The Boundary Layer of Tropical Storm Erika (2015) Observed by Airborne Doppler Wind Lidar

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Statement of Problem

- Previous theoretical and numerical studies have demonstrated the important role of the boundary layer in TC intensification process and operational forecast (e.g.,Ooyama 1969; Emanuel 1986;1995; Smith et al. 2009; Nolan et al. 2009; Kepert 2010; Bryan and Rotunno 2009; Bryan 2012; Montgomery and Smith 2014; J. Zhang et al. 2012; 2015).

- However, the TC boundary layer is the least observed part of a storm due to safety constraint for in-situ measurements; TC Boundary layer observations over the ocean are mainly relied on dropsondes which are limited by sample size.

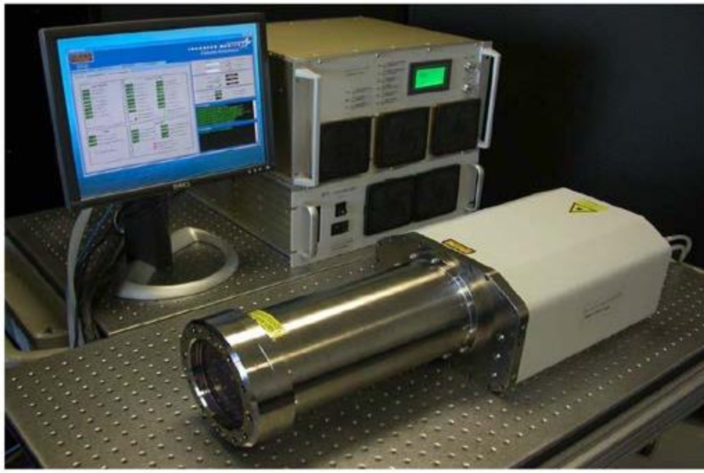
- Previous observational studies of TC boundary layer structure over the ocean mainly used a composite approach to merge data from multiple storms (e.g., Barnes 2008; J. Zhang et al. 2011, 2013; J. Zhang and Uhlhorn 2012).

This study presents a promising instrument onboard NOAA's WP-3D aircraft for TC boundary-layer observations.

NOAA P3 Doppler Wind Lidar (DWL)

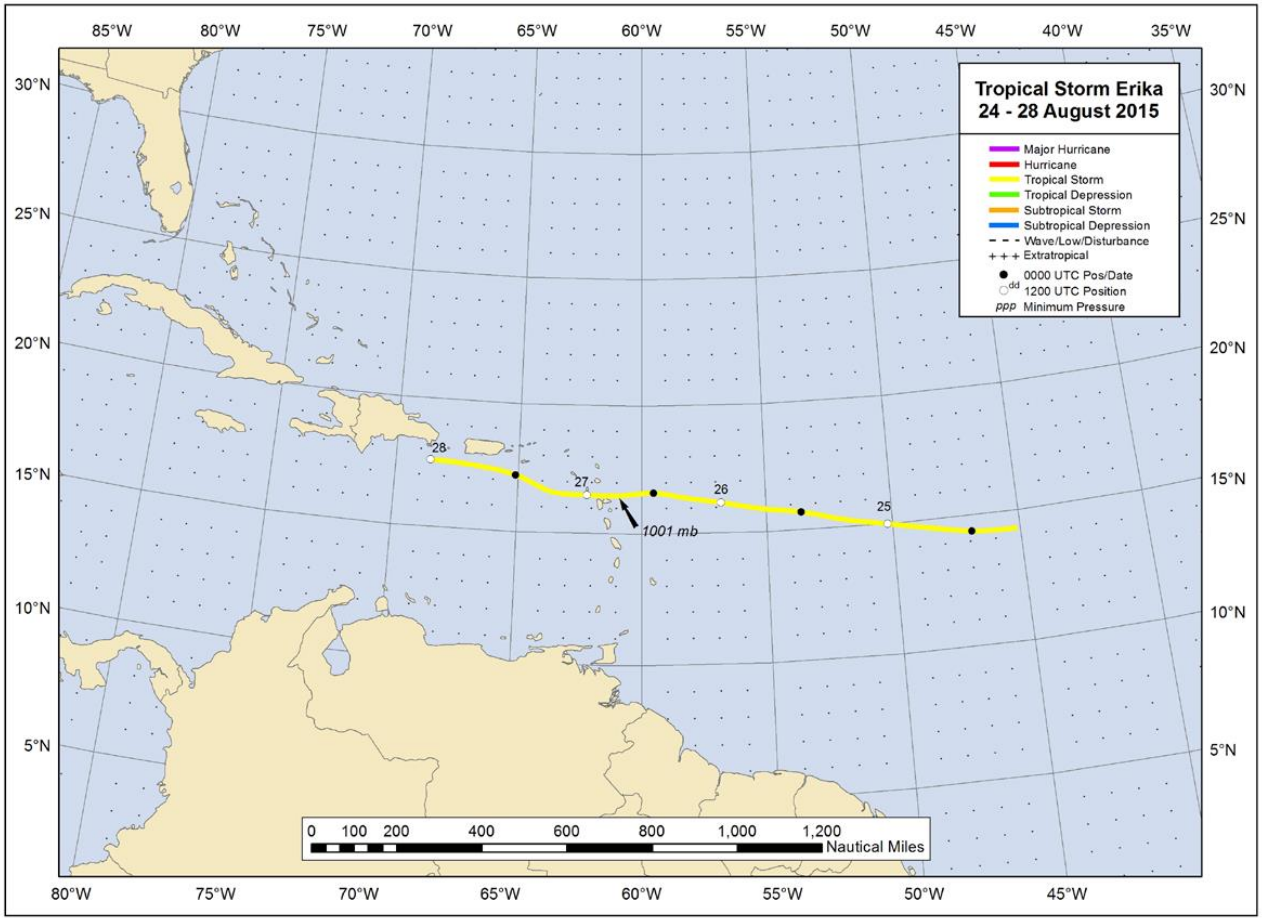
- Side mounted cylindrical scanner from NASA/LaRC
  (10 cm bi-axis scanner)

- 1.6 µm coherent CTI WindTracer (WTX) transceiver from Lockheed Martin Coherent Technology



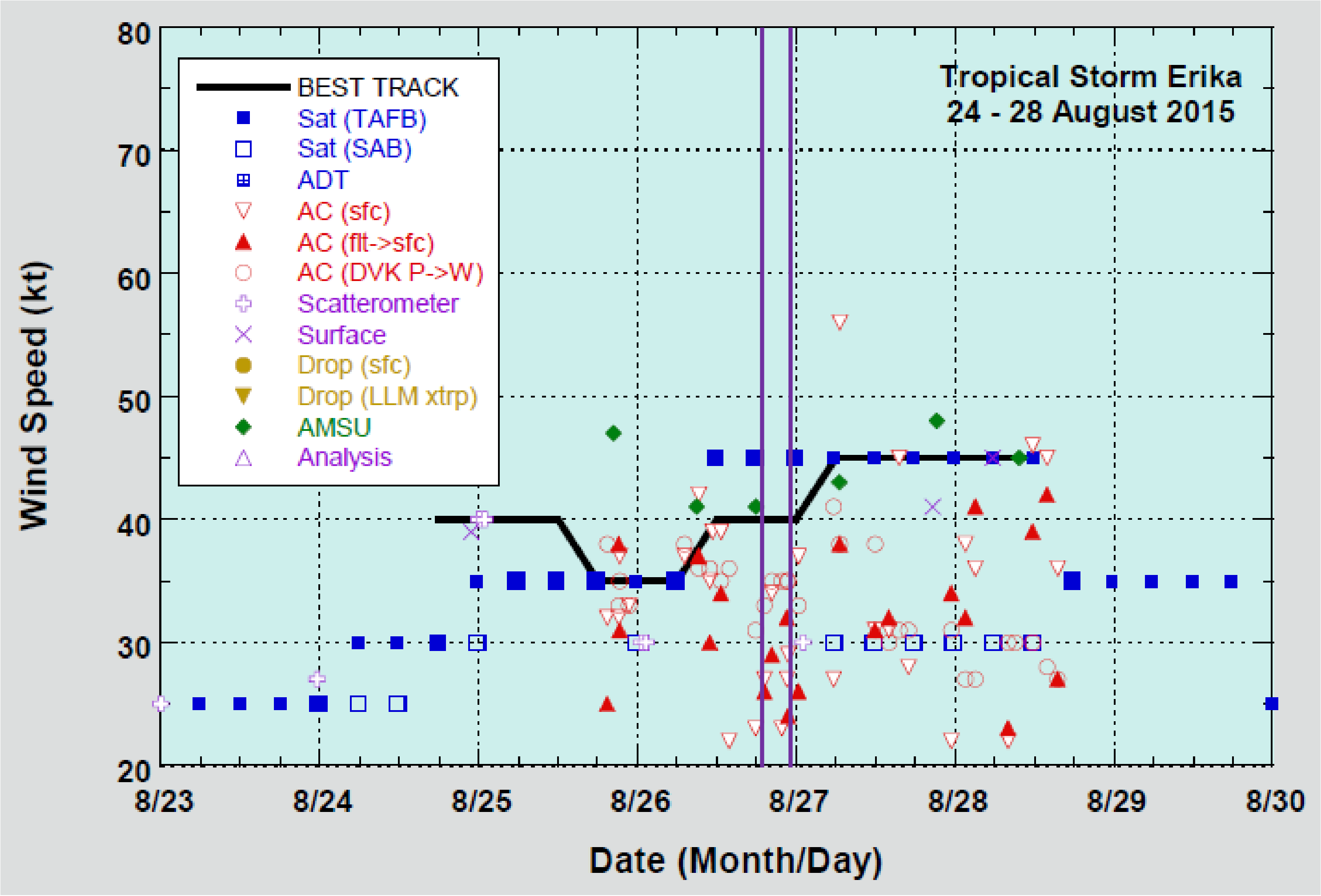
For the first time, the Doppler Wind Lidar (DWL) has been successfully operated on NOAA's P3 aircraft.

Track of Tropical Storm (TS) Erika (2015)



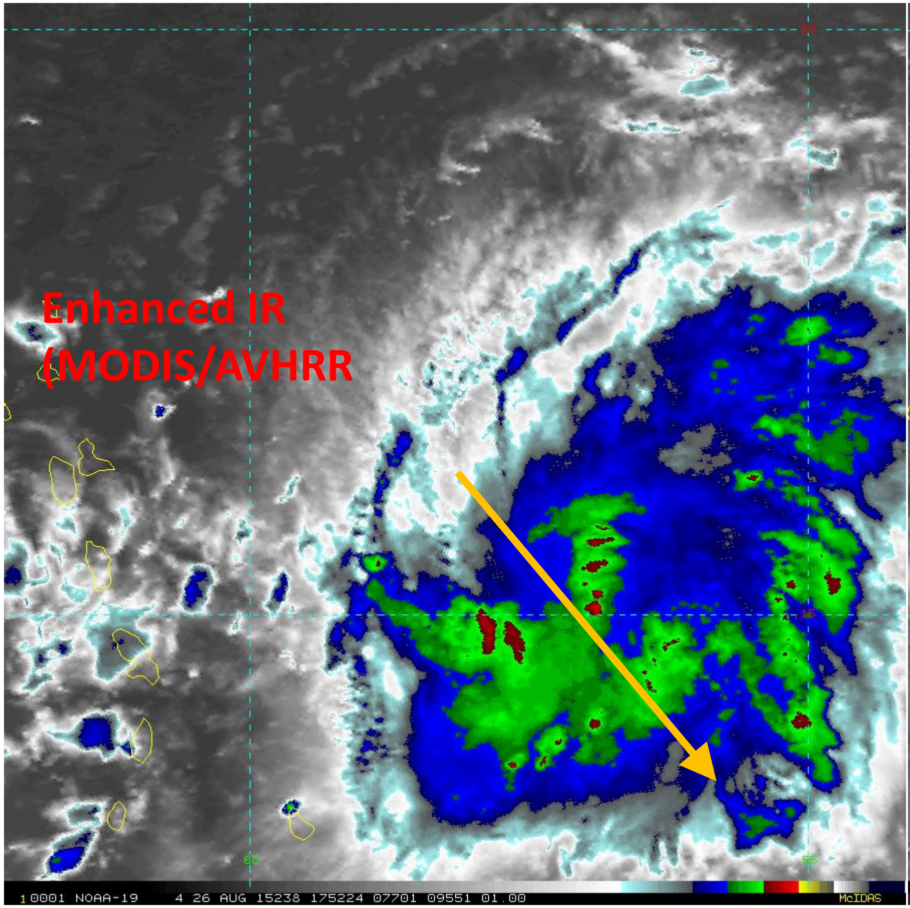
- DWL observations were taken on 8/26 between 17:30 UTC to 21:00 UTC when Tropical Storm Erika moved to the west.

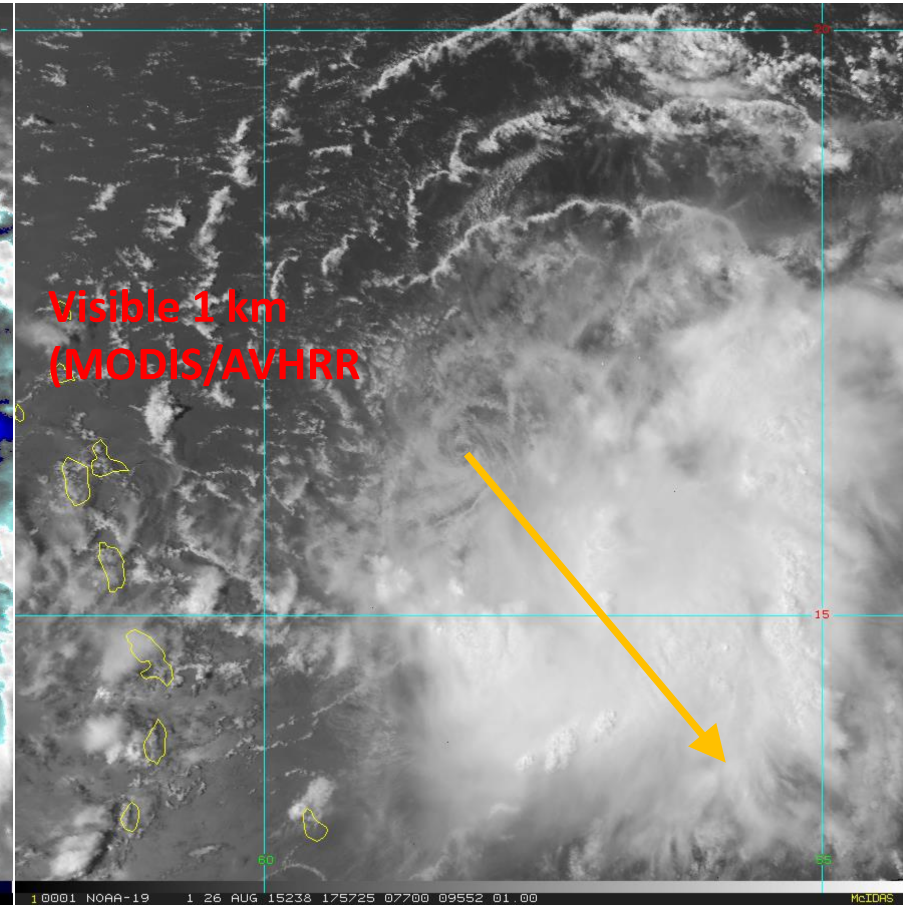
Intensity of TS Erika (2015)



DWL observations were taken on 8/26 between 17:30 UTC to 21:00 UTC right before the weak intensification of Tropical Storm Erika from 40 to 45 kt.

TS Erika: 18 UTC August 26th

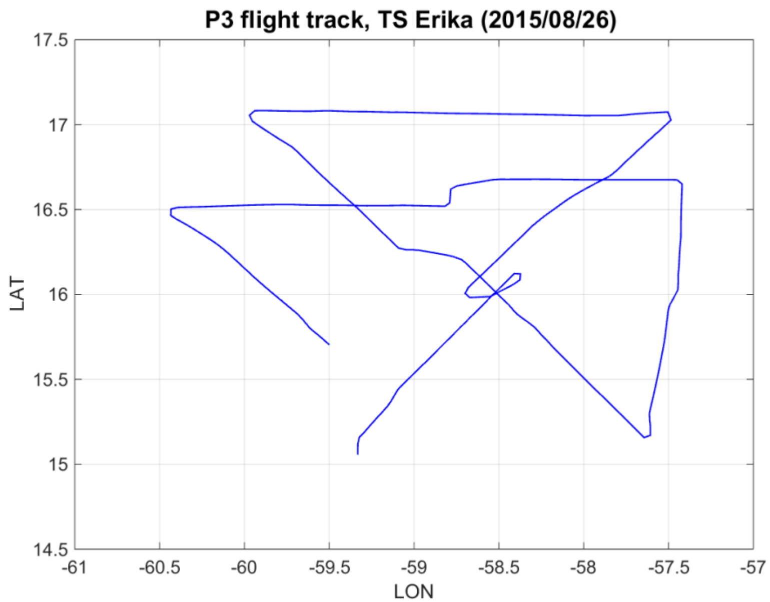




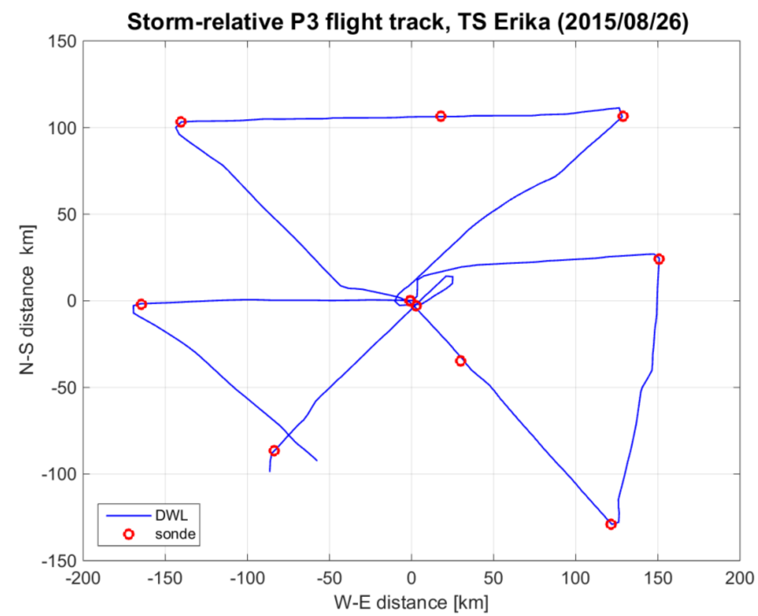
- Tropical storm Erika was under strong environmental vertical wind shear. The shear magnitude is 20 kt and shear direction is 290 degree (northwesterly shear).
- Relative strong convection was mainly observed at the west side of the storm and mostly at the downshear side quadrants.

P3 aircraft track (2015/08/26 N43 flight)

Earth – relative

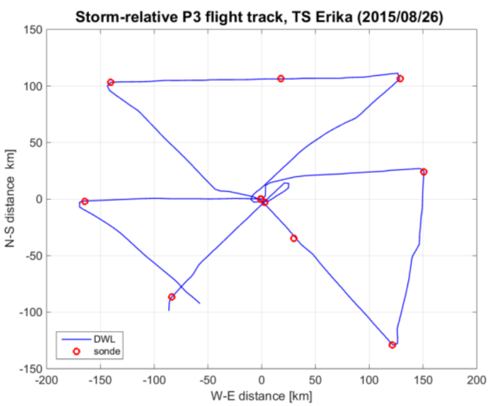


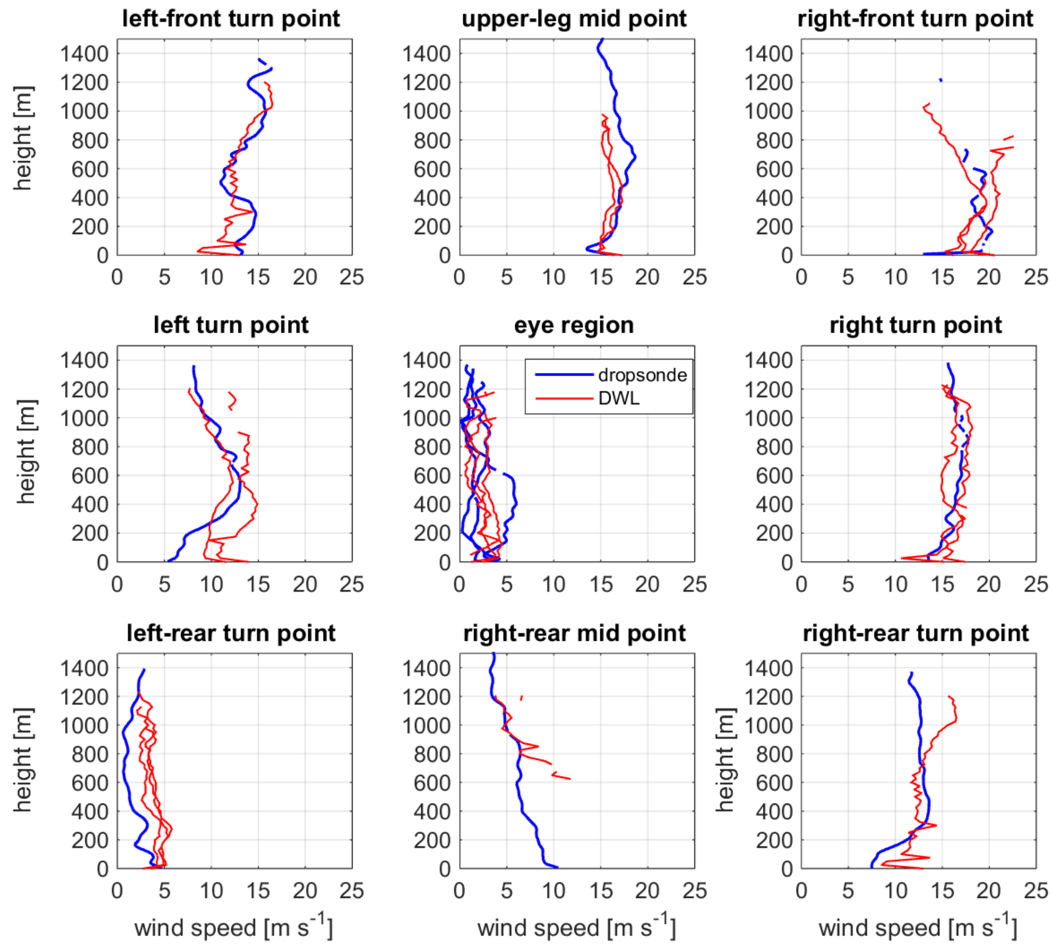
Storm – relative



- DWL wind profiles were collected every ~ 2 minutes along the flight track.
- Dropsondes were released at the center of the storm, middle of the flight leg and turn points (red circles on the right side figure).

DWL wind profile validation against dropsonde data



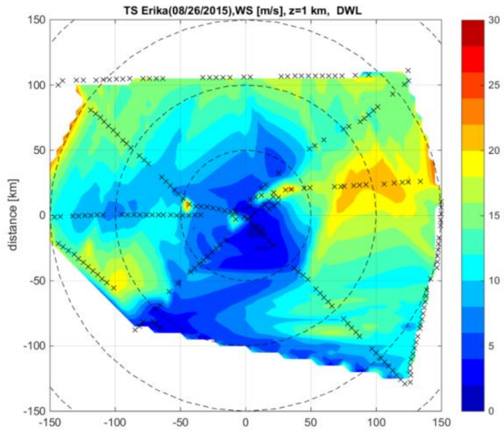


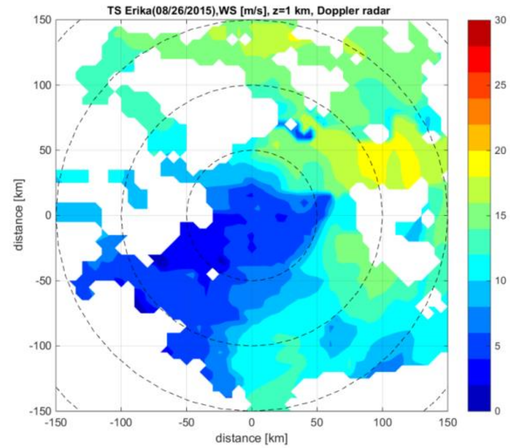
- Comparisons between the DWL and dropsonde measured vertical wind profiles show excellent agreement.
- The DWL captured the boundary layer wind asymmetry observed by the dropsondes.

Wind speed from DWL vs Tail Doppler radar

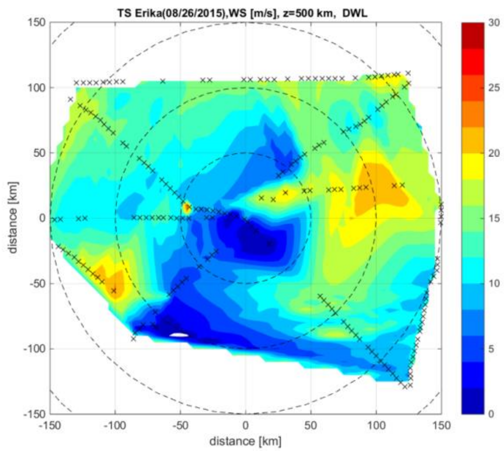
Lidar | Radar

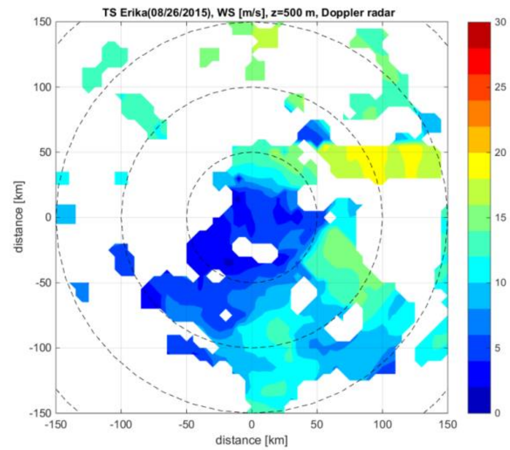
1 km altitude





500 m altitude





Vertical resolution:

Lidar- 25 m

Radar-500 m

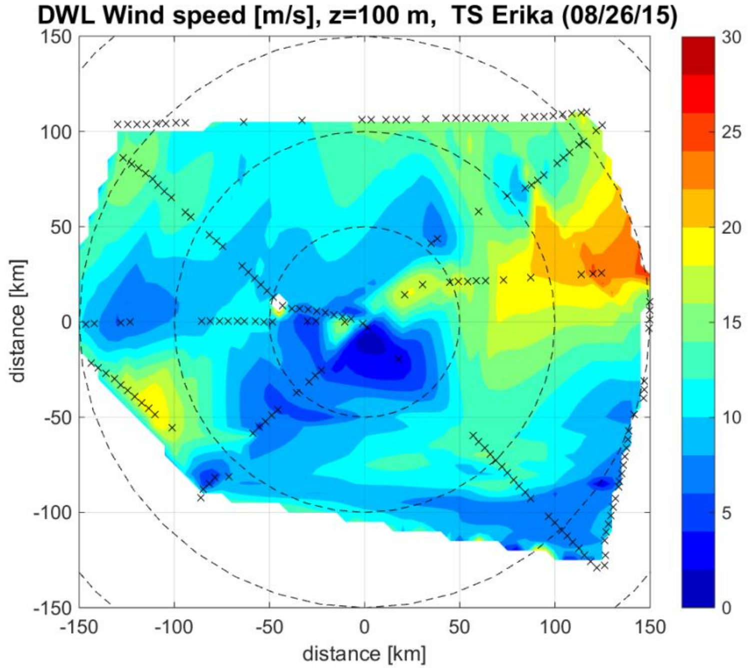
Data coverage below 500 m:

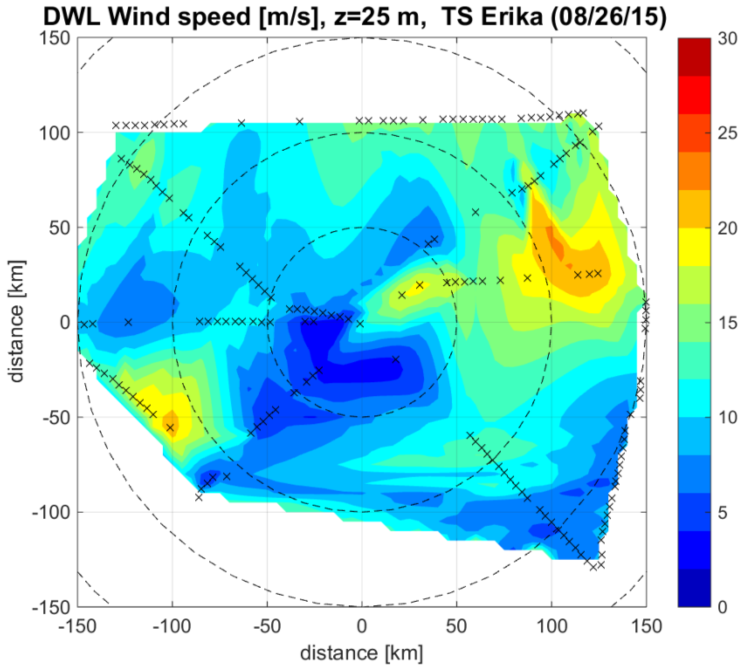
Lidar – good

Radar – very little

- The DWL data captured the asymmetric pattern of wind speed observed by the Doppler Radar;
- The DWL compliments the Doppler radar observations above 500m in rain-free region;
- The DWL provides excellent data converge below 500 m where Doppler radar data is very limited.

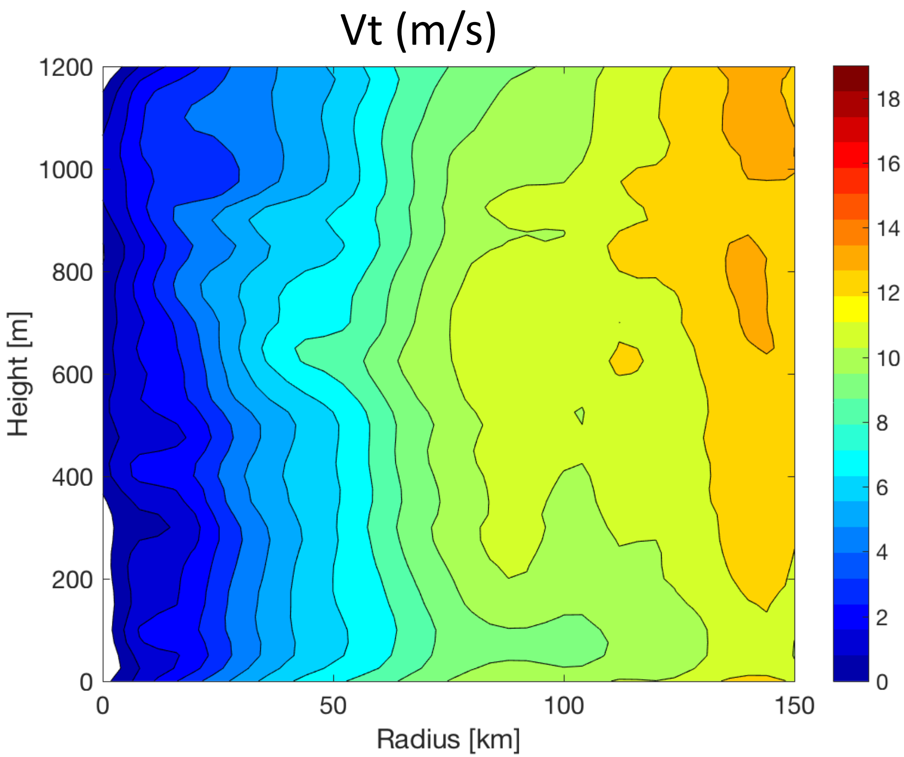
DWL measured near surface winds

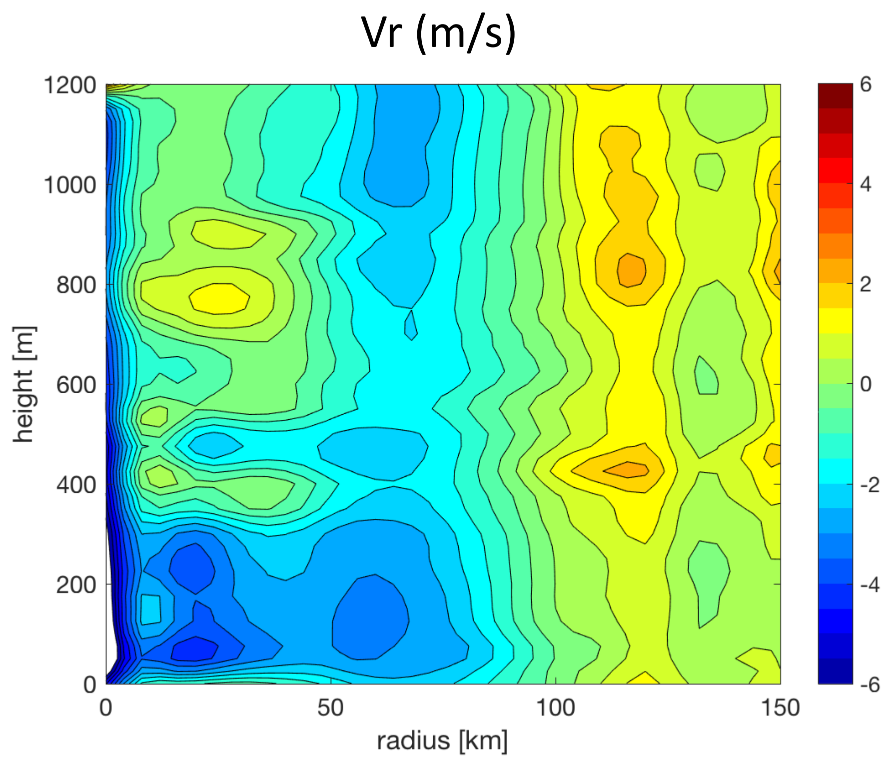




- DWL can measure wind speed down to the sea surface with vertical resolution of 25 m.
- Full 3D wind fields can be measured by the DWL in the boundary layer.

Azimuthally averaged tangential (Vt) and radial (Vr) wind velocities





- Vt max is located at much larger radius compared to the location of peak inflow.

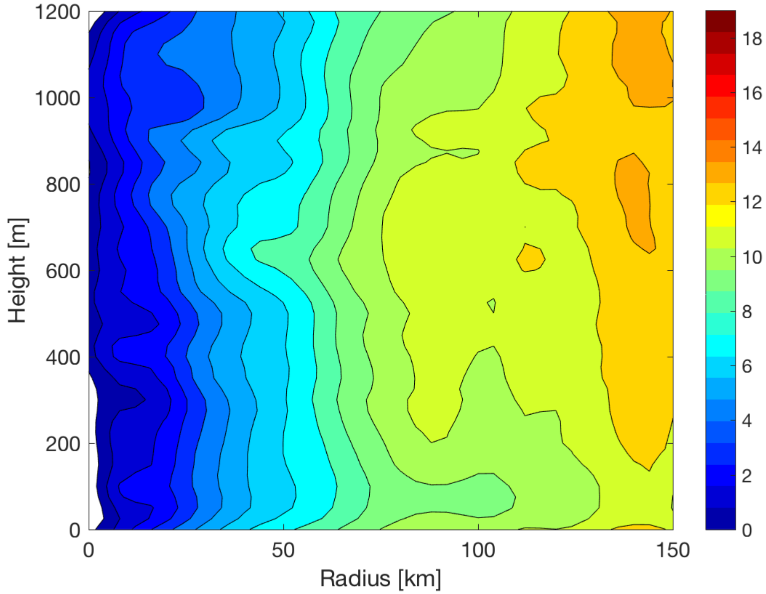
Where is the top of the boundary layer in a tropical storm strength TC?

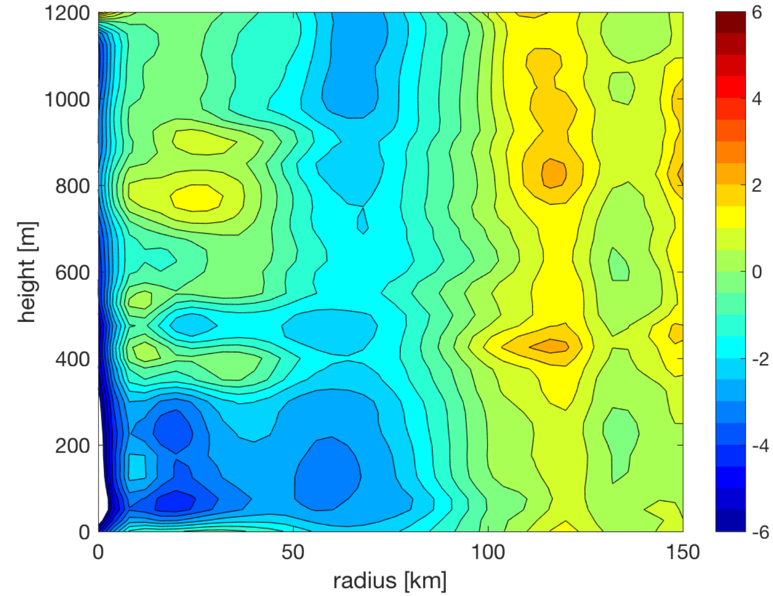
Vt (m/s)

Vr (m/s)

Tropical Storm Erika(2015)

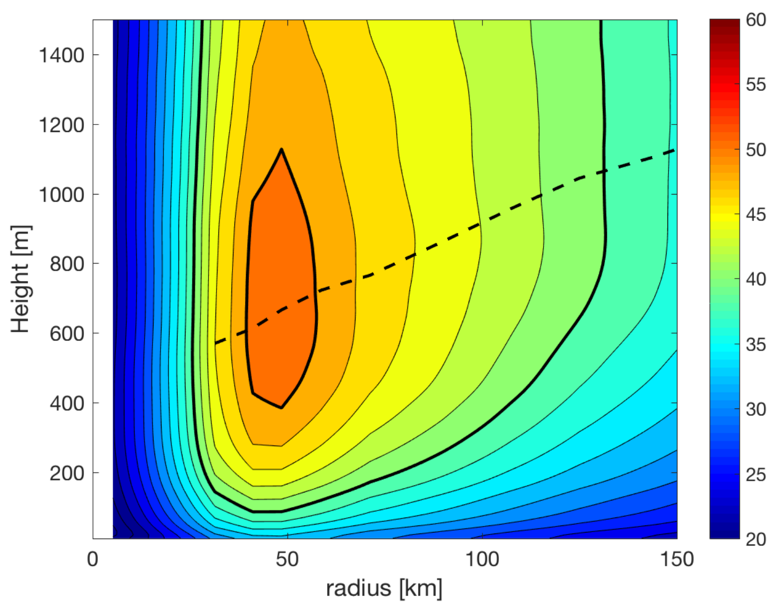
DWL data

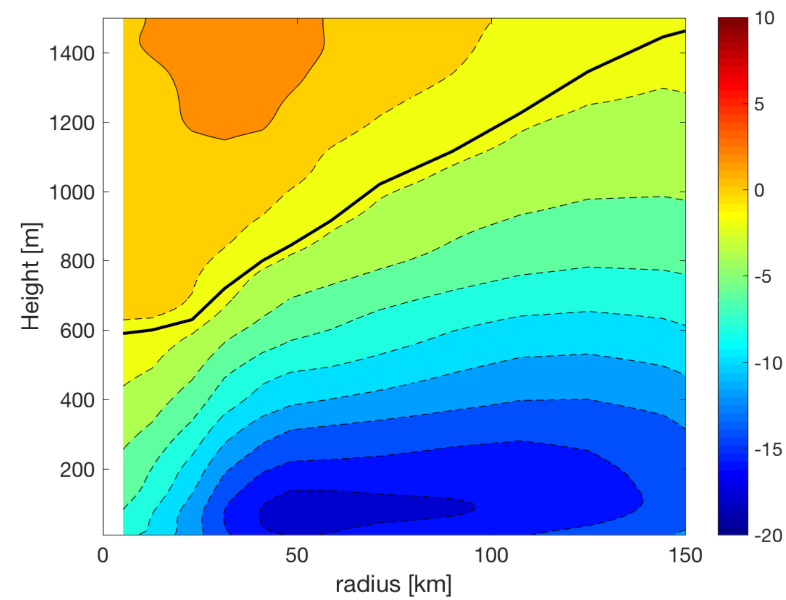




Hurricane dropsonde composite

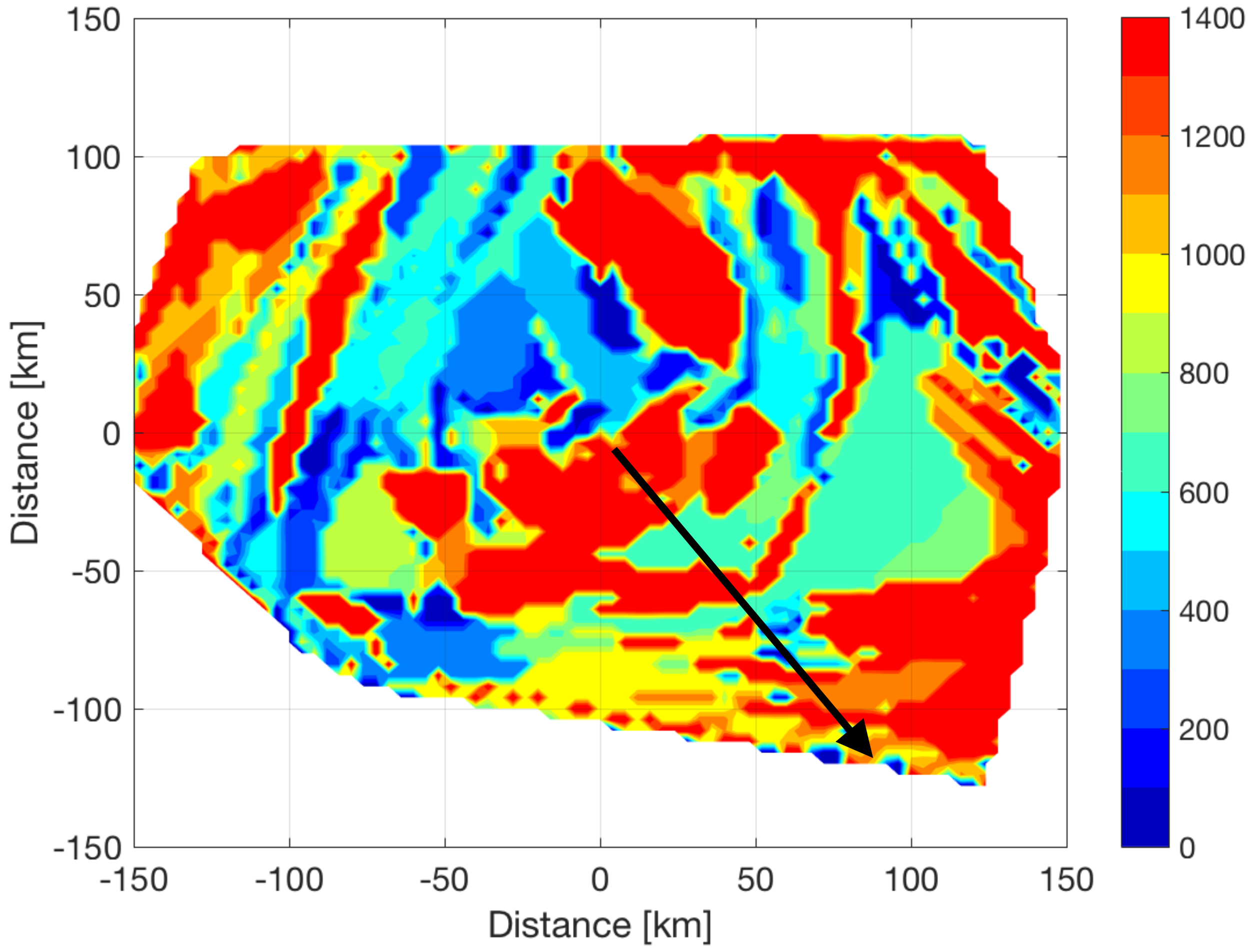
Jun Zhang et al. (2011)





- The axisymmetric structure of Tropical storm Erika (2015) is very different from that of a typical hurricane.

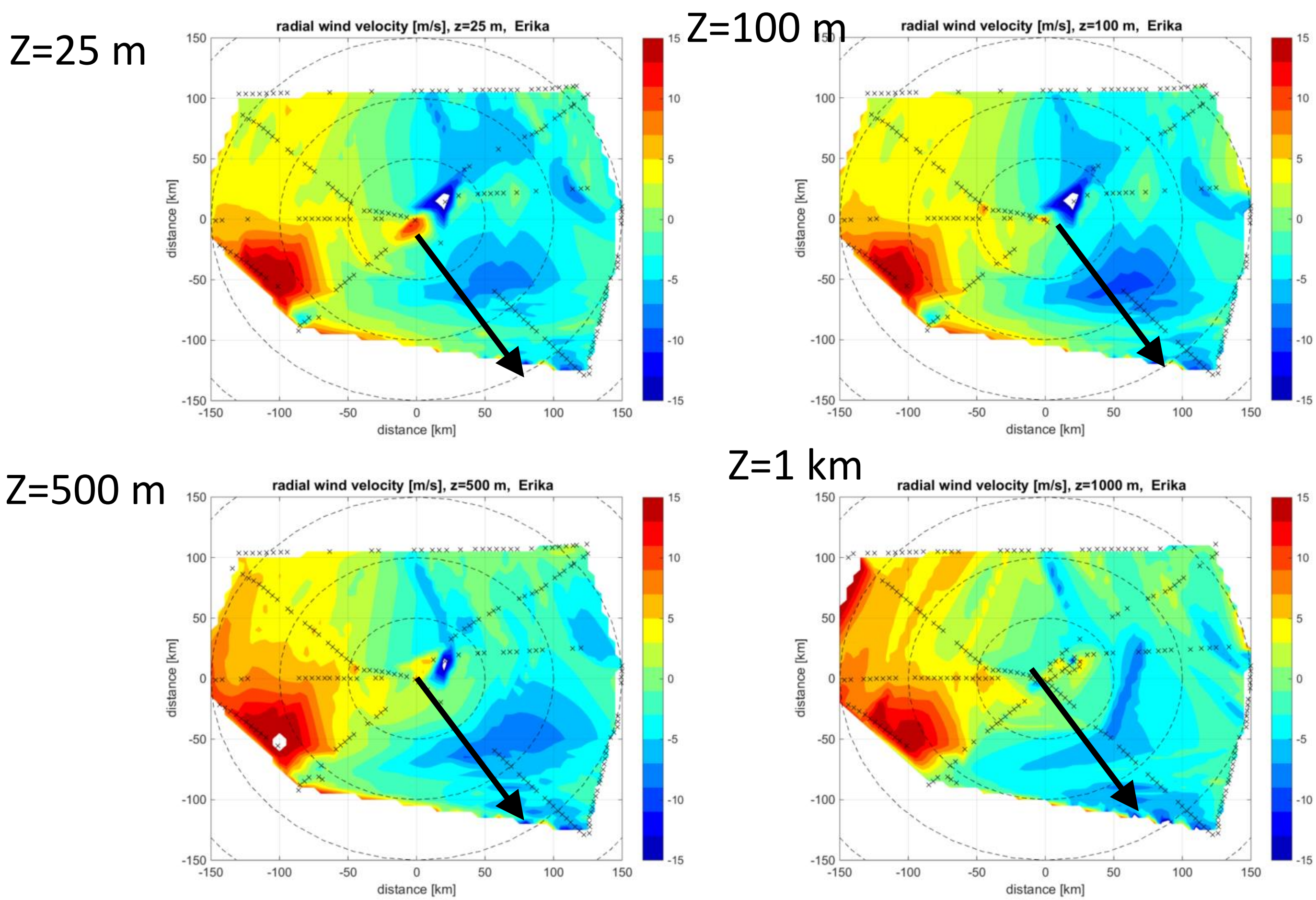
Height (m) of the maximum tangential wind speed (Vt)



Black arrow is the shear direction

- The boundary layer defined using the height of maximum Vt is deeper in the downshear side quadrants than the upshear side, which is consistent with the dropsonde composite from J. Zhang et al. (2013).

Boundary-layer Inflow and outflow of Erika (2015)



Shading - radial wind velocity

Negative value - inflow

Positive value – outflow

Black arrow – shear direction

- Inflow layer depth may not be a good representation of the top of the boundary layer in a sheared tropical storm as certain quadrant does not have inflow.
- The inflow layer is deeper in the downshear side quadrants than the upshear side, which is consistent with the dropsonde composite from J. Zhang et al. (2013).

Can hurricane spin-up theory be applied to tropical-storm conditions?

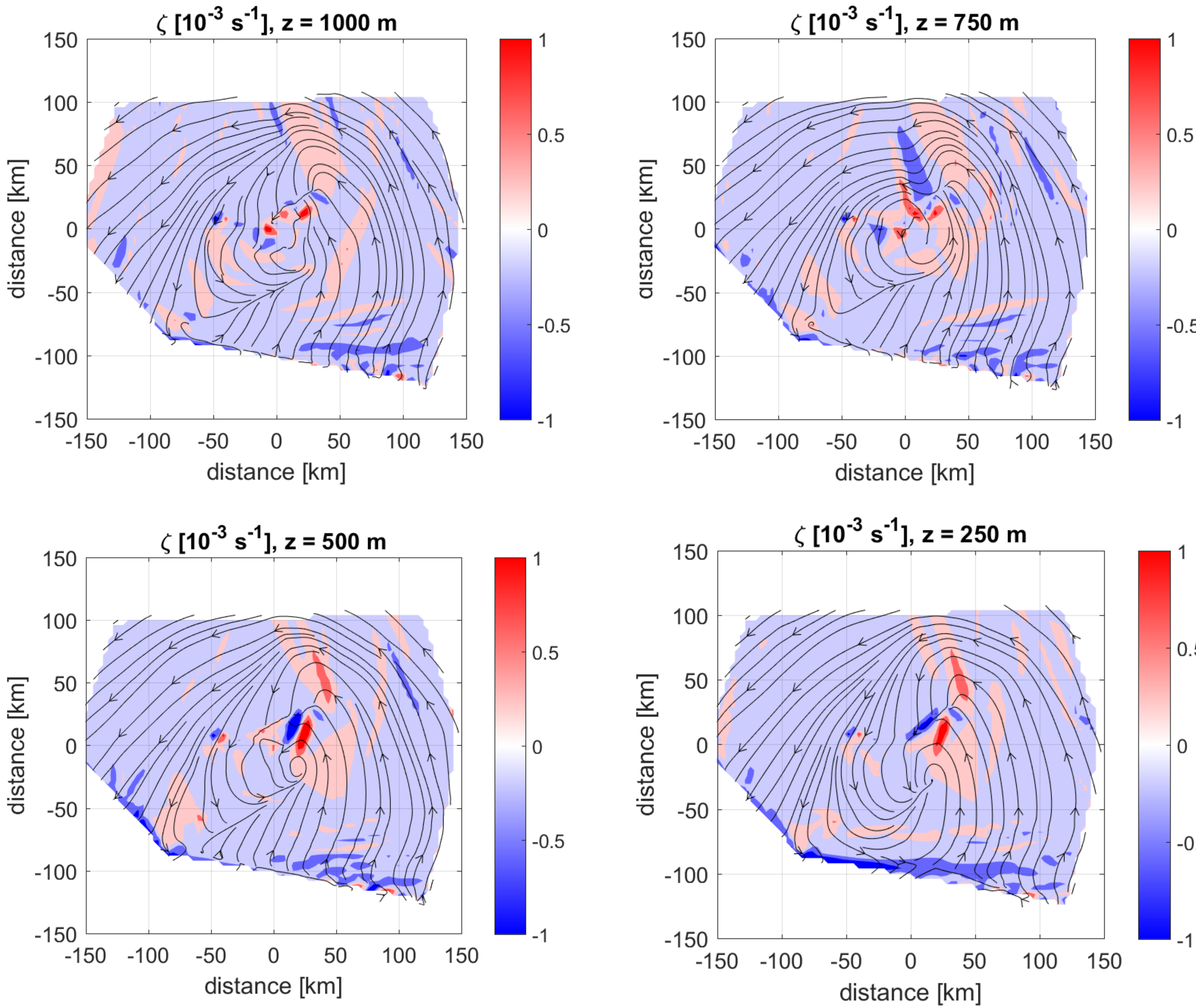
One of the key components of the hurricane spin-up theory of Smith et al. (2009), Montgomery and Smith (2014) may not be met in a tropical storm:

The maximum tangential wind speed is within the boundary layer that is defined as the strong inflow layer.

Can vorticity budget help explain TC intensification at tropical-storm stage (e.g., Raymond and Carrillo 2011)?

$$\frac{\partial \zeta_z}{\partial t} = -\boldsymbol{\nabla}_h \cdot \boldsymbol{Z}, \text{where } \boldsymbol{Z} = \boldsymbol{v}_h \zeta_z - \boldsymbol{\zeta}_h v_z + \widehat{\boldsymbol{k}} \times \boldsymbol{F} = conv + tilt + frict.$$

How close is the vorticity balance in the boundary layer of Tropical Storm Erika (2015) right before the weak intensification?

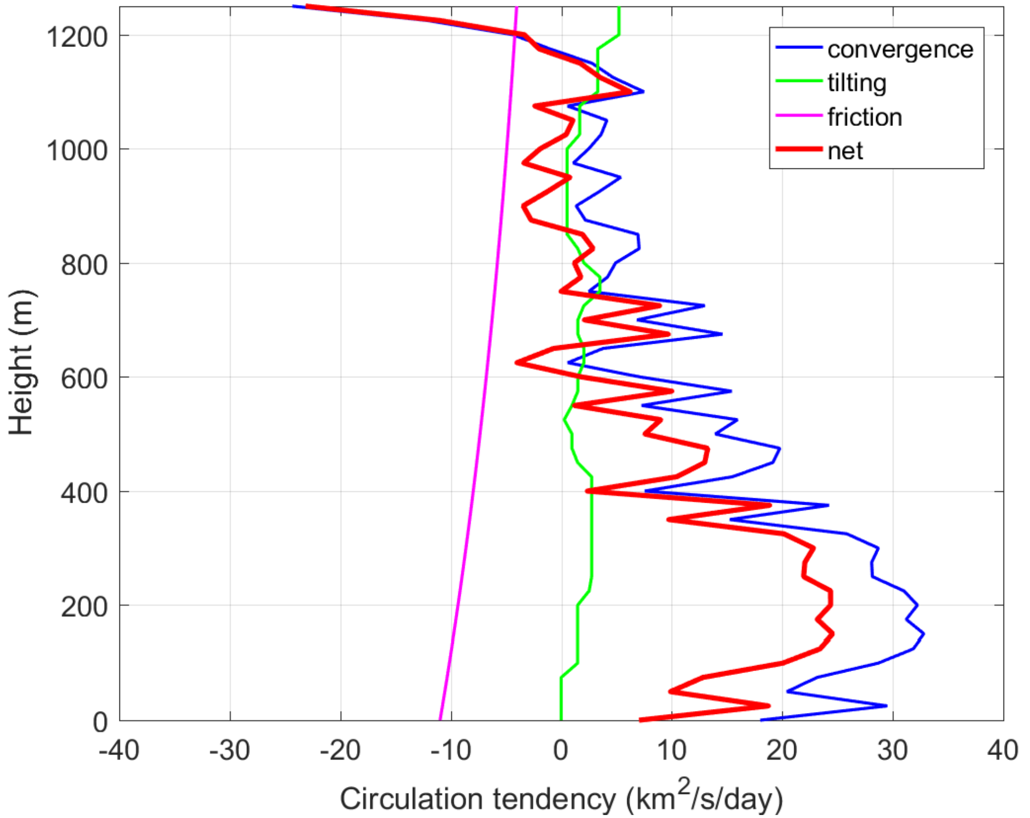


ζ [10^-3 s^-1], z = 1000 m
ζ [10^-3 s^-1], z = 750 m
ζ [10^-3 s^-1], z = 500 m
ζ [10^-3 s^-1], z = 250 m
distance [km]
distance [km]
150
100
50
0
-50
-100
-150
1
0.5
0
-0.5
-1

Circulation tendency terms

$$\frac{d\Gamma}{dt} = -\oint v_n \zeta_z dl + \oint \zeta_n v_z dl + \oint F_t dl$$

$$\Gamma = \int \zeta_z dA.$$



- The vorticity convergence dominants other circulation tendency terms in the boundary layer, which may support the spin-up of Tropical Storm Erika (2015).
- The boundary layer is not in vorticity balance in a tropical storm like Erika case, which is in agreement with Raymond and Carrillo (2011).

Summary

- Wind profile data were collected in Tropical Storm Erika (2015) by a Doppler wind lidar (DWL) successfully installed on NOAA P3 aircraft.
- Comparisons between DWL and dropsonde measured vertical wind profiles show good agreement.
- The DWL captured the wind asymmetry above 500 m where Doppler radar data were available; the DWL also provided unique observation of boundary layer structure below 500 m with excellent data coverage.
- The axisymmetric boundary layer structure of Tropical Storm Erika (2015) is different from that a typical hurricane boundary layer.
- The boundary-layer wind asymmetry in Erika is generally consistent with that in hurricane dropsonde composite in shear relative framework.
- The boundary layer of TS Erika is far from vorticity balance, with vorticity convergence being the main source term in the circulation tendency equation that offsets the friction. This may help explain why Erika weakly intensified in strong environmental wind shear.

Forward Sweep Scanning Pattern