Strengths and weakness of using multi-instrument, multi-mission climate data records to understand how the Earth System is changing

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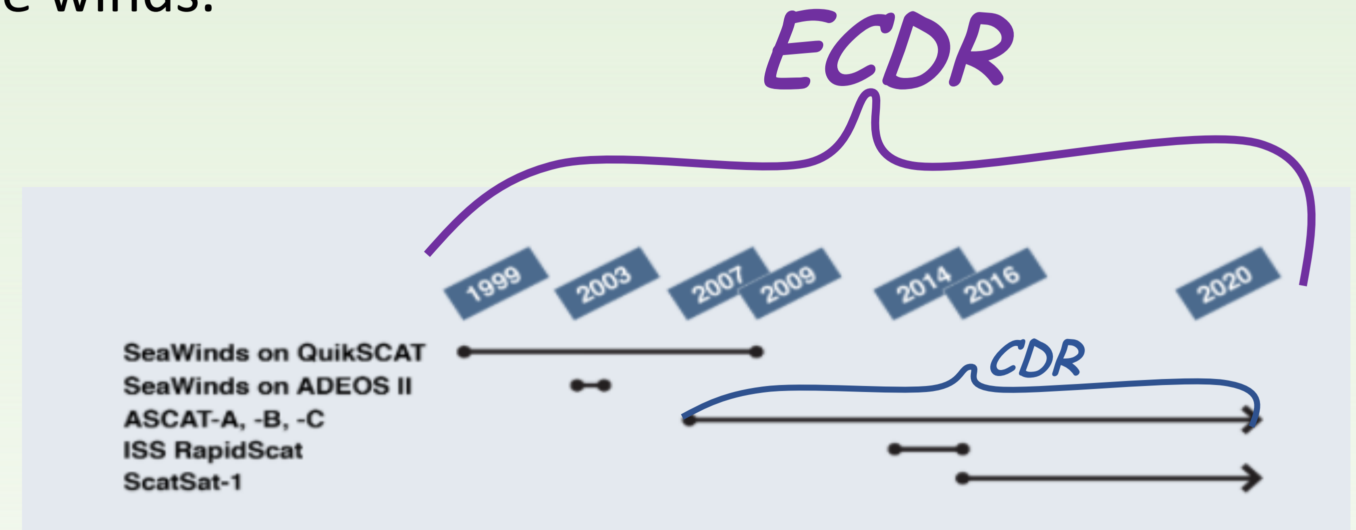
2021 IOVWST Meeting

- **Climate change and climate variability**
    - are among the most compelling scientific issues today, with huge societal impact
    - however, the magnitude and the rate of change are still uncertain.
- **Satellite observations provide a unique, global and longer-term perspective** allowing us
    - to address this paramount question and
    - to provide the information necessary for the development of intelligent and responsive strategies for our future.
- Here we will discuss **the strengths and the weakness/challenges that we face when studying the climate variability and trends by using Extended Climate Data Records (ECDR) developed by joining retrievals from multiple instruments and missions**.
    - How to develop an ECDR?
    - How to evaluate different ECDRs?
    - Benefits of having multiple ECDRs?
        - What can we learn?
        - Can we provide better uncertainty estimates?

How we observe the 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.
- **We call this the Extended Climate Data Record (ECDR)**



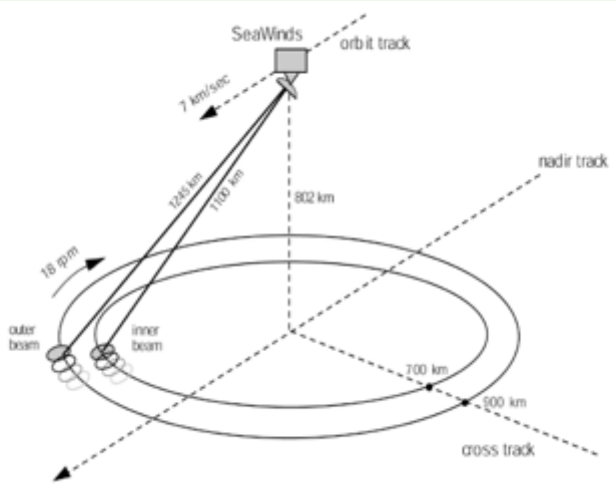
Launched between 1999 and 2016, these NASA, NOAA, ISRO and ESA scatterometers create a full, continuous picture of ocean surface winds that help improve weather forecasting.

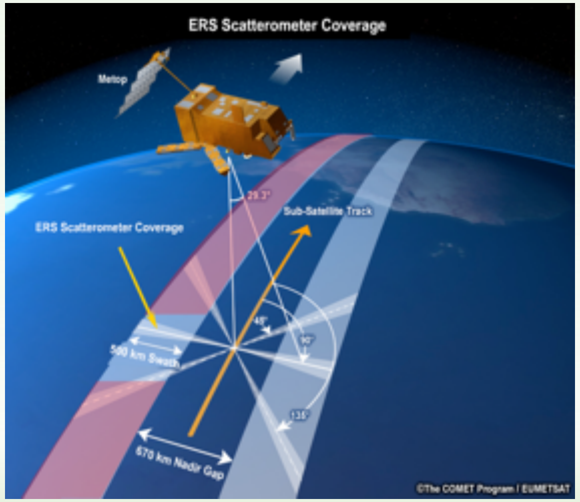
How we observe the wind vectors today

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

- **There is a significant diversity in the instrument geometry (incidence angle, azimuthal diversity), spatial resolution and the mission-specific Local-Time-of-Day (LTD) of the observations.**
- The scatterometer missions can be broadly classified in only two categories, defined by the:
  - channel-of-choice (the electromagnetic frequency)
  - the scanning strategy
- These are:
  - **the Ku-band, conically-scanning pencil** beam instruments (NASA and the Indian Space Research Organization - ISRO);
  - **the C-band, push-broom instruments -** EUMETSAT.
  - The pencil-beam approach provides a much wider swath than the push-broom one. However, the Ku-band that is used traditionally with this geometry has stronger sensitivity to rain (a negative impact)
- **The two different measurement frequencies produce measurements that have 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	Instrument Resolution	Retrieval Resolution	Incidence angles [°]	Scan Characteristics	Frequency [GHz]
QuikSCAT	25 x 7 km	25 & 12.5 km	46 & 54	Conical scan – One wide swath	Ku band (13.4)
SeaWinds	25 x 7 km	25 & 12.5 km	46 & 54	Conical scan - One wide swath	Ku band (13.4)
ASCAT	20 x 10 km	25 & 12.5 km	25 to 65	Push broom - Two narrower swaths	C band (5.25)
OSCAT	30 x 7 km	50 & 25 km	49 & 58	Conical scan - One wide swath	Ku band (13.5)
RapidScat	25 x 12km	12.5km	Variable	Conical scan – One swath (narrower)	Ku band (13.4)
ScatSat	30 x 7 km	50 & 25 km	49 & 58	Conical scan - One wide swath	Ku band (13.4)





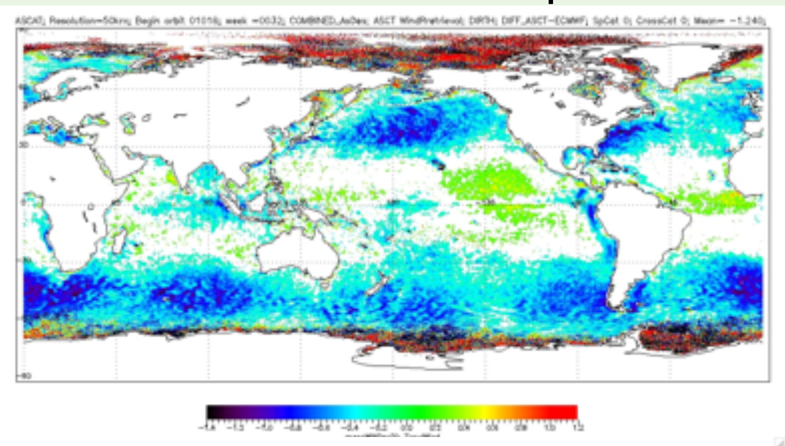
Schematic of the observation geometry for the two different observing systems: the rotating pencil beam of the Ku-band scatterometers (left) and the push-broom fan beam sampling by the C-band scatterometers (right)

Are the existing products consistent?

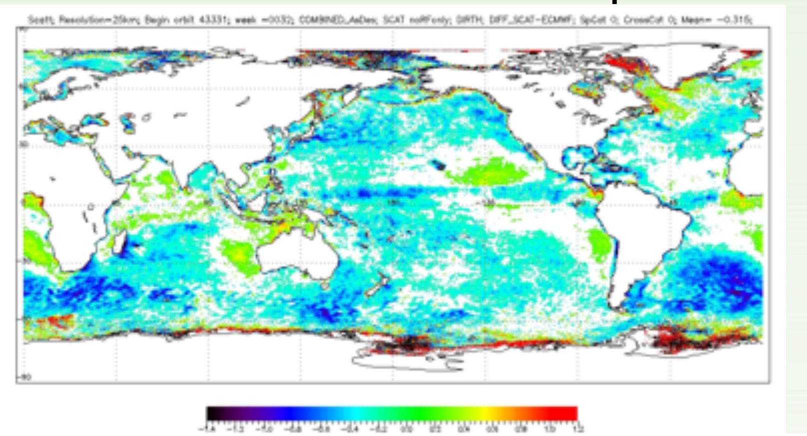
- Achieving consistency between the wind estimates from the different scatterometers has been a long-standing goal of the **International Ocean Vector Wind Science Team (IOVWST)**.

- Significant effort has gone into instrument calibration, algorithm validation and cross-evaluation. **Under most rain-free conditions the differences between retrievals from different instruments are small**.
- **Yet, these small differences have a systematic impact on power density spectra for vorticity and hence they are important in the context of derivative products.**
- **These discrepancies have geographical patterns that suggest differences in the estimated large-scale atmospheric circulation and in the estimated forcing of the ocean.**

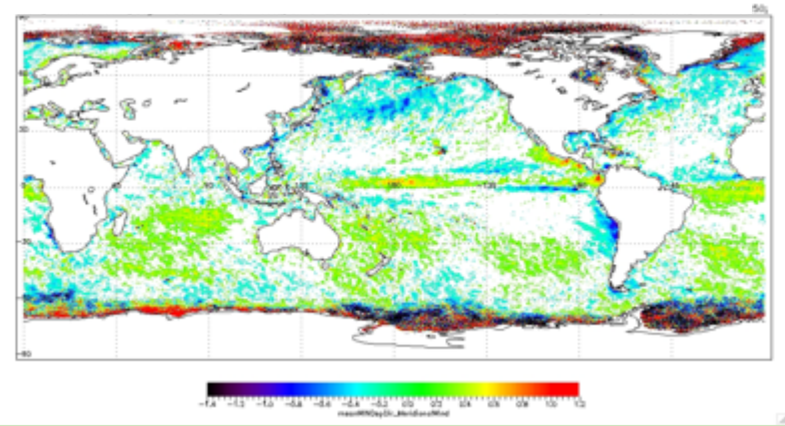
ASCAT-ECMWF – Zonal Wind Component



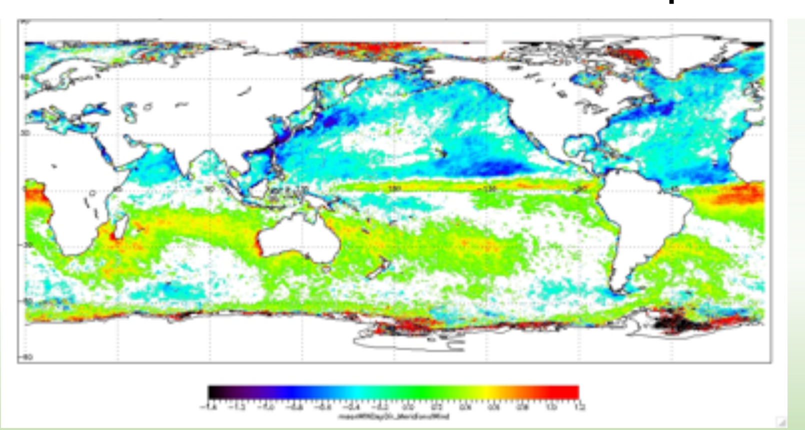
QuikSCAT-ECMWF – Zonal Wind Component



ASCAT-ECMWF – Meridional Wind Component

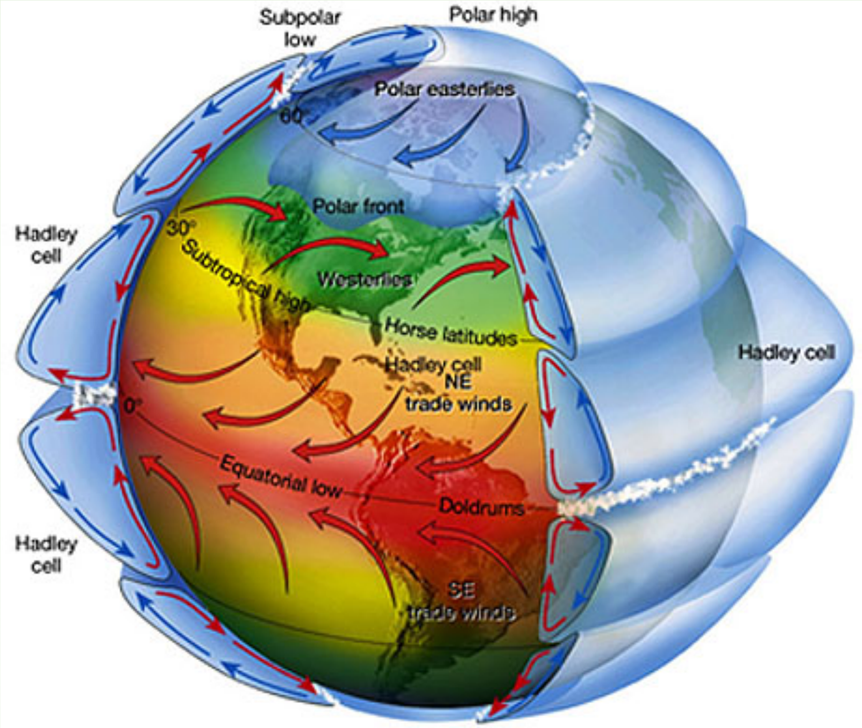


QuikSCAT-ECMWF – Meridional Wind Component



Does it matter if the scatterometer retrievals are consistent?

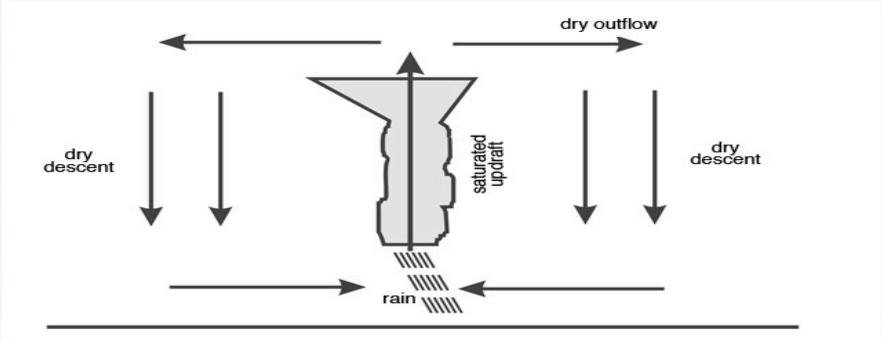
The Global Circulation and the Hadley cell

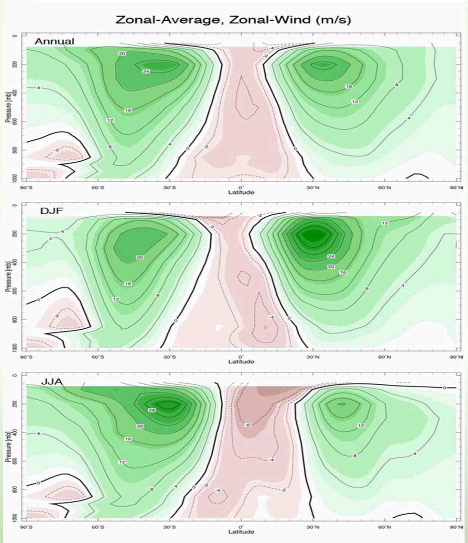


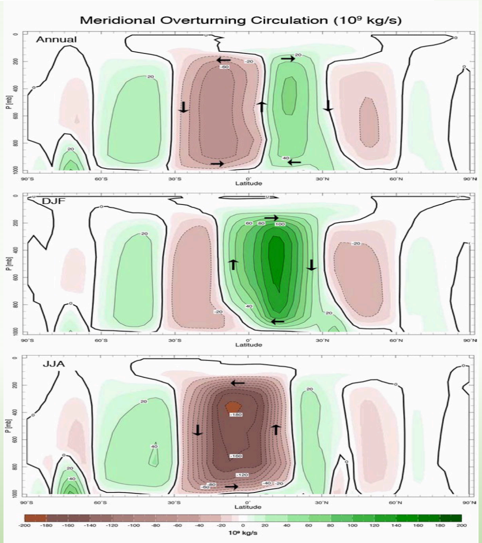
3D view of the global surface wind circulation due to unequal heating at the equator and the poles.

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







- 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.

Does it matter if the scatterometer retrievals are consistent?

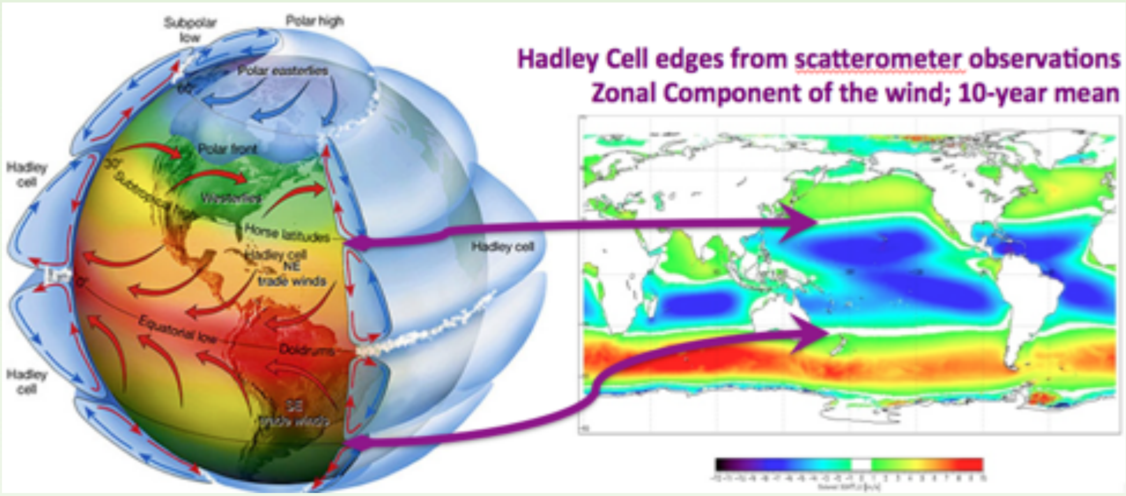
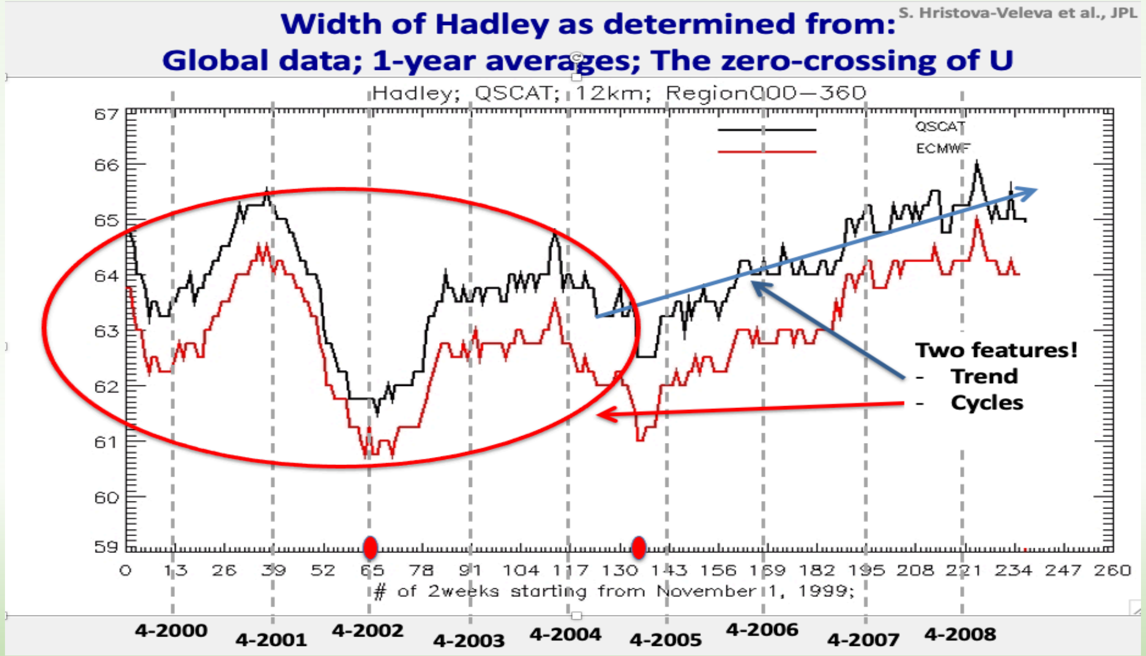


Fig. 1. Schematic of the large-scale circulation (left panel) and the zonal component of the surface wind as determined from QuikSCAT (right panel).

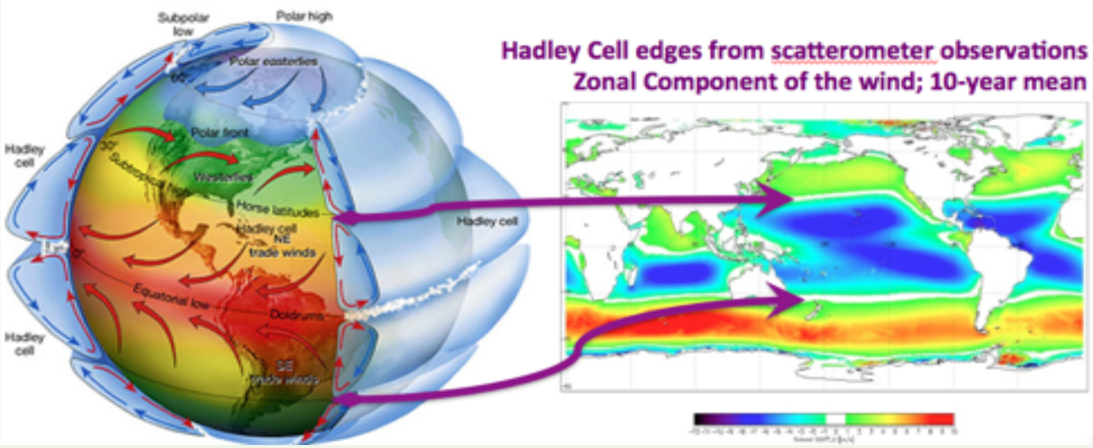


- Ocean surface vector winds, derived from scatterometer observations, provide for the first time an accurate depiction of the large-scale circulation and allow the study of the Hadley cell evolution through analysis of its surface branch.
- In a 2015 study we determine the extent of the Hadley cell 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*: Hadley cell trends and variability as determined from scatterometer observations: How Rapidscat will help establishing reliable long-term record," 2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Milan, Italy, 2015, pp. 1211-1214, doi:10.1109/IGARSS.2015.7325990*

- **We found:**
    - 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;

Does it matter if the scatterometer retrievals are consistent?



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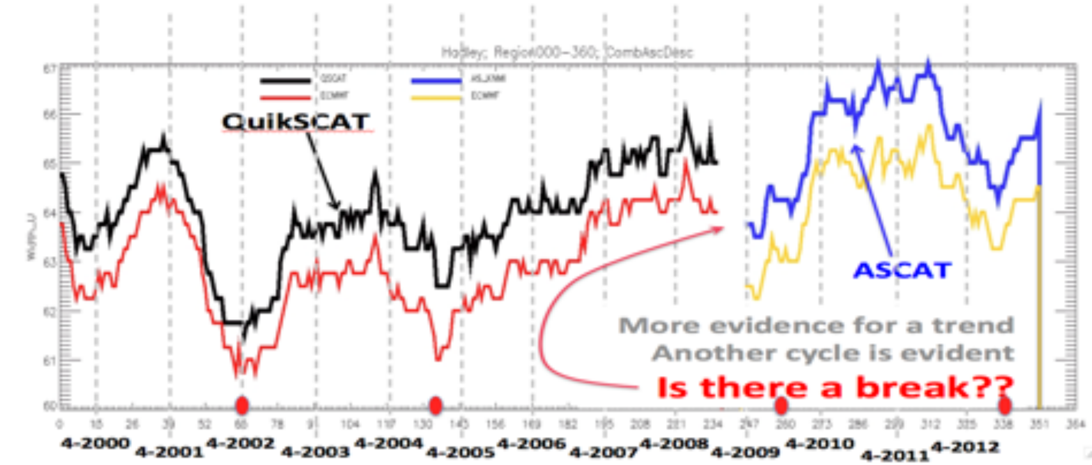

Fig. 2. Time evolution of the width of the combined Hadley cell as determined from the zero crossing of the mean zonal wind (from 1-year running averages)

- 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). We found:
  - 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;
- 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?**

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Sources of uncertainty in the ECDRs

- **There are three main sources that contribute to the uncertainty of the global wind estimates.**
  - **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**;
    - **instrument design and geometry** (push-broom vs pencil beam, variable incidence angles of the observations and variable azimuth diversity);
  - **Retrieval algorithms and assumptions**
    - **inconsistencies remain in the different components of the different retrieval schemes**.
  - **Diurnal variability of the winds**
    - Previous research clearly indicated that **there is diurnal variability of the winds, the diurnal signal having significant geographical variability** (e.g. Gille et al., 2005; Turk et al, 2021).
    - Even today, **we 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);**

What can we do?

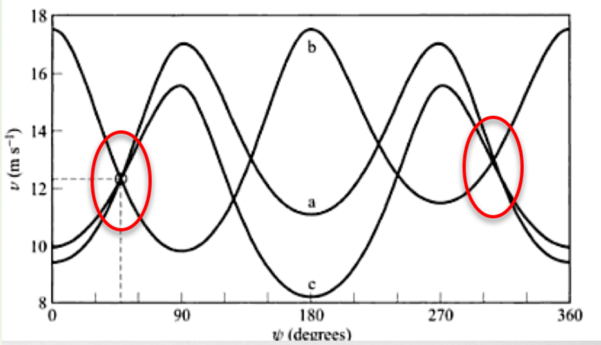
1. **Develop consistent ECDRs** – having several would be more beneficial
   - Indeed this what has been happening recently: **KNMI, RSS, JPL**
2. **Evaluate each of the ECDRs**
   - Against independent measurements and models
   - Using self consistency
3. **Cross-compare the ECDRs to understand the differences**.
   - Will provide a **deeper understanding** of the impact of these retrievals on the atmospheric and ocean dynamics and processes
   - This will provide **another estimate of uncertainty**

1. Develop a consistent ECDR – Approach

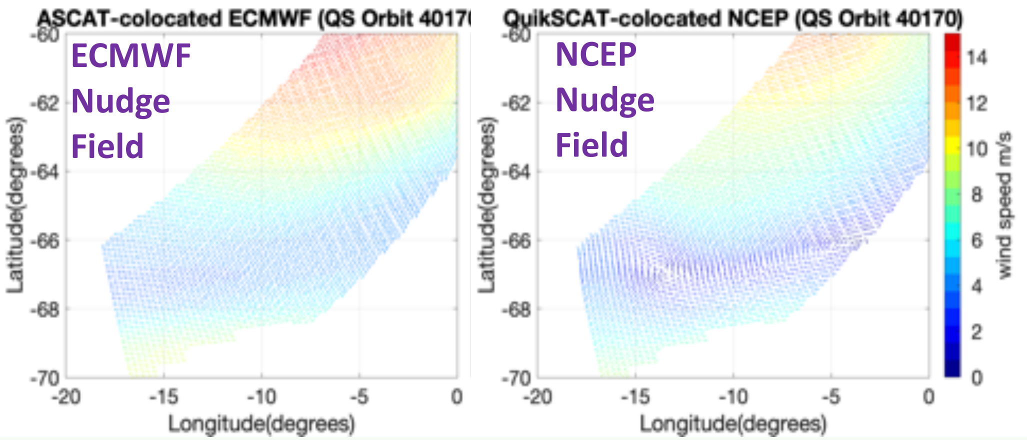
a. Addressing the uncertainty coming from Retrieval algorithms and assumptions

- **There are two main factors** for inconsistencies
  1. **Differences in the retrieval algorithms, their assumptions and the use of ancillary data;**
     - The wind vector is estimated by retrieval algorithms that invert the GMF, given several σ0 measurements at different azimuth angles, typically obtaining a few possible solutions at each observation point (ambiguities).
     - Different producers make use of different techniques for selecting solutions from the ambiguities. A background wind and its spatial error estimate (from a global NWP model) is generally used to produce a unique and self-consistent wind vector field. In this process, the associated spatial filtering can be performed in a number of different ways (e.g., median-filter versus 2DVAR).
  - **Addressing this source of difference by using the same retrieval system**, with the same assumptions and ancillary data.

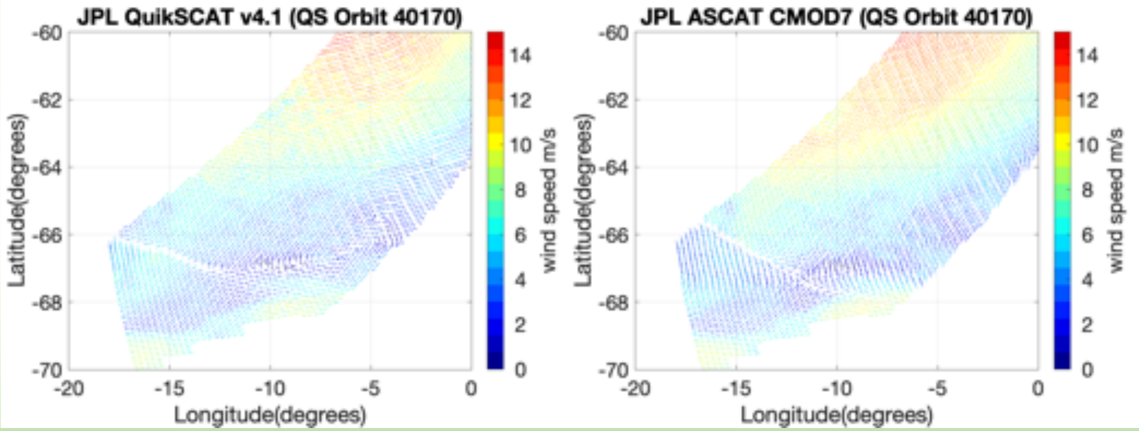
Ambiguities



Determination of wind velocity over an ocean surface using three scatterometer measurements: a) looking north; b) looking east; c) looking south. In this case, the two likely solutions are where the GMFs retrievals from all three observations agree - ~48^{O} and ~312^{O} .



Courtesy: Bryan Stiles



1. Develop a consistent ECDR – Approach

a. Addressing the uncertainty coming from Retrieval algorithms and assumptions *(cont.)*

IOWVST 2021 -Stiles et al.; Fore et al.;

- **There are** two main factors for inconsistencies
    2. **differences in the frequency-dependent and incidence angle dependent Geophysical Model Function (GMF)**.
- **Addressing the second source of difference by modifying one of the GMFs so that the retrieved winds are "harmonized".**
    - One could assume that either the Ku-band or the C-band GMF are the correct ones.
    - Hence, to achieve our goal we need to modify the other GMF
        - Using the same retrieval system
        - Comparing collocated retrievals
        - Modifying the second GMF to achieve the "harmonization"

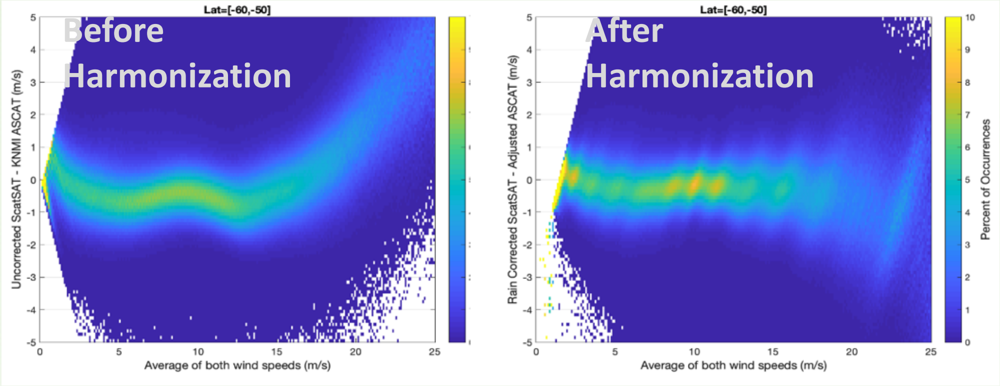
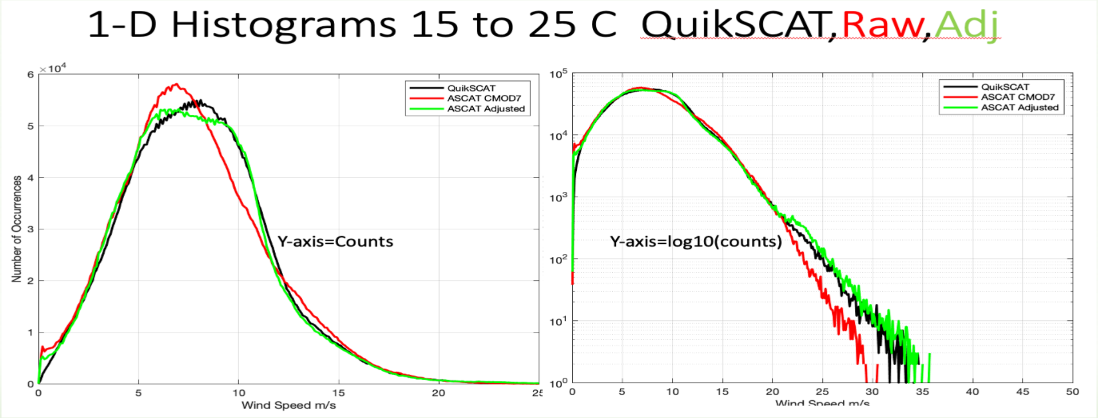


Fig. 1 ***ScatSat-ASCAT*** *biases in Southern Ocean (50 to 60 S). The average of both wind speeds is shown on the x-axis and the difference of these same two wind speeds is plotted on the y-axis.*

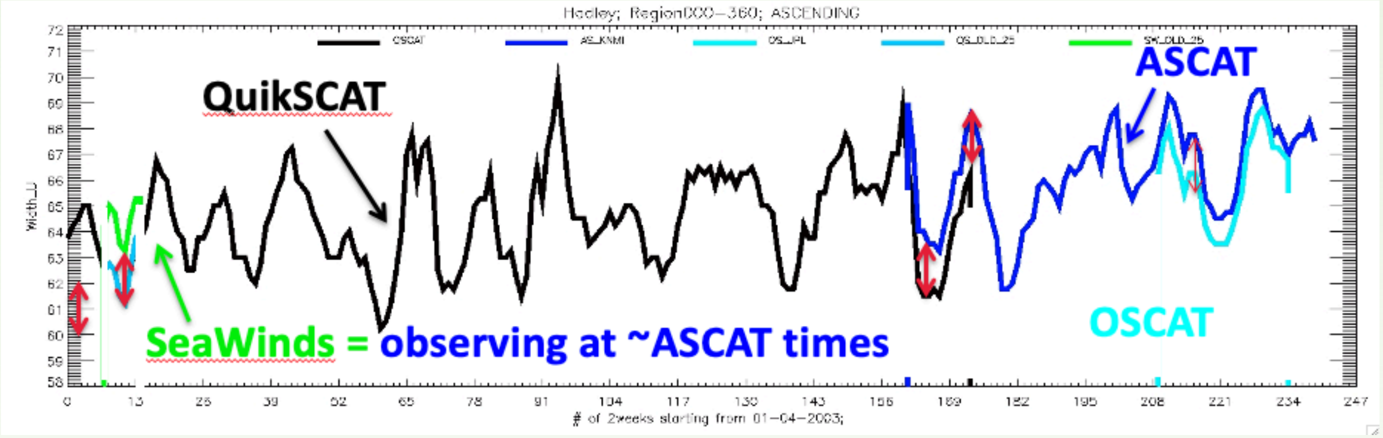


Univariate (single parameter) Probability Density function (PDF) of the retrieved speeds. Left panel show the PDF on a linear scale while the right panel shows the same on the log scale.

1. Develop a consistent ECDR – Approach

b. Addressing the uncertainty coming from the diurnal variability; Using Tandem missions

- Previous research clearly indicated that **there is diurnal variability of the winds, the diurnal signal having significant geographical variability** (e.g. Gille et al., 2005; Turk et al, 2021).
- largely facilitated by the 7-month tandem QuikSCAT/SeaWinds missions in 2003. **The short record did not allow for in-depth understanding of the diurnal signal**.

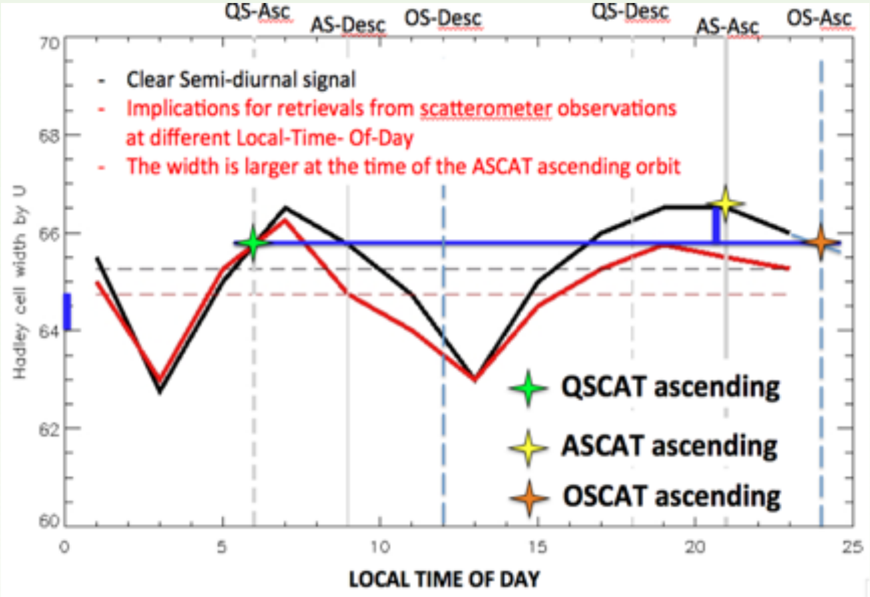


- The launch of the RapidScat mission in 2014 provided, for the first time a much closer look into the diurnal signal as its non-sun-synchronous orbit allowed sampling the diurnal variability, using observations from a single instrument. **This mission also did not operate long enough to allow de-convolving of the diurnal from the seasonal variability.**
- Thus, even today, **we 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);**

NASA's ISS-RapidScat was launched on September 21st 2014. The ISS (International Space Station) orbit provided unique opportunity to help understand and untangle the diurnal signal.

Hristova-Veleva et al., 2015: "Hadley cell trends and variability as determined from scatterometer observations: How Rapidscat will help establishing reliable long-term record," *2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, Milan, Italy, 2015, pp. 1211-1214, doi:10.1109/IGARSS.2015.7325990.

Hadley Cell Width from RapidScat

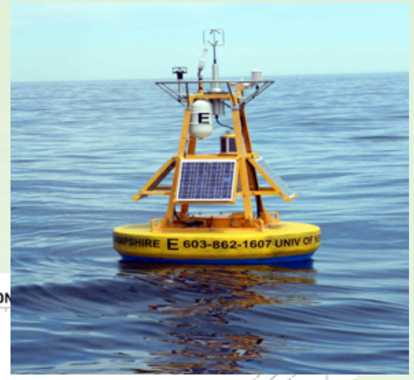


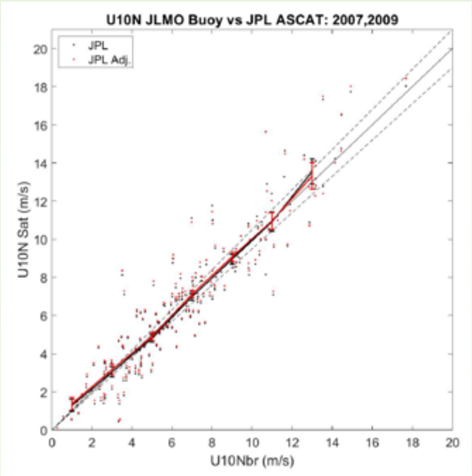
Our analyses of the RapidScat observations showed the presence of a clear semidiurnal signal in the width of the Hadley cell.

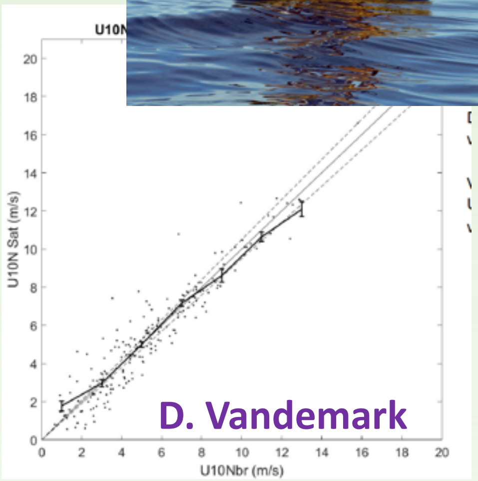
This helps better explain previously found discrepancies.

What can we do?

1. Develop consistent ECDRs – having several is better
2. **Evaluate each of the ECDRs**
   - Against independent measurements and models
   - Using self consistency

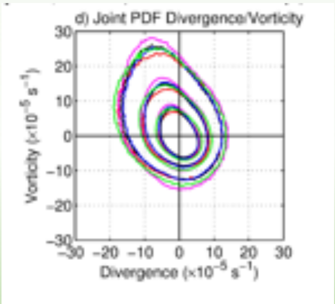






D. Vandemark

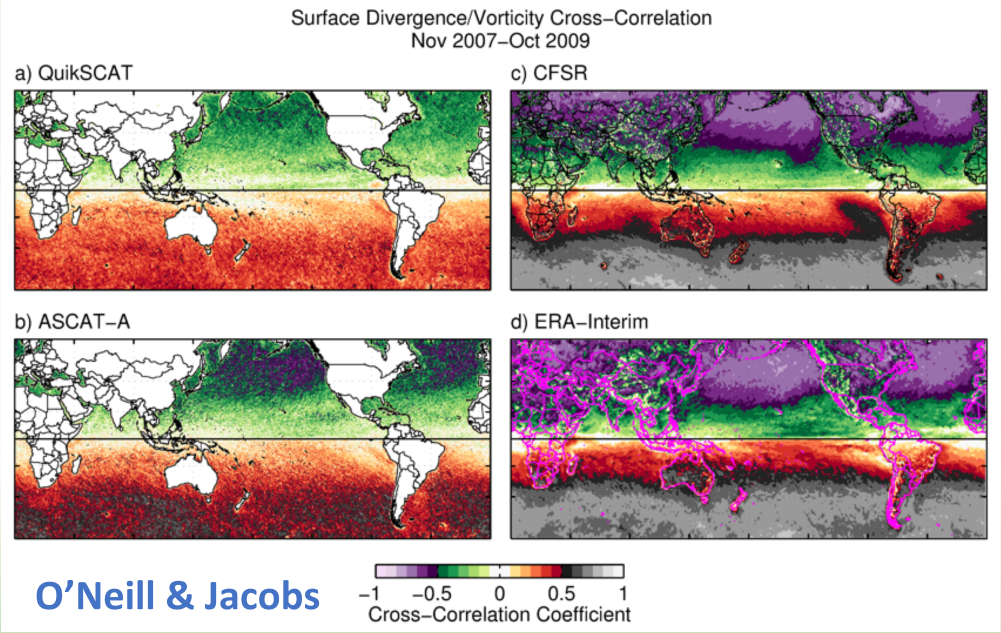
- Convergence and cyclonic vorticity extremes are fairly well correlated
- Fair correlations for weaker div/curl cases, which comprise the majority of observations
- *Main point: surface divergence and vorticity are correlated*



Scatterometers (left) and reanalyses (right) show a **strong and robust correlation between surface wind divergence and vorticity** away from the tropics that has not been reported previously.

The degree of correlation differs strongly between observations and models.

Investigation into the nature of the correlation and the source of these differences are currently underway as part of the MEaSUREs project (**O'Neill and Jacobs).**

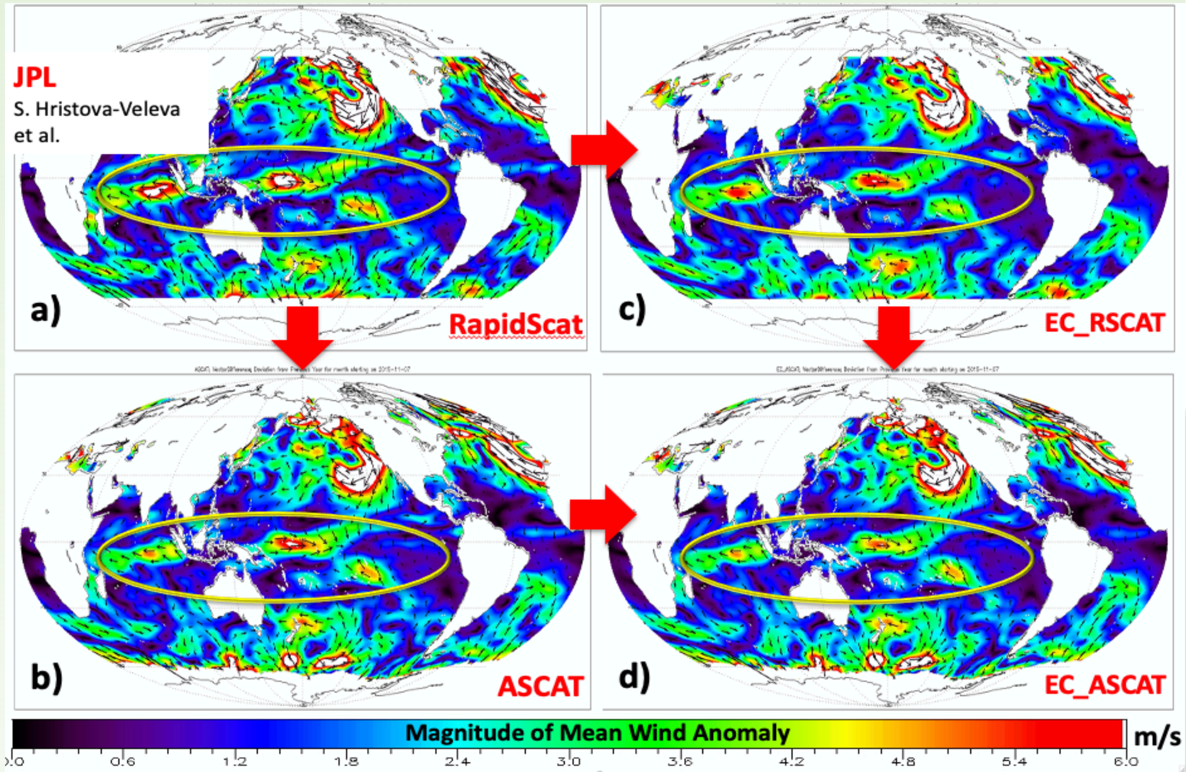


O'Neill & Jacobs

What can we do?

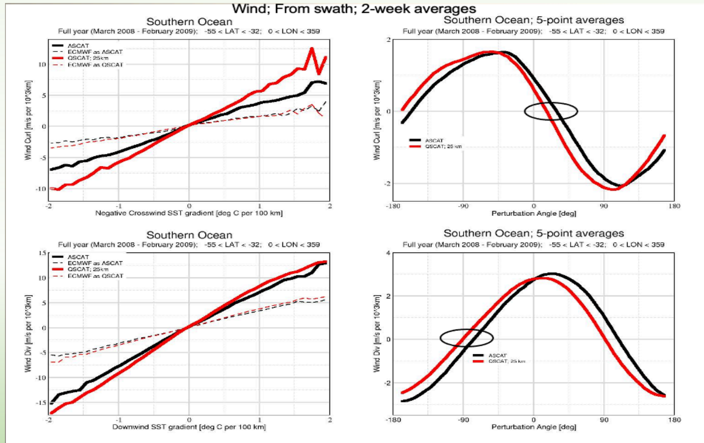
1. Develop consistent ECDRs – having several is better
2. Evaluate each of the ECDRs
3. **Cross-compare the ECDRs to understand the differences <u>in how they depict various phenomena</u>**
   - **Will provide a deeper understanding of the impact of these retrievals on the atmospheric and ocean dynamics and processes**
     - the extent and the intensity of the **tropical convergence zone**, its diurnal variability and relationship to the observed diurnal variability in precipitation in the tropical regions;
     - the **track and intensity of tropical and extratropical cyclones**;
     - the **relationship between the near-surface winds and such phenomena as Madden-Julian Oscillation (MJO) and the El-Nino-Southern Oscillation (ENSO)**;
     - The **ocean-atmosphere coupling** in regions of strong SST gradients
   - **This will provide another estimate of uncertainty**
     - **As a function of other geophysical variables**
     - **With geographical and temporal variability**

Depiction of a phenomena: The 2015-16 El Niño
Example here: comparing depictions from RapidScat, ASCAT and ECMWF
Proposed future comparisons: How ASCAT retrievals from different ECDRs would depict the same event? Would the different ECDRs agree?



Depiction of a phenomena: the ocean-atmosphere coupling in regions of strong SST gradients
Example here: comparing ASCAT and QuikSCAT depictions

Proposed future comparisons: How ASCAT retrievals from different ECDRs would depict the coupling? Would the different ECDRs agree?



What will the ECDRs do for us?

- Only after we achieve all the steps we would be able to study the trends and variability in the climate system to support a wide-range of the studies
  - **establishing the variability and trends of the ocean surface winds on a variety of spatial and temporal scales** (diurnal, intraseasonal and decadal);
  - **understanding the processes** at the air-sea interface that drive
    - **the global ocean circulation;**
    - **the wind-related components of the water cycle: i) air-sea fluxes; ii) surface moisture convergence; iii) their relationship with the observed convection**
    - **The global atmospheric circulation as depicted by its surface branch**
  - **evaluating and improving models**.