Jet Propulsion Laboratory
California Institute of Technology

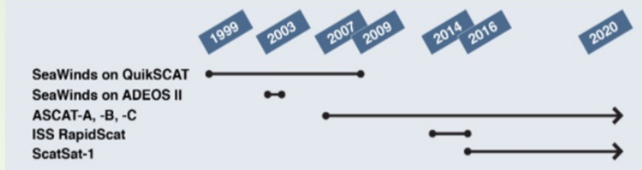
New Climate Data Record of the Ocean Surface Winds, Stress and Their Dynamically-Significant Derivatives – Vorticity and Divergence: Supporting Studies of Trends and Variability in the Large-Scale Circulation

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]

[1] - Jet Propulsion Laboratory, California Institute of Technology
[2] - Florida State University
[3] - University of New Hampshire, Durham
[4] - Oregon State University

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:



There is a significant diversity in the
- instrument geometry (incidence angle, sampling strategy),
- spatial resolution and the
- mission-specific Local-Time-of-Day (LTD) of the observations.

Missions	Diurnal Sampling Ascending-Descending
QuikSCAT	6:00am – 6:00pm
SeaWinds	10:30pm – 10:30am
ASCAT	9:30pm - 9:30am
OSCAT	12:00am – 12:00pm
RapidScat	Diurnal Sampling
ScatSat-1	~9:00pm – ~9:00am

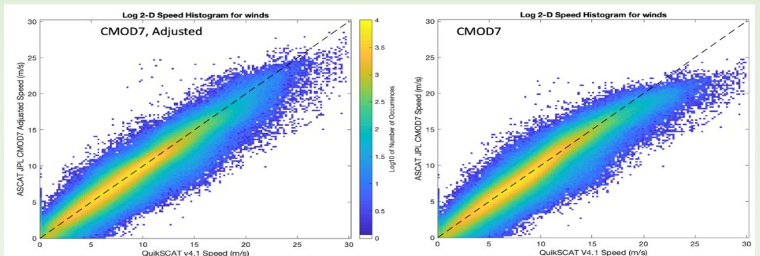
Instrument	Instrument Resolution	Retrieval Resolution	Incidence angles [°]	Scan Characteristics (swath)	Frequency [GHz]
QuikSCAT	25 x 7 km	25 & 12.5	46 & 54	Conical scan – 1 wide swath	Ku band
SeaWinds	25 x 7 km	25 & 12.5	46 & 54	Conical scan - 1 wide swath	Ku band
ASCAT	20 x 10 km	25 & 12.5	25 to 65	Push broom - 2 narrower swaths	C band
OSCAT	30 x 7 km	50 & 25 km	49 & 58	Conical scan - 1 wide swath	Ku band
RapidScat	25 x 12km	12.5km	Variable	Conical scan – 1 swath (narrower)	Ku band
ScatSat	30 x 7 km	50 & 25 km	49 & 58	Conical scan - 1 wide swath	Ku band

1. **Creation of a consistent long-term Earth Science Data Record (ESDR - CDR)** 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.

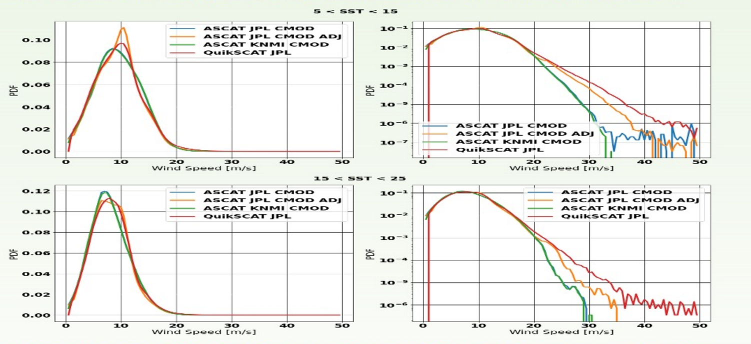
APPROACH

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.

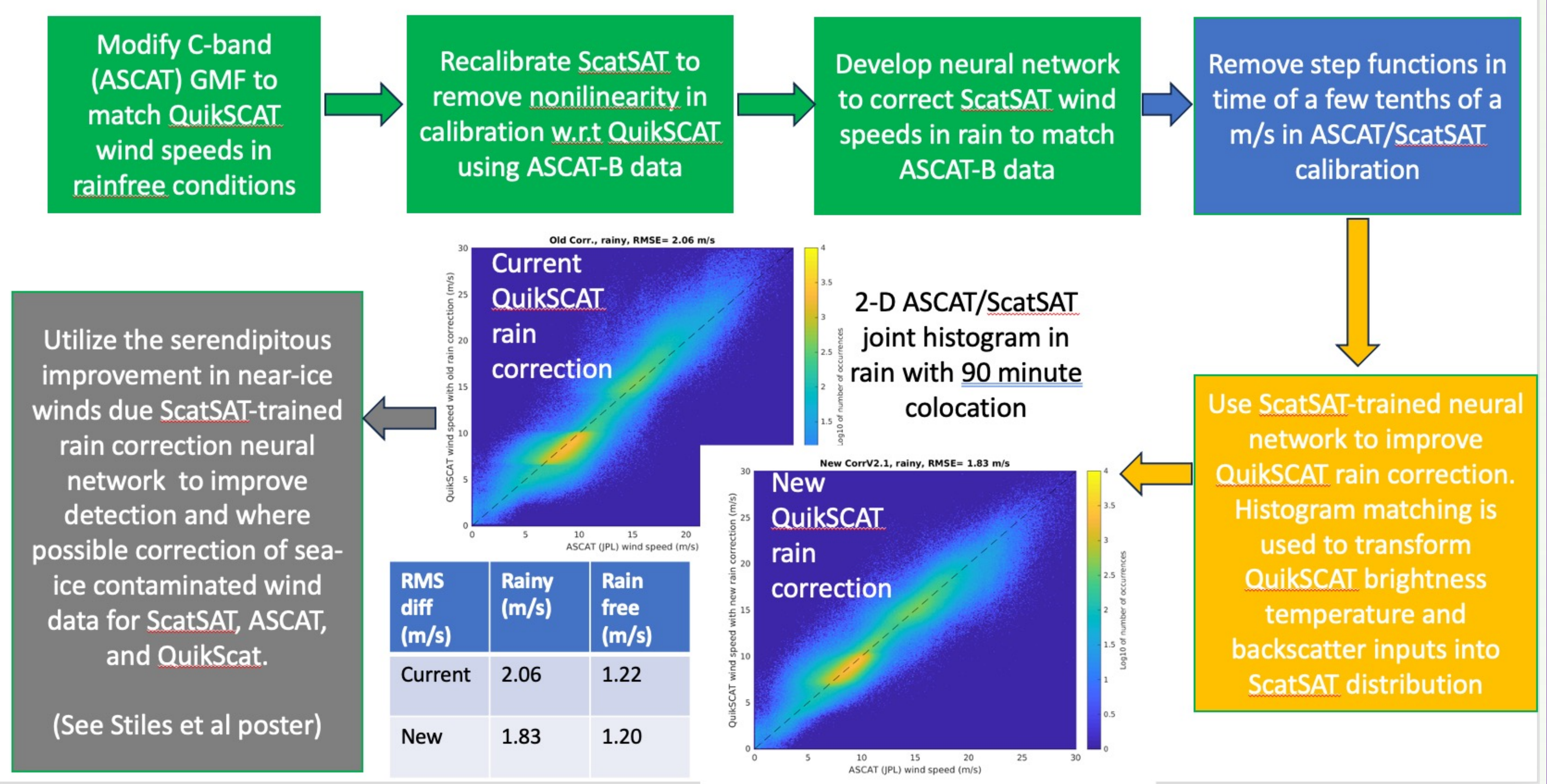


Joint histograms of ASCAT and QuikSCAT retrieved wind speeds, both using the JPL retrieval algorithm with two GMFs: new adjusted CMOD7 (left panel) and the original CMOD7 (right panel). As it was constructed to do, the adjusted GMF results in better agreement between the two sensors. The primary improvement 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.



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.

Flowchart of Ku/C-band rain correction and harmonization work- Bryan Stiles et al.
(Green – completed in past years, Blue – completed this year, Orange – nearing completion, Gray – Future work described in poster.)



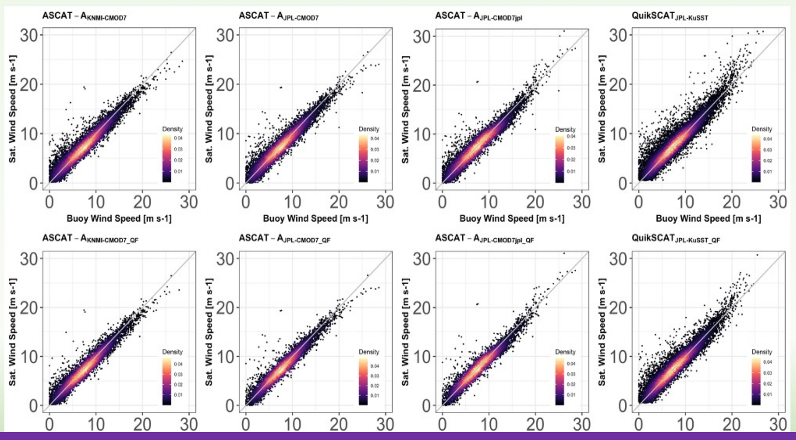
	RMS diff (m/s)	Rainy (m/s)	Rain free (m/s)
Current	2.06	1.22	
New	1.83	1.20	

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):
  - $ASCAT\text{-}A_{KNMI\text{-}CMOD7}$,
  - $ASCAT\text{-}A_{JPL\text{-}CMOD7}$,
  - $ASCAT\text{-}A_{JPL\text{-}CMOD7jpl}$ and
  - $QuikSCAT_{JPL\text{-}KuSST}$
- 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
$ASCAT\text{-}A_{KNMI\text{-}CMOD7}$	14228	-0.04	1.07	1.07	0.96
$ASCAT\text{-}A_{KNMI\text{-}CMOD7\_QF}$	11507	-0.13	0.95	0.94	0.97
$ASCAT\text{-}A_{JPL\text{-}CMOD7}$	12063	-0.10	1.04	1.03	0.96
$ASCAT\text{-}A_{JPL\text{-}CMOD7\_QF}$	8718	-0.16	0.95	0.93	0.97
$ASCAT\text{-}A_{JPL\text{-}CMOD7jpl}$	12064	-0.02	1.05	1.05	0.96
$ASCAT\text{-}A_{JPL\text{-}CMOD7jpl\_QF}$	8719	-0.08	0.95	0.95	0.97
$QuikSCAT_{JPL\text{-}KuSST}$	25068	0.10	1.25	1.25	0.94
$QuikSCAT_{JPL\text{-}KuSST\_QF}$	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.



NEW PRODUCTS

Types of L2 (swath) files

- The new products are organized in three types of files that will be available for both the L2 and the L3 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** (are being **produced now).** 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.

Quality Indicator

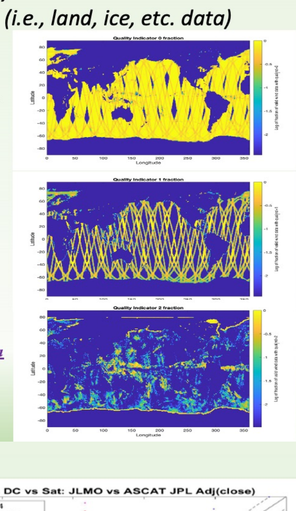
- Traditionally, scatterometer surface wind retrieval products include a *significant number of flags* that indicate the quality of each individual retrieved value.
  - These flags are meant to attest to: the quality of the input data; proximity of land or ice that could be contaminating the original 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. *This data set comprises 75.8% 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.

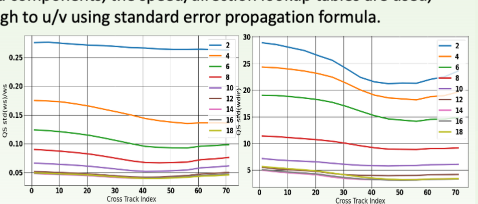
Quality Indicator 1 – Insignificantly corrupted retrieval - high quality retrievals; recommended for use in general research. *This data set comprises 18.1% of the data with retrieved winds.* The bias with respect to ERA-5 is 0.3 m/s. The standard deviation with respect to ERA-5 is 1.76 m/s.

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.



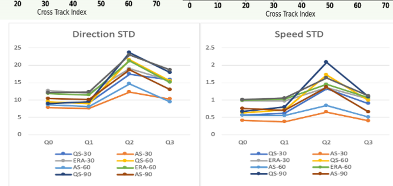
Uncertainty

- 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.
- **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.

- 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.**



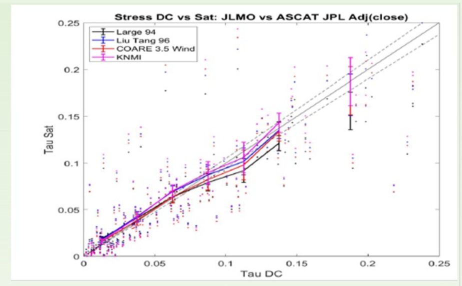
Estimations of stress

- 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_d)**, a term parameterizing the effective surface aerodynamic roughness. de Kloe et al. (2017) provides a review of the issues surrounding validation and potential biases involved in the supposed equivalence between the true observed wind stress (τ), friction velocity (u_*), and the satellite scatterometer 10m equivalent neutral wind data (U_{10EN}) relative to the ocean surface provided by the data centers where the vector stress is given by

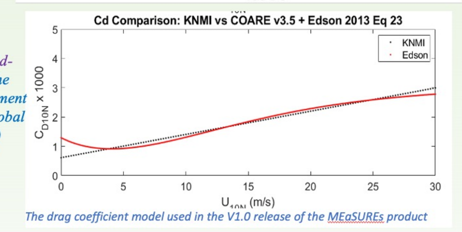
$$\boldsymbol{\tau} = \rho_a \cdot |\mathbf{u}_*|\, \mathbf{u}_* = \rho_a \cdot C_{D10EN} \cdot |\mathbf{U}_{10EN}|\, \mathbf{U}_{r10EN}$$

where ρ_a is the air density and C_{D10EN} the neutral drag coefficient (C_d hereafter).

Comparison of stress estimates made from satellite observations to buoy eddy covariance flux observations. The comparisons are done using four different bulk formulas for the drag coefficient. But more recent and improved in situ wind stress data and experiments indicate that latest C_d algorithms (Kudryavtsev and Makin, 2001; Bourassa, 2006; Drennan et al. 2005; Suzuki et al. 2013; Edson et al., 2013) differ considerably from Large et al. (1994) formulation, especially at wind speeds above 10 m/s.



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. This $C_d(U_{10EN})$ model is contained in the Coupled Ocean-Atmosphere Response Experiment (COARE) version 3.5 algorithm (Edson et al., 2013).



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

The assessments that can be made with the limited buoy stress data in hand (top Fig.) indicate that
- ***the Large et al. model would lead to stress underestimation at winds above about 8 m/s and that***
- ***the linear wind-dependent KNMI model agreed well enough with COARE3.5 as to be equivalent for wind speeds up to 20 m/s .***
- *Given that this C_d model is already in use for ASCAT data production (Copernicus Marine Environment Monitoring Service, CMEMS L3), is simple to implement as a first-cut MEaSUREs version, and can be improved in future versions, we chose to adopt this following KNMI C_d model for the L2 stress estimates.*
- ***The model is***

$$C_d = a*(U10EN) + b, \quad \text{where } a=7.94e\text{-}5 \text{ and } b = 6.12e\text{-}4.$$

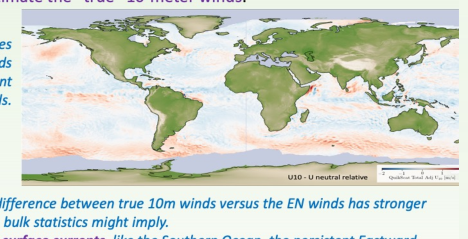
Estimation of True Winds

- **Scatterometers are sensitive to the roughness of the ocean's surface.**
- Through GMFs, we convert scatterometer measurements of roughness into "winds."
- **However, this surface roughness is not generated by the wind per-se, but instead by the wind stress.** As discussed above, the wind stress (τ) is related to the wind speed by $\tau = \rho_a*Cd*(U10-Us)|U10-Us|$. Note the difference between U10 and Us; this is referred to as the moving reference frame, or the "relative winds" [Us = surface speed, i.e., including currents]. In terms of scatterometer data products this stress is written as

$$\tau = \rho_\alpha * CdN * U10EN * |U10EN|.$$

- By training scatterometer GMFs to transform between winds and surface roughness, **we are really training to go between stress equivalent winds given a neutral boundary layer and surface roughness.**
- The question we like to address is: ***Can we make an adjustment to our resulting stress equivalent neutral winds to give something that more closely resembles "true winds?"***
- **Estimating the "true" winds is an important step towards reconciling in-situ wind measurements with remotely sensed scatterometer wind data, which can exhibit persistent differences in regions of strong currents or SST fronts.**
- **We developed a system to estimate the "true" 10-meter winds from scatterometer data.**
  - Pulling in ancillary SST, planetary boundary layer height, and air temperature from ECMWF ERA-5 analyses, along with surface current from the GlobCurrent project, and
  - Combining them with scatterometer stress-equivalent 10-meter neutral winds (EN winds) to estimate the "true" 10-meter winds.

Map of the differences between the 10m "true" winds and the "Stress Equivalent Neutral (EN)" winds.



As illustrated above, the difference between true 10m winds versus the EN winds has stronger regional significance than bulk statistics might imply.
- ***In regions with strong surface currents**, like the Southern Ocean, the persistent Eastward blowing wind and Eastward currents significantly reduce the surface stress compared to the real wind. This results in a strong positive correction in the real wind product.*
- *Other places with substantial correction are in areas of large sea-air-temperature difference, (e.g., off of Alaska).*

Owing to the bulk calibration done in scatterometer data, and to the GMF training, the average correction globally is likely very close to zero.
But most areas around the globe have substantial ~1 m/s scale adjustments between real wind and EN wind. Comparisons between scatterometers and in-situ real wind data would be wise to take this into account, especially if regional influence from currents or SST is expected.

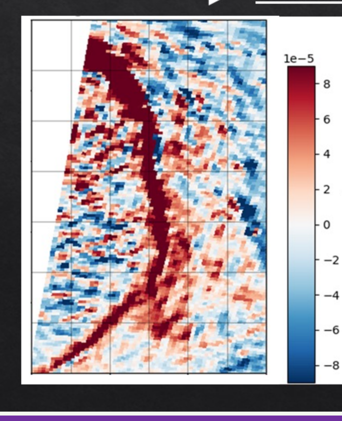
Comparing Wind Derivative Calculation Methods from Orbital Swath Winds

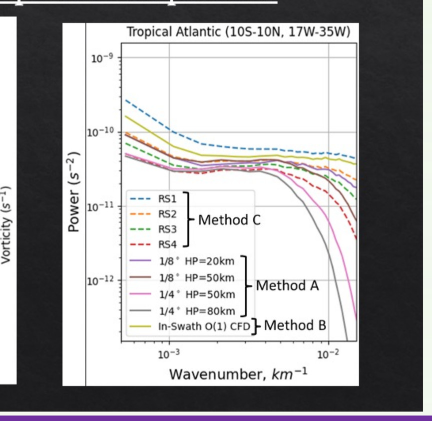
Ethan Wright and Mark Bourassa. COAPS Florida State University

How do the noise characteristics of wind divergence and vorticity change with common methods of calculation and preprocessing of orbital (L2) wind data?

Derivative Calculation Methods
- A. Finite differencing on a uniform grid
- B. Finite differencing on the orbital swath grid
- C. Circulation about a central point using a line integral of surrounding wind cells

Power Spectra Comparisons

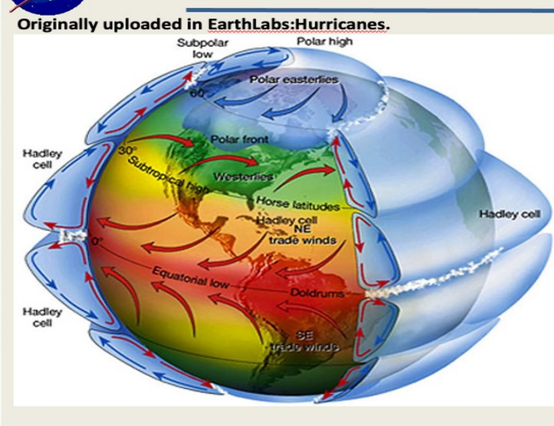




STUDYING TRENDS IN THE CIRCULATION

The Global Circulation and the Hadley Cell

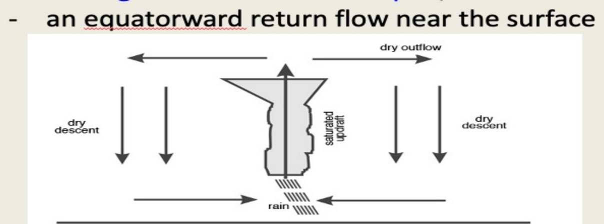
Originally uploaded in EarthLabs:Hurricanes.

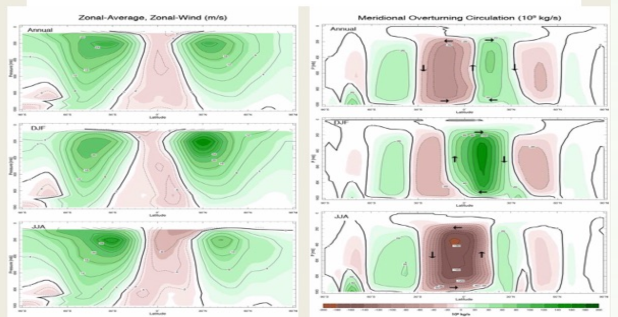


3D view of the global wind circulation due to unequal heating at the equator and the poles.

The Hadley cell depicts the equator-to-pole heat exchange in the tropical atmosphere.

Relatively simple overturning circulation, with
- rising motion near the equator
- poleward motion near the tropopause
- sinking motion in the subtropics, and
- an equatorward return flow near the surface





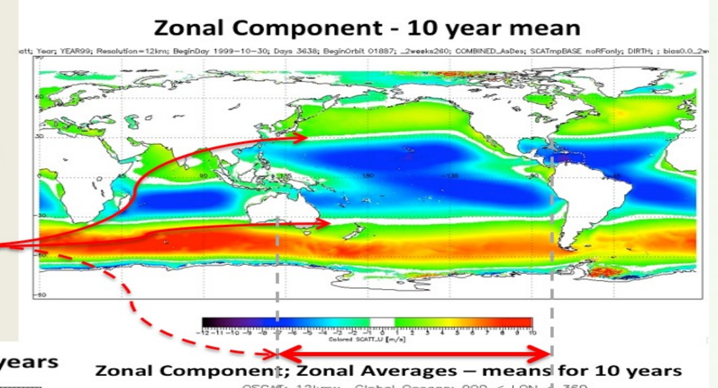
Are the tropics expanding as an atmospheric response to the observed tropical ocean warming trend? If so, this widening of the Hadley cell could have a substantial impact on water resources and the ecology of the sub-tropics.

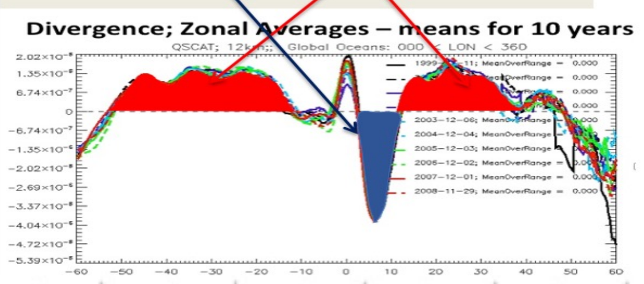
- Until now, the understanding of the mechanisms that govern the changing width of the tropics has been confined to models and proxies because of the **unavailability of systematic observations of the large-scale circulation.**

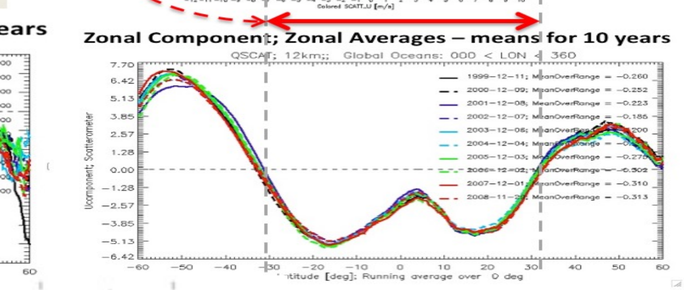
- Ocean surface vector winds, derived from scatterometer observations, provide for the first time an accurate depiction of the large-scale circulation and allow the study of the Hadley cell evolution through analysis of its surface branch.

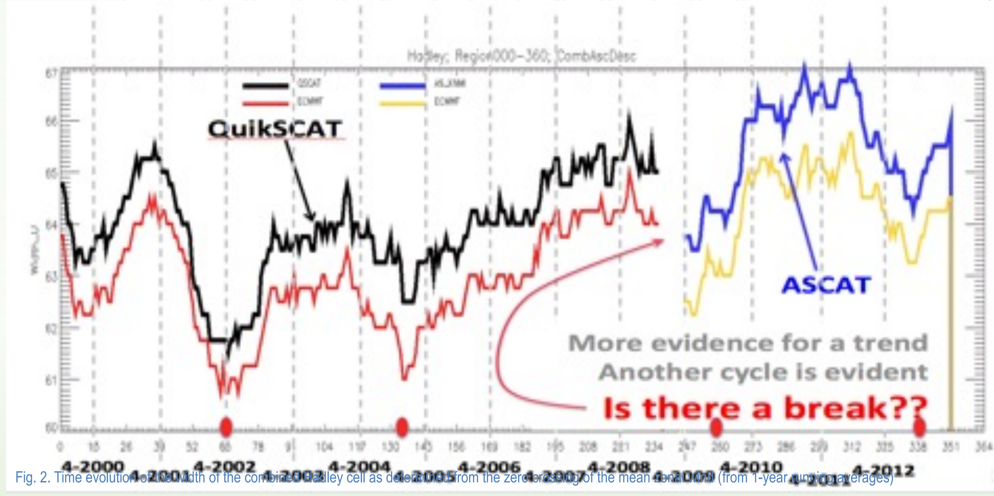
Approach

- Use the observations from QuikSCAT and ASCAT. **Compute statistics from time composites (1-year and 3-month running averages, offset by 2 weeks.)**
- Determine the **extent of the Hadley cell** as defined by the subtropical zero-crossing of the zonally-averaged zonal wind component (the separation between the midlatitude westerlies and the easterly winds in the tropics).
- Determine the **circulation strength** as defined by the area of divergence/ convergence.









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 - (Hristova-Veleva et al., 2015).

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?**