Development & Early Results of the Surface Heat Flux Product for the CYGNSS Mission

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Introduction

- Latent (LHF) & sensible (SHF) heat fluxes aid in transport of heat & energy b/w atmosphere-ocean
  - Primarily driven by winds and air-sea differences in temperature and humidity
- Increase baroclinicity & instability within boundary layer, influencing climate/weather systems like:
  - Tropical Cyclones (TC)
  - Extratropical Cyclones (ETC)
  - Tropical Convection (e.g. MJO)
- Remote sensing instruments do not consistently provide estimates of LHF/SHF due to:
  - Signal attenuation from precipitation
  - Low spatial/temporal frequency
- The **Cyclone Global Navigation Satellite System (CYGNSS)** provides improved surface wind speeds observations over tropical and subtropical oceans
  - Combined with MERRA-2 for temperature and humidity, can be used to estimate LHF/SHF
- While CYGNSS is a tropical mission, its orbit will allow it to observe a large number of the high surface heat fluxes observed over the oceans (Fig. 1)

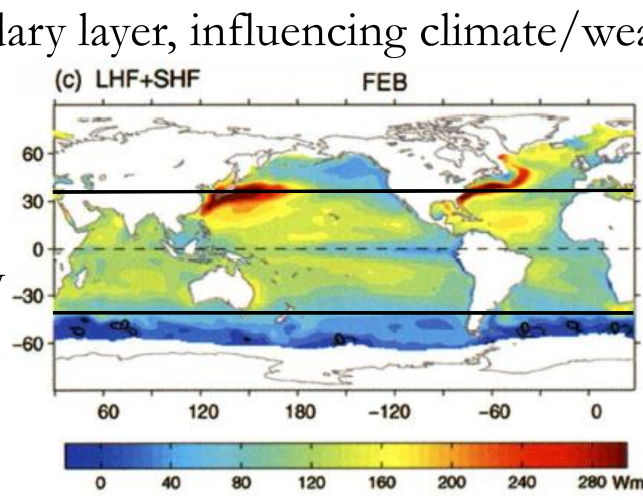

Fig. 1: Adapted from Yu & Weller (2007, BAMS), combined LHF+SHF climatological averages in February over the world's oceans. Black lines represent poleward extent of CYGNSS observations.

The resulting surface heat flux estimates from CYGNSS have been used to develop a Level-2 (L2) Surface Heat Flux product. It will be made publically available by Fall 2019, and will provide LHF and SHF estimates throughout the entire CYGNSS mission.

Data & Methods

Cyclone Global Navigation Satellite System (CYGNSS)

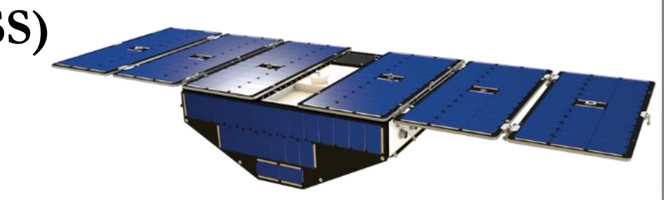

Fig. 2: Artistic visualization of one of the deployed CYGNSS observatories. *(Source: NASA)*

- 8 observatories (Fig. 2), low-orbit inclination of 35°
  - Antenna pattern view up to ±38°
- GPS L1 Channel (1575 MHz, 19-cm wavelength)
  - Does not attenuate in presence of precipitation
  - Up to four specular point observations per second per observatory (32 specular points per second for entire constellation)
- Two wind speed products: **Fully Developed Seas (FDS)**: assumes sea state in equilibrium with wind speed; **Young Seas Limited Fetch (YSLF)**: designed to capture sea states not in equilibrium with the local wind and matched with Stepped Frequency Microwave Radiometer (SFMR) observations from the NOAA P-3 Hurricane Hunters.

Coupled Ocean-Atmosphere Response Experiment (COARE) Algorithm

- Based on Monin-Obukhov Stability Theory (MOST) to estimate LHF and SHF over the ocean surfaces using the bulk aerodynamic formulas (**Eq. 1 & 2**)
- Parameterizes surface heat flux drag coefficients (C_D) as a function of gustiness, surface roughness, & atmospheric stability (**Eq. 3**)
- COARE 3.5 verified up to 25 m/s, yields accurate estimates over the open oceans.

$$LHF = \rho_a L_v C_{DE} U (q_s - q_a) \quad \text{(Eq. 1)}$$

$$SHF = \rho_a c_p C_{DH} U (T_s - T_a) \quad \text{(Eq. 2)}$$

$$C_D(z/z_o, z/L, G) = \frac{-\overline{uw}}{U_r S_r} = \frac{-\overline{uw}}{U_r^2 G} = \left[\frac{\kappa}{\ln(z/z_o) - \psi_m(z/L)}\right]^2 \quad \text{(Eq. 3)}$$

Preliminary Results of the CYGNSS Surface Heat Flux Product

As Hurricane Florence made landfall in September 2018, its center remained close to the coast as it travelled to the southwest, causing major coastal flooding in this region. Large latent heat fluxes (over 300 W/m^2) were observed as the center of the hurricane remained on the coast, possibly impacting the storm's development (Fig. 3). Given that CYGNSS's YSLF winds are higher than FDS winds, and therefore surpass the 25 m/s limit of the COARE algorithm, there are less observations associated with the LHF w/ YSLF winds product.

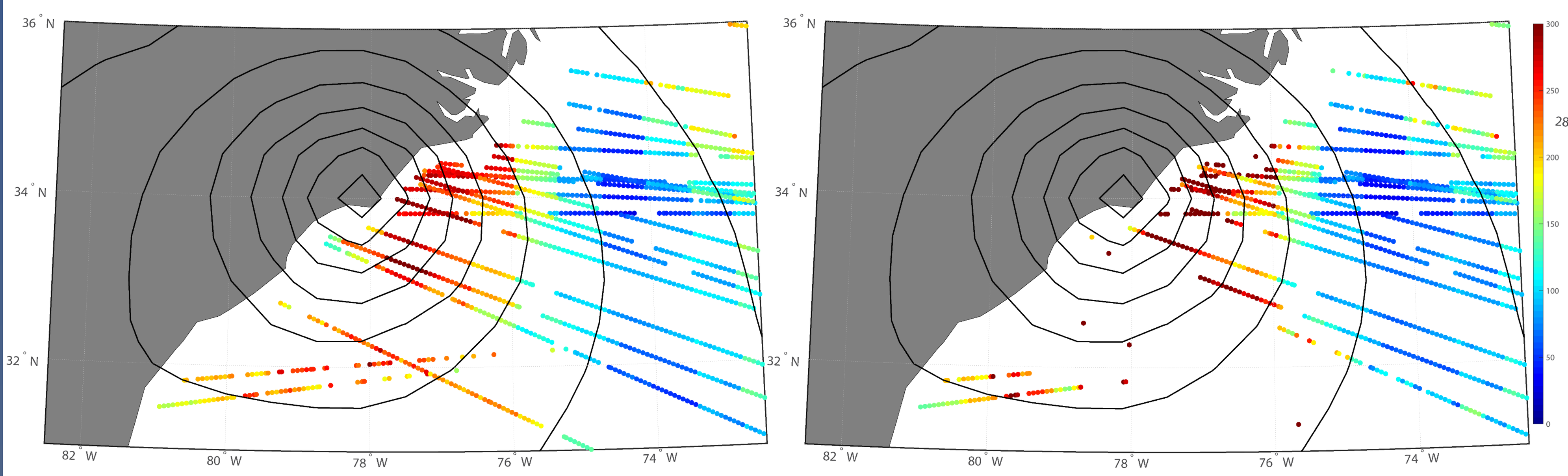

Fig. 3: Latent heat flux estimated with FDS winds (left) and with YSLF winds (right) for Hurricane Florence on 2018-09-14. MSLP (black contours) at 1800 UTC, with CYGNSS Observations ±3 hours from this time.

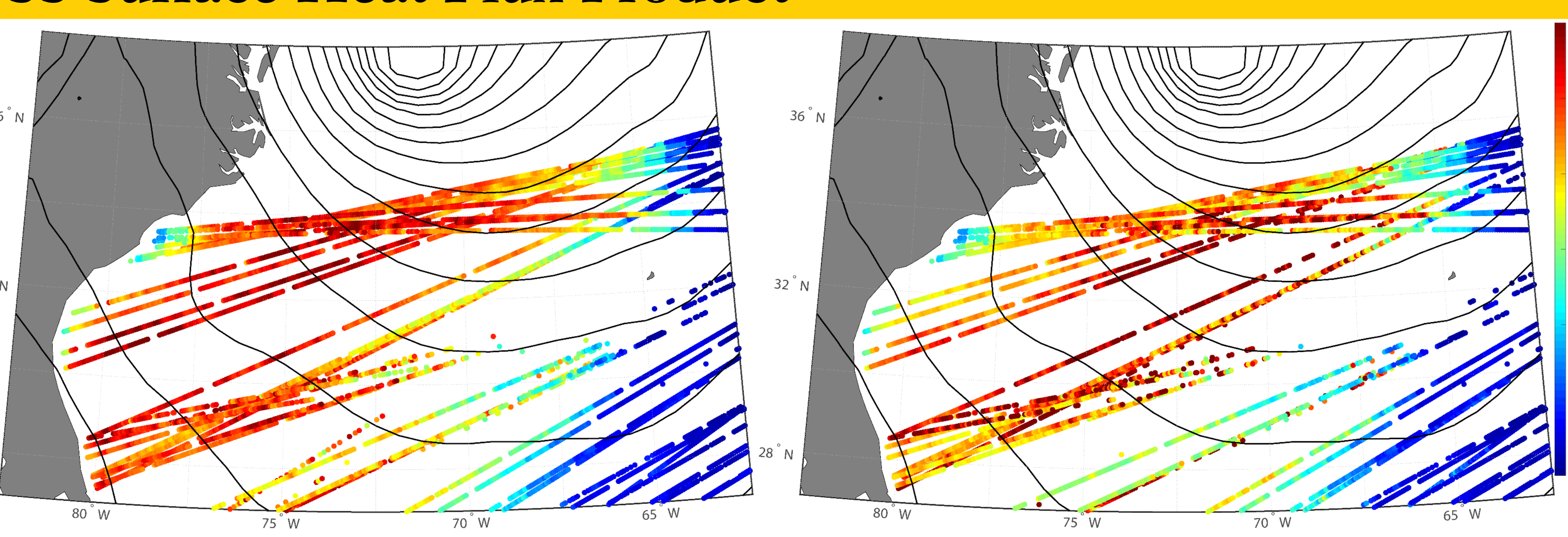

Fig. 4: Latent heat flux estimated with FDS winds (left) and with YSLF winds (right) for an extratropical cyclone on 2018-01-04. MSLP (black contours) at 1500 UTC, with CYGNSS Observations ±3 hours from this time.

In early January 2018, a rapidly developing extratropical cyclone (aka: '*bomb cyclone*') developed off the US East Coast, and produced a significant amount of snowfall. CYGNSS observed the equatorward side of the ETC, observing the large latent heat flux values (over 600 W/m^2) associated with this system (Fig. 4). While YSLF gives one higher fluxes than FDS, it can sometimes yield noisier results than the LHF/SHF product with FDS winds.

Comparisons with Buoy Data

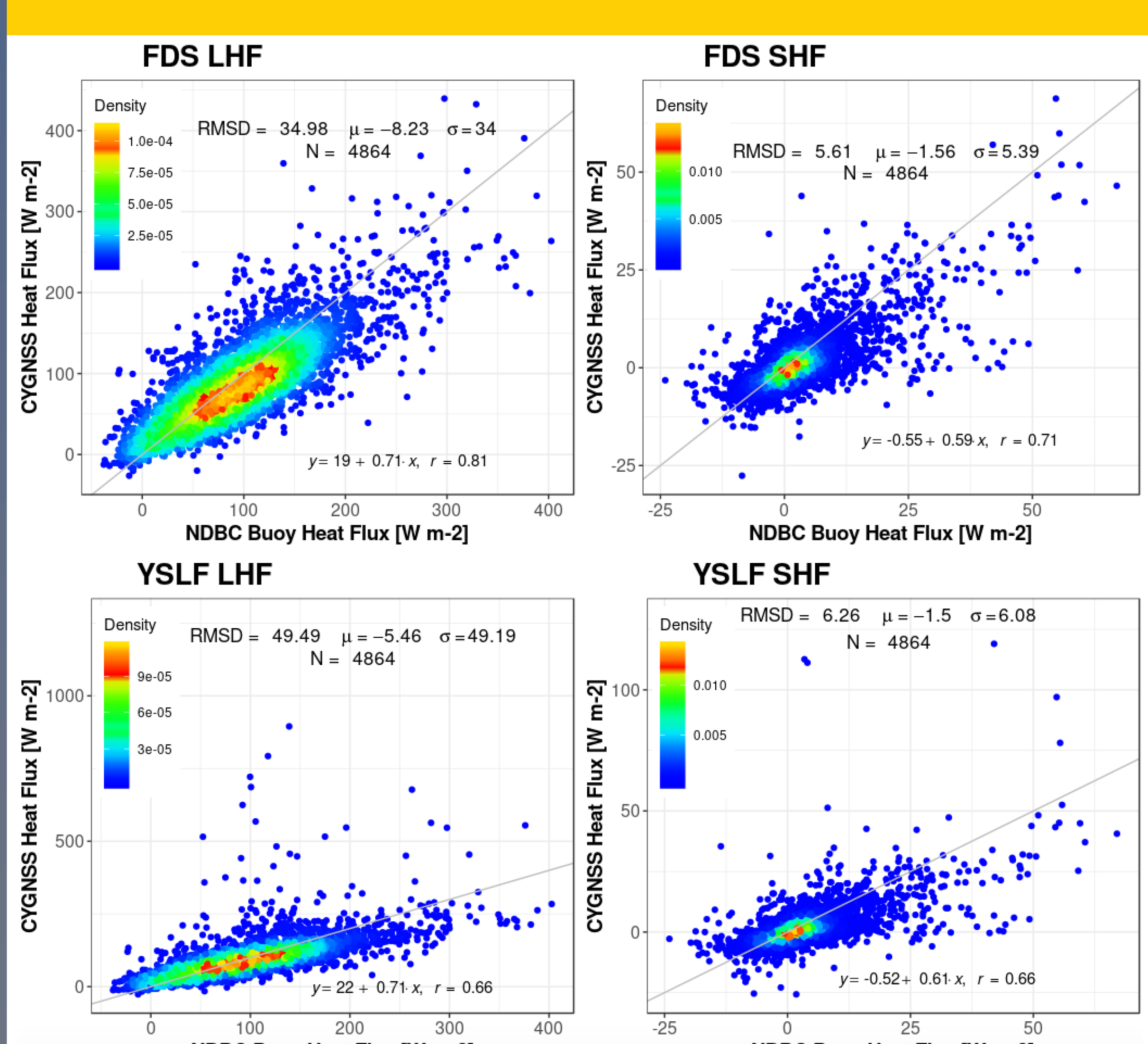

Fig. 5: Buoy comparisons of CYGNSS LHF (left) and SHF (right) products that use FDS (top) and YSLF (bottom) surface winds.

Comparisons of LHF/SHF estimates between the CYGNSS Surface Heat Flux Product and data from the **Kuroshio Extension Observatory (KEO)** buoy and **National Data Buoy Center (NDBC)** show how well the CYGNSS fluxes compares to ground truth data.

- CYGNSS heat flux estimates compare well to the buoy data, at lower flux values, with slight underestimate (Fig. 5)
- Greater scatter and disagreement at higher fluxes between CYGNSS and the buoy data (Fig. 5)
- Differences between CYGNSS LHF/SHF & buoy estimate increases as buoy fluxes increase (Fig. 6)
  - Though CYGNSS is underestimating higher wind speeds, the difference is minimum under 10 m/s (Fig. 6)
- Other factors (i.e. MERRA-2) could impact flux estimates
  - Difference b/w air temperature & SST (*airt-sst*) (Fig. 6)
  - Further analysis and more ground truth data at higher fluxes are needed to address these differences

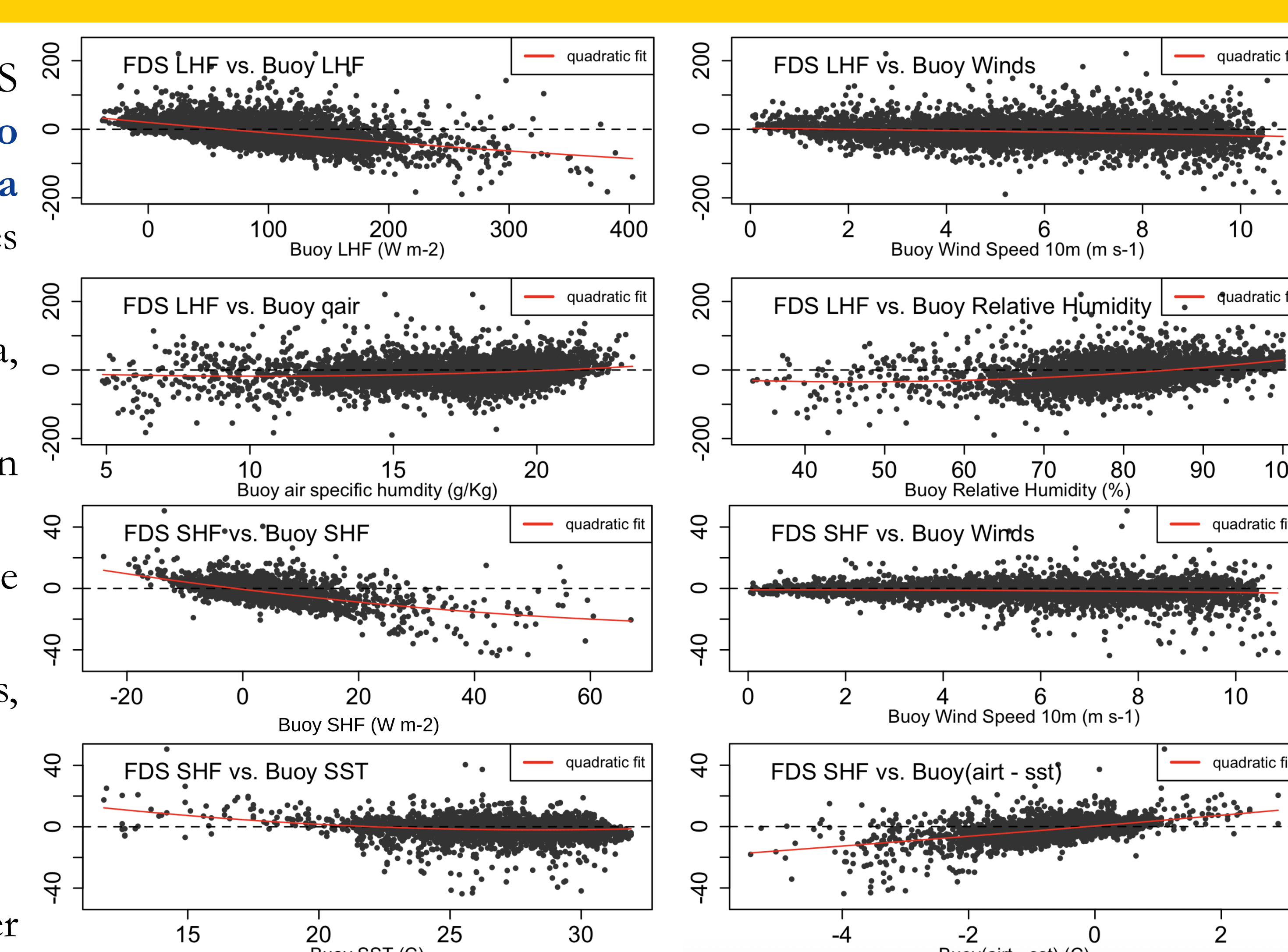

Fig. 6: How differences between LHF (top 4) and SHF (bottom 4) and buoy data vary among different variables associated with LHF/SHF estimations.

Future Product Development

- Newer versions of the CYGNSS Level-2 Winds are expected to be an improvement over the current v2.1 data at higher wind speeds. This could lead to improved surface heat flux estimates, especially at higher wind speeds
- While MERRA-2 suffices for this initial release of the surface heat flux product, it can be limited as a reanalysis dataset, and has a long latency (2-3 weeks after a month has ended). Future versions of the product may utilize a different source for temperature and humidity, though that is still being discussed.
- Future development is needed in order to estimate LHF/SHF with wind speeds greater than 25 m/s due to uncertainties regarding the drag coefficient and the impact of sea salt spray on LHF/SHF at high wind speeds.

Conclusions

- We have developed a Level-2 Surface Heat Flux Product for the entire CYGNSS mission by utilizing its L2 winds combined with MERRA-2 reanalysis data.
- The product offers good estimates at lower values, underestimates higher valued fluxes as CYGNSS underestimates higher wind speeds.
- Future improvements of the CYGNSS L2 surface wind speed observations could improve higher heat flux estimates.
- Initial product release made available through Physical Oceanography Distributed Active Archive Center (PO.DAAC) by Fall 2019.

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