USE OF KALMAN FILTERING TO IMPROVE CYGNSS AIR-SEA INTERACTION APPLICATIONS

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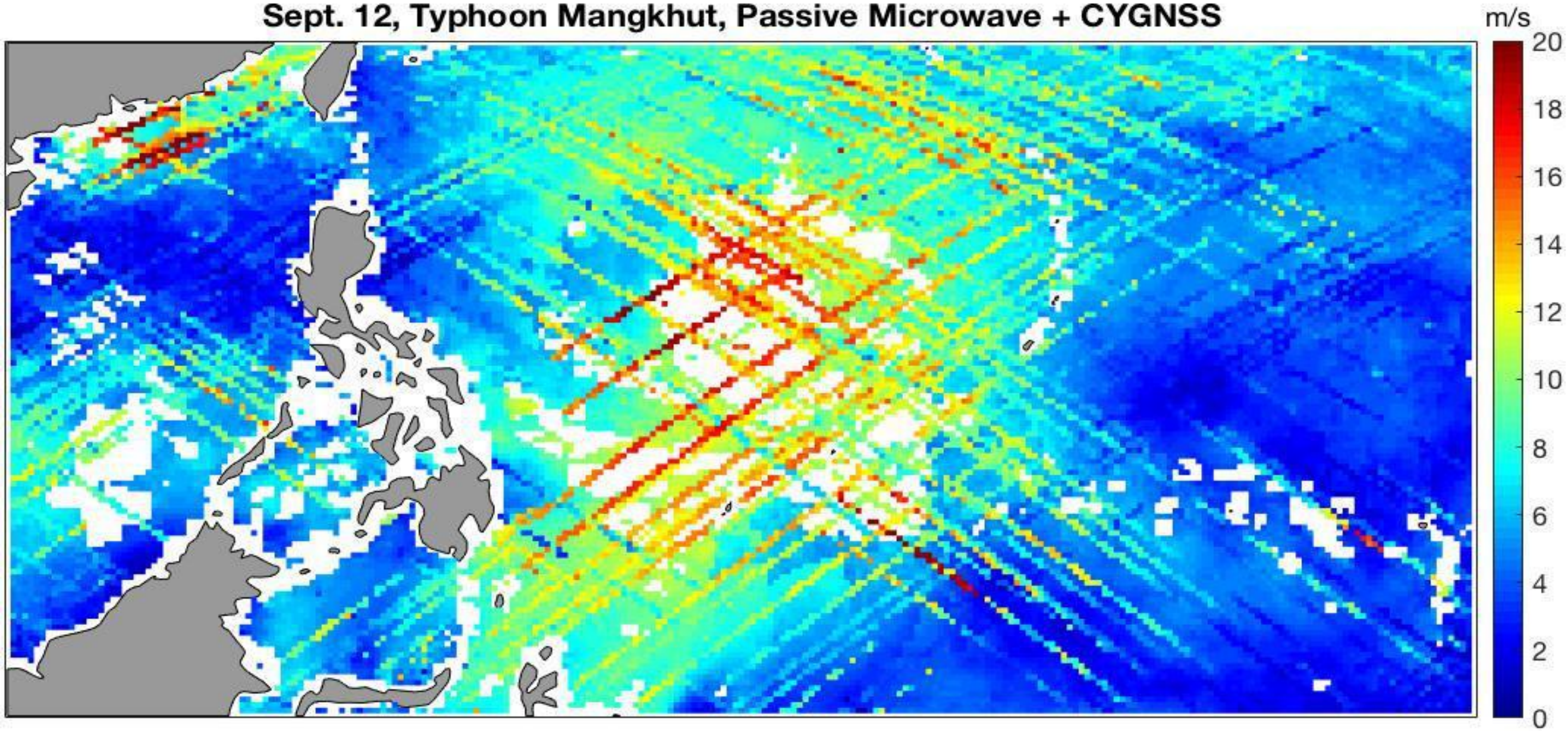
Cyclone Global Navigation Satellite System (CYGNSS) Observations and Applications

- How can we use ocean winds observed by CYGNSS to study physical processes of air-sea interaction?
  - Winds alone aren't as useful as in combination with other over-ocean observations. Estimating turbulent fluxes, for example, requires knowledge of temperature and humidity.
- What are (some of) the limitations, and can we address them?
  - Data quality and sampling, in conjunction with other available data (e.g. clouds/precipitation), are critical for air-sea processes

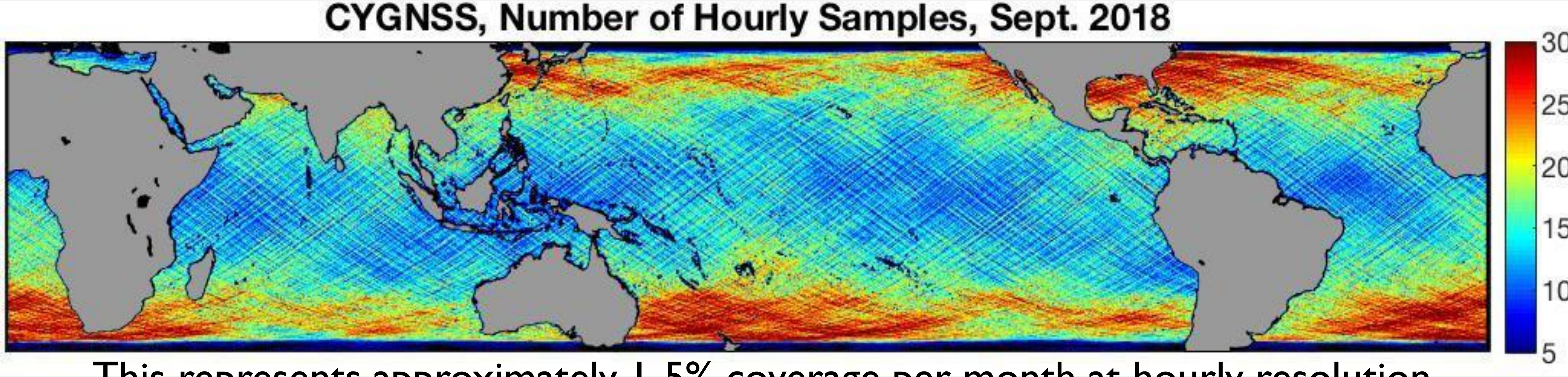
CYGNSS SAMPLING - THE GOOD

- CYGNSS can provide rapid revisit times of quickly evolving tropical systems
- It can improve upon and fill in gaps where other microwave sensors are unable to provide estimates due to rain contamination. Note, CYGNSS if estimating higher winds than passive microwave in most convective areas.



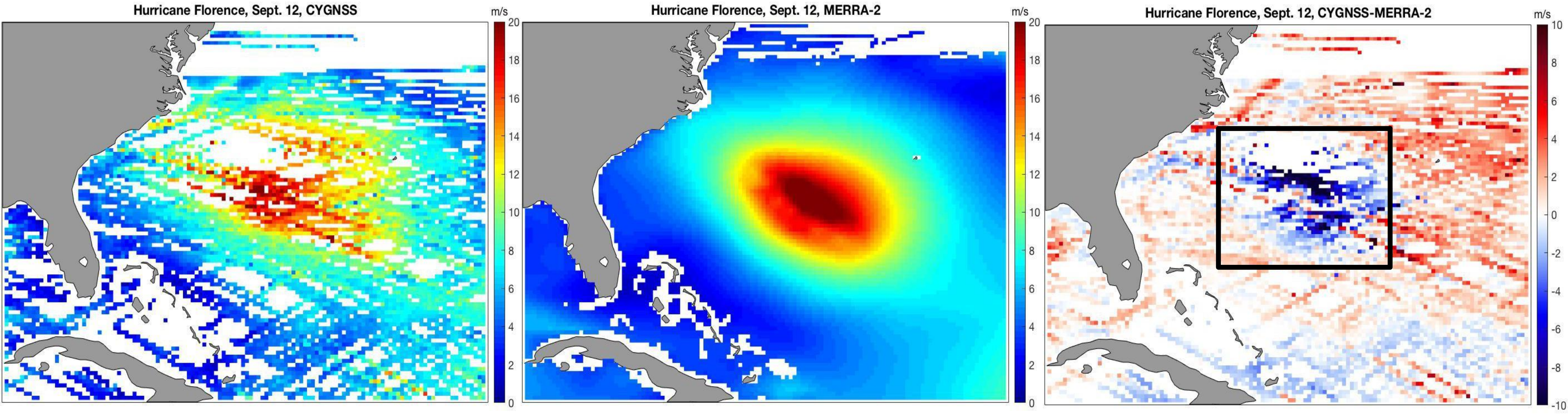
CYGNSS SAMPLING - NOT SO GOOD

- The nature of CYGNSS sampling results in very short median revisit times but often interspersed with longer intervals
- Quality control (e.g. not including specific GPS sources, RCG flagging, etc.) can also substantially reduce sampling
- For the hourly-sampled L3 product, we are left to estimate monthly statistics (if desired) using samples covering 1-5% of possible samples; often with high spatial variability in the sampling pattern



This represents approximately 1-5% coverage per month at hourly resolution

AIR-SEA INTERACTION STUDIES: TURBULENT FLUXES



*This example is *not* using the limited fetch retrieval over the storm center*

- For tropical systems, turbulent fluxes over a broad area must be considered for characterizing energy supply
- For Hurricane Florence, you would expect increased turbulent heating to supply energy given the stronger winds (vis-à-vis MERRA-2) in the surrounding environment;
- Improving spatial sampling requires aggregating in time to get enough data for areal budgets

KALMAN FILTERING

- Goal: *Generate a blended product that leverages the continuity and model-dynamics based evolution from the reanalysis with the available sampling from CYGNSS*
- Challenge: *Must take into account uncertainties of the CYGNSS observations and uncertainties in 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 observations,

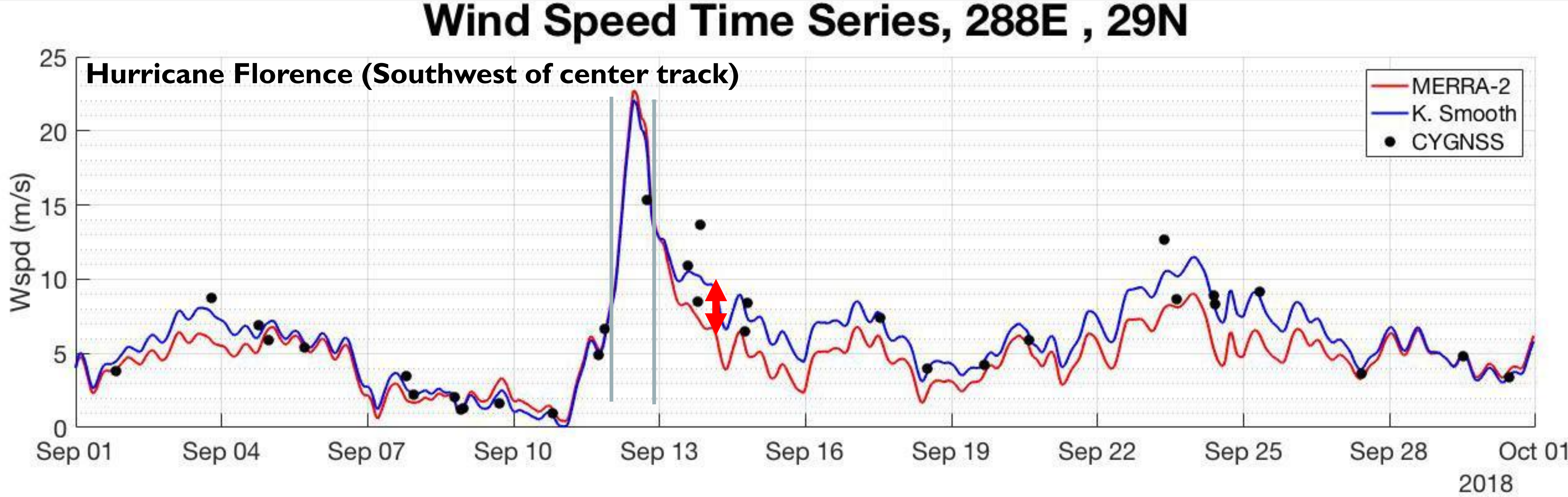
$\mathrm{A} = \mathrm{H} = \mathrm{B} = \mathrm{I}$,

u_k are MERRA-2 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

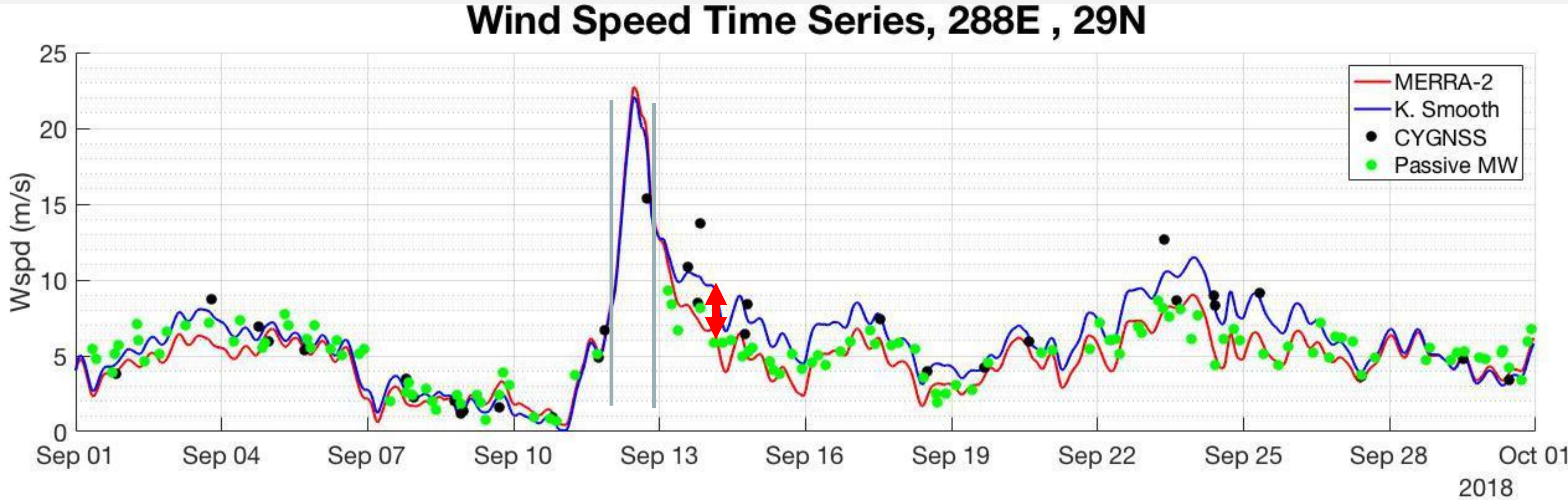
* Actually a Kalman Smoother is implemented using the RTS algorithm

HOW DOES THIS LOOK AT A POINT?



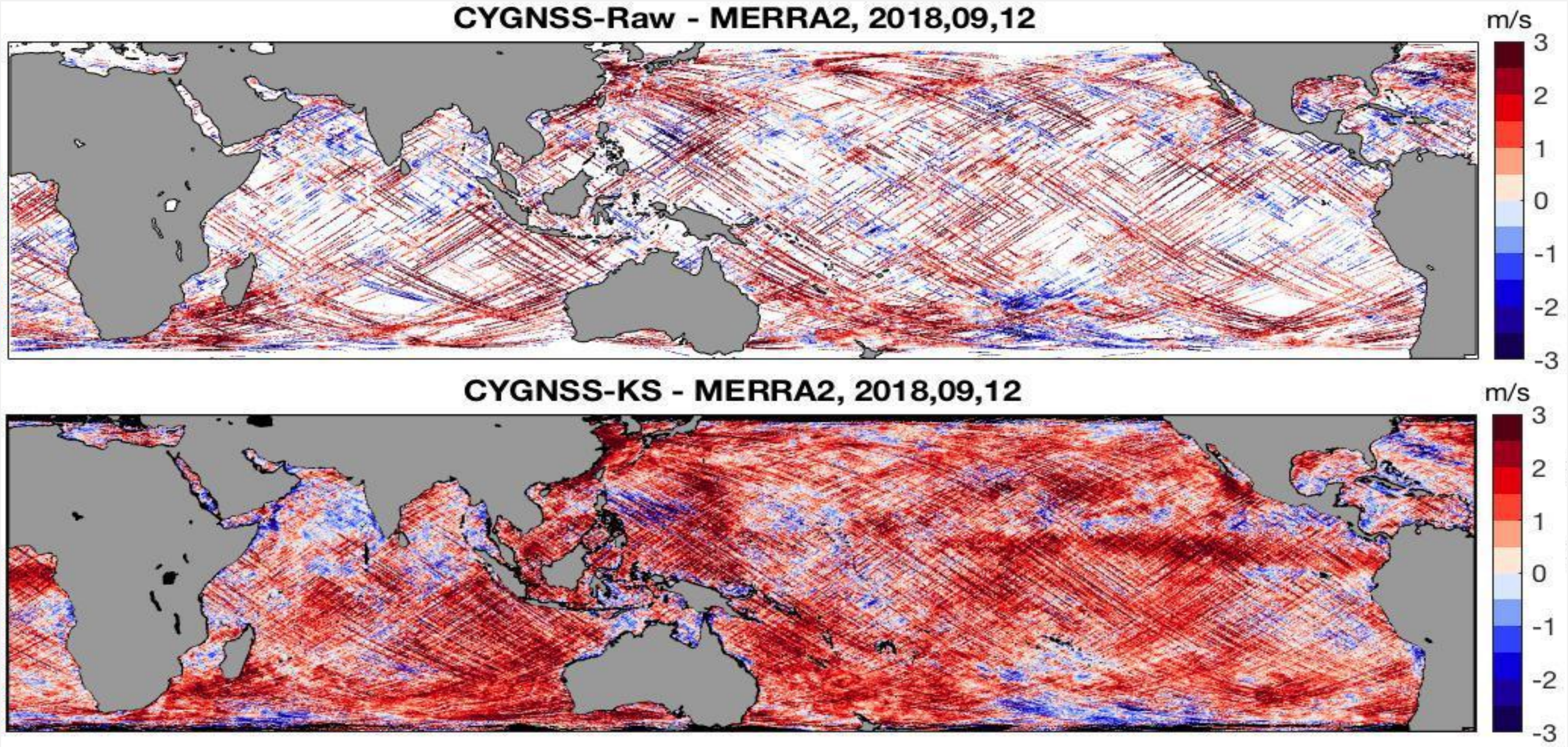
- For the month, only 31 hourly samples out of a possible 720 (4%); CYGNSS sampling bracketed the main passage of the storm at this location.
- Because MERRA-2 captures the general synoptic evolution, these tendencies are able to steer the Kalman Smoothing estimate into agreement with the CYGNSS observations and also recover the large-scale passage of the storm.
- Note that CYGNSS winds are generally higher than the MERRA-2 winds and the KS estimates are tuned towards the observed mean.

HOW DOES THIS LOOK AT A POINT?



- Here, we overlay the available passive microwave estimates (GMI + AMSR2 + SSMIS); Much increased sampling is available. Early in the month, PMW and CYGNSS are both in agreement and higher than MERRA2
- PMW are completely missing in the storm environment and in the post-storm environment CYGNSS is consistently observing stronger winds than the PMW.
- MERRA-2 sub-daily "wiggles" appear to generally line up with the PMW estimates; this could possible be a reflection of microwave winds assimilation.

HOW DOES THIS LOOK FOR A MAP?

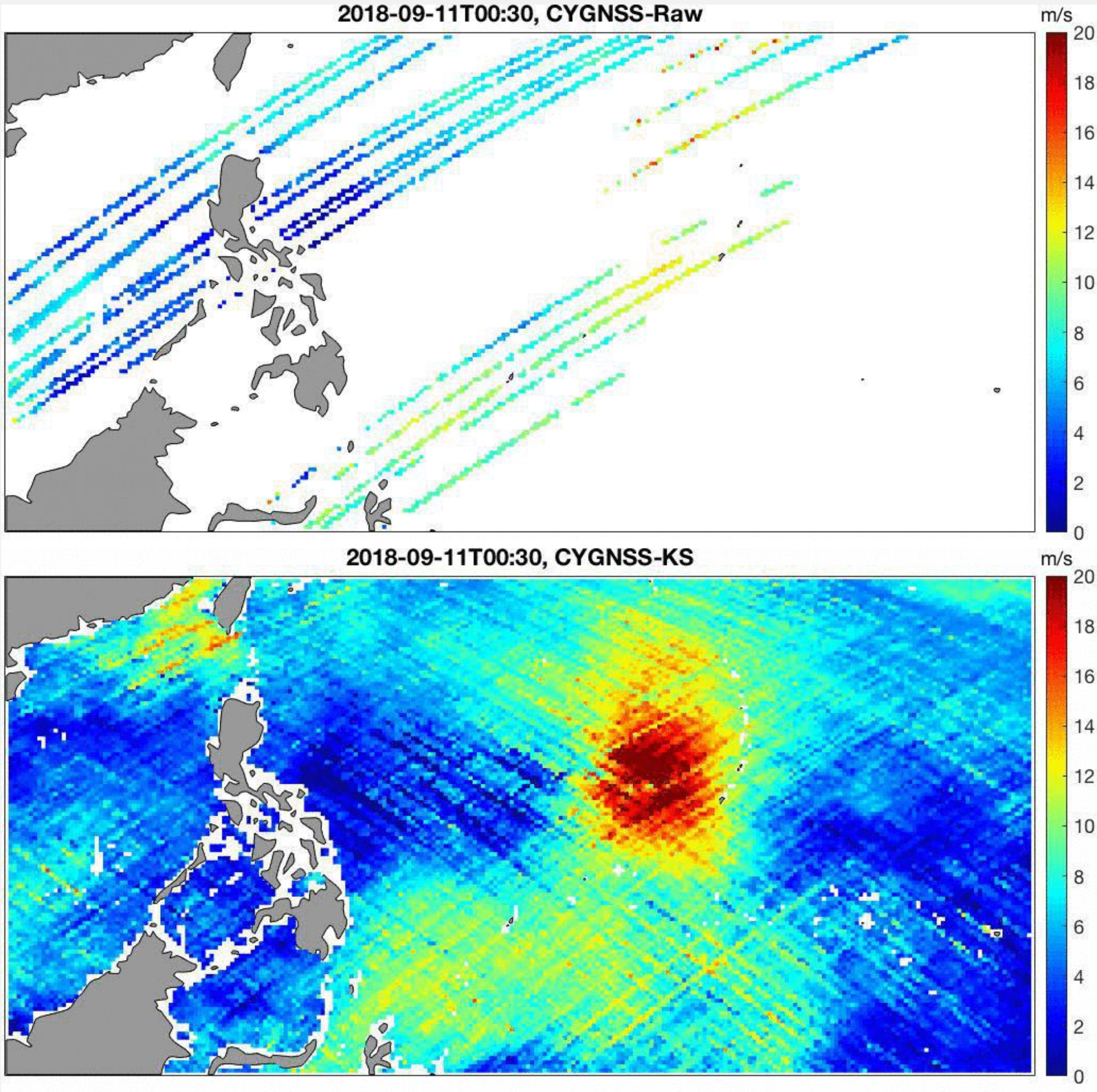


- The Kalman filtered estimates are now continuous in space and time (hourly resolution); they generally recover the large scale patterns very well; The filtered estimates are drawn towards the higher observed CYGNSS winds (not MERRA2).
- However, a remaining challenge is the artificial edges that get introduced as a result of applying the KF locally. We need to spread the information around in space as well. We've tested this with an OI but there are tradeoffs on space-time windowing to be considered.

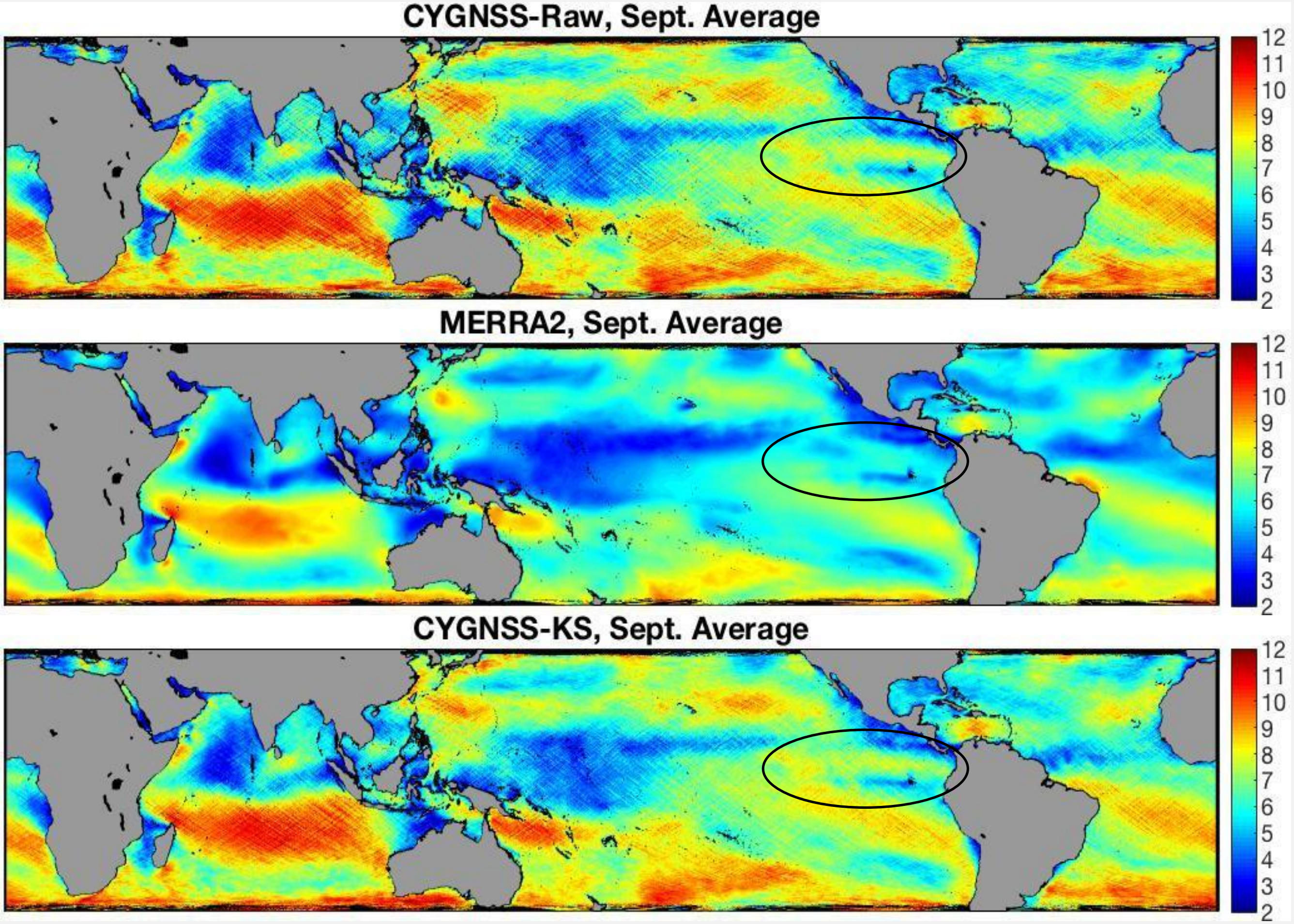
TYPHOON MANGKHUT ANIMATION

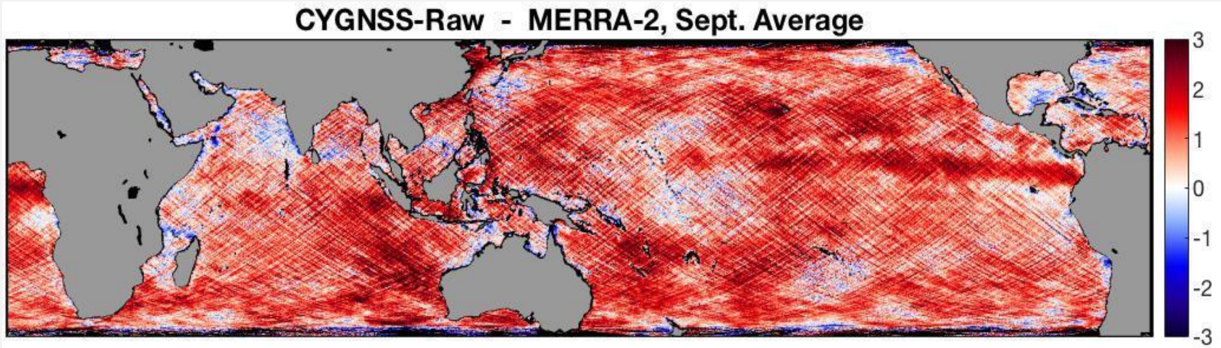
RAW AND KALMAN ESTIMATE

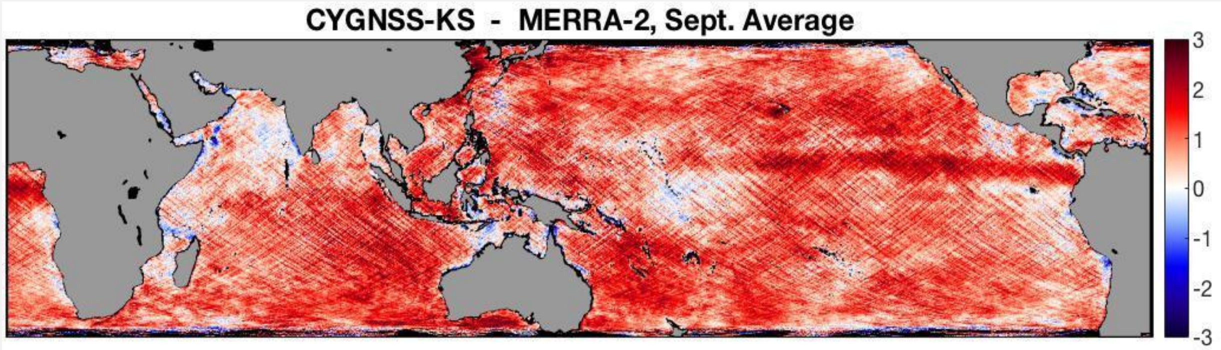
- Top panel shows the hourly evolution of sampling by CYGNSS (L3) wind speed estimates
- Bottom panel shows the gap-free hourly evolution upon using the Kalman smoother to combine the CYGNSS observed winds with MERRA2.
- With Kalman estimate, we can develop more complete estimates of area-average turbulent fluxes, including their temporal evolution



MONTHLY STATISTICS: MEAN

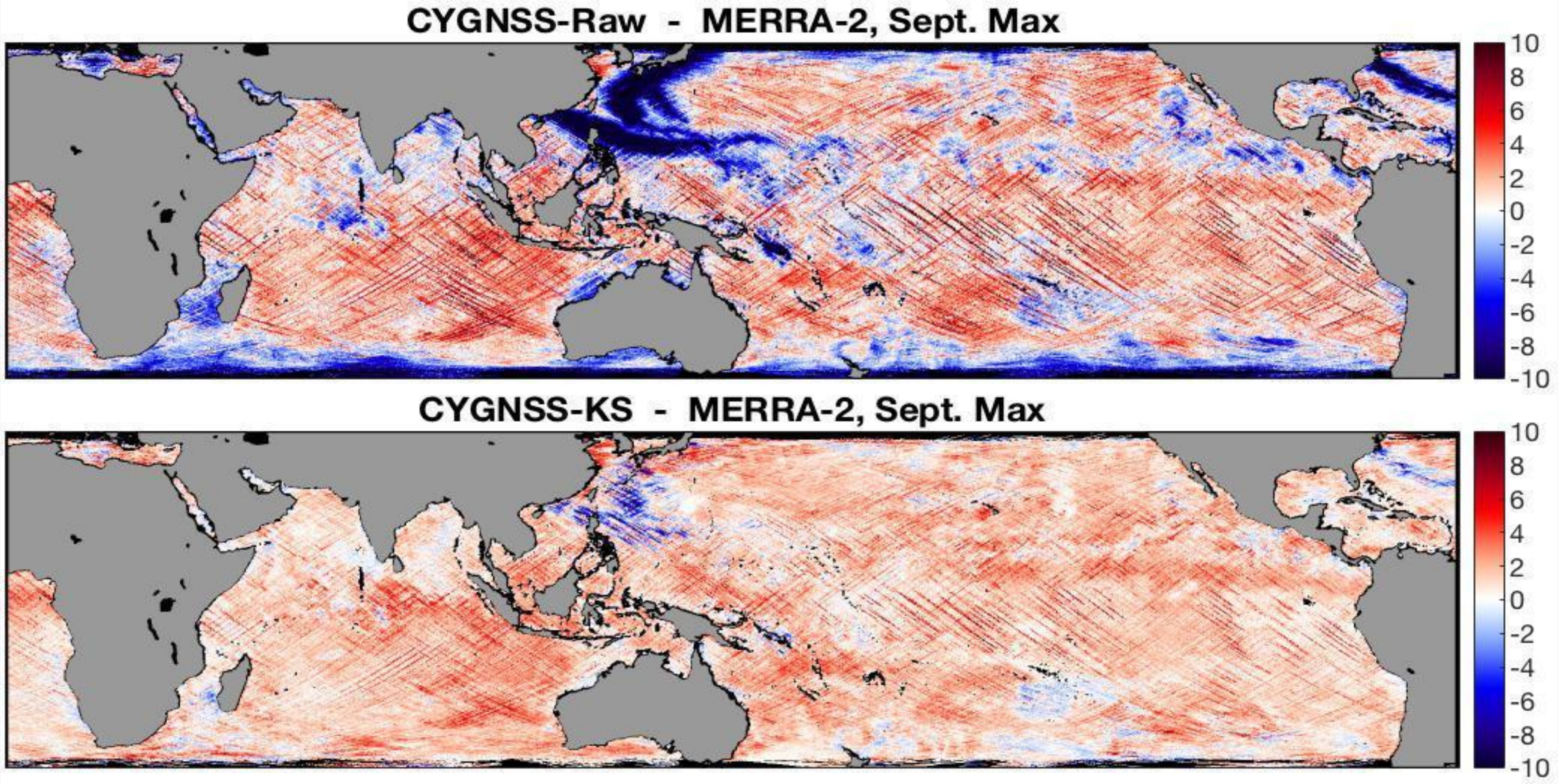






- The Kalman smoothed estimates result in a slightly smoother monthly average than the raw observations
- However, the general patterns and amplitudes of the Kalman estimates closely mirror the raw CYGNSS observations

MONTHLY STATISTICS: MAX WIND



- The CYGNSS raw samples show strong underestimation (compared to MERRA-2) of maximum observed wind in Sept. 2018. This is generally associated with the tropical cyclone storm tracks; This results from both the use of the fully-developed seas retrieval *and* sampling variability around the times of peak winds at a location.
- The Kalman estimates help strongly mitigate the underestimates related to sampling; but, it can't correct for the choice of using the fully-developed seas vs. limited-fetch retrievals

SUMMARY & FUTURE WORK

Summary

- The sampling variability of CYGNSS can impact its utility for performing analyses of air-sea interaction (e.g. turbulent fluxes).
- Using the raw CYGNSS data alone, there is a tradeoff related to accumulating enough data in time to have a good spatial representation of tropical systems, in particular.
- However, CYGNSS does provide the unique all-weather observations needed to sample through many tropical systems where passive (and some active) microwave systems are unavailable.
- We have developed an implementation of a Kalman Filter to leverage continuous large-scale dynamical evolution fields (i.e. the model tendencies) together with CYGNSS observations to result in a gap-free wind field estimate that can be used to mitigate the need to tradeoff temporal resolution of rapidly evolving systems.

Future work

- Need to consider performing a spatial OI to mitigate the "edge" effects related to high pixel-to-pixel sampling variability. We have already developed code to do this but more testing is needed.
- Developing a single "best" wind estimate still requires addressing the choice of which of the CYGNSS wind speed estimates to use at any time and location (i.e. fully-developed-sea or limited-fetch)