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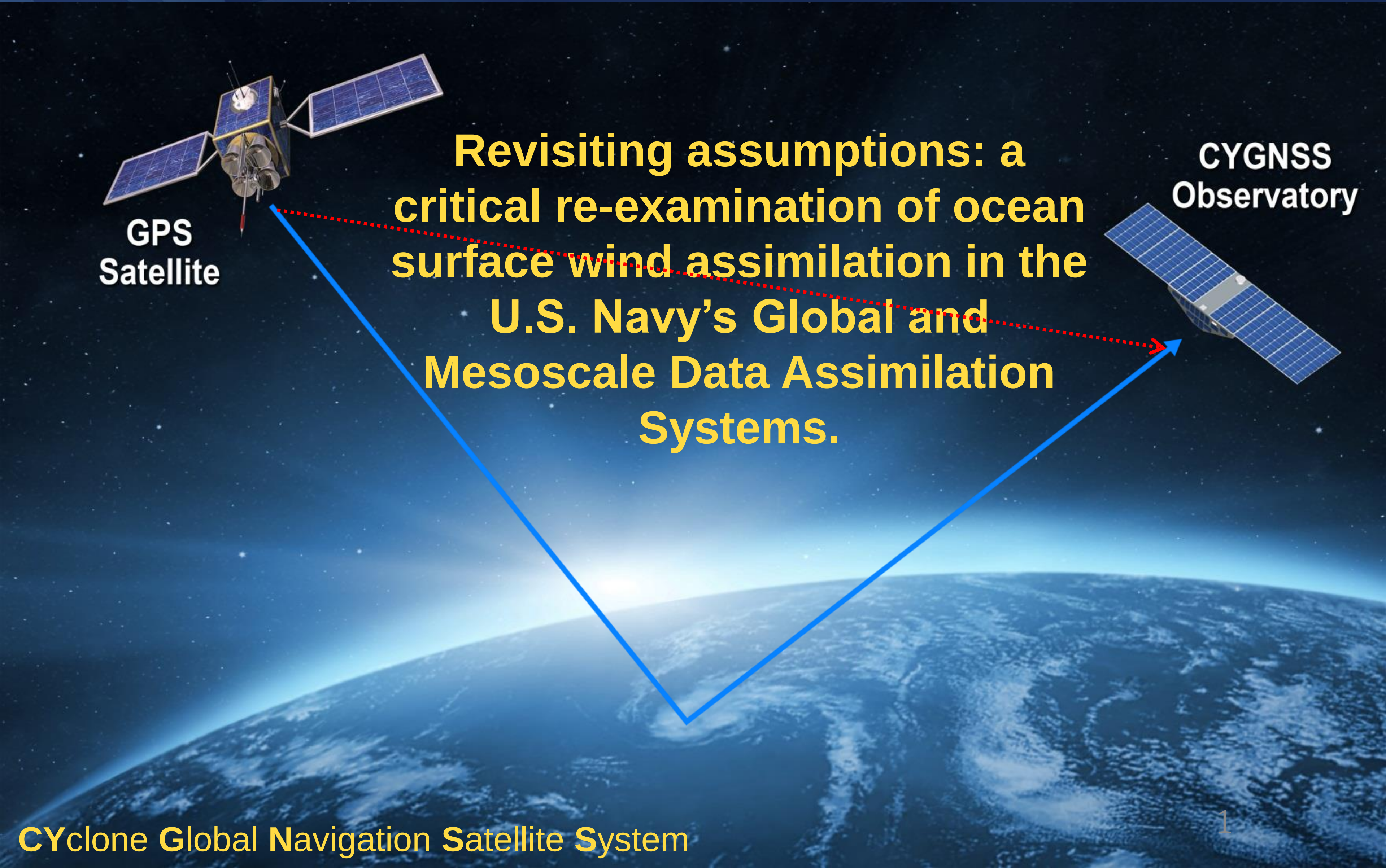
Revisiting assumptions: a critical re-examination of ocean surface wind assimilation in the U.S. Navy's Global and Mesoscale Data Assimilation Systems.



CYclone **G**lobal **N**avigation **S**atellite **S**ystem

Outline

- Motivation – NRL funded project to examine the potential impact of NASA CYGNSS wind speed observations
- Comparison of the impact of ocean surface wind speed and wind vector assimilation
- Wind speed assimilation considerations
- The CYGNSS mission and observables
- CYGNSS assimilation considerations
- Future research
- Concluding remarks

Motivation

- The US Navy has been assimilating ocean surface wind speed observations operationally in the Navy's global forecast system with beneficially impact since 1990 (Phoebus and Goerss, 1991).
  - Historically, the **F**orecast **S**ensitivity **O**bservation **I**mpact (FSOI) statistics for NAVGEM indicate that, on average, SSMIS wind speed observations had ~ 1/2 to 1/3 of the impact of ASCAT and WindSat wind vectors per observation. This ratio has progressively decreased over time.
  - We assumed that this was primarily due to Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (/Sounder) (SSMI/S) sensor degradation with age, and increasing calibration issues.
- Closer examination indicates that wind speed assimilation as currently implemented in the global NAVGEM Hybrid 4D-Var (NAVDAS-AR) is clearly sub-optimal.
- We re-examine our current methods for assimilating ocean surface wind speed and wind vector retrievals.

*NRL Atmospheric Variational Data Assimilation System – Accelerated Representer
*Navy Global Environmental Model

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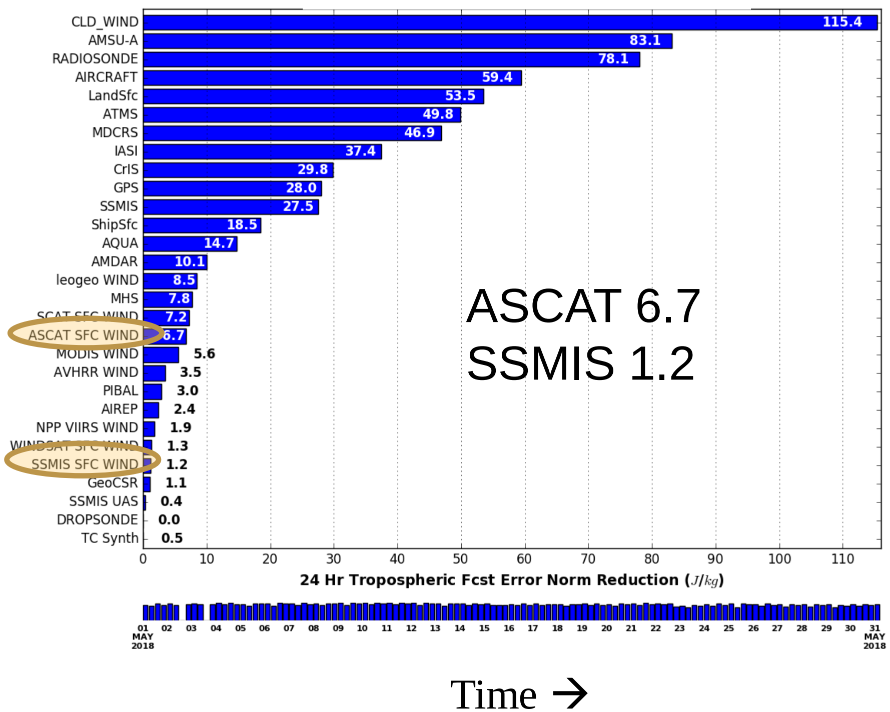
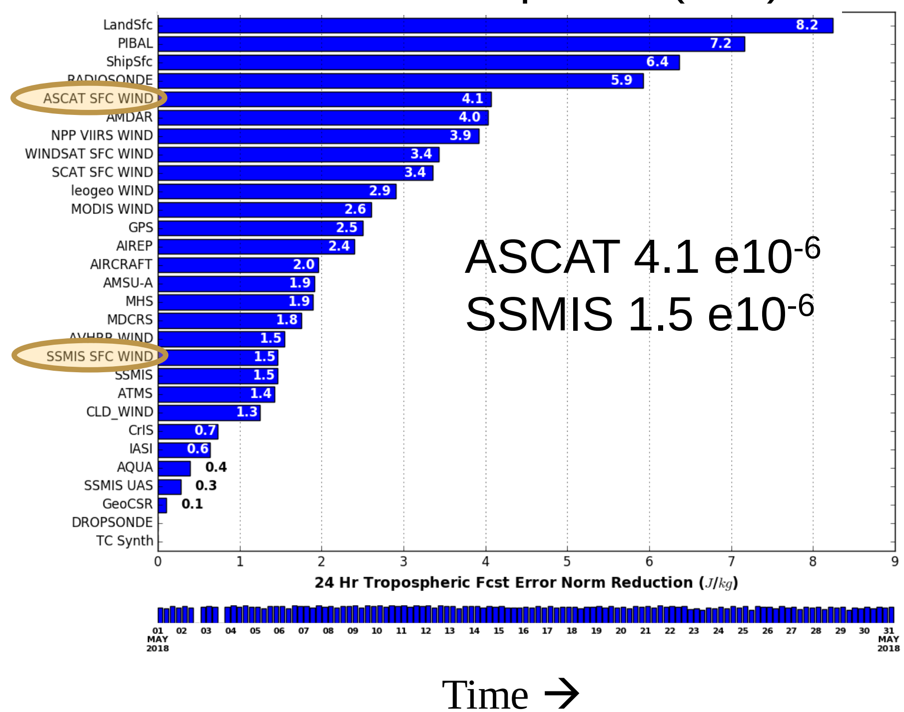
NAVGEM Hybrid 4D-Var FSOI for May 2018

NAVGEM FSOI



NAVGEM FSOI per ob (10^{-6})



The reduction of the 24-hr moist error norm (J/kg) or FSOI, according to observing platform (left) and per observation (right; scaled by 10^{-6}) for May 2018. Per observation, the impact of a single SSMIS wind speed is ~ 1/3 the impact of a single wind vector component (super-ob). The SCAT SFC wind is ScatSat-1 gap-filler for OceanSat-2 OSCAT. This is actually a “better” month for SSMIS winds.

Ocean Surface Wind Speed vs. Wind Vector Assimilation

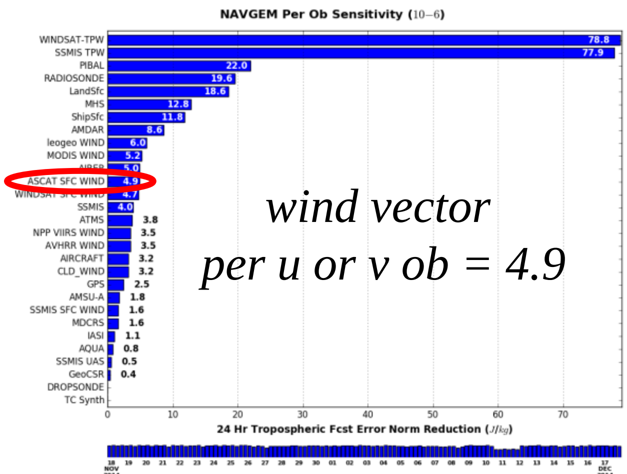
- We might expect a 2:1 ratio for FSOI, as wind vectors provide two observations, whereas wind speed provides only one.
- This comparison does not take into account differences due sensor quality and resolution (and averaging), ability to retrieve winds in precipitating regions, and effective data coverage relative to other observing platforms.
- Ocean surface wind vectors (OSWV) are provided by scatterometers (e.g., ASCAT, ScatSat-1) and polarimetric microwave imagers (WindSat), while retrievals of ocean surface wind speed (OSWS) are provided by microwave imagers (e.g. SSMIS) or GNSS-R (CYGNSS).
- To examine these questions in more detail, we modified our global NAVGEM system to assimilate ASCAT wind vectors as wind speed observations.

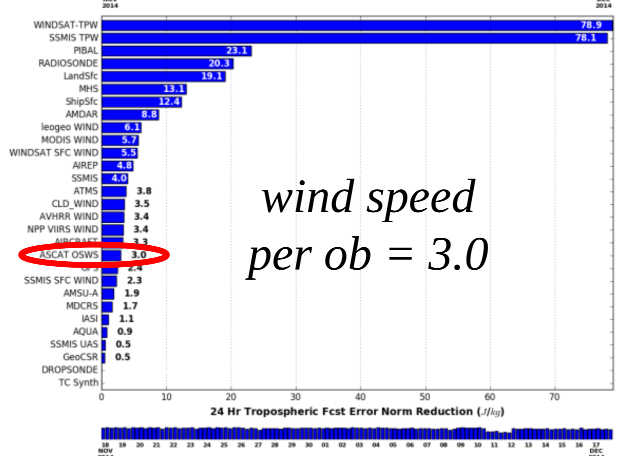
NWP Experiment Design

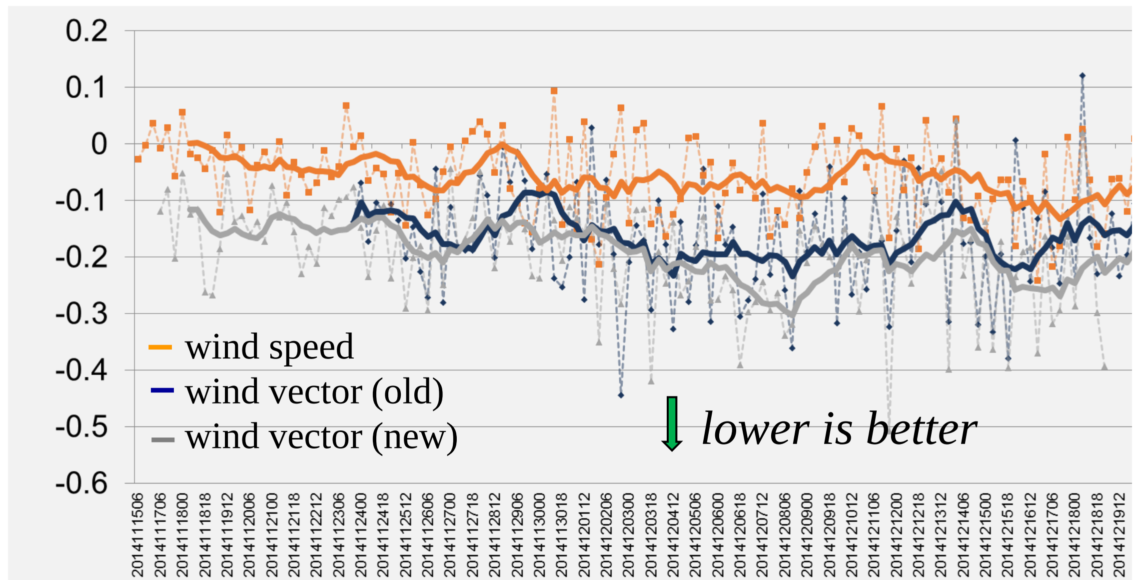
- **Data Preprocessing and QC**
  - The ASCAT wind vectors are processed through the same data selection and quality control algorithms, and then only the wind speed is retained.
  - The satellite wind processing software generates superobs for the ASCAT wind speeds following the procedure used for SSMIS.
- **Forecast Model: NAVGEM* v1.4.3**
  - T425L60, model top 0.04 hPa (around 70 km), horizontal resolution ~ 31 km
  - Semi-Lagrangian/Semi-Implicit dynamical core, forecast model, explicit clouds
- **Data Assimilation: 4DVar (NAVDAS-AR*)**
  - Hybrid 4D-Var using accelerated representer technique (25% ensemble,75% static)
  - T425 outer loop, T119 (~ 111 km) inner loop resolution
  - Outer loop and weak-constraint options available but not used operationally
  - Approximately 4.5 million obs/6 hrs (late data cut)
  - Variational radiance bias correction; began with spun-up bias coefficients
- **NH fall/early winter case: 01 October - 25 December, 2014**
  - 5-day forecasts at 00, 12 UTC
  - Observation impact computed every 6 hrs
  - Includes active EPAC, CPAC and WPAC season (Phanfone, Vongfong, Nuri, Hagupit)

ASCAT wind vector vs. wind speed

Forecast Sensitivity Observation Impact - FSOI







FSOI (J/kg) vs. time
15 Nov 2014 – 19 Dec 2014

On a per observation basis, ASCAT wind vector components reduce the forecast error more than wind speed retrievals. *“New” corrects for missing forward operator adjustment to 10m.*

Considerations: Wind Speed Assimilation

Following Daley and Barker (2001 NAVDAS Source Book)

The forward wind speed observation operator is non-trivial and nonlinear.

$$w = H(u,v) = (u^2 + v^2)^{1/2} \quad , \qquad (5.7)$$

where w denotes wind speed, u and v are the wind components.

H(u,v) is linearized about the background wind vector interpolated to the observation location and time. The tangent linear operator **H** is given by

$$\mathbf{H} = [dH/du_b \;\; dH/dv_b\,] = [\, u_b/(u_b{}^2+v_b{}^2)^{1/2} \quad v_b/(u_b{}^2+v_b{}^2)^{1/2} \,]. \qquad (5.8)$$

For the simple case of a **single** wind speed observation in a 3DVar context,

$$\mathbf{v}^a = \mathbf{v}^b + \begin{pmatrix} \varepsilon_v^2 & 0 \\ 0 & \varepsilon_v^2 \end{pmatrix} \left(\frac{1}{\varepsilon_v^2 + \varepsilon_r^2} \right) \mathbf{H}^T \left[w_r - H(u^b, v^b) \right]$$

$$= \left(\varepsilon_v^2 + \varepsilon_r^2 \right)^{-1} \left[\varepsilon_r^2 + \varepsilon_v^2 w_r \left(u^{b2} + v^{b2} \right)^{-1/2} \right] \mathbf{v}_b, \qquad (5.11)$$

where ε_r^2 and ε_v^2 are the wind speed observation error, and the background wind vector errors respectively. w_r is the observed wind speed.

Non-linear derivation also ends up with (5.11)

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Considerations: Wind Speed Assimilation

- **Wind Speed Assimilation (following Daley and Barker, 2001 NAVDAS Source Book)**
  - For a single observation, the analyzed wind speed is a linear combination of the wind speed observation and background wind speed.

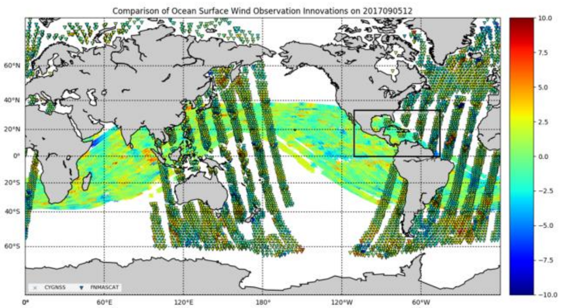
$$H(u_a,v_a) = (u_a^2 + v_a^2)^{1/2} = (\varepsilon_v^2 + \varepsilon_r^2)^{-1}(\varepsilon_r^2 (u_b^2+v_b^2)^{1/2} + w_r \varepsilon_v^2) \quad , \qquad (5.12)$$

  - The analyzed direction is given by $\tan^{-1}(u_a/v_a)$, and is equal to the background wind direction $\tan^{-1}(u_b/v_b)$.
  - In the absence of other observations, or nonlinear data assimilation (e.g. second outer loop), the assimilation process cannot adjust the background wind directions, only the wind speed.
  - Daley and Barker (2001) showed that assimilation of wind speed observations may be able to improve the background estimate of wind direction under certain conditions (analyzing observations together, background error is non-divergent and red). [*cf.* VAM, Hoffman et *al.* 2003]
  - Daley also showed that creating pseudo-obs (using background wind direction) gives no new wind direction information and can degraded the analysis.

Simple Hybrid 4DVar Examples

- Begin with spun up initial conditions for 12 UTC on 5 Sept. 2017, during Hurricane Irma’s intensification
- Spun-up initial conditions and VarBC coefficients
- Visualize increments for only ASCAT wind speed (OSWS) or wind vectors (OSWV)
- Plus one CYGNSS example…
- Observations limited to an area 11N to 22N; -63W to 53W

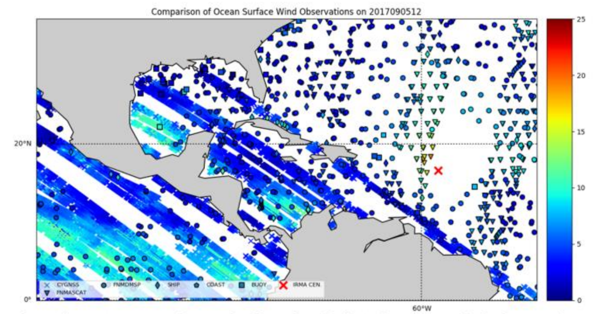
Hybrid 4DVar Increments



Global locations, types, and magnitudes of assimilated ASCAT and CYGNSS surface wind observations for 12 UTC September 5, 2017

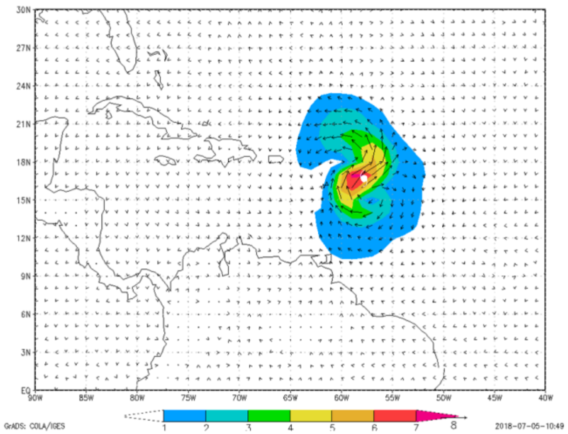
Hurricane Irma
2017090512

10m wind increments

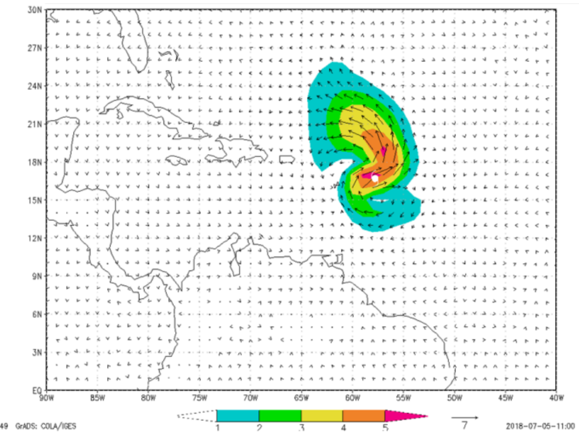


Locations, types, and magnitudes of assimilated surface wind observations for 12 UTC September 5, 2017

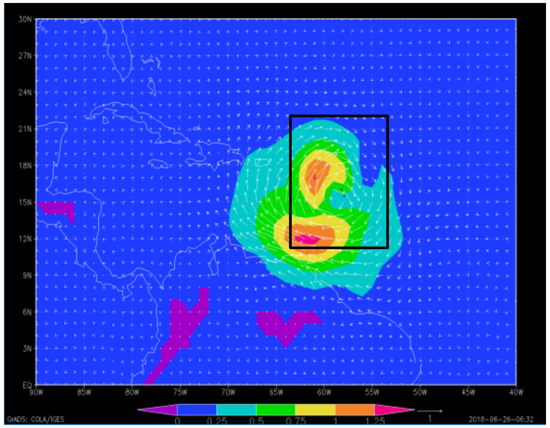
ASCAT Ocean Surface Wind Vector



ASCAT Ocean Surface Wind Speed



CYGNSS Ocean Surface Wind Speed



Hybrid 4DVar ocean wind increments at 12UTC at 950 hPa. Wind vector assimilation and wind speed assimilation both shift Irma to the northwest but with different structure. CYGNSS winds weaken Irma to the south reflecting the storm movement to the NW.

Single Observation
Irma's intensification period

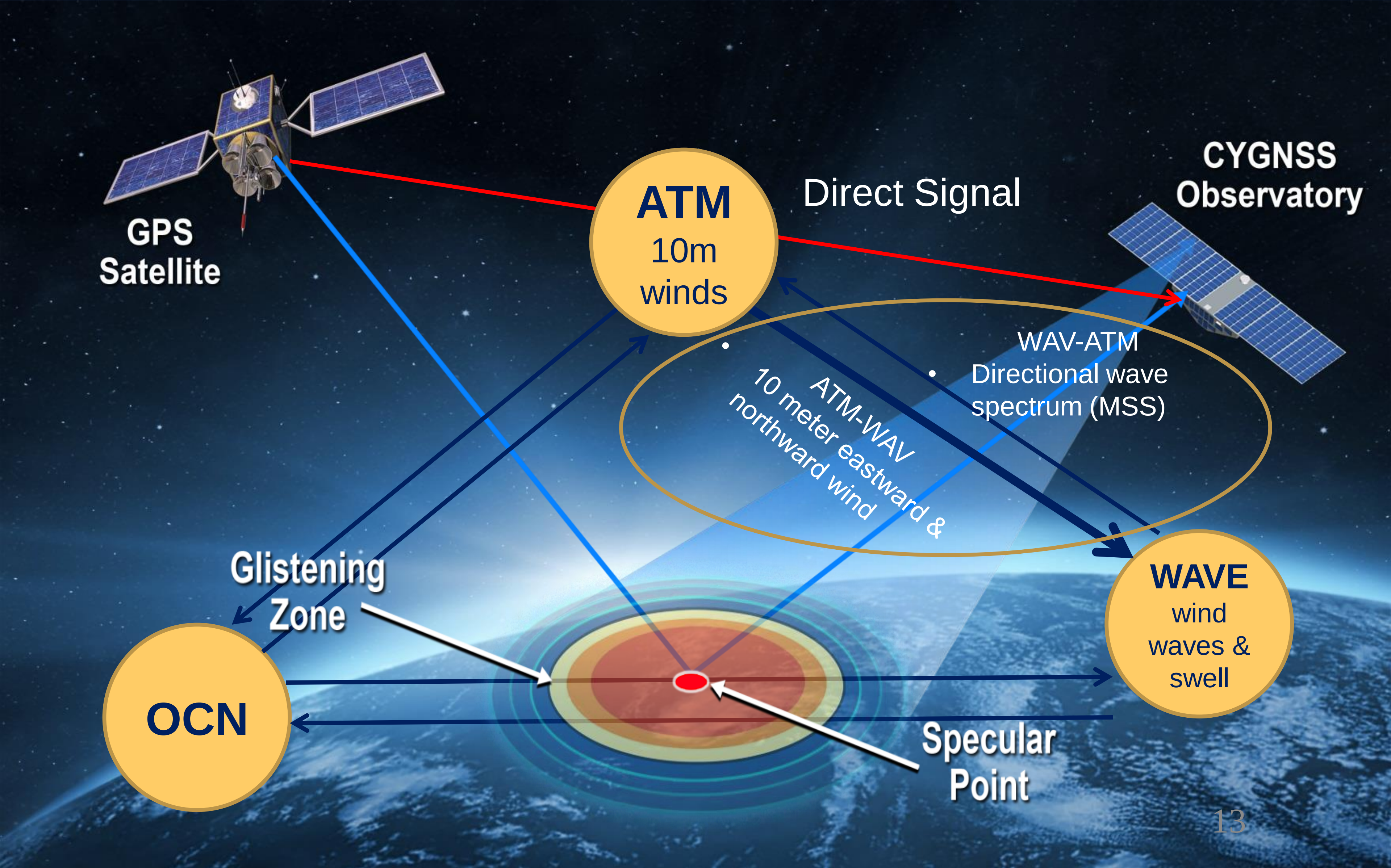
- 12 UTC @September 5th, 2017
- Single observation at 19.91N,60.17W, 13.3UTC

Ob	ws_b	u_b	v_b	Dir_b	innov	u_a	v_a	ws_a	Dir_a	
12.56	10.72	-9.81	-4.32	246.23	1.84	-11.50	-5.06	11.99	246.23	Hybrid 4DVar
						-11.03	-4.86	12.06	246.23	Analytic

Ob	ws_b	u_b	v_b	Dir_b	innov	u_a	v_a	ws_a	Dir_a	
-11.44	10.86	-9.89		245.63	-1.55	-10.95		12.02	245.72	Hybrid 4DVar
-5.20			-4.48		-0.72		-4.97			
12.56						-10.56	-4.88	11.63	245.21	Analytic

Hybrid 4DVar does not change the background wind direction for single wind speed observation assimilation

NASA CYGNSS
Cyclone Global Navigation Satellite System



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What is CYGNSS?

- First NASA Earth Venture satellite mission selected. Constellation of 8 small satellites (6U) in an equatorial orbit.
- Reflections of GNSS signals off the ocean surface. L-band (1.4 GHz) means that the signals are largely insensitive to clouds and precipitation. Theoretical range 2-70 ms^{-1}.
- Nominal 3 year mission with $150M cost cap that includes development, launch, science team funding and satellite/ground communications. Project led by Prof. Chris Ruff, U Michigan
- Cost of communications limits real time routine availability of data. More frequent downlinks are planned for hurricanes, and some of that data will meet late analysis data cuts.

Why is CYGNSS assimilation such a challenge?

- CYGNSS GNSS-R measurements are intrinsically linked to both the ocean surface wind speed and ocean wave state (local wind waves and non-local swell)
- Level 1b measurements are the Delay Doppler Map (DDM) of Bistatic Radar Cross Section (BRCS), the Delay Doppler Map Average (DDMA) of the Normalized Bistatic Radar Cross Section (NBRCS), and the Leading Edge Slope (LES) of the integrated delay
- Geophysical model function (end-to-end simulator) links level 1b DDM and LES to wind speed and mean square slope (MSS)
- The retrieval process from MSS to wind speed uses statistical relationships.
- Retrievals are affected by use of a prior, and underlying assumptions (analogous to atmospheric sounder radiance vs. retrieval assimilation)
- DDM and LES are more fundamentally related to MSS than wind speed

CYGNSS Assimilation
Wind speed or MSS; coupled or uncoupled?

- **Assimilate wind speed or MSS?**
  - Fundamental CYGNSS measurement is closer to MSS, a sea state measurement
  - Since ocean waves are primarily due to local forcing by atmospheric winds, we need to link MSS to ocean surface wind speed for consistency
- **Uncoupled MSS assimilation**
  - MSS assimilation would complement altimeter SWH assimilation to correct non-directional wave spectrum.
  - Prof. Jim Garrison and team at Purdue are developing an EKF forward model based on E2ES to compute DDMs and Jacobians to retrieve/assimilate MSS
- **Coupled atmosphere/wave assimilation**
  - Goal is to provide balanced initial conditions for coupled forecast models
  - Assimilate MSS in a coupled atmosphere/wave framework (strong or weak)

CYGNSS Assimilation
Wind speed or MSS; coupled or uncoupled?

- **Coupled assimilation (initial steps)**
  - Uncoupled atmosphere and wave model provide the prior
  - Add MSS control variable to atmospheric DA, or assimilate MSS in wave model
  - Explicitly determine cross covariances between wave model MSS and atmosphere U10 (ensemble or regression)
  - Increment is U10 or 10 m wind speed.
- **Weakly coupled assimilation**
  - Prior comes from a coupled atmosphere, ocean and wave model for assimilation in the individual components
  - Assimilate MSS with wave model DA
  - An additional outer loop with 4D DA will generate implicit covariances between fluids
- **Strongly coupled assimilation options**
  - Explicitly determine cross-fluid covariances from a coupled ensemble
  - Using 4DVar, apply TLM/ADJ of the ocean wave flux coupler

Next Steps

CYGNSS Assimilation

- Do multiple outer loops improve ocean surface wind speed assimilation?
- Use CYGNSS MSS for WW3 validation

Diversify wind assimilation approaches

- Implement and test assimilation of wind speed and wind direction
  - Useful for in situ and satellite AMVs (Huang et al., 2013; Gao et al., 2015)
- MISR atmospheric motion vectors
  - Cross track and along track components have very different observation errors and do not map directly into u,v components at high latitudes.
  - Assimilate cross/along track components (Mueller *et al.*, 2017)
- Aeolus winds Line of Sight winds
  - Single wind component will align primarily with u-wind component

Bigger Picture

- JEDI approach with Unified Forward Operators

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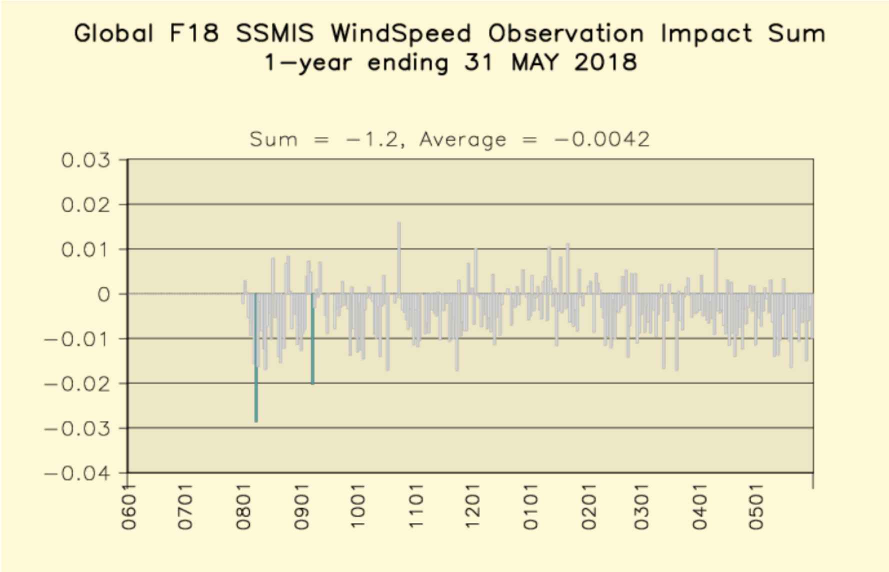
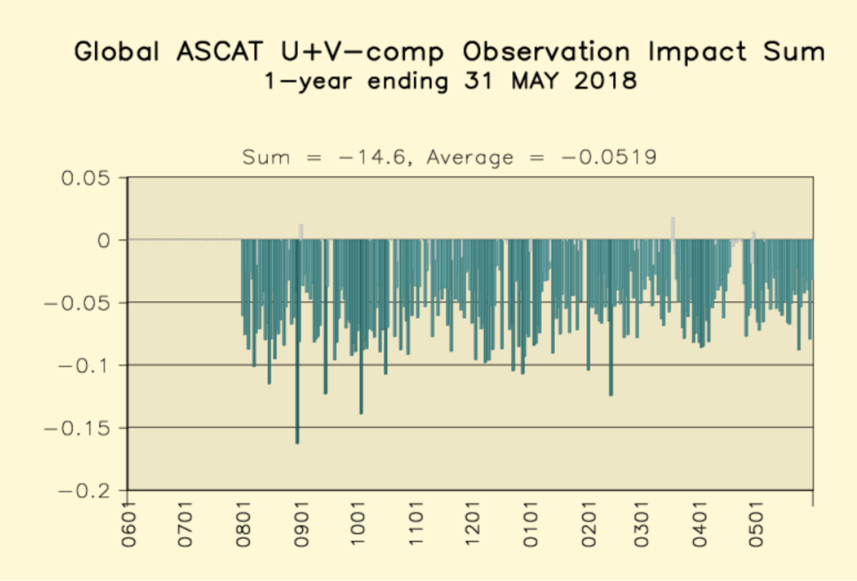
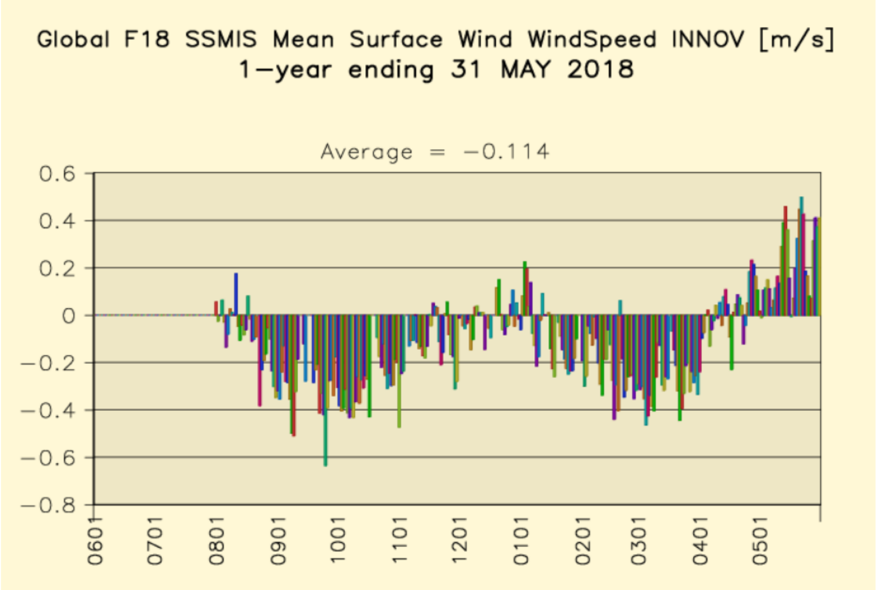
Thank you

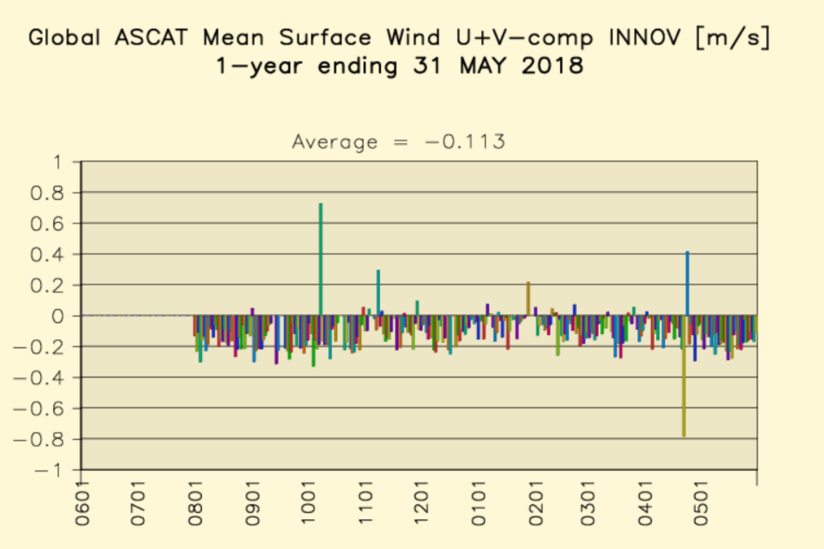
FSOI SSMIS vs. ASCAT

01 Aug 2017 – 31 May 2018

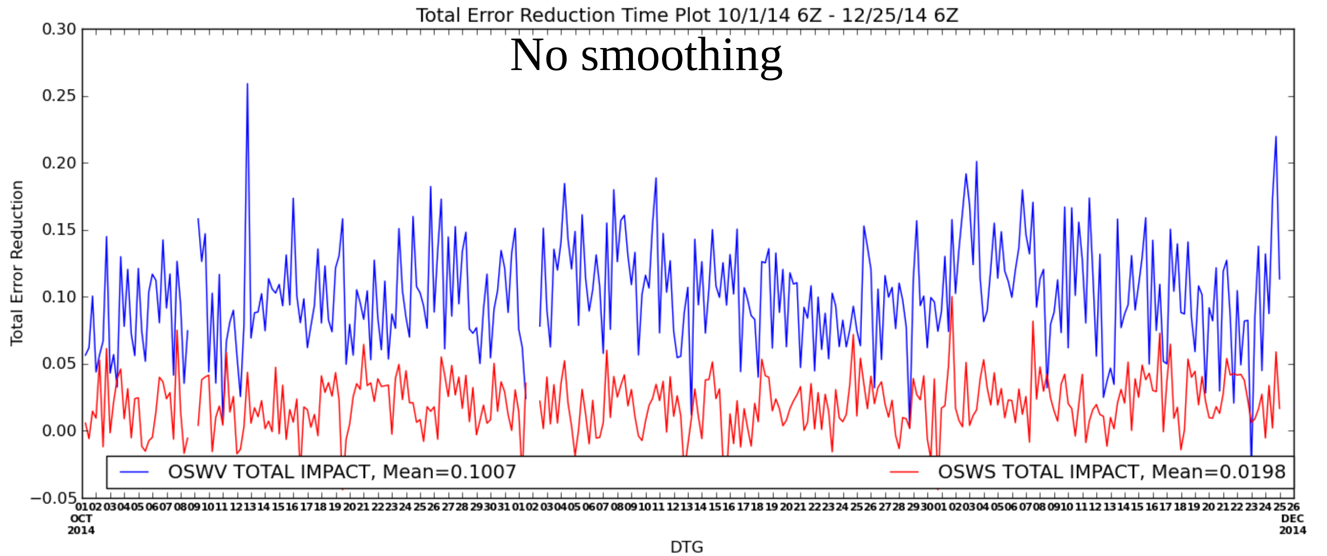


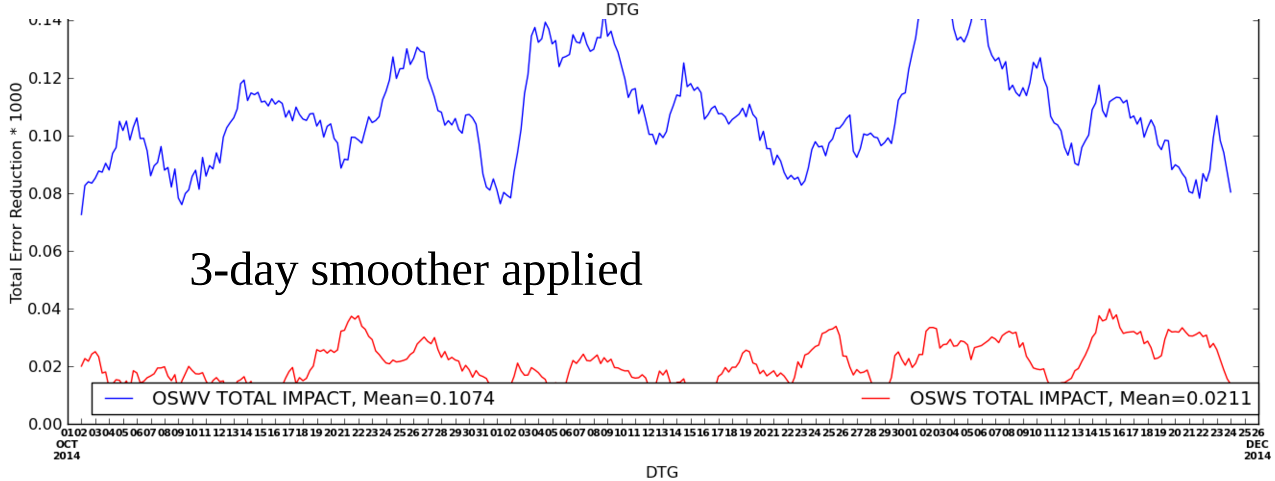






A Closer Look at Observation Impacts

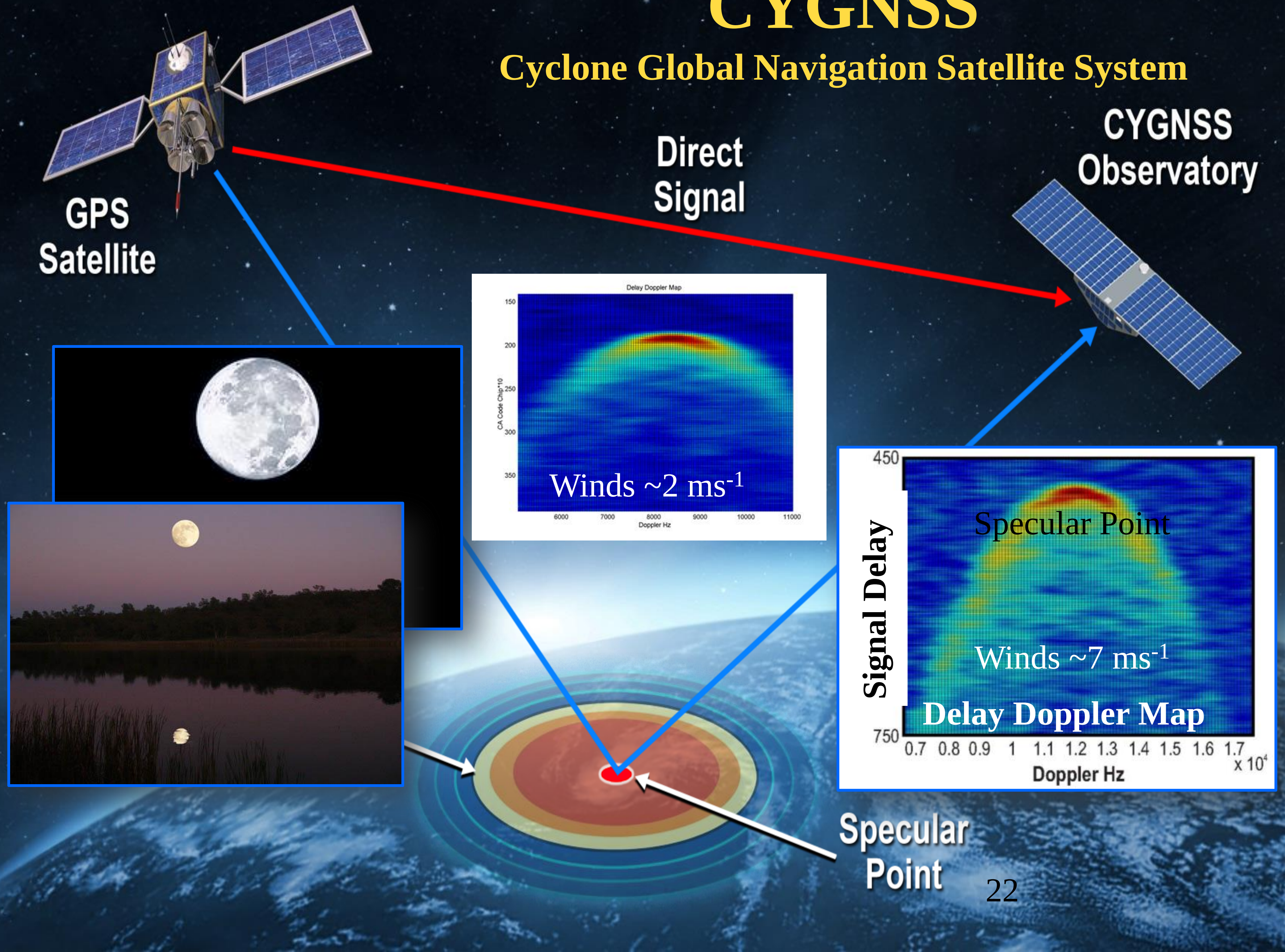




For a given date/time, OSWS observations can be non-beneficial overall

CYGNSS

Cyclone Global Navigation Satellite System



CYGNSS Observable

- CYGNSS measures the sigma0 of the ocean surface, not the full spectrum, but up to a cutoff determined by the L-band signal
- Returned power is greater for light winds
- Wave spectrum is decomposed into two components, local wind (short wave), non-local (long wave)
- There is a factor of kappa (wavenumber) squared in the integral over the wave spectrum, which makes the signal more sensitive to the shorter waves. The effect of kappa mostly removes the contribution from swell.
- Signal from ocean waves for all wind speeds, with a stronger effect at lower wind speeds.
- Kappa* defines the upper limit of the wavenumber spectrum, GPS wavelength and incidence angle dependence.
- WW3 stops integration at kappa smaller than kappa* so need to correct WW3 to append a spectral tail (either use WW3 tail or Elfouhaily spectrum).

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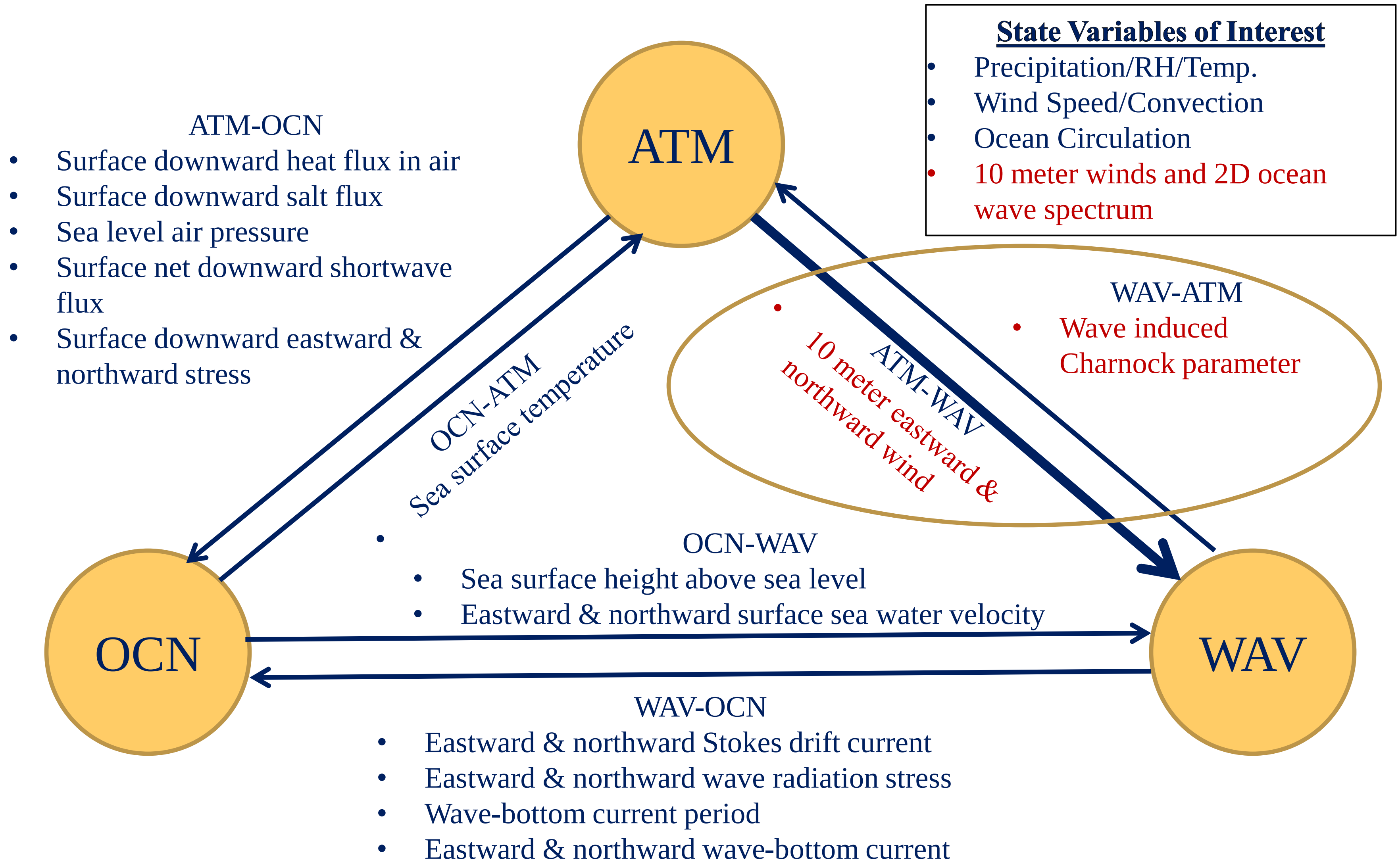
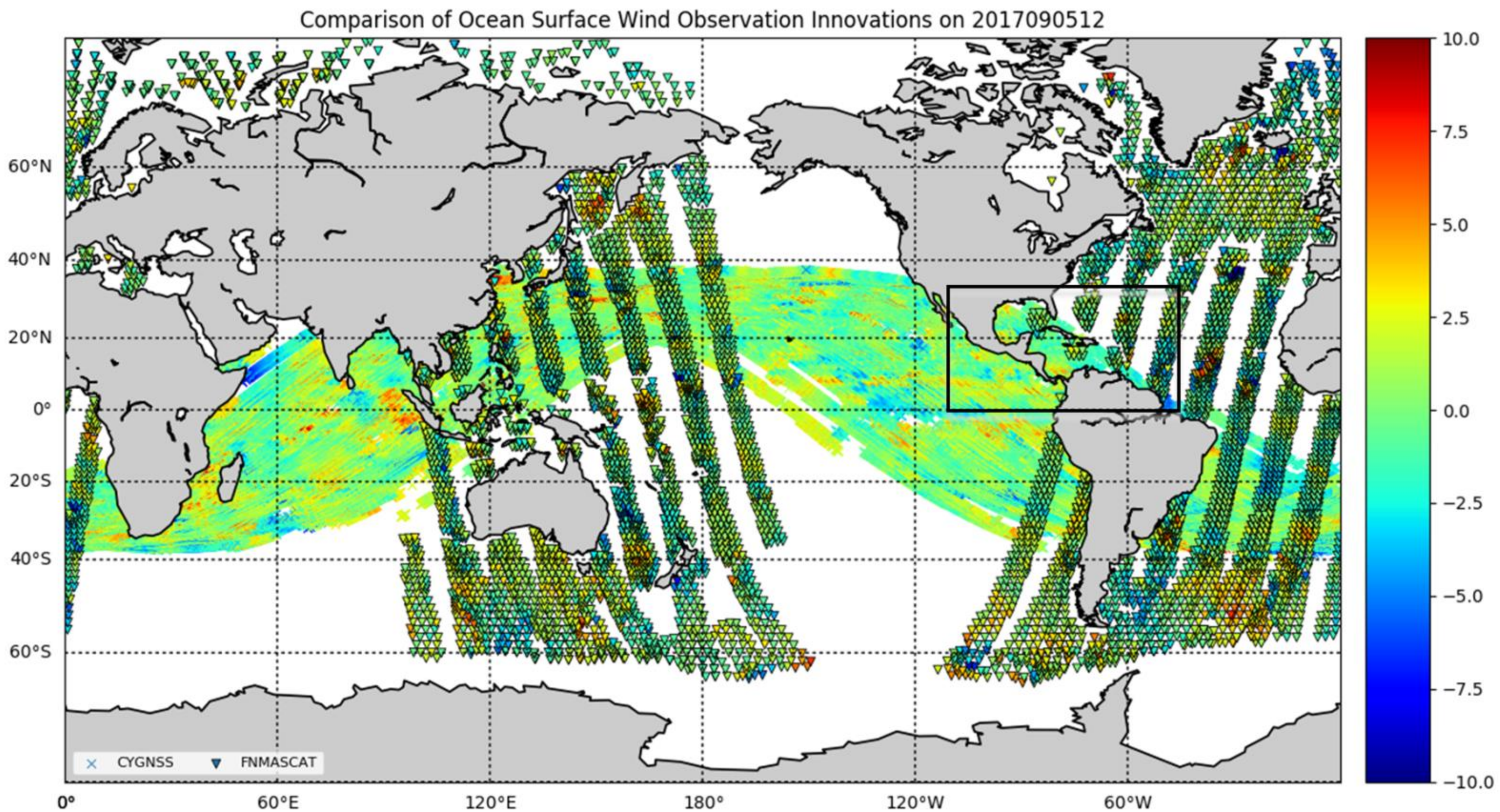
COAMPS® Coupled Modeling

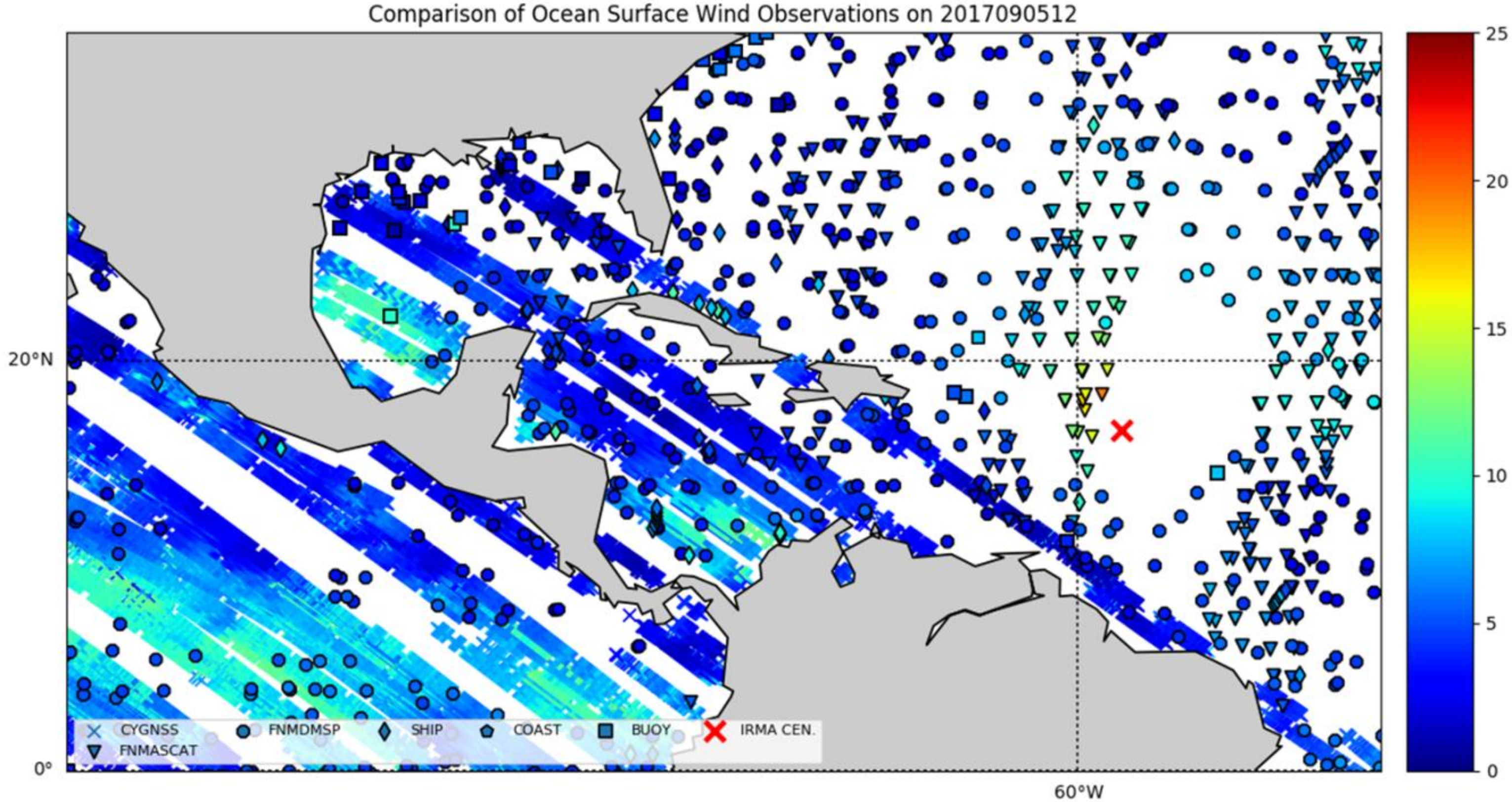


Comparison of Surface Wind Innovations



Global locations, types, and magnitudes of assimilated ASCAT and CYGNSS surface wind observations for 12 UTC September 5, 2017

Comparison of Surface Wind Speed



Locations, types, and magnitudes of assimilated surface wind observations for 12 UTC September 5, 2017