Surface turbulent fluxes in convection: Using CYGNSS observations to improve sampling of satellite-based flux estimates in the tropics

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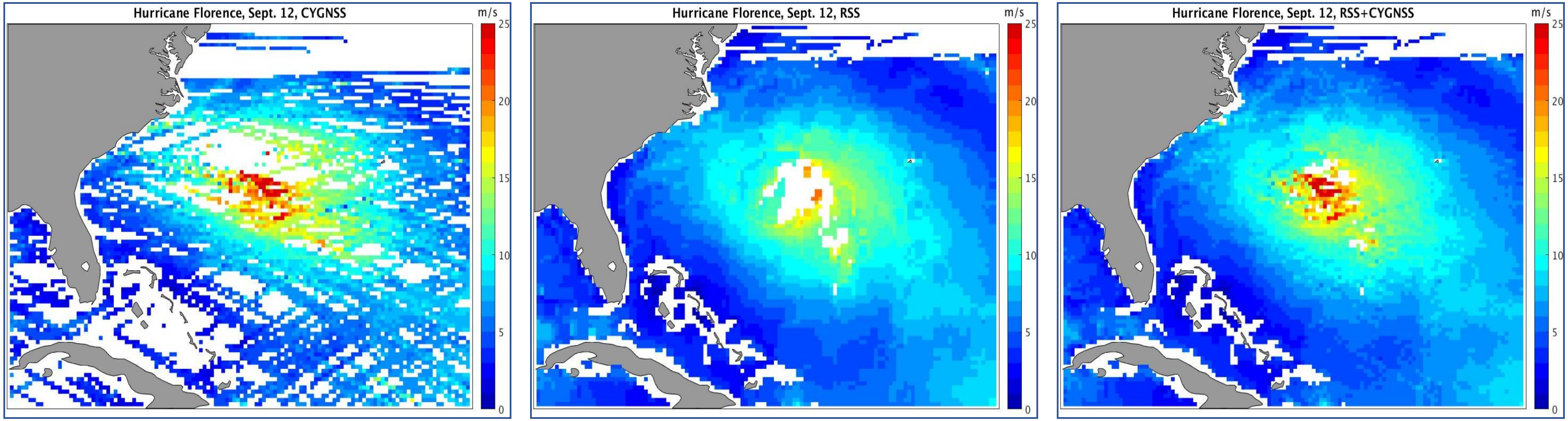
Motivation: Satellite-based Fluxes and Tropical Convection

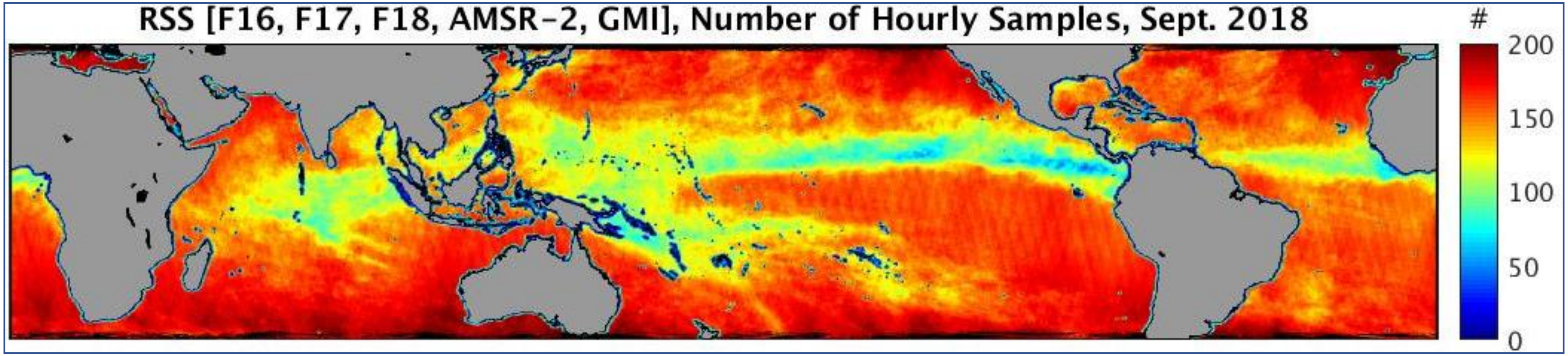
CYGNSS (24-hours) | **RSS (24-hours; F16, F17, F18, AMSR-2, GMI)** | **RSS + CYGNSS**



- Tropical systems can be very dynamic; Sampling from microwave imagers (primarily polar orbiting) still limited to a few samples and systematically missing in raining conditions.
  - ***Note* The above figures required aggregating all observations over a 24-hour window.***
- Tropical systems often draw energy from a large area surrounding the storm environment; thus it is important to sample winds (and turbulent fluxes) not only from the storm center but more broader area.

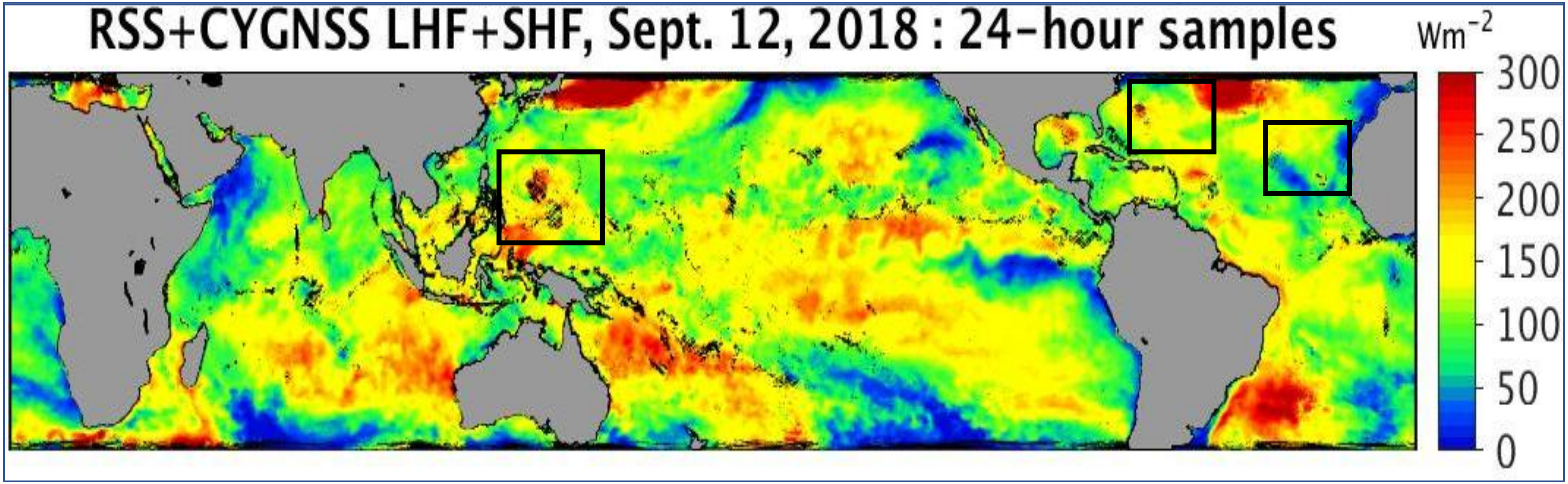
CYGNSS Sampling - Irregular sampling in space and time

- The nature of CYGNSS sampling results in very short median revisit times but interspersed at longer intervals
- Quality control — flagging data for specific GPS sources, signal strength, etc. — also reduces sampling
- For the hourly-sampled L3 product, we are left to estimate monthly wind speed (and/or flux) statistics using samples covering 1-5% of possible samples **often with high spatial variability in the sampling pattern**
- An alternative strategy is to work towards combining the passive microwave record with CYGNSS observations; these provide more robust sampling in all but raining conditions.



CYGNSS Sampling: Providing estimates in All-Weather conditions

- CYGNSS provides rapid revisit times of quickly evolving tropical systems including raining conditions
- It can improve wind speed estimates by providing estimates where other microwave sensors are unable to provide estimates due to rain contamination.
- We can compute the turbulent fluxes using the COARE 3.5 algorithm together with temperature and humidity estimates from MERRA2



Synthesizing Microwave Imager and CYGNSS Winds: Kalman Filtering

- *Goal: Generate a gap-free surface wind analysis that follows closely the satellite observations but mitigates biases due to sampling variability.*
- *Challenge: Must take into account uncertainties of the CYGNSS, microwave imager observations, and any model background/evolution*
- *Solution: Make use of a local Kalman Filter*, and in particular make use of the "control-input" formulation*

$$x_k = Ax_{k-1} + Bu_{k-1} + w_{k-1}, \quad p(w) = \mathcal{N}(0, Q)$$
$$z_k = Hx_k + v_k, \quad p(v) = \mathcal{N}(0, R)$$

where:

x_k is the desired surface wind speed state, for a single map grid box

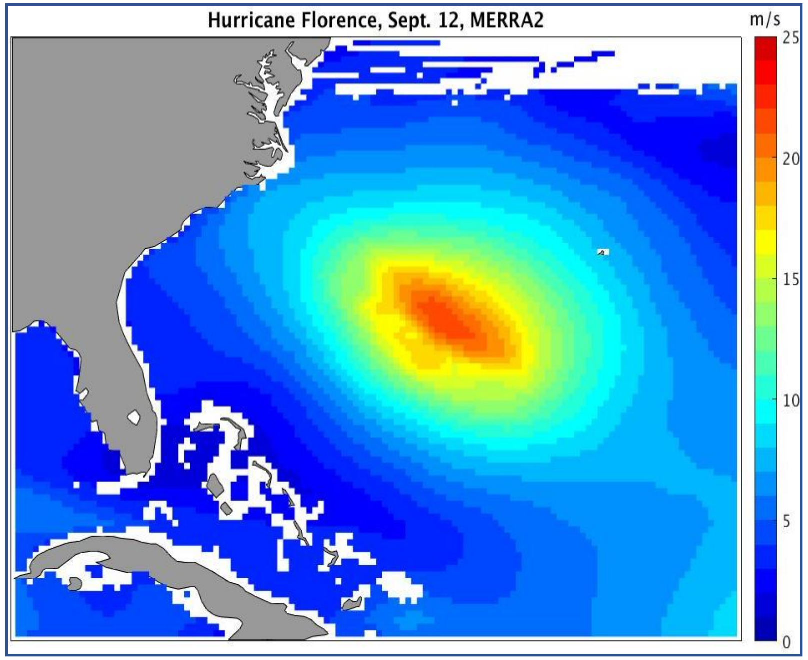
z_k are CYGNSS and/or microwave imager observations,

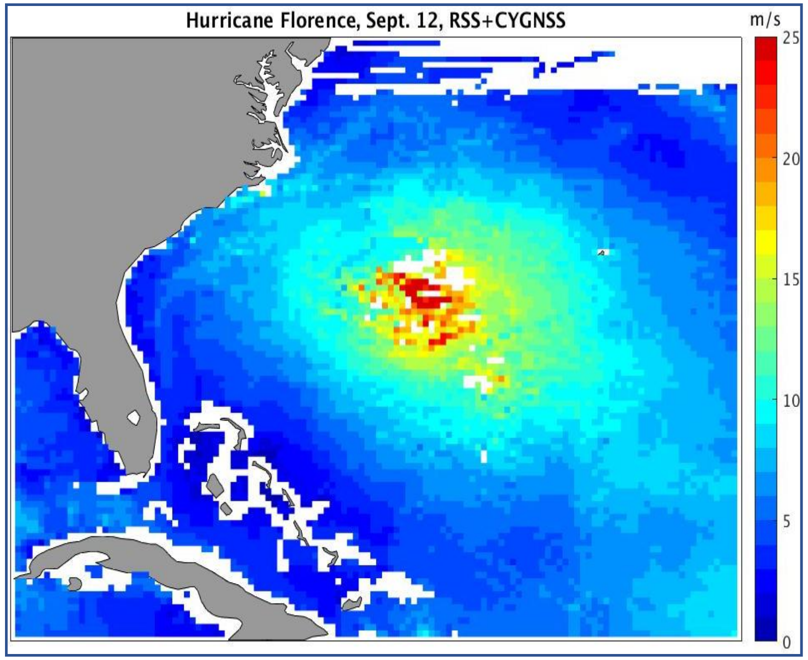
u_k are MERRA2 hourly time-tendencies, and

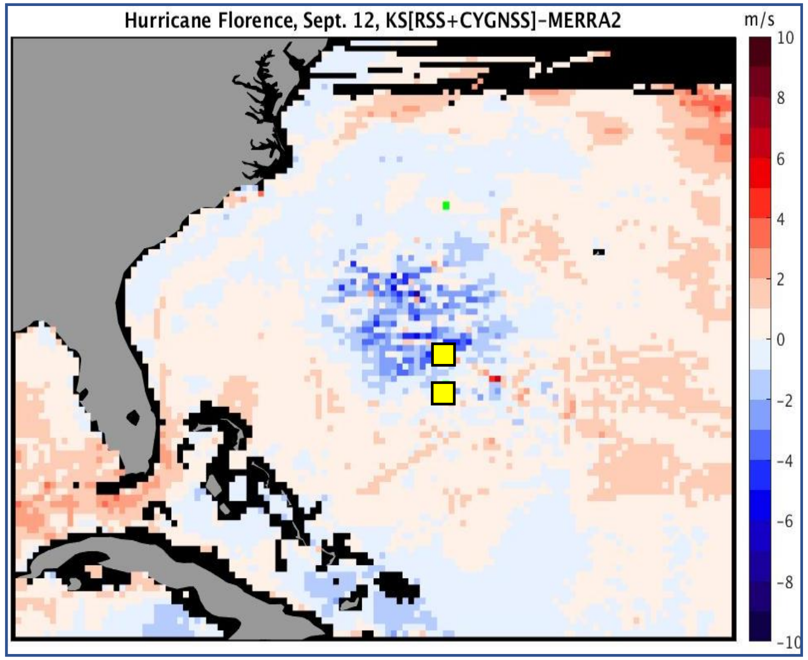
w, v are zero-mean Gaussian noise with process noise Q and observational noise R ; We use L3 wind speed errors for v

* Actually a Kalman Smoother is implemented using the RTS algorithm

Kalman Smoother: Filling in the (Time) Gaps

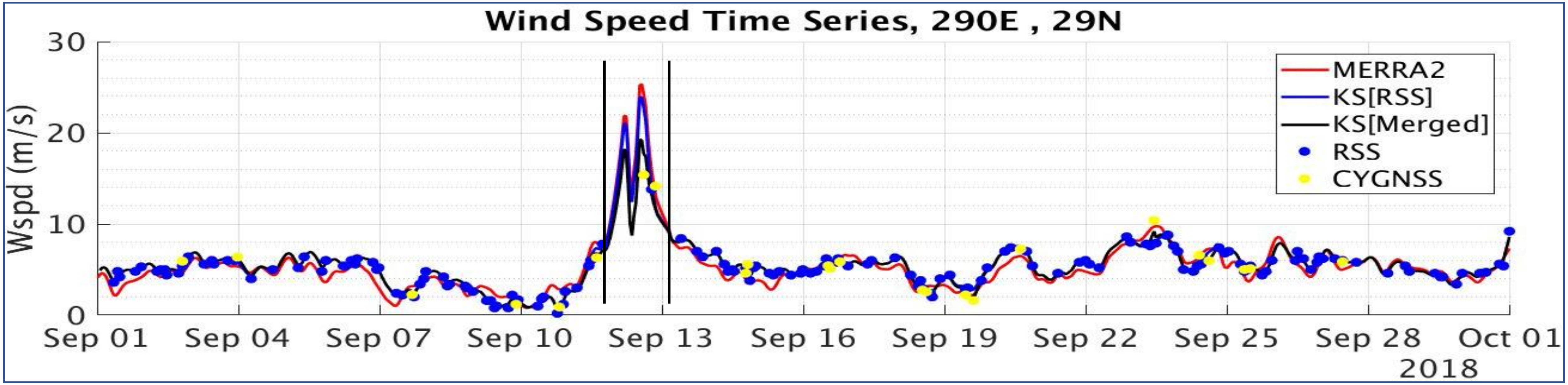






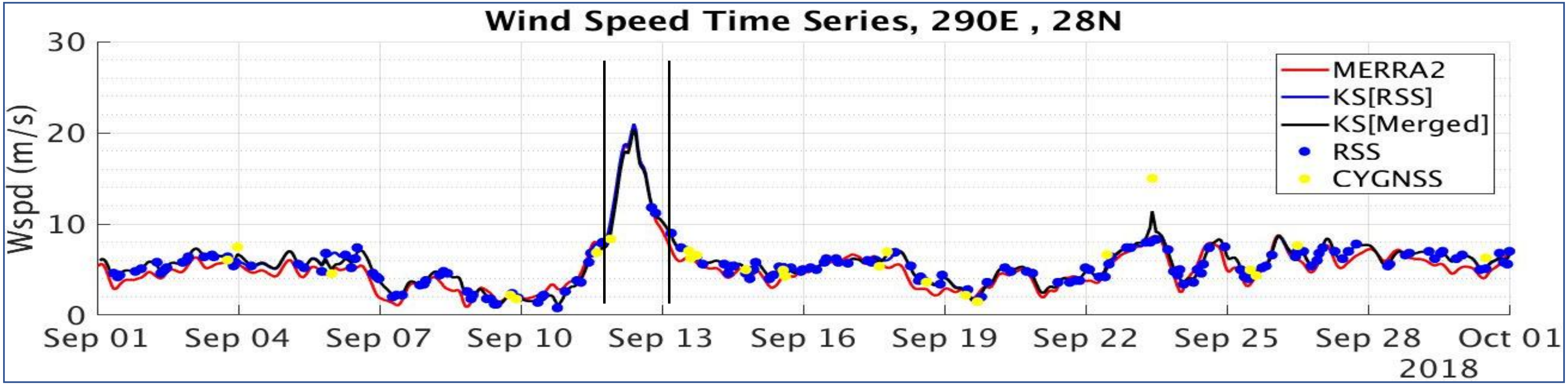
- MERRA2 provides continuous time series of wind speed estimates; however it is known to have biases that would impact the downstream estimation of turbulent fluxes. But, it is able to provide a continuously evolving state estimate that captures large scale dynamics (e.g. advection). ***Blending the tendencies ... not the wind estimates themselves.***
- Application of the Kalman smoother (KS) results in a gap-free time series of surface winds that are able to follow the satellite based estimates;
- Note, however, that the CYGNSS wind speed estimates remain somewhat biased low against MERRA2 in some tropical systems; In the surrounding environment satellite observations are ~1-2 m/s stronger over a large area.

A time series perspective



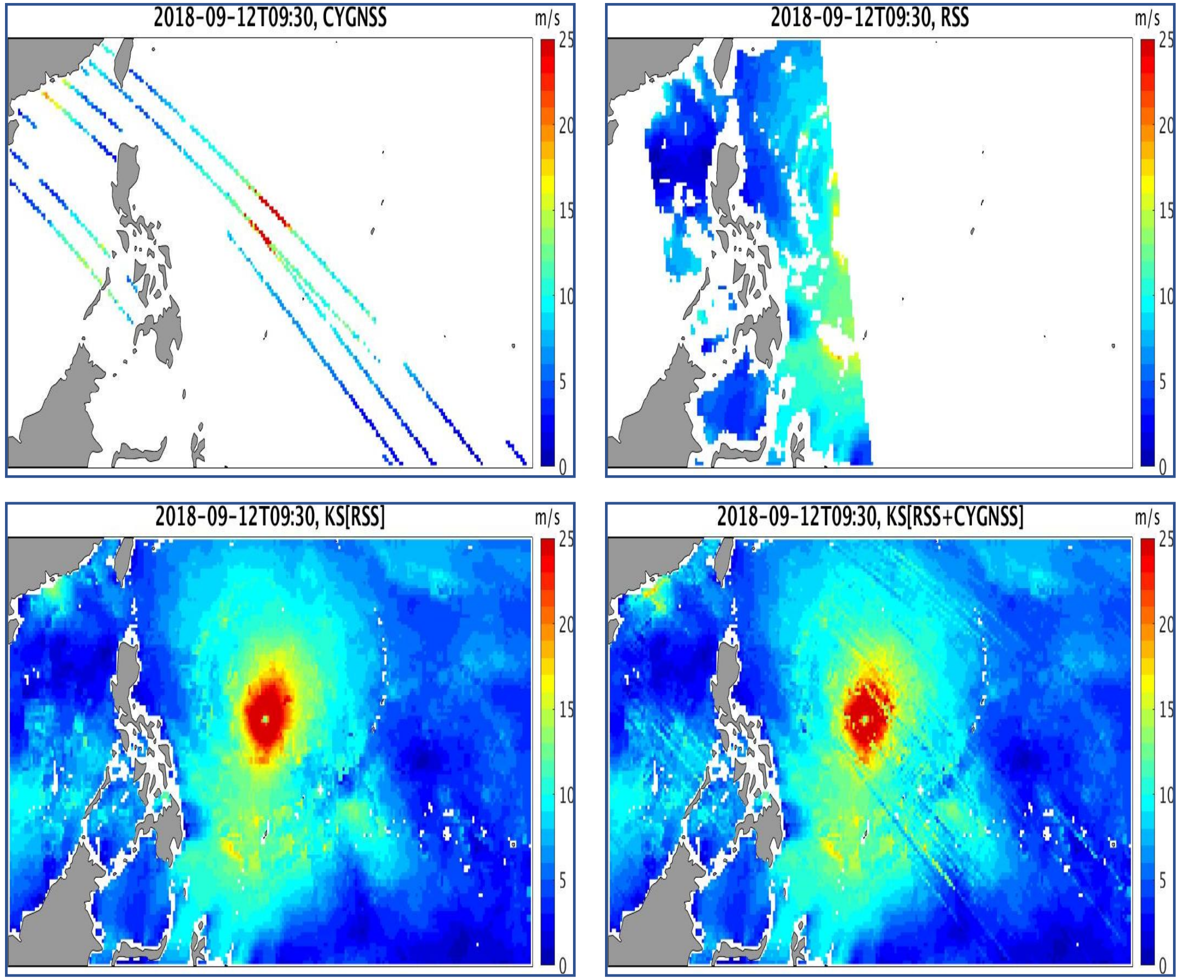
- There are only about 25 samples by CYGNSS for the entire month at this location (~3.5%). In contrast, a combination of 5 microwave imagers results in ~150 samples (~20%); ***but the imagers (RSS) are missing during storm passage!***
- Because MERRA-2 captures the general synoptic evolution, these tendencies are able to steer the Kalman Smoothing estimate into agreement with the CYGNSS and RSS observations and also recover the large-scale passage of the storm.
- However, the CYGNSS observations during storm passage were much lower than those from MERRA2 and resulted in weaker estimates of winds. If you didnt include the CYGNSS observation, the smoothed estimates would be higher at storm center.
- Outside of the storm environment, CYGNSS and RSS are in good agreement (well-calibrated).

A time series perspective



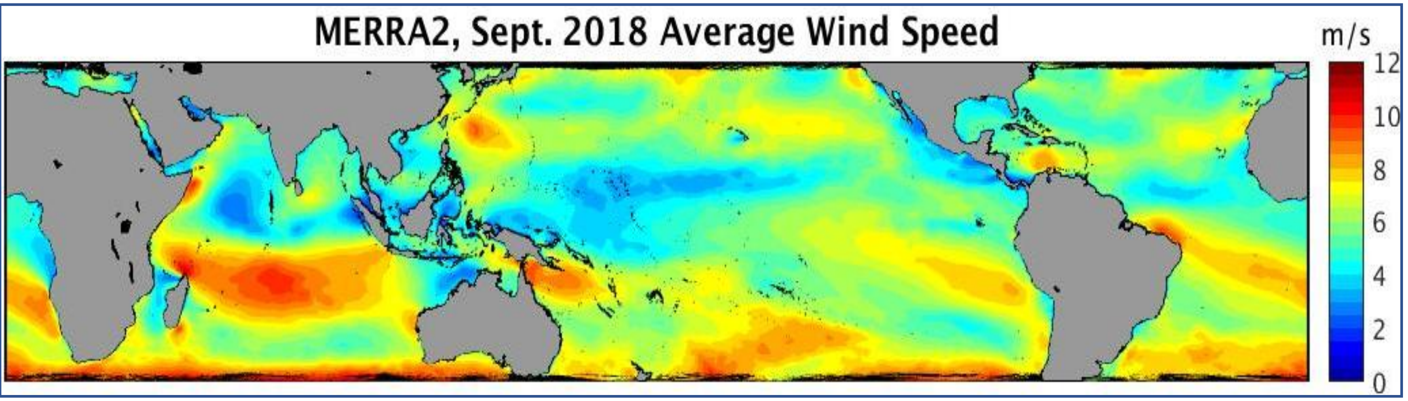
- At a point just south of where the tropical system passed, there was a significant increase in wind speeds.
- The early increase was captured in both the RSS and CYGNSS estimates, but there were no observations during the primary event passage.
- The dynamical tendencies from MERRA2, however, allowed the passage of the storm to be recovered.
- Outside of the tropical events, the KS estimates mostly follow the satellite observations (generally biased stronger than MERRA2).

A Space and Time Perspective: Typhoon Mangkhut

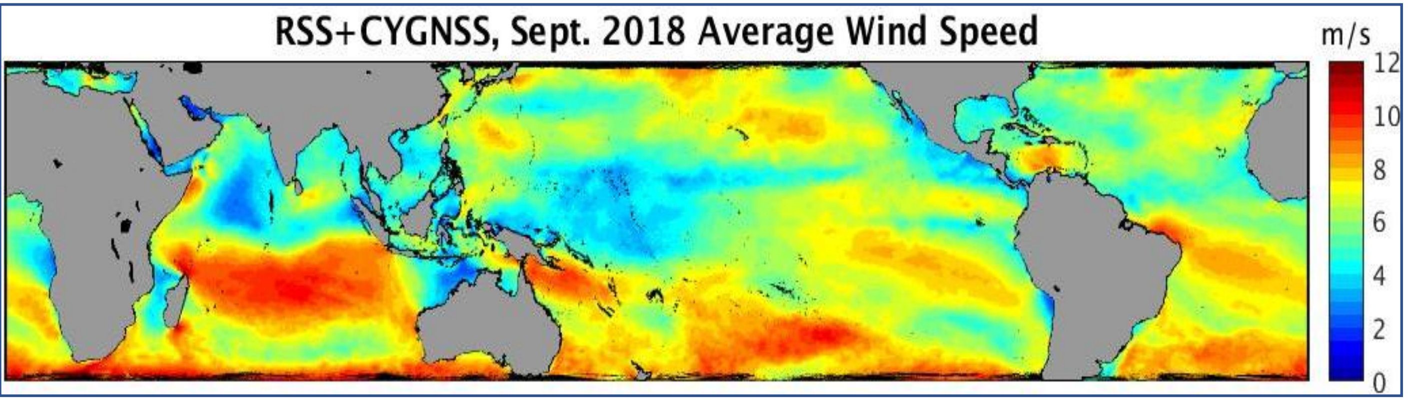


- At any single hourly snapshot, much of the region around a tropical system may be unobserved.
- This significantly impacts the ability to characterize the winds and associated turbulent fluxes driving the tropical cyclone.
- The Kalman smoother allows state estimation using observations before *and* after a specific time.
- Somewhat smoother estimates are generated using only the microwave imager observations. More effort may be needed to blend CYGNSS data together.

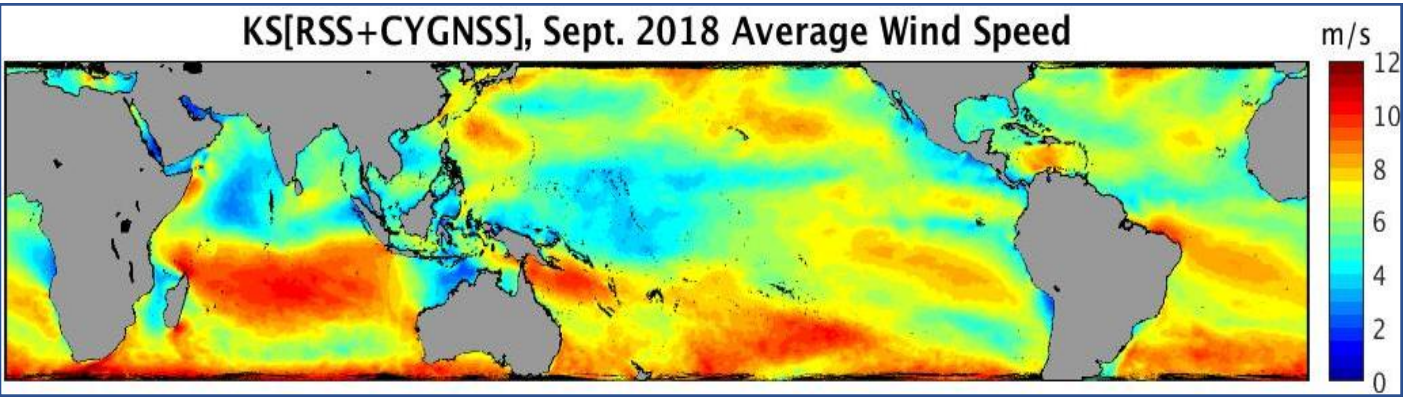
Monthly Statistics: Mean Wind Speed



- The MERRA2 monthly average wind speeds generally capture the same patterns as the satellite observations.
  - However, they are in general biased lower by more than 1 m/s, especially in the ITCZ



- The addition of CYGNSS winds tends to result in increased monthly mean winds by about 0.2 m/s over those of the microwave imager winds alone.



- The Kalman smoothed estimates have mean patterns that largely mimic the raw satellite observations but these fields are now continuous in space and time.
- *Compared to the satellite observations alone, improved sampling results in wind speed estimates that are 0.5-1.0 m/s higher.*

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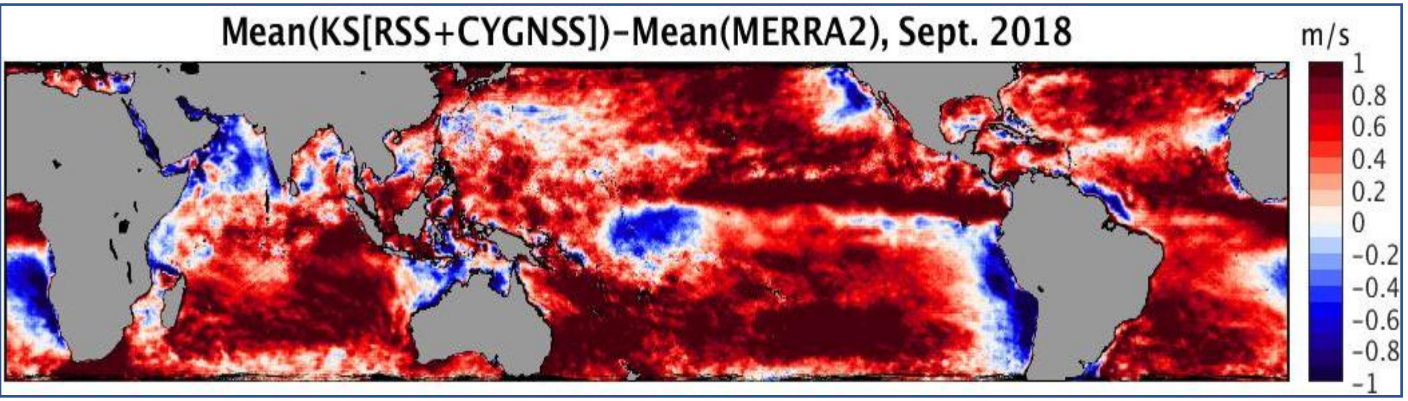

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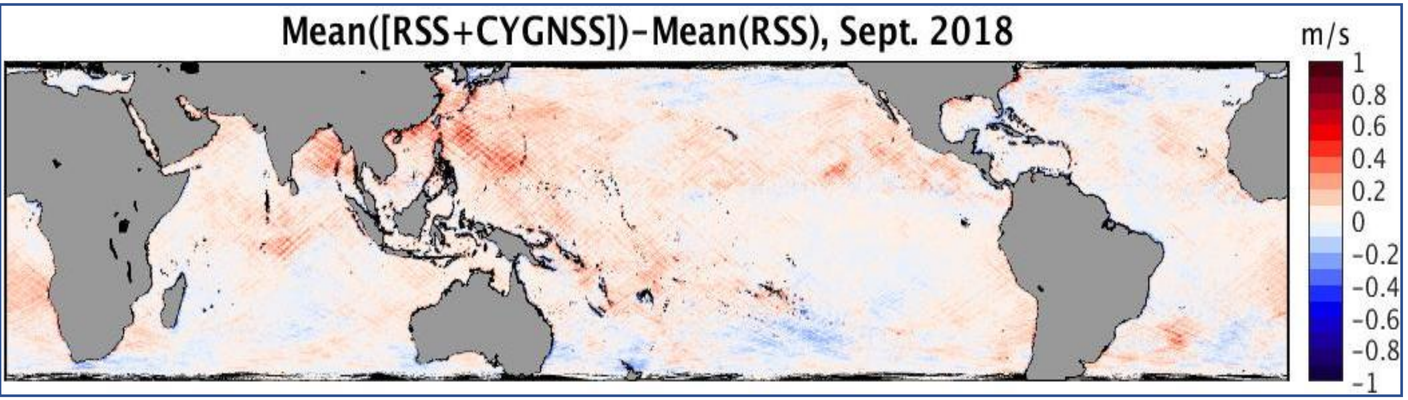

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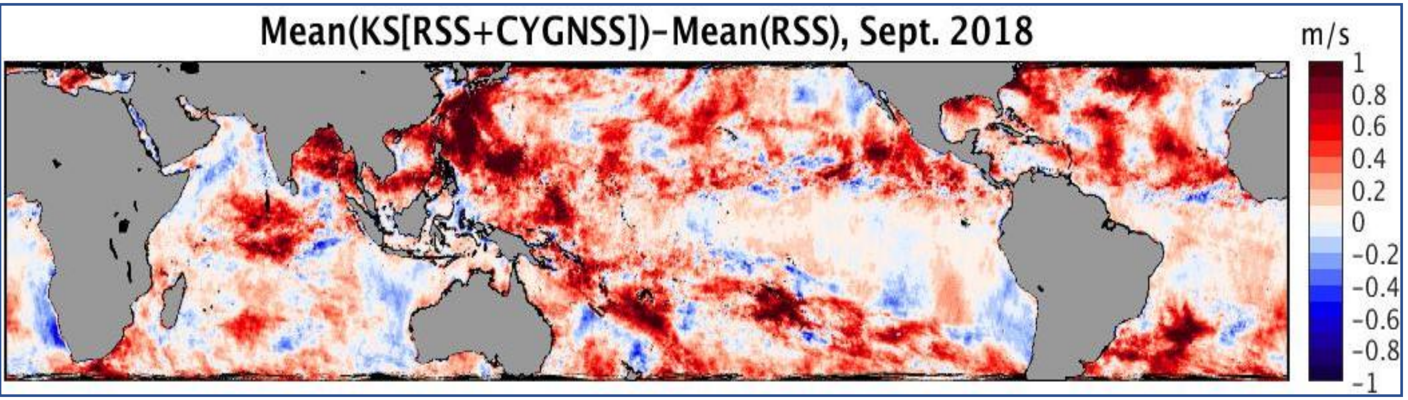

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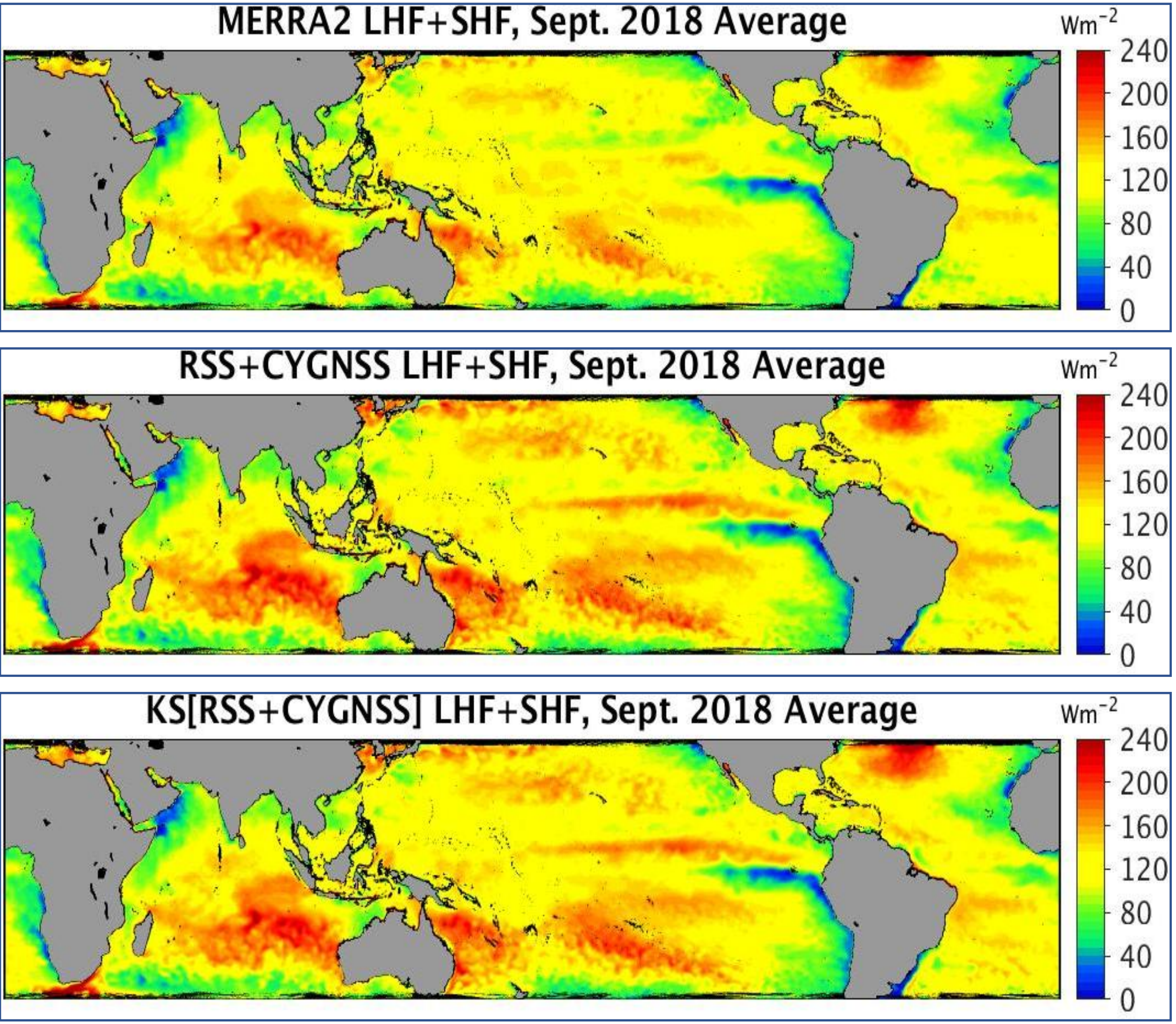
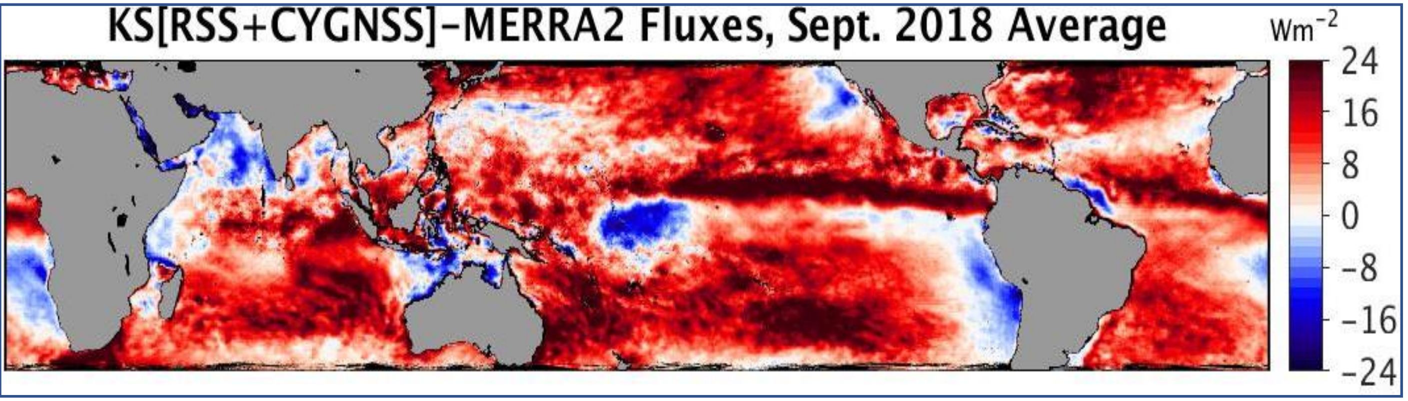
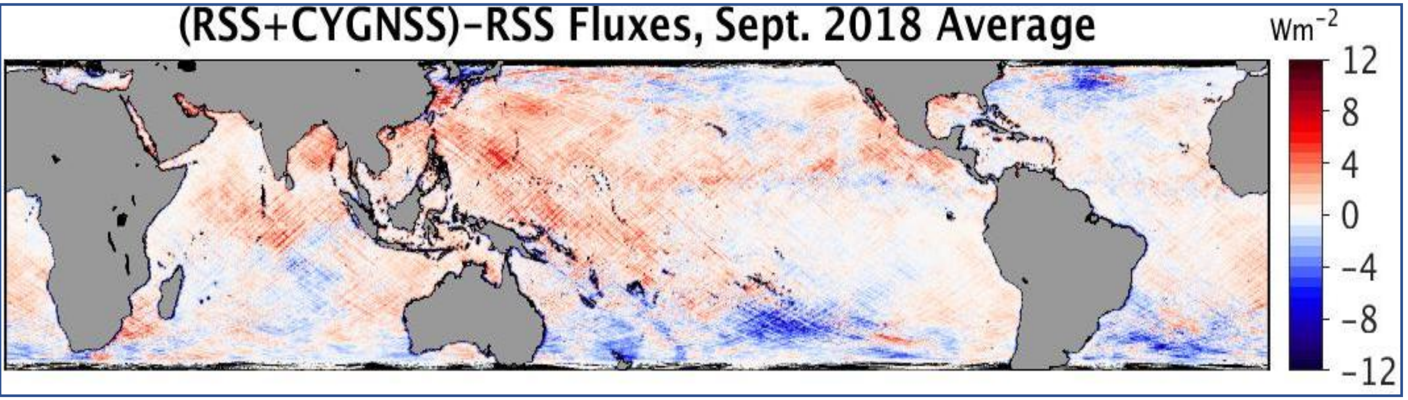
Monthly Statistics: Mean Turbulent Flux

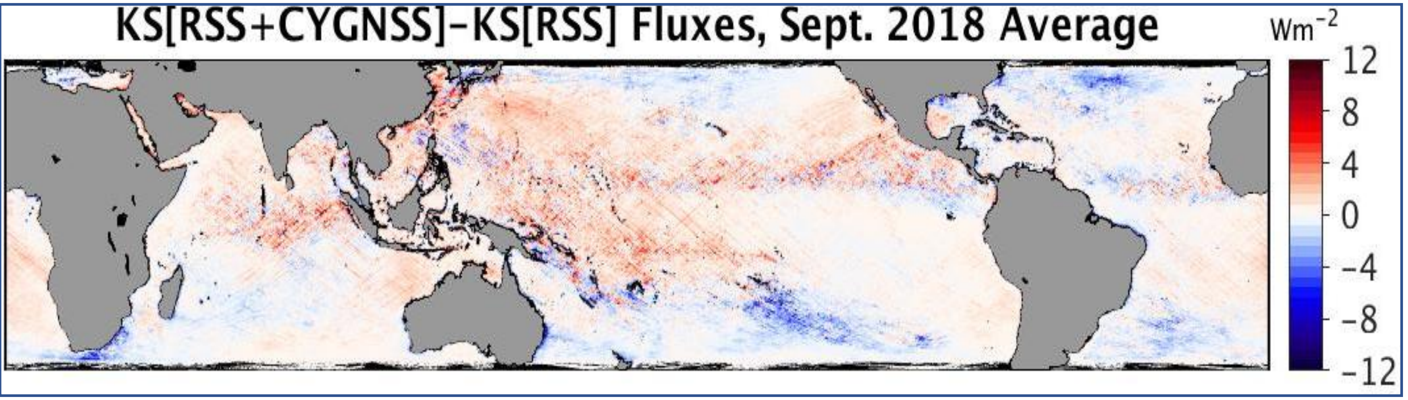


- The MERRA2 monthly average turbulent fluxes generally capture the same patterns as the satellite observations.
  - In the ITCZ and storm tracks however, they are systematically weaker by up to 20 W/m^2
- The addition of CYGNSS winds tends to result in increased monthly average turbulent fluxes by about 2-3 W/m^2 (~3%) over those that use only the microwave imager winds.
- The Kalman smoothed estimates account for changes on the order of 10% (not shown) in many areas.
- After accounting for sampling, the inclusion of CYGNSS observations maintains the increase of 3% in the turbulent fluxes over regions with tropical systems.

Monthly Statistics: Mean Turbulent Flux







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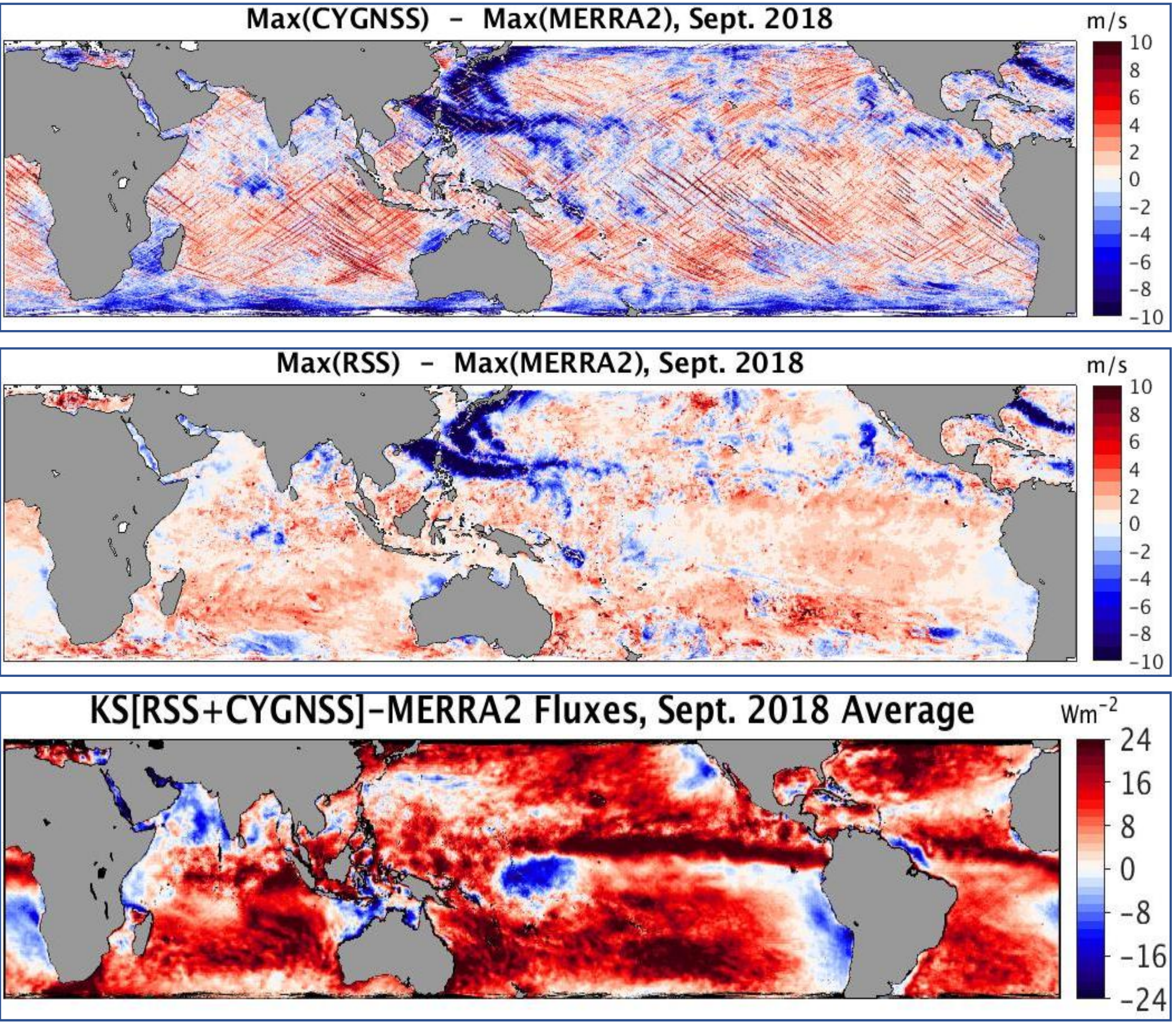
Monthly Statistics: Max Wind



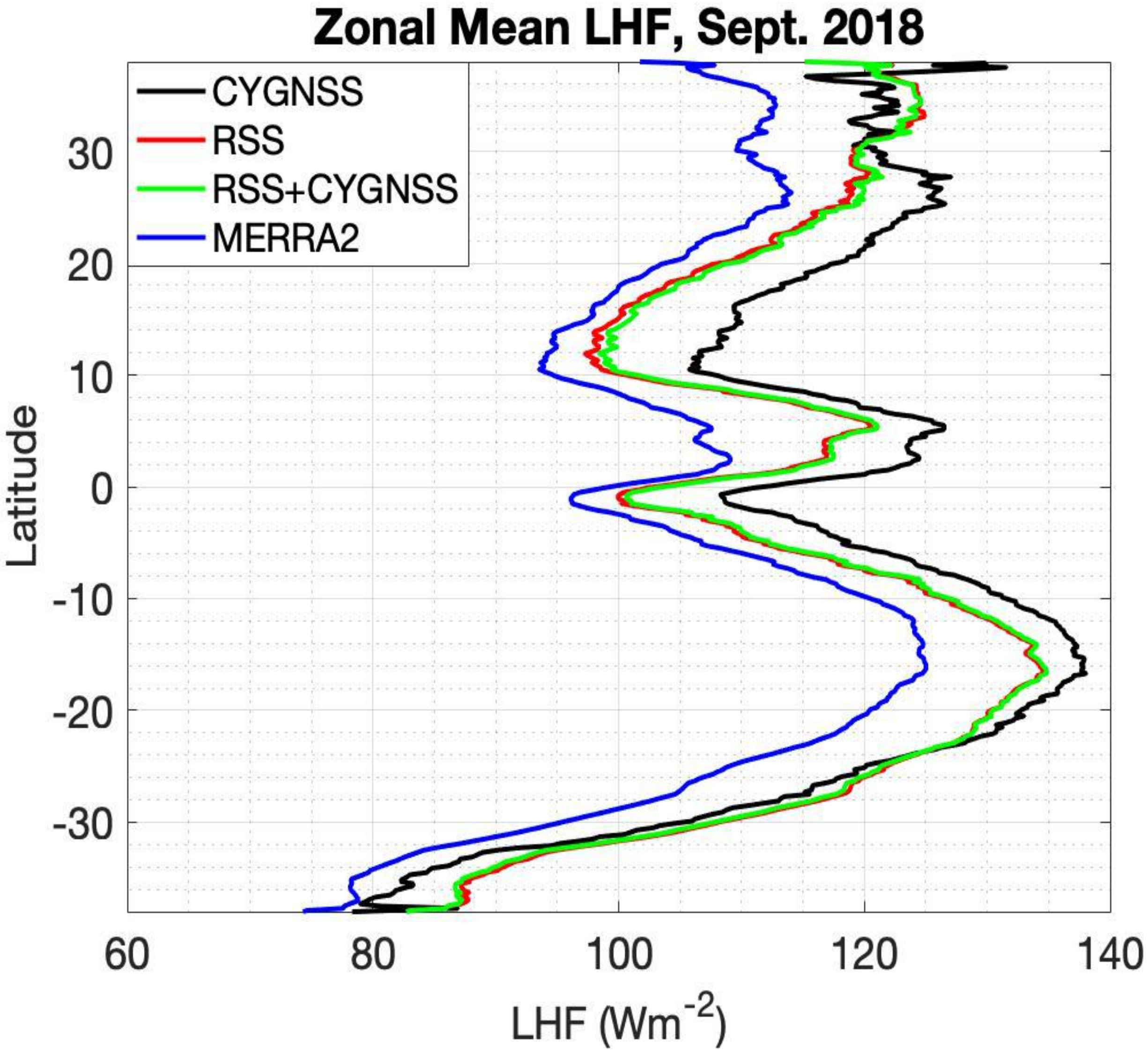
- Both the CYGNSS observations and microwave imager observations alone tend to miss the strongest wind events associated with tropical cyclones.
- These significant events impact the ability to resolve the monthly mean wind speed and associated turbulent fluxes.
- The Kalman smoothed estimates, however, appear to recover much of the bias driven by sampling variability.

Limitations on Impacts of CYGNSS

- If we examine zonal means of the CYGNSS fluxes alone (i.e. not merged with the microwave imagers), we find a more significant increase in the turbulent fluxes (5-10 W/m^2) across most latitudes.

- This is not as evident when looking at the combination of RSS and CYGNSS together. This is likely a result of:
    1. CYGNSS observations are only available about 3-5% of the month at any one location compared to 20%+ for the microwave imagers.
    2. Further, they provide most "extra value" during the fraction of the month when (a) it is raining and (b) CYGNSS samples when it is raining. Outside of rain events, CYGNSS and the microwave imagers provide similar wind speed retrievals.

- Increased impact may be felt if/when the full suite of CYGNSS samples is available and/or retrieval uncertainties are decreased.



Summary

- The sampling variability of CYGNSS observations significantly impacts the ability to perform analyses of air-sea interaction including the turbulent fluxes
- However, it is able to preferentially provide observations in raining conditions that microwave imagers have traditionally been unable to provide estimates.
- Combining CYGNSS observations with microwave imagers results in modestly higher monthly average wind speeds (~0.2-0.3 m/s) and turbulent fluxes (3-5 W/m^2)
- Application of a Kalman smoother to address sampling variability, however, significantly improves the ability to resolve transient systems and capture significant wind events and their associated turbulent fluxes. It allows us to take advantage of the sampling from both microwave imagers and CYGNSS.

Caveats

- *This study focused only on a single month and highlighted tropical systems and convection.*
- *A more comprehensive evaluation is needed to study all available months and ascertain the cumulative impacts on the estimation of turbulent fluxes. For example, cold air outbreaks/extratropical systems along the western boundary currents are a prominent feature in flux climatologies that are not evaluated here.*