New Climate Data Record of the Ocean Surface Winds, Stress and Their Dynamically-Significant Derivatives – Vorticity and Divergence: Supporting Studies of Trends and Variability in the Large-Scale Circulation

Svetla Hristova-Veleva[1], Bryan Stiles [1], Alexander Fore [1], Alexander Wineteer [1], David Moroni [1], Mark Bourassa [2], Douglas Vandemark [3], Larry O'Neill [4], Shakeel Asharaf [1], Ethan Wright [2], Xiaosu Xie [1], F. Joseph Turk [1], Marc Emond [3], P. Peggy Li [1], Brian Knosp [1], Quoc Vu [1], Joseph Jacob [1], Federica Polverari [1], Philip Callahan [1]

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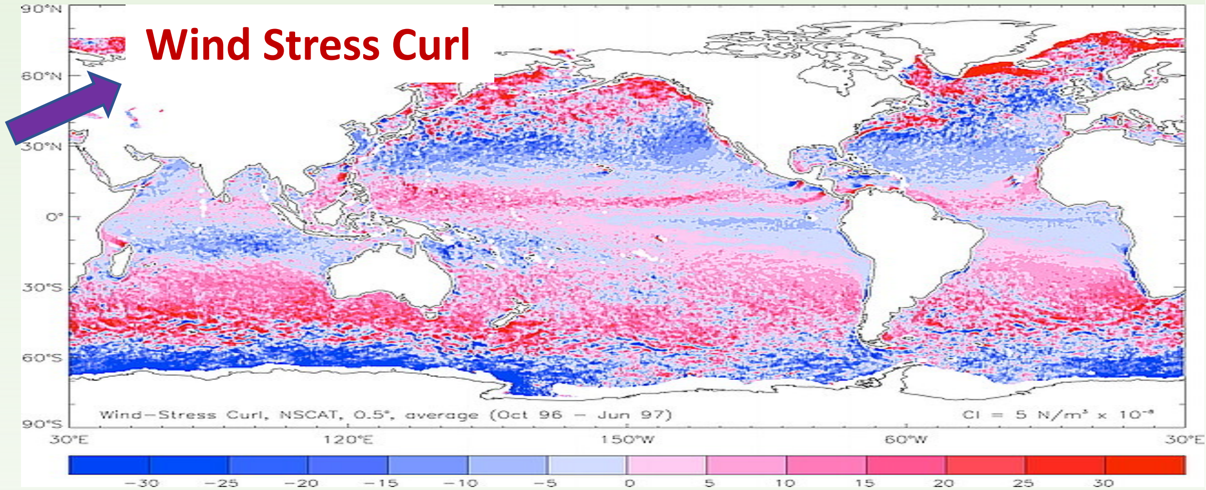
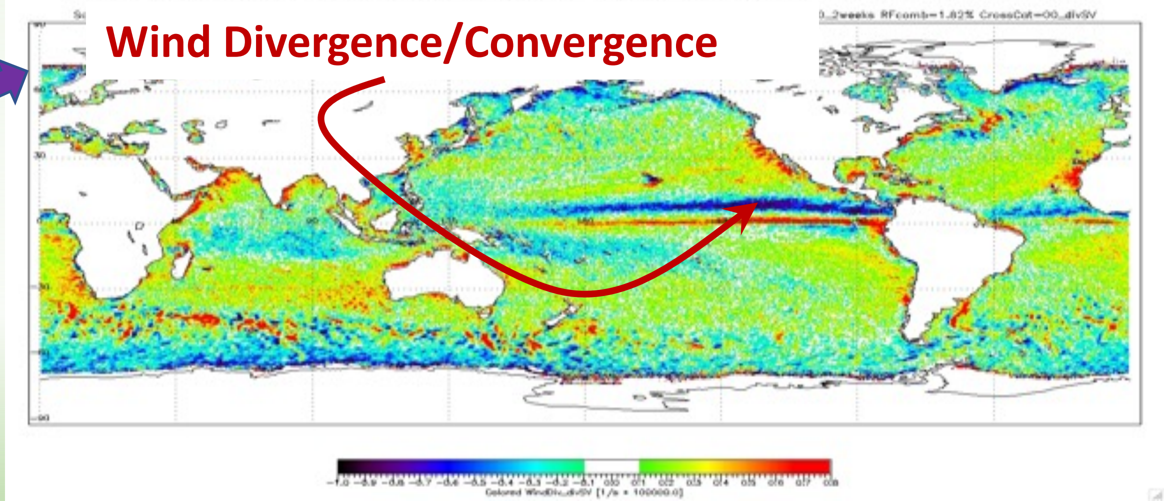
- **Ocean surface winds are one of the key components of the Earth system**. Indeed, the ocean surface winds and stress are **Essential Climate Variables (ECV)** identified by the Global Climate Observing System (GCOS) [GCOS-200, 2016].
- They represent a **unique measurement at the interface of two fluids – the ocean and the atmosphere**. As such, they reflect the interactions at this interface and **modify the boundary layers in each one of them.**
- **They are a major driver of**
    - **the ocean circulation through the surface stress curl**
    - **affect the air-sea interactions**
        - provide fuel to the weather systems by modulating the sensible and latent heat fluxes.
        - modify the turbulent mixing in the upper levels of the ocean
    - **drive the atmospheric convection by providing dynamical forcing through the convergence of the near-surface winds**
- Understanding these interactions is critical for improving ocean modeling and weather forecasting on a variety of spatial and temporal scales.

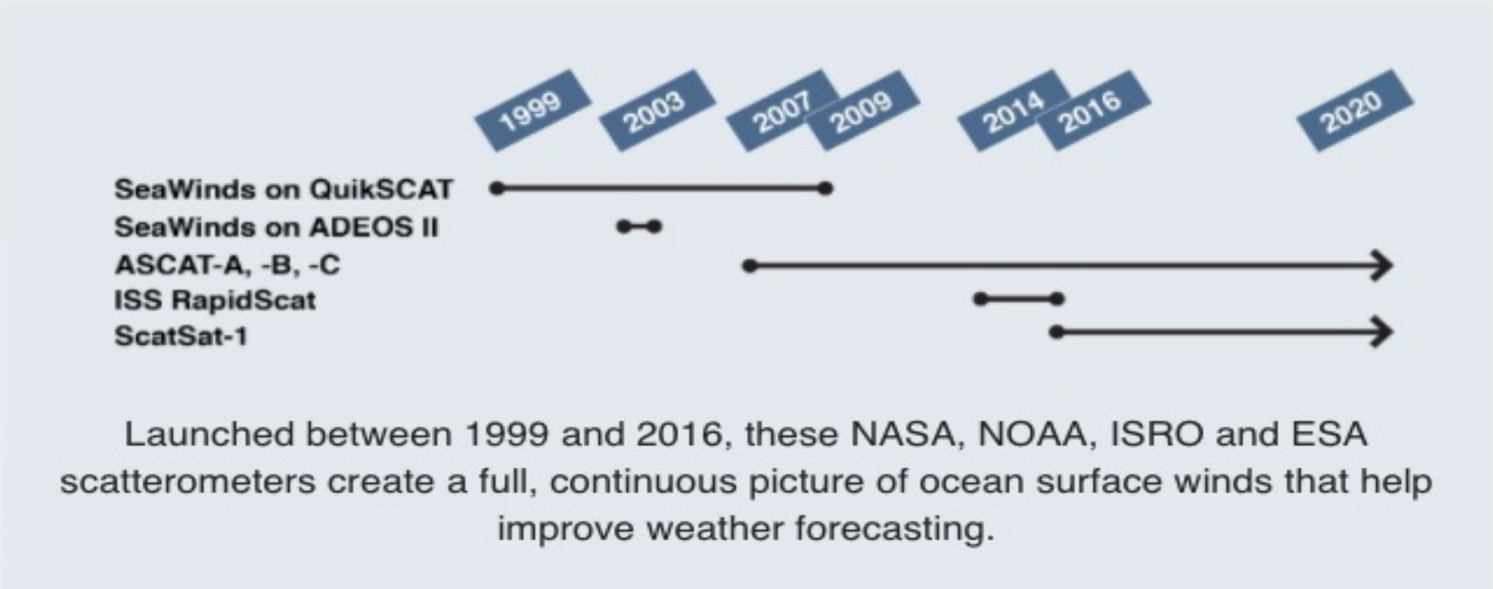




How we observe the ocean-surface wind vectors today

Space-borne scatterometer observations have been used extensively for over two decades to estimate the ocean surface winds.

- Satellite scatterometer observations have been made by a number of missions over a period of more than 20 years.
- Here we focus on the continuous scatterometer data record that started with the launch of NASA's QuikSCAT in 1999.



Three Main Sources of Uncertainty of the Global Wind Estimates

- **Diurnal variability of the winds**
  - still do not know well enough the diurnal variability of the winds, and the geographical variability of this diurnal signal, to allow us to properly isolate its contribution to the differences in the wind estimates from missions that observe at different Local Times of Day (LTD);
- **Differences in the observing systems**
  - frequency of the observations (**Ku vs C band**), with **possible differences in the physics of the relationship between the observations (σ^0) and the underlying winds**; Also having different sensitivity to
    - atmospheric parameters (most importantly rain)
    - ocean surface parameters such as wind speed, sea surface temperature (SST) and sea state (e.g. significant wave height)
  - **instrument design and geometry** (push-broom vs pencil beam, variable incidence angles of the observations);
- **Retrieval algorithms and assumptions - inconsistencies remain in the different components of the different retrieval schemes.**

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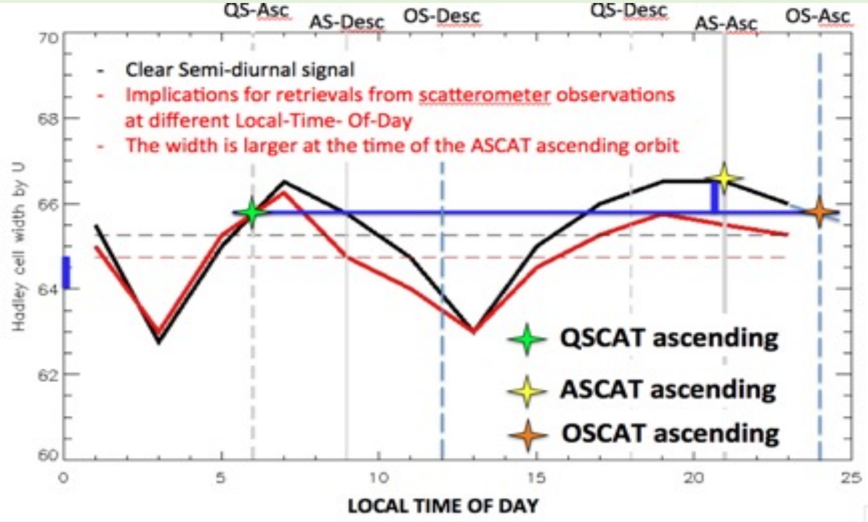
Hadley Cell Width from RapidScat



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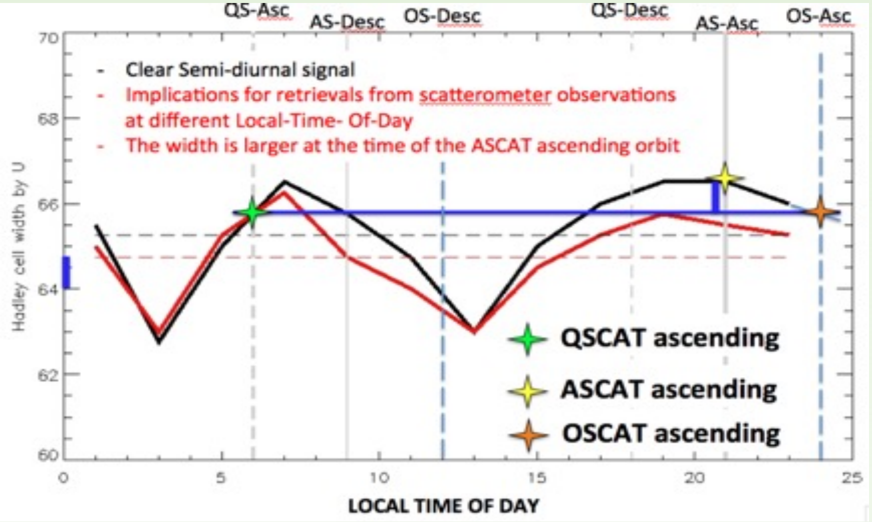

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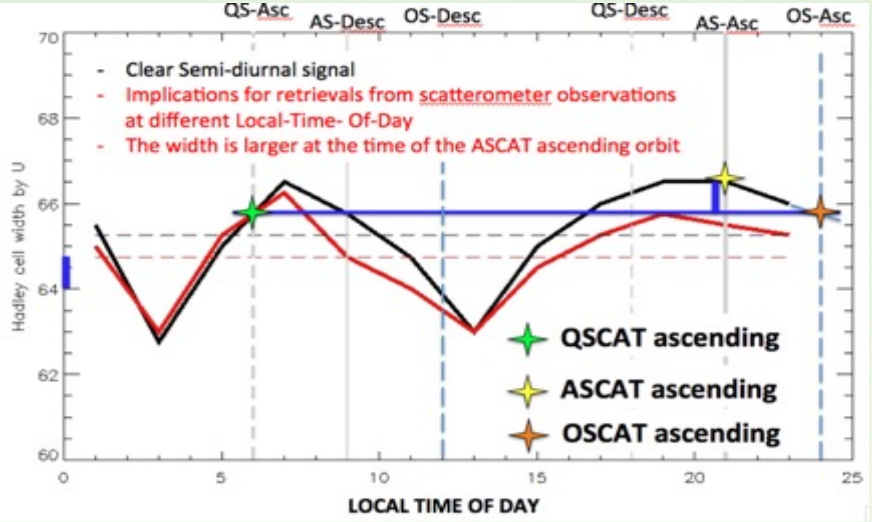

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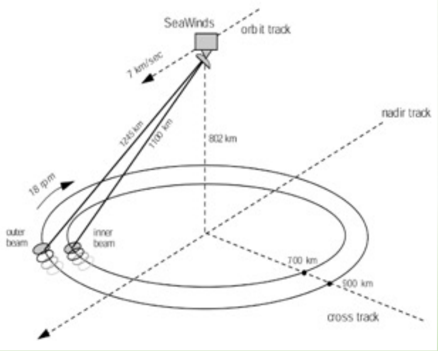
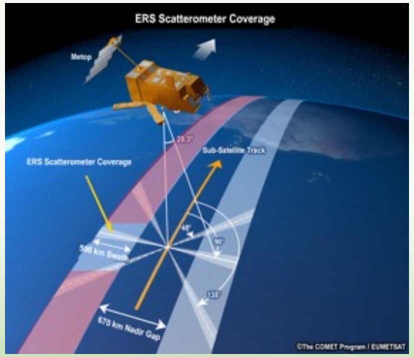
Schematic of the observation geometry for the two different observing systems: the rotating pencil beam of the Ku-band scatterometers (left) and the push-broom fan beam sampling by the C-band scatterometers (right)





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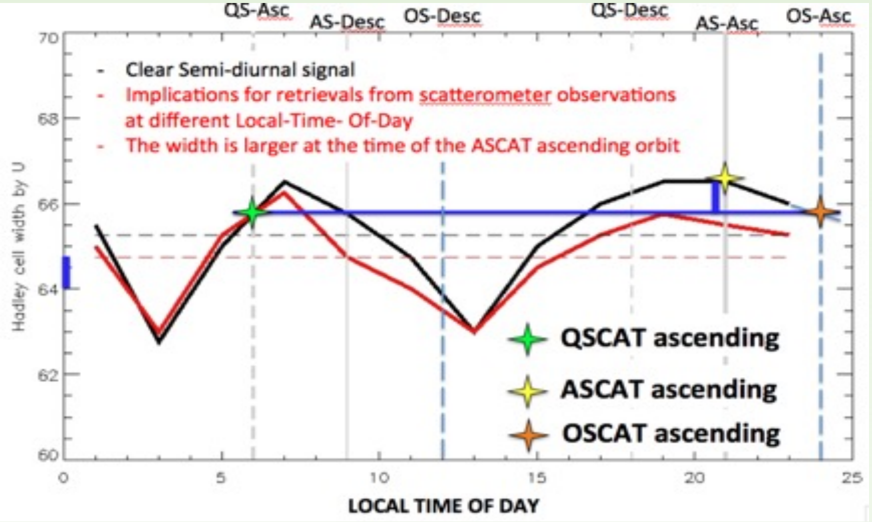

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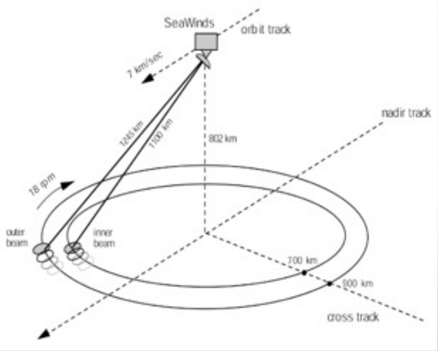

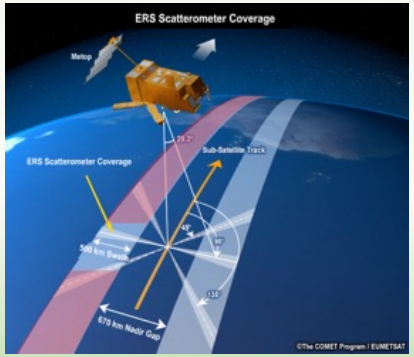

The goals of our MEaSUREs project

After nearly 20 years of continuous scatterometer observations of the ocean surface vector winds by a variety of scatterometer instruments we are now positioned to address three issues of significant importance that still face the ocean surface vector wind user community:

1. **Creation of a consistent long-term Earth Science Data Record (ESDR)** that includes observations from all different missions while eliminating inconsistencies between them.
2. **Development of the dynamically-significant derived products,** including the surface wind stress, and the curl and divergence of the surface wind and stress. These products need to be generated at the highest possible resolution of the observations (i.e. at the swath - Level 2);
3. **Development of scatterometer-only user-friendly gridded products (Level 3 products)** of the wind, stress, curl and divergence of the wind and the stress. These new ocean wind L3 products will fill an unmet user need and complement existing L4 products, which have their own roles.

Types of L2 (swath) files

- The new products are organized in **three types** of files that will be available for both the L2 (swath) and the L3 (gridded) files, and based on observations from **QuikSCAT, ASCAT-A/B/C and ScatSat**:

1. **Scatterometer-based estimates** of:
    - the Equivalent Neutral (EN) wind, the **stress** and the **10 m true wind** (accounting for the stability of the atmosphere, and for the surface currents).
    - For each of these fields, the files include:
        - the magnitude and the direction;
        - **the zonal and meridional components;**
        - **the uncertainty in magnitude and direction;**
        - a number of traditionally-used quality flags;
        - **a new, and simplified, Quality Indicator flag (values 0-5), in addition to the number of quality flags used in the past, to help the users more easily navigate the maze of flags.**
2. **Ancillary data – to support the evaluation of the new products**
    - **collocated in space and time wind/stress data from ERA-5**
        - **including SST, surface pressure, 2m temperature and relative humidity)**
    - **surface precipitation from IMERG, and**
    - **the surface currents from GlobeCurrents.**
3. **Derivatives of the wind and the stress** (will **be produced soon).** These files will contain the following derivative fields: Curl and divergence of the EN wind; Curl and divergence of the stress; Curl and divergence of the 10m real wind; Same from ECMWF-ERA5 fields

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QuikSCAT & ASCAT-A - Achieving consistency in the retrievals

- **Sources of uncertainty** in the the scatterometer-based retrievals of ocean surface winds:
    - **the frequency- and incident-angle-dependent GMF**,
    - **the retrieval (inversion) algorithm** and all its assumptions, and
    - the frequency-dependent **atmospheric corrections.**
- To avoid these sources of inconsistency in the CDR we take the following approach:
    - **develop a GMF for C-band starting with CMOD7 and adjusting it to match the ASCAT-A retrievals to those from QuikSCAT, using collocated observations**;
    - **utilize consistent measurement resolution** by retrieving winds on the same resolution grid with the same measurement binning method;
    - convert (NRCS) σ^0 measurement to winds **using the same (JPL's) wind retrieval algorithm and the same ancillary data** (e.g., NCEP model fields) for nudging.

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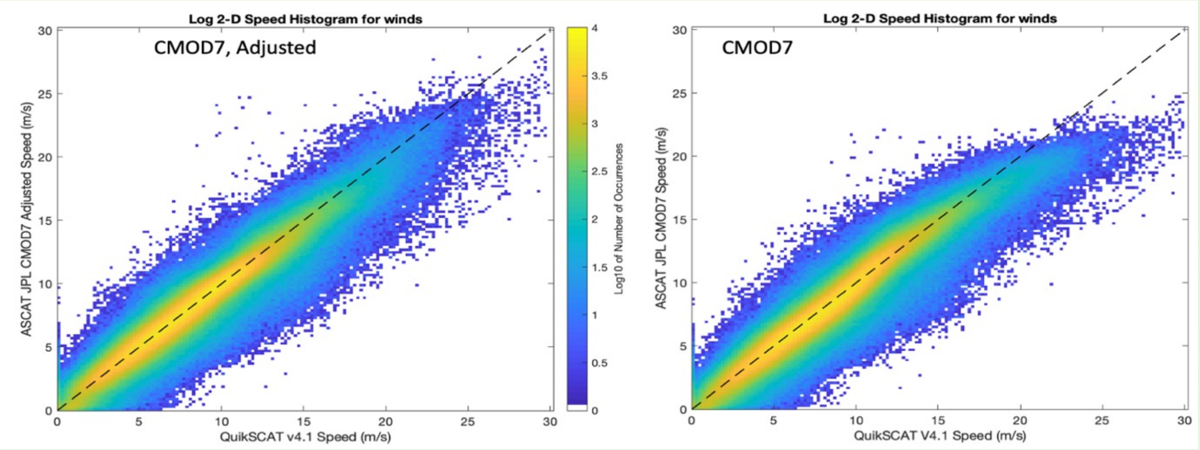

Joint histograms of ASCAT and QuikSCAT retrieved wind speeds, both using the JPL retrieval algorithm with two GMFs: new adjusted CMOD7 (left panel) and the original CMOD7 (right panel). As it was constructed to do, the adjusted GMF results in better agreement between the two sensors. The primary improvement is an increase in ASCAT winds over 15 m/s to match QuikSCAT. There is also a reduction in the slight meandering of the distribution along the one-to-one line for lower winds.

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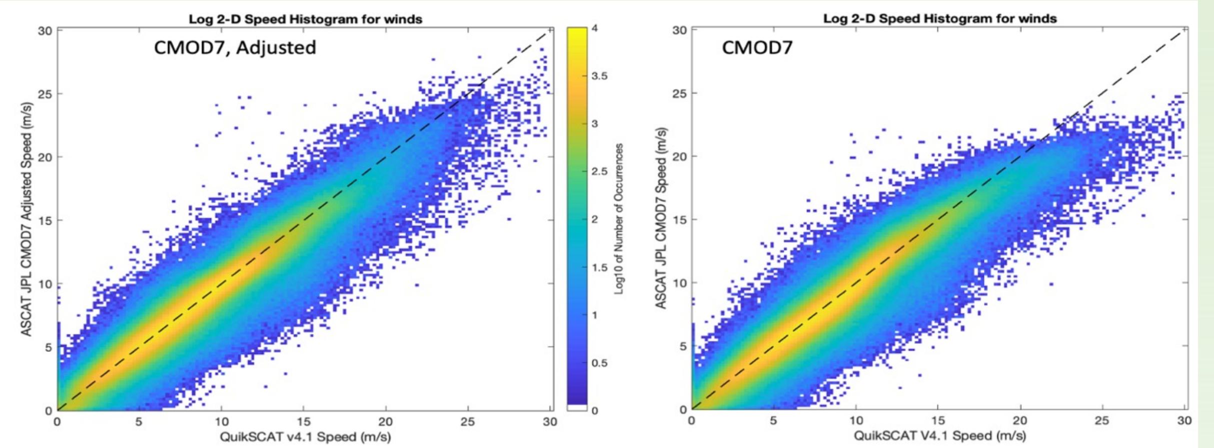

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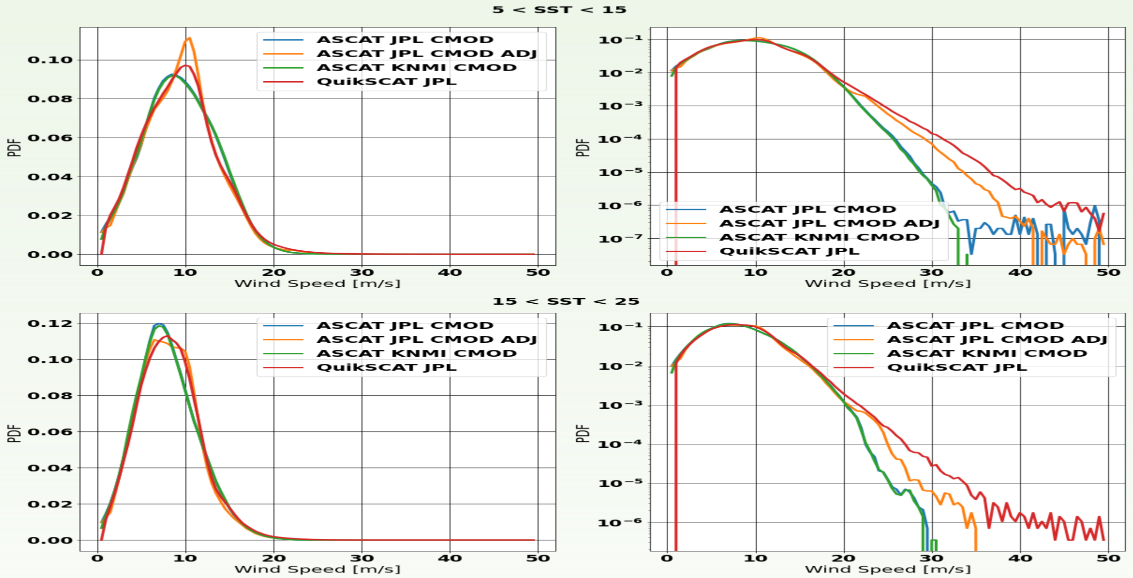


Probability Density Functions (PDFs) for four types of retrievals from collocated observations (four different colors in each of the four panels). Top and bottom panels show comparisons for 2 different SST regimes. Left column shows comparisons on the linear scale., revealing the PDF differences in the dominant wind regimes. The right column shows the PDF comparisons on the log scale, revealing the PDF differences in the tales of the distributions.

Quality Indicator

- Traditionally, scatterometer surface wind retrieval products include a ***significant number of flags*** that indicate the quality of each individual retrieved value.
  - These flags are meant to attest to: the quality of the input data; the proximity of land or ice that could be contaminating the original measurements; the presence of rain within the scatterometer field of view; or other assumptions and factors that might adversely affect the quality of the retrievals.
- Our new products continue the tradition and provide a number of flags used in the past.
  - These flags are there to help the experienced researcher to weed out retrievals with questionable value, according to their specific research interests.
  - However, the rules to use these flags might also be very cumbersome. In reality, their use could also create confusion among the new users with less familiarity with scatterometer data and retrieval approaches.
- **Here, for the first time, we also provide a more general Quality Indicator , to help the users more easily navigate the maze of flags**.

The quality indicator in the Level 2 (orbital) data files developed by our MEaSUREs project is an integer between 0 and 5 that denotes *the quality category* of the data, with 0 being the highest quality and 5 the lowest.

Here the general description:

Category 0: No retrieval corruption

Category 1: Insignificantly corrupted retrieval

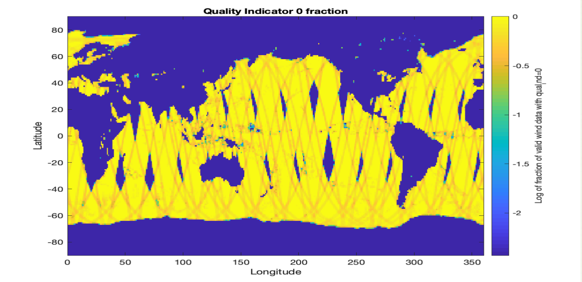
Category 2: Possible Significant Error

Category 3: Likely Significant Error

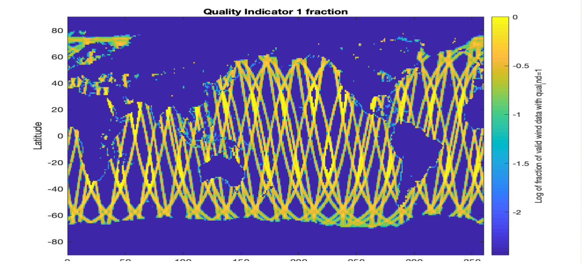
Category 4: No winds retrieved due to quality control

Category 5: No data over liquid water in cell (i.e., land, ice, etc. data)

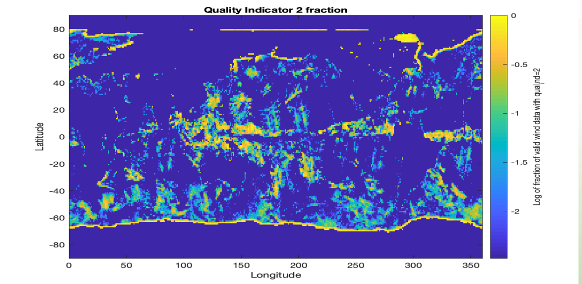
Quality Indicator 0 – No Retrieval corruption - the best possible retrievals; to be used when needing highest quality data – e.g. for development of GMFs. ***The data set comprises 73.8% of data for which winds were retrieved*. The bias w.r.t to ERA-5 is 0.22 m/s.; The standard deviation is 1.34 m/s**.



Quality Indicator 1 – Insignificantly corrupted retrieval - high quality retrievals; recommended for use is general research. ***This data set comprises 18.1% of the data with retrieved winds.* The bias with respect to ERA-5 is 0.3 m/s. The standard deviation with respect to ERA-5 is 1.76 m/s.**



Quality Indicator 2 - Possible Significant Error – data should be excluded if rain contamination issues are of importance and the correction to the wind speed applied in rain is deemed insufficient. ***This data set comprises 5.3% of the data with retrieved winds.* The bias with respect to ERA-5 is 2.38 m/s. The standard deviation is 6.2 m/s. When latitude is restricted to within + or - 70 degrees. Bias=1.55 m/s; standard deviation=3.4 m/s.**



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- Under this project we are **providing estimation of the uncertainty for each wind retrieval cell**.
- These estimates are **needed while**
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- Uncertainty estimates were developed by performing **triple-collocations among QuikSCAT, ASCAT-A (JPL retrievals with new GMF), and ERA-5 model first guess (FG) winds (interpolated in space and time to the collocated scatterometer observations).**
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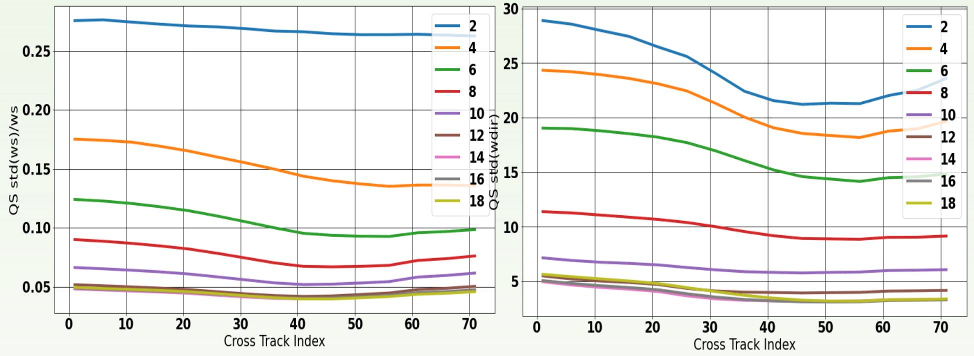
- Since scatterometer wind errors vary depending on look geometry and wind speed, **we performed this triple colocation analysis as a function of wind speed (for ASCAT and QuikSCAT) and cross-track position (for QuikSCAT).** Future versions of this product will estimate errors also as a function of ASCAT cross-track position.
- **Initially, only data of the highest quality (QI 0 or 1) were used.**
  - A lookup table was formed for QuikSCAT that estimates EN wind speed and wind direction error as a function of wind speed and cross track location.
  - Created based on three years of data between 2007-2010.
  - Errors in wind speed and direction were chosen (as opposed to u/v components) to maintain the relationship between cross-track location and speed/direction error, a relationship that does not similarly exist when using components.
  - To estimate errors in u/v wind components, the speed/direction lookup tables are used, with errors propagated through to u/v using standard error propagation formula.

Standard deviation of the QuikSCAT wind speed (left panel) and wind direction (right panel), computed as a function of cross-track position (0 is at nadir) and wind magnitude for several wind regimes. The errors (uncertainties) were computed from triple collocation error analyses of QuikSCAT, ASCAT and ERA-5 EN winds.



Uncertainty

- Under this project we are **providing estimation of the uncertainty for each wind retrieval cell**.
- These estimates are **needed while**
  - **performing detailed analyses of the scatterometer wind retrievals and**
  - **critically needed when assimilating the wind retrievals** into numerical weather prediction models.
- Uncertainty estimates were developed by performing **triple-collocations among QuikSCAT, ASCAT-A (JPL retrievals with new GMF), and ERA-5 model first guess (FG) winds (interpolated in space and time to the collocated scatterometer observations).**
- The triple collocation technique (Vogelzang et al, 2012; Freilich and Dunbar 1999) uses three data sets and allows random error terms to be estimated for all three. Biases and scaling factors are also determined for two data sets with respect to the third.

- Since scatterometer wind errors vary depending on look geometry and wind speed, **we performed this triple colocation analysis as a function of wind speed (for ASCAT and QuikSCAT) and cross-track position (for QuikSCAT).** Future versions of this product will estimate errors also as a function of ASCAT cross-track position.
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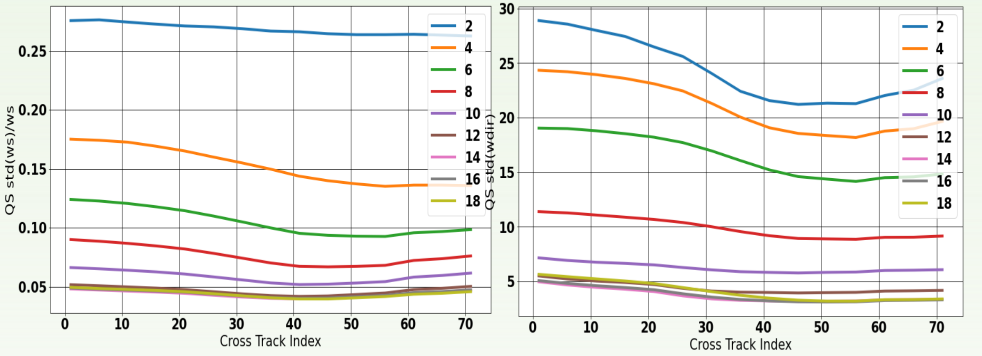
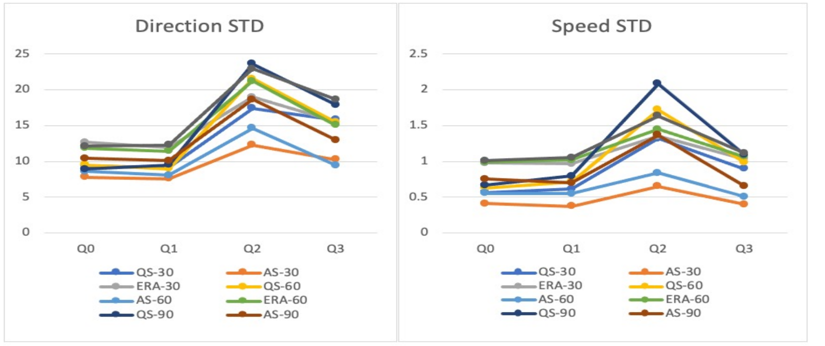


- Significantly larger errors are expected where rain (or other footprint contamination) exists than the estimated ones using triple colocation from quality indicator 0,1 data.
- Since not enough data exist to perform this analysis stratified by cross track location, wind speed, and quality indicator, **we estimate bulk scaling factors between QI=0,1 vs QI=2,3 data, and apply those scaling factors to data where QI=2,3.**

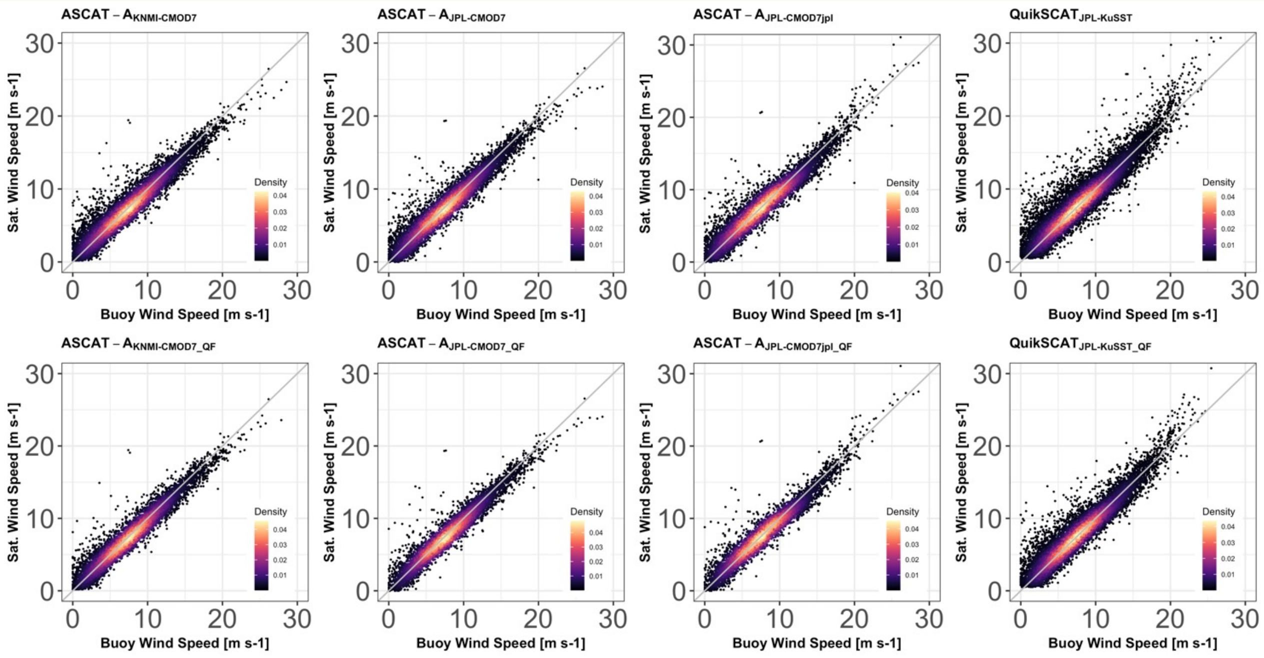


Buoy Evaluation

- In this work we took advantage of the NDBC buoy measurements to quantitatively characterize and validate the four scatterometer-derived ocean surface wind products (for 2008):
  - ASCAT-A$_{KNMI-CMOD7}$,
  - ASCAT-A$_{JPL-CMOD7}$,
  - ASCAT-A$_{JPL-CMOD7jpl}$, and
  - QuikSCAT$_{JPL-KuSST}$
- The retrieved winds compared fairly well with buoys in the presence of QC-flags (QF), though at low and high wind speeds scatterometer measurements may be somewhat affected.

Scatterometer	N	μ m s^{-1}	RMSD m s^{-1}	σ m s^{-1}	ρ
ASCAT-A$_{KNMI-CMOD7}$	14228	**-0.04**	1.07	1.07	0.96
ASCAT-A$_{KNMI-CMOD7_QF}$	11507	**-0.13**	0.95	0.94	0.97
ASCAT-A$_{JPL-CMOD7}$	12063	-0.10	1.04	1.03	0.96
ASCAT-A$_{JPL-CMOD7_QF}$	8718	-0.16	0.95	0.93	0.97
ASCAT-A$_{JPL-CMOD7jpl}$	12064	**-0.02**	1.05	1.05	0.96
ASCAT-A$_{JPL-CMOD7jpl_QF}$	8719	**-0.08**	0.95	0.95	0.97
QuikSCAT$_{JPL-KuSST}$	25068	0.10	1.25	1.25	0.94
QuikSCAT$_{JPL-KuSST_QF}$	18887	0.06	1.14	1.13	0.95

- The overall ASCAT-A initial comparison indicates a very slight improvement in wind speed quality going from the KNMI original ASCAT-A to JPL processed ASCAT-A data.
- The JPL QuikSCAT retrievals compare very slightly better in the mean bias but have larger RMSD and standard deviation compared to the ASCAT comparisons to the buoy (Table below).
- **These results support the validity of our approach.**
- Future plans involve continued use of the buoys for validation, with considerations to examine impacts from tropical rain/convection including the recently available ScatSAT retrieved data.



Data location, visualization, formats

- ## Location of the data

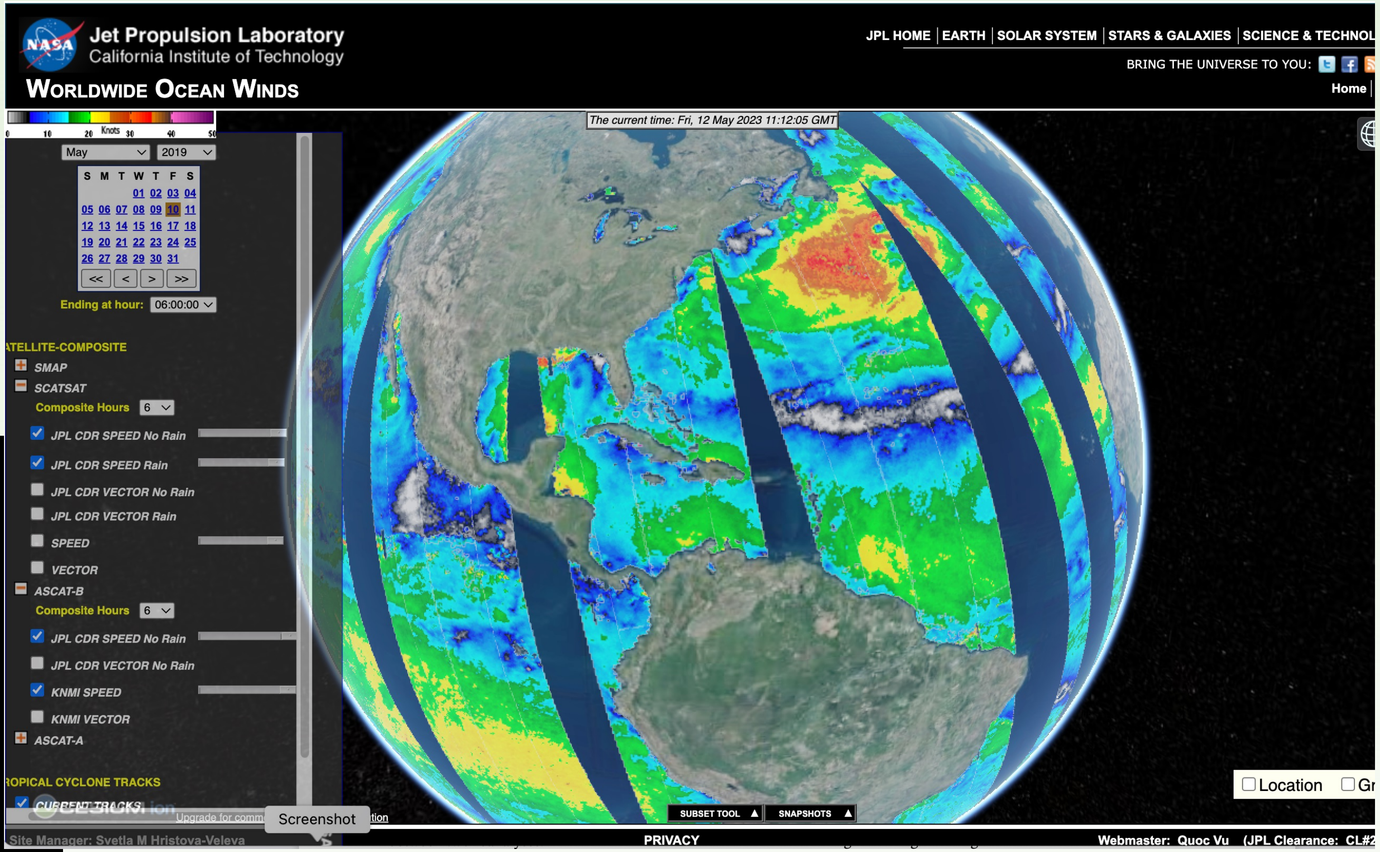
  now available to the public via PO.DAAC

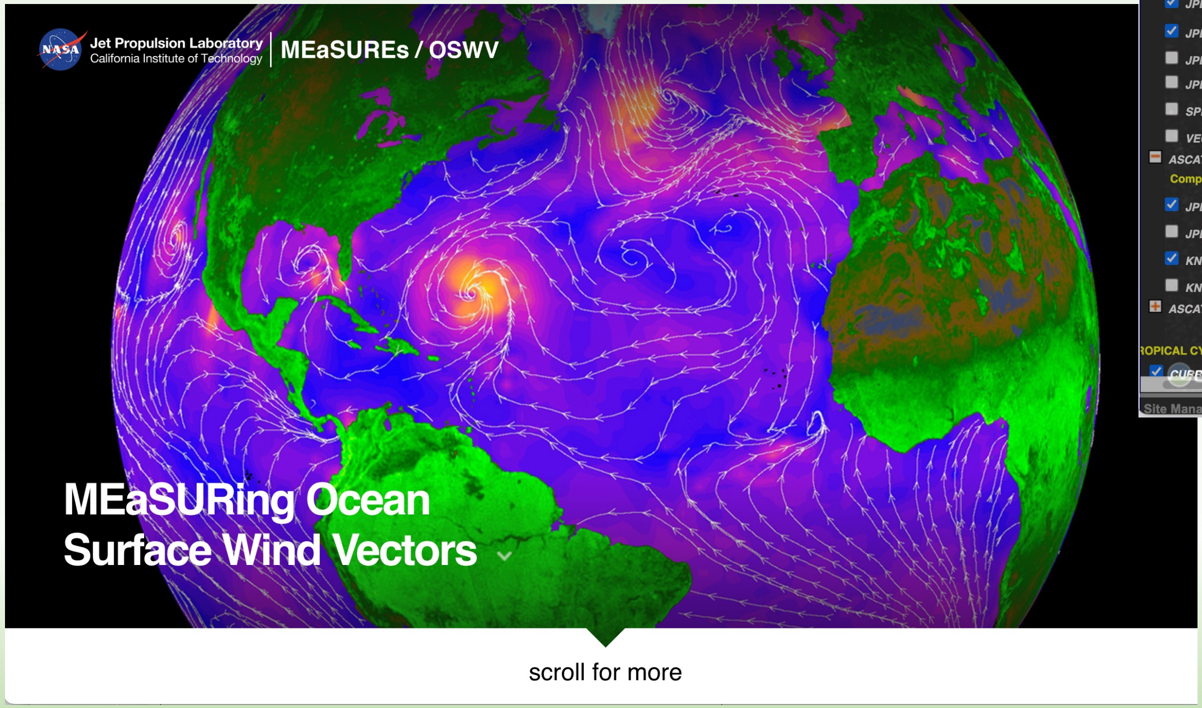
  https://podaac.jpl.nasa.gov/datasetlist?values=MEaSUREs/OSWV&view=list&ids=Projects

  And with the following DOIs:

  QuikSCAT L2 - 10.5067/ESDQS-L2W10
  QuikSCAT L2 ancillary - 10.5067/ESDQS-L2C10
  ASCAT-A L2 - 10.5067/ESASA-L2W10
  ASCAT-A L2 ancillary - 10.5067/ESDAA-L2C10

WOW.jpl.nasa.gov





- ## File Formats
  - netCDF-4 format with internal compression
  - README files to serve as a quick reference guide can be found

Does it matter if the scatterometer retrievals are consistent?

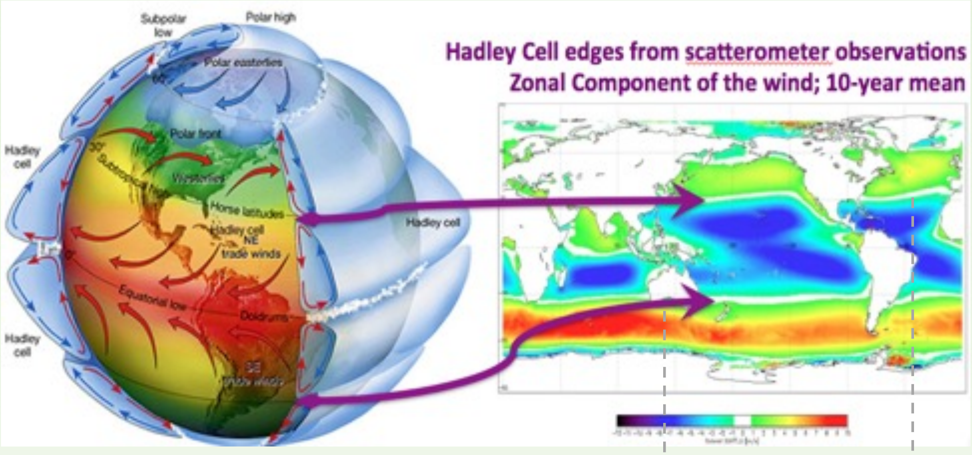
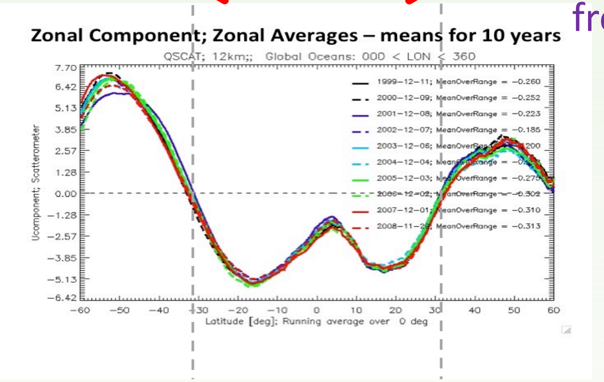
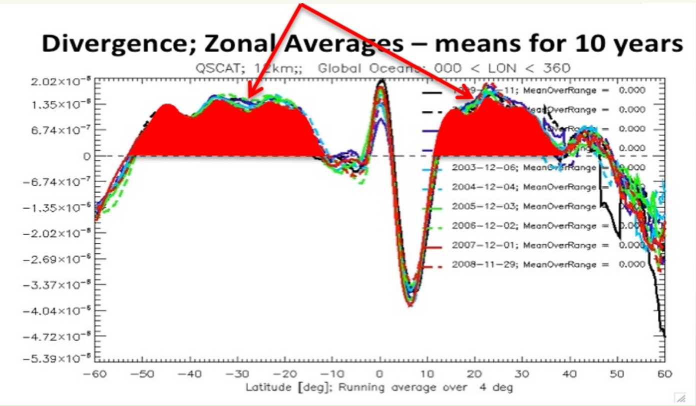


Fig. 1. Schematic of the large-scale circulation (left panel) and the zonal component of the surface wind as determined from QuikSCAT (right panel).

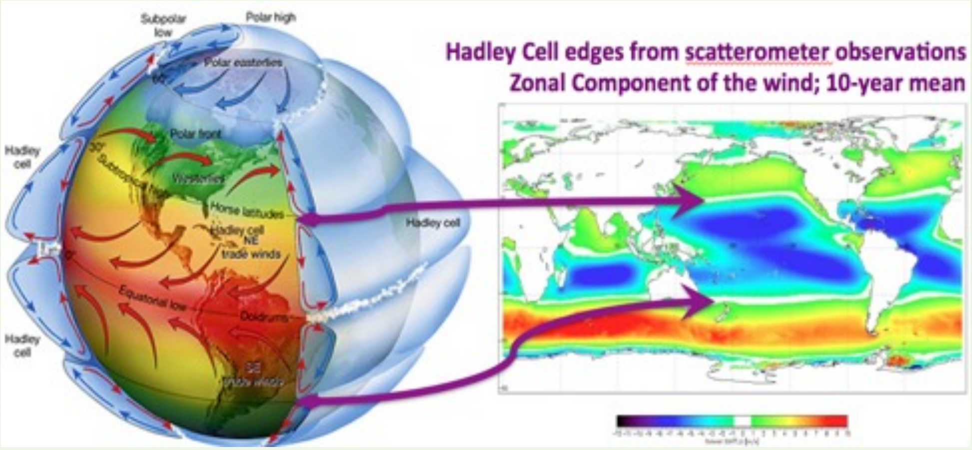


- Recent evidence suggests that the tropics have expanded over the last few decades by a very rough 1º latitude per decade, considered to be an atmospheric response to the observed tropical ocean warming trend. If continued, the expansion of the tropics (the widening of the Hadley cell) could have a substantial impact on water resources and the ecology of the sub-tropics.
- Until now, the understanding of the mechanisms that govern the changing width of the tropics has been confined to models and proxies because of the unavailability of systematic observations of the large-scale circulation.
- Ocean surface vector winds, derived from scatterometer observations, provide for the first time an accurate depiction of the large-scale circulation and allow the study of the Hadley cell evolution through analysis of its surface branch.
- In a 2015 study we determine the extent of the Hadley cell as defined by the subtropical zero-crossing of the zonally-averaged zonal wind component, determined from QuikSCAT observations (Fig. 1) - (Hristova-Veleva et al., 2015).



- Determine the **circulation strength** as defined by the area of divergence.

Does it matter if the scatterometer retrievals are consistent?



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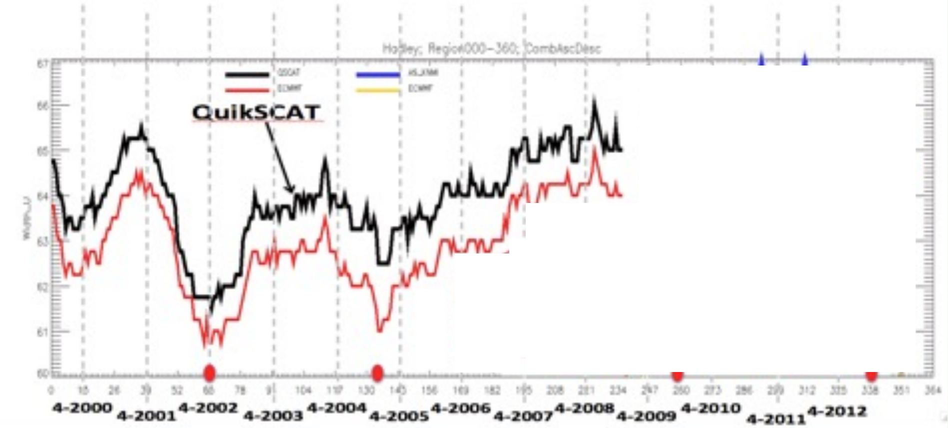

Fig. 2. Time evolution of the width of the combined Hadley cell as determined from the zero crossing of the mean zonal wind (from 1-year running averages)

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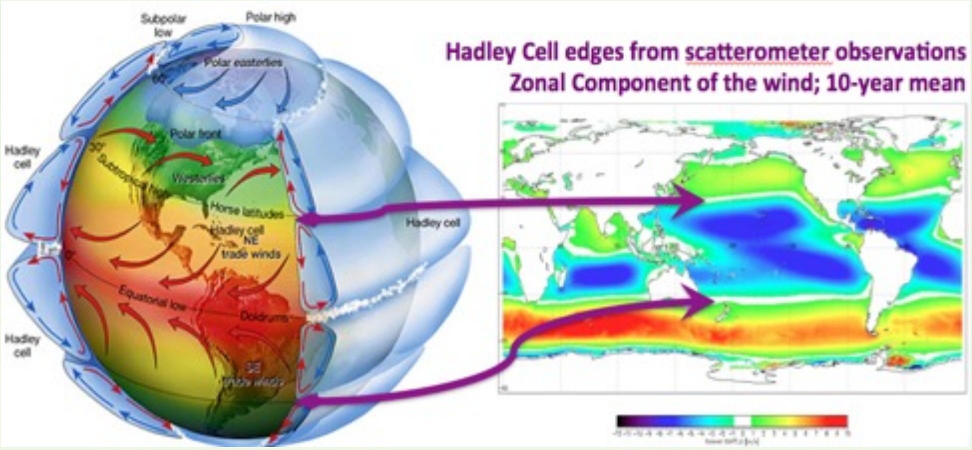

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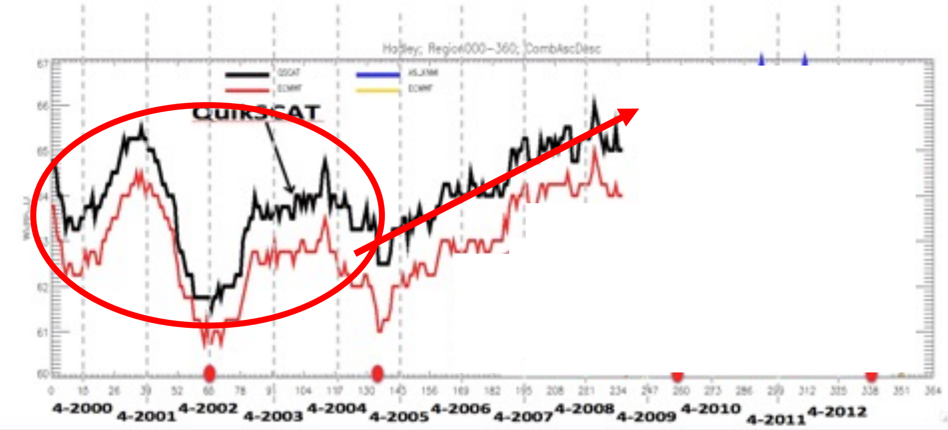

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    - The first half of the 10-year record shows two distinct cycles in the width of the Hadley cell while the latter part of the record shows a steady increase in the width, as has been shown by others (~1^{o}/decade, both south and north, for a total of about 2^{o} / decade);
    - The two cycles in the 1999-2004 time period are likely a reflection of the modulation of the Hadley cell by the La Nina (1999) /El Nino (2002) events that dominated this period;

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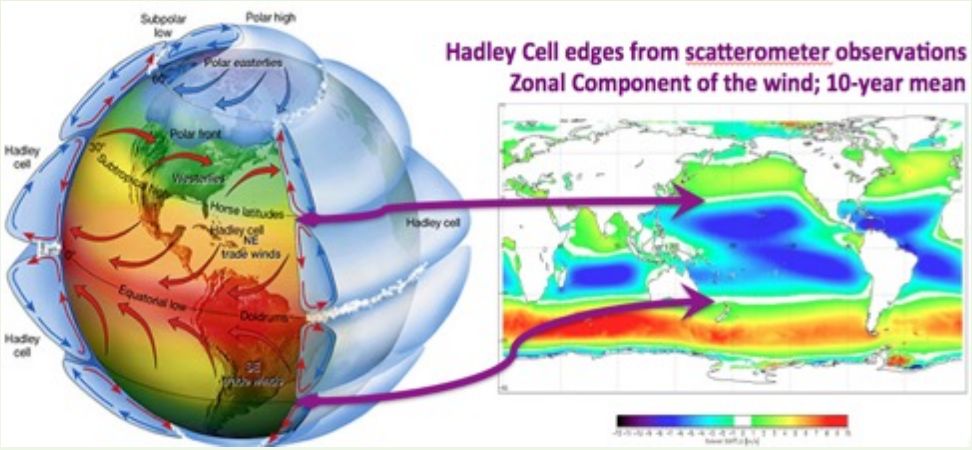

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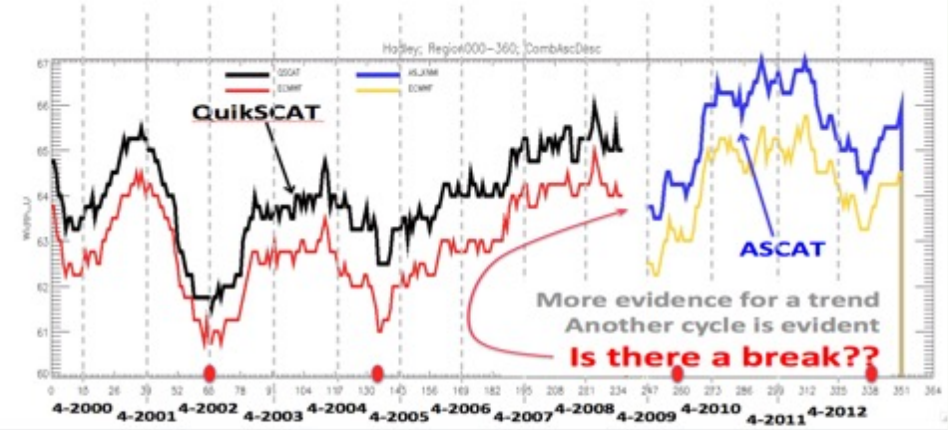

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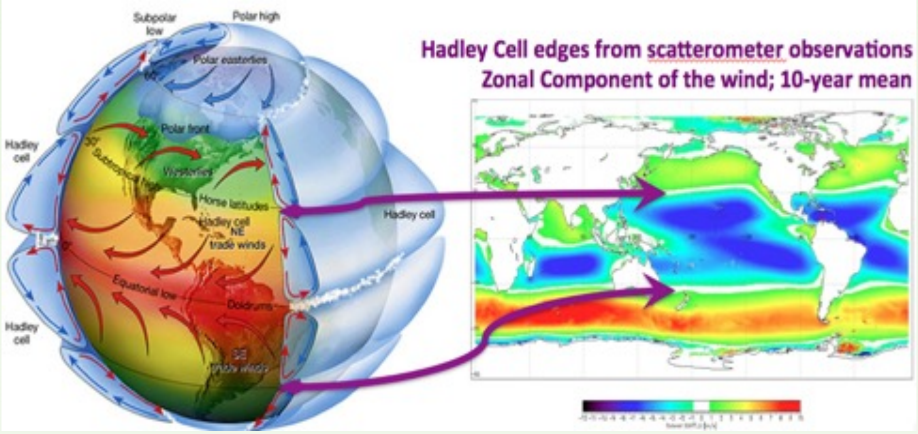
  - The two cycles in the 1999-2004 time period are likely a reflection of the modulation of the Hadley cell by the La Nina (1999) /El Nino (2002) events that dominated this period;
- To investigate the consistency in the trends and variability when determined by different scatterometers, we performed similar analysis of the Hadley cell using the wind estimates from ASCAT. **We found an apparent discontinuity in the signal when the data source changes from one observing system to another (Fig. 2). What is the reason? Diurnal signal or retrieval inconsistencies?**

Other CDRs and Why Does it Matter

- **This effort is not the first of a kind,** following with the traditions of others - the Climate Data Records (CDRs) being developed at
  - RSS - https://www.remss.com/announcement/ASCAT-ABC-ocean-surface-wind-CDR/
  - EUMETSATs OSI SAF by KNMI - https://scatterometer.knmi.nl/archived_prod/
- **Here we provide an alternative set of consistently retrieved products** based on
  - different retrieval algorithms (JPL’s versus KNMI’s versus RSS’),
  - different C-band Geophysical Model Function (GMF), and
  - the use of different nudge fields (NCEP versus ECMWF).
- By developing the MEaSUREs-funded set of products we are now providing an additional ESDR of climate quality.
- ***Only through analyses of a number of different ESDRs we can obtain a better understanding of the uncertainties associated the retrieval approaches and the creation of the climate-quality ESDRs*.**
- Such understanding is critically needed when analyzing the EDSRs to establish climate trends and variability, and to understand the processes and the evolution of the large-scale phenomena such as the MJO, ENSO and the Hadley Cell. Even the depiction of the diurnal variability of the winds might be affected by the uncertainties associated with the different retrieval approaches.



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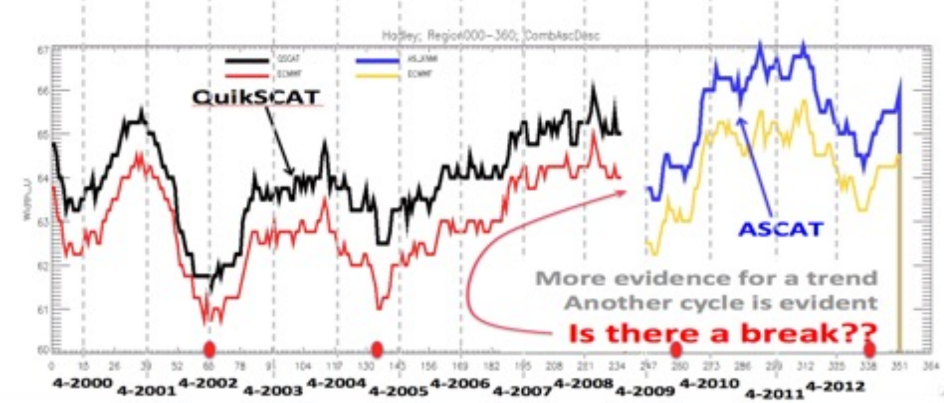

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BACKUP

Estimations of stress

- We provide **L2 scatterometer wind stress estimates derived from the highest resolution, swath-based wind products**. This preserves vector wind stress estimate accuracy and properly reflects the full dynamic range and spatial variability that can be obtained using the scatterometer.
- **The key factor needed to derive wind stress data from scatterometer 10m EN winds is the drag coefficient (C_{D10EN})**, a term parameterizing the effective surface aerodynamic roughness.

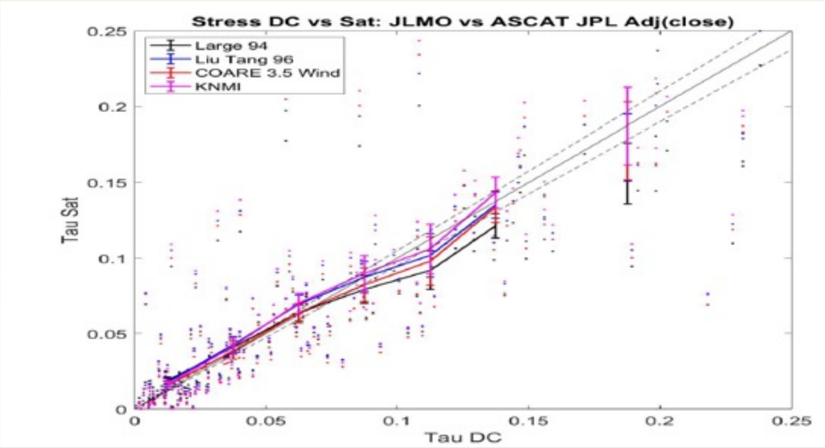
$$\boldsymbol{\tau} = \rho_a \cdot |\mathbf{u}_*|\, \mathbf{u}_* = \rho_a \cdot C_{D10EN} \cdot |\mathbf{U}_{10EN}|\, \mathbf{U}_{r10EN}$$

  - Under this project, we are **employing and testing several candidate drag coefficient** models in developing the wind stress data products
  - then **assessing their validity and impact on product uncertainty using satellite data matchups with in situ data**. (e.g. three differing drag coefficients representing consensus (COARE4) and extremes (Large94, YTaylor2002) were applied against in situ data.)

Limited buoy and scatt data in 2007-2009; Limited higher wind data
ASCAT-A = 243 matchups; QSCAT = 238

Comparison of stress estimates from satellite observations to buoy eddy covariance flux observations using four different bulk formulas for the drag coefficient C_{D10EN}.

Recent and improved in situ wind stress data and experiments indicate that latest C_{D10EN} algorithms differ considerably from Large et al. (1994) formulation, especially at wind speeds above 10 m/s.



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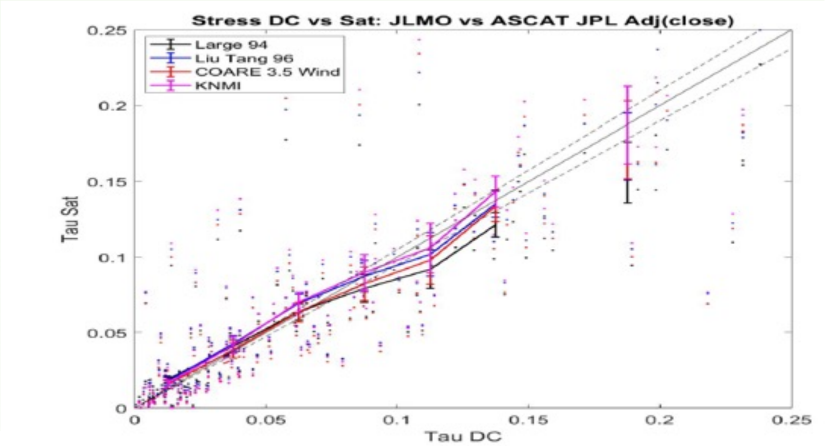
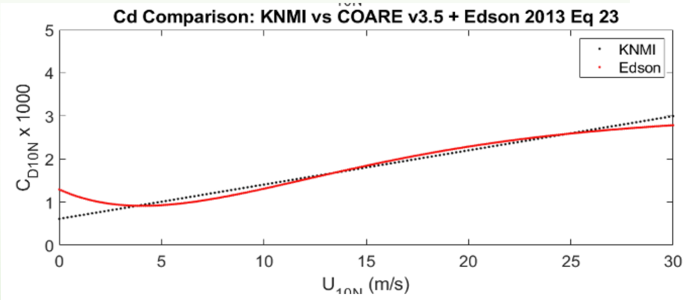




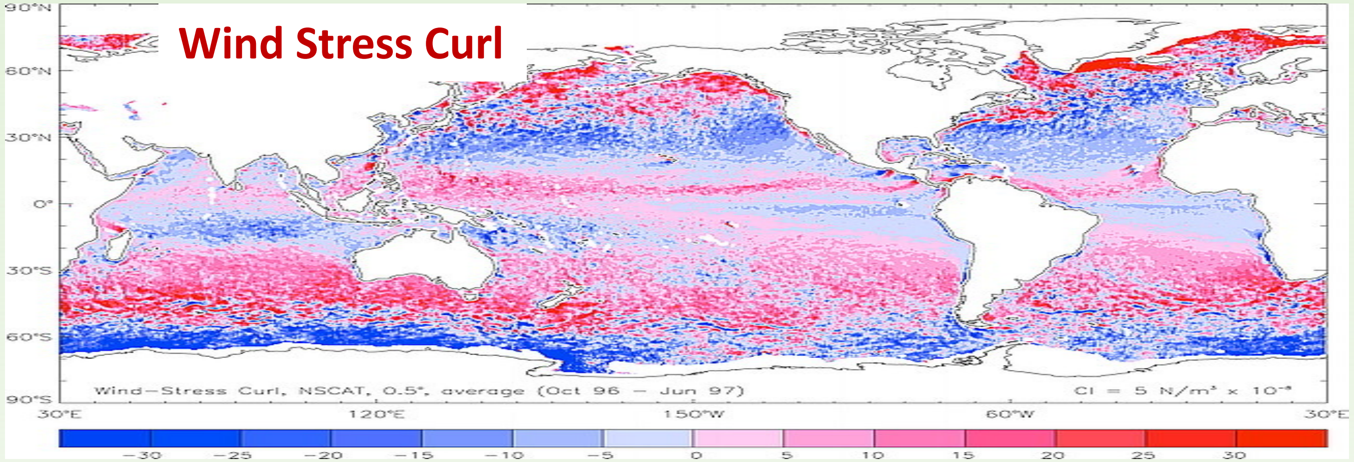
The drag coefficient model used in the V1.0 release of the MEaSUREs product

Edson et al. (2013) produced a wind-dependent drag formulation over the open-ocean that shows good agreement with both field observations and global reanalysis datasets.

Derivatives of winds and stress

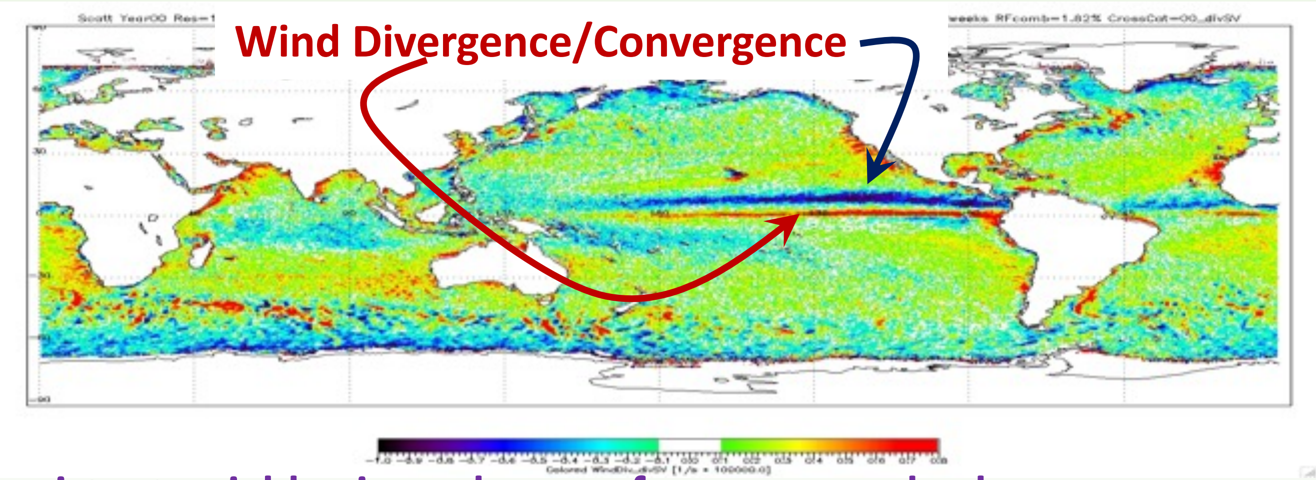
(O'Neill & Jacob; Bourassa & Wright; Hristova-Veleva; Kilpatrick; Rodriguez)

- ***Spatial derivatives*** **of surface winds and the wind stress are of paramount importance for many dynamical processes in the ocean and atmosphere.**
    - the mid-latitude basin-scale ocean circulation is driven by the **wind stress curl (**Sverdrup circulation),
    - rainfall anomalies are often coupled with low-level **wind convergence**
    - scatterometers provide practically the only means to estimate the surface derivative wind fields over most of the global oceans on a regular basis and **with higher resolution and accuracy.**
    - ***A data record consisting of carefully constructed estimates of these dynamically important fields is thus an opportunity to further our understanding of the general atmospheric and oceanic circulation.***



Milliff & Morzel, 2001

DOI: https://doi.org/10.1175/1520-0469(2001)058<0109:TGDOTT>2.0.CO;2



- **To avoid shortfalls of producing derivatives from time-inconsistent neighboring values, or from averaged values, we propose to compute the spatial derivatives from the L2 swath-based data for which all neighboring points come from the nearly-coincident observations in time (within several minutes).**
- **The big advantage of this approach is the ability to preserve and properly reflect the intensity of the small-scale and transient features (e.g. the frontal convergence).**

File formats, data structures and location of the data.

- **File Formats**
  - netCDF-4 format with internal compression
  - To obtain a complete listing of science data variables and associated metadata type *ncdump -h <filename>.nc*
  - “ncdump” is open-source and is installed by default as part of the netCDF-4 package: https://www.unidata.ucar.edu/software/netcdf/.
  - For a “quick” view (2-D mapped plotting) of the netCDF data and metadata use the free and open-source Panoply application, which can be installed on Windows, Mac OSX, and Linux: https://www.giss.nasa.gov/tools/panoply/
  - README files to serve as a quick reference guide can be found under */data/measures/esdr_v1.0/L2/documents.*

- **Location of the data**
  - **JPL Server:** sftp://oceansftp.jpl.nasa.gov
  - user: oceanuser
  - pass: request through e-mail to svetla.hristova@jpl.nasa.gov or alexander.fore@jpl.nasa.gov

- **Directory structure**

```
/data/measures/esdr_v1.0/L2
                              /documents
                              /scatterometer_data
                                                  /QuikSCAT/year/day-of-year
                                                  /ASCAT-A/year/ …
                              /ancillary_data
                                            /QuikSCAT/year
                                            /ASCAT-A/year
```