small and variable to be an important contributor to errors in CCMP. In the tropics, currents can approach 1.0 m/s and are relatively consistent in direction. To test our hypothesis that the currents contribute to CCMP and buoy biases in the tropics, we adjusted buoy winds to be relative to the ocean surface by subtracting the vector current from the Ocean Surface Current Analysis Real-time (OSCAR) surface current analysis (Johnson et al., 2007) from the vector wind in CCMP. The OSCAR product is not ideal for this purpose, since it is representative of the average motion in the top 30 m of the ocean, not the surface. We view

Figure 10. Binned mean differences (gridded product – buoy) for zonal winds. The error bars show the standard deviation of the differences in each mean wind speed bin.
the use of OSCAR as a first step toward accounting for surface current in the analysis of satellite winds. When the OSCAR adjustment is applied, the biases in both zonal wind (Figure 11b) and wind speed (Figure 12b) for the buoys in the Tropical Pacific are substantially reduced for the cases when satellite data are present. For the cases without satellite data, the OSCAR adjustment does not improve the zonal wind biases as expected, since the background field winds are relative to the fixed Earth. The OSCAR adjustment does appear to improve the wind speed biases for the NO SAT case.

5. Discussion

We have described and evaluated two new versions of CCMP (CCMP-NO-BUOY and CCMP-NRT) that do not use buoy observations. This allows the use of high-quality moored buoy winds as a validation data set for these versions. Compared to CCMP 2.0, these new versions do not agree as well with buoys since the CCMP 2.0 analysis is “pulled” towards the buoy winds. The new validation results for CCMP-NO-BUOY (see Table 1), which used the same ERA-Int background as CCMP 2.0, are likely to be a better measure of the general accuracy of CCMP 2.0 particularly in regions far from buoy measurements. For both CCMP-NO-BUOY and CCMP-NRT, the wind speed accuracy determined by buoy comparison is improved when satellite data are present. The NRT version, CCMP-NRT, can be produced with a short latency of several days (instead of months), increasing the usefulness of CCMP for diagnosing recent winds, which may be useful for applications, including, for example, driving ocean models, and regional studies of ongoing weather/oceanographic events. The two buoy-free versions also are free of spurious features in
derivative fields near the buoy locations. We plan that future versions of CCMP will not directly use buoy measurements, instead reserving buoy measurements as an independent data set to be used for comparison. We recommend that users sensitive to the details of the derivative fields use CCMP-NO-BUOY or CCMP-NRT.

During our analysis, we found that the presence of ocean currents can lead to biases in CCMP relative to buoys for cases when satellite data are available. This is because CCMP, as currently configured, combines 10-m neutral stability winds from satellites that are relative to the ocean surface and 10-m winds from NWP analyses and buoys that are relative to the fixed Earth. Clearly, improvements to the CCMP system are needed to address these problems. Future versions of CCMP will use neutral stability winds from NWP products as the background and then remove any mean bias of the NWP analysis winds and the satellite winds before the CCMP analysis is performed.

Data Statement

CCMP results and satellite data used as the starting point for this analysis are available freely from Remote Sensing Systems via our website (www.remss.com). Buoy measurements are available from the National Data Buoy Center (www.ndbc.noaa.gov). The background fields from the ERA-Interim reanalysis are available from the European Center for Medium Range Weather Forecasting (ECMWF) (http://apps.ecmwf.int/datasets/). The NCEP background fields are available from the National Center for Environmental Prediction (http://www.nco.ncep.noaa.gov/pmb/products/gfs/).
Acknowledgments

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References


