Examination of the Combined Effect of Deep-Layer Vertical Shear Direction and Lower-Tropospheric Mean Flow on Tropical Cyclone Intensity and Size Based on the ERA5 Reanalysis

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Outline

- Abstract
- Introduction
- Data and methods
- Relationships between LMFrot orientation and TC intensity and size
- Sensitivity of shear-relative LMF's effect to other environmental factors
- Effects of LMFrot in various basins
- Conclusions

Abstract

- A way to further understand the VWS profile's effect is to examine the interaction between a TC and various shear-relative low-level mean flow (LMF) orientations. This study mainly uses the ERA5 reanalysis to verify that.

- Based on analyses of 720 TCs from multiple basins during 2004–16, a TC affected by an LMF directed toward downshear-left in the Northern Hemisphere favors intensification, whereas an LMF directed toward upshear-right is favorable for expansion.

- The relationship between shear-relative LMF and intensification is not significantly modified by other factors [inner-core sea surface temperature (SST), VWS magnitude, and relative humidity (RH)].

- The relationship regarding expansion is partly attributed to environmental SST and RH variations for various LMF orientations.

- For Atlantic TCs, the relationship between LMF orientation and intensification is inconsistent with all-basin statistics.

1. Introduction

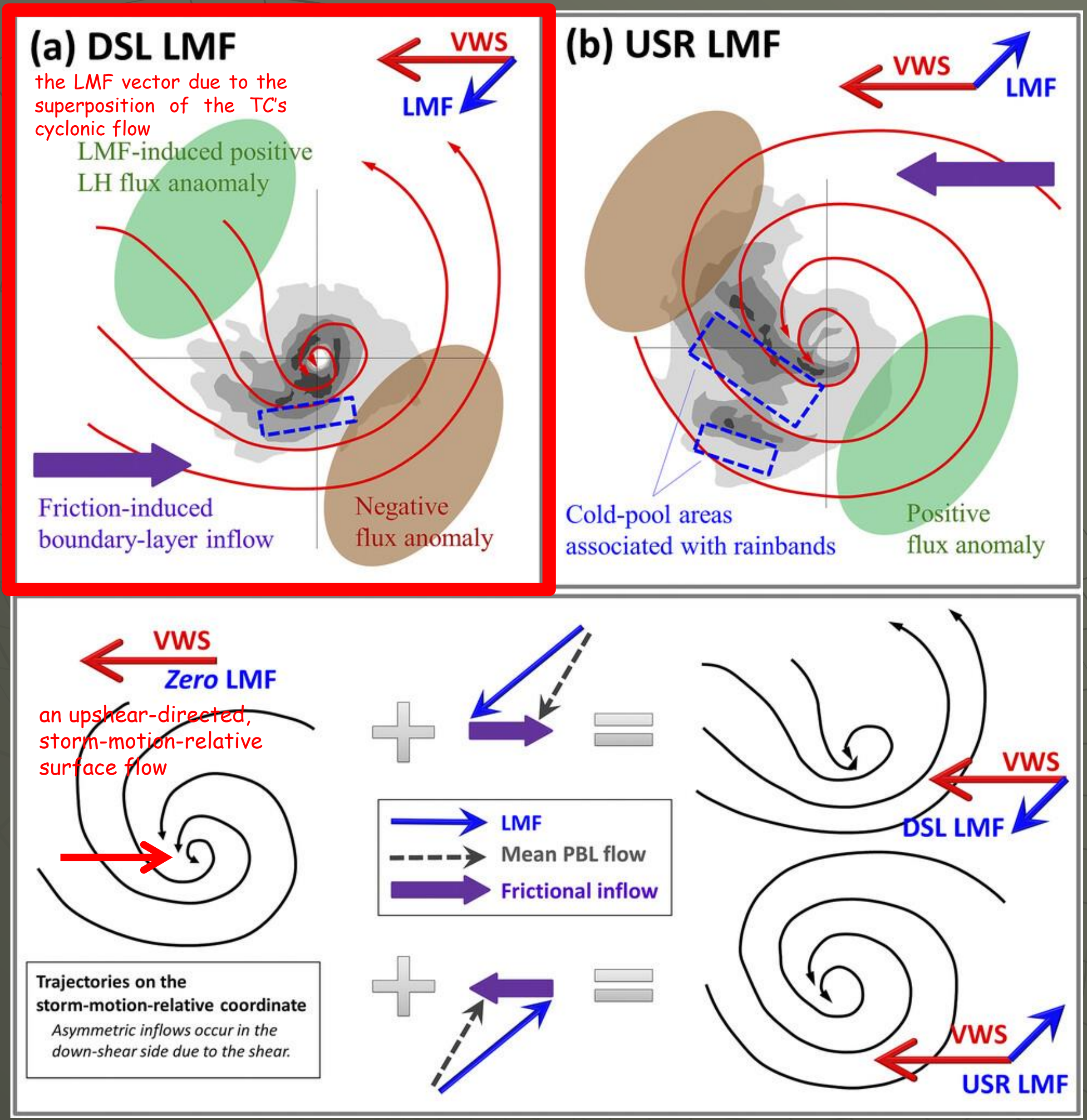
- Accurately predicting tropical cyclone (TC) intensification and structural development is a critical issue in TC forecasting and disaster warning. Therefore, it is important to understand the underlying physical processes.

- Although TC development is to some degree related to environmental factors including tropospheric relative humidity (Hill and Lackmann 2009; Dunion and Velden 2004), ocean conditions beneath the inner-core (Lin et al. 2013), and upper-level flow patterns that affect angular momentum import/export (Elsberry and Jeffries 1996; DeMaria et al. 1993; Hanley et al. 2001), the influences from the environmental wind profile seem to be especially critical.

- For example, a strong deep-layer vertical wind shear (VWS) magnitude generally limits TC intensification (DeMaria and Kaplan 1994, 1999; Kaplan et al. 2010), and moderate shear that has a magnitude of approximately 4.5–11.0 m s^−1 (Rios-Berrios and Torn 2017) reduces the predictability of TC intensity (Emanuel et al. 2004; Bhatia and Nolan 2013; Zhang and Tao 2013; Onderlinde and Nolan 2014; Finocchio et al. 2016).

- Moreover, even in comparable VWS magnitudes, the VWS can force downshear convective asymmetries with highly different magnitudes and azimuthal distributions (Nguyen et al. 2017; Rios-Berrios and Torn 2017). A relatively axisymmetric precipitation distribution is generally favorable for TC intensification in VWS (Zagrodnik and Jiang 2014; Alvey et al. 2015; Nguyen et al. 2017; Fischer et al. 2018).

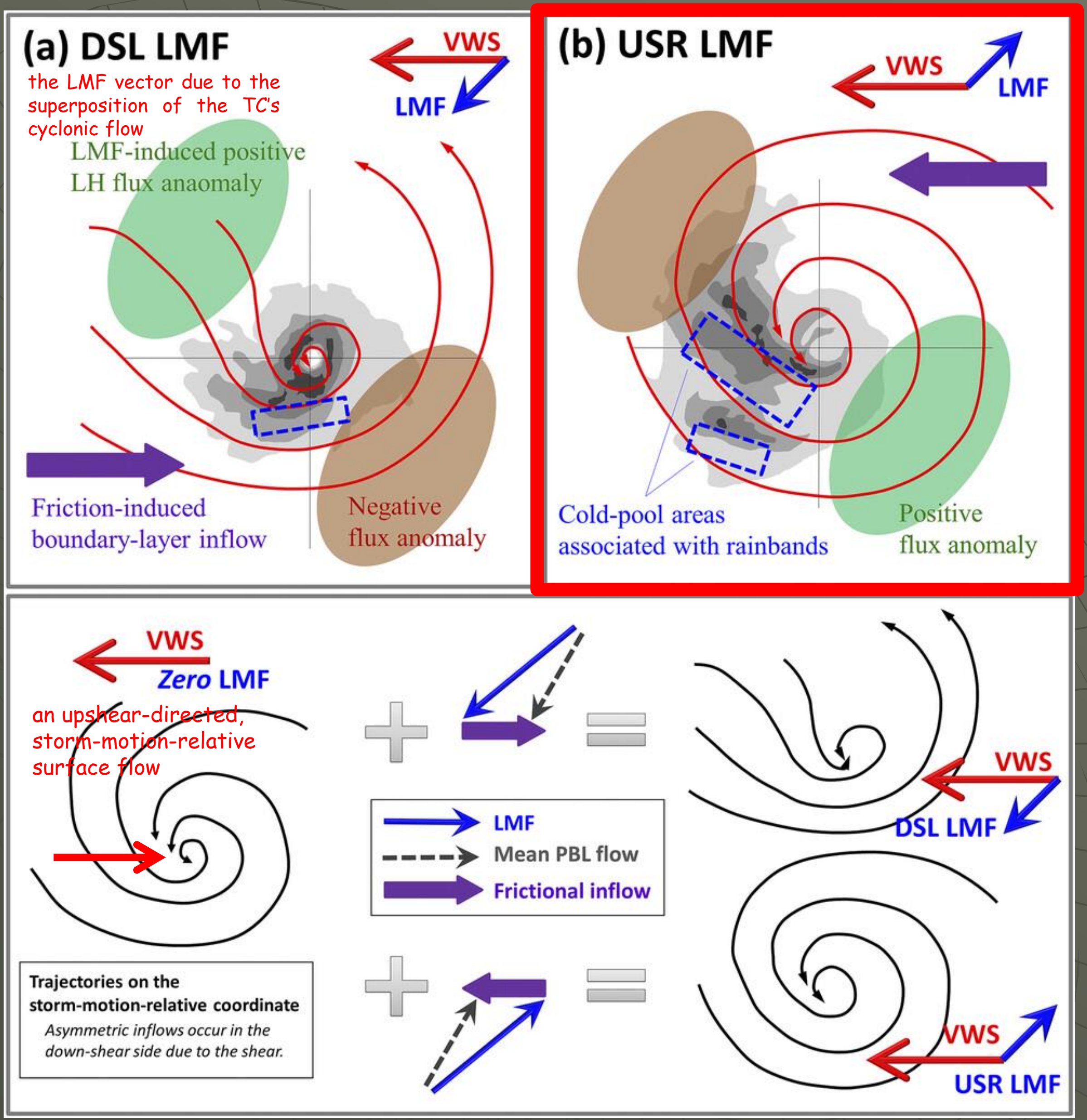
1. Introduction cont.



- For a TC affected by a downshear-left LMF, the frictionally induced inflow adds to the shear-induced inflow, creating a strong inflow, and hence the trajectory goes mainly into the core rather than around the periphery of the core (air parcels are from a source region with larger fluxes). Consequently, higher moisture fluxes into the inner-core result in the relatively compact and axisymmetric rainfall distribution and the subsequent TC intensification.

Chen et al. 2019

1. Introduction cont.



- For a TC affected by an upshear-right LMF, the frictionally induced inflow cancels the shear-induced inflow, and trajectories mainly encircle the storm without penetrating into the inner core (the air mass originating from the upshear-left outer region). Active rainbands are promoted due to the relatively high boundary layer equivalent potential temperature in the downshear moisture envelope. Thus, the heating effect of these active rainbands may result in a large size-expansion rate.

Chen et al. 2019

2. Data and methods——TC data

- The intensity: the maximum sustained wind (kt; 1 kt ≈ 0.51 m s^−1). The size: the averaged radii of 34-kt wind over the four quadrants (n mi; 1 n mi = 1.852 km).

- TC best track datasets from 2004 to 2016 (JTWC; HURDAT2).

- TC structure change: the 24-h difference in intensity/size.

	TC No.	Sample No.	Intensity change (kt day^{-1})	Size change (n mi day^{-1})
All samples	720	4737	21.8	22.4
WP	214	1592	**23.6 (+)**	**25.0 (+)**
EP	136	908	22.1	**19.9 (−)**
AL	191	1089	**17.4 (−)**	22.2
SH	179	1148	**23.4 (+)**	21.2

Table 1. TC characteristics for various basins: number of unique TCs, sample numbers of 24-h intensity/size change events, mean 24-h intensity changes, and mean 24-h size changes. The bold text and "+" ("−") indicate a significantly positive (negative) difference relative to the all-sample mean at the 99% confidence level based on two-sample Student's t tests.

2. Data and methods——
Determining the shear-relative LMF and other environmental factors with reanalysis data

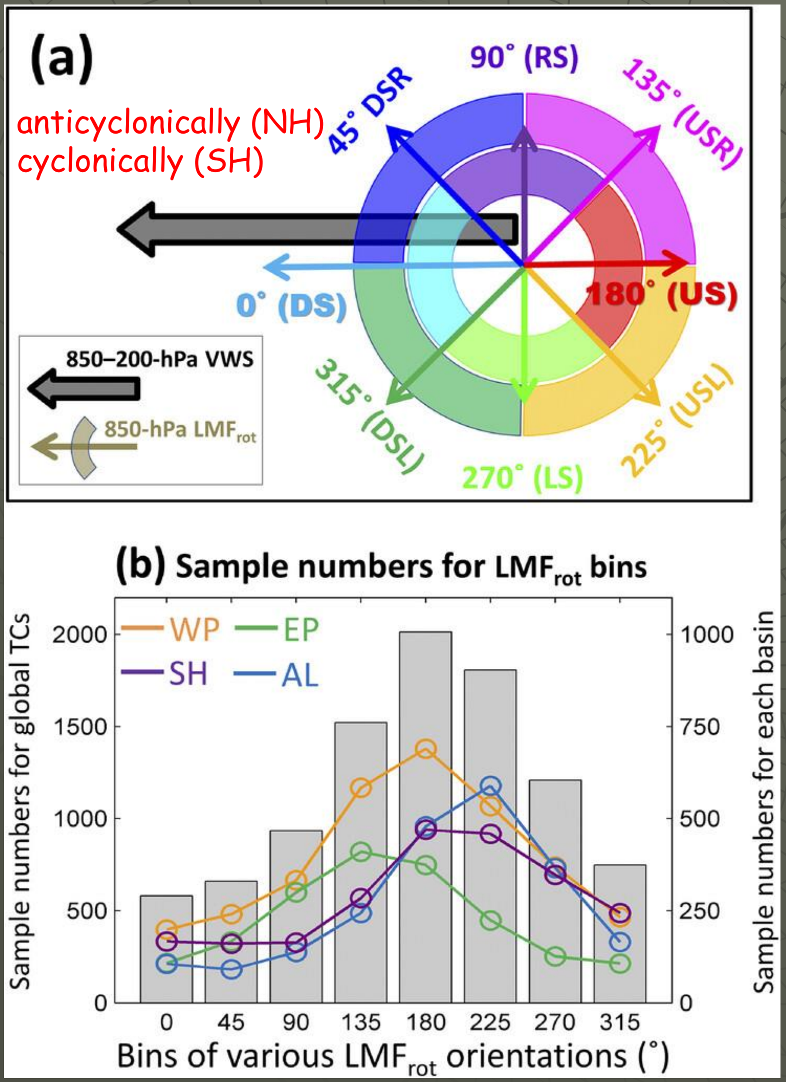
- Using the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis product (Hersbach and Dee 2016; Hersbach et al. 2020), outputs are interpolated to 37 pressure levels and are available at 0.25° resolution.

- ERA5 has a more consistent sea surface temperature (Hersbach and Dee 2016; Hirahara et al. 2016; Hersbach et al. 2020) due to the assimilation of the Hadley Centre Global Sea Ice and Sea Surface Temperature version 2 (Titchner and Rayner 2014) and Operational Sea Surface Temperature and Sea Ice Analysis (Donlon et al. 2012), which is available at a resolution of 0.05° × 0.05° daily.

- VWS is defined as the difference between 200 and 850 hPa mean flows based on the ERA5 reanalysis, and LMF is defined as the 850 hPa mean flow.

- The mean flow is the averaged environmental wind vector within a 500 km radius after removing the TC vortex.

2. Data and methods——
Determining the shear-relative LMF and other environmental factors with reanalysis data cont.



- The shear-relative LMF (LMFrot) is defined as the rotated LMF vector in a shear-relative coordinate in which the VWS vector points toward 0° (or 360°).
- Each sample was shared by two LMFrot bins, and the sample numbers for the eight LMFrot orientations ranged from 580 to 2013.
- Evaluated the sensitivity of the relationship between LMFrot orientation and TC development to other environmental factors, including VWS magnitude, SST (100 km radius from the TC center), and lower tropospheric relative humidity between 850 and 600 hPa (500 km radius from the TC center).

2. Data and methods——
Composite analysis of rain rate and ERA5 fields

- Examine the convective asymmetry diagnosed by satellite precipitation rates obtained from the Climate Prediction Center morphing technique (CMORPH; Joyce et al. 2004) and the ERA5 fields, such as surface winds, equivalent potential temperature (θe), SST, and surface latent heat flux.

- First, samples associated with TCs that interacted with the eight LMFrot orientations were classified into multiple categories by 90° azimuthal bins.

- Then, the CMORPH rain rate within a 10° radius from the TC center was rotated to align each sample along the VWS vector.

- Finally, the composites could be constructed by these rotated CMORPH rain rates for different LMFrot orientations.

- Only four of those are presented in the manuscript to illustrate the results: 45° (downshear-right for a Northern Hemisphere TC), 135° (upshear-right), 225° (upshear-left), and 315° (downshear-left) directions.

2. Data and methods——
Statistical experiments constraining the effects from other environmental factors

An analog approach was employed to control the distribution of a specific factor for an LMFrot bin. For example, the steps for constraining the SST distribution are described as follows.

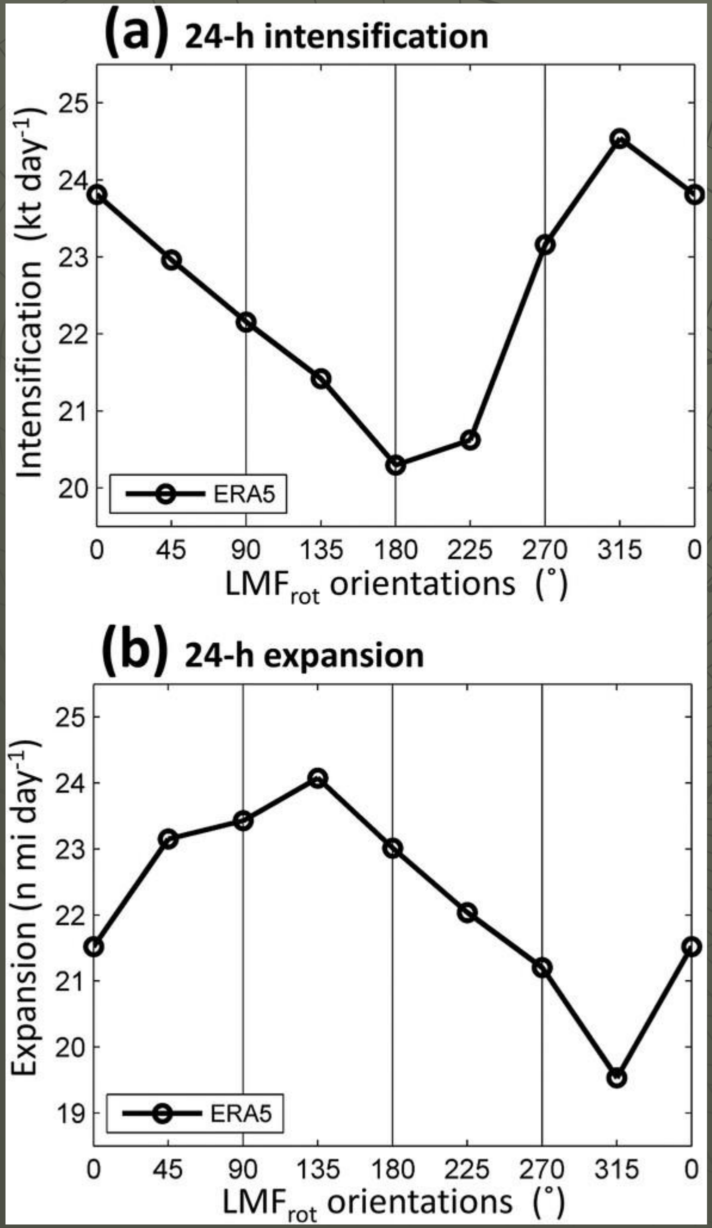
1. The histogram of the SST for samples of all LMFrot bins is first calculated; this is the target histogram for adjusting the unique SST histogram of each LMFrot bin.

2. For each LMFrot bin (e.g., 135°), a total of 500 samples are selected by sampling with replacement (bootstrap) from samples within this LMFrot bin. Moreover, the SST histogram of the 500 samples is required to be similar to the target histogram. Consequently, a unique structure change event can appear more than once in this resampled data.

3. Repeat step 2 for every one of the eight LMFrot bins. (4000 samples can be equally divided into eight LMFrot bins)

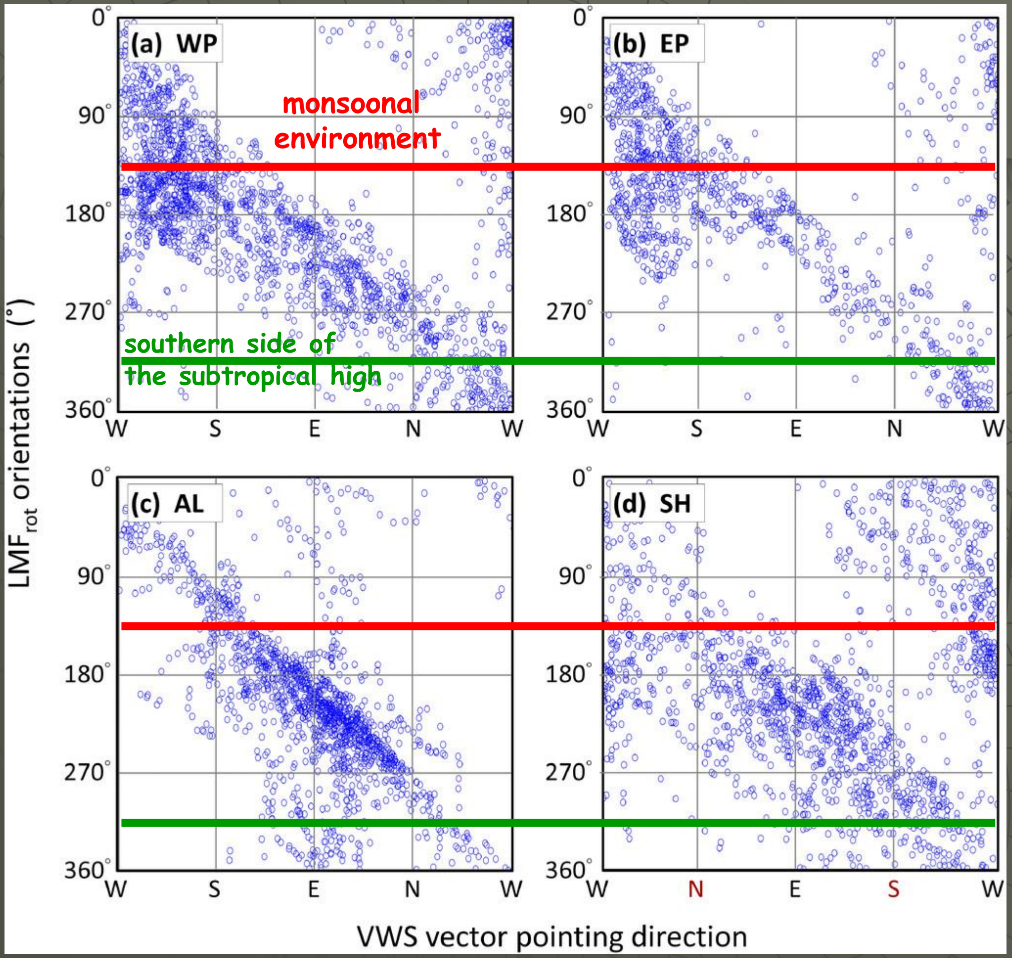
4. Repeat step 3 100 times to create 100 resampled datasets.

3. Relationships between LMFrot orientation and TC intensity and size——Statistical results based on all samples



- TCs affected by LMFrot oriented toward 315° (i.e., downshear-left for Northern Hemisphere TCs) exhibit the largest mean 24-h intensification rate greater than 24 kt day^−1 , and TCs have the lowest mean intensification rate, approximately 20 kt day^−1, when the LMFrot is directed toward 180° (i.e., upshear for Northern Hemisphere TCs).
- The highest mean expansion rate is present as the LMFrot is directed toward 135° (i.e., upshear-right for Northern Hemisphere TCs). The lowest expansion rate is present as the LMFrot is directed toward 315° (downshear-left).

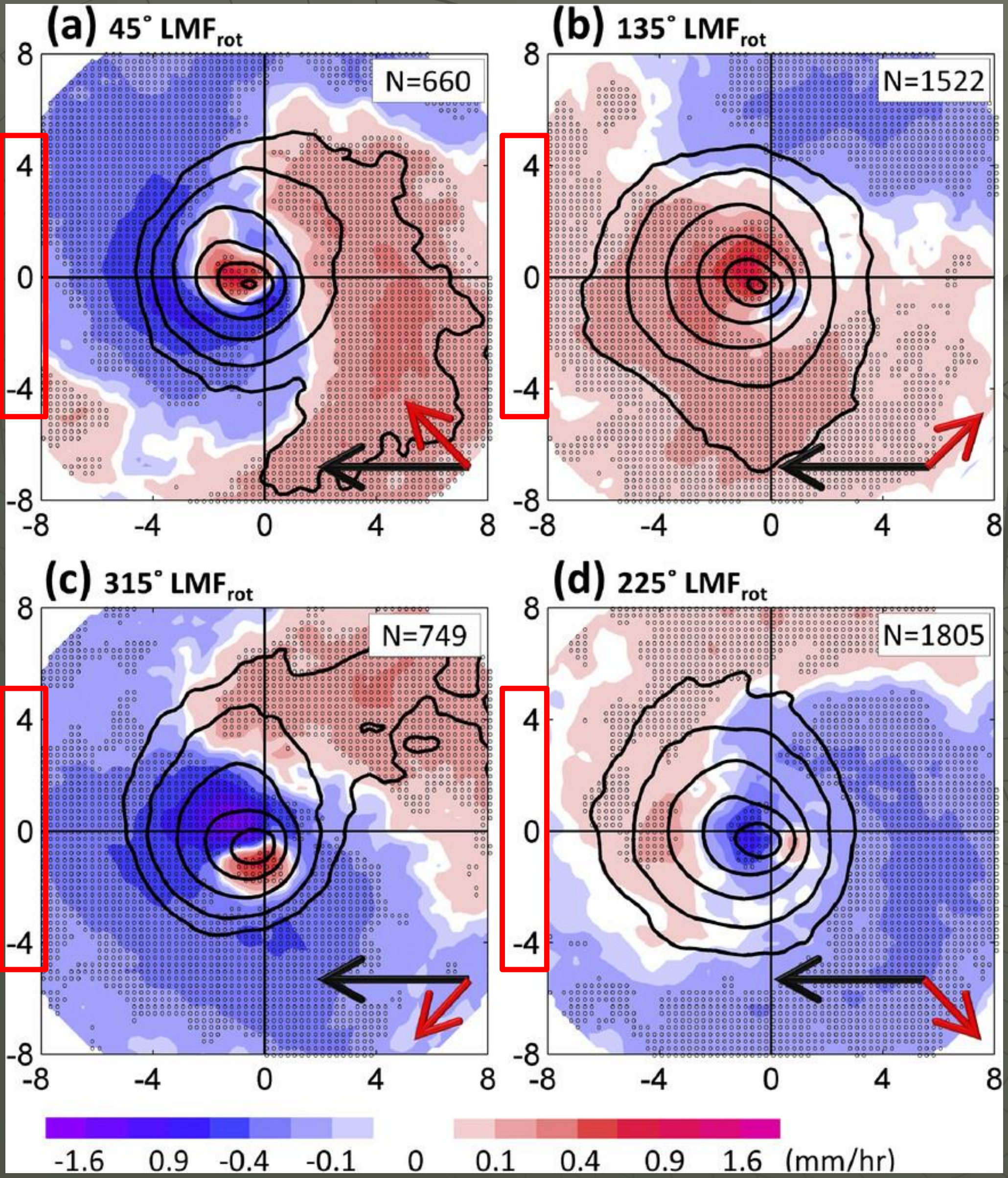
3. Relationships between LMFrot orientation and TC intensity and size——Statistical results based on all samples cont.



- For all basins, an 135° LMFrot tends to be associated with a VWS vector pointing to the equator, while a 315° LMFrot tends to be associated with a VWS vector pointing poleward.

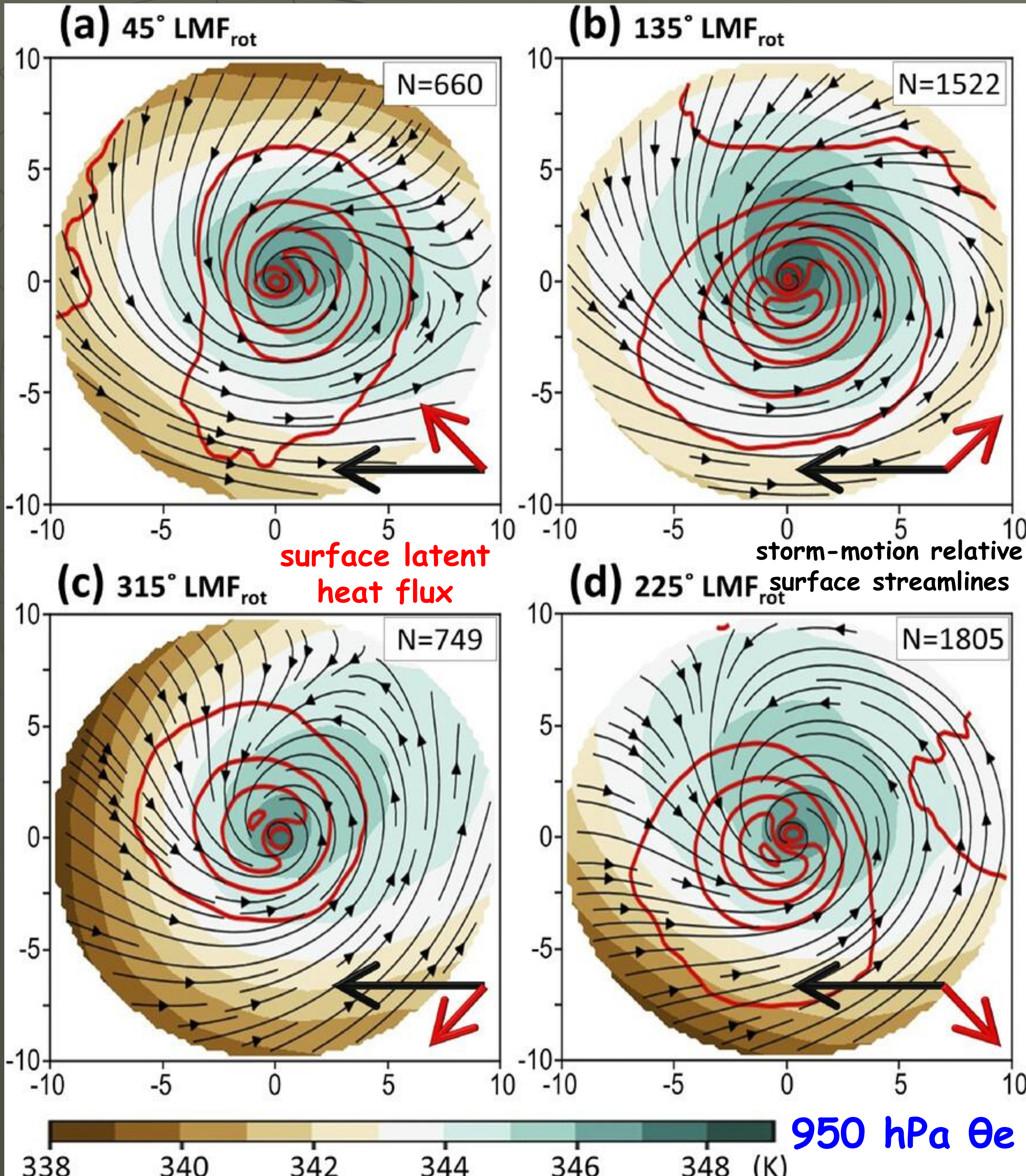
- In the AL, a TC is more likely to experience a westerly shear instead of an easterly shear that is more common in the WP and EP basins; this TC affected by the westerly shear may have a higher chance of interacting with air from the North where the environmental gradients increase.

3. Relationships between LMFrot orientation and TC intensity and size——Composite analysis revealing the associated physical processes



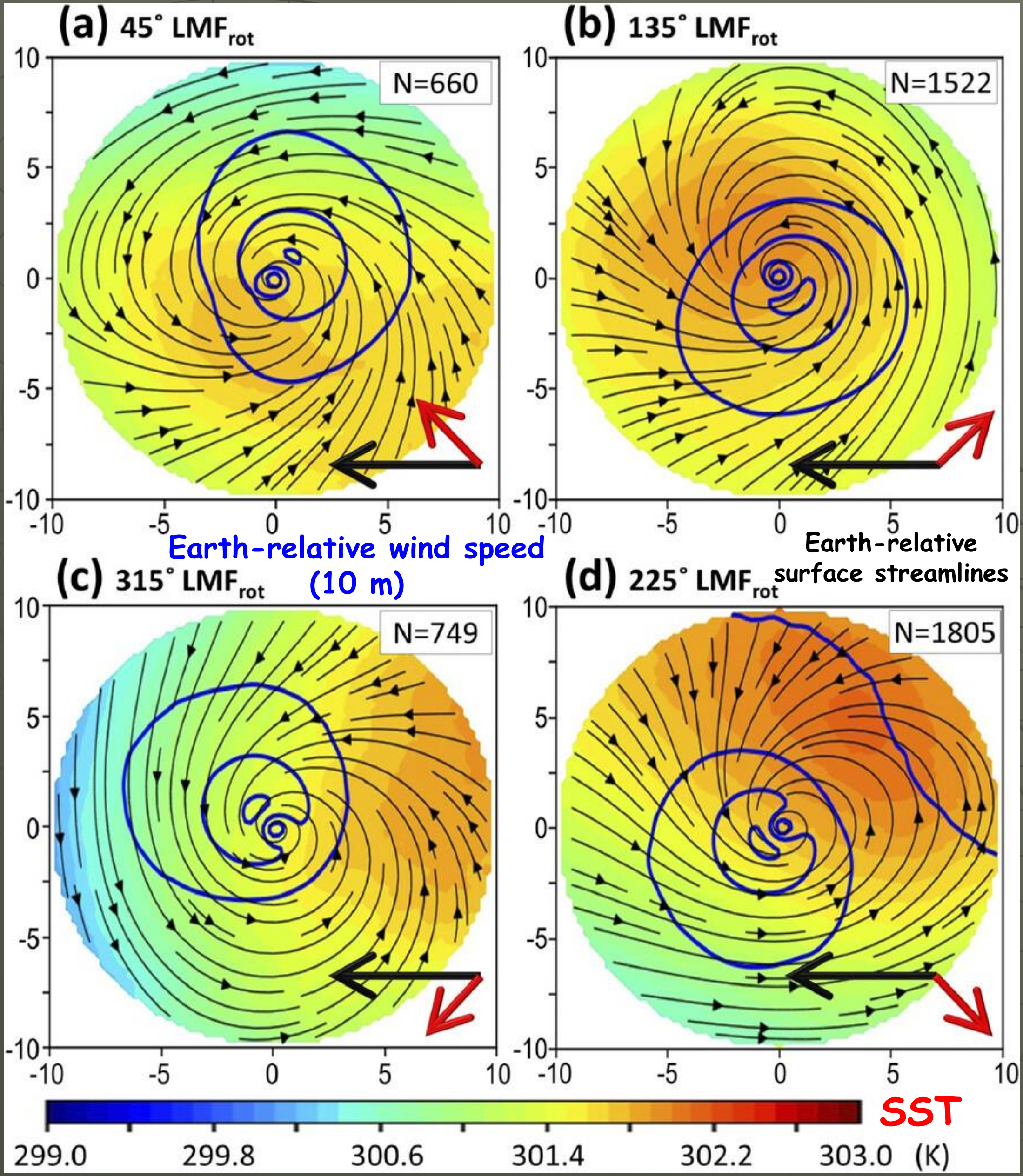
- By examining CMORPH rain rate differences between each composite and the all-sample mean, the 135° (upshear-right) LMFrot composite exhibits the largest area with positive rain rate differences (b). In contrast, the 315° (downshear-left) LMFrot composite exhibits the largest area with negative rain rate differences (c).
- A TC affected by a 135° (upshear-right) LMFrot orientation favors active downshear rainbands, whereas a TC affected by a 315° (downshear-left) LMFrot orientation tends to have a relatively axisymmetric rainfall distribution and a small rainfall extent (1°–2°).

3. Relationships between LMFrot orientation and TC intensity and size——Composite analysis revealing the associated physical processes cont.



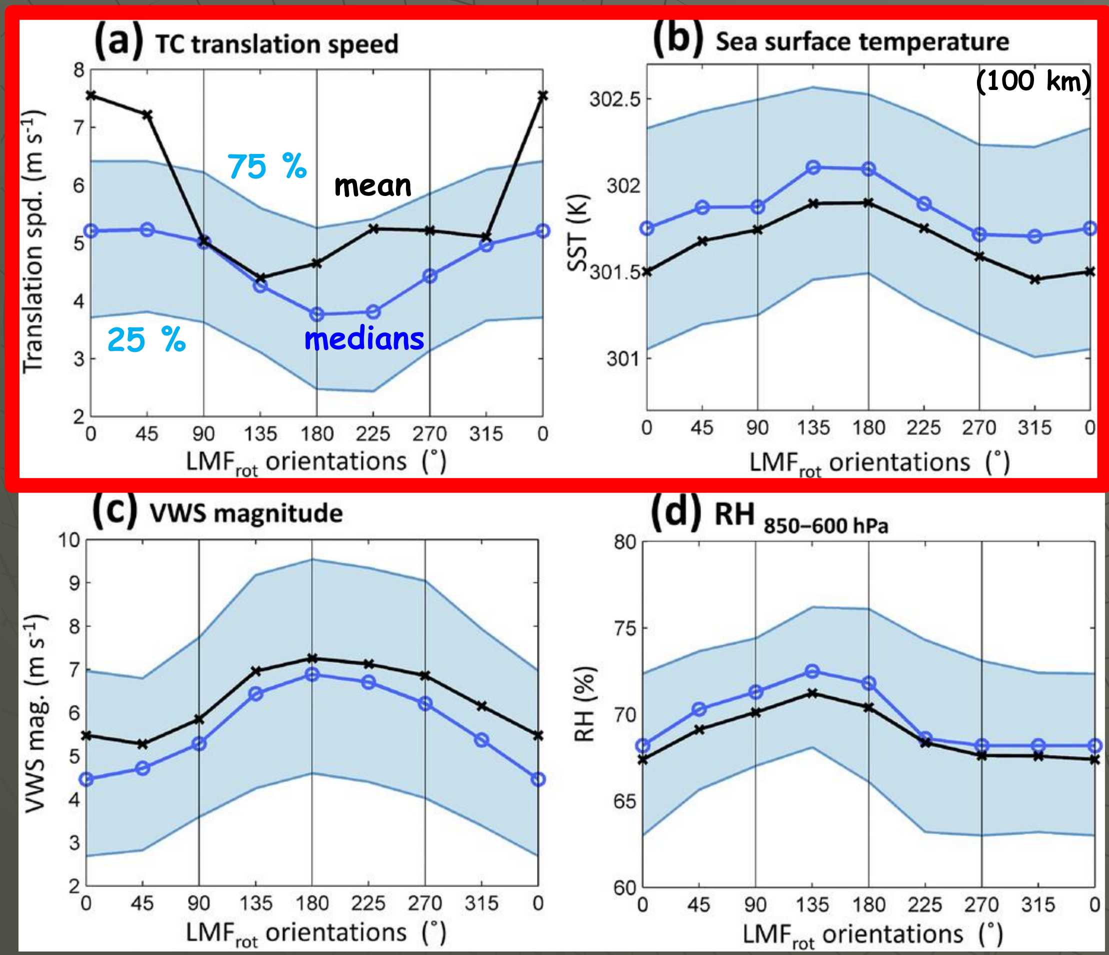
- For the upshear-right LMFrot orientation, the air mass originating from the left-of-shear high-surface-flux region (b) is wrapped around the TC and transported by the storm-relative streamlines into the downshear right rainband region. This process may lead to more active rainbands due to the relatively high 950 hPa θe in the downshear-right quadrant.
- In (c), this storm-motion relative inflow transports the air from the downshear high-surface-flux region into the TC inner core and leads to a compact and relatively symmetric distribution of the inner-core θe within approximately 200 km from the center.

3. Relationships between LMFrot orientation and TC intensity and size——Composite analysis revealing the associated physical processes cont.



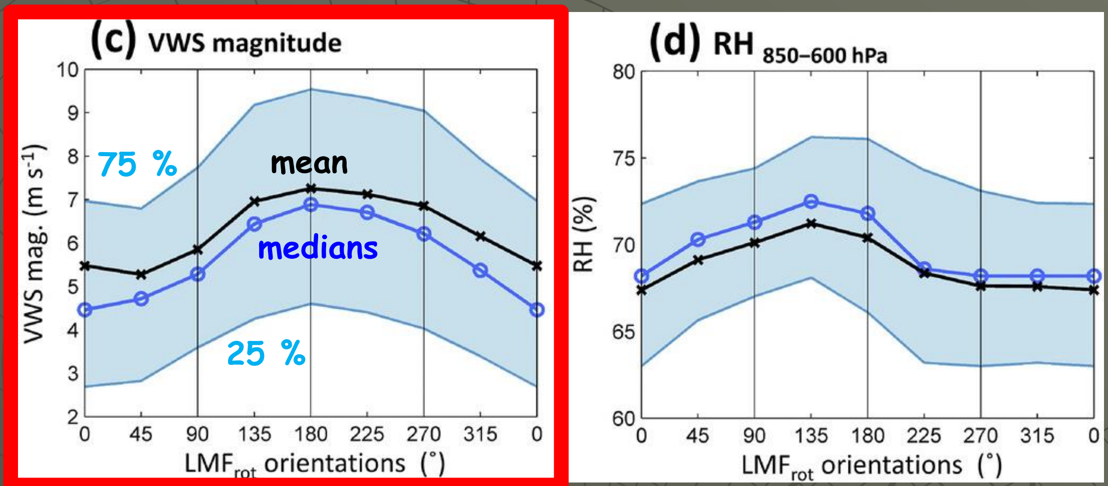
- The SST gradients are large and unlike the homogenous conditions in the idealized simulations. It may result in inconsistent relationships of the LMFrot orientation and TC intensification based on idealized simulations and statistical analyses of real TCs. The higher SST for the 135° LMFrot orientation compared to that of the 315° LMFrot orientation does not lead to larger intensification rates.
- The distribution of surface fluxes is primarily determined by the ground relative wind speed as the distribution of these two variables are similar.

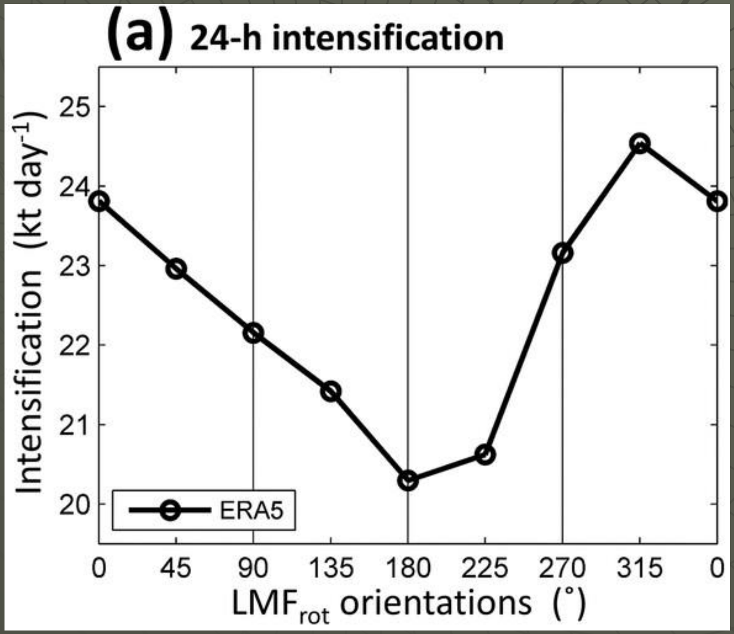
4. Sensitivity of shear-relative LMF's effect to other environmental factors



- The physical meaning of the linkage between the relatively slow TC movement (90°–315° LMFrot bins) and the lower intensification rate for the 180° LMFrot is still unclear (do not pass the Student's t tests).
- The highest mean SST for the 135° LMFrot (upshear-right) orientation does not significantly differ from the lowest mean SST for the 315° LMFrot (downshear-left) orientation at the 95% confidence level. It is suggested that the variation of SST for various LMFrot orientations may not significantly affect the relationship between LMFrot orientation and intensification.

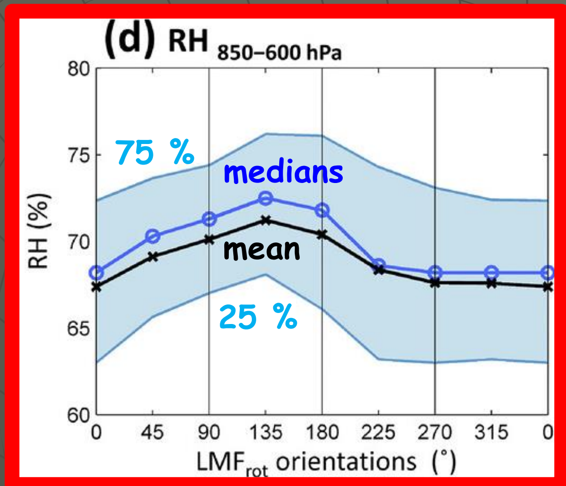
4. Sensitivity of shear-relative LMF's effect to other environmental factors cont.

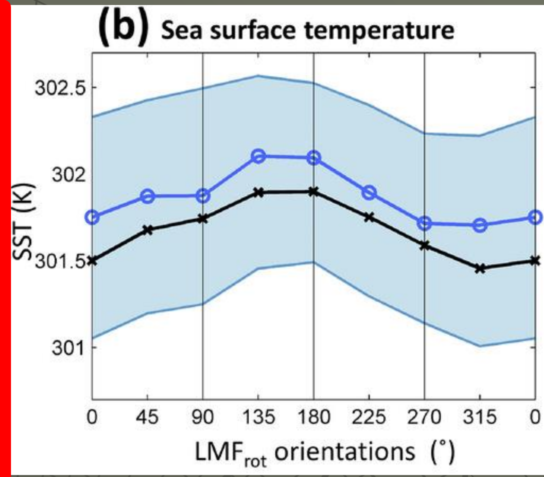


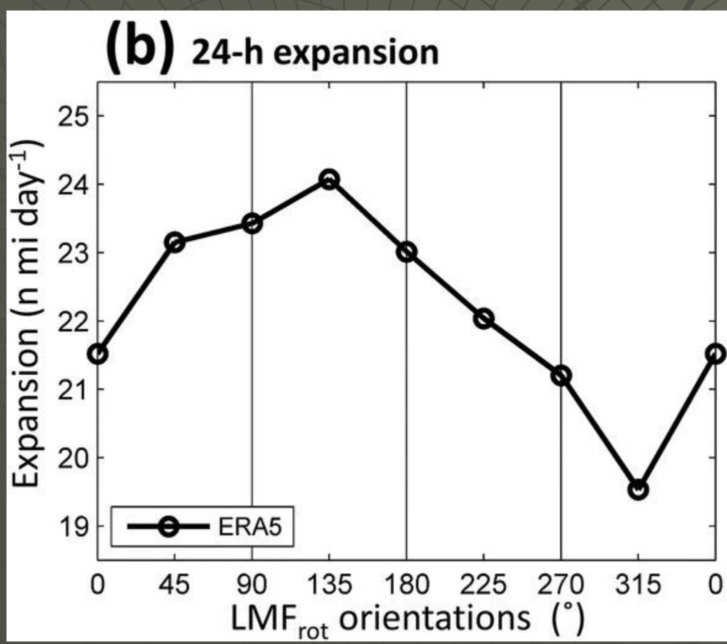


- The VWS magnitudes associated with 135°–225° LMFrot bins are significantly higher than that of the 0° and 45° LMFrot bins and may contribute to low intensification rates for these LMFrot orientations (a). The moderate VWS magnitude for the 315° (downshear-left) LMFrot orientation could not explain the highest intensification rate (a).
- From a statistical view, the relationship between LMFrot orientation and TC development is not simply a consequence of the variation of mean SST or VWS magnitude for various LMFrot bins. (critical to the highest intensification rate for the 315° LMFrot bin)

4. Sensitivity of shear-relative LMF's effect to other environmental factors cont.

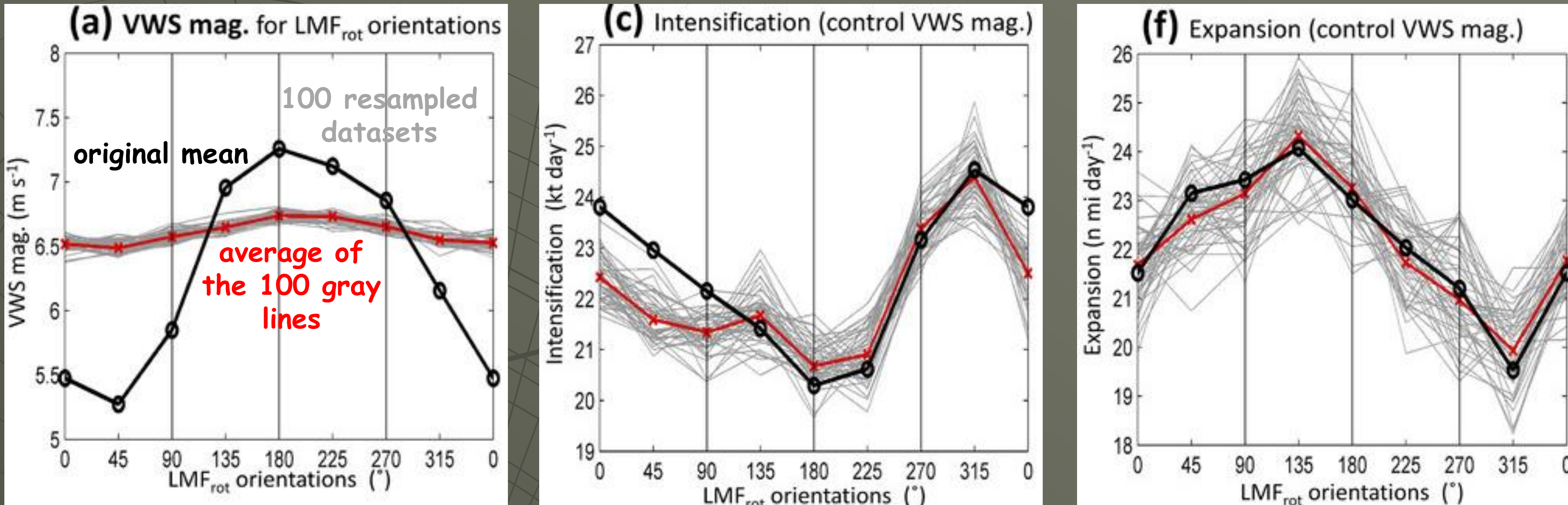






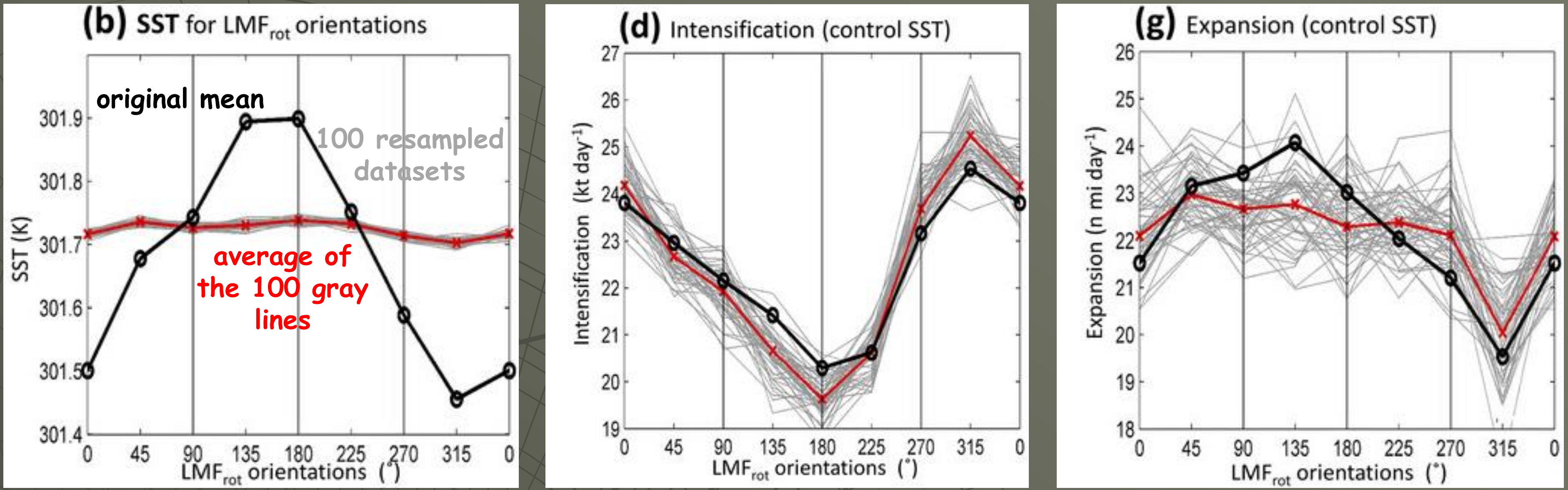
- The largest median and mean values are associated with the 135° LMFrot (upshear-right for Northern Hemisphere TC) bin, which also has the largest mean expansion rate (bottom b).
- The variation of RH850–600 hPa (d) is similar to and positively correlates with the variation of SST (b), suggesting at a statistical viewpoint that the SST variation may modify the RH850–600 hPa and indirectly affect the TC expansion along with the other physical processes.

4. Sensitivity of shear-relative LMF's effect to other environmental factors cont.



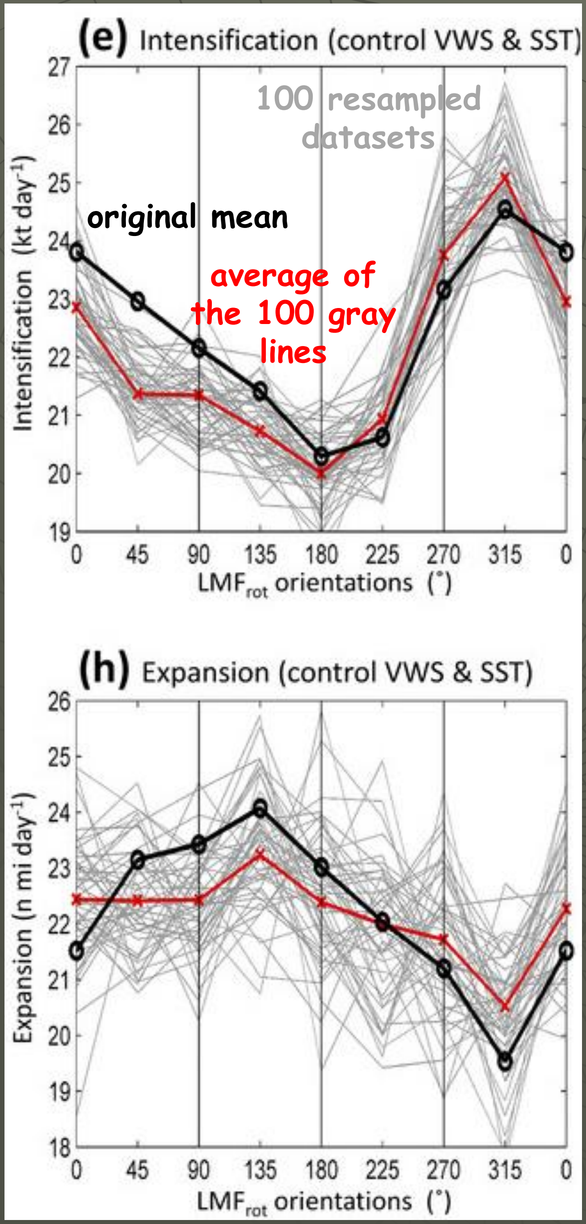
- Constraining the VWS distributions, high TC intensification rates are still associated with the 315° LMFrot (downshear-left) orientation (c). Intensification rates for 0° and 45° LMFrot bins significantly decrease once their favorable VWS magnitudes are accounted for.
- The LMFrot orientation is also important for TC intensification, particularly for the downshear-left LMF orientation that causes large intensification rates.
- The relationship between TC size expansion and LMFrot orientation does not significantly change (f) after constraining the VWS distributions. Therefore, variation of the VWS magnitude does not affect the effect of LMFrot orientation on TC size.

4. Sensitivity of shear-relative LMF's effect to other environmental factors cont.



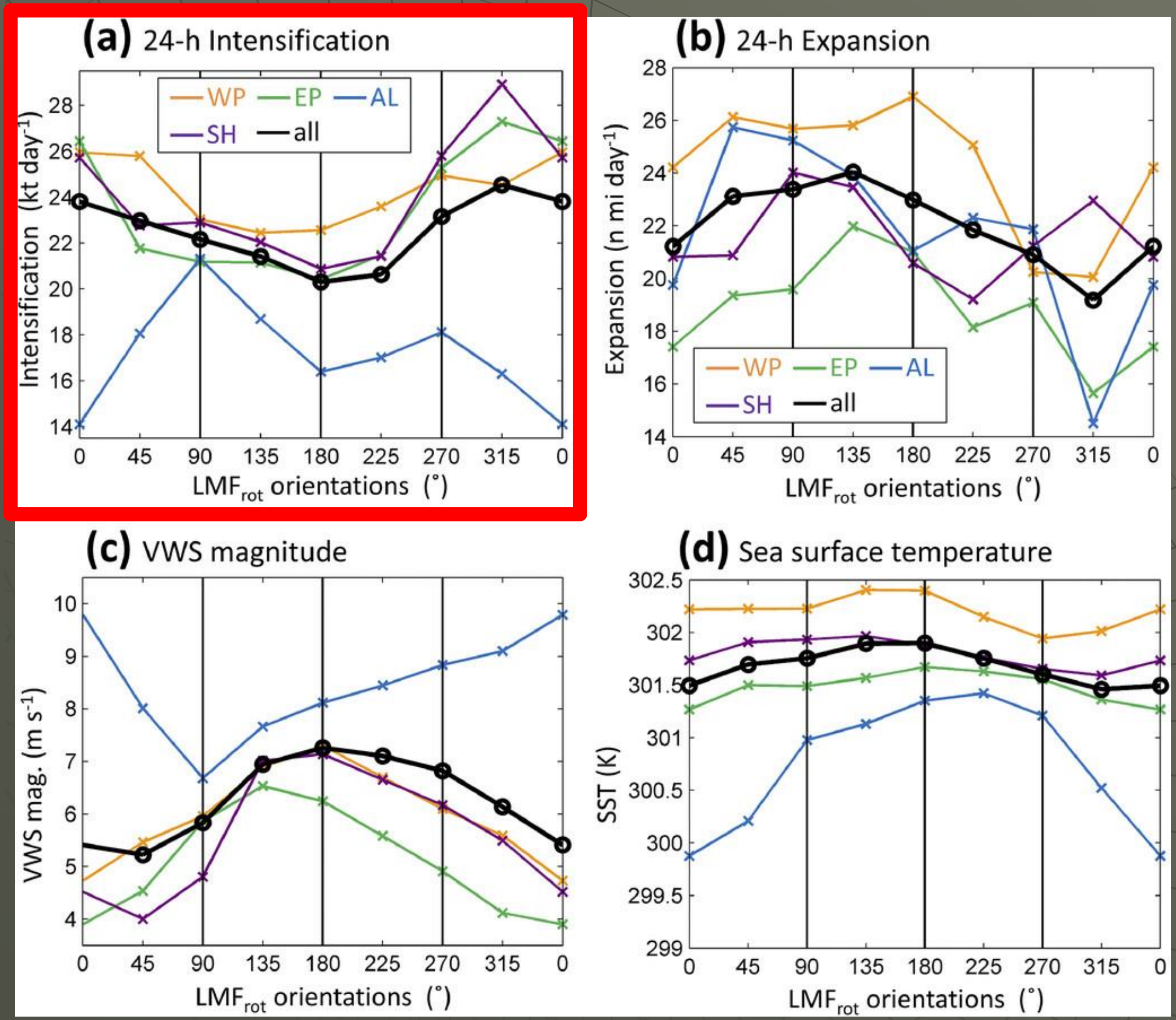
- Positive SST deviations for 135°-225° LMFrot bins and negative SST deviations for 270°-360° LMFrot bins were removed (b). The resampled datasets exhibit a similar relationship between LMFrot orientation and TC intensification to that of the original samples (d).
- The effect of LMFrot orientation on intensification is not a consequence of the variation of SST for various LMFrot bins.
- The initially large TC expansion rates associated with 90°-180° LMFrot (upshear-right) bins considerably decrease (g), implying that the relationship between LMFrot and expansion is partly attributed to the variation of SST (decreased environmental RH and the consequent rainband activity for the 135° LMFrot).

4. Sensitivity of shear-relative LMF's effect to other environmental factors cont.



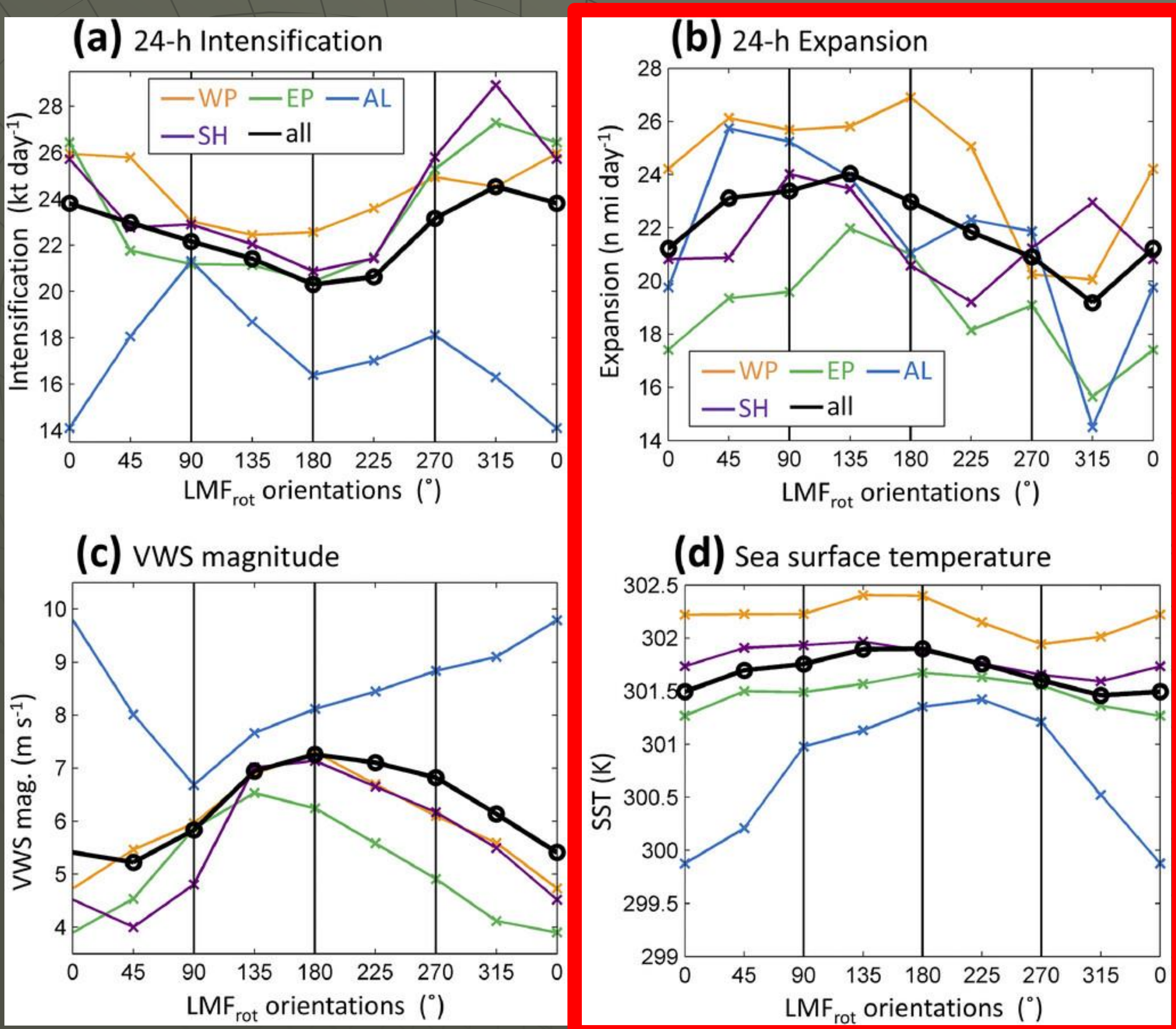
- The results suggest that the variation of both VWS and SST does not interrupt the relationship of LMFrot orientation on TC intensification, as revealed by the statistics of the original dataset (e).
- The mean intensification rate for the 315° LMFrot becomes higher, and the mean intensification rates for 0°–135° bins become lower, suggesting a more robust effect of LMFrot orientation on modulating TC intensification.
- The difference in expansion rate between the 135° and 315° bins becomes smaller (h). This result suggests that, for real TCs, the relationship between shear-relative LMF and TC expansion is partly attributed to other environmental factors and partly attributed to the interaction between the TC and various LMFrot orientations.

5. Effects of LMFrot in various basins



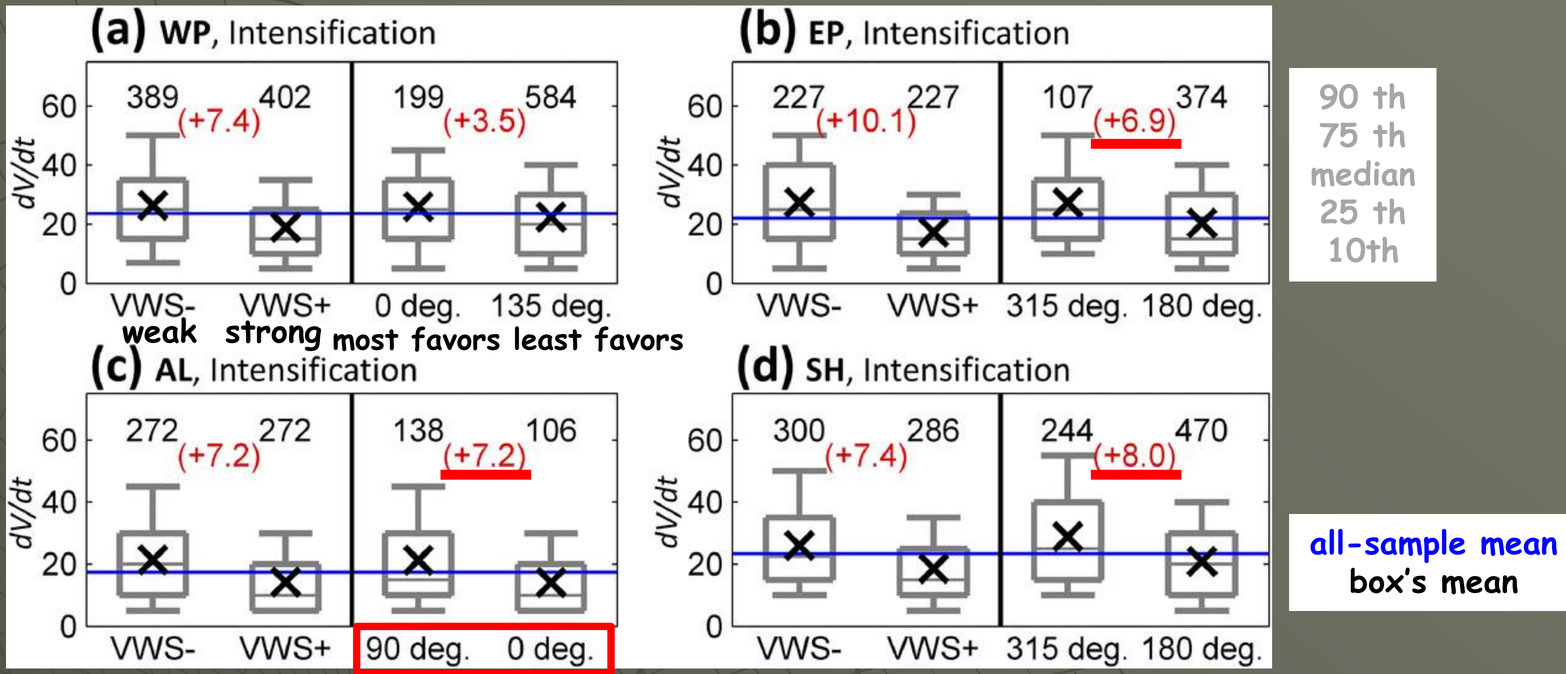
- TCs in the SH and EP basins (a) have the highest intensification rates for the 315° LMFrot (downshear-left for EP but downshear-right for SH) orientation and low rates for the 180° bin.
- A relatively weak relationship is found between LMFrot orientation and intensification of WP TCs with maxima for the 360° (downshear) bin and minimum for the 135° bin (upshear-right).
- TCs in the AL basin (a,) exhibit an opposite relationship to the all-sample statistic between intensification and LMFrot orientation.

5. Effects of LMFrot in various basins cont.



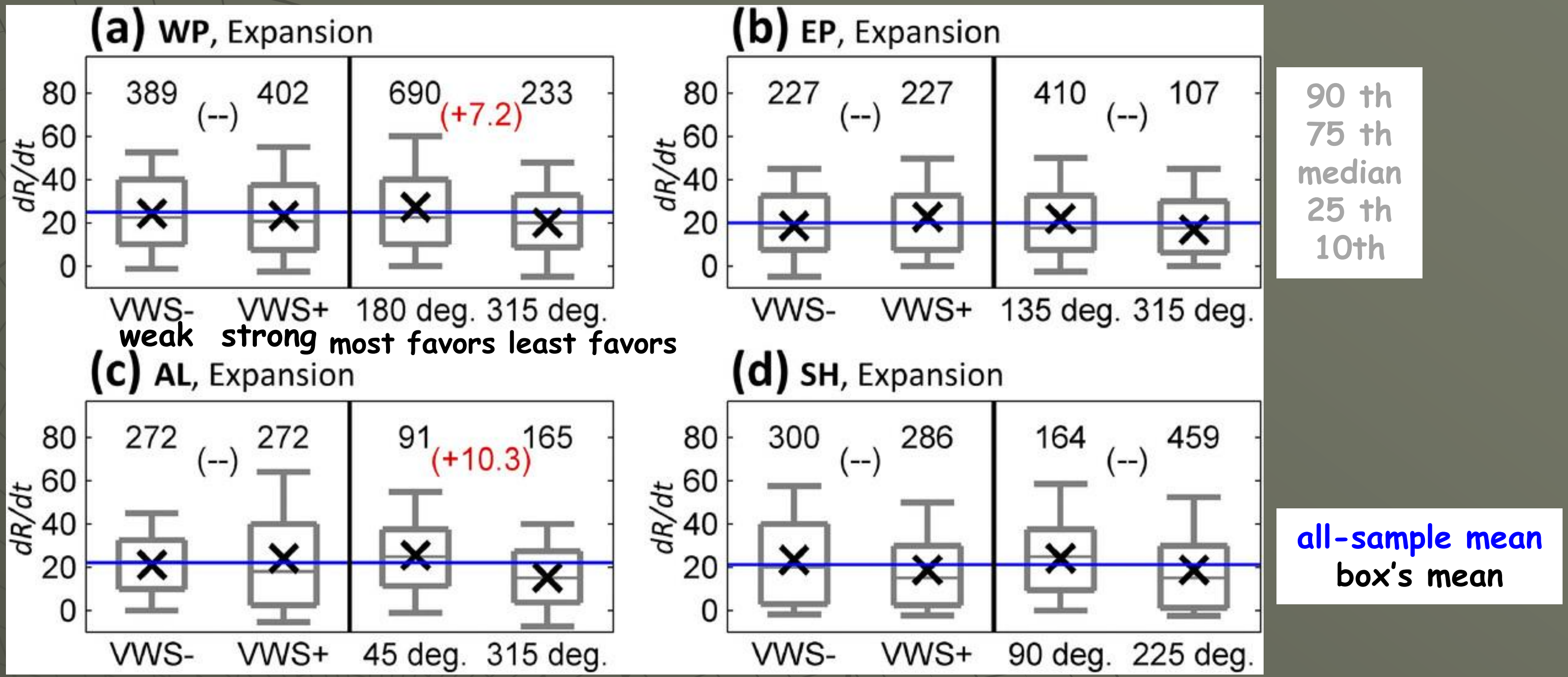
- The behavior of TC expansion associated with LMFrot orientation is generally consistent across various basins except for SH TCs (b), with high expansion rates for 45°–180° LMFrot orientations and low expansion rates for 315° LMFrot bin.
- The large expansion rates associated with 45°–180° LMFrot orientations for the WP TCs may be partly related to the large SST (d).

5. Effects of LMFrot in various basins cont.



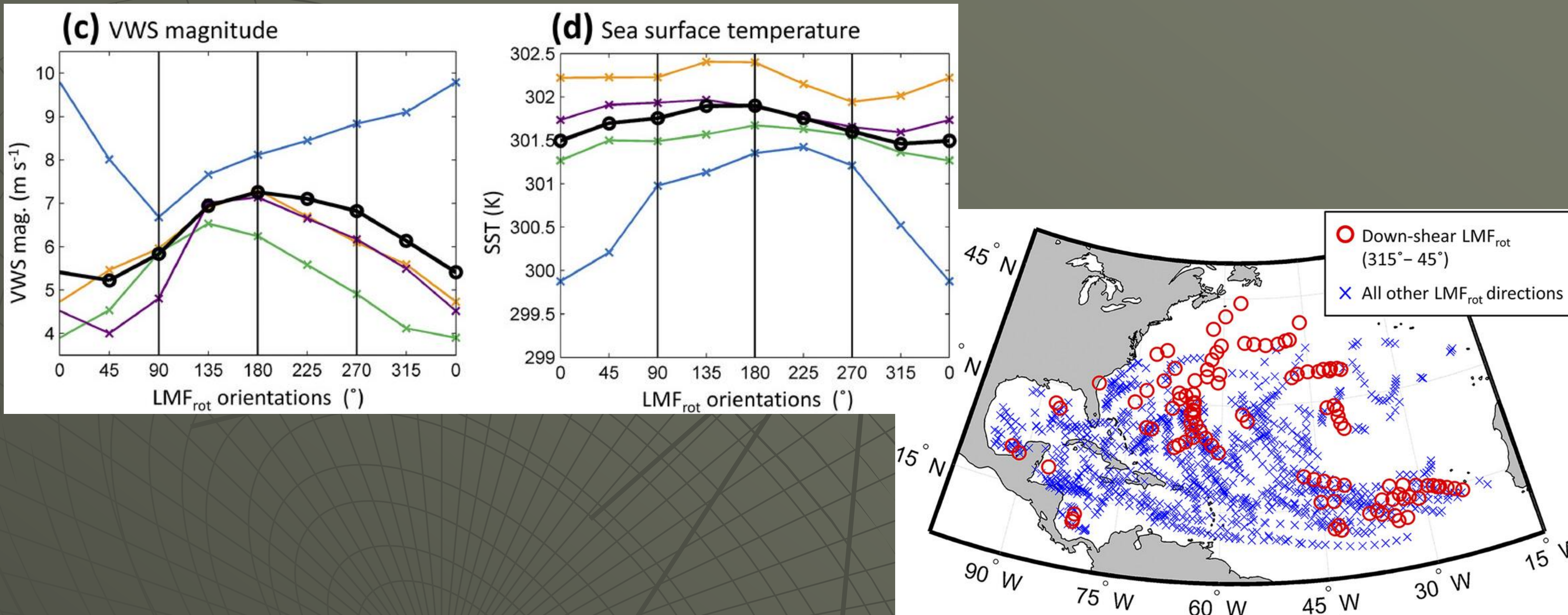
- The mean differences of intensification rates between the weak VWS and strong VWS subgroups are significant for all of the four basins at the 99% confidence level.
- The difference in the intensification rates between the two LMFrot orientations is significant and larger than 5 kt day^1 for the EP, AL, and SH basins.
- The AL TCs exhibit an opposite relationship between intensification and LMFrot orientation to the TCs in other basins.

5. Effects of LMFrot in various basins cont.



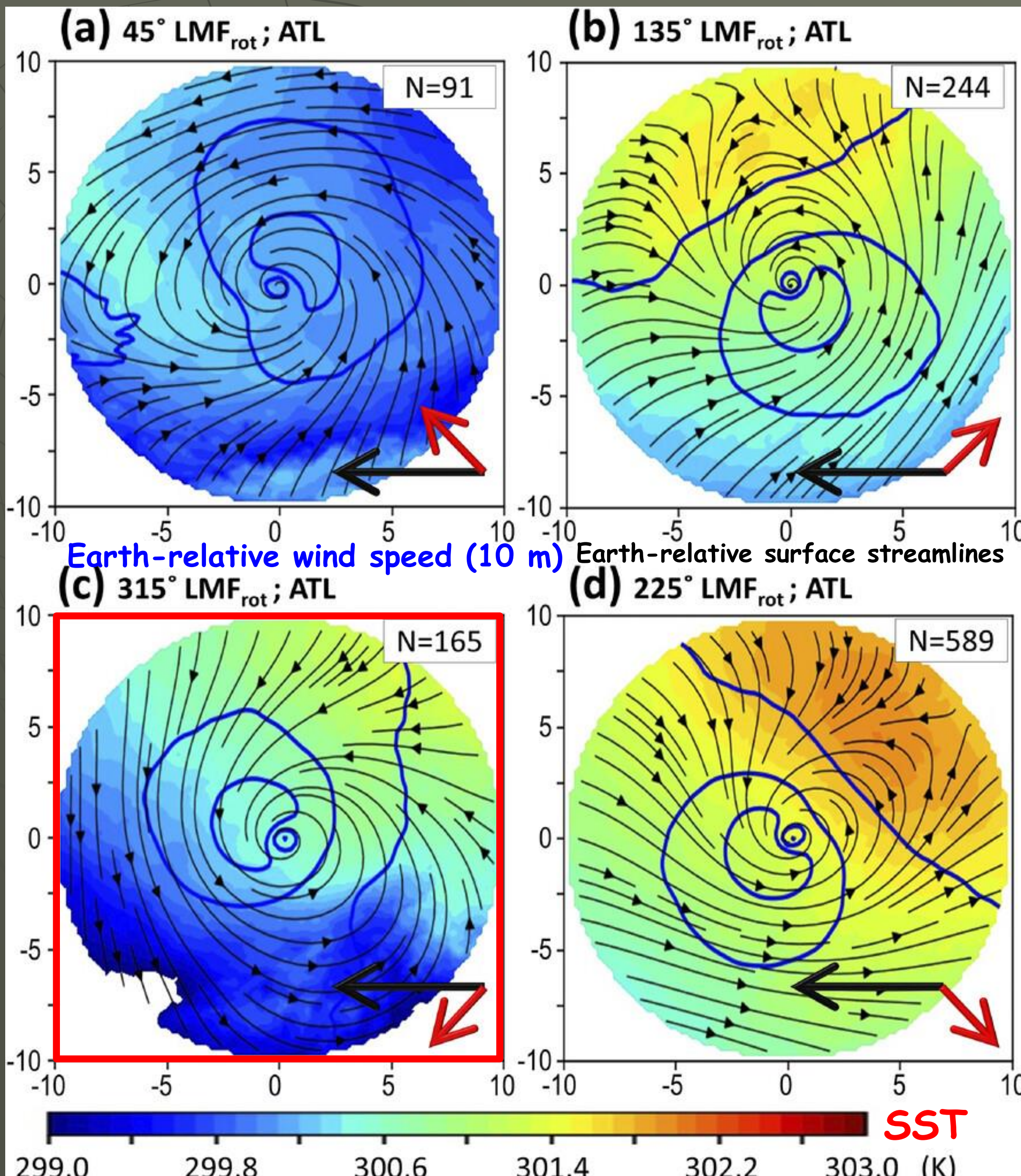
- The VWS magnitude is not critical to TC size expansion for all basins.
- The right pair of boxplots reveals significant differences between the two LMFrot orientations for the WP (a, 7.2 n mi day^1) and AL (c, 10.3 n mi day^1) basins at the 99% confidence level.

5. Effects of LMFrot in various basins cont.

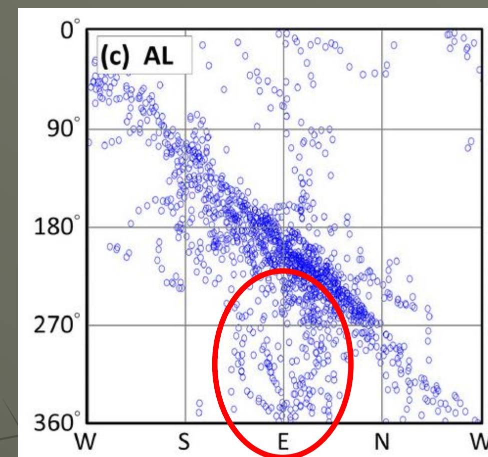


- Compared with other basins, AL TCs are generally affected by low SST and high VWS magnitudes and thus have a lower mean intensification rate of 17.4 kt day^1 (Table 1).
- The 315°–45° LMFrot bins (downshear orientation) in the AL basin are accompanied by considerably larger VWS magnitudes (c) and cooler SST (d) because many AL TCs affected by downshear LMFrot (315°–45°) orientations are located at higher latitudes.

5. Effects of LMFrot in various basins cont.

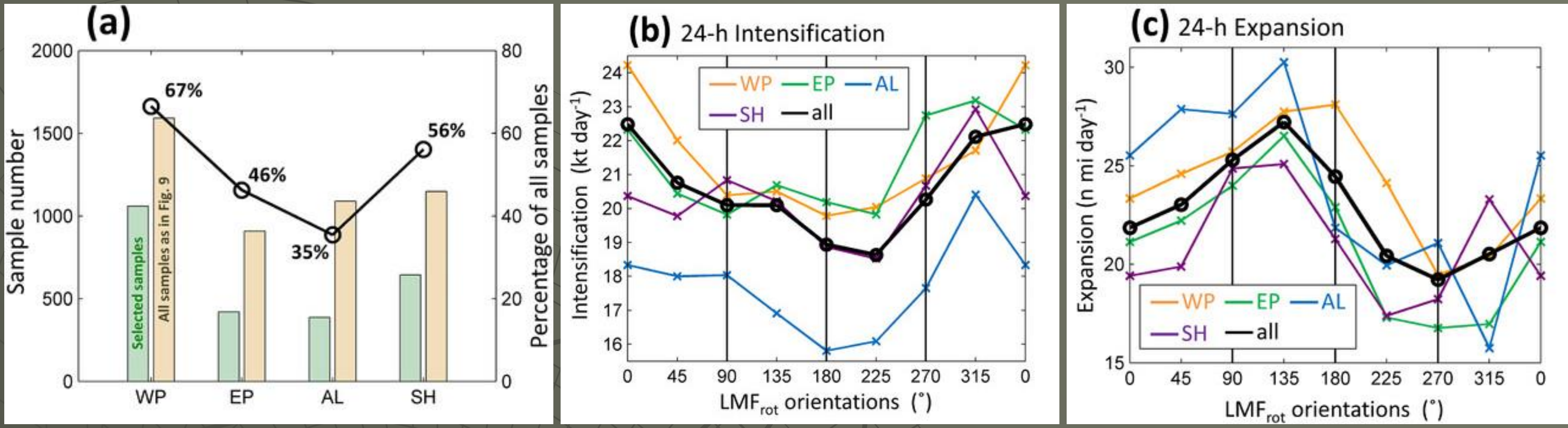


- The AL composite of 45° and 315° LMFrot (a,c) is much cooler than the all-sample composites. A large environmental SST gradient to the lower-left of the figure.



- A higher portion of AL TCs affected by 270°–360° LMFrot is accompanied by westerly VWS.
- The lower environmental SST and the large SST gradient are located north of the TC center on a geography map.
- This SST distribution may also be unfavorable for TC intensification because it reduces the surface fluxes and boundary layer θe in the TC outer region.

5. Effects of LMFrot in various basins cont.



- A subset of all samples is selected by excluding samples with top 20% VWS, bottom 20% environmental SST calculated over 500 km radius, latitudes larger than 25°, or top 10% intensification rates.
- After excluding the cases with extreme environmental conditions and the extraordinarily intensifying cases for which inner-core dynamics could be critical, 67%, 46%, 35%, and 56% of samples are left for the WP, EP, AL, and SH basins, respectively.
- The maximum intensification rate is associated with the 315° (downshear-left) bin for the subset of AL cases, while the minimum intensification rate is associated with the upshear LMFrot.
- High expansion rates are found in 90°–180° LMFrot (right-of-shear to upshear) bins for the subsets of various basins.

6. Conclusions

- In agreement with (Chen et al. 2018, 2019), statistical results suggest that an LMFrot directed toward 315° (downshear-left for North Hemisphere TCs) favors intensification, whereas an LMFrot directed toward 135° (upshear-right for North Hemisphere TCs) is favorable for size expansion.

- Examining the CMORPH rain rate and ERA5 composites, a Northern Hemisphere TC affected by a downshear-left LMFrot orientation favors a relatively symmetric rainfall distribution, whereas an upshear-right LMF promotes active downshear rainbands.

- The relatively symmetric rainfall distribution and the small rainfall extent associated with the downshear-left (315°) LMFrot orientation may favor TC intensification due to better intensification efficiency (Nolan and Grasso 2003; Nolan et al. 2007) and a large radial flux of azimuthal mean vorticity in the boundary layer near the radius of maximum wind (Chen et al. 2019).

- TC size expansion is promoted by a positive radial flux of eddy vorticity near the radius of 34-kt wind when a simulated TC is affected by an upshear-right (135°) LMFrot orientation because the vorticity associated with active rainbands is in phase with the storm motion-relative inflow (enhanced rainband activity can lead to a larger TC size due to rainband heating).

6. Conclusions cont.

- Based on the analysis of the ERA5, the relationship between shear-relative LMF and intensification is not significantly modified by other environmental factors, including inner-core SST, VWS magnitude, and environmental relative humidity. The relationship regarding expansion is mainly attributed to the LMFrot and partly to environmental SST and RH variation for various LMFrot orientations.

- Both the VWS magnitude and the LMFrot orientation impact TC intensification in the EP and SH basins. In contrast, the relationship between the LMFrot orientation and TC expansion is particularly significant in the WP and AL basins. However, the VWS magnitude shows no significant relationship to TC expansion.

- For AL TCs, the variations of the VWS and environmental SST for different LMFrot orientations contribute to the inconsistent relationship to the all-sample statistic between TC intensification and LMFrot orientation. For AL TCs, the relationship between LMF orientation and intensification is only valid by focusing on a representative subset of samples associated with generally favorable conditions.

The End…

Thanks !

Questions??