Using new global Sentinel SAR data to investigate organized eddies in the marine boundary layer

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Background

- Marine atmospheric boundary layer (MABL)
  - 1-2 km deep
  - Turbulent air-sea transfers all occur here
- Roll vortices in the MABL
  - Quasi-coherent turbulent structure
  - Theory: Forced by **shear AND convection**
  - Eddies span depth of ABL – h_{ABL} sets L
  - Surface L of *O*(3-5*h) -> 2-5 km
  - Largely unresolved non-local turb. flux
  - Poorly or un-parameterized in current numerical weather and climate models
  - Common, but unclear on prevalence
- Lack of systematic observation
  - Radar, lidar, tower and aircraft observations are limited to mostly field experiments
  - Cloud top analyses
  - Calipso lidar on A-Train, profiling
  - Synthetic aperture radar (SAR) is known means, yet relatively untapped

(Brown 1980; Thompson et al. 1983; Etling and Brown 1993; Alpers et al. 1994; Atkinson et al. 1996; Lehner et al. 1998; Levy 2001; Young et al. 2002; Li et al. 2013; Li et al. 2013; Zhao et al. 2016; ......)

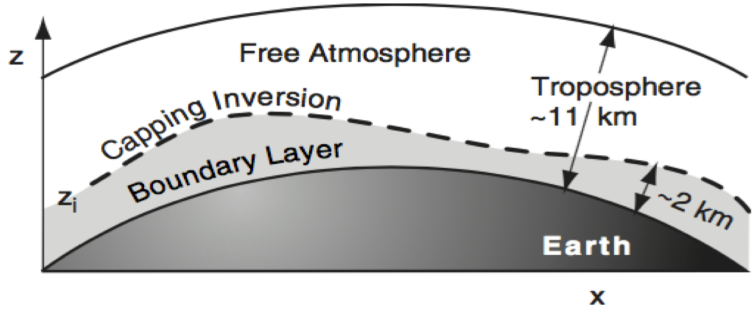


Figure 18.1
Location of the boundary layer, with top at z_i.

After Brown, R.A., 2000

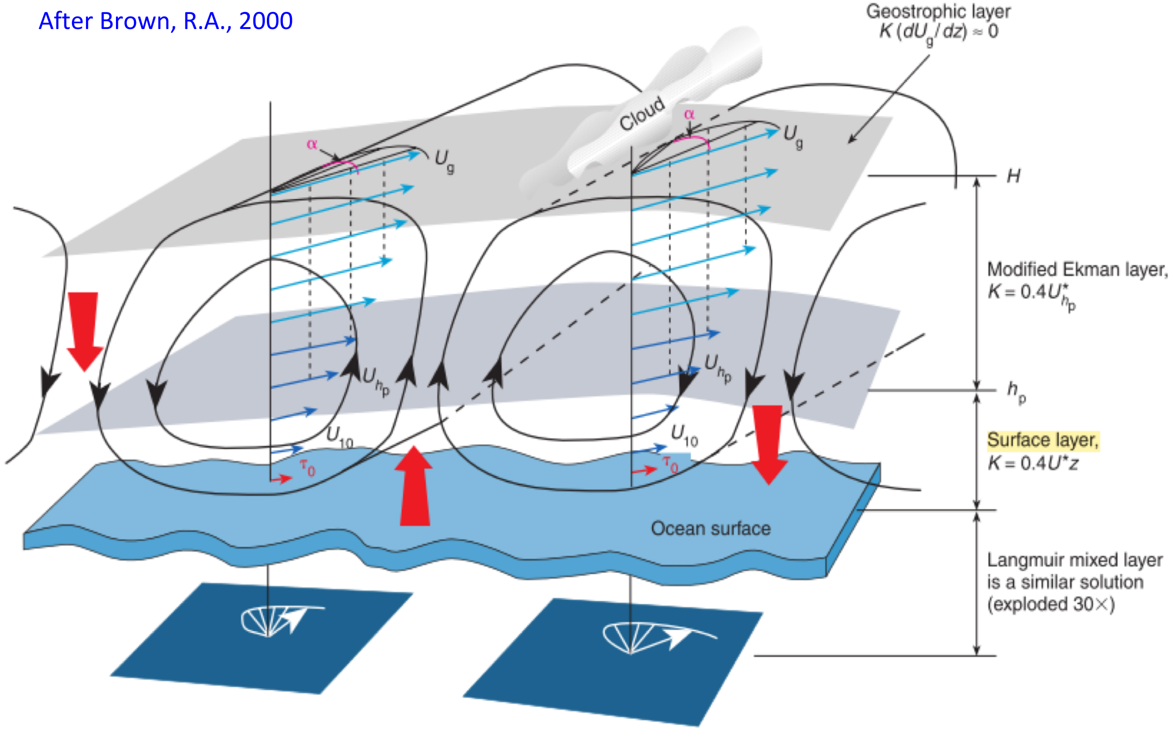


Figure 3. Sketch of two-layer similarity model for the PBL. Shown are boundary layers (modified Ekman layer, dark blue; surface layer, light blue, OLEs (circular patterns), geostrophic wind (U_g), patch height (h_p), 10-m wind (U_{10}), angle of turning (α), and surface stress (τ_0). (K = eddy viscosity, H = height of the geostropic layer, and U^* = surface friction velocity.) Large red vectors indicate direction of fluxes (momentum, heat, moisture, etc.).

Recall : OLE field also observed in QSCAT via UHR wind data (Plagge, Long et al. IGARSS 2008)

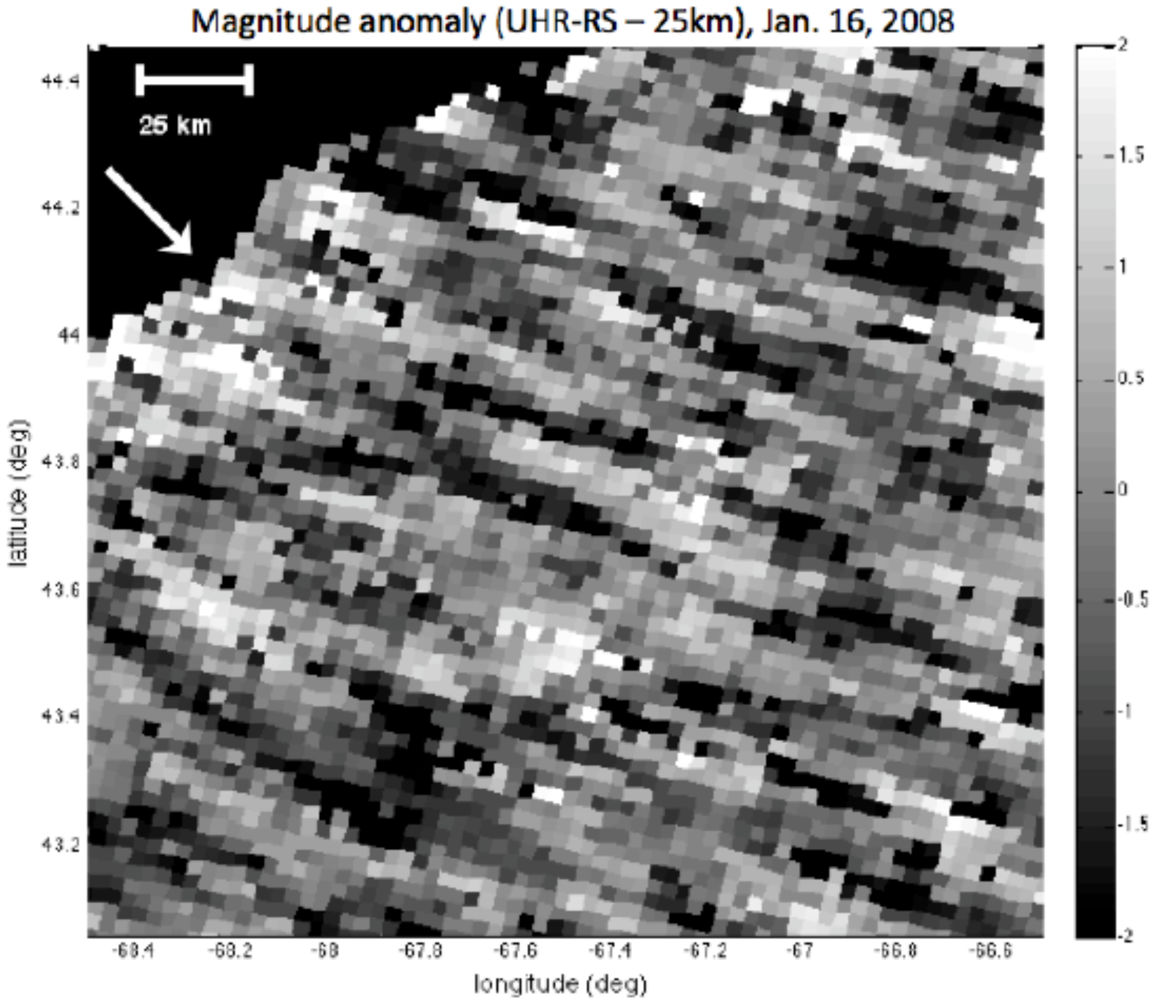
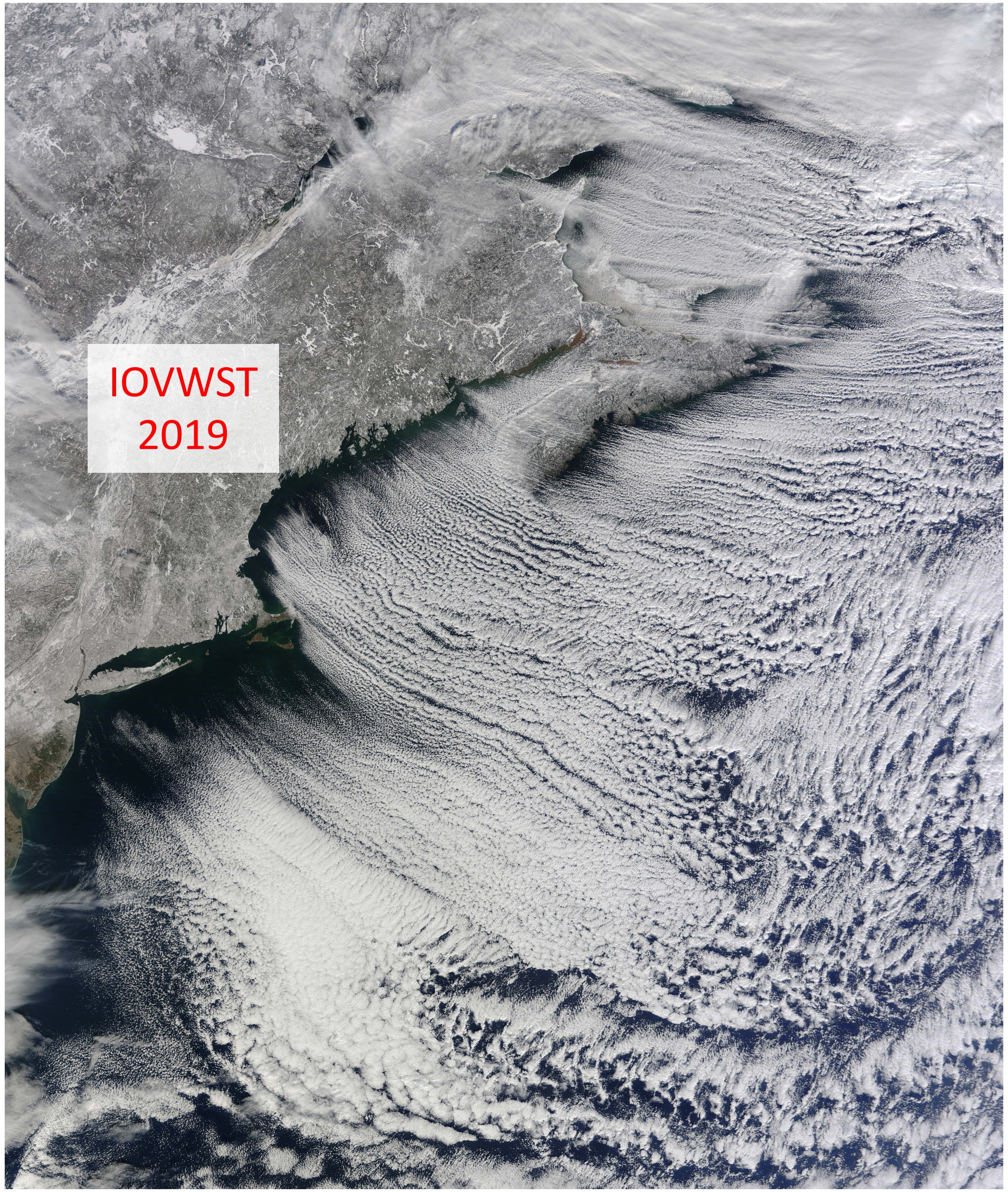


Fig. 8. Evidence of roll vortices during NW flow event, January 16, 2006. White arrow shows prevailing wind direction.



SENTINEL- 1A, -1B (1C,…) S1 SAR IMAGETTES/WAVE MODE = HI-RES (5 m) NRCS SNAPSHOTS

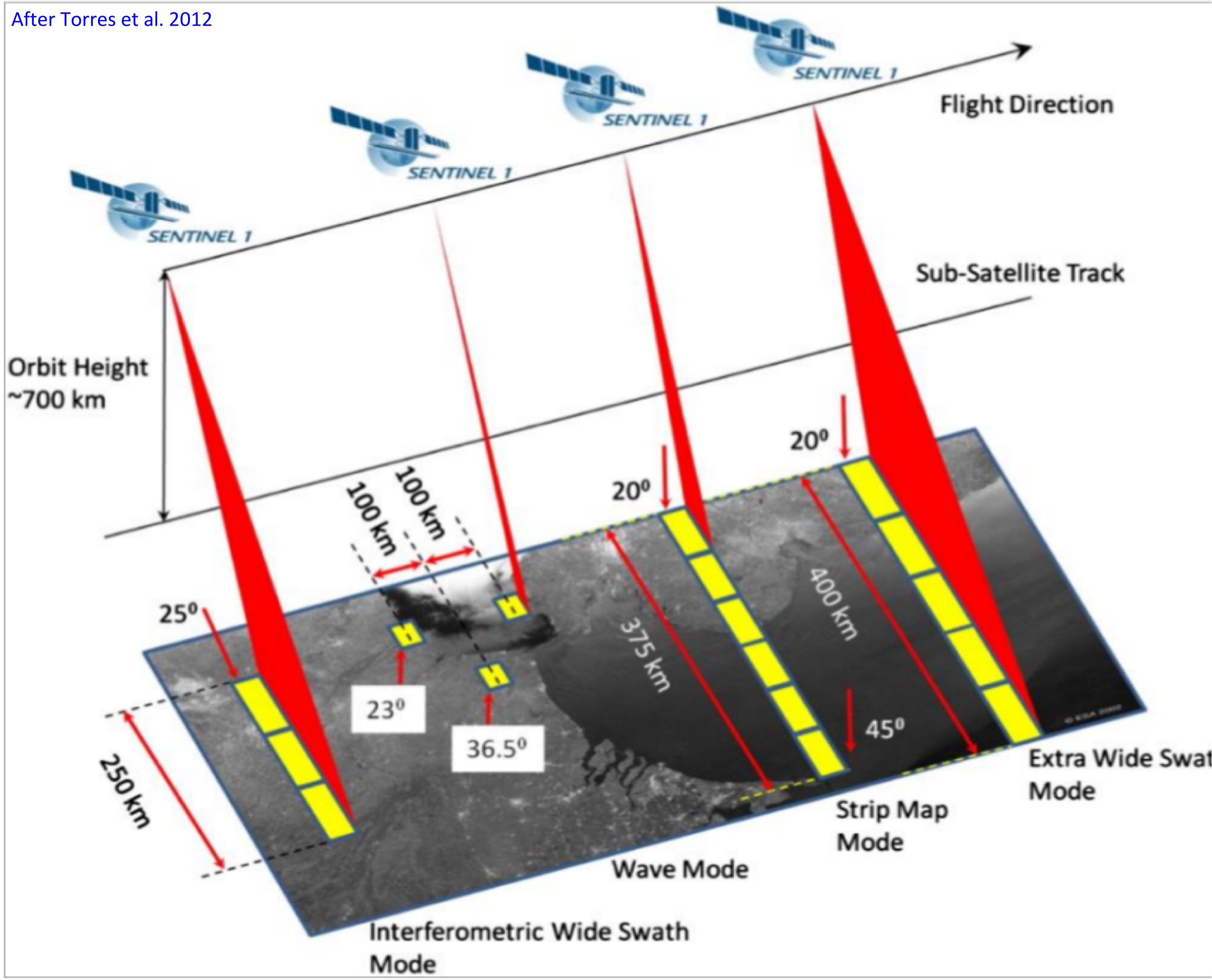
Satellite SAR data

- Sentinel-1A starting in 2016, S-1B in 2017
- 20 × 20 km, 5 m resolution SAR images
- Two incidence angles: 23° (WV1) and 36.5° (WV2)
- Routine acquisition, 15,000 WV2 images/month/satellite, from global open ocean
- Results from S-1A WV2 in 2016, 2017. ~642,000 in total
- Excluding data over island, sea ice and low signal quality
- Rolls signatures are frequently captured, visible as quasi-periodic patterns

Co-located Meteorological data

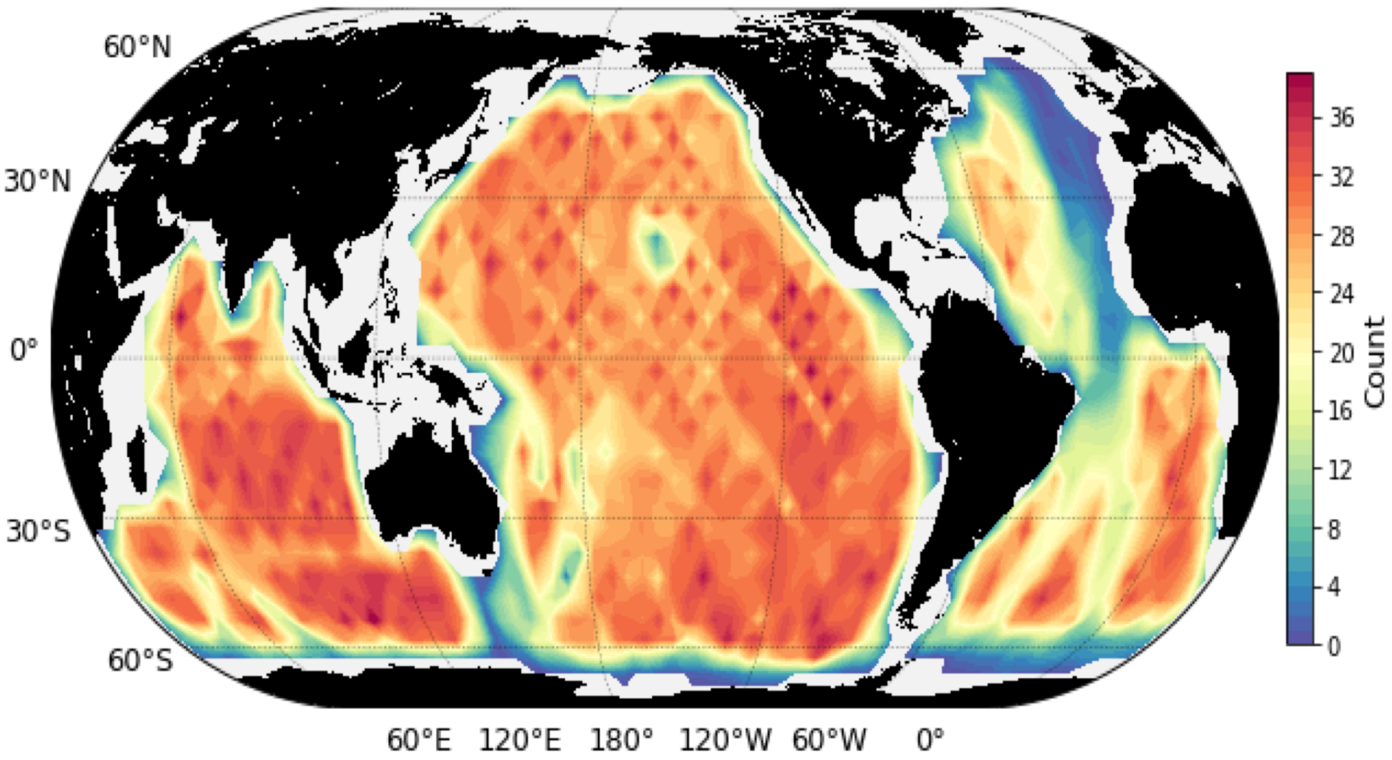
- ECMW forecast & ERA-5 reanalysis product
- 0.25°×0.25°, hourly
- Near surface variables incl PBL height, dP/dx/dP/dy
- Collocated with each WV2 SAR imagery
- Calculate U_{10}^N, ΔT_V, Ri_B^N (10-m height), using COARE

After Torres et al. 2012



SENTINEL- 1A, -1B (1C,…) S1 SAR IMAGETTES/WAVE MODE = HI-RES (5 m) NRCS SNAPSHOTS

Coverage very good in Pacific, Indian Ocean, and Southern Oceans



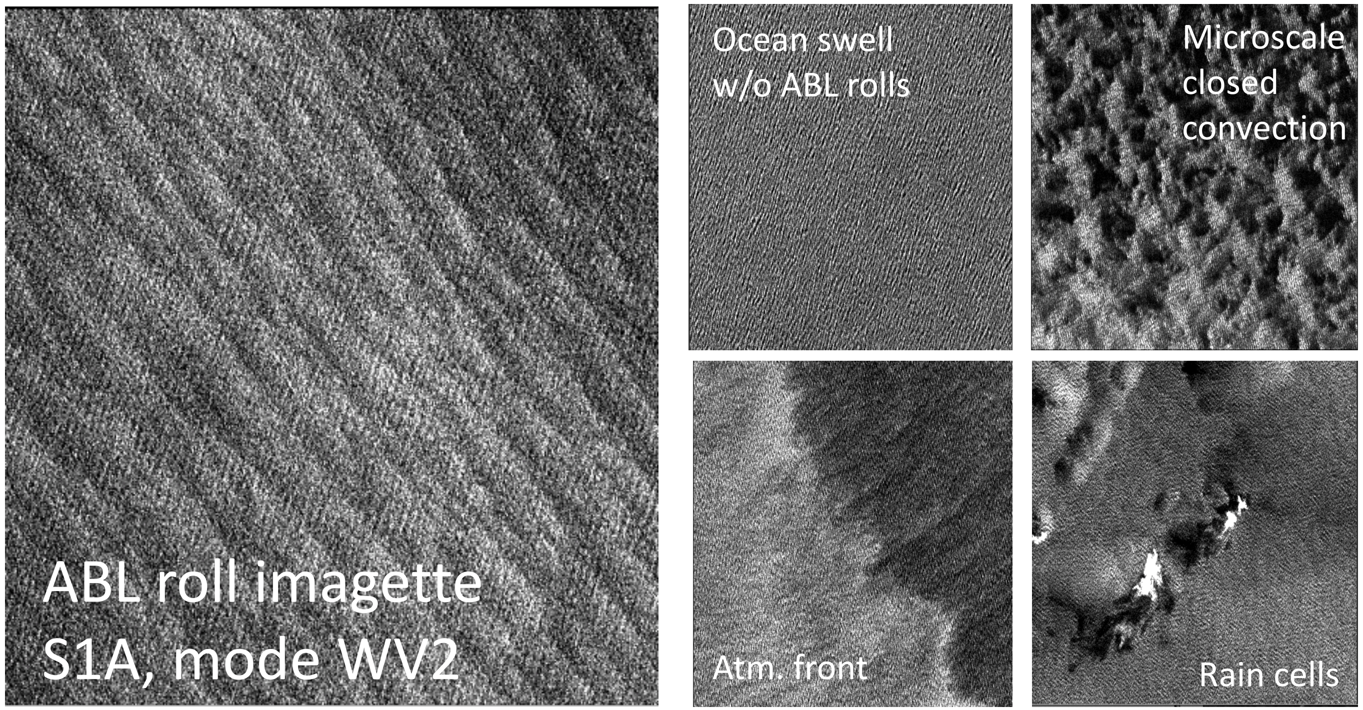
Spatial gridded monthly average of Sentinel-1A WV2 acquisitions in 2016 and 2017. The color denotes # SAR imagettes in each 5° by 5° grid box

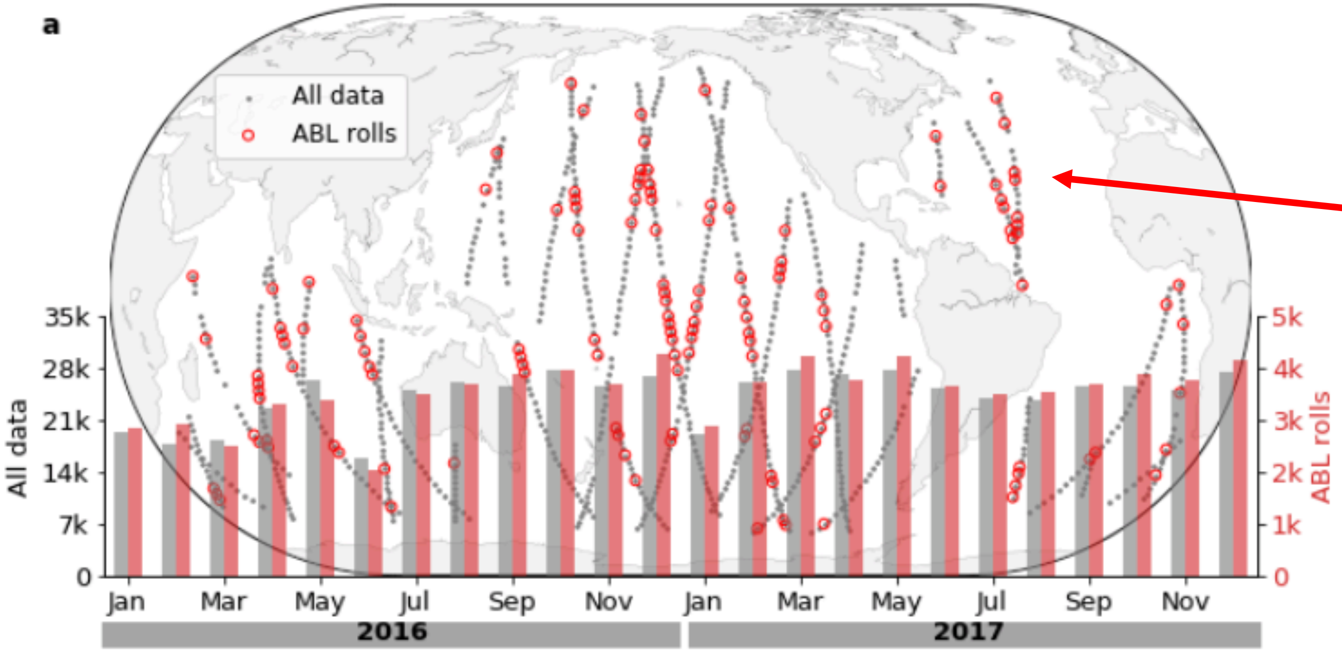
S1A ABL surface signatures resolved and classified – WV2

Many imagettes (200k+/year) – S1A

Sparse along-track sampling (100km) so similar to Aeolus

Automated TensorFlow CNN used to classify all images into 10 classes - imperfect but high confidence for most classes





4 ABL surface classes chosen:

- Organized large eddies (rolls)
- Closed cell convection
- Atmos. front
- Rain impacted

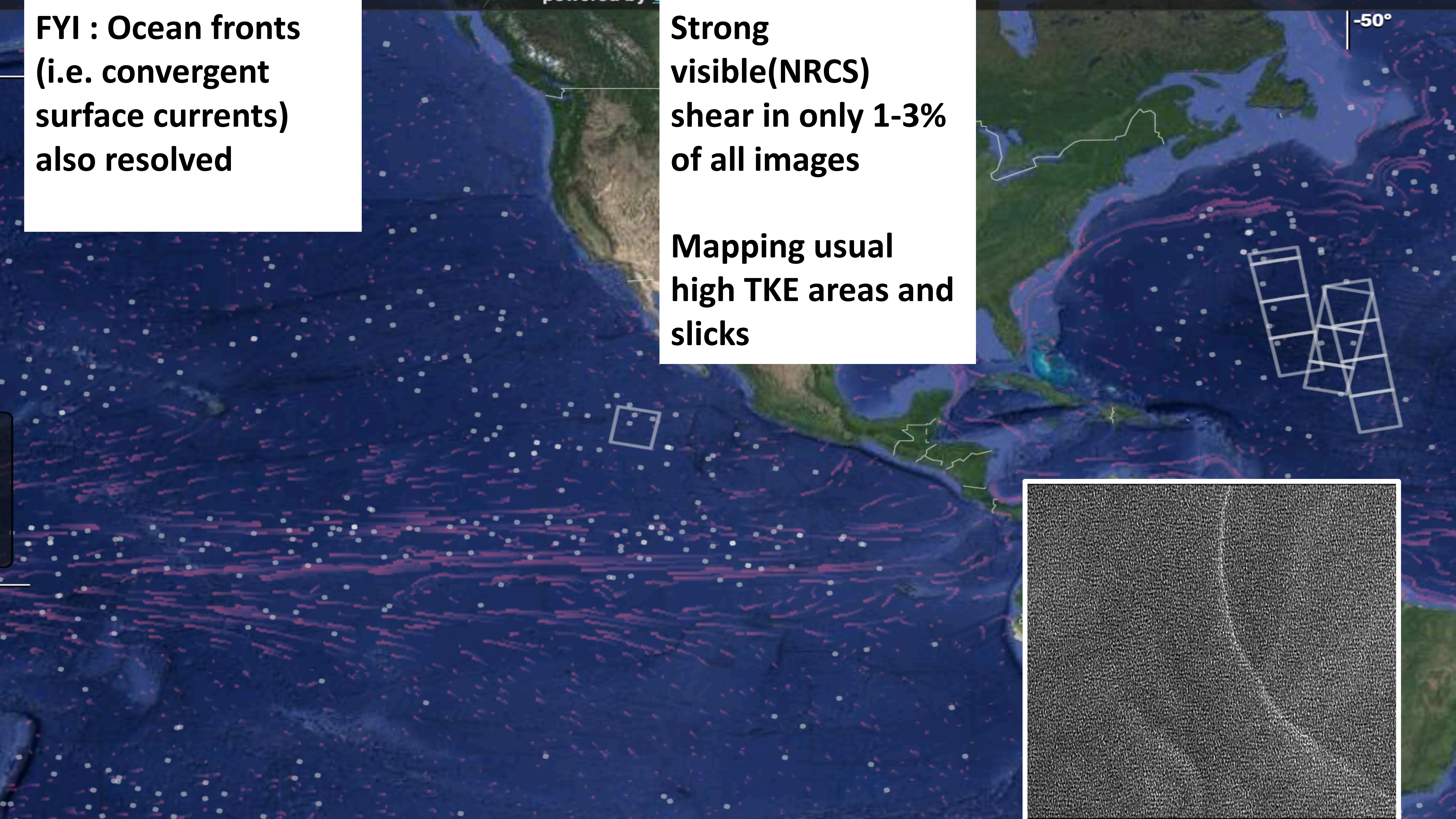
1 Day of detected OLE events

- 3k/month
- Lower limit, 20-30% OLE

FYI : Ocean fronts (i.e. convergent surface currents) also resolved

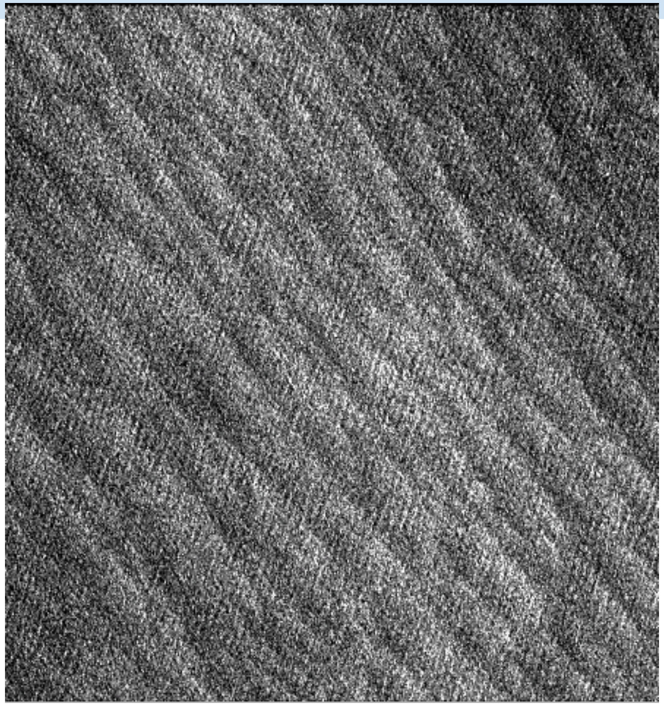
Strong visible(NRCS) shear in only 1-3% of all images

Mapping usual high TKE areas and slicks



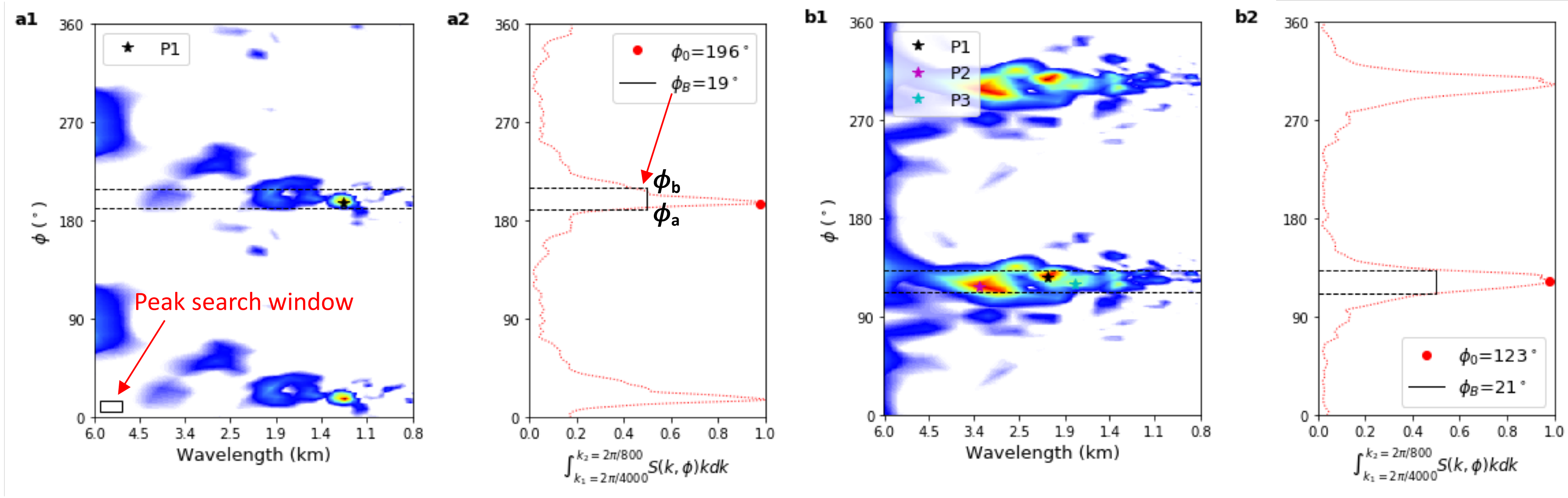
Back to OLEs

Spectral analysis for all imagettes – but focus then on T-Flow detected rolls for study 1



1. SAR image spectrum S(k, ϕ), through 2-D FFT
   a. symmetry, 0° and 90° correspond to the azimuth and rage direction on SAR image.
2. Dominant roll orientation $\boldsymbol{\phi_0}$, maximum of S(ϕ)= $\int_{k=2\pi/4000}^{k=2\pi/800} S(k,\phi)kdk$
3. Orientation band width $\boldsymbol{\phi_B=\phi_b-\phi_a}$, ½ power width of $\boldsymbol{\phi_0}$
4. Integrated energy E_0 of the OLE/roll spectral band $\int_{k_2=2\pi/6000}^{k_1=2\pi/800}\int_{\phi a}^{\phi b} S(k,\phi)kdkd\phi$
5. Peak detection within the spectral band, using local maximum.
6. Find top three most energetic peaks: P_i (i=1, 2, 3), sort with decreasing peaks energy (**E_i**)
7. Single, double and triple scale when $E_2<f*E_1$, $E_2>f*E_1$ & $E_3<f*E_1$ and $E_3>f*E_1$, where f=0.5
8. Peak wavelengths and orientations: $\boldsymbol{\lambda_i}$ and $\boldsymbol{\phi_i}$

Example 1: single peak



Example 2: two peaks

Multi-scale

Objectives & Results Tied to OLE investigations

QUESTIONS GOING IN:

Are OLE easily detected using S1 SAR WV data?

Do observed OLE length scales track with aspect ratio of 3-5 x PBLh ?

Does OLE orientation align between geostrophic and surface wind?

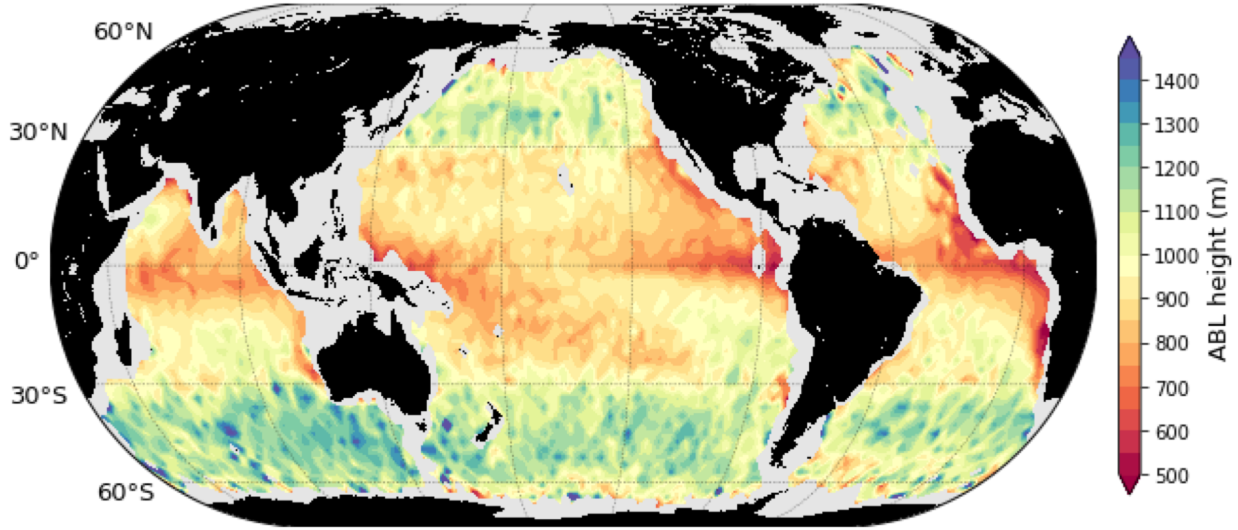
What are the ABL conditions (wind, stability, shear) when OLE are observed?

Where are they observed?

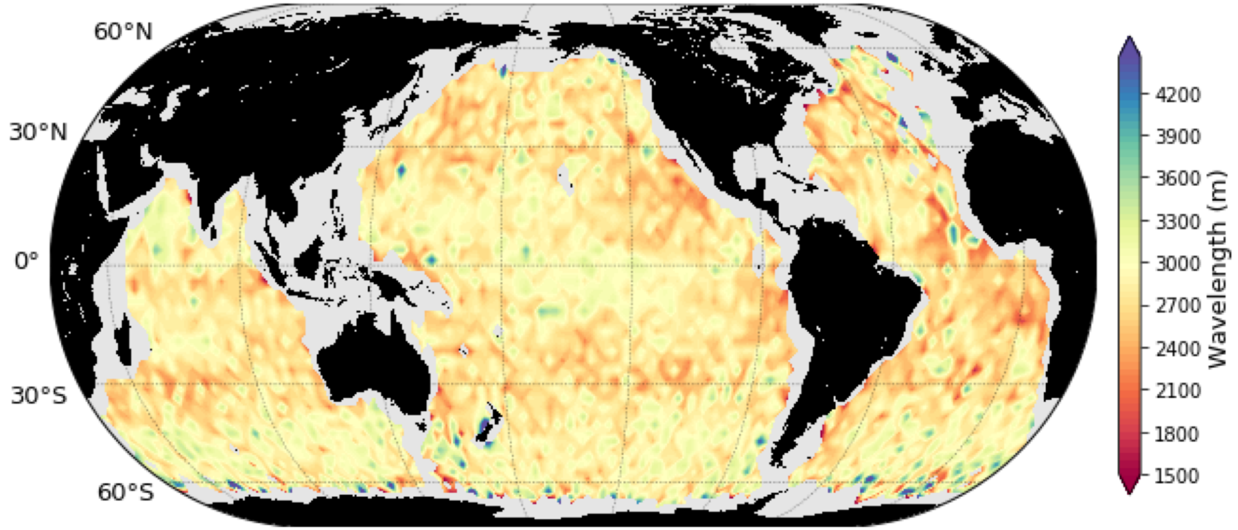
How variable are OLE characteristics and what controls this?

Can we relate S1-observed OLE structure to BL stability, BL height, etc…

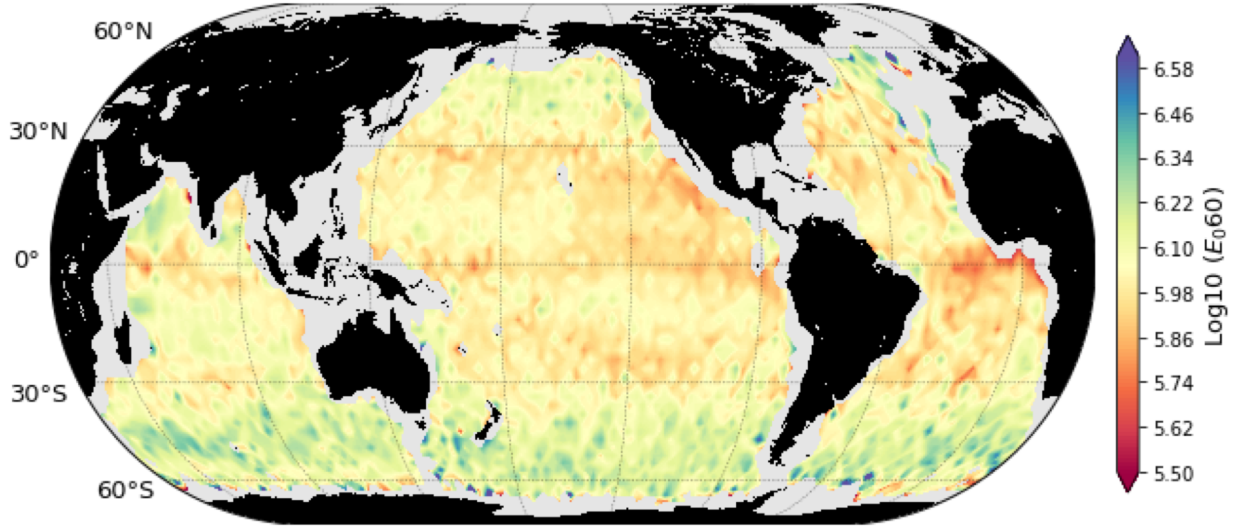
Results: OLE wavelength, energy, aspect ratio



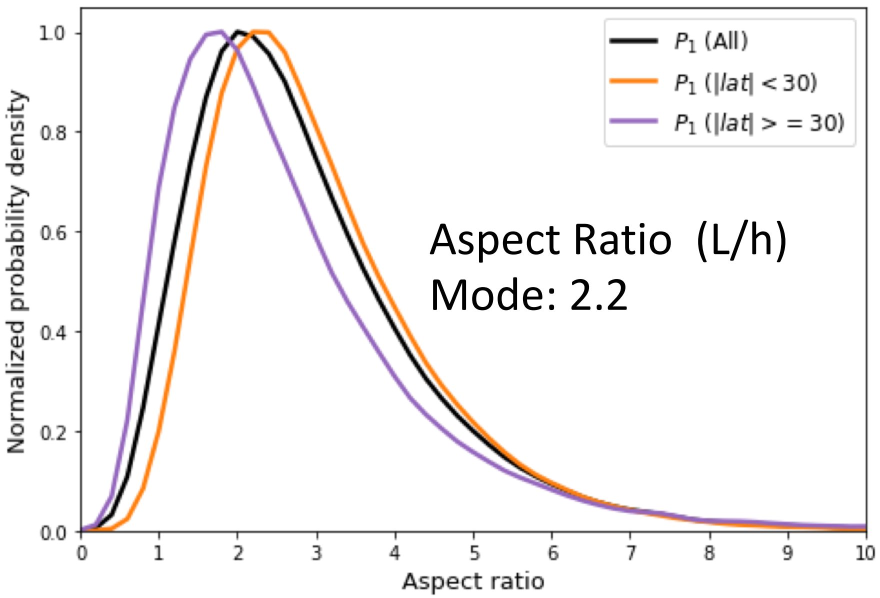
ERA-5 PBL height



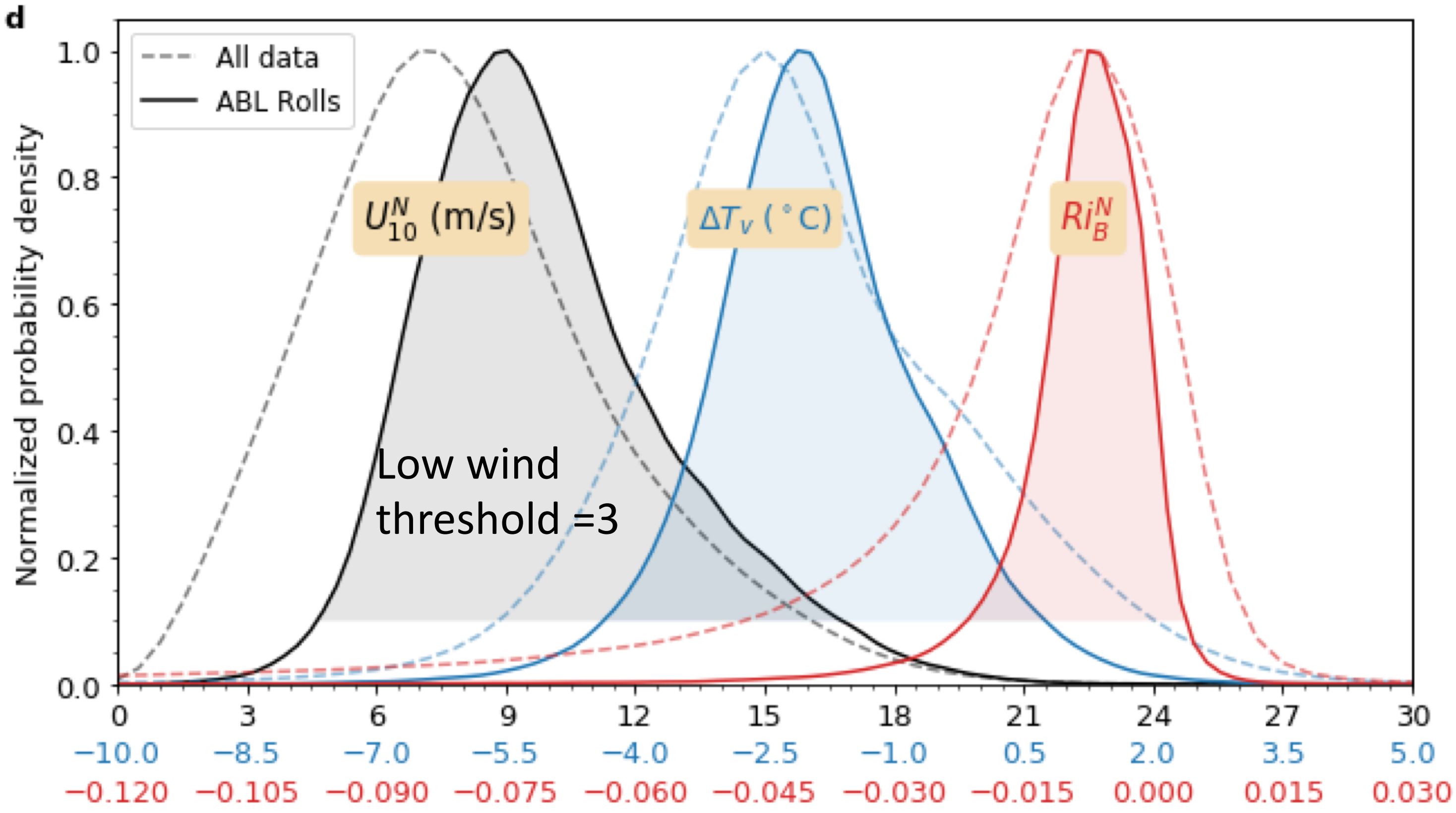
Mean OLE wavelength (~2.6 km)



Mean OLE
Peak energy



Results: Atmospheric conditions of roll occurrence

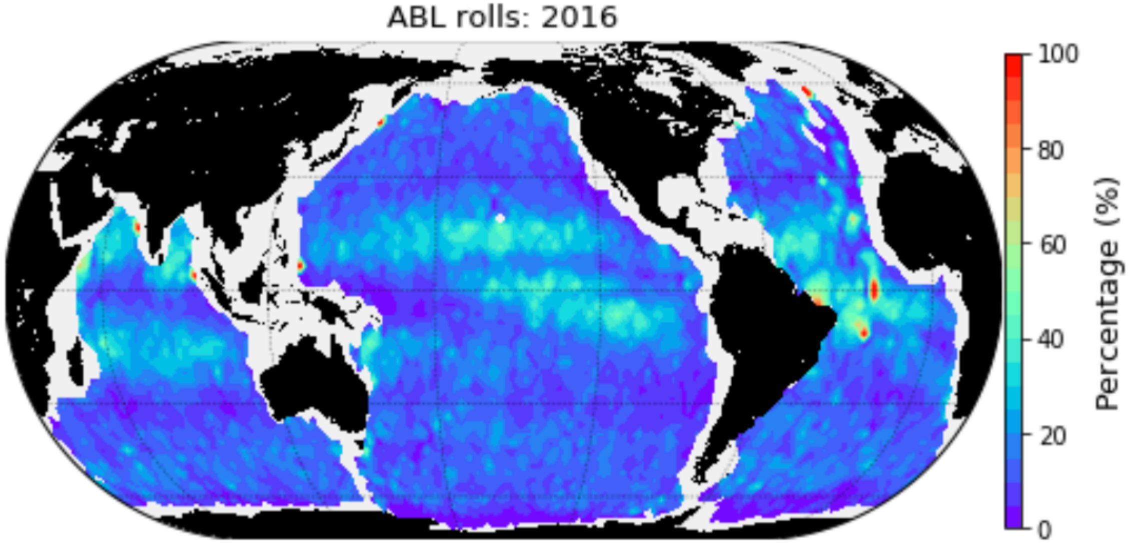


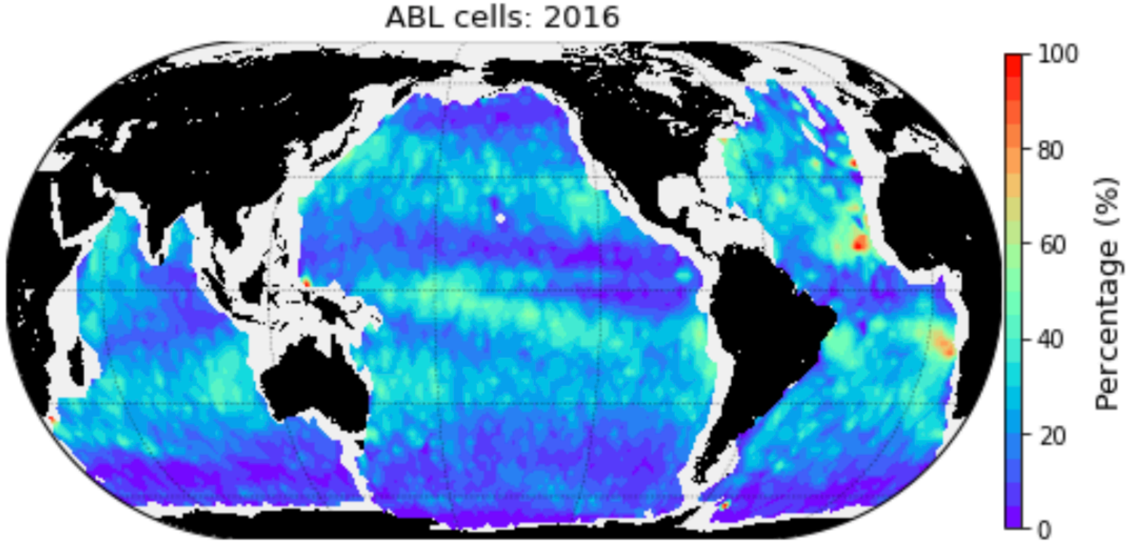
SOLID = OLE
DASHED =ALL

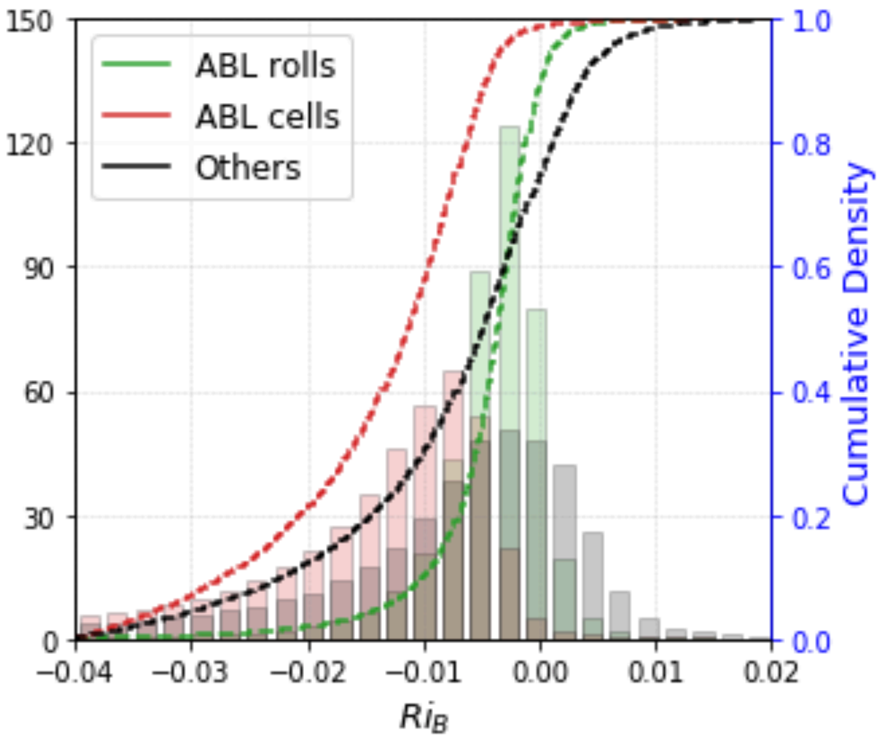
Narrow band of Richardson number for OLE vs. all data

- OLE Atmospheric conditions are **distinct** from the overall average conditions
- **Stronger surface wind**: 5-17 m/s, centred at 9 m/s
- **Less unstable Air-Surface temperature difference**: -4.5-0.5 °C, centered at -1.7 °C
- **Slightly unstable to near-neutral in Richardson number** (**expected**): -0.02-0.005, centred at -0.075

Results: Atmospheric conditions of rolls contrasts with closed cellular (isotropic)







- Unstable for cells, near neutral for OLE
- Quite distinct separation
- Should allow access to air-sea T

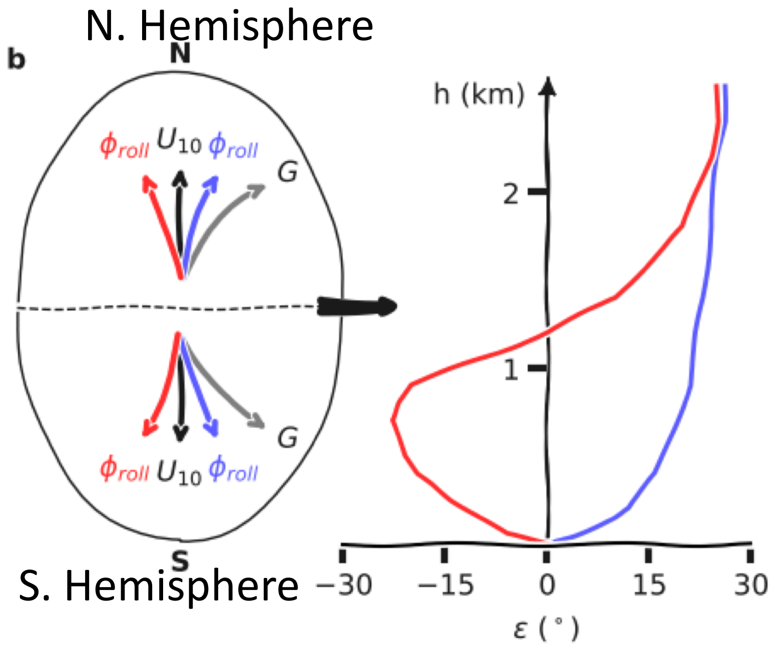
ALL NEW GLOBAL RESULTS AND VERY EXCITING

BUT…..

A MORE PUZZLING RESULT WITH ORIENTATION

Most Puzzling – what's a few degrees in wind direction amongst friends?

- Orientation of the OLE direction with respect to surface is expected to be -15 deg. in N. Hemisphere
- Lies between Surface and Geostrophic wind atop ABL
- **But – we see subtropical shift to OLE field that swings past surface wind direction????**

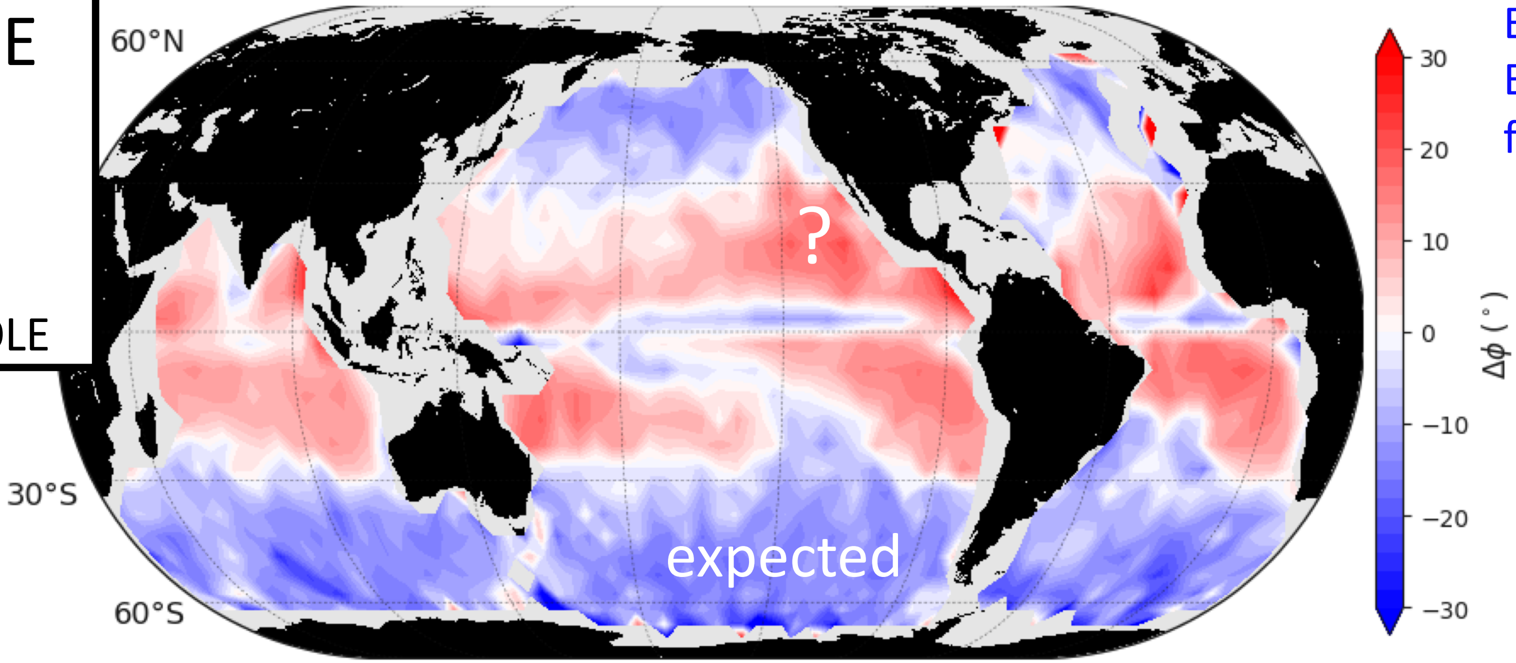


Inflection point, Type II instability with Ekman layer, Brown 1972

OLE vs. SURFACE WIND DIRECTION*

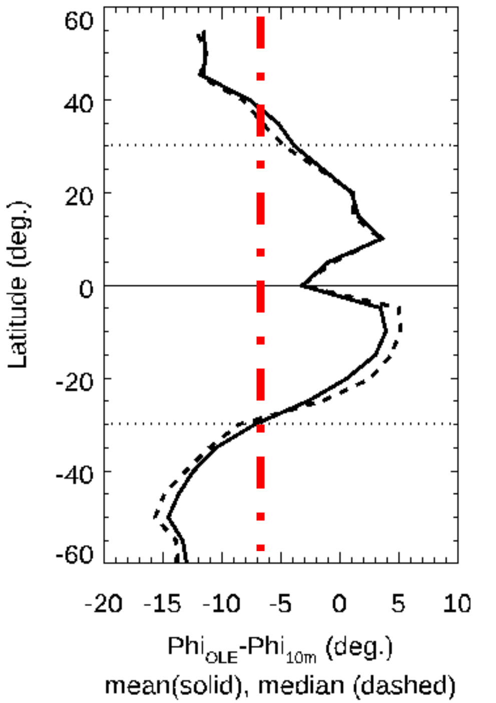
$\Delta\phi = \phi_{10m} - \phi_{OLE}$

*Sign flipped in S. Hem.

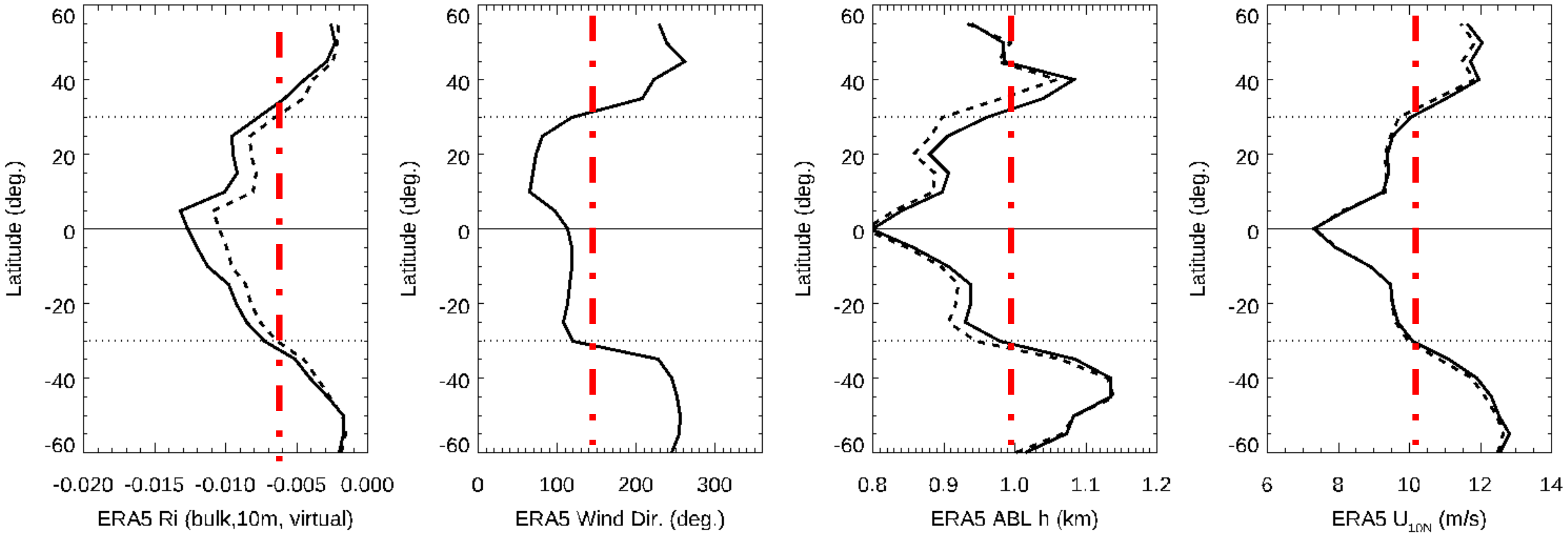


EXPECTED -18 deg. Based on most/all field data

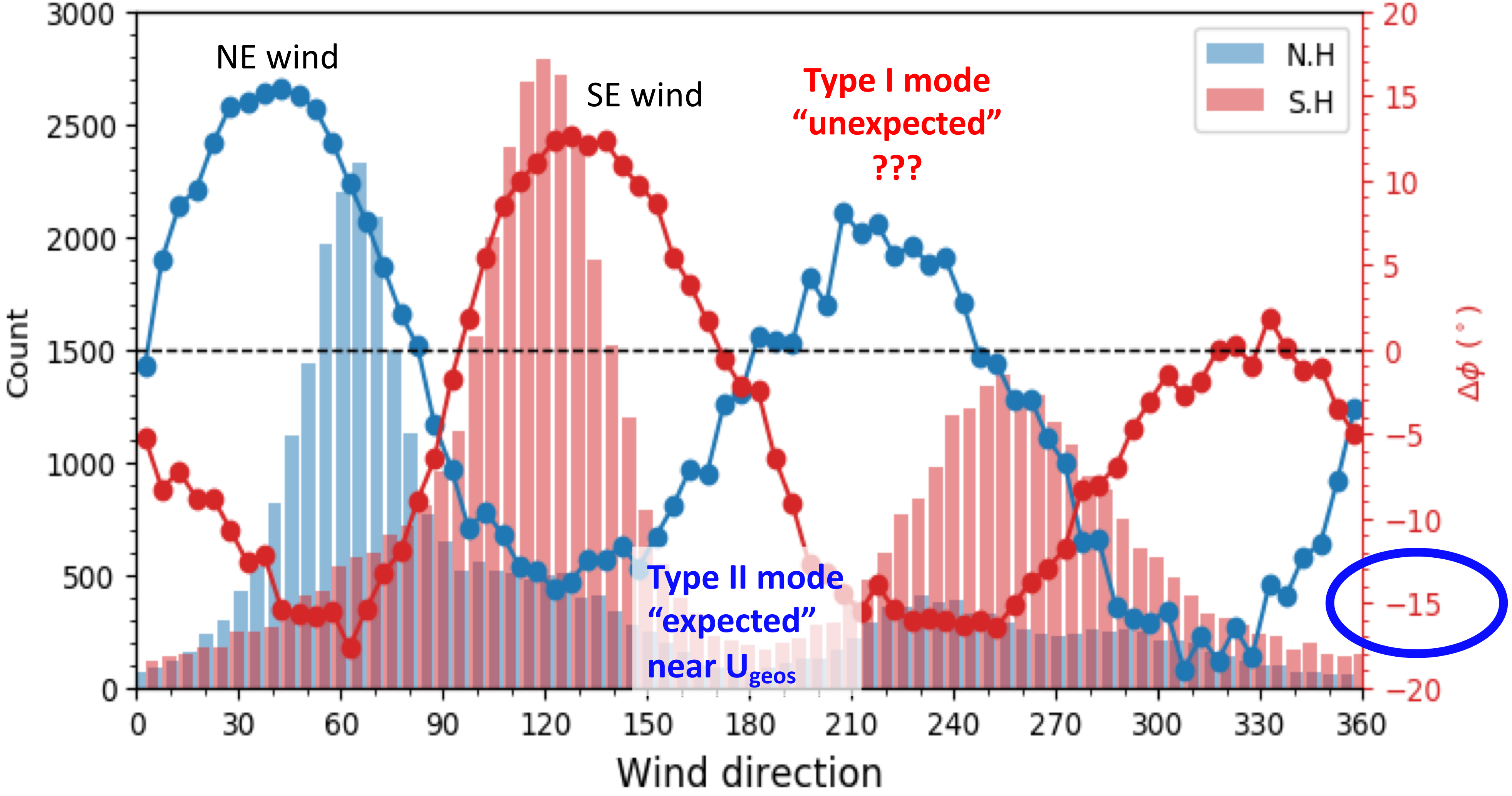
ATTRIBUTION



- Zonal-averaged Δϕ vs. latitude – global two year result
- Red line crosses data at 30 deg. latitude in S. Hemisphere
- Ri, ABL h, and wind all changing
- Maybe aligns best with wind direction shift to trades near equator?



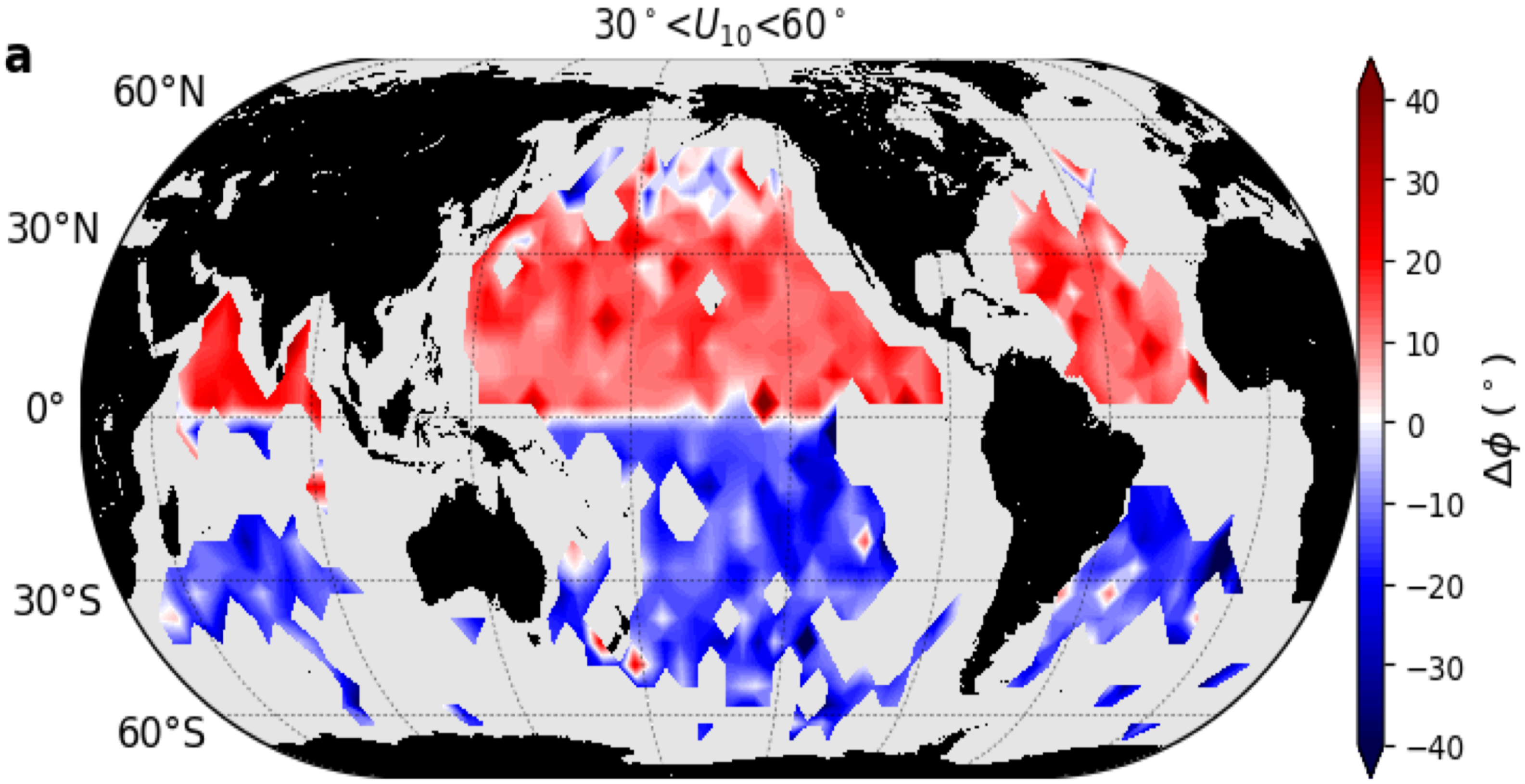
ROLL ORIENTATION WITH RESPECT TO WIND DIRECTION, BROKEN OUT BY HEMISPHERE



Type I mode
“unexpected”

Type II mode
“expected”
near U_{geos}

NORTHEAST WIND, MODE FLIPS HEMISPHERE FOR SAME WIND DIRECTION

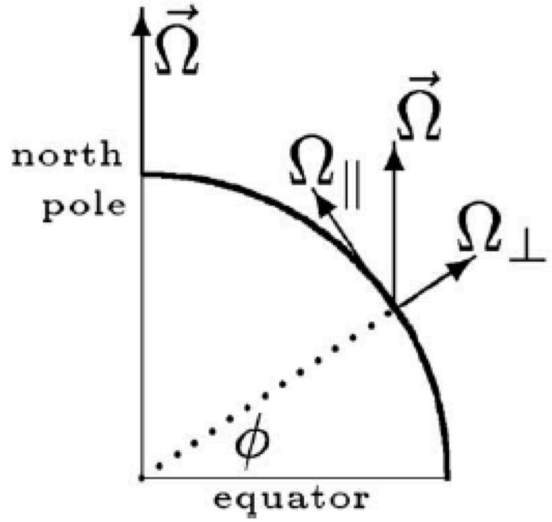


Type I mode
“unexpected”

Type II mode
“expected”

CONSISTENT WITH HOR. CORIOLIS FORCE IMPACTS

WIND DIRECTION IMPACTS ON ROLL FIELD ORIENTATION ? **LIKELY EXPLANATION IS HORIZONTAL CORIOLIS EFFECT**



$$-2\vec{\Omega}\,\mathrm{X}\,\vec{V} = \hat{\imath}(fv - f_h\,w) - \hat{\jmath}(fu) + \hat{k}(f_h u)$$

$$where \quad f = 2\Omega\,cos\lambda \;\; and \;\; f_h = 2\Omega\,cos\lambda)$$

Traditional approximation neglects f_h (thin-layer, Ekman), leaving isotropic f impacts:

$$-2\vec{\Omega}\,\mathrm{X}\,\vec{V} = \hat{\imath}(fv - \cancelto{0}{f_h w}) - \hat{\jmath}(fu) + \hat{k}(\cancelto{0}{f_h u})$$

But large eddies in ABL of rel. small scale h (1-3 km) but **long T scales** ($O(\Omega^{-1})$) where f_h may be non-negligible. Then:

Zonal winds (EW) ➔ vertical impact $(f_h\, u)\, \hat{k}$
Vertical flow (w) ➔ horizontal (zonal) impact $- (f_h\, w)\, \hat{\imath}$

NET EFFECT IN MOMENTUN PERT. IS WIND DIRECTION INFLUENCE ON ROLL FIELD VORTICITY/FORMATION/STRUCTURE :

- Easterly flows constructive, Westerly destructive in either hemisphere
- Predicted maximum TKE impacts for NE flow in N. Hemis. , but SE in S. Hemisphere (it flips)
- Effect should weaken as approach poles (> 50 deg.)
- Impact thought to be too weak to observe for OLE field…. (Etling 1971; Brown 1972)

Review:

Gerkema, T., J. T. F. Zimmerman, L. R. M. Maas, and H. van Haren (2008), Geophysical and astrophysical fluid dynamics beyond the traditional approximation, Rev. Geophys., 46, RG2004, doi:10.1029/2006RG000220.

Atmospheric Boundary Layers:

Lilly, D.K. 1966: Instability of Ekman boundary flow. J. Atmos. Sci.,23, 481-494.

Etling, D., 1971: Einfluß der thermischen Schichtung auf der Stabilitat einer Ekmanschen Grenzschichtstromung, Beitr. Phys. Atmos., 44, 168–186.

Leibovich, S., and S. Lele, 1985: The influence of the horizontal component of Earth's angular velocity on the instability of the Ekman layer. J. Fluid Mech., 150, 41–87.

Haeusser T. M. and S. Leibovich, 2003: Pattern Formation in the Marginally Unstable Ekman Layer, J. Fluid Mech. **479**, 125–144.

Glazunov, A. V.: **On the effect that the direction of geostrophic wind has on turbulence and quasi-ordered large-scale structures in the atmospheric boundary layer**, Izvestiya, Atmos. Ocean. Phys., 46, 727–747, 2010.

Oceanic Boundary Layers:

Garwood, R. W., P. C. Gallacher, and P. Muller (1985a), Wind direction and equilibrium mixed layer depth: General theory, J. Phys. Oceanogr., 15, 1325–1331.

Zikanov, O., D. N. Slinn, and M. R. Dhanak, 2003: Large eddy simulations of the wind-induced turbulent Ekman layer. J. Fluid Mech., 495, 343–368, https://doi.org/10.1017/S0022112003006244.

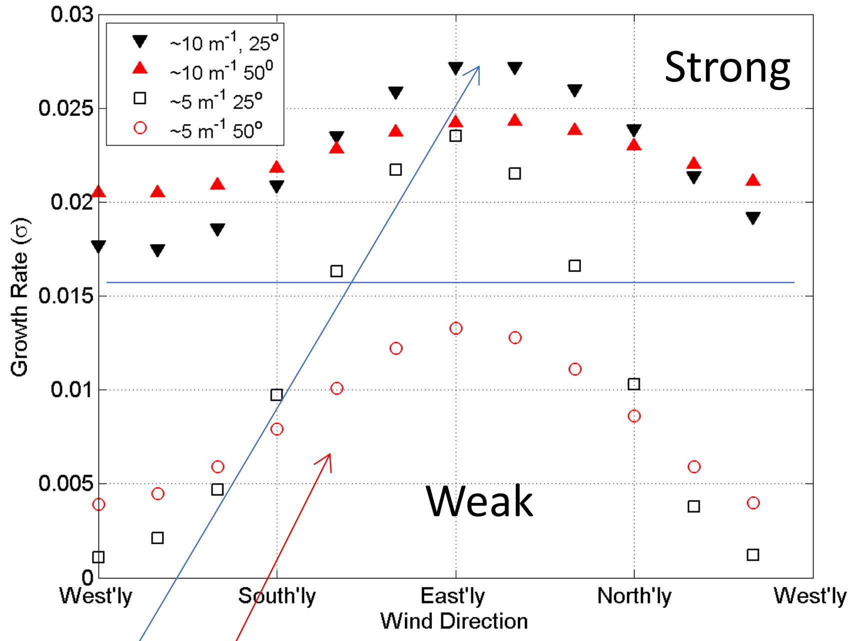
Liu, J., J.-H. Liang, J. C. McWilliams, P. P. Sullivan, Y. Fan, and Q. Chen, 2018: Effect of planetary rotation on oceanic surface boundary layer turbulence. *J. Phys. Oceanogr.*, **48**, 2057–2080.

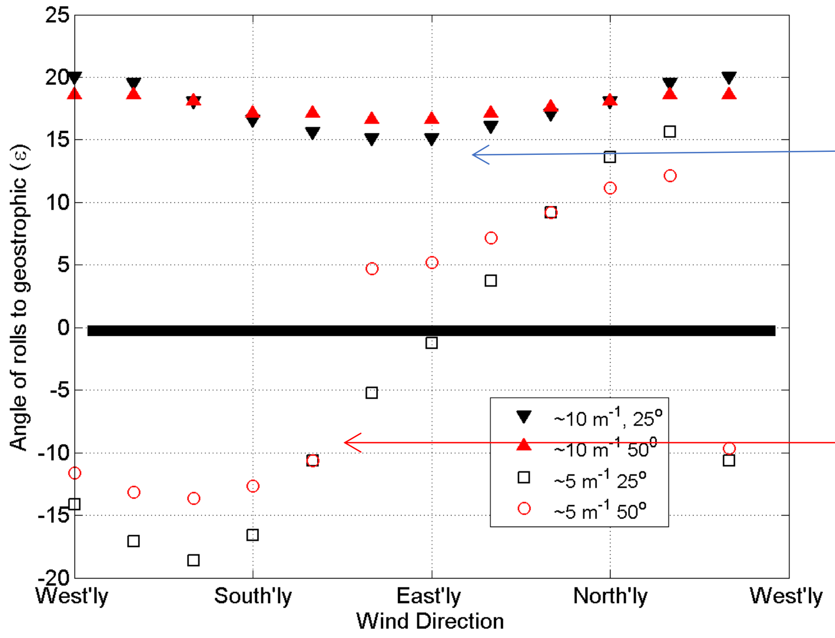
A subsample of many theoretical and numerical (LES,DNS) studies on the potential impacts of horizontal Coriolis force (wind direction and latitude) on BL/Ekman Layer turbulence and structure

Yet – little to no observational support in ocean of atmosphere…

R. Foster   Revised PBL Ekman model to include f_h

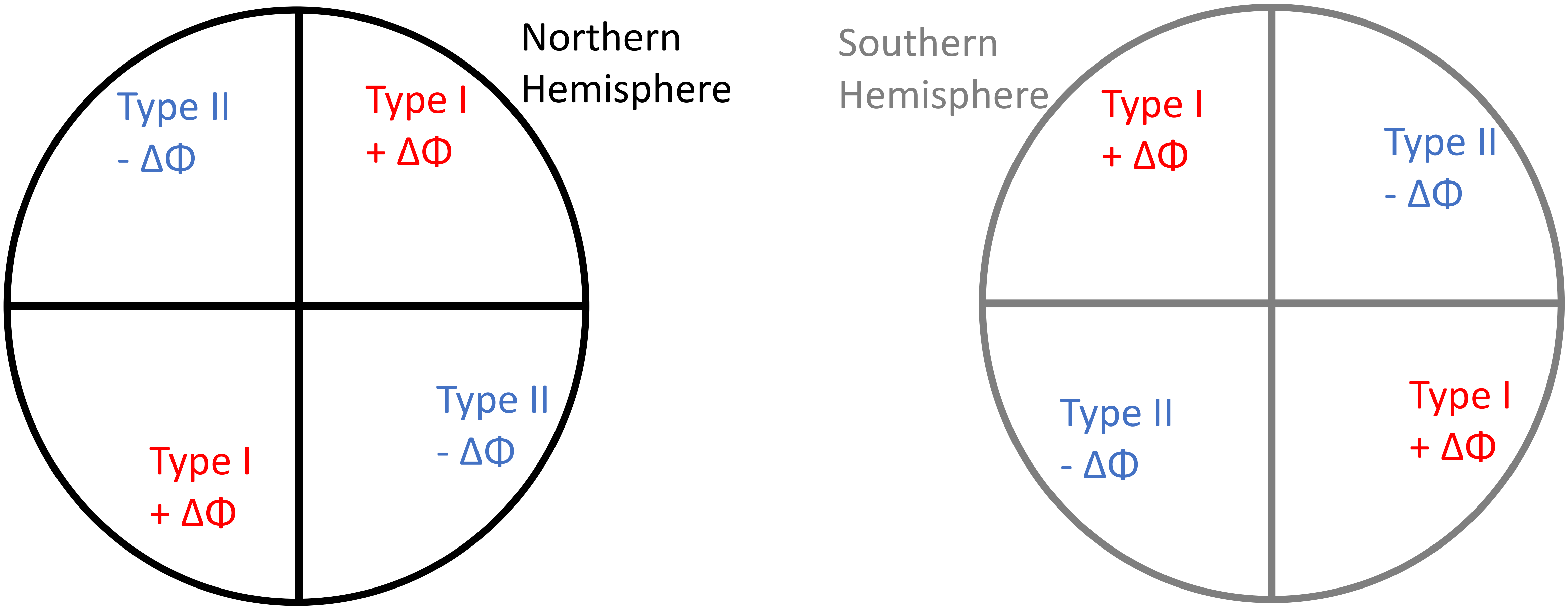
- Idealized Ekman Profile (Ri = 0)
- High Growth Rate → strong instability
- Weak wind, low latitude case can produce strong instability in ~Easterly flow (black squares in plot)





- Type II modes (neglects f_h)
  - Stronger growth rates
  - "classic" rolls
  - Shorter wavelength (1 to 3 km)
  - Positive turning from Geostrophic
- Type I modes (includes f_h)
  - Weaker growth rates
  - Lower winds
  - Longer wavelength
  - Turning from geostrophic= ?

Possible dominance of MABL OLE instability modes by wind direction quadrant



- ΔΦ is OLE field wind direction CCW from the surface wind in N.H.
- Type II is inflection point instability (Brown 1972) where -ΔΦ ~= -18 deg. , i.e. the OLE streak direction lies between surface and geostrophic wind direction (i.e. within Ekman spiral)
- Type I is unexpected +ΔΦ aligned nearer to surface wind direction and perhaps tied to wind direction (and latitude) via horizontal Coriolis term (Leibovich and Lele, 1986); predictions also suggest stronger TKE in NE sector vs. SW sector (in N. Hemisphere).

Summary

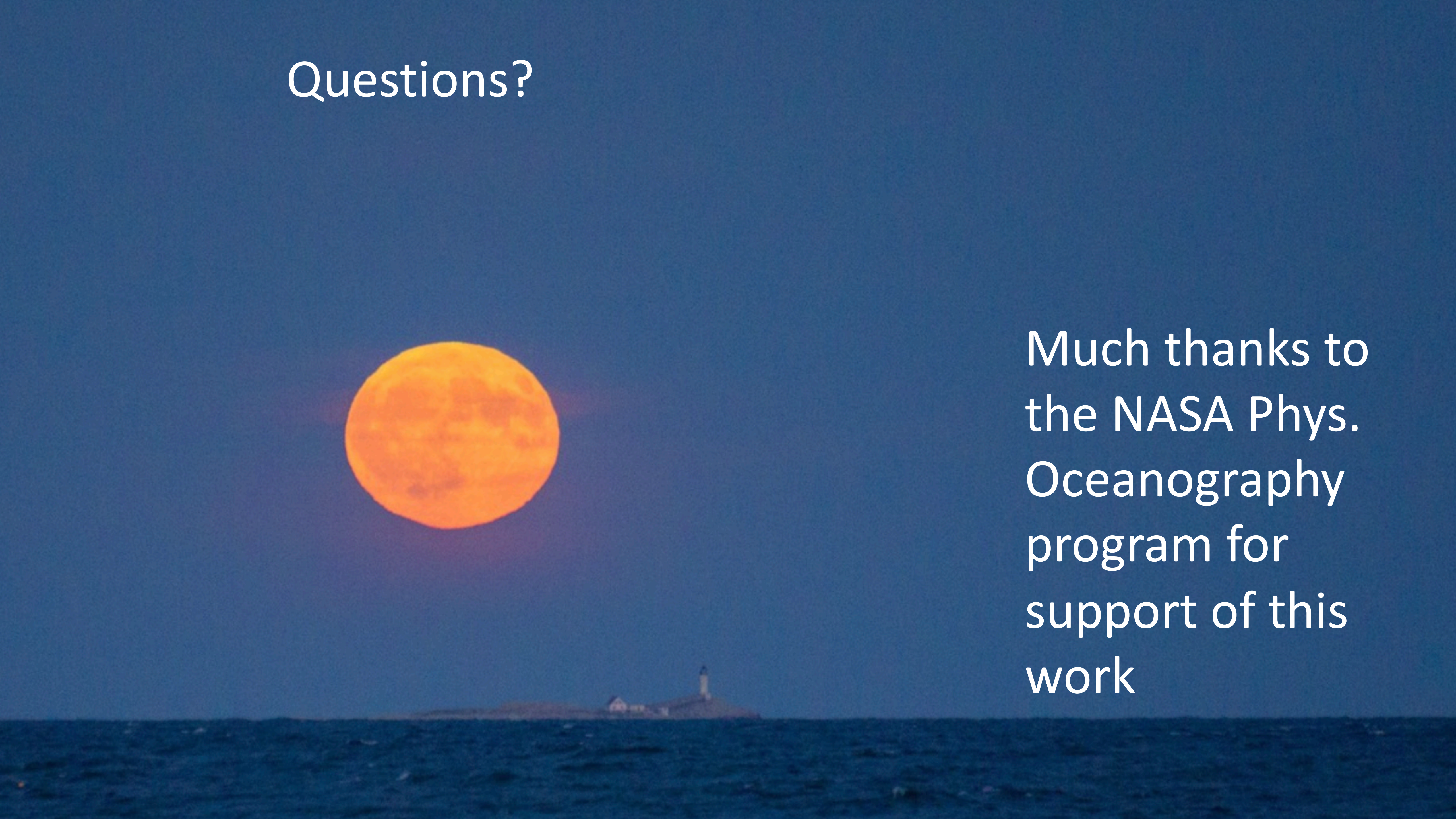
S1A gives new global view of 0.5-5 km NRCS variations and MABL dynamics

Biggest new results related to coherent eddy field in MABL are:

- OLE prevalence (already have 20-30% estimate, likely closer to 50+%)
- All new capability to document scales, energy in OLE field at 800-5000 m
- Likely first/strongest field-observed evidence of the earth rotation impact on turbulent characteristics in Atmos. Ekman layer
- Theoretical support in progress

One Future Direction (of many)

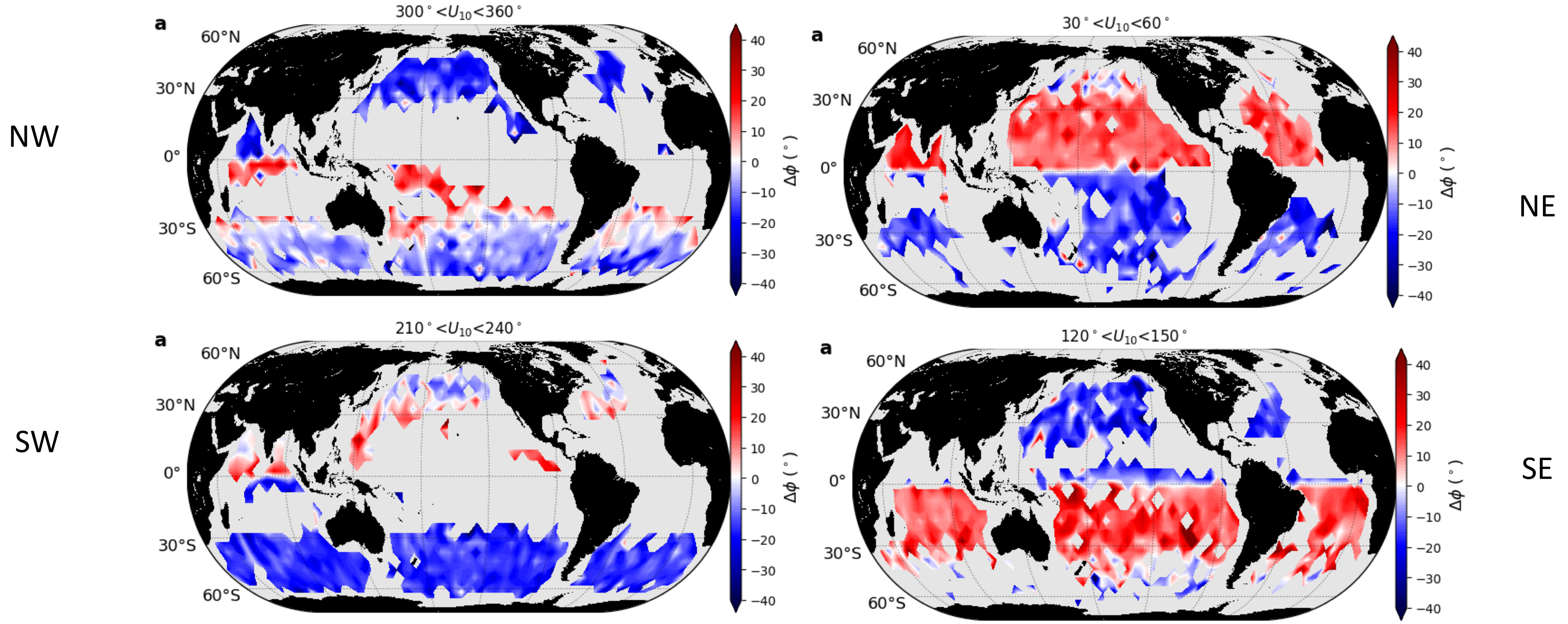
- Improve routine detection of most/all OLE and MCC events and then the mixed/transitional cases using even larger S1A + S1B database
- Net combination are present in large % of moderate to high wind conditions (> 70%?)
- Together these allow access to air-sea T difference (neutral-to-unstable) in all new method to support NWP and future PBL missions



Questions?

Much thanks to the NASA Phys. Oceanography program for support of this work

Extra Slides


NW
a
300° <U10<360°
60°N
30°N
0°
30°S
60°S
Δφ (°)
NE
a
30° <U10<60°
SW
a
210° <U10<240°
SE
a
120° <U10<150°
40
30
20
10
0
−10
−20
−30
−40

Needed reference wind direction correction for either ERA-5 or ECMWF (larger)

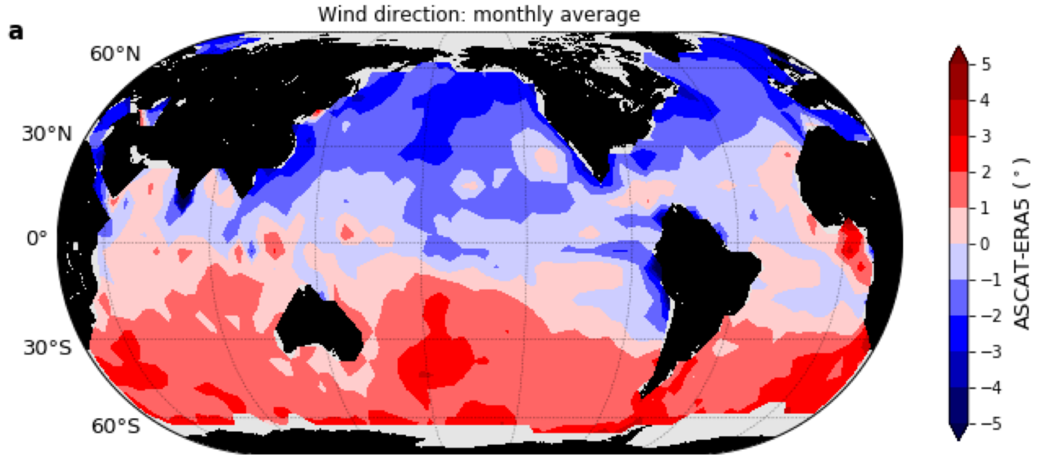
Resolved/fit using ASCAT vs. NWP data for 2016

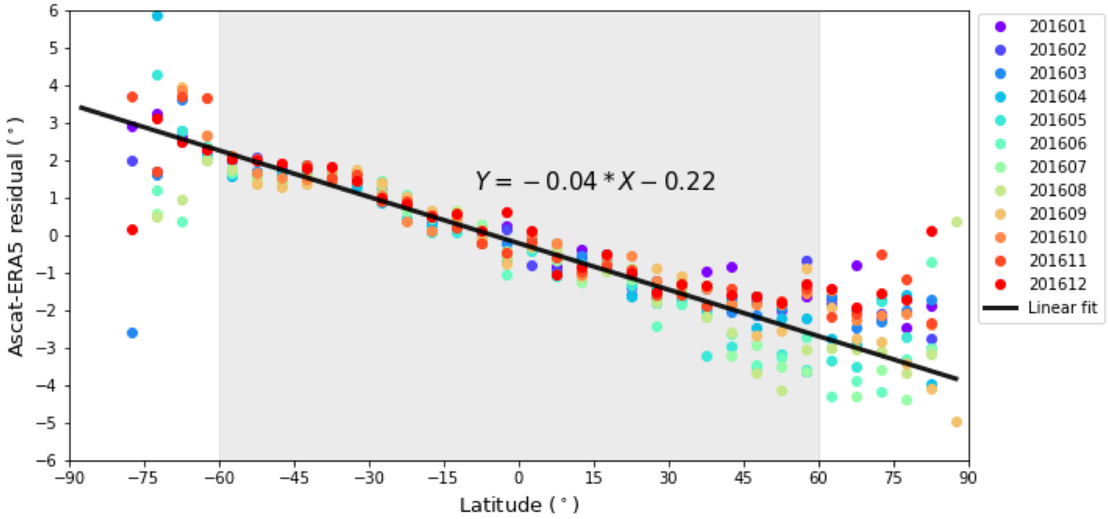
Consistent with previous results (e.g. Sandu et al 2013; Stoffelen presentations)

Due to veering/backing error in model PBL (personal comm. Sandu)

Neglect does not change key conclusions tied to OLE vs. surface wind directions

ASCAT-ERA5 comparison





Surface wind direction error function: $\mathbf{U_e}$**=-0.04*Latitude-0.22**

- Systematic error along with latitudes
- Much noise when close to polar
- Linear fit using data within -60°N, 60°S

ASCAT-ERA5 comparison for January vs. July