Identifying the Development of a Tropical Depression into a Tropical Storm over the South China Sea

HUIJUN HUANG, JINNAN YUAN, GUANHUAN WEN, XUEYAN BI, LING HUANG, AND MINGSEN ZHOU

Institute of Tropical and Marine Meteorology, China Meteorological Administration, Guangzhou, China

Speaker：Mao-Cheng, Lee

Nov. 16 2021

Abstract

- Examine the dynamic and thermodynamic variables of 74 tropical depressions over the South China Sea, 52 of which developed into storms, hereafter "developing," with the remaining being classified as "nondeveloping."
- Using the National Centers for Environmental Prediction Final (NCEP FNL) data, verified with ECMWF forecast data, we examine the dynamic and thermodynamic statistics that characterize these tropical cyclones.
- Based on these characteristics, we propose seven criteria to determine whether a tropical depression will develop. Five had been used before, but two new criteria are also found to be useful.
- These two are associated with the diabatic heating rate: 1) presence of a regular diurnal variation of the diabatic heating rate at the center and 2) occurrence of specific peaks in the radiative-heating profile.
- Test all seven criteria on all tropical depression cases in 2018/19 before the system developed or decayed, showing that these criteria can help to operationally identify whether or not a tropical depression develops into a tropical storm with an average lead time of 36.6 h.

1. Introduction

- Compared to tropical cyclones (TCs) that form in the west North Pacific (WNP), TCs that form over the South China Sea (SCS) have distinct climatic features and synoptic background (Lee et al. 2006; Lin and Lee 2011; Yuan et al. 2015; Ling et al. 2016; Wang 2017).
- Compared to the TCs over the WNP, the cyclones over SCS are weaker and have smaller median radii (using wind speed as a criterion; Yuan et al. 2007).
- According to climatological statistics, about 67% percent of the rapidly intensifying TCs offshore of China occur in the SCS, much larger than the 23% in the East Sea and 10% in the Yellow Sea (Liu and Rong 1995; Yan 1996; Lin et al. 2006).
- With their rapid intensification, sudden changes in their track, and their complex rainstorm pattern, tropical cyclones in the SCS nearly always bring severe damage to South China or Vietnam (Chen et al. 2004; Zhang et al. 2009; Duan et al. 2014; Wen et al. 2019; Tran-Quang et al. 2020).

1. Introduction cont.

- Compared to forecasting the track of a tropical cyclone, forecasting the intensity is more difficult because it depends on processes with length scales spanning many orders of magnitude, including smaller-scale thermodynamical processes and larger-scale fluid dynamics (Montgomery and Smith 2017).

- Forecasting the intensity has greatly improved with the help of NOAA's Hurricane Forecast Improvement Project (HFIP), but the forecasting of rapid intensification needs much more improvement (Cangialosi et al. 2020). It has remained difficult to accurately predict when a given tropical depression (TD) will develop into a tropical storm (TS) (Gray 1998; Emanuel 2003; Zawislak and Zipser 2014).

- In the SCS, forecasters still need more effective criteria to determine if a given TD will become a TS (Gray 1998; Kerns and Chen 2013; Huang et al. 2014).

2. Dataset and the TC developing stage —Dataset and statistical method

- Observation: NCEP FNL (Final) Operational Global Analysis data on a 1° × 1° grid spacing (provides values once every 6 h)
- Forecast: ECMWF data on a 0.125° × 0.125° grid spacing and 17 vertical levels (provides values once every 6 h)
- SST data from the NOAA optimum interpolation (OI) SST V2 (0.25° daily mean)
- The area is the South China Sea (SCS) and nearby (100°–120.5°E, 0°–25°N) from 2000 to 2017.
- The track data of the TC positions are from the China Meteorological Administration (Ying et al. 2014).

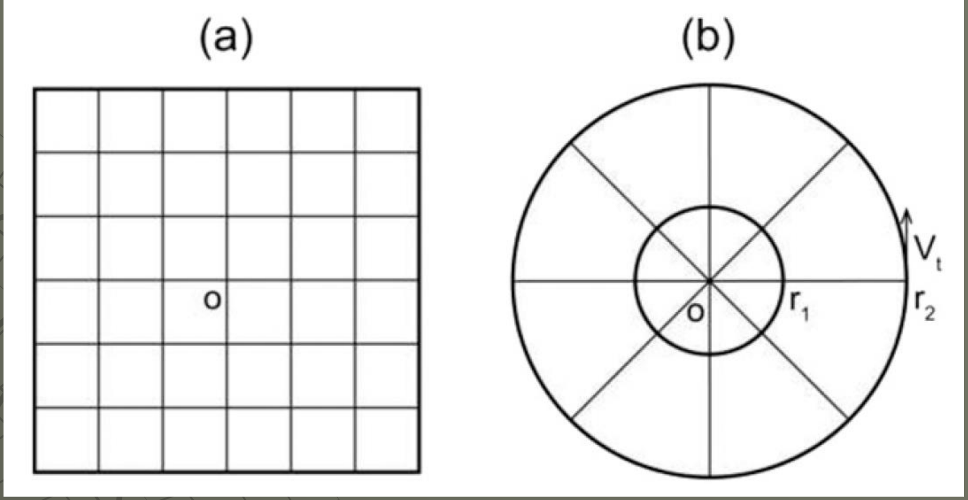
TABLE 1. The 57 developing (TY) and 29 nondeveloping (TD) tropical depressions formed in the South China Sea 2000–17. The initial date and time format is YYYYMMDDHH (UTC).

Year	TC case (initial date and time)		
2000	TY0002 (2000051712)	TD0005 (2000061612)	TY0017 (2000082900)
	TD0003 (2000052000)	TY0007 (2000070212)	TY0020 (2000090518)
	TD0004 (2000053018)	TY0015 (2000082106)	TY0023 (2000100700)
2001	TY0101 (2001050912)	TY0103 (2001062906)	TY0111 (2001080900)
	TD0113 (2001081600)	TY0116 (2001082706)	TD0127 (2001112000)
2002	TD0205 (2002052800)	TY0206 (2002060500)	TY0210 (2002070718)
	TY0215 (2002080118)	TY0217 (2002081506)	TY0221 (2002090918)
	TY0223 (2002092300)		
2003	TY0305 (2003052506)	TY0306 (2003053000)	TD0314 (2003081906)
	TD0319 (2003100712)		
2004	TD0405 (2004051406)	TY0407 (2004060418)	TY0414 (2004072606)
	TY0425 (2004091018)		
2005	TY0508 (2005072818)	TY0516 (2005091506)	TY0521 (2005102806)
2006	TD0605 (2006070218)	TD0614 (2006082206)	TD0617 (2006091006)
	TY0619 (2006092100)		
2007	TY0703 (2007070300)	TY0706 (2007073118)	
2008	TD0801 (2008011306)	TY0805 (2008051412)	TY0810 (2008080312)
	TY0818 (2008092718)	TD0820 (2008101306)	
2009	TY0902 (2009050218)	TY0903 (2009061706)	TY0914 (2009090900)
	TD0923 (2009101800)		
2010	TY1006 (2010082200)	TY1007 (2010082712)	TD1014 (2010100412)
	TD1018 (2010111218)		
2011	TD1101 (2011040118)	TD1105 (2011053100)	TY1106 (2011060818)
	TY1122 (2011092318)	TD1125 (2011110618)	TD1126 (2011121118)
2012	TY1202 (2012032600)	TY1206 (2012061606)	TY1221 (2012092900)
	TD1225 (2012111200)		
2013	TY1305 (2013061918)	TY1309 (2013072818)	TY1310 (2013080500)
	TD1321 (2013091700)	TY1323 (2013092518)	
2014	TY1407 (2014060900)	TY1408 (2014061312)	TD1415 (2014081812)
	TD1417 (2014090606)		
2015	TY1508 (2015061918)	TY1520 (2015091300)	
2016	TD1601 (2016052606)	TY1605 (2016072512)	TY1610 (2016081506)
	TY1617 (2016091112)		
2017	TD1701 (2017041800)	TY1703 (2017061006)	TY1705 (2017071412)
	TY1708 (2017072206)	TY1709 (2017072212)	TY1711 (2017072806)
	TY1717 (2017083100)	TD1721 (2017092312)	TD1722 (2017100900)

2. Dataset and the TC developing stage ——Dataset and statistical method cont.

- Apply two main statistical methods:

1) the square box statistic method, for the vertical wind shear, the horizontal average range is ±5° of longitude or latitude from the TD center, but ±3° for other dynamical statistics.



2) the cylindrical method. This latter method is used for calculating the radial and tangential wind. Calculate the values with a fixed longitude and latitude interval at eight directions along lines from the cyclone center. Other than the center point, each line has 10 fixed points at which to calculate the value and make an average (at 0.52°, 0.78°, 1.04°, 1.30°, 1.56°, 1.82°, 2.08°, 2.34°, 2.60°, and 2.86° from the cyclone center). These fixed points extend from about 57 to 316 km from the cyclone center, but we restrict the valid data to lie inside the annulus of 60-300 km.

2. Dataset and the TC developing stage ——Dataset and statistical method cont.

- We construct a 95% confidence interval for statistical variables are given by the general formula (Larsen and Marx 2018):

$$\left(\bar{y} - 1.96\frac{\sigma}{\sqrt{n}}, \bar{y} + 1.96\frac{\sigma}{\sqrt{n}}\right)$$

where $\bar{y}$ is the mean value, σ is the standard deviation, and n is the sample number of the statistical variable.

2. Dataset and the TC developing stage
——TC-developing stages

TABLE 2. Time stages for tropical cyclone intensity analysis (6-h resolution).

Developing		Nondeveloping	
Stage	Explanation	Stage	Explanation
TY0 (initial)	Initial time of TD[a]	TD0 (initial)	Initial time of TD
TY1 (pre-storm)	Immediately before wind speed > 17 $m\ s^{-1}$	TD1 (peak)	Time of maximum wind speed (last peak)
TY2 (storm)	When wind speed > 17 $m\ s^{-1}$	TD2 (decaying)	Immediately after maximum wind speed
TY3 (peak)	Time of maximum wind speed (first such time)		None

[a] TD = tropical depression (10.8–17.1 $m\ s^{-1}$); TS = tropical storm (17.2–24.4 $m\ s^{-1}$).

- Based on the track data, the average wind speed (the officially determined intensity; 2-min average maximum wind speed near the center) of all 52 TY1 cases was 15.0 and 14.7 m/s for the 22 TD1 cases.

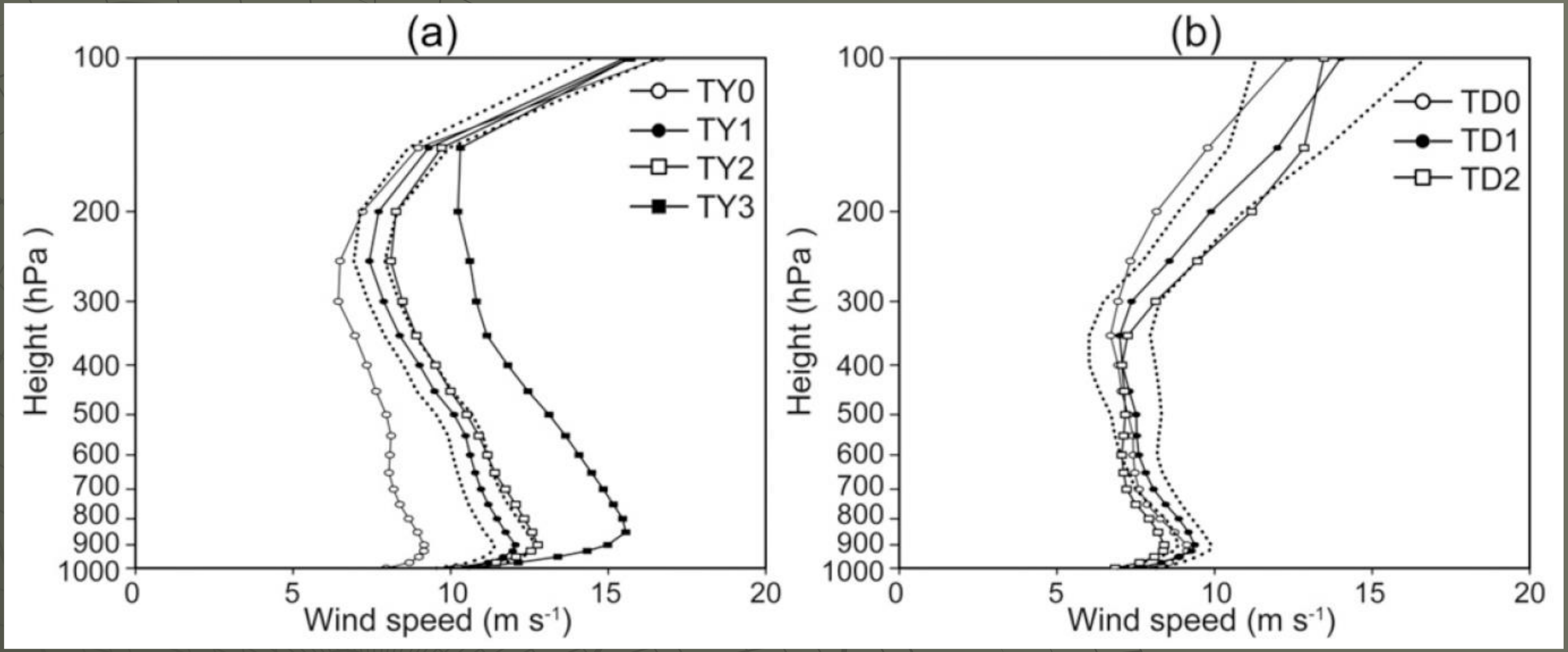
2. Dataset and the TC developing stage —TC-developing stages cont.

TABLE 3. Number and percentage (in parentheses) of TY2 and TD2 times (UTC, where LST is UTC + 8 h).

Stage	0000	0600	1200	1800	Total
TY2	16 (30.8)	15 (28.8)	11 (21.2)	10 (19.2)	52
TD2	6 (27.3)	9 (40.9)	4 (18.2)	3 (13.6)	22

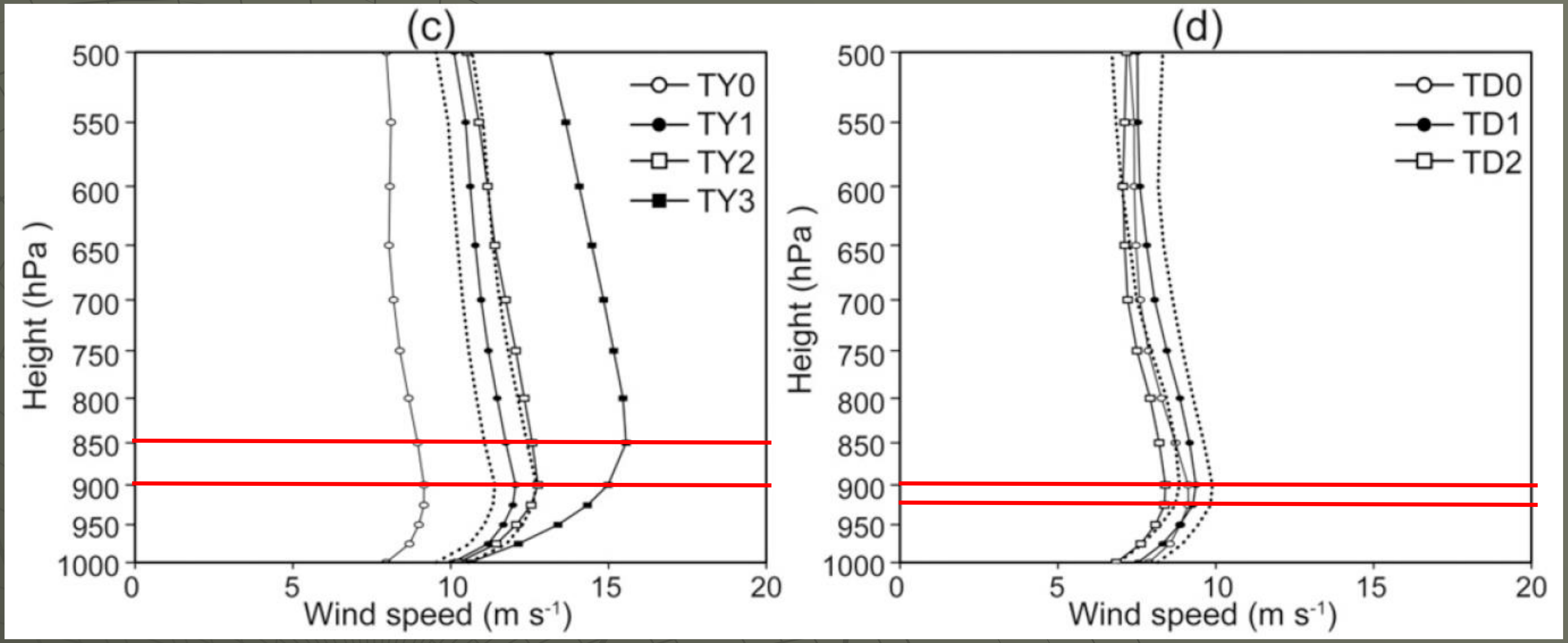
- A large proportion of times TY2 (59.6%) and TD2 (68.2%) occurred at 0000 and 0600 UTC, which are 0800 and 1400 LST. Hence, we mainly focus on 0000 or 0600 UTC (0800 or 1400 LST) time to calculate features of the diabatic heating rate.
- Define the upper level as that above 300 hPa, the midlevel as that within 800–300 hPa, and the low level as that below 800 hPa.

3. Dynamic and thermodynamic statistics ——Wind speed



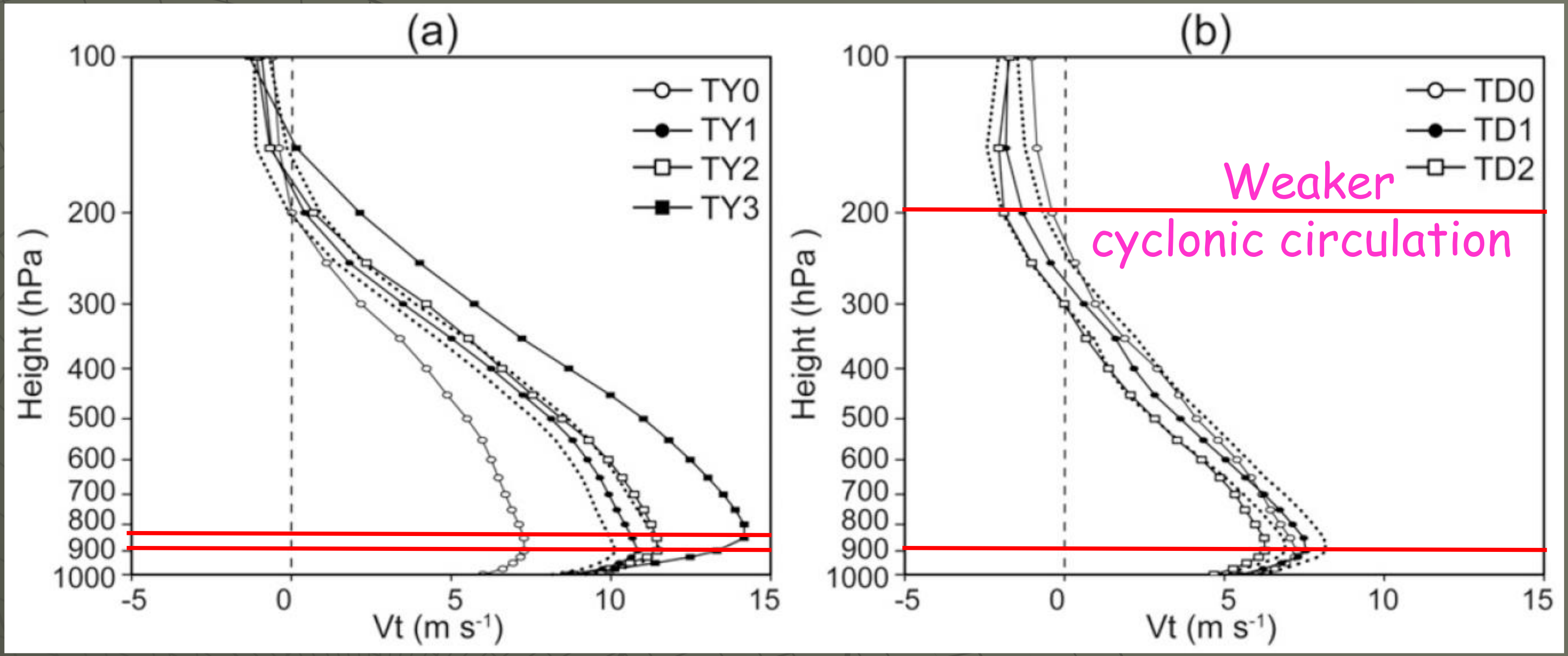
- For the developing case, the wind speed increases at all levels for all times, whereas for the nondeveloping case, wind speed at the lower level has a maximum value at TD1, then decreases at TD2.

3. Dynamic and thermodynamic statistics ——Wind speed cont.



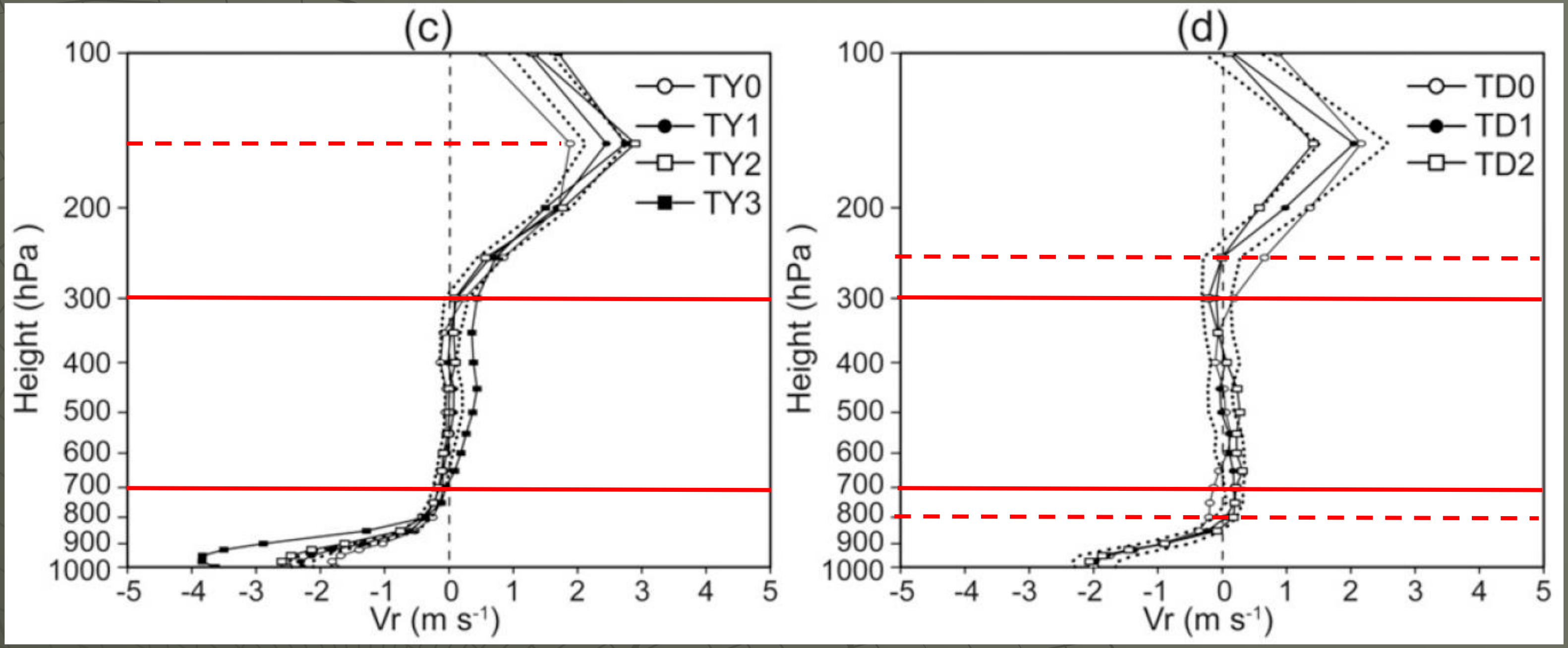
- For the developing TD, height of the maximum wind speed at 900 hPa during the TY0–TY2 stages and at 850 hPa when the TD reach its maximum wind speed at stage TY3.
- For the nondeveloping case, the maximum wind speed occurs at 925 hPa at the initial time TD0, changing to 900 hPa at the TD1 and TD2 stages. In addition, below 950 hPa, the wind speed at the peak (TD1) stage is lower than that at the initial (TD0) stage.

3. Dynamic and thermodynamic statistics ——Tangential velocity



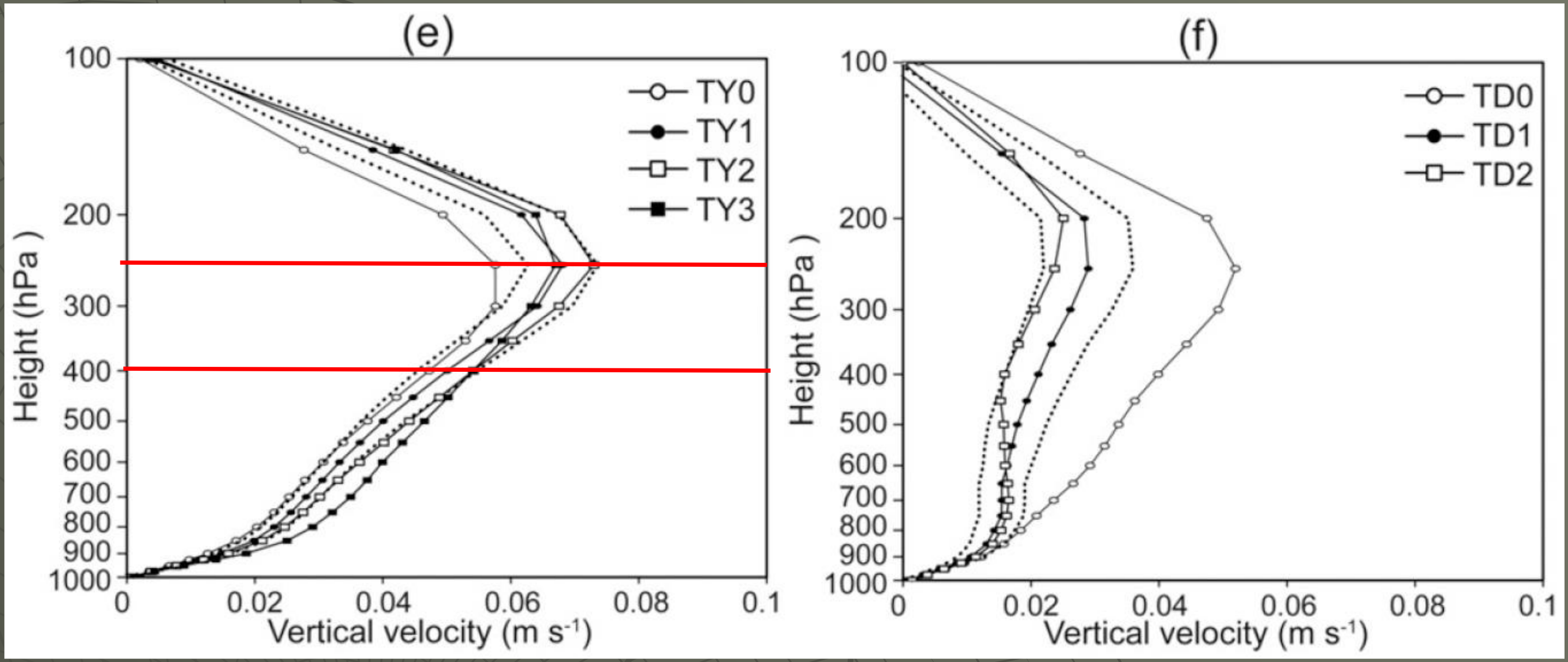
- For the tangential velocity component in the developing case, the values below 100 hPa steadily increase with time. The maximum value occurs at 900 hPa during TY0–TY2, rising to 850 hPa at TY3.
- For the nondeveloping case, the maximum tangential velocity remains at 900 hPa at all three times. At levels above about 200 hPa, this case has stronger anticyclonic winds than the developing case, with the transition from cyclonic to anticyclonic also occurring at a much lower height than that in a developing TD.

3. Dynamic and thermodynamic statistics ——Radial velocity



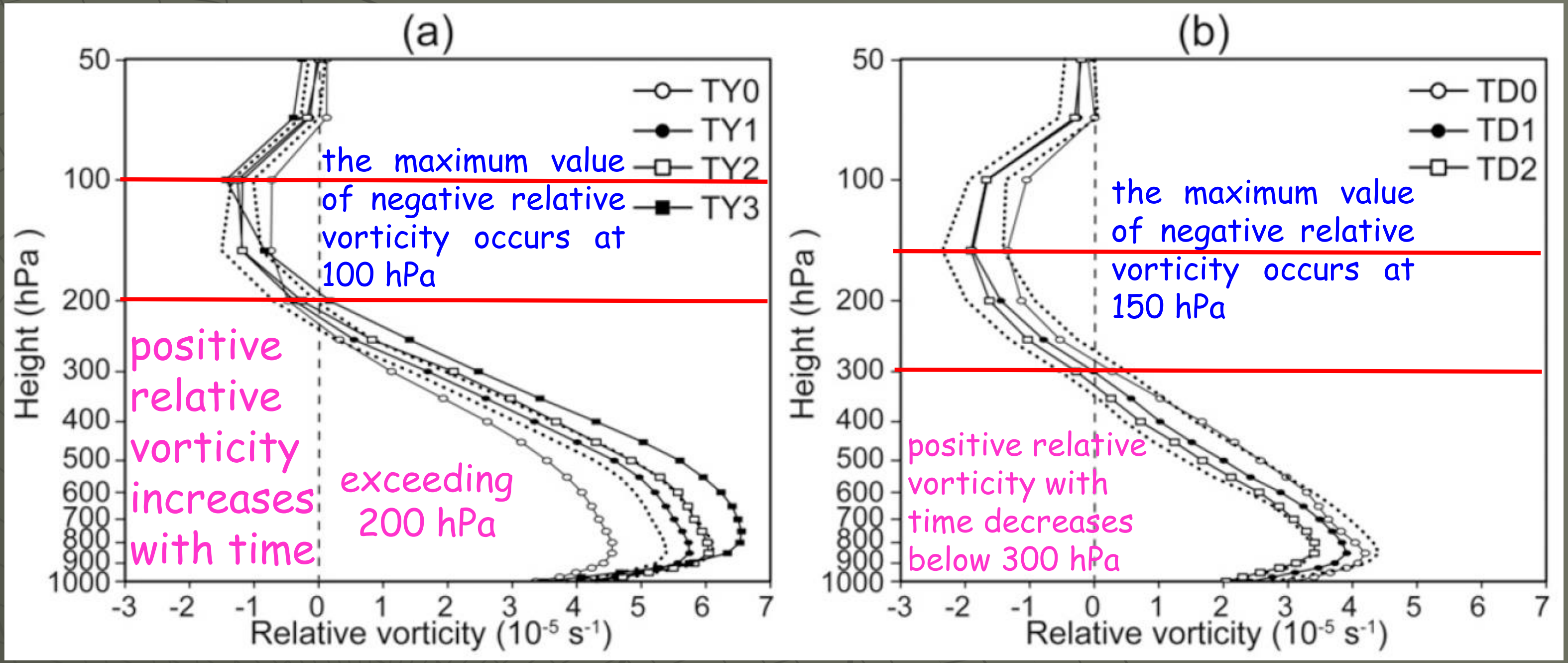
- For both cases, the radial velocity is inward below about 700 hPa, but outward above about 300 hPa. For the developing case, the inflow at low level and outflow at high level both generally increase with time, the exception being at 150 hPa where the outflow at TY3 is less than that at TY2. The cause of this change might be due to the newly added outflow between 700 and 300 hPa causing a deeper outflow layer at TY3. For the nondeveloping case, neither the inflow below 800 hPa nor the outflow above 250 hPa increase with time.

3. Dynamic and thermodynamic statistics ——Vertical velocity



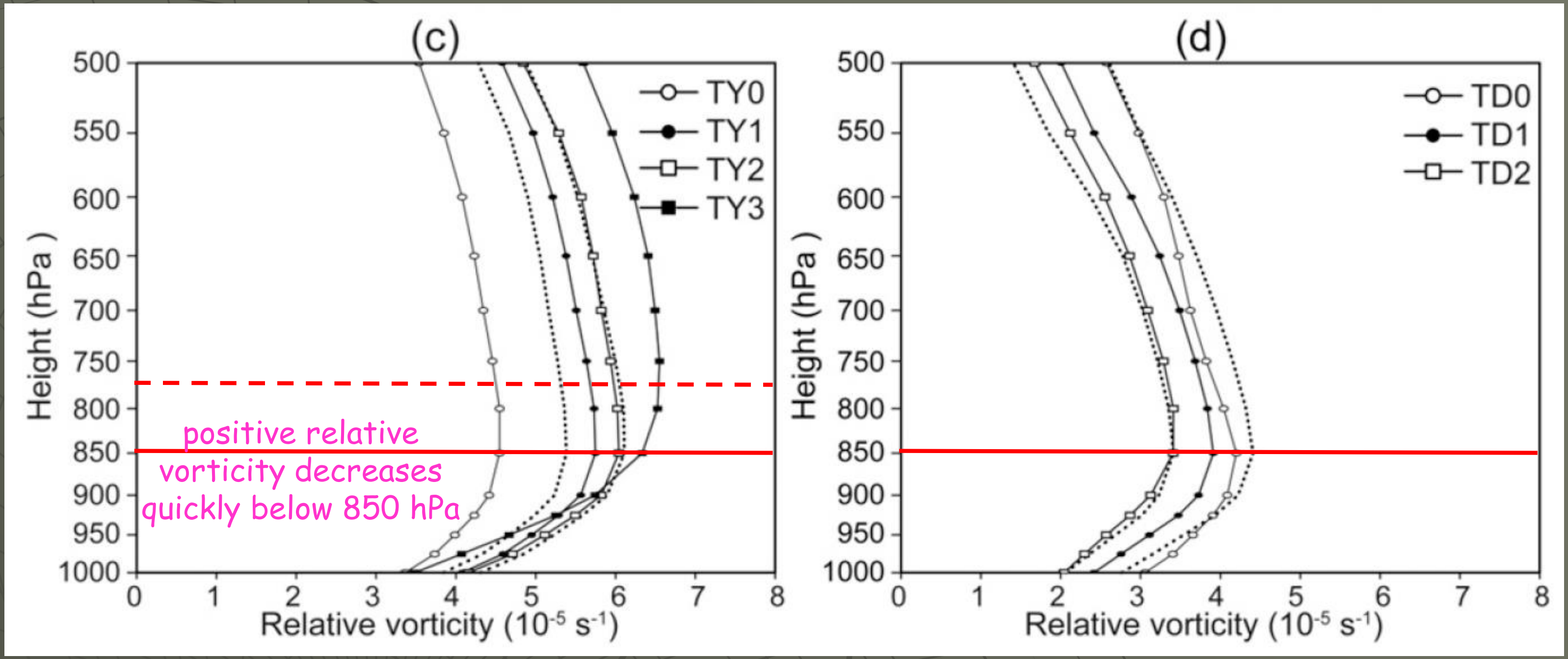
- In the developing case, this component has a maximum at 250 hPa at all stages. From TY1 to TY2, the vertical velocity increases throughout the layer. But from TY2 to TY3, the vertical velocity increases only below 400 hPa.
- For the nondeveloping case, the vertical velocity decreases throughout the layer from the start at TD0.

3. Dynamic and thermodynamic statistics —— Relative vorticity $\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$



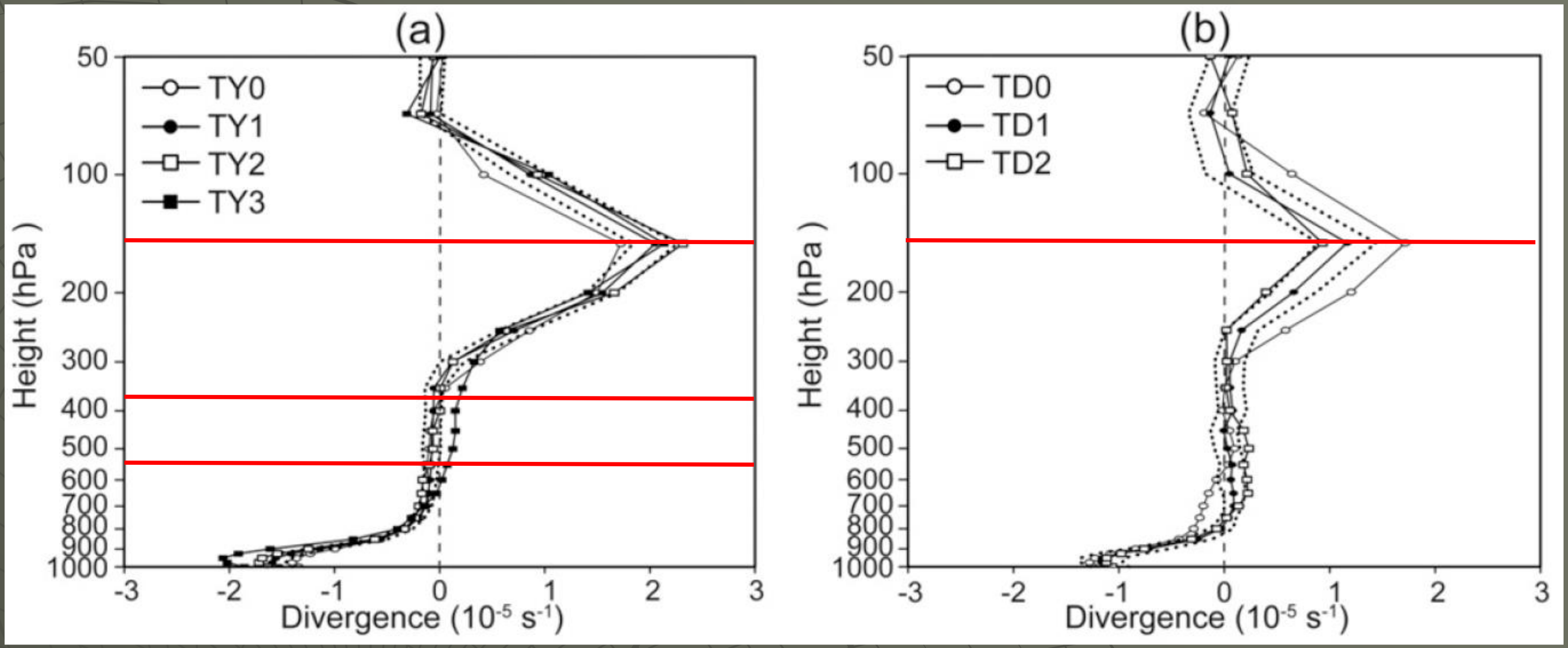
- An increase in thickness of the positive relative-vorticity layer correlates to the development of TD.
- The ratio of the magnitudes of the upper level maximum relative vorticity to the maximum at the lower level (here about 0.21 for the developing, 0.48 for the nondeveloping), the larger ratio indicates a strong anticyclone circulation at the upper-level with a relatively weak cyclone circulation at the lower-level.

3. Dynamic and thermodynamic statistics ——Relative vorticity cont. $\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$



- For the developing case, the value at 850 hPa increases with time, consistent with previous work (Dunkerton et al. 2009; Montgomery et al. 2010). The maximum of the positive relative vorticity moves from 850 hPa at TY0-TY2 to 800-750 hPa at the mature stage of TY3.
- For nondeveloping TD, the maximum positive relative vorticity occurs at 850 hPa and decreases from TD0 to TD2.

3. Dynamic and thermodynamic statistics ——Divergence $D = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$

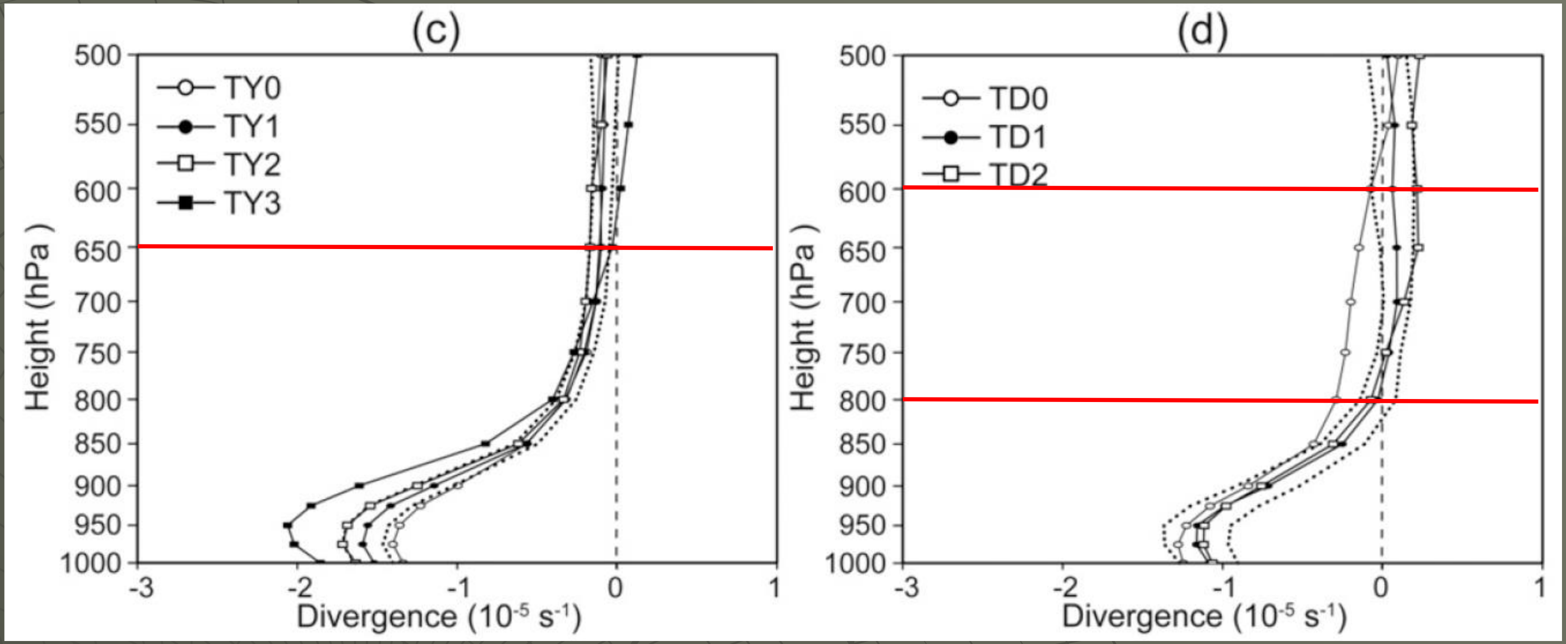


- Both cases have positive divergence at the upper level and negative divergence at the lower level, with the magnitudes larger for the developing than the nondeveloping case.

- Both the developing and nondeveloping cases have their maximum upper-level divergence at 150 hPa, so we use this pressure level in one of the criteria.

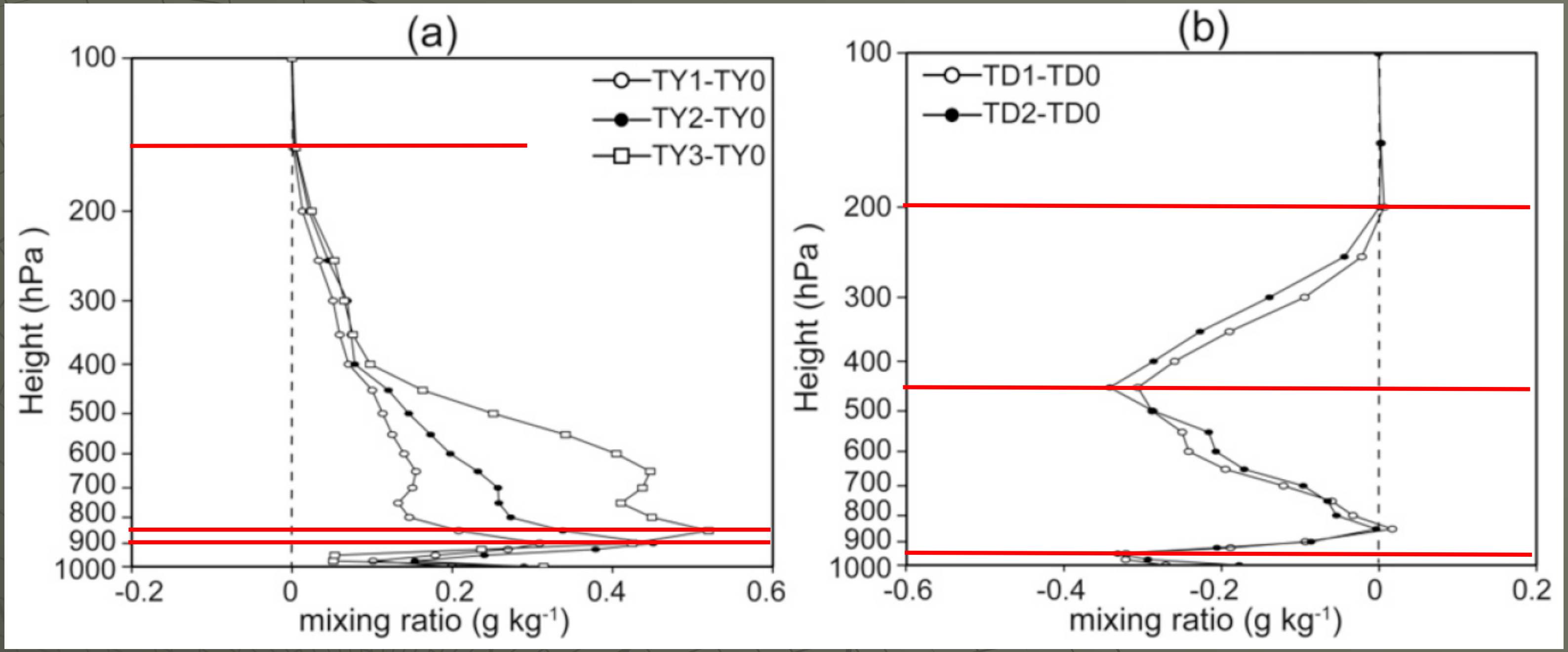
3. Dynamic and thermodynamic statistics ——Divergence cont.

$$D = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$$



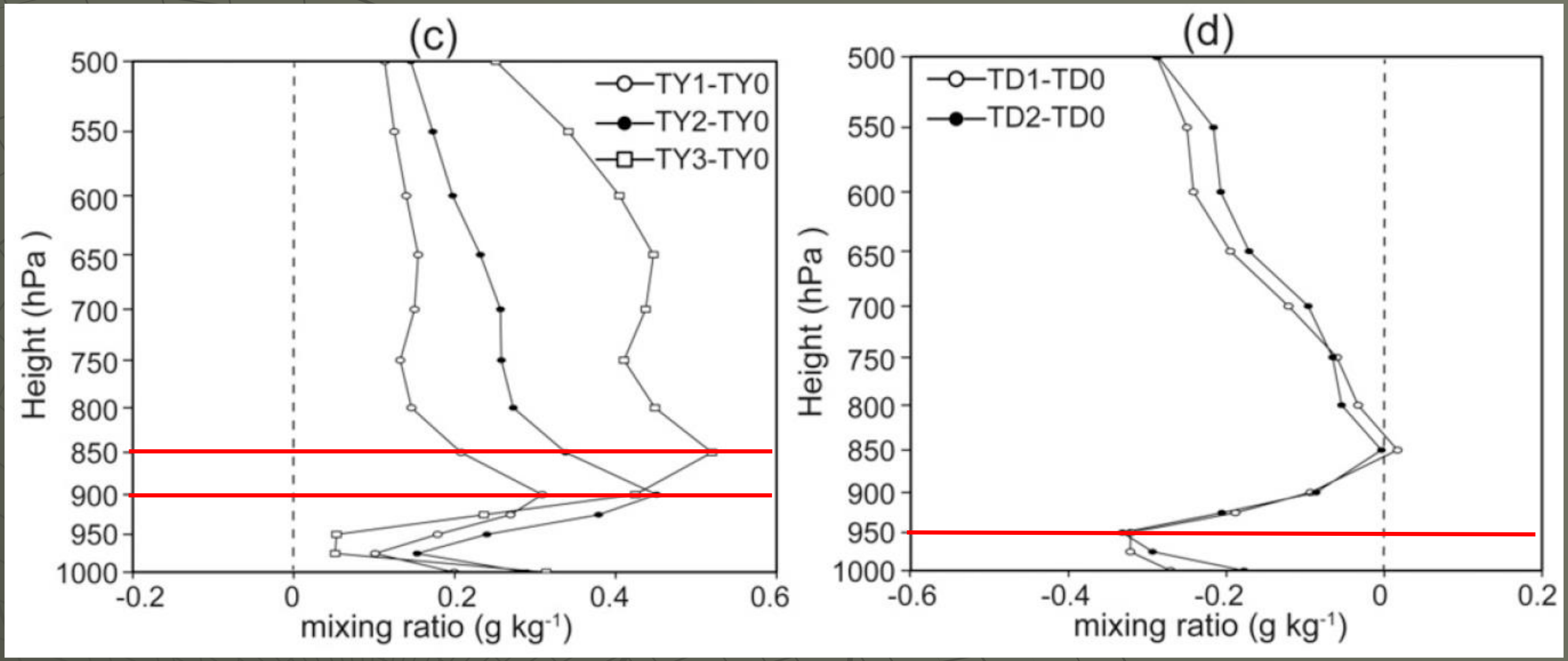
- In the developing case, the depth of the convergent layer is about 350-400 hPa at times up to TY2, then drops to 650 hPa at TY3. The value of positive divergence at the upper level and negative divergence at the lower level increases fromTY0 to TY3.
- For the nondeveloping case, the depth of the convergent layer is much lower—about 600 hPa in the TD0 stage, dropping to 800 hPa for TD1 and TD2. The value of positive divergence at the upper level and negative divergence at the lower level decreases from TD0 to TD2.

3. Dynamic and thermodynamic statistics ——Water vapor mixing ratio



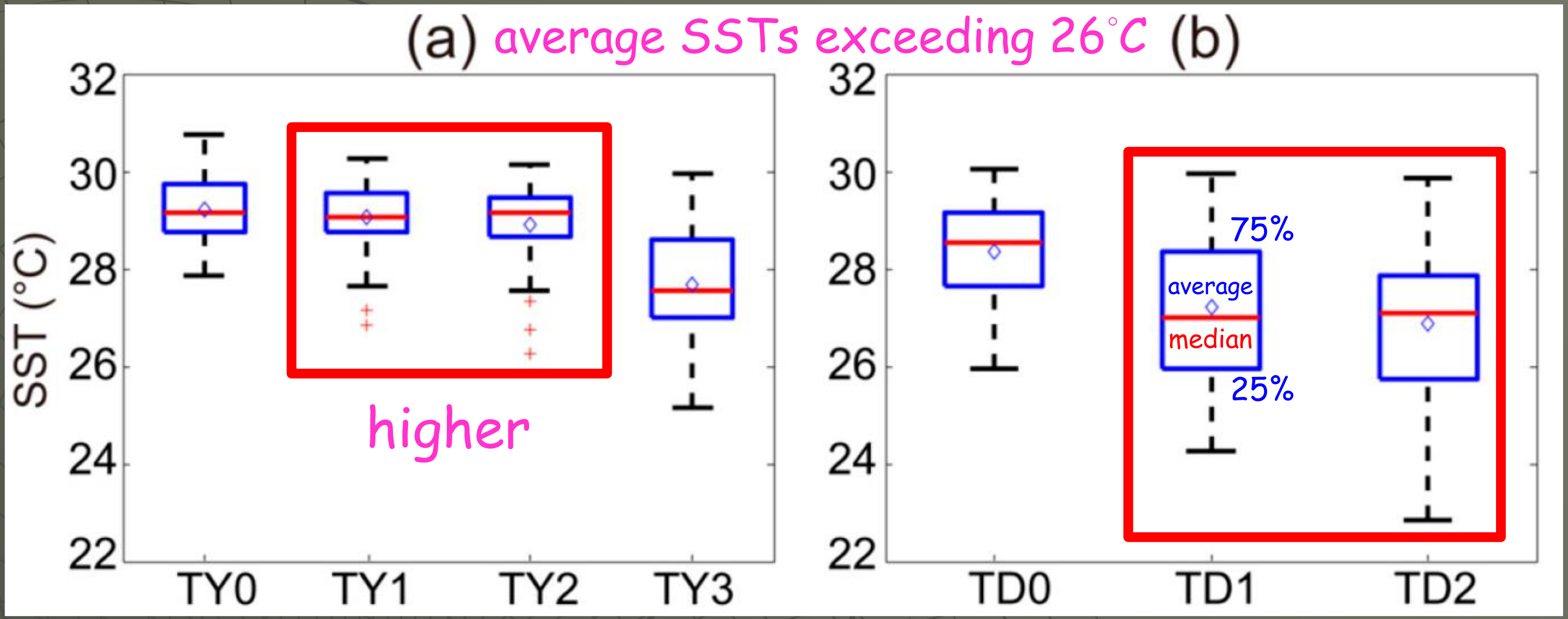
- For the developing case, this change is positive throughout the troposphere, but for the nondeveloping case, it is mostly negative.
- In the developing case, the change occurs below the 150 hPa level, peaking between 900 and 850 hPa.
- In the nondeveloping case, the change instead decreases below 200 hPa, peaking at both 450 and 950 hPa.

3. Dynamic and thermodynamic statistics ——Water vapor mixing ratio cont.



- For the developing case, the maximum value occurs at 900 hPa during TY1 and TY2, then moves higher to 850 hPa at TY3. The WVMR change below 900 hPa is larger at TY3 than at TY2.
- For the nondeveloping case, the WVMR changes below 500 hPa are nearly the same at TD1 and TD2.

3. Dynamic and thermodynamic statistics —Sea surface temperature

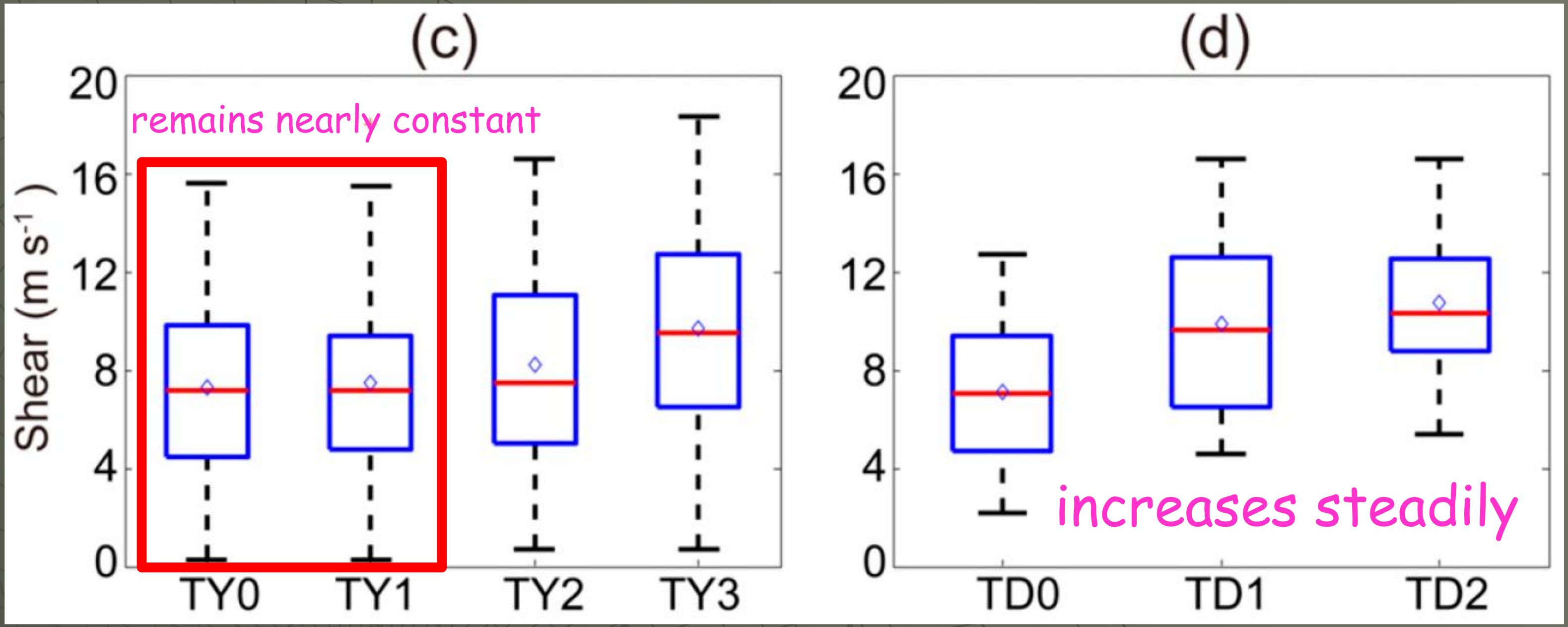


- Comparing TD1 and TD2 to TY1 and TY2 shows that the boxes do not overlap, meaning that 75% of the TD1 and TD2 values are lower than all but the lowest 25% of the TY1 and TY2 values of SST.

- For both cases, the SST decreases with time. As the basic source of energy for tropical cyclones is heat transfer from the ocean (e.g., Emanuel 2003), these SST decreases indicate that the ocean's thermal energy transferred into the atmosphere. Upper-ocean mixing can also cause the SST to decrease (Price 1981).

3. Dynamic and thermodynamic statistics ——Vertical wind shear

$$VWS = \sqrt{(\overline{u}_{200} - \overline{u}_{850})^2 + (\overline{v}_{200} - \overline{v}_{850})^2}$$



- For the developing case, the VWS value remains nearly constant from TY0 to TY1, then increases gradually from TY1 through TY3.

- For the nondeveloping case, the average VWS increases steadily from TD0 through TD2.

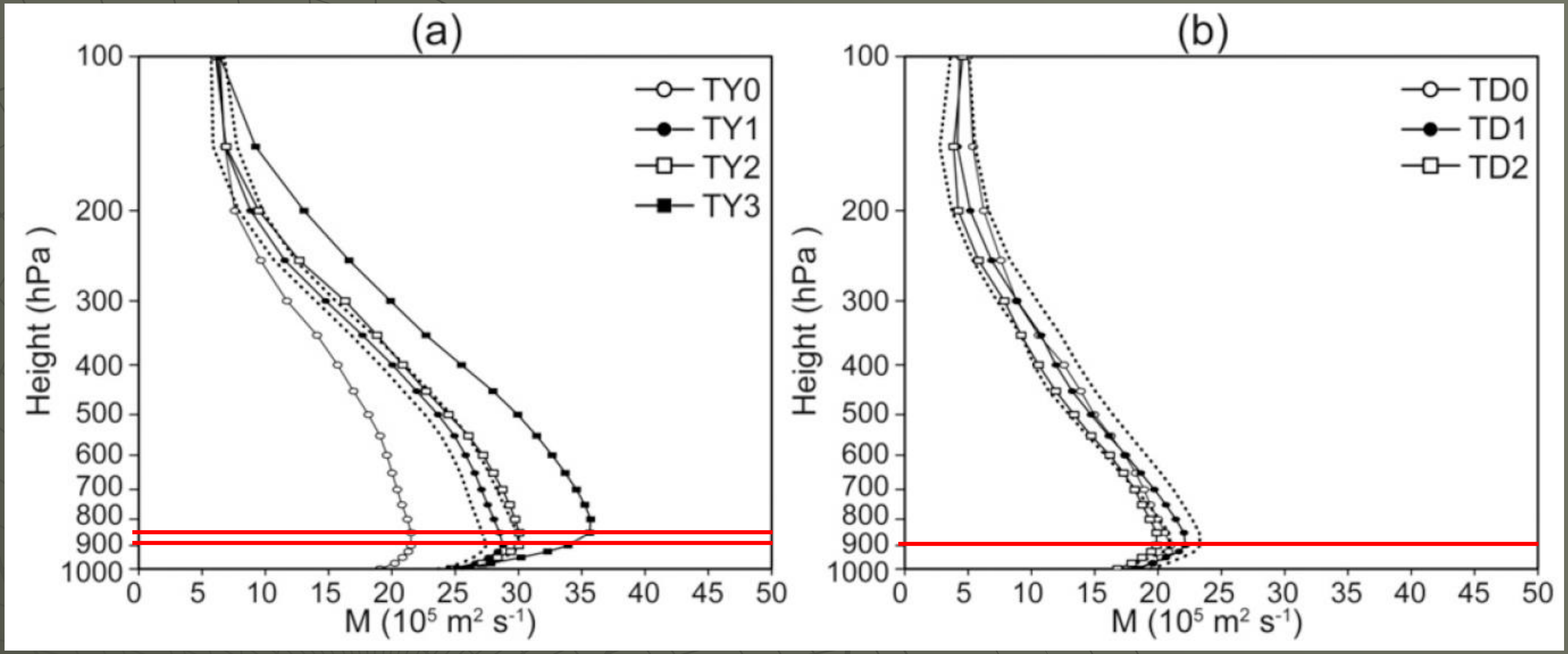
3. Dynamic and thermodynamic statistics
——Sea surface temperature and vertical wind shear

TABLE 4. Average sea surface temperature (SST, over ±3°) and vertical wind shear (VWS, over ±5°) in developing and nondeveloping tropical depressions.

	Developing		Nondeveloping	
Stage	SST (°C)	VWS ($m\,s^{-1}$)	SST (°C)	VWS ($m\,s^{-1}$)
TY0/TD0	29.2	7.3	28.3	7.1
TY1/TD1	29.0	7.4	27.2	9.9
TY2/TD2	28.9	8.2	26.9	10.7
TY3	27.7	9.7		

- The VWS might be a dominant factor that can hinder the TD from developing in SCS.
- However, the difference in VWS between developing and nondeveloping systems is not statistically significant, with no clear threshold value separating the two cases.

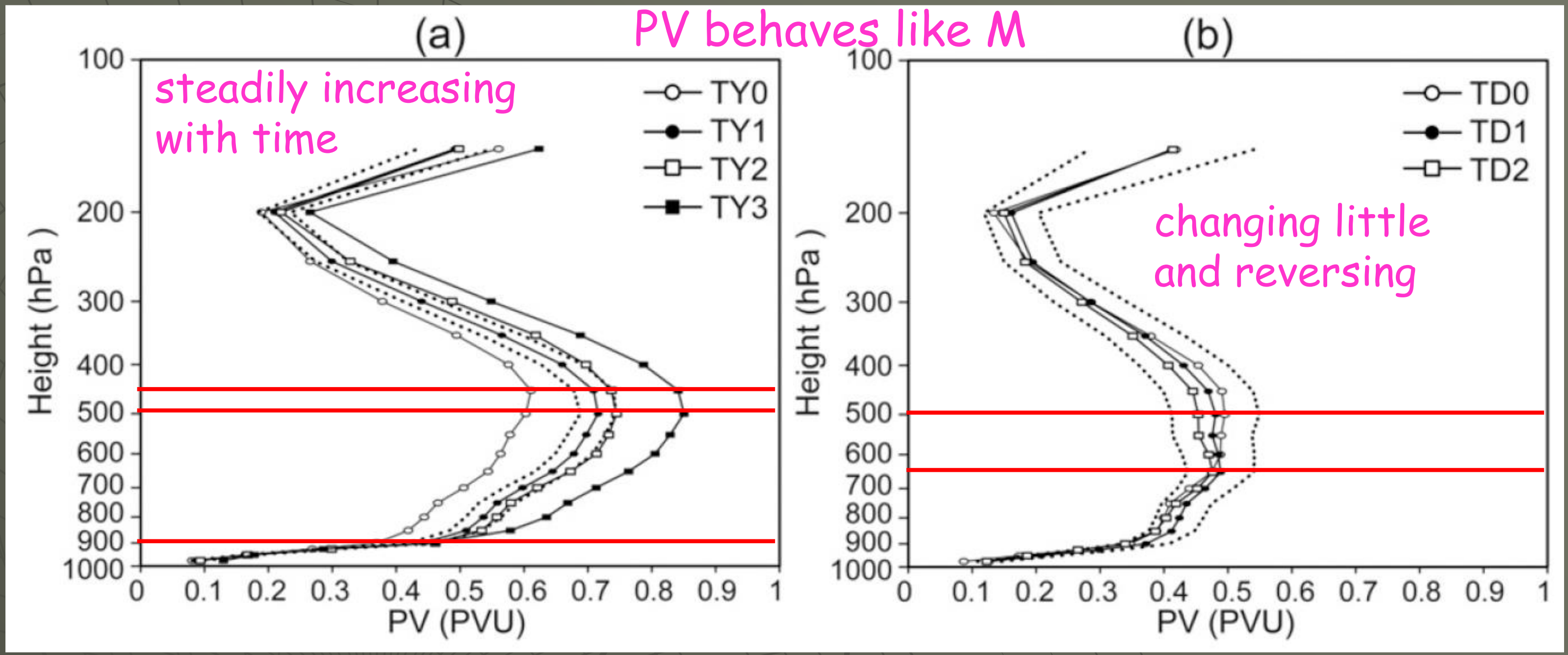
3. Dynamic and thermodynamic statistics ——Absolute angular momentum $M = \frac{fr^2}{2} + rV_t$



- In the developing case, M increases with time. An increasing height of its maximum value, from being at 900 hPa at TY0- TY2 to being at 850 hPa at TY3.
- In the nondeveloping case, M increases to TD1 then decreases. An height of its maximum value at 900 hPa at all times.

3. Dynamic and thermodynamic statistics ——Potential vorticity

$$\mathrm{PV} \approx -g(\zeta + f)\frac{\partial\theta}{\partial p} + g\left(\frac{\partial v}{\partial p}\frac{\partial\theta}{\partial x} - \frac{\partial u}{\partial p}\frac{\partial\theta}{\partial y}\right)$$



- For the developing case, PV increases only above 900 hPa after the pre-storm stage (TY1). The maximum value occurs at 450 hPa at TY0, but later moves down to 500 hPa.
- For the nondeveloping case, the height of the maximum PV also decreases from 500 hPa at TD0 to 650 hPa at TD1 and TD2.
- Both the developing and nondeveloping cases have their maximum PV layer at 500 hPa, so we use the PV at 500 hPa as part of one criterion.

3. Dynamic and thermodynamic statistics ——The Okubo-Weiss parameter

- OW is defined as

$$\mathrm{OW} = \zeta^2 - S_1^2 - S_2^2 = (V_x - U_y)^2 - (U_x - V_y)^2 - (V_x + U_y)^2$$

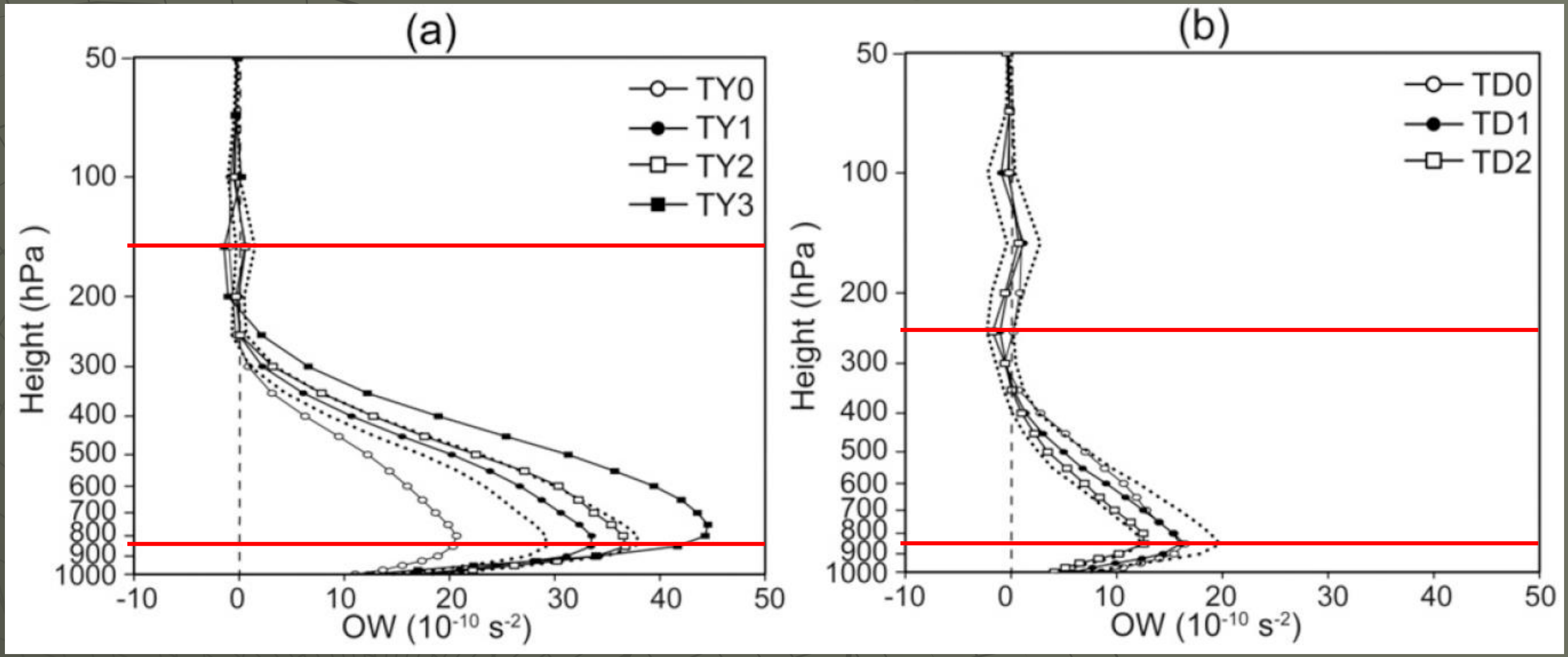
where ζ is relative vorticity, S_1 is the stretching deformation, and S_2 is the shearing deformation.

- Raymond et al. (2011) define a normalized Okubo-Weiss parameter as

$$\mathrm{OW}_{\mathrm{nor}} = \frac{\zeta^2 - S_1^2 - S_2^2}{\zeta^2 + S_1^2 + S_2^2}$$

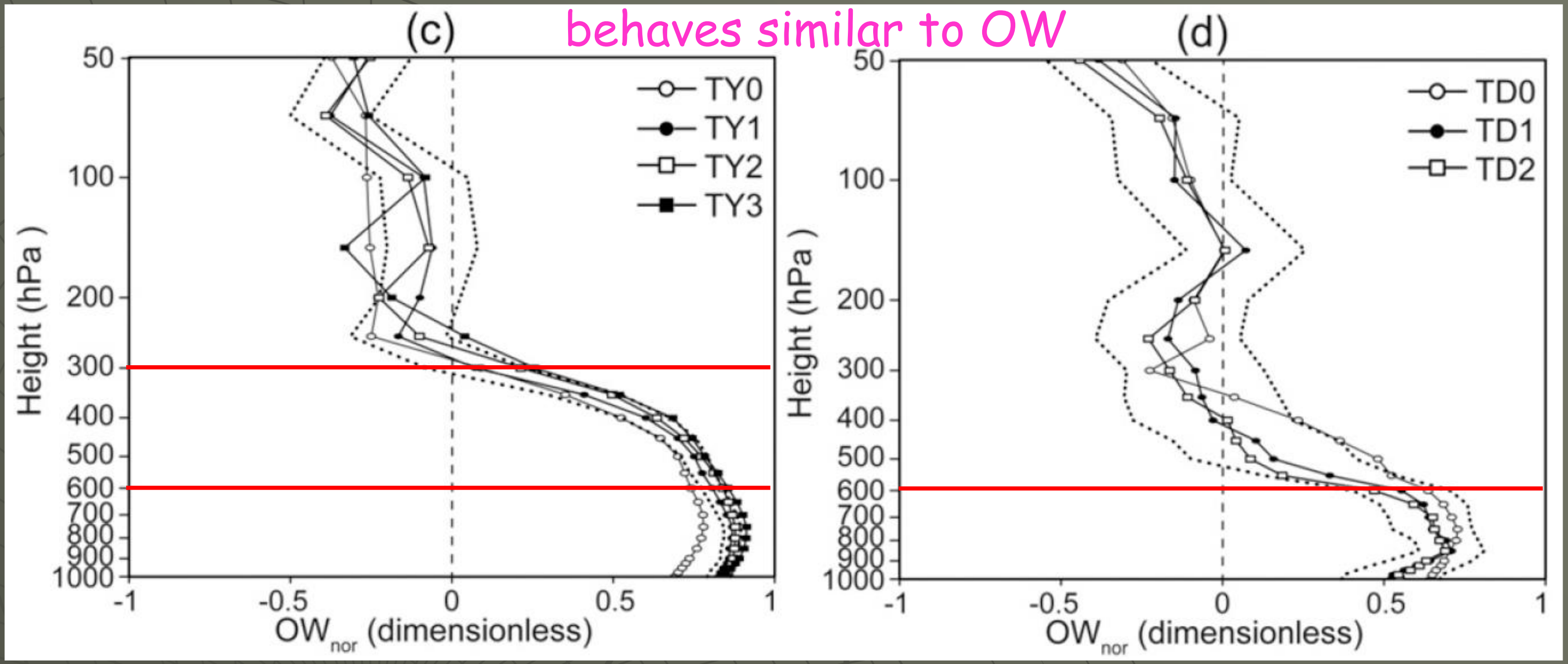
- This parameter equals 1 when the flow is completely rotational, -1 when it is completely strained, and 0 for unidirectional shear flow. It is useful for evaluating the tendency of strain to disrupt a rotational flow.

3. Dynamic and thermodynamic statistics ——The Okubo-Weiss parameter cont.



- For the developing case, OW steadily increases with time below 250 hPa.
- For the nondeveloping case, OW steadily decreases with time below 350 hPa.
- This difference between the two cases is strongest near 850 hPa, so we use the OW value at this pressure in one of the criteria.

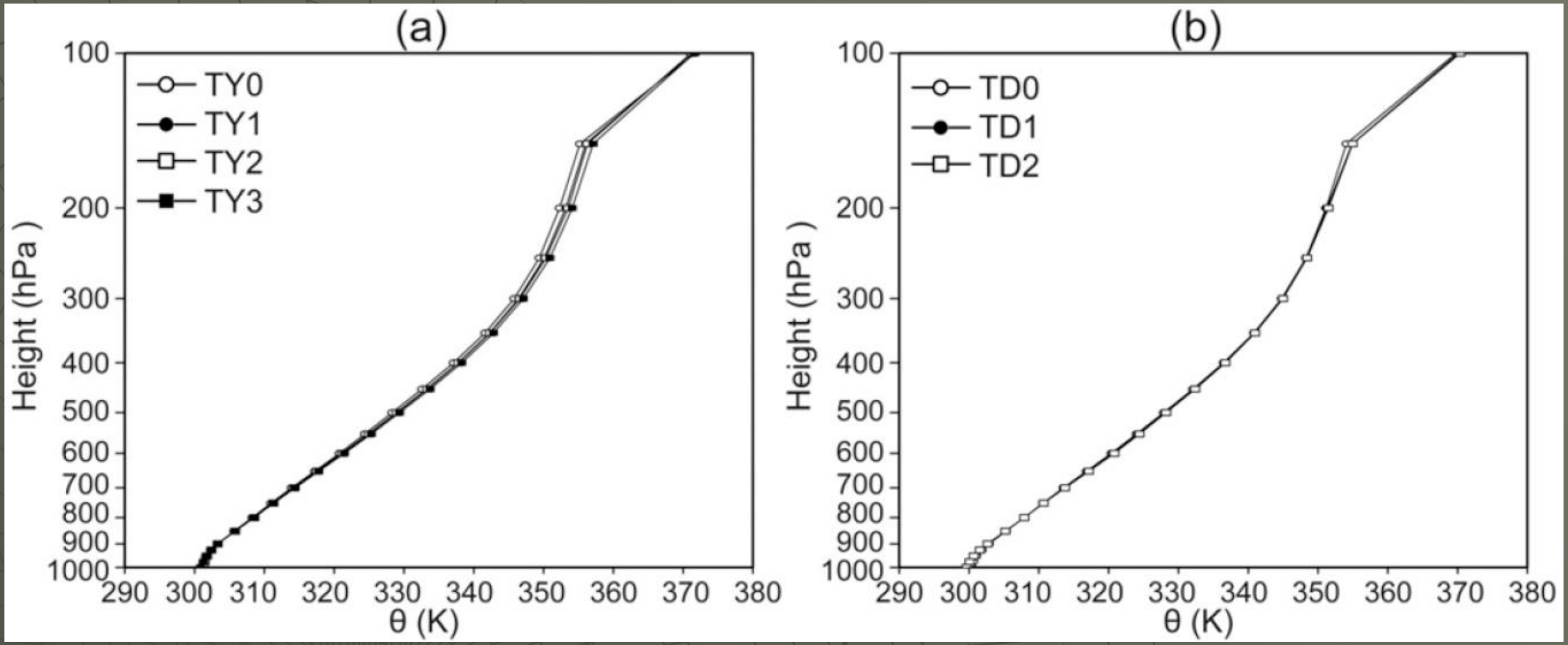
3. Dynamic and thermodynamic statistics ——The Okubo-Weiss parameter cont.



- For the developing case, it steadily increases with time below 300 hPa. In magnitude, the developing case exceeds 0.75 below 600 hPa from TY1 to TY3.

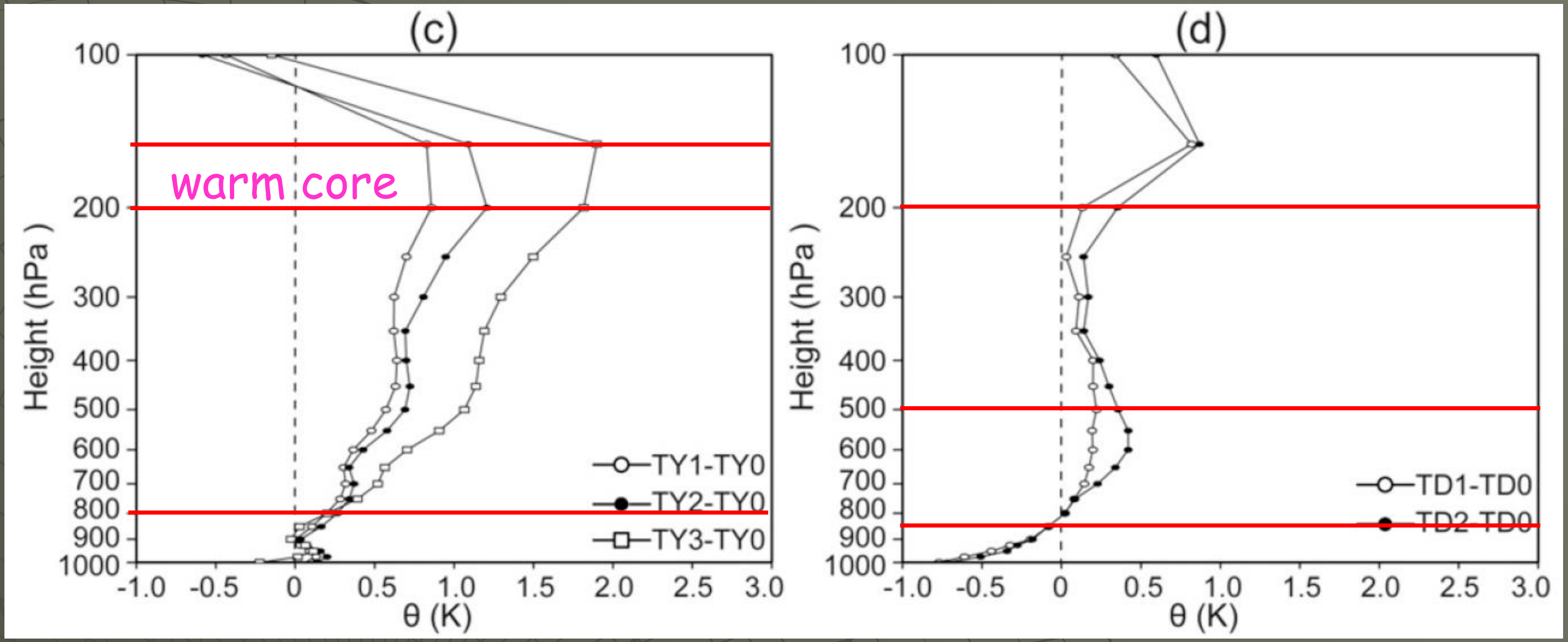
- For the nondeveloping case, it decreases. In magnitude, it remains below 0.7 from TD1 to TD2.

3. Dynamic and thermodynamic statistics ——Potential temperature



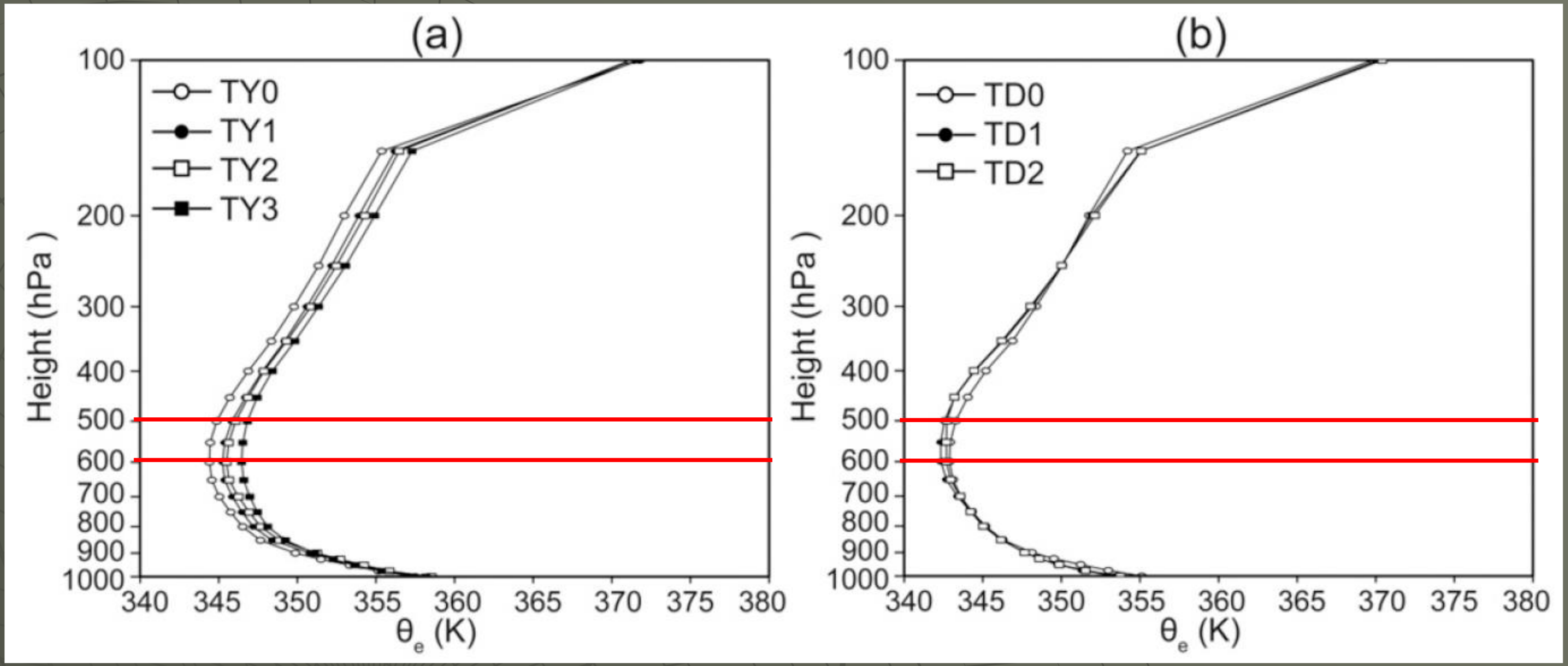
- The potential temperature Θ continuously increases with height in both developing and nondeveloping cases.

3. Dynamic and thermodynamic statistics ——Potential temperature cont.



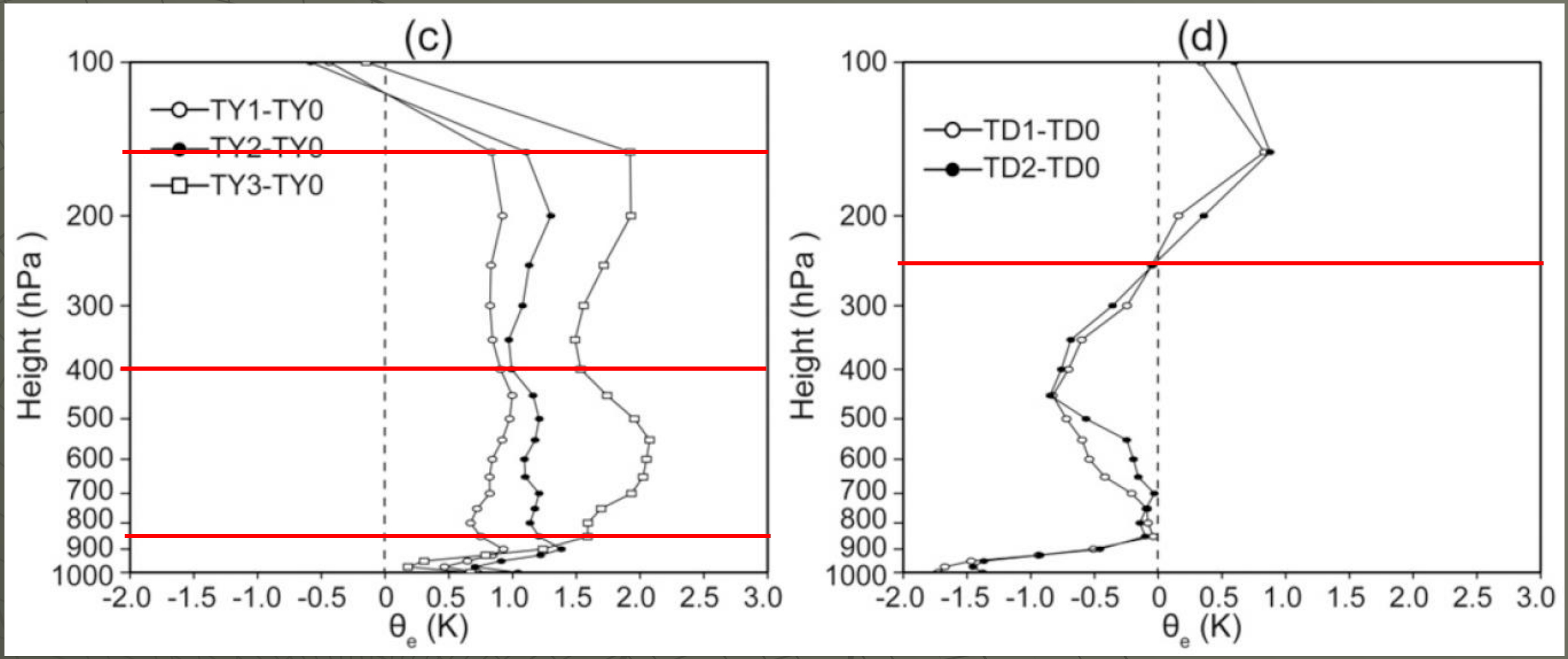
- In the developing case, the Θ steadily increases with time, especially between 800 and 150 hPa. The maximum increase occurs at 200 hPa for TY1 and TY2, but at 150 hPa for TY3. During TY1 and TY2, the upper troposphere warms by about 1.0 K. At TY3, this warming increases nearly 2.0 K at 150 hPa.
- In the nondeveloping case, the Θ decreases with time below 850 hPa and has less heating than the developing case between 500 and 200 hPa. Also, there is no evident increase in the warm core at 150-300 hPa.

3. Dynamic and thermodynamic statistics ——Equivalent potential temperature



- All average profiles have minima within 500-600 hPa, but the values for the developing case are about 2-3 K higher than those in the nondeveloping case.

3. Dynamic and thermodynamic statistics ——Equivalent potential temperature cont.



- In the developing case, the difference of Θe also generally keeps increasing, not only between 400 and 150 hPa, but also between 850 and 400 hPa.
- In the nondeveloping case, the Θe below 250 hPa decrease after TD0.

3. Dynamic and thermodynamic statistics —Diabatic heating rate

- The thermodynamic equation can be expressed in terms of the Θ (Iribarne and Godson 1981; North and Erukhimova 2009; Huang et al. 2015):

$$C_p \frac{T}{\theta}\frac{d\theta}{dt} = \frac{dQ}{dt}$$

- If we neglect the heating by conduction, the diabatic heat-exchange rate equals that by phase change Q_L and by radiation Q_r:

$$\frac{dQ}{dt} = \frac{dQ_L}{dt} + \frac{dQ_r}{dt} \quad ; \quad \frac{dQ_L}{dt} = -L\frac{dq_s}{dt}$$

where L is the latent heat of vaporization and q_s is the saturation mixing ratio.

3. Dynamic and thermodynamic statistics —Diabatic heating rate cont.

- Combining Eqs.

$$C_p \frac{T}{\theta} \frac{d\theta}{dt} = -L \frac{dq_s}{dt} + \frac{dQ_r}{dt}$$

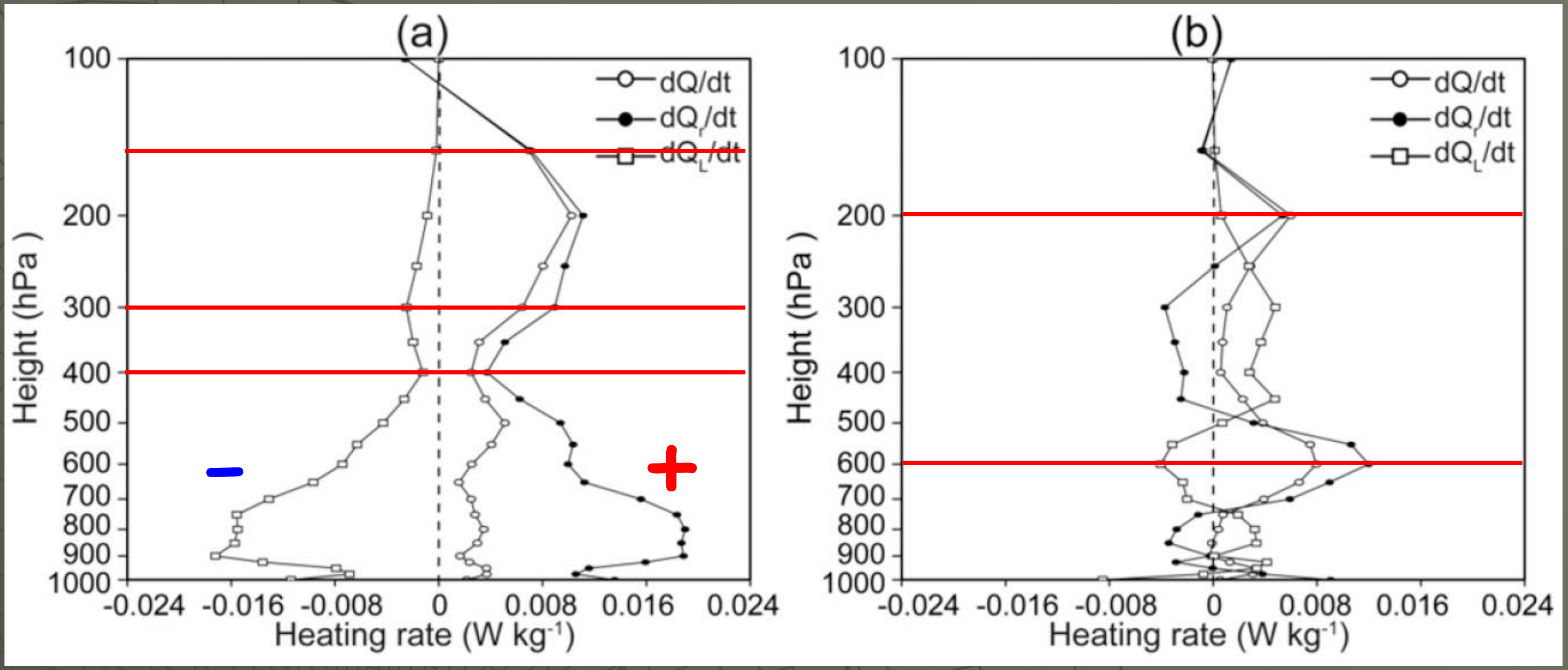
- which is rewritten as

$$C_p \frac{T}{\theta} \frac{d\theta}{dt} + L \frac{dq_s}{dt} = \frac{dQ_r}{dt}$$

- Using the definition of Θe (Wallace and Hobbs 2006),

$$\theta_e \approx \theta \exp\left(\frac{Lq_s}{C_p T}\right) \longrightarrow C_p \frac{T}{\theta_e} \frac{d\theta_e}{dt} = \frac{dQ_r}{dt}$$

3. Dynamic and thermodynamic statistics —Diabatic heating rate cont.



- For the developing case, the diabatic heating rate between TY1 and TY2 has a peak between 150 and 300 hPa, with smaller values lower down where the negative contribution from the phase change counters the positive contribution from radiation. The phase-change influence is especially large below 400 hPa.
- For the nondeveloping case, the diabatic heating rate between TD1 and TD2 has a small peak near 200 hPa and a larger peak near 600 hPa.

3. Dynamic and thermodynamic statistics —Diabatic heating rate cont.

- The features shown here in the developing case are similar to those during the reintensification of TD Sinlaku (Park and Elsberry 2013): maximum heating rates in the upper troposphere in the region of a strong updraft, and maximum cooling rates in the lower troposphere in the region of a strong convective-scale downdraft.
- In general, these trends are common in developing TD, generating convective cooling in convective regions at relatively low levels (here, below 600 hPa) and accumulating convective heating at relatively high levels (here, 150-300 hPa) (Kepert 2010; Montgomery and Smith 2017; Emanuel 2018).
- Hence, the radiative contribution in developing TD here has two peaks, one at 150-300 hPa and one below 600 hPa.

3. Dynamic and thermodynamic statistics —Diabatic heating rate cont.

- Dunion et al. (2014) found the 6-h brightness temperature decreasing within radii of about 200–500 km from the early morning to late afternoon (LST), followed by a distinct maximum in warming from the early evening to early morning hours.
- A regular diabatic heating rate of the center TC relates to a regular TC diurnal cycle, meaning that the convective structure remains intact, allowing the TC to intensify.

4. Application to 2018/19 TD cases —Determination of criteria for TS development

TABLE 5. Confidence interval limits and threshold values of the criteria based on 74 tropical depressions in the SCS.

	TD1			TY1			
	Lower limit	Mean	Upper limit	Lower limit	Mean	Upper limit	Threshold value/unit
Vorticity (850 hPa)	3.41[a]	3.91	4.41	5.39	5.75	6.11	$>4.5 \times 10^{-5}\, s^{-1}$
Divergence (150 hPa)	0.89	1.17	1.44	1.84	2.05	2.26	$>1.5 \times 10^{-5}\, s^{-1}$
OW (850 hPa)	12.29	16.02	19.76	29.19	33.44	37.69	$>20 \times 10^{-10}\, s^{-2}$
OW_{nor} (below 600 hPa)	0.48	0.61	0.74	0.81	0.85	0.88	>0.75
PV (500 hPa)	0.41	0.48	0.55	0.69	0.72	0.74	>0.55 PVU
Wind speed (900 hpa)	8.85	9.37	9.89	11.40	12.06	12.72	Not used ($m\, s^{-1}$)
Tangential wind (900 hpa)	6.92	7.55	8.18	10.15	10.84	11.52	Not used ($m\, s^{-1}$)
Radial wind (950 hPa)	−2.22	−1.80	−1.39	−2.32	−2.14	−1.96	Not used ($m\, s^{-1}$)
M (900 hPa)	20.99	22.15	23.31	27.45	28.79	30.12	Not used ($10^5\, m^2\, s^{-1}$)

[a] Lower limit and upper limit belong to 95% confidence interval for each statistical variable.

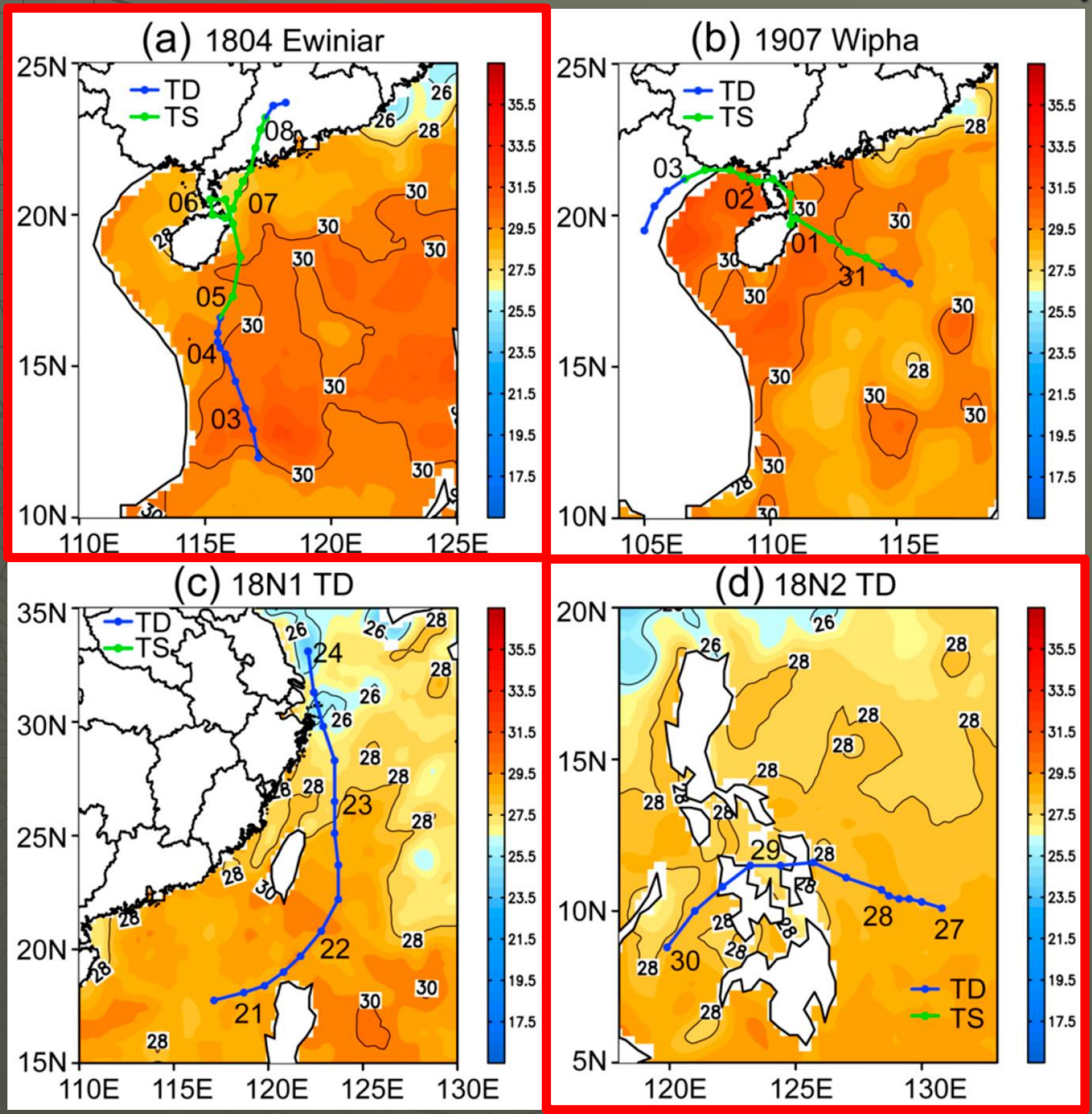
duplicate

overlap

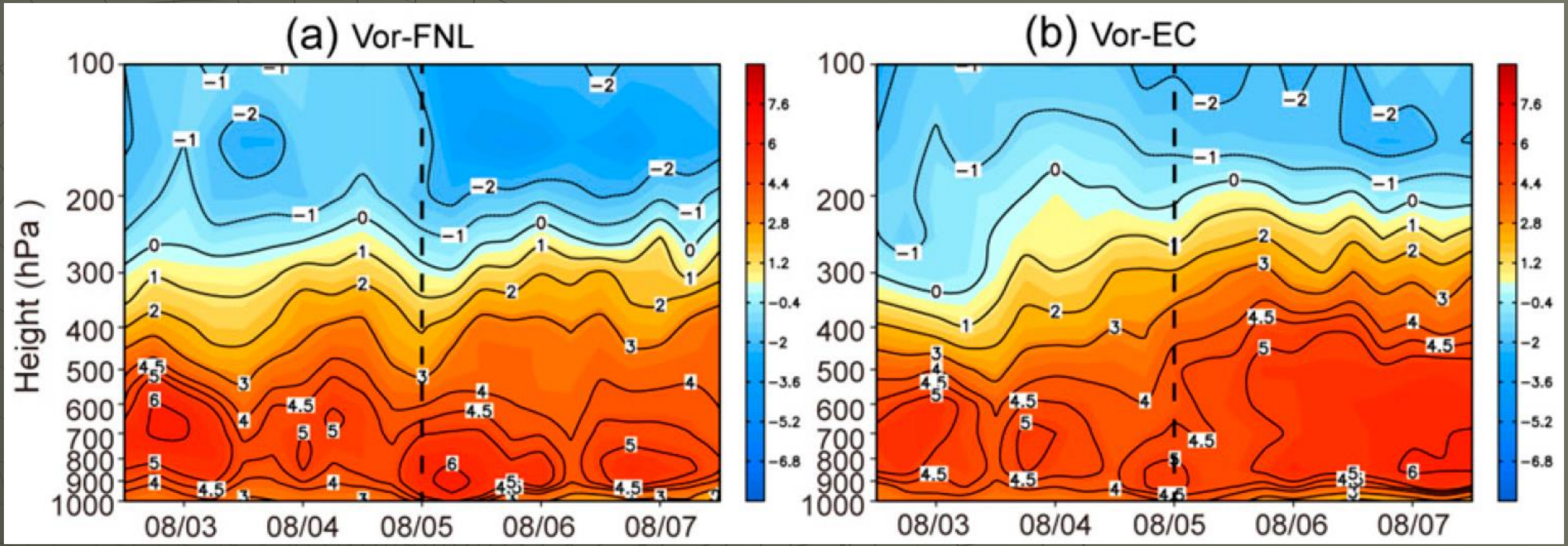
- Set the threshold values to equal (or slightly exceed) the upper limit of the variable at time TD1 based on a 95% confidence interval values.

- Four other criteria are also shown in Table 5 but not used. They are not used because they either do not show a clear threshold or they give similar results as the above five. For example, the radial wind at 950 hPa of TD1 and TY1 overlap. Also, the three criteria at 900 hPa relate to low-level dynamic features that duplicate the result of the criterion for relative vorticity at 850 hPa.

4. Application to 2018/19 TD cases
——Determination of criteria for TS development cont.

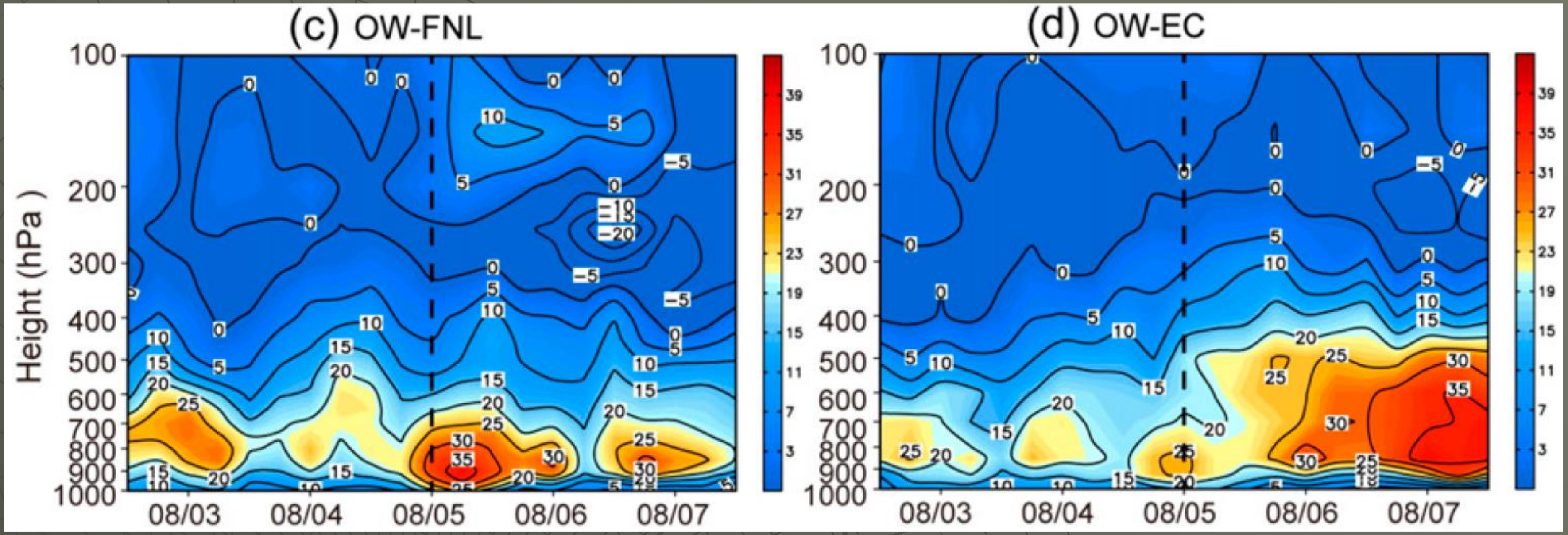


4. Application to 2018/19 TD cases —Developing case of Ewiniar (1804)



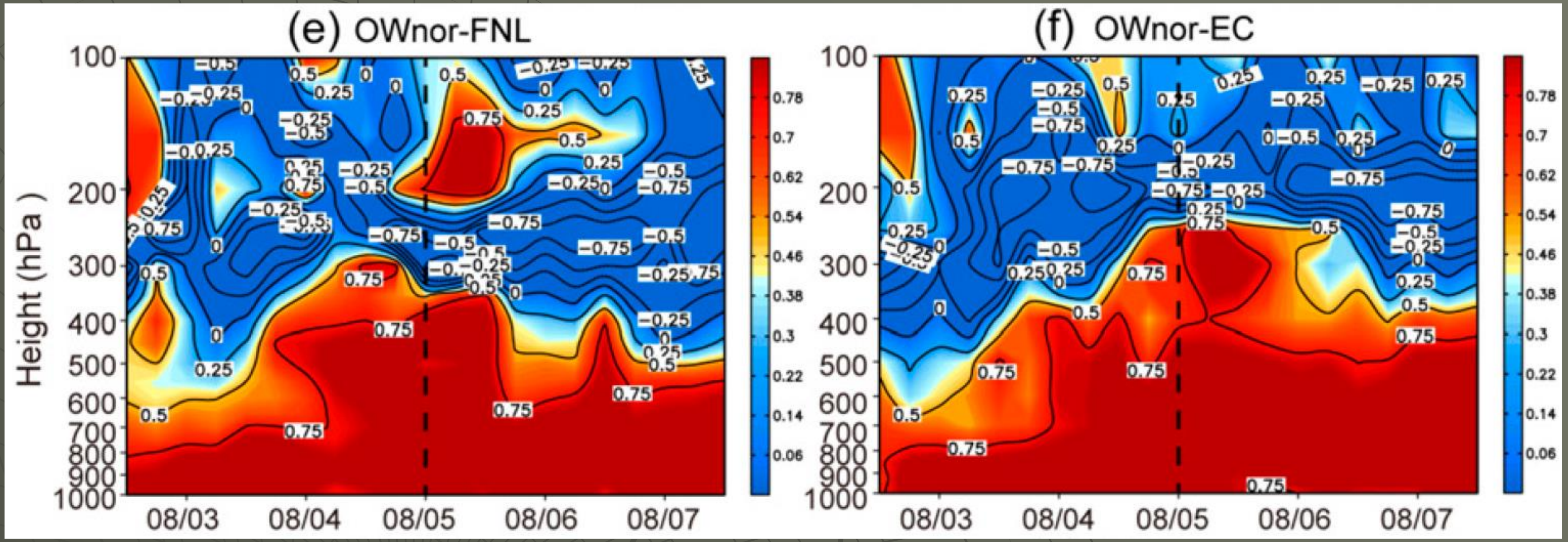
- At 850 hPa, the relative vorticity exceeds the criterion value of $4.5 \times 10^{-5}\ \mathrm{s}^{-1}$ after this TD forms.
- The forecast values are consistent with the observed values.

4. Application to 2018/19 TD cases —Developing case of Ewiniar (1804) cont.



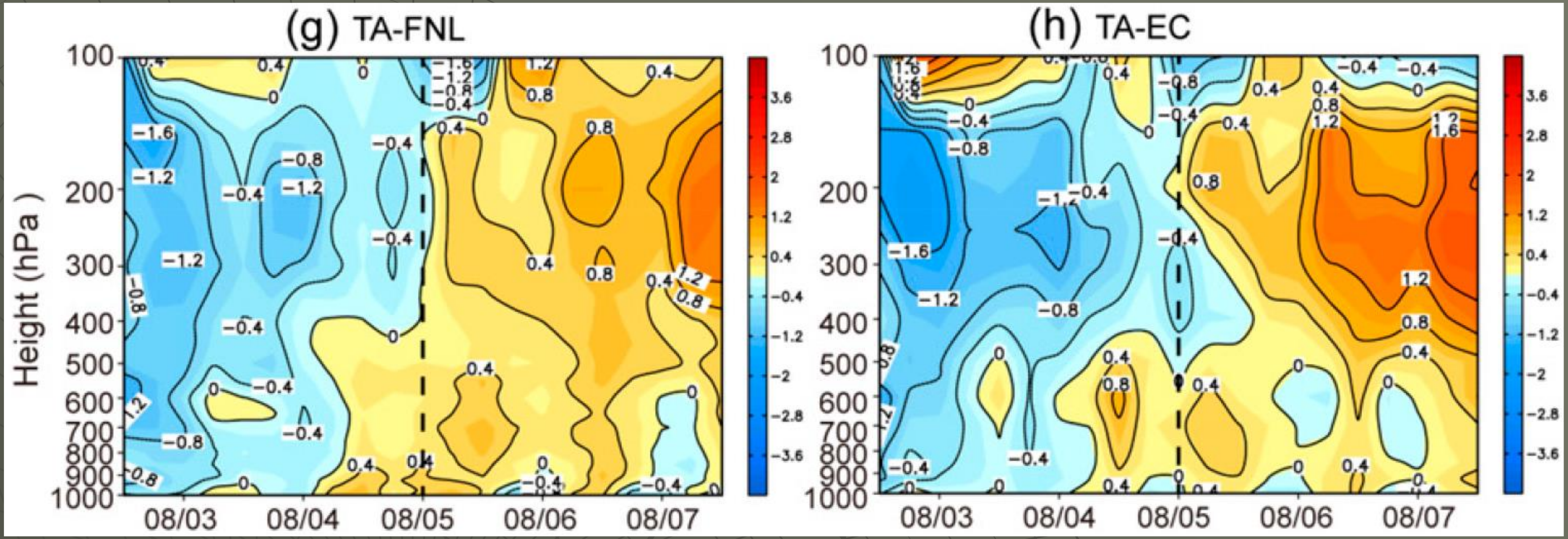
- For the OW test, the value is less than the threshold at the 850-hPa level in observational data, but exceeds the threshold in the forecast result.
- The forecast shows the same trend, except the large values extend up higher, to about 400 hPa.

4. Application to 2018/19 TD cases
——Developing case of Ewiniar (1804) cont.



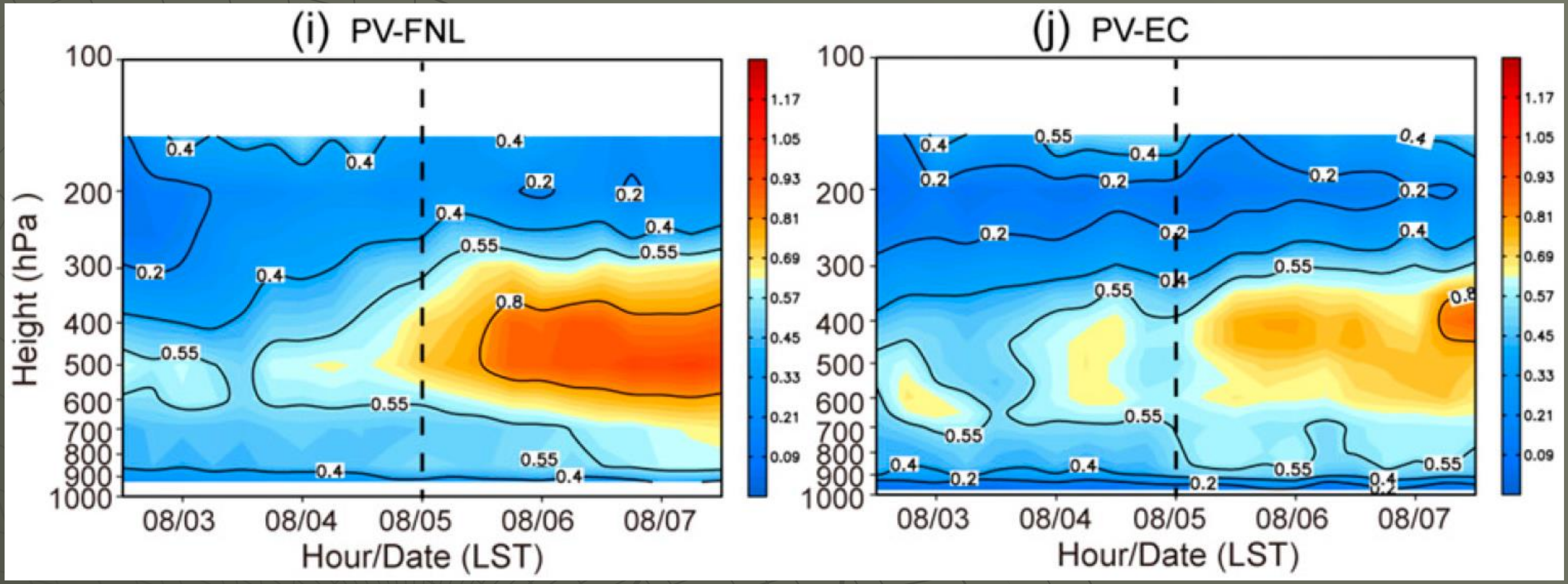
- The normalized values OWnor exceed the threshold value of 0.75 in both the forecast data and the observations.

4. Application to 2018/19 TD cases —Developing case of Ewiniar (1804) cont.



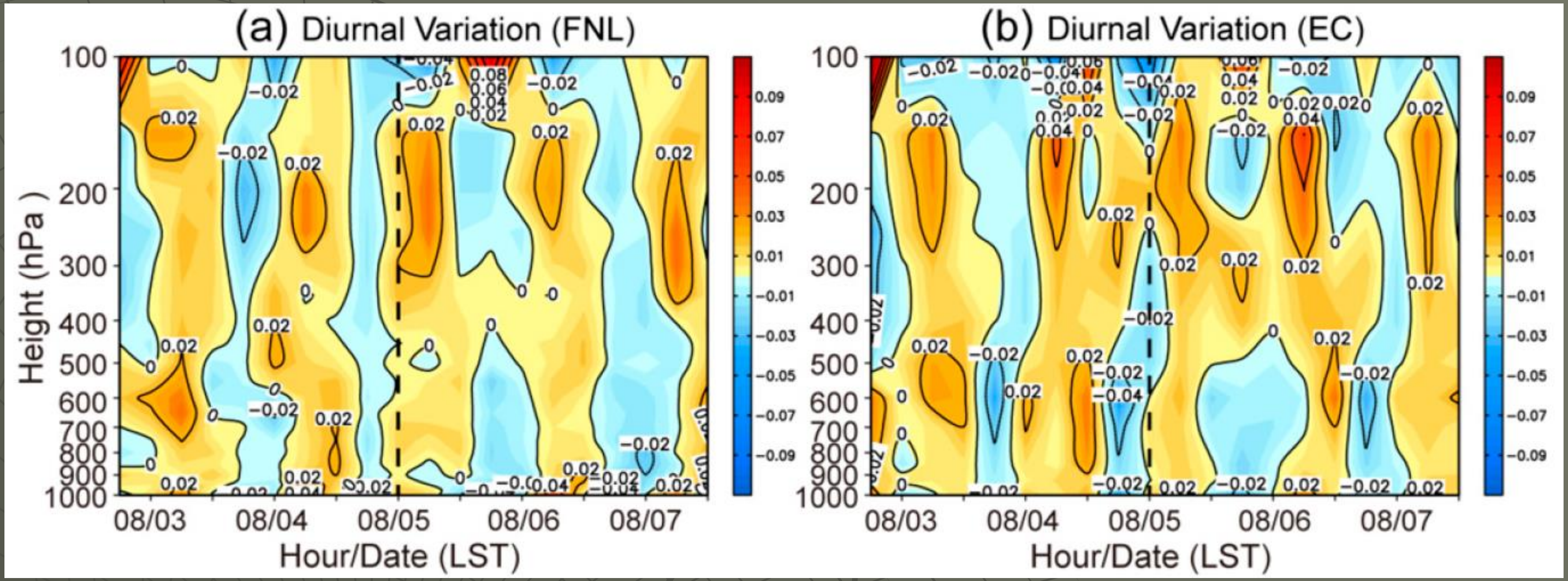
- The observation data shows that the core at 150-300 hPa gradually warms, becoming positive after developing into a tropical storm.
- The forecast data shows a similar trend, with some larger values.

4. Application to 2018/19 TD cases
——Developing case of Ewiniar (1804) cont.



- After Ewiniar develops into a tropical storm, its average potential vorticity gradually increases, especially between about 350 and 700 hPa.
- These trends are largely replicated by the forecast, although the forecast predicts larger values.
- Potential vorticity values in both datasets exceed 0.5 PVU at 500 hPa before and after the depression develops into a storm, satisfying the criterion.

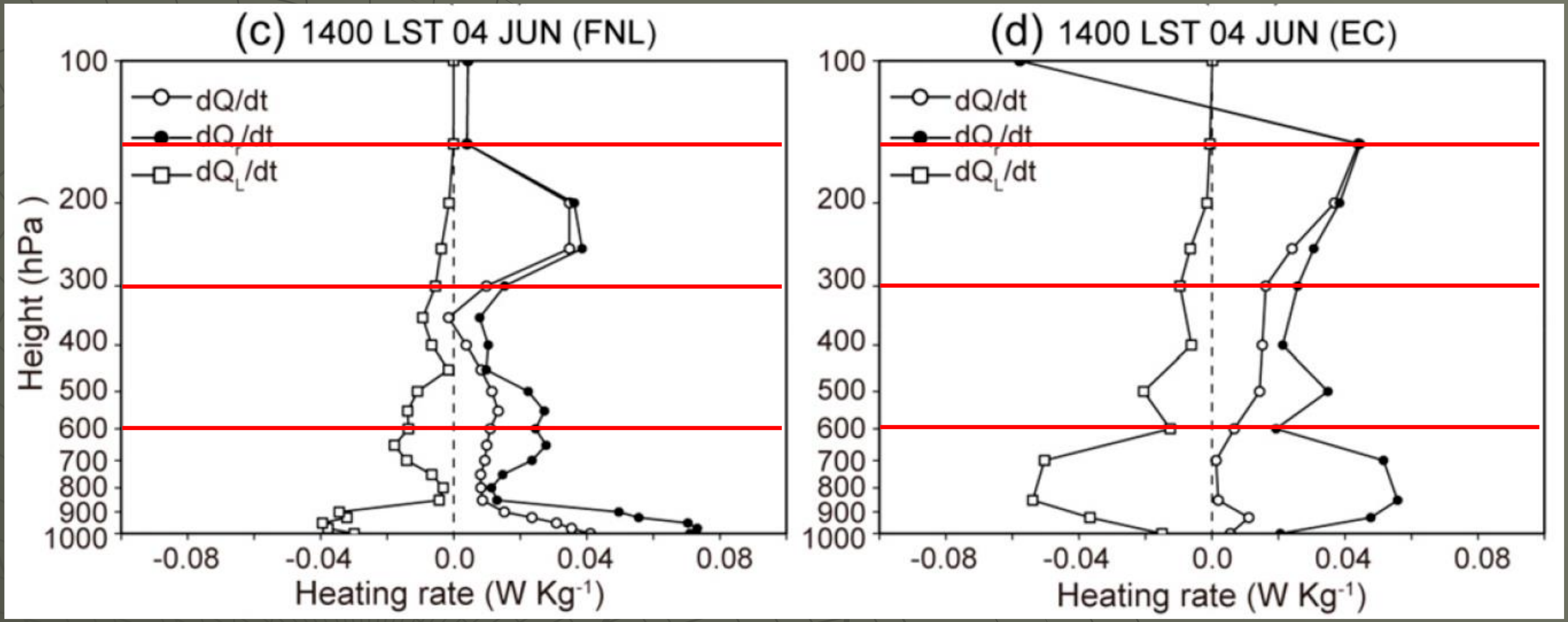
4. Application to 2018/19 TD cases —Developing case of Ewiniar (1804) cont.



- This rate varies diurnally, heating the whole vertical layer between about 0800 to 2000 LST, then cooling between about 2000 to 0800 LST the next day.

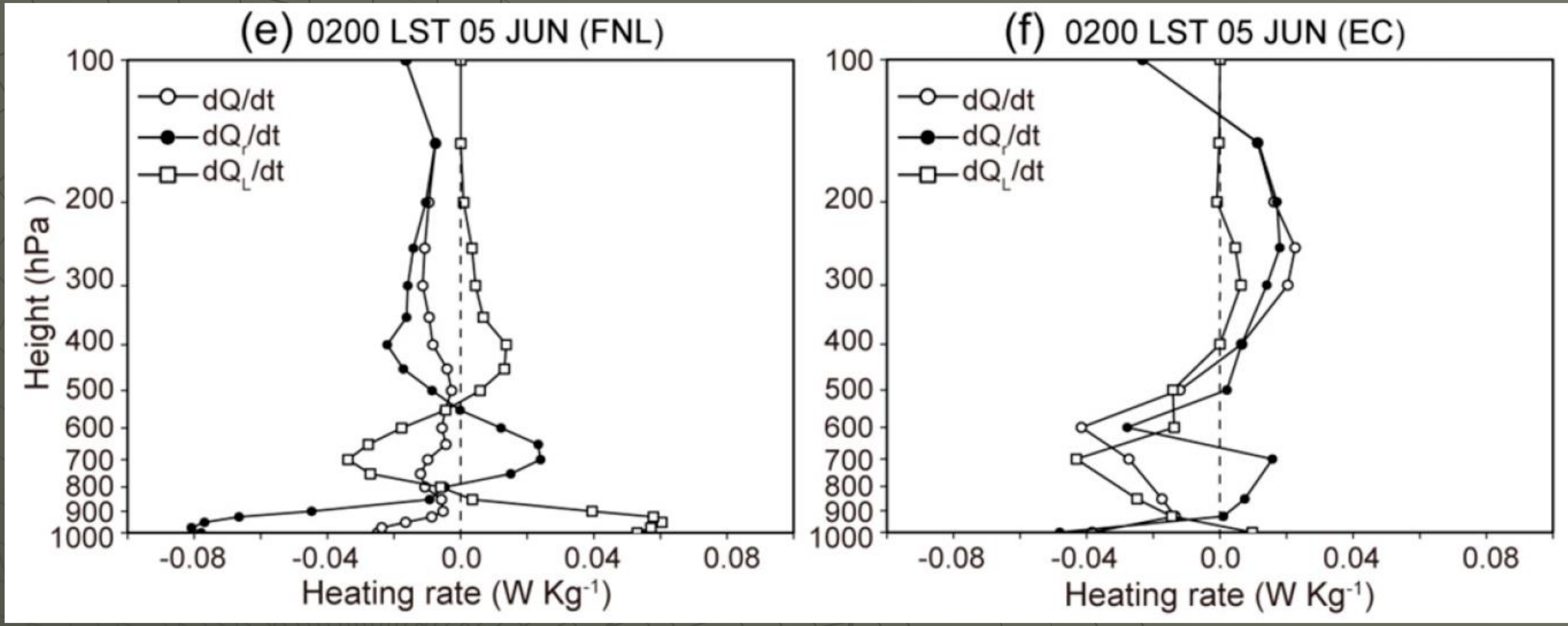
- This diurnal variation of the diabatic heating rate indicates that this TD will develop into a TS, and thus satisfies criterion.

4. Application to 2018/19 TD cases ——Developing case of Ewiniar (1804) cont.



- Before the TD develops into a TS at 1400 LST 4 June, both the observations and forecast data show the radiation term (dQr /dt) peaking in 150-300 hPa and below 600 hPa.

4. Application to 2018/19 TD cases —Developing case of Ewiniar (1804) cont.



- At night, both the observations and forecast data give irregular profiles of radiative heating.

4. Application to 2018/19 TD cases —Developing case of Ewiniar (1804) cont.

TABLE 6. Criteria that pass (Y) for TD Ewiniar (1804) to develop (Dev) into a TS. Three or more failures (N) indicate that the TD will not develop (Nondev) to TS. Ewiniar (1804) develops at 0800 LST 5 Jun.

Pre-storm time	Data	C1 Vorticity	C2 Divergence	C3 OW	C4 OW_{nor}	C5 PV	C6 Heating (diurnal)	C7 Heating (profile)	No. of failures	Result
2000 LST 2 Jun	FNL	Y	Y	Y	N	Y	Y	—		
	EC	Y	Y	Y	N	Y	Y	—		
0200 LST 3 Jun	FNL	Y	Y	Y	N	Y	Y	Y	1	Dev
	EC	Y	Y	Y	N	Y	Y	Y	1	Dev
0800 LST 3 Jun	FNL	Y	Y	Y	N	Y	Y	Y	1	Dev
	EC	Y	Y	Y	N	N	Y	Y	2	Dev
1400 LST 3 Jun	FNL	Y	Y	Y	N	Y	Y	Y	1	Dev
	EC	Y	Y	Y	N	N	Y	Y	2	Dev
2000 LST 3 Jun	FNL	N	Y	N	N	N	Y	Y	4	Nondev
	EC	N	Y	N	N	N	Y	Y	4	Nondev
0200 LST4 Jun	FNL	N	N	N	N	Y	Y	Y	4	Nondev
	EC	Y	Y	Y	N	Y	Y	Y	1	Dev
0800 LST 4 Jun[a]	FNL	Y	N	Y	N	Y	Y	Y	2	Dev
	EC	Y	Y	Y	Y	Y	Y	Y	0	Dev
1400 LST4 Jun	FNL	Y	Y	N	Y	Y	Y	Y	1	Dev
	EC	Y	Y	Y	Y	Y	Y	Y	0	Dev
2000 LST4 Jun	FNL	Y	Y	Y	Y	Y	Y	Y	0	Dev
	EC	N	Y	N	Y	Y	Y	Y	2	Dev
0200 LST 5 Jun	FNL	Y	N	Y	Y	Y	Y	Y	1	Dev
	EC	Y	Y	Y	Y	Y	Y	Y	0	Dev

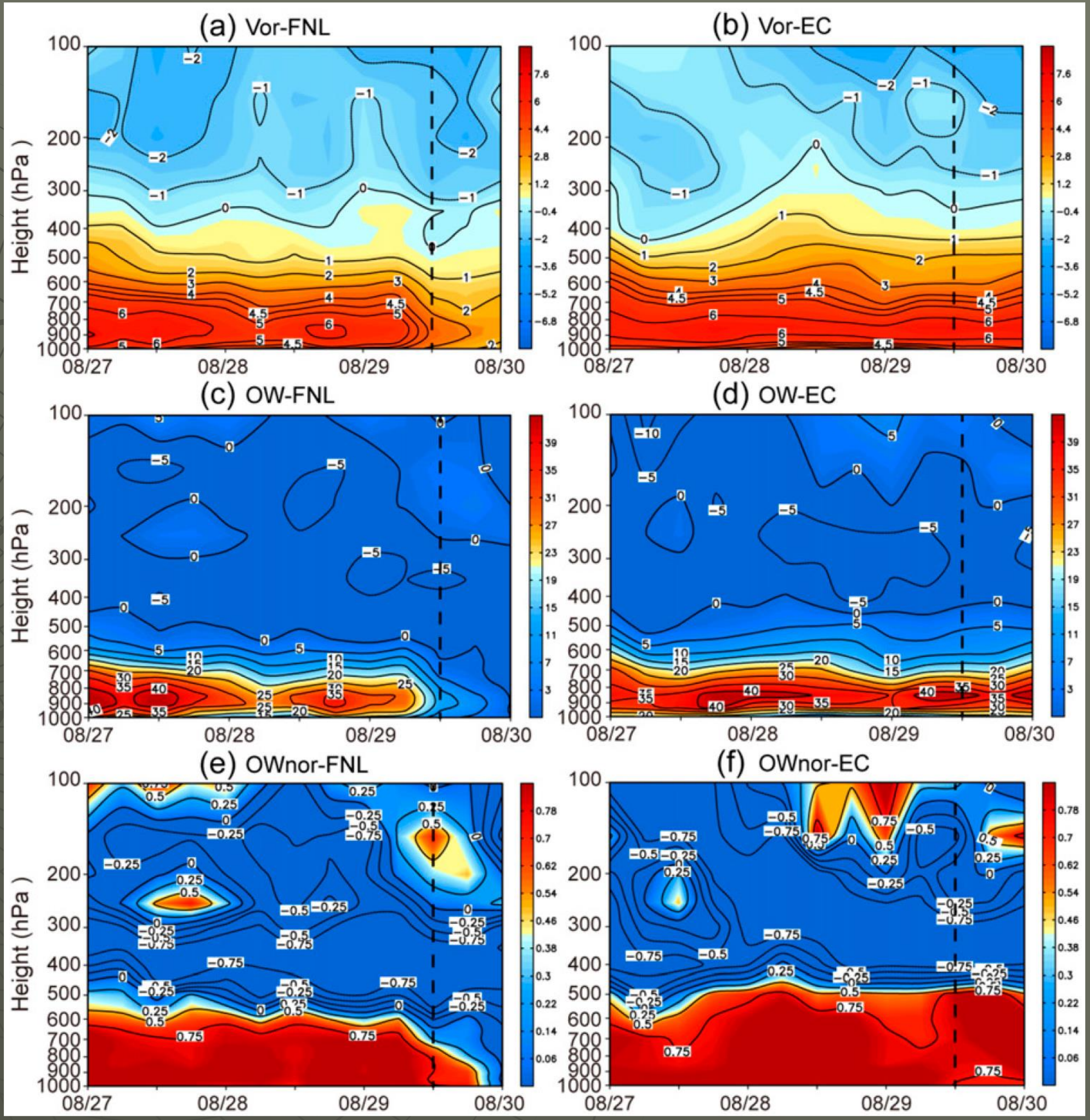
[a] The forecast time that the TD will develop to TS.

short-term fluctuations

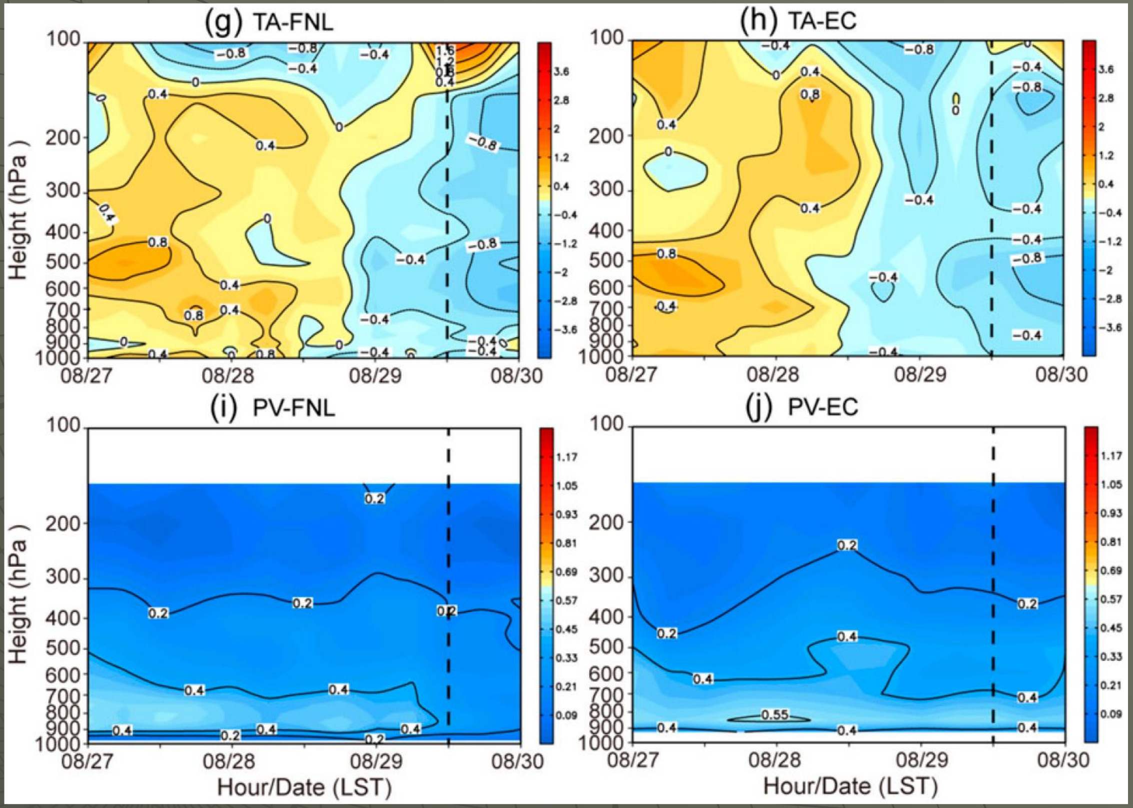
4. Application to 2018/19 TD cases
——Nondeveloping TD2 (18N2)

- This depression shows stronger dynamic features that could erroneously lead one to predict storm development.

- Of the first five criteria, four of them (relative vorticity at 850 hPa, the divergence at 150 hPa, the OW parameter at 850 hPa and the average normalized parameter OWnor below 600 hPa) are all satisfied.



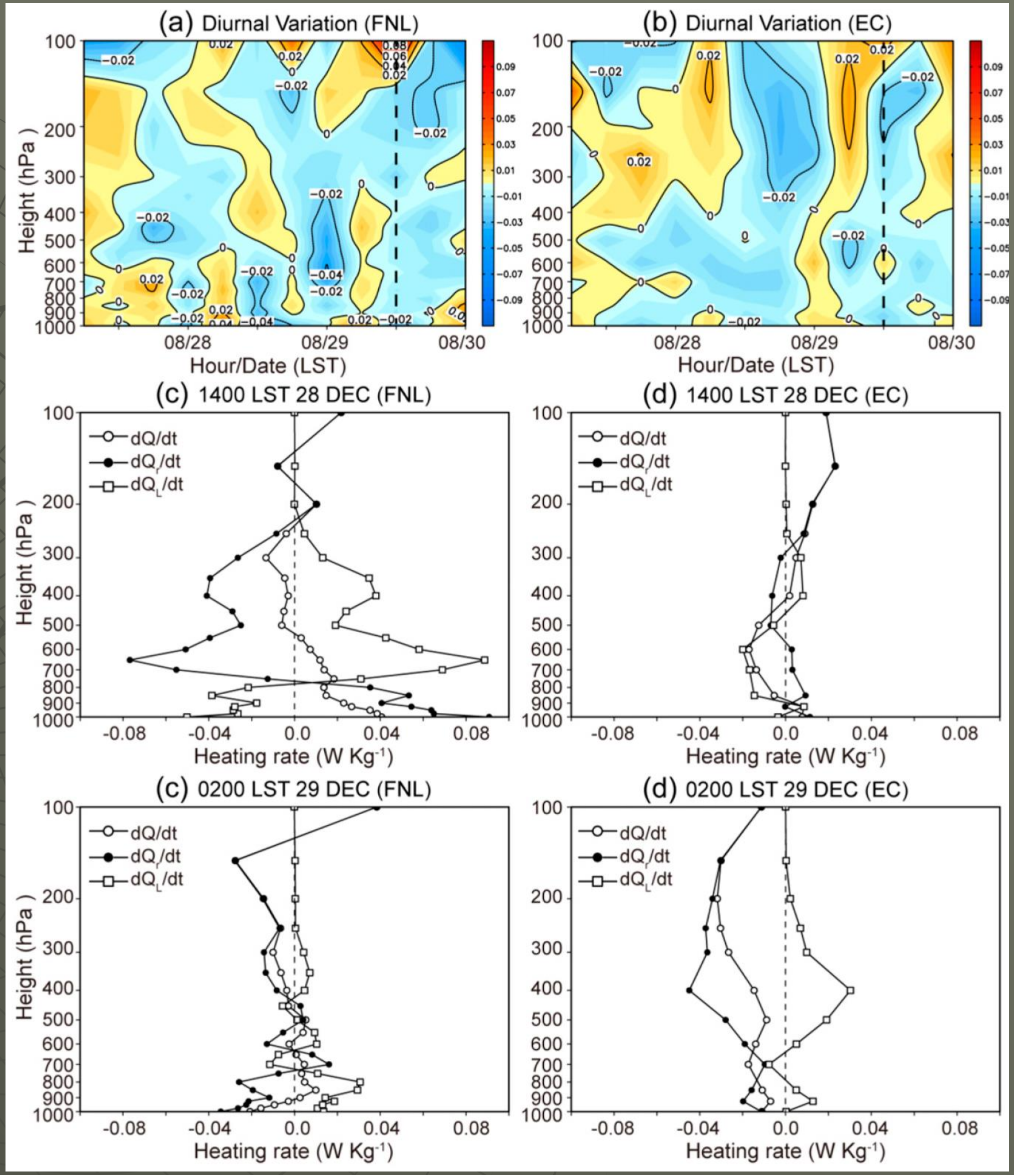
4. Application to 2018/19 TD cases
——Nondeveloping TD2 (18N2) cont.



- The center temperature difference show that the warm core disappears at 150-300 hPa.
- The criterion for the potential vorticity at 500 hPa is satisfied for neither observation nor forecast.

4. Application to 2018/19 TD cases —Nondeveloping TD2 (18N2) cont.

- This case has no regular diurnal variation of the diabatic heating rate, as well as no normal profile of the radiative heating term at the pre-decaying time.



4. Application to 2018/19 TD cases —Nondeveloping TD2 (18N2) cont.

TABLE 9. As in Table 8, but for TD (18N2). Decay time is 2000 LST 29 Dec.

Pre-decay time	Data	C1 Vorticity	C2 Divergence	C3 OW	C4 OW_{nor}	C5 PV	C6 Heating (diurnal)	C7 Heating (profile)	No. of Failures	Result
0800 LST 27 Dec	FNL	Y	Y	Y	Y	N	N	—		
	EC	Y	Y	Y	Y	N	N	—		
1400 LST 27 Dec[a]	FNL	Y	N	Y	Y	N	N	N	4	Nondev
	EC	Y	N	Y	Y	N	N	N	4	Nondev
2000 LST 27 Dec	FNL	Y	N	Y	Y	N	N	N	4	Nondev
	EC	Y	Y	Y	N	N	N	N	4	Nondev
0200 LST 28 Dec	FNL	Y	Y	Y	Y	N	N	N	3	Nondev
	EC	Y	Y	Y	Y	N	N	N	3	Nondev
0800 LST 28 Dec	FNL	Y	Y	Y	Y	N	N	N	3	Nondev
	EC	Y	Y	Y	Y	N	N	N	3	Nondev
1400 LST 28 Dec	FNL	Y	Y	Y	Y	N	N	N	3	Nondev
	EC	Y	Y	Y	Y	N	N	N	3	Nondev
2000 LST 28 Dec	FNL	Y	Y	Y	Y	N	N	N	3	Nondev
	EC	Y	Y	Y	Y	N	N	N	3	Nondev
0200 LST 29 Dec	FNL	Y	Y	Y	Y	N	N	N	3	Nondev
	EC	Y	Y	Y	Y	N	N	N	3	Nondev
0800 LST 29 Dec	FNL	Y	Y	Y	Y	N	N	N	3	Nondev
	EC	Y	Y	Y	Y	N	N	N	3	Nondev
1400 LST 29 Dec	FNL	Y	Y	Y	Y	N	N	N	3	Nondev
	EC	Y	Y	Y	N	N	N	N	3	Nondev

[a] The forecast time that TS will decay to TD.

4. Application to 2018/19 TD cases
——Other cases in 2018/19

TABLE 10. Prediction of all the TD cases in SCS in 2018/19.

Storm No.	No. (Name)	Type	Result	Lead time
1	1801 (Bolaven)	Developing	Unsuccessful	None
2	1804 (Ewiniar)	Developing	Successful	24 h
3	1816 (Bebinca)	Developing	Successful	72 h
4	1823 (Barijat)	Developing	Successful	42 h
5	1904 (Mun)	Developing	Successful	36 h
6	1907 (Wipha)	Developing	Successful	36 h
7	1914 (Kajiki)	Developing	Successful	18 h
8	1922 (Matmo)	Developing	Successful	24 h
9	1924 (Nakri)	Developing	Successful	42 h
10	18N1 (nameless)	Nondeveloping	Successful	18 h
11	18N2 (nameless)	Nondeveloping	Successful	54 h
	Average			36.6 h

- For all 11 cases, only one TD case was unsuccessful. Specifically, case 1801 was predicted as nondeveloping, yet actually developed, possibly due to an underestimate of the intensity. The other six TD cases were successfully predicted, with an average lead time of 36.6 h.

5. Conclusions and discussion

- For the developing case, we found the vertical velocity had maximum values at 250 hPa at all four stages. From the prestorm TY1 to storm TY2 stage, the vertical velocity increased throughout the layer, but at peak stage increased only below 400 hPa.
- The average sea surface temperatures were larger in developing tropical depressions than those in nondeveloping tropical depressions, and in both cases the temperatures decreased during the depression.
- The absolute angular momentum and the potential vorticity steadily increased in the developing case. In contrast, for the nondeveloping case, the absolute angular momentum and the potential vorticity decreased after peak stage.
- For the developing case, the potential temperature and the equivalent potential temperature steadily increased with time between 800 and 150 hPa. The maximum increase of the potential temperature occurred at 200 hPa in the prestorm and storm stages, but at 150 hPa in peak stage.
- The diabatic heating rate between prestorm and storm had relatively large values in 150-300 hPa, with smaller values below 500 hPa.

5. Conclusions and discussion cont.

- For the nondeveloping case, the potential temperature decreased after the initial time below 850 hPa. Also, the equivalent potential temperatures at peak and decaying stages were lower than those at the initial stage below 250 hPa.
- We applied all seven criteria to all 11 tropical depression cases in 2018/19, finding that they correctly determined whether or not 10 of the 11 tropical depressions developed. For these 10 successful cases, the prediction was on average 36.6 h before the depression developed or decayed.
- The thresholds and the profiles might be sensitive to the choice of model and its resolution (e.g., diabatic heating profiles can greatly vary). Moreover, we have not examined how well these criteria may apply to storms in other regions.
- Concerning the application of the two new criteria, the diabatic heating profiles might be retrievable using radar or satellite observation (Bessho et al. 2010). In this way, the proposed method may be assimilated into the initial conditions of an existing model for improving TC forecasts in real time.
- A well-organized field experiment should be run in the South China Sea to examine the genesis and development of tropical cyclones.


The End…
Thanks !
Questions??