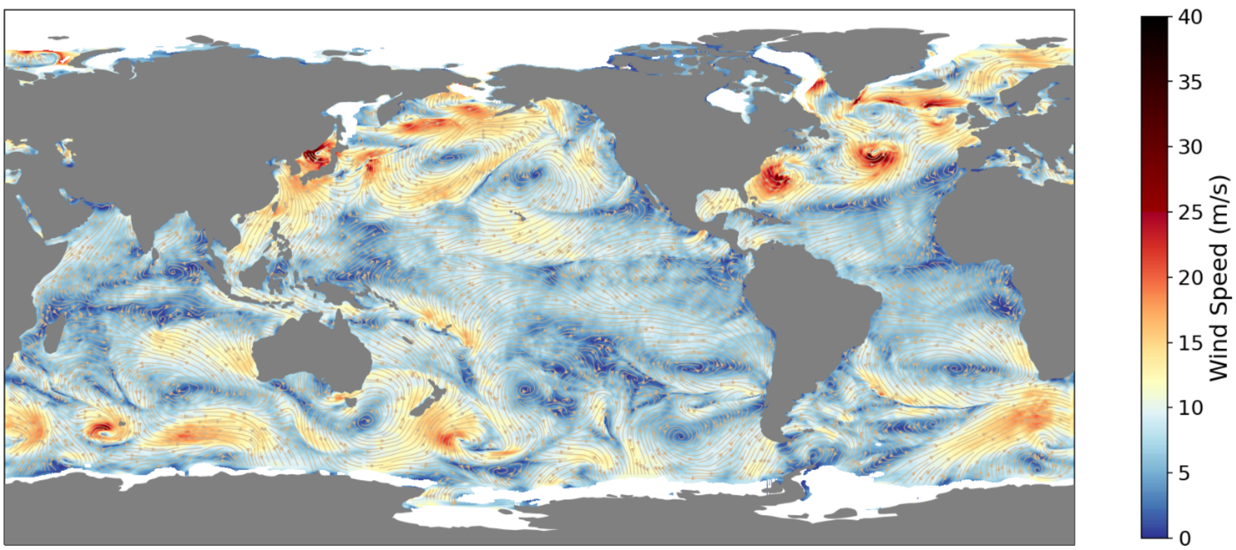
Cross-Calibrated, Multi-Platform (CCMP) Ocean Surface Wind Velocity Product

User Guide

15 July 2024
Version 3.1



Example Wind Field from CCMP 3.1

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2. Abstract:

The Cross-Calibrated Multi-Platform (CCMP) Ocean vector wind analysis is a level-4 product that uses a variational method to combine satellite retrievals of ocean winds with a background wind field from a numerical weather prediction (NWP) model. The result is a spatially complete estimate of global ocean vector winds on six-hour intervals that are closely tied to satellite measurements. For CCMP 3.1, we used the ECMWF Reanalysis 5 (ERA5). Because ERA5 winds are biased towards lower values at higher wind conditions, in CCMP 3.1 we correct bias by matching ERA5 wind speeds with satellite scatterometer wind speeds using a histogram matching method. The result is an easy to use, accurate vector wind product valid over the world's ice-free oceans.

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4. Background:

Ocean surface vector winds (OSVW) are important to scientific research and operational applications in oceanography, meteorology, and climate. In the past few decades, OSVW has been observed using microwave-sensing satellites and *in situ* platforms. Because of the rich spectrum of spatiotemporal variability of OSVW, monitoring OSVW adequately over the global oceans with high-accuracy is difficult. Moorings provide accurate point-like measurements of OSVW but are sparse and mostly confined to the tropics and continental margins. Satellite winds generally have more uniform spatiotemporal sampling and good geographical coverage. However, the sampling and coverage on shorter (e.g daily to sub-daily) time scales are inadequate because of gaps between the satellite swaths. Reanalysis systems assimilate satellite and mooring winds and thus have the potential to alleviate some limitations of the wind observing systems (e.g., sampling and coverage). However, reanalysis winds have significant uncertainties due to model errors, inhomogeneity of input data (part of which related to observing system changes), and limitation in data assimilation methods.

CCMP is a wind analysis intended to minimize these limitations. CCMP is spatially complete and strongly tied to homogenized satellite-based wind observations. CCMP combines winds from a background field derived from numerical weather prediction (NWP) analysis fields with satellite measurements using a variational analysis which minimizes a cost function. The analysis constrains both the differences between the inputs and the final product, and the smoothness of these differences. The resulting wind field is very close to the satellite winds at locations and times where they are available, and then smoothly transitions to the adjusted background field with increasing distance from the satellite swath.

The current version of CCMP is version 3.1. Table 4.1 summarizes the evolution of CCMP through version changes.

Table 4.1. Version history for CCMP

Version	Background Field	Radiometers Included	Scatterometers Included	Buoys Included?	Pre-Analysis Adjustments?
1.0	ERA-40	SSM/I, SSMIS	QuikSCAT	Yes	None
2.0	ERA-40, ERA-Interim	SSM/I, SSMIS, AMSRE, WindSat, TMI, AMSR2	QuikSCAT, ASCAT-A	Yes	None
3.0	ERA5 Neutral Winds	SSM/I, SSMIS, AMSRE, WindSat, TMI, AMSR2, GMI	QuikSCAT, ASCAT-A	No	ERA5 and Radiometers
3.1	ERA5 Neutral Winds	SSM/I, SSMIS, AMSRE, WindSat, TMI, AMSR2, GMI	QuikSCAT, ASCAT-A, ASCAT-B	No	ERA5 and Radiometers

The most recent CCMP paper (C. Mears et al., 2022) describes version 3.0. To produce 3.1, we added data from ASCAT-B. No other processing changes were made. ASCAT-C and buoy winds are withheld to provide independent winds for comparison.

5. Processing Methodology:

Figure 5.1 is a flow chart that summarizes CCMP 3.1 processing. ERA5 neutral stability winds are adjusted to account for the moving ocean surface, and then adjusted to statistically match scatterometer winds. Radiometers winds are also adjusted to match scatterometer winds. Then the background field (adjusted ERA5) is combined with the satellite winds using the CCMP variational analysis. More detail about the variational analysis is available in (Atlas et al., 2008, 2011). More detail about the pre-analysis adjustments is provided in Section 6 below and in (C. Mears et al., 2022).

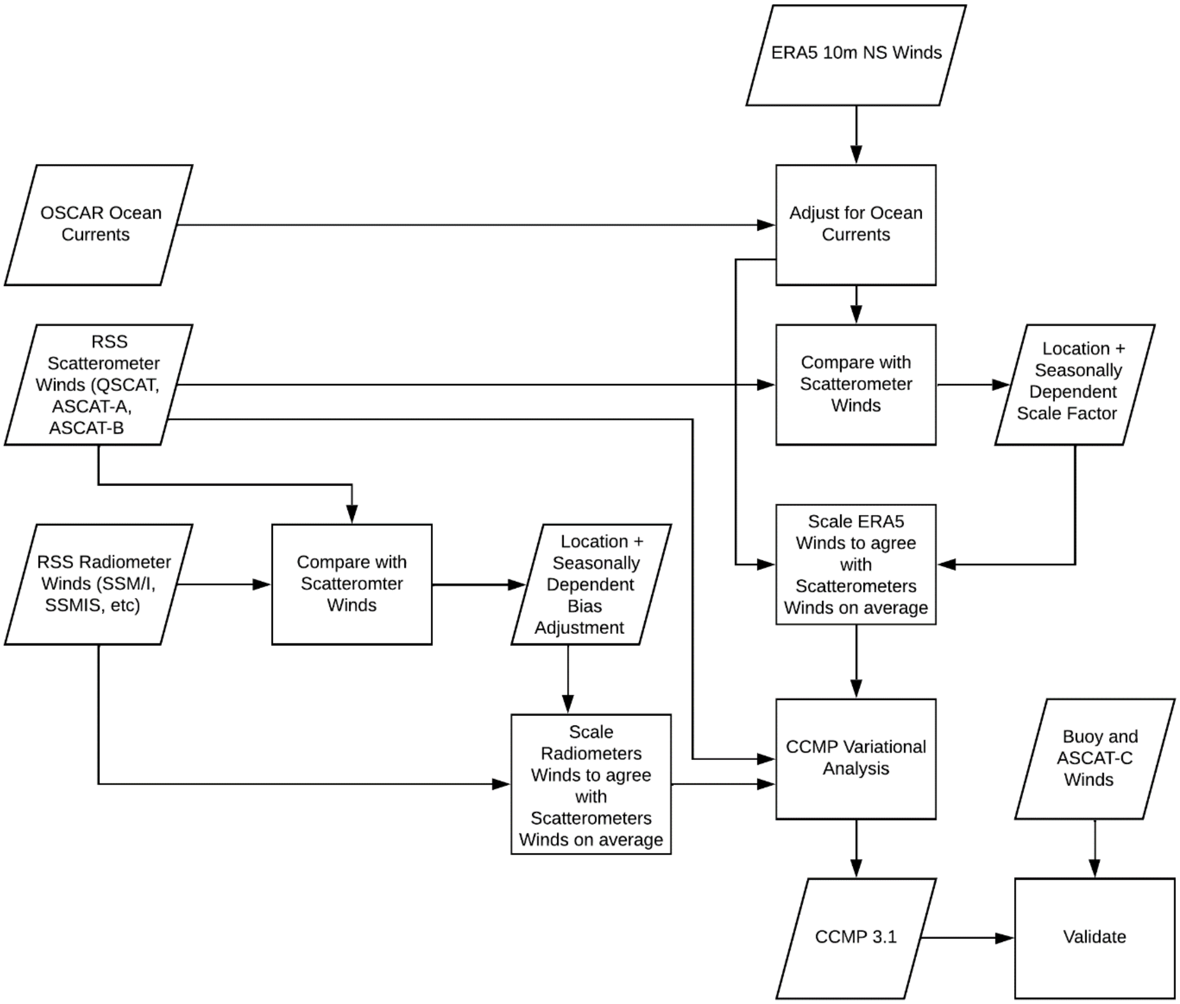

Fig 5.1. Flow chart summarizing the CCMP 3.1 processing methods.

6. Assimilated Data Products:

Satellite Winds

Wind information from almost all U.S., Japanese, and European conical-scanning microwave instruments are included in CCMP 3.1. Radiometers (SSM/I, SSMIS, AMSRE, AMSR2, TMI, WINDSAT and GMI) generally only measure scalar wind speed (C. A. Mears et al., 2001; Meissner & Wentz, 2005; Wentz, 1997, 2015; Wentz & Draper, 2016). WINDSAT also measures wind direction, but this information is not used in CCMP 3.1. Scatterometers (QuikSCAT, ASCAT-A, ASCAT-B) measure wind direction and this information is included in CCMP 3.1 (Manaster et al., 2019; Ricciardulli & Manaster, 2021a; Ricciardulli & Wentz, 2015). We use wind products from Remote Sensing Systems in CCMP 3.1. The time line of satellites used is shown in Fig 6.1.

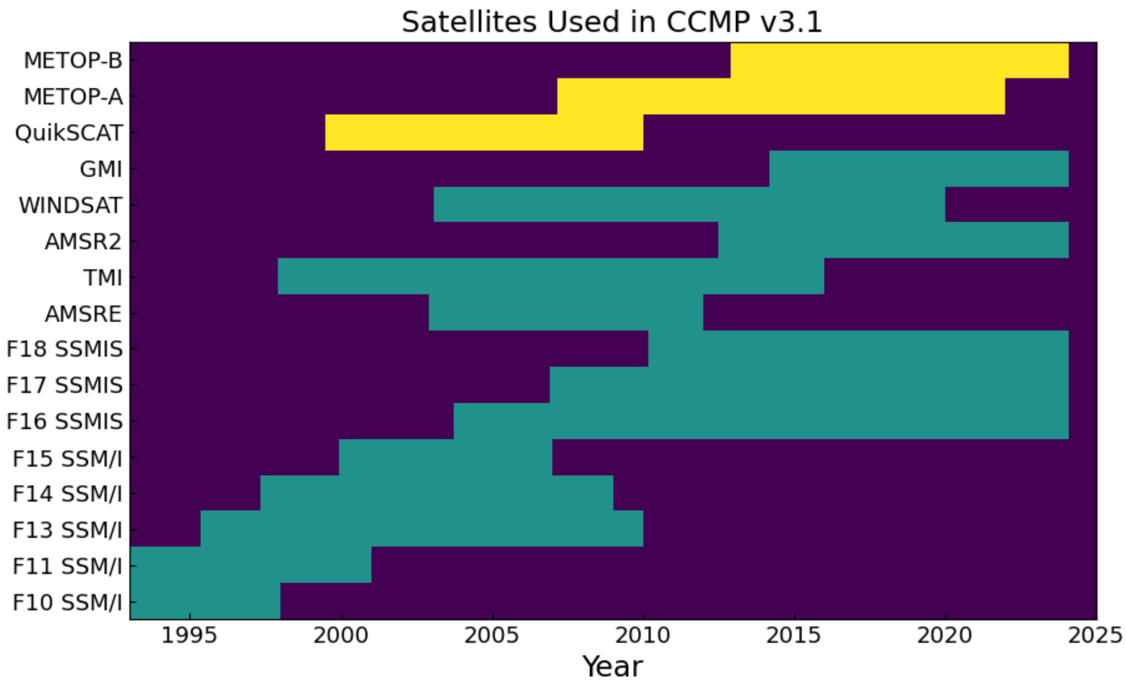

Fig 6.1. Satellites assimilated into CCMP 3.1. Blue denotes instruments where direction information is either not available or not used (WINDSAT). Yellow denotes instruments when wind direction is available and is used.

Model Background Field.

For a background field, we use neutral stability winds from ERA-5. The choice of neutral stability winds was made because both types of satellite winds are based on measurements of wind-induced changes in roughness. The roughness is closely aligned to wind stress, and thus neutral stability wind speed.

7. Pre-assimilation adjustments and quality control

We perform a number of quality control and data adjustment steps before performing the CCMP assimilation process. These are summarized below and described in more detail in Mears et al. (2022).

Satellites: Rain Flagging

For both types of satellite instruments, the presence of rain can degrade performance.

- All of the radiometers simultaneously measure total column cloud water and rain rate. If the total cloud water is greater than 0.18 mm, rain is likely to occur and the wind speed is not used in CCMP.
- Rain in scatterometer retrievals is detected by a rain-detecting algorithm in the retrieval algorithm. Any retrievals that were flagged as influenced by rain are not used in CCMP

Satellites: Sea Ice

No satellite retrievals that were influenced by the presence of sea ice are used in CCMP.

Satellites: Wind Speed Adjustments

Wind speeds from radiometers are adjusted to agree with scatterometer winds. The small additive adjustments that we applied vary with time and year and location on the Earth. They were determined by assessing maps of collocated speed differences. The adjustments are different for SSM/I-like instruments that do not include a 11 GHz channel, and the other instruments that do include an 11-GHz channel.

Model Adjustments: Ocean Currents

Satellites sense the surface wind relative to the moving surface. To get a better match between the ERA5 background winds and the satellite winds, we adjust the ERA5 neutral stability winds using a global ocean surface current product, OSCAR.

Model Adjustments: Speed adjustments.

ERA5 winds tend to be slightly lower than satellite winds, especially at high wind speed. To improve the match with satellite winds, we apply a multiplicative adjustment,

$$\begin{aligned} W_{ERA5-ADJ} &= \alpha\left(W_{ERA5}\right)W_{ERA5} \\ U_{ERA5-ADJ} &= \alpha\left(W_{ERA5}\right)U_{ERA5} \\ V_{ERA5-ADJ} &= \alpha\left(W_{ERA5}\right)V_{ERA5} \end{aligned} \tag{1.1}$$

The functional form of $\alpha\left(W_{ERA5}\right)$ was determined by matching wind speed histograms of the adjusted ERA5 winds with collocation scatterometer observations. The multiplicative form allows us to apply the same adjustment to the vector components of the ERA5 winds.

Model Adjustment: Vector adjustments

After applying the speed adjustments, there are still small biases in the U and V components of the ERA5 winds relative to scatterometers. We removed these by subtracting seasonally varying, smoothed bias maps from U and V in ERA5.

8. Data Set Description

Daily Files

Each daily files contains analyzed wind maps at 00z, 06z, 12z, and 18z. Three maps are included: Wind Speed (ws), zonal wind (uwnd) and meridional wind (vwnd). Another map (nobs) indicates the number of satellites assimilated at each grid point. Values of nobs = 0 indicates that no satellite observations were available inside the 6-hour assimilation window.

File Names

The daily files follow a naming convention:

CCMP_Wind_Analysis_YYYYMMDD_V03.1_L4.nc.

YYYY is the year of the observations

MM is the month of the observations

DD is the day of the month of the observation.

Daily File Structure

All files are CF-compliant netCDF4 files with extensive metadata.

Table 8.1 Variable in each daily file

Variable	Dimension	Description
latitude	720	Latitude at the center of the grid cells
longitude	1440	Longitude at the center of the grid cells
nobs	(4,720,1440	Number of satellites assimilated at each cell
time	(4)	Time of analysis, (hours since 1987-01-0100:00:00)
uwnd	(4,720,1440	10m neutral zonal wind at each cell (m/s)
vwnd	(4,720,1440	10m neutral meridional wind at each cell (m/s)
ws	(4,720,1440	10 neutral wind speed at each cell (m/s)

Monthly Files

Monthly means files are also available. They contain both average wind speed and vector component maps, as well as anomalies relative to a 1995-2014 climatology. We note that the average wind speed can be very different from the magnitude of the vector component averages.

File Names

The monthly files follow a naming convention:

CCMP_Wind_Analysis_YYYYMM_monthly_mean_V03.1_L4.nc.

YYYY is the year of the observations

MM is the month of the observations

Monthly File Structure

All files are CF-compliant netCDF4 files with extensive metadata.

Table 8.2 Variable in each monthly file

Variable	Dimension	Description
latitude	720	Latitude at the center of the grid cells
longitude	1440	Longitude at the center of the grid cells
nobs	720,1440	Number of time steps averaged at each cell
time	1	Time of analysis, (hours since 1987-01-0100:00:00)
u	720,1440	10m neutral zonal wind average at each cell (m/s)
u_anom	720,1440	10m neutral zonal wind anomaly at each cell (m/s)
v	720,1440	10m neutral meridional wind average at each cell (m/s)
v_anom	720,1440	10m neutral meridional wind anomaly at each cell (m/s)
w	720,1440	10 neutral wind speed average at each cell (m/s)
w_anom	720,1440	10 neutral wind speed anomaly at each cell (m/s)

9. Validation

Two potential sources of high-quality vector wind measurements are not used in CCMP 3.1. These are wind retrievals from ASCAT-C, and wind measurements from moored buoys. Both of these data sources can be used to estimate the uncertainty of the CCMP 3.1 winds.

Comparison with ASCAT-C

ASCAT-C is a C-band scatterometer similar to ASCAT-A and ASCAT-B but is not included in the CCMP analysis. ASCAT-C data is available from 2019-07-01 to the present time (2024-07). For the results present here, we evaluate retrievals from 2019-07 to 2023-05.

Figure 9.1 shows 2-D histograms of CCMP 3.1 comparison with ASCAT-C. Both the wind speed (W) and wind components (U and V) are shown.

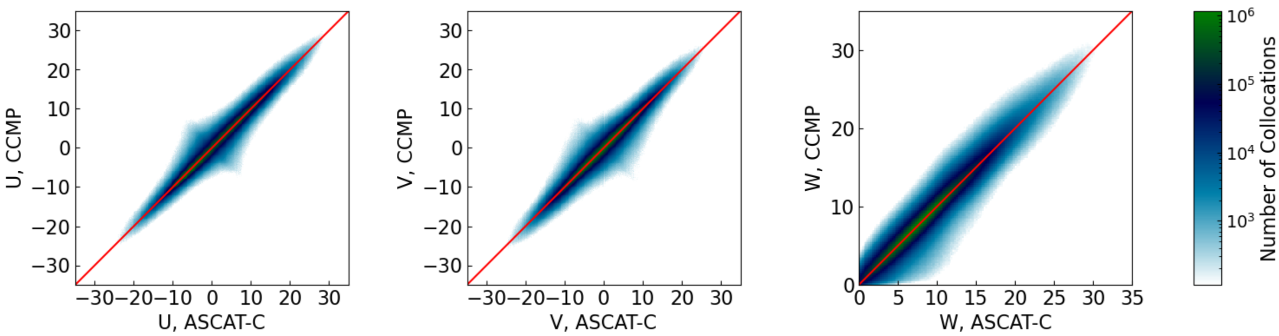

Figure 9.1. 2-D histograms of CCMP and ASCAT-C winds. Note that the color bar is logarithmic. CCMP 3.1 agrees well with the independent from ASCAT-C.

Figures 9.2-9.4 show binned mean difference statistics versus ASCAT-C for the wind components U, V, and W.

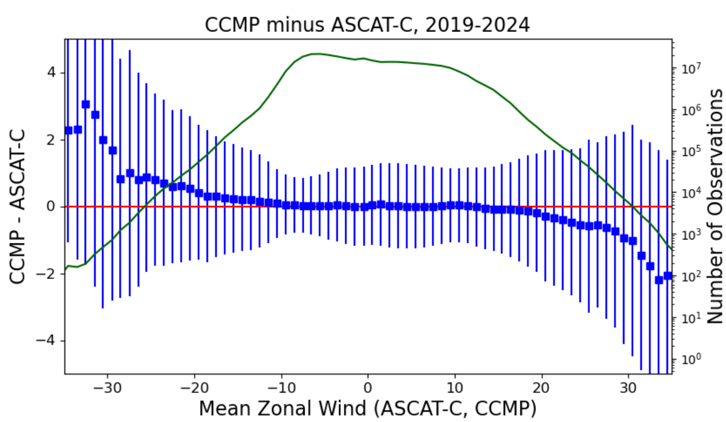

Figure 9.2. Binned mean difference statistics for CCMP 3.1 versus ASCAT-C for zonal wind (U). Blue dots are values of the binned mean difference, and the blue whiskers show the standard deviation. The green line shows the number of collocations in each bin. CCMP and ASCAT-C agree well up to ~25 m/s.

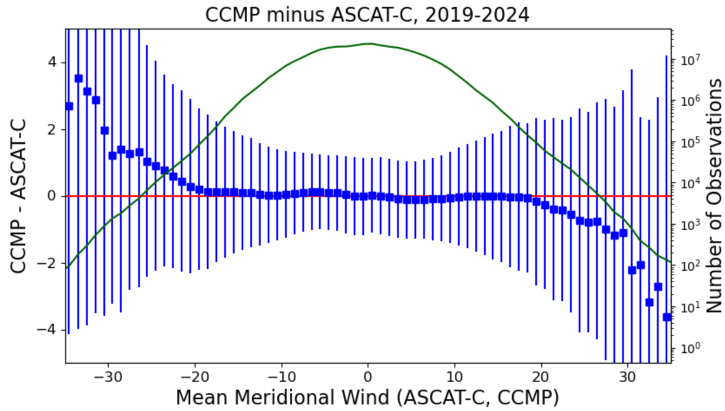

Figure 9.3. Binned mean difference statistics for CCMP 3.1 versus ASCAT-C for meridional wind (V). CCMP and ASCAT-C agree well up to ~25 m/s.

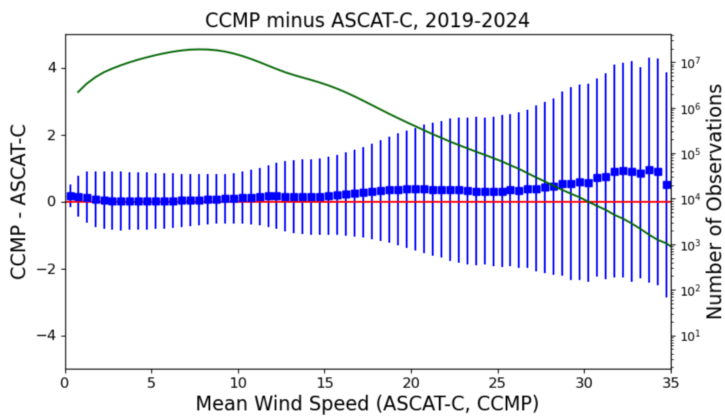

Figure 9.4. Binned mean difference statistics for CCMP 3.1 versus ASCAT-C for wind speed (W). CCMP and ASCAT-C agree very well up to ~16 m/s. Above this wind speed, CCMP is slightly biased high vs. ASCAT-C. This likely reflects a small low bias for ASCAT-C vs ASCAT-B at high winds.

Table 9.1 Overall Wind Speed Difference Statistics (CCMP 3.1 minus ASCAT-C) for difference collocation subsets

Collocation Subset	Mean Difference (m/s)	Std. Dev (m/s)
ALL	0.08	0.88 (0.62)
SAT	0.10	0.75 (0.53)
NOSAT	-0.03	1.25 (0.88)

Table 9.1 shows overall difference statistics for CCMP 3.1 versus ASCAT-C wind speeds. The collocations are divided into 3 subsets. ALL contains all collocations, SAT contains collocations where at least one satellite was included at that location and time step, and NOSAT contains collocations where there is no available satellite for CCMP 3.1. The SAT collocations show markedly better standard deviations than the

NOSAT collocations. This effect may be overstated by this analysis, because a lot of NOSAT collocations are at high latitudes, where the wind speed is likely to be higher, causing larger deviations.

Comparison with Moored Buoys

A second comparison dataset is vector winds from moored buoys available from the National Data Buoy Center (NDBC). These are mostly situated along the coast of North America, and throughout the tropical oceans. Moored buoys are the highest quality "ground truth" available for ocean vector winds with a few caveats. 1) Above about 15 m/s, the buoy winds are biased low, because of wave shadowing, tilt of the buoy platform, and sea spray landing on the mechanical anemometer. This problem increases with increasing winds. 2) Any comparison with a point-like buoy measurement and a spatially-extended wind from a satellite product or NWS model output will contain "representativeness errors" because of the different spatial scales being sampled. We try to minimize this effect by comparing CCMP with hour-long averages from buoys, which are thought to more directly comparable. In the last few years, the instrument packages in the TAO buoys have been updated, resulting in a increase in reported winds of about 10%. This increase has not been seen in satellite winds or NWS model output. After the instrument replacement for each buoy, we adjusted the winds by multiplying by 0.9.

Figure 9.5 shows 2-D histograms for comparisons with moored buoys over 1993-2022. These plots represent millions of CCMP – buoy collocations.

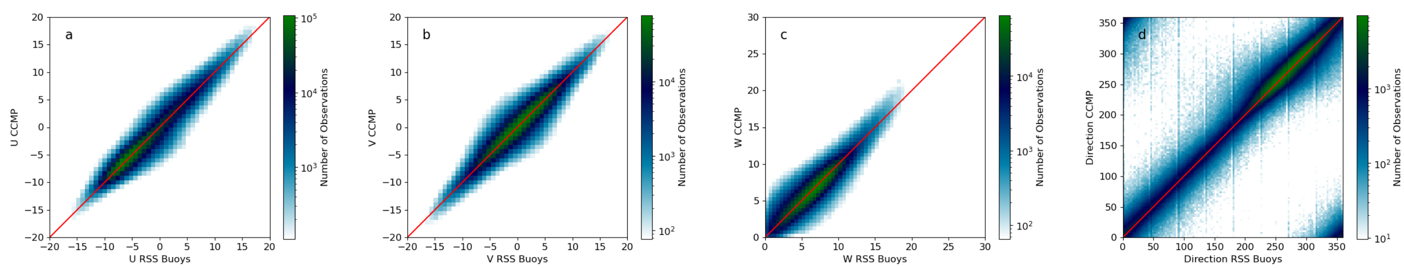

Figure 9.5. Two-Dimension histograms for CCMP – Buoy comparisons. Panels a and b show results for zonal and meridional wind components. Panel c shows the wind speed, and panel d shows the wind direction. At higher wind speeds, the plots show the CCMP 3.1 winds are slightly higher than the buoy winds, as expected.

In Figure 9.6, the same collocations are plotted as binned means and standard deviations. These plots show more clearly the bias between buoy winds and CCMP 3.1 winds at high wind speed.

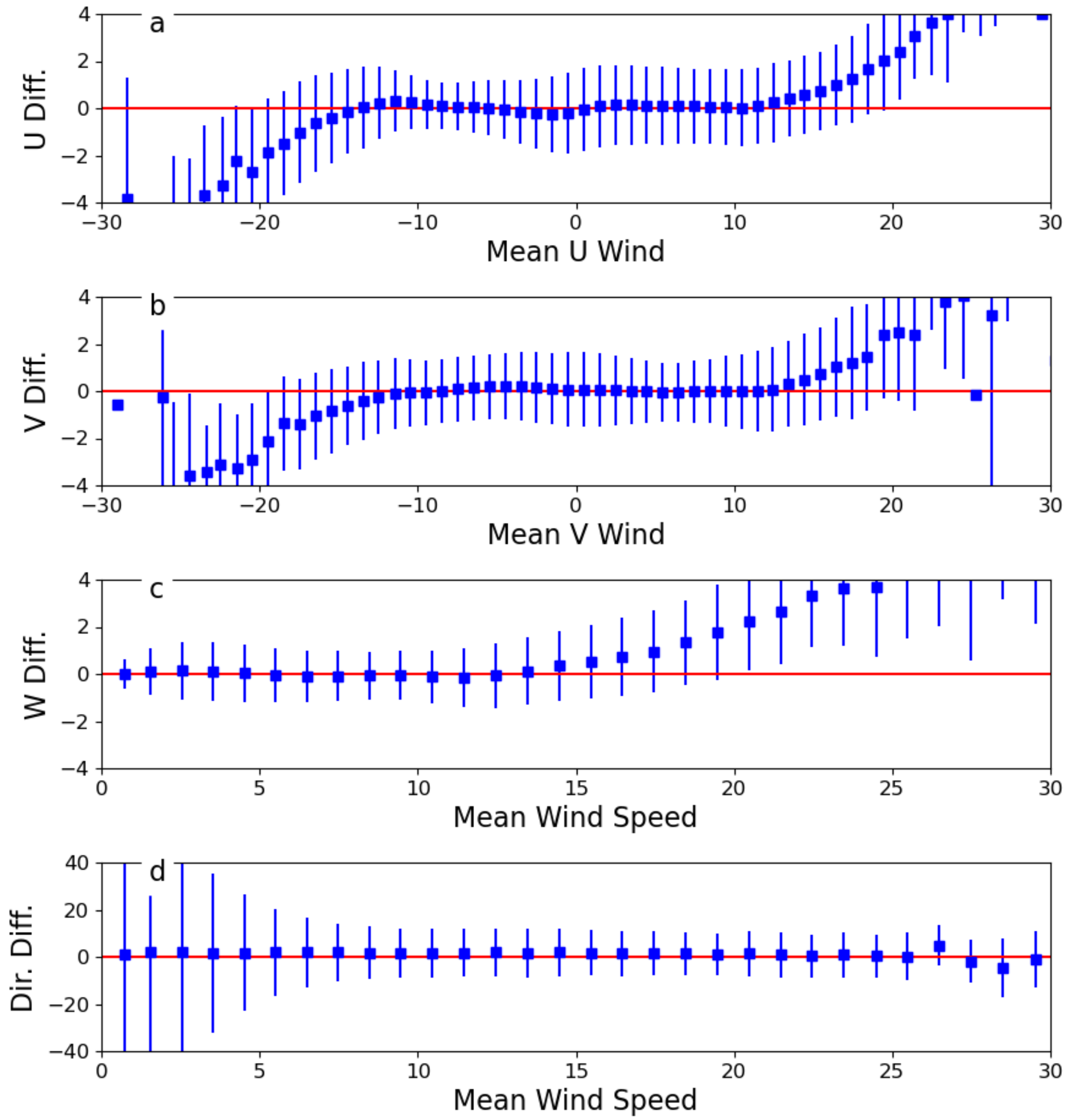

Fig. 9.6. Binned means statistics for (a) zonal wind (U), (b) meridional wind, (c) wind speed and (d) wind direction.

Table 9.2 shows the overall difference statistics for CCMP 3.1 versus Buoy wind speed and vector components. The collocations are divided into 3 subsets as in Table 9.1 above.

Table 9.2 Wind Comparison Statistics versus Moored Buoys

	ALL		SAT		NO SAT	
	# Collocations: 3,585,474		# Collocations: 2,558,946		# Collocations: 1,026,528	
	Bias	Std. Dev.	Bias	Std. Dev.	Bias	Std. Dev.
U	-0.006	1.38	0.053	1.99	-0.153	1.74
V	0.067	1.46	0.067	1.27	0.066	1.85
W	-0.022	1.13	-0.015	0.97	-0.038	1.45

Both types of comparison (ASCAT-C and Moored Buoys) show very good agreement at low and moderate wind speeds. Above ~15 to 18 m/s, the CCMP 3.1 winds are biased high relative to these comparison sources. This is understood and by design. The higher winds are supported by comparison with airborne radiometers, dropsondes, sail drones, oil platforms, and winds from L-Band radiometers like SMAP (Manaster et al., 2019; Ricciardulli et al., 2022; Ricciardulli & Manaster, 2021b).

10. Caveats and Limitations

Tropical Cyclones

Tropical cyclones and other intense, compact wind events are not well resolved in ERA5, and the satellite data is often missing due to rain contamination. Do not use CCMP for analysis of these events.

Long-Term Trends

For global or ocean-basin scales, decadal trends in wind speed are likely to be small. Large changes in global wind speed would result in large changes in evaporation unless balanced by offsetting changed in the marine boundary layer. There is no evidence for large changes in evaporation or precipitation. At these large scales, the changes are likely to be small, or comparable to long-term errors in CCMP 3.1. Use long-term changes in CCMP 3.1 at large spatial scales with caution. (Long term trends in other wind datasets, including reanalysis, are likely even larger.) In regions or time periods where the changes are larger than a few tenths m/s, the changes should be useable.

11. References

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