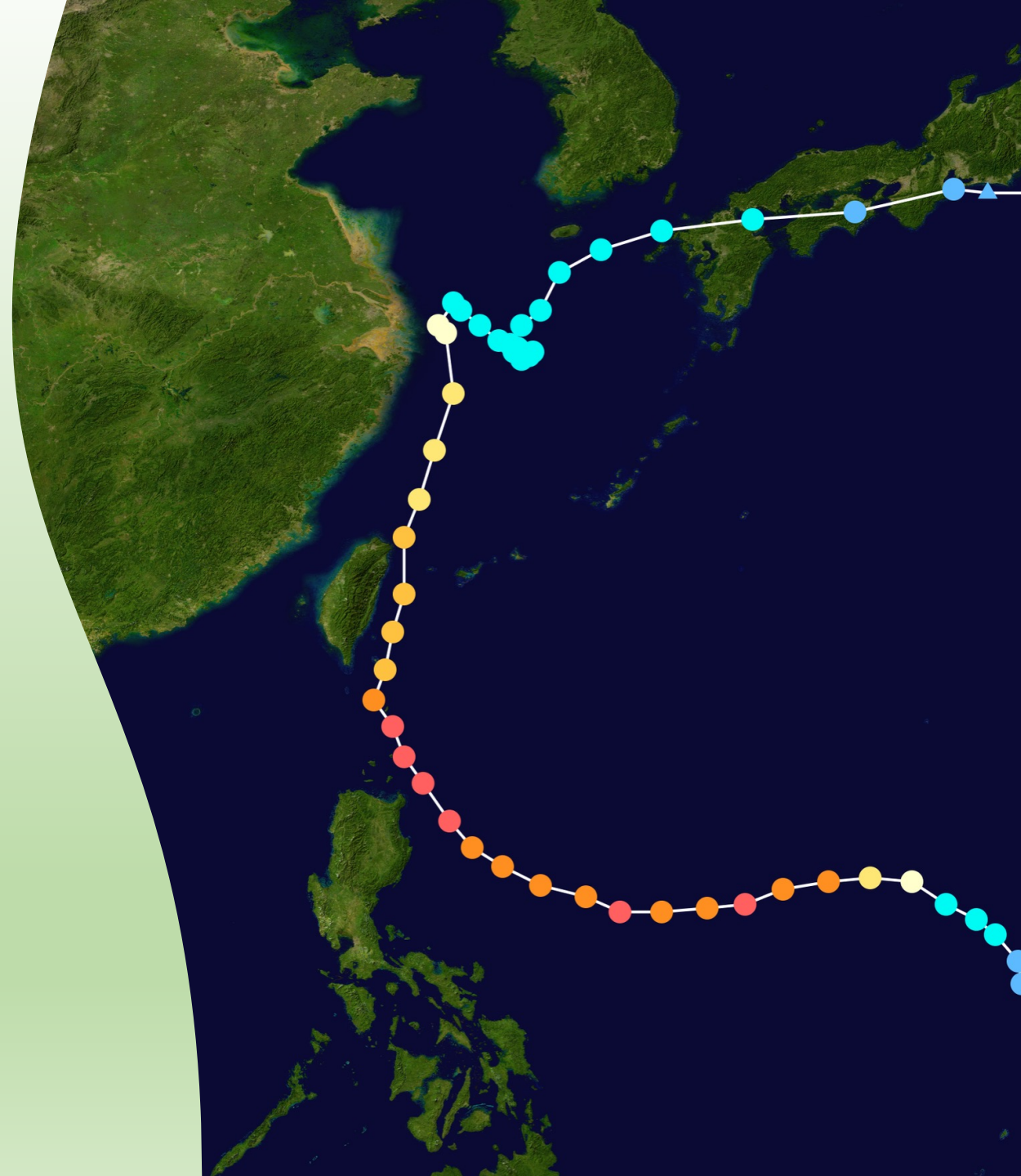


How Does Environmental Humidity Induce the Rapid Enlargement of Typhoon Chanthu (2021) as it Moved into the Monsoon Trough

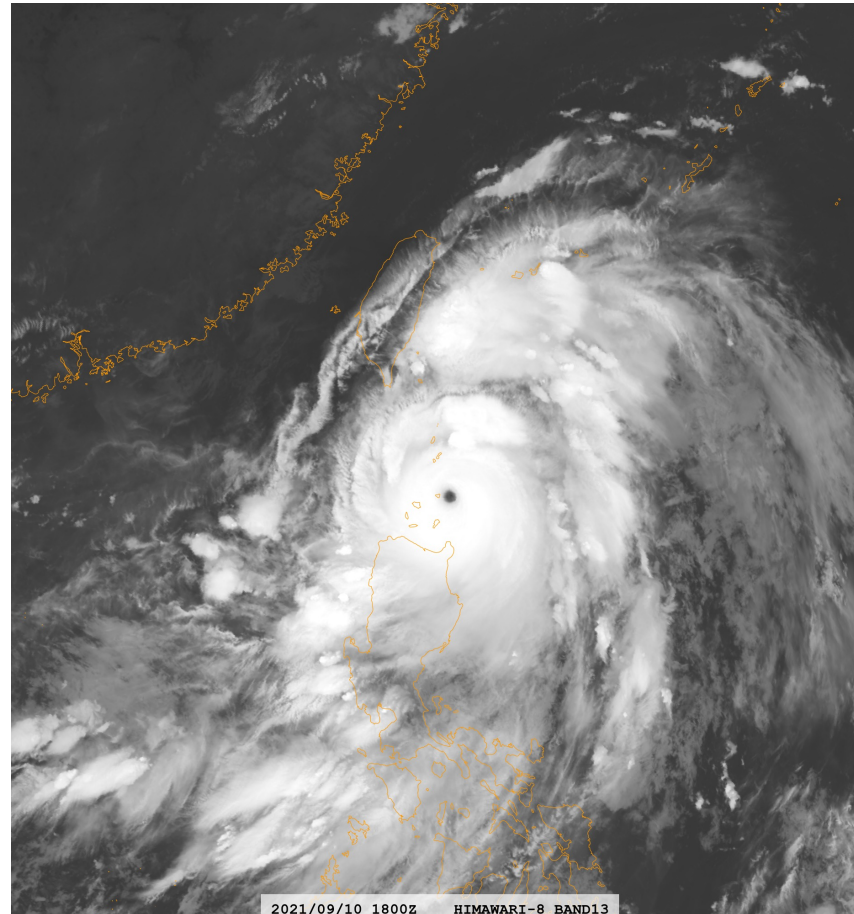
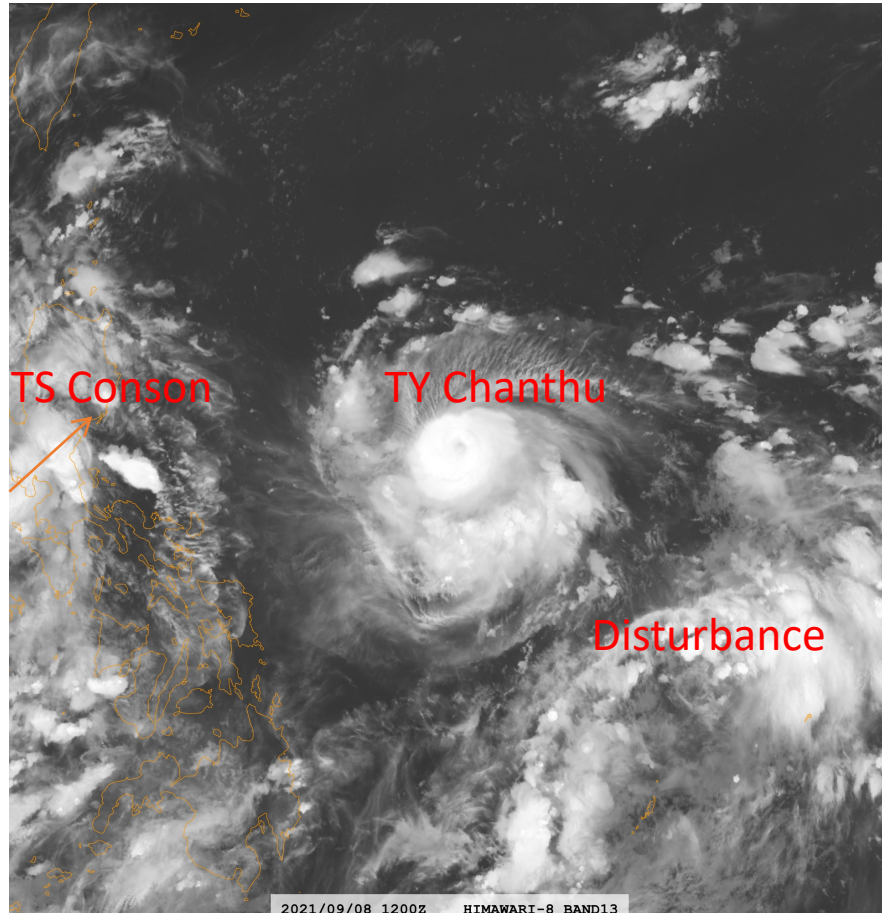
Yushan Han

ATM 255 Project

Winter 2023



The impressive growth of Chanthu...



Initially, Chanthu looks bounded, by the other two systems aside

Within the two days:
Size grew 7-8 times larger!

What happened?

21/09/08/12Z



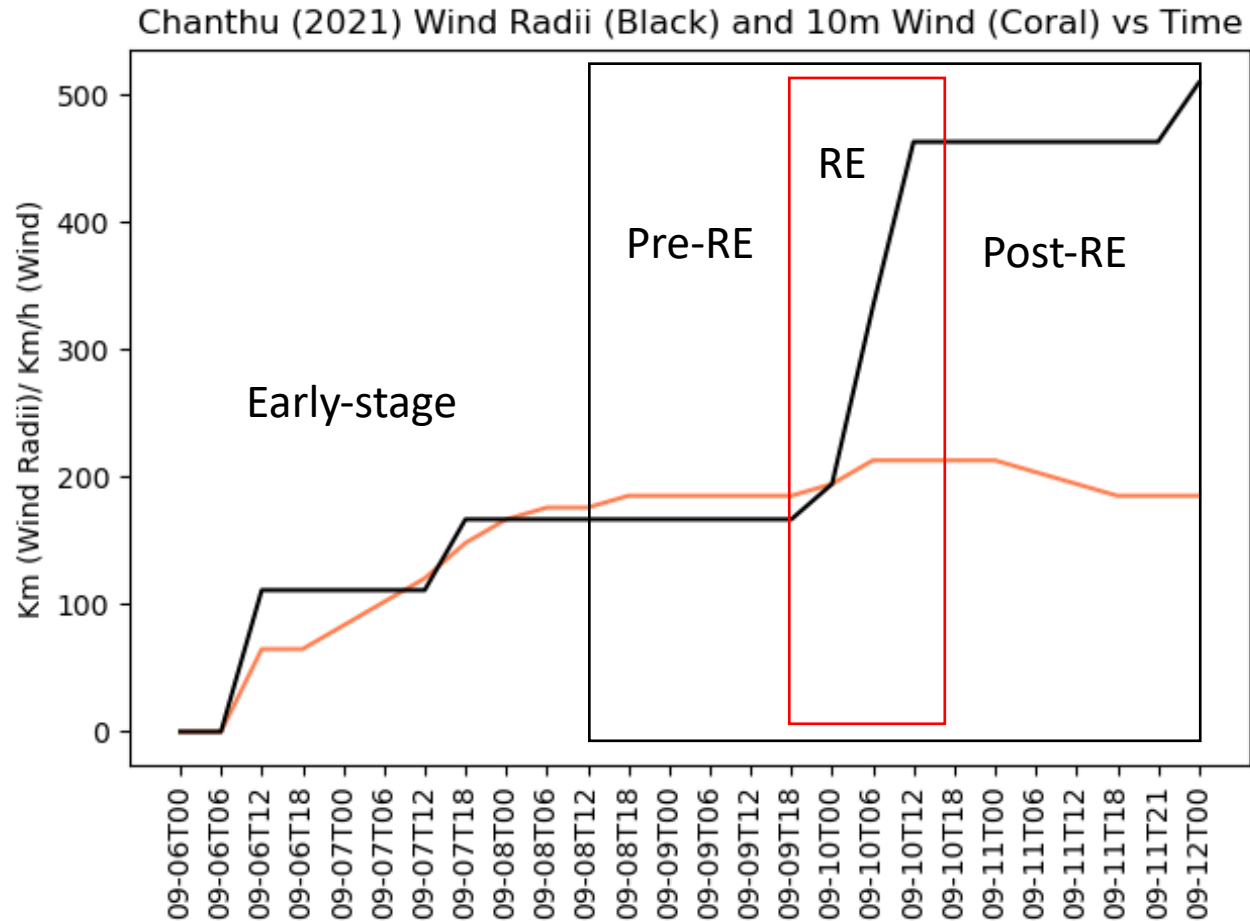
21/09/10/18Z

Not only intensity, size also matters! Bigger size means more widespread influences

Data Source: NICT (Himawari-8)

A little taste of the real Chanthu...

Size is determined by 10m 30knot (~15m/s) wind radii (in km)



Red Box: Time frame of the Rapid Enlargement (RE), when size grew fast.

(Approx. 21-09-09-18Z to 21-09-10-18Z)

Chanthu went from a ITCZ (easterly-wave) environment to a monsoon environment.

Note that 10m wind speed didn't change much as size grew.

Black Box: Time frame of my interest.

(09-08-12Z to 09-12-00Z)

Includes Pre-RE, RE, and Post-RE stages

Initiation at early-stage not recommended, as Typhoon Conson (2021) adds many uncertainties

Monsoon Trough vs ITCZ

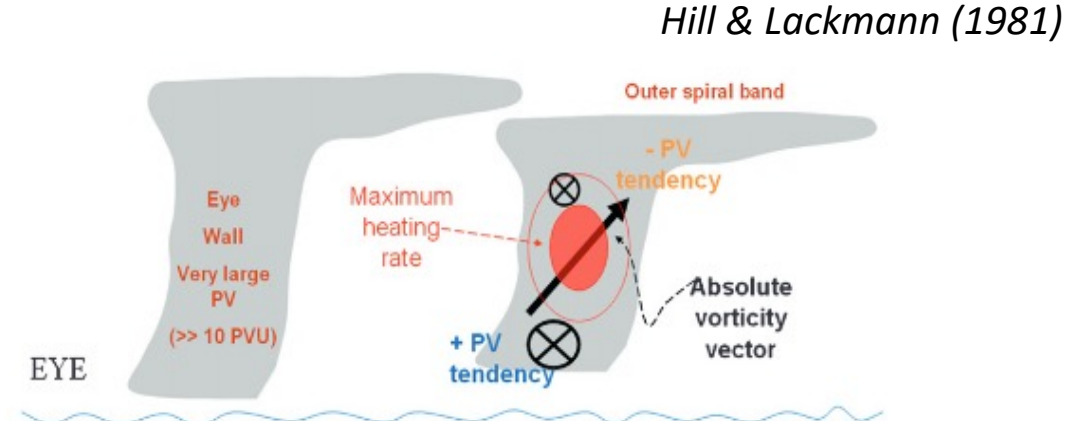
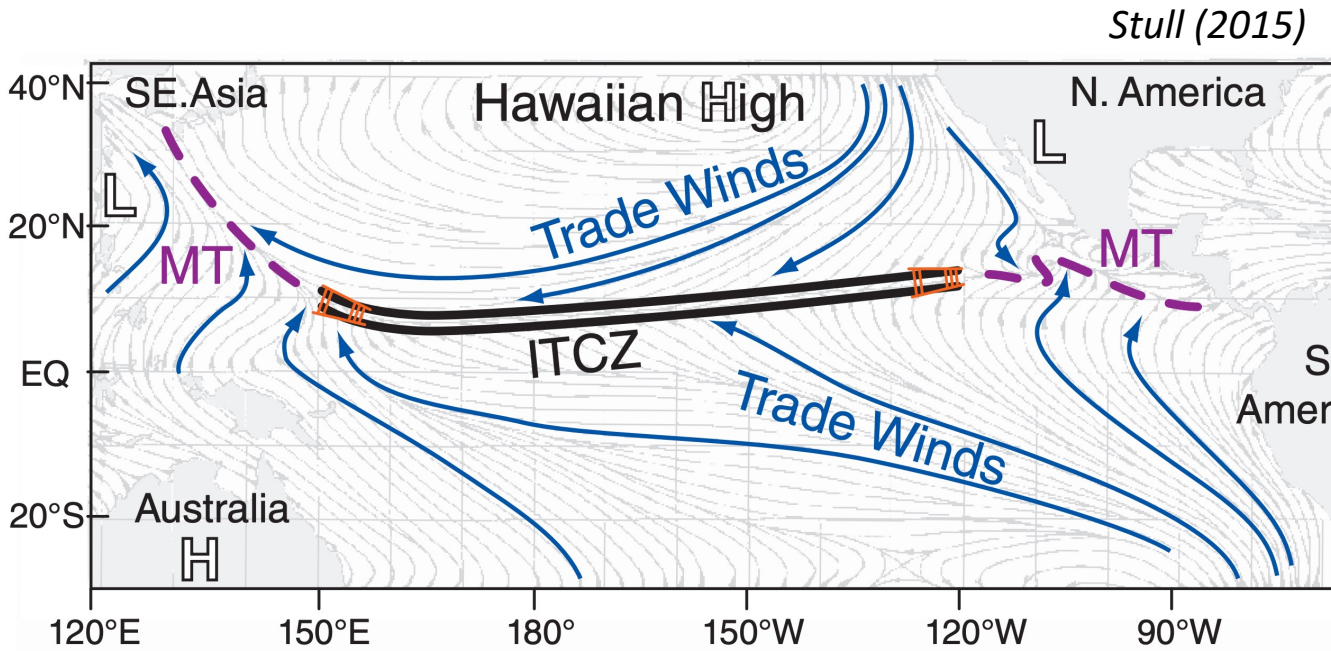


FIG. 2. Idealized schematic of the diabatic PV redistribution in an outer rainband of a tropical cyclone. The maximum heating rate due to condensation is shown as a shaded oval, with a superimposed absolute vorticity vector shown as a black arrow. In a warm-core system, the vorticity vectors will slope outward with height where the circulation is decreasing with height. Positive PV tendencies are found in the lower troposphere and radially inward from the radius of maximum heating.

Monsoon Trough environment is usually more humid than easterly-winds environment in the Western North Pacific.

Humid environment has been shown to favor tropical cyclone (TC) enlargement (and intensification).

Why? **Potential Vorticity (PV) might be crucial.** PV is generated when there's diabatic heating, which can be fed by moist convection and precipitation. More humid means more moisture, more cumulus clouds, and more PV.

TCs' outer rainbands grow on available PV, and the outer PV flows into the inner eyewall PV tower.

Hence, more humid → more PV → wider/more rain bands; and wider eyewall !

More on Potential Vorticity...

- **PV can be as simple as this:** $PV = \frac{\zeta_a \cdot \nabla \theta}{\rho}$

- Which says PV is conserved if assumed adiabatic and frictionless. PV is proportional to dry static stability.

- **Or it can be as complex as its budget equation:**
$$\frac{\partial}{\partial t} \bar{\Gamma}_a \bar{Q} + \nabla \cdot (\bar{\mathbf{V}} \bar{\Gamma}_a \bar{Q}) + \frac{\partial}{\partial p} (\bar{\omega} \bar{\Gamma}_a \bar{Q}) - \bar{Q} \frac{\partial \bar{v}}{\partial p} \cdot \nabla \bar{\theta}$$

- **Take-away terms from this long equation:**

1. Local Changes (Horizontal, Vertical advection)
2. Horizontal, Vertical Divergence/Convergence
3. Vertical convergence of cumulus mass flux M_c
4. Vertical differential of radiative effects
5. Frictional Stresses

$$+ \bar{\Gamma}_a \left(\frac{\partial \bar{\omega}}{\partial x} \frac{\partial \bar{v}}{\partial p} - \frac{\partial \bar{\omega}}{\partial y} \frac{\partial \bar{u}}{\partial p} \right) = - \frac{\partial}{\partial p} (\bar{Q} M_c \bar{\Gamma}_a) - (\bar{Q}/c_p) \frac{\partial}{\partial p} \left[\left(\frac{p_0}{p} \right)^{R/c_p} \bar{H}_R \right] + \bar{\Gamma}_a \left(\frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y} \right) - \bar{\Gamma}_a \left(\frac{\partial M_c}{\partial x} \frac{\partial \bar{v}}{\partial p} - \frac{\partial M_c}{\partial y} \frac{\partial \bar{u}}{\partial p} \right) \quad (9)$$

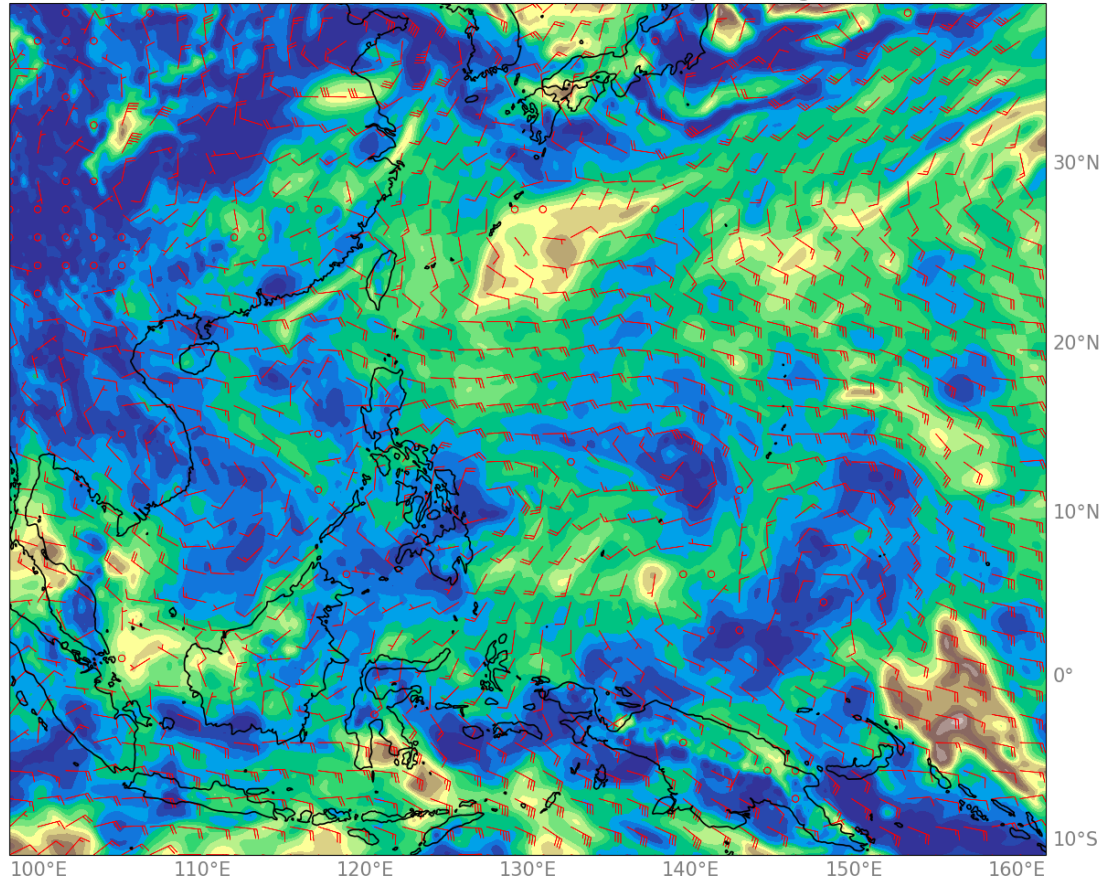
\bar{Q} is absolute vorticity

Yang & Krishnamurti (1981)

We might not have enough time to dig deep into each term, but we might get a taste of how the patterns of environmental humidity affect TC structure and the surrounding PV field. And we can infer from that.

More about the real case...

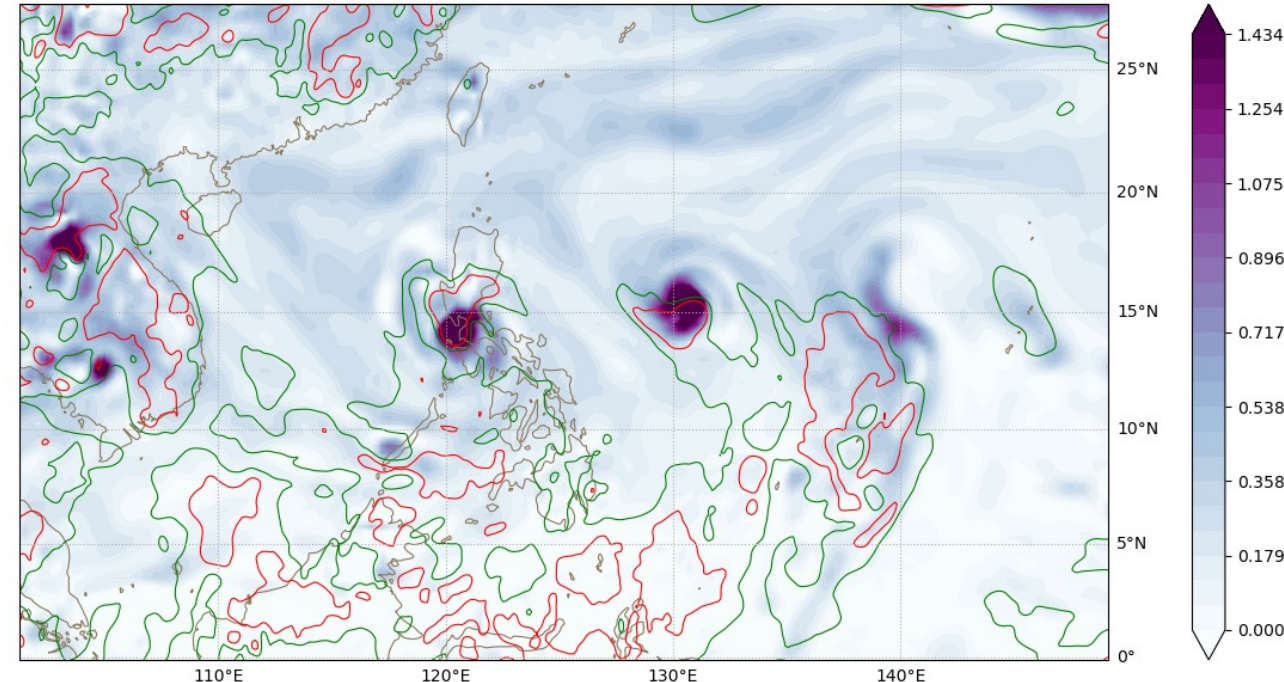
Reanalysis 850 MB Wind Barbs (m/s) and Relative Humidity (Shading) at 2021-09-06T00



Reanalysis 850 MB Wind Barbs (m/s) and Relative Humidity (Shading) at the three stages.

RH: Not so much difference in the boundary layer, but differences at 700mb.
PV: Noticeable Differences.

700 MB Potential Vorticity (PVU) and RH (80%, 90% intervals) at 2021-09-08T12

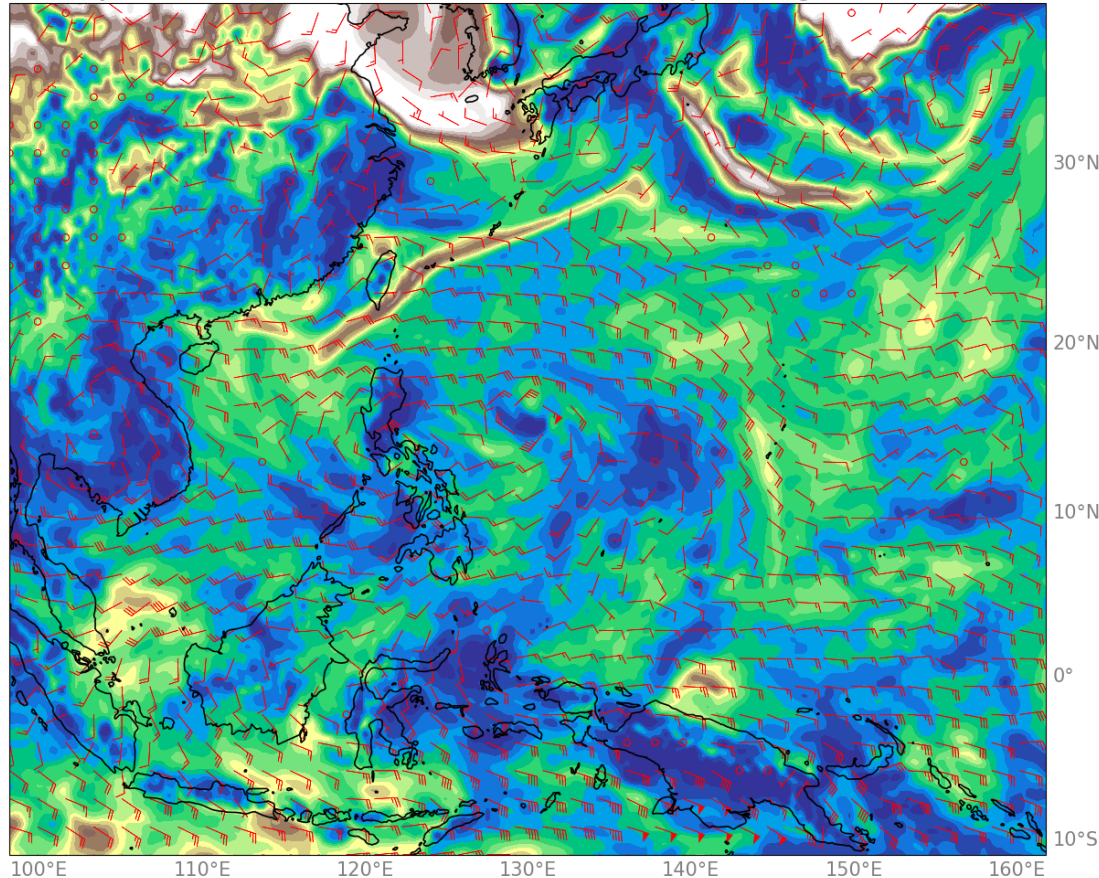


Reanalysis 700 MB Potential Vorticity (PVU) and RH (80%, 90% intervals) at the three stages.

$$1 \text{ PVU} = 10^{-6} \text{ m}^2 \text{ s}^{-1} \text{ K kg}^{-1}$$

More about the real case...

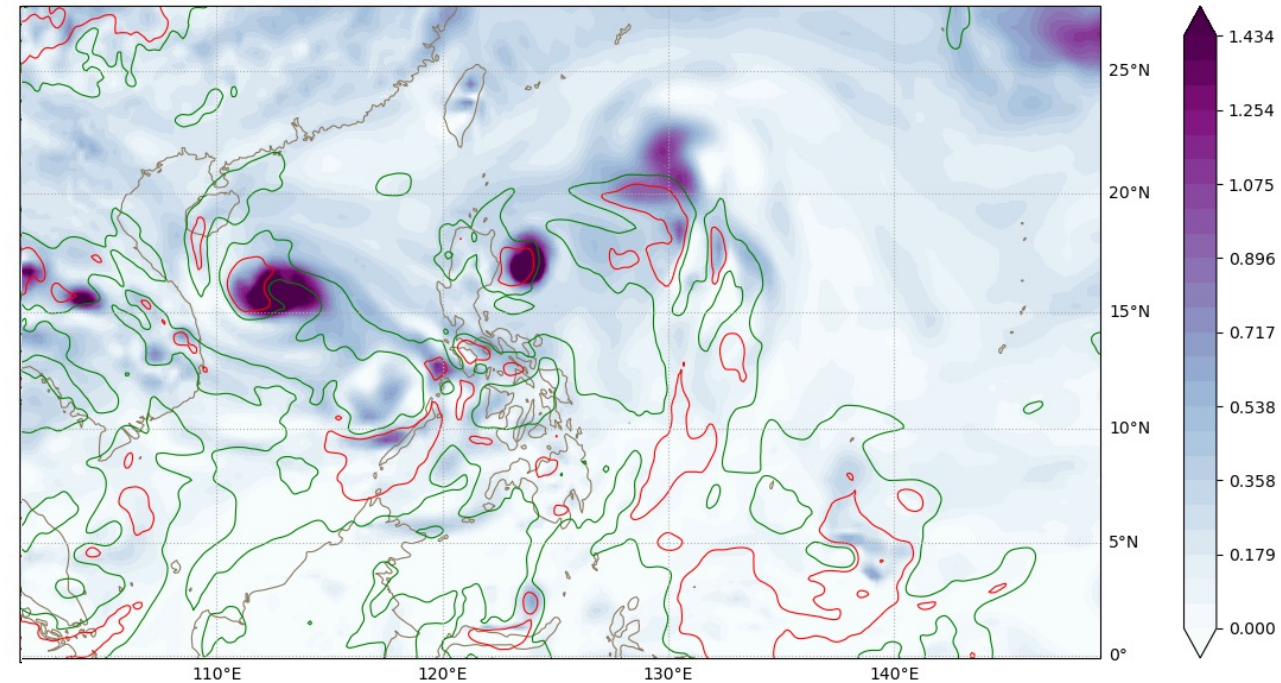
Reanalysis 850 MB Wind Barbs (m/s) and Relative Humidity (Shading) at 2021-09-08T12



Reanalysis 850 MB Wind Barbs (m/s) and Relative Humidity (Shading) at the three stages.

RH: Not so much difference in the boundary layer, but differences at 700mb.
PV: Noticeable Differences.

700 MB Potential Vorticity (PVU) and RH (80%, 90% intervals) at 2021-09-10T00

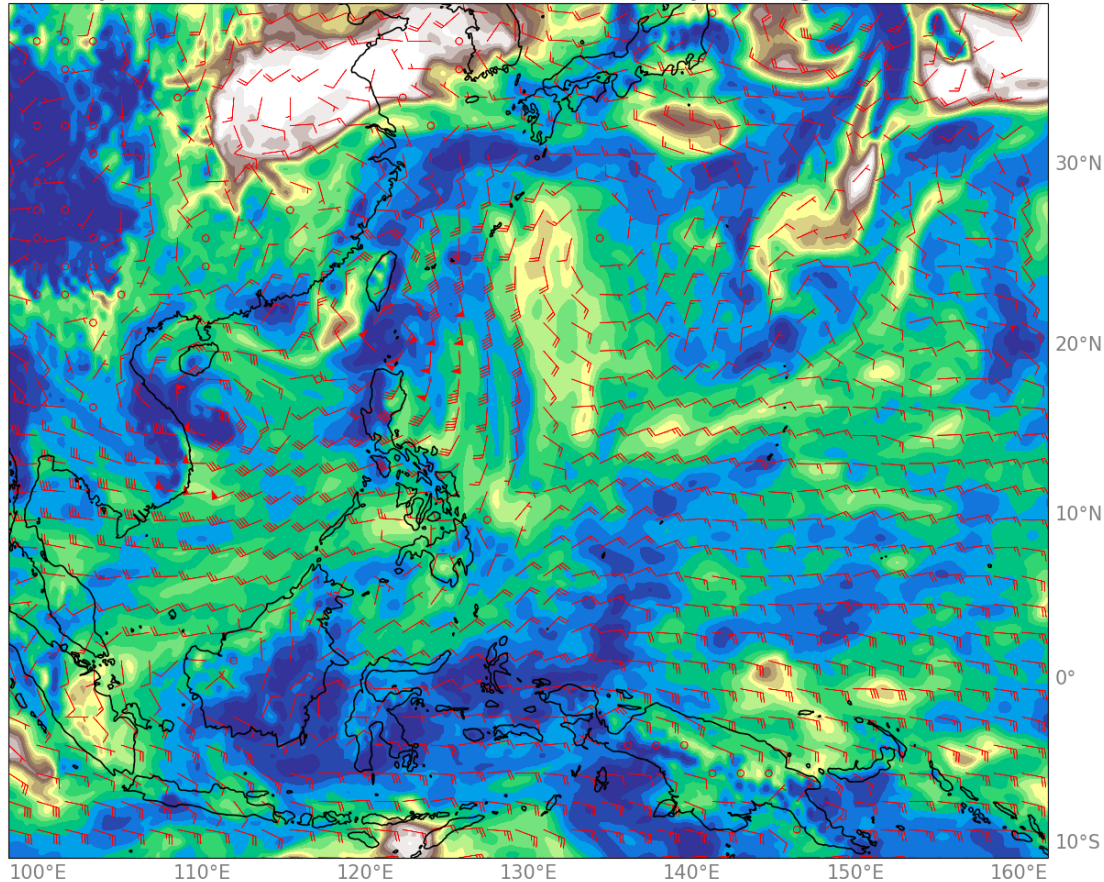


Reanalysis 700 MB Potential Vorticity (PVU) and RH (80%, 90% intervals) at the three stages.

$$1 \text{ PVU} = 10^{-6} \text{ m}^2 \text{ s}^{-1} \text{ K kg}^{-1}$$

More about the real case...

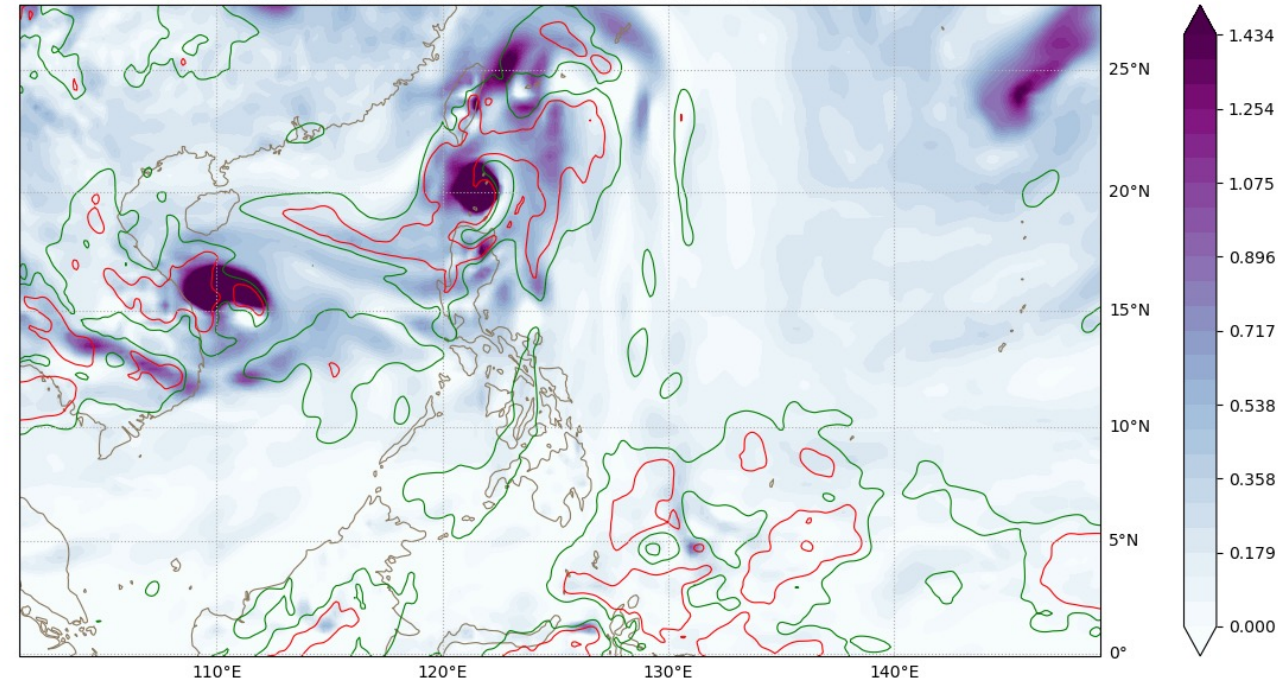
Reanalysis 850 MB Wind Barbs (m/s) and Relative Humidity (Shading) at 2021-09-11T00



Reanalysis 850 MB Wind Barbs (m/s) and Relative Humidity (Shading) at the three stages.

RH: Not so much difference in the boundary layer, but differences at 700mb.
PV: Noticeable Differences.

700 MB Potential Vorticity (PVU) and RH (80%, 90% intervals) at 2021-09-11T00



Reanalysis 700 MB Potential Vorticity (PVU) and RH (80%, 90% intervals) at the three stages.

$$1 \text{ PVU} = 10^{-6} \text{ m}^2 \text{ s}^{-1} \text{ K kg}^{-1}$$

Model run (normal run) set-up

The modified “TROPICAL” suite

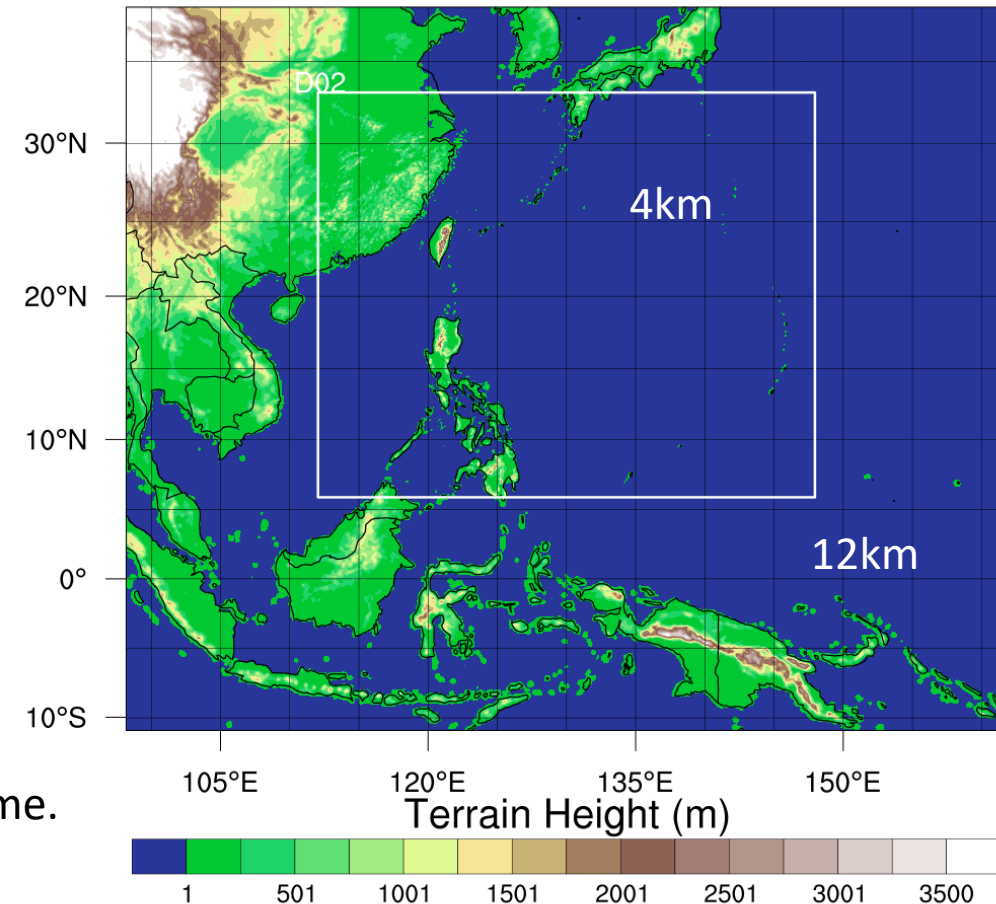
6h ERA5 (0.25*0.25)

model top	2000 Pa
microphysics	WSM 6-class graupel
cumulus	Newer Tiedtke (only domain 1)
longwave radiation	rrtmg scheme
shortwave radiation	rrtmg scheme
boundary-layer	YSU scheme
surface-layer	Old MM5 scheme
land-surface	Unified Noah land-surface model

TC size not very sensitive to the choice of single-moment microphysics scheme.
(Chan & Chan, 2016)

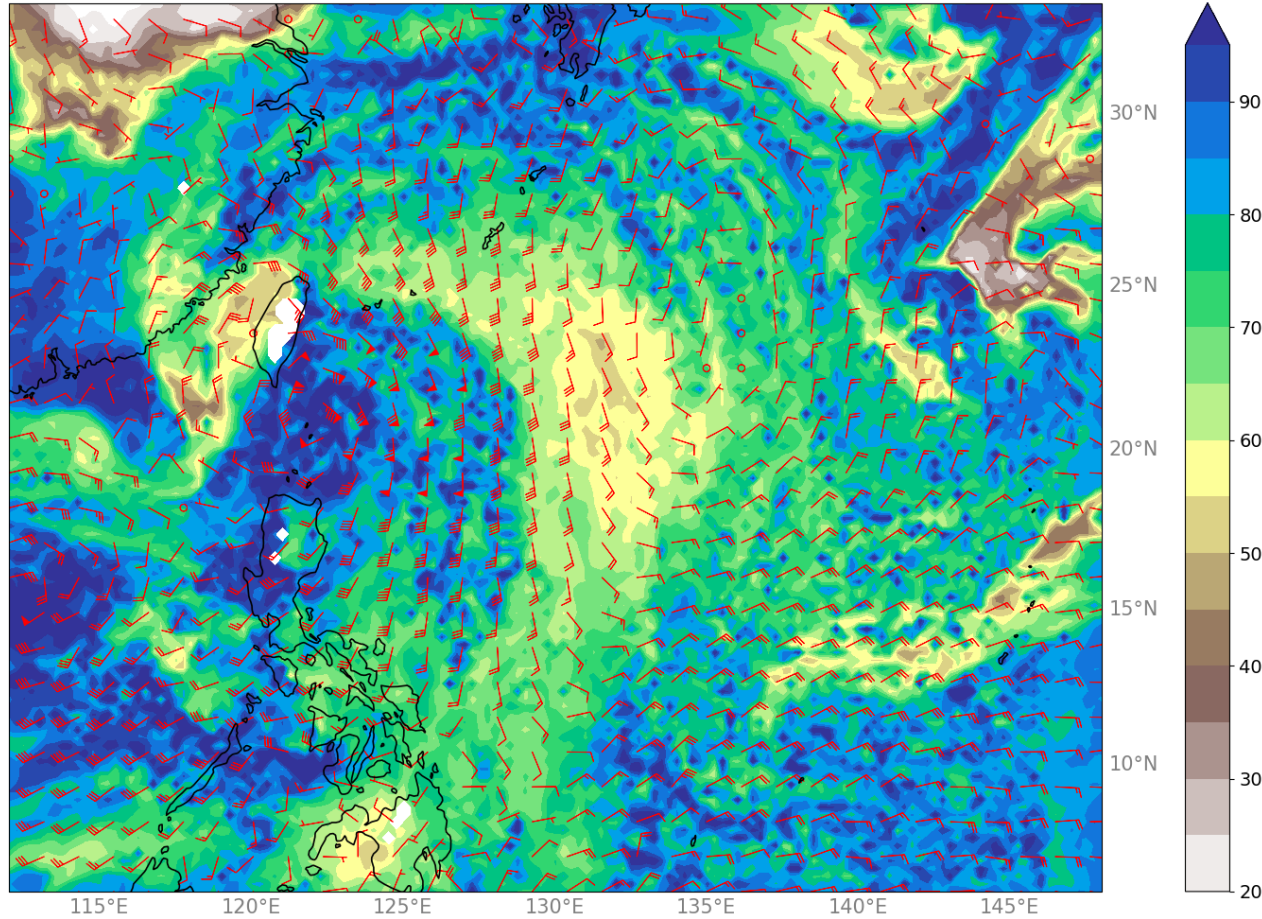
But might be sensitive to cumulus scheme options (*Zhang & Wang (2018)*).

WPS Domain Configuration



Model run (normal run) results

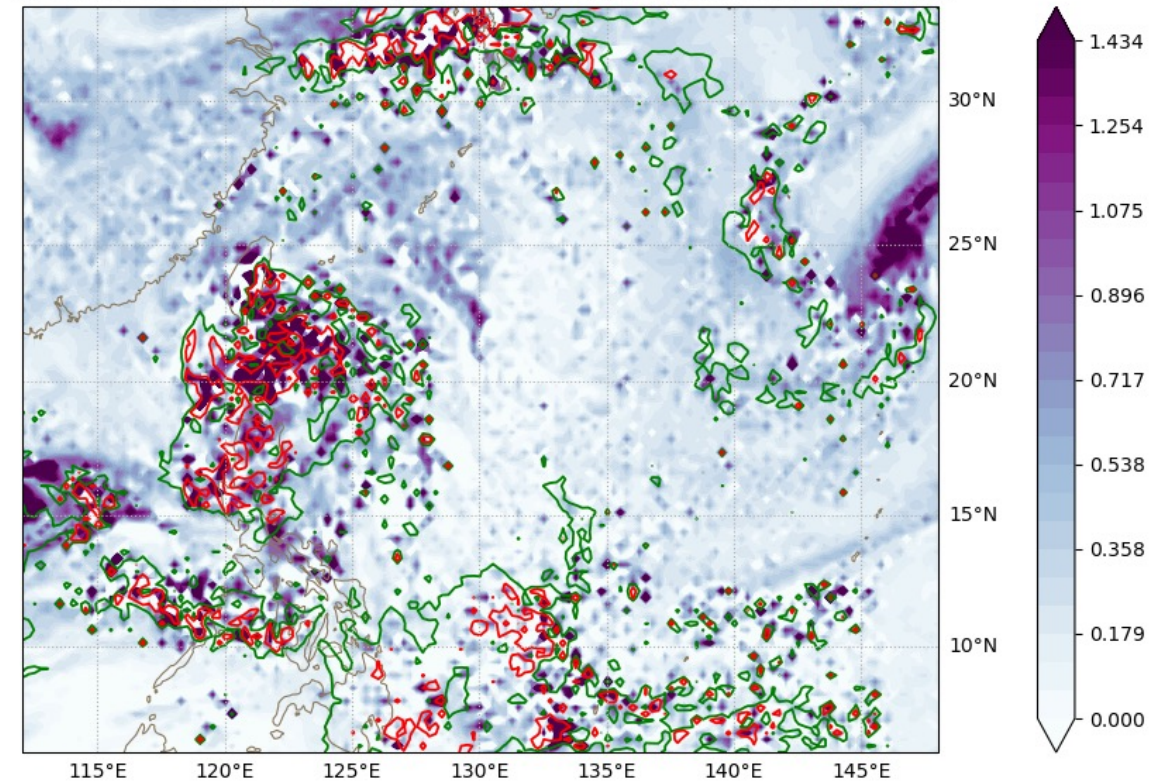
Normal Run 850 MB Wind Barbs (m/s) and Relative Humidity (Shading) at 2021-09-11T00



Normal run 850 MB Wind Barbs (m/s) and Relative Humidity (Shading) at the three stages.

Generally drier, might be embedded in the ERA5 reanalysis?

700 MB Potential Vorticity (PVU) and RH (80%, 90% intervals) at 2021-09-11T00



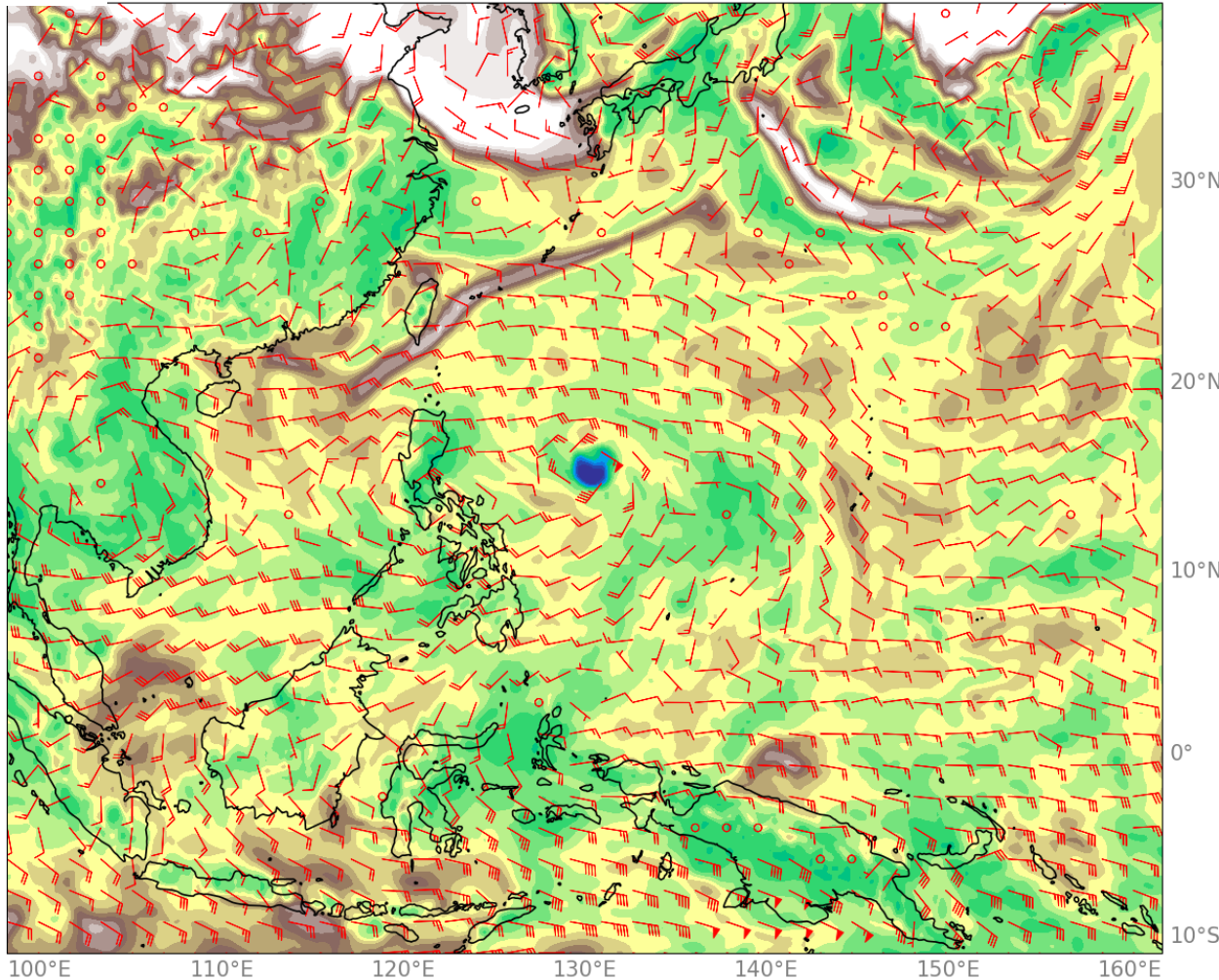
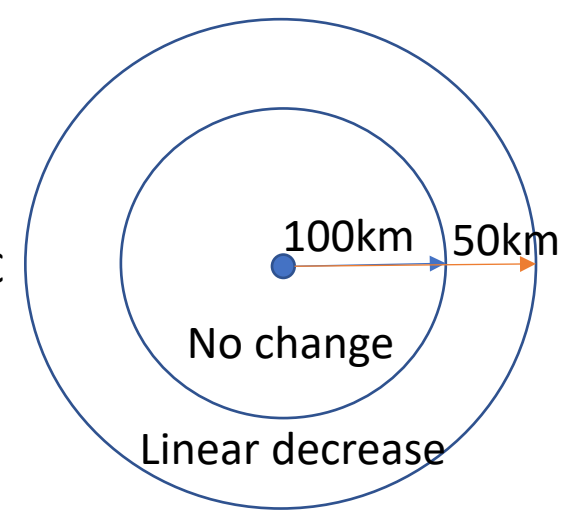
Normal run 700 MB Potential Vorticity (PVU) and RH (80%, 90% intervals) at the three stages.

Model run (“cruel” run) set-up

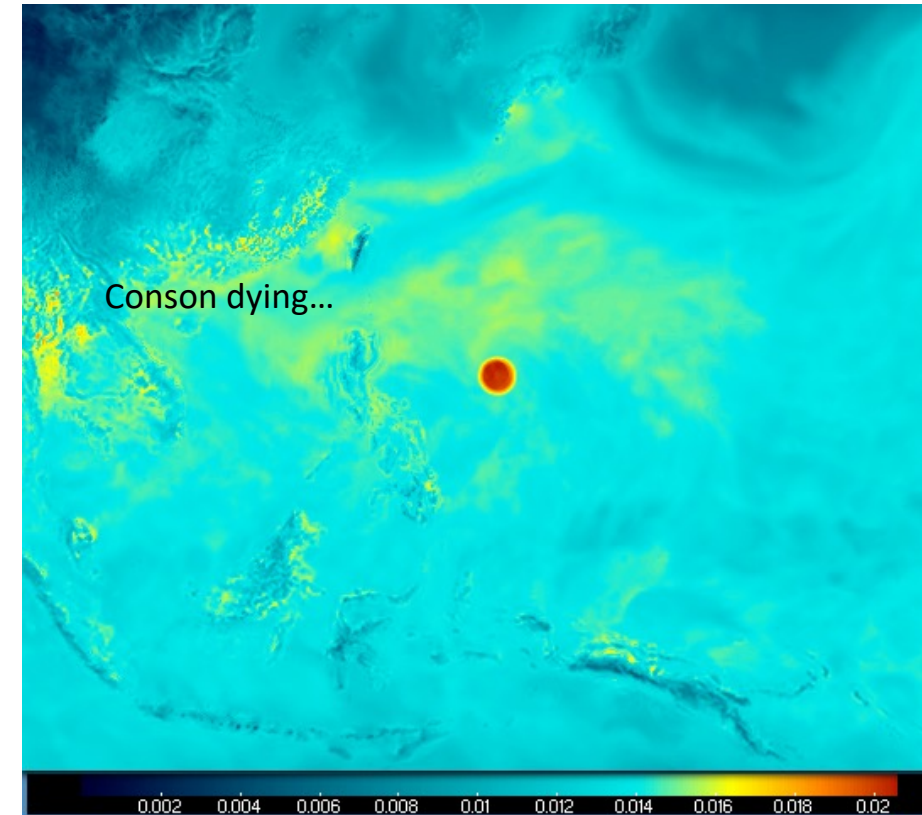
Both initial and boundary RH condition changed
Other fields almost untouched,

Gentle Run 850 Wind Barbs (m/s) and Relative Humidity (Shading) at 2021-09-08-12

Within 100km of the center: Maintained
Dry rate =25% outside of 150km from the TC
Buffer zone of 50km for linear decreasing



Water Vapor (g/kg)

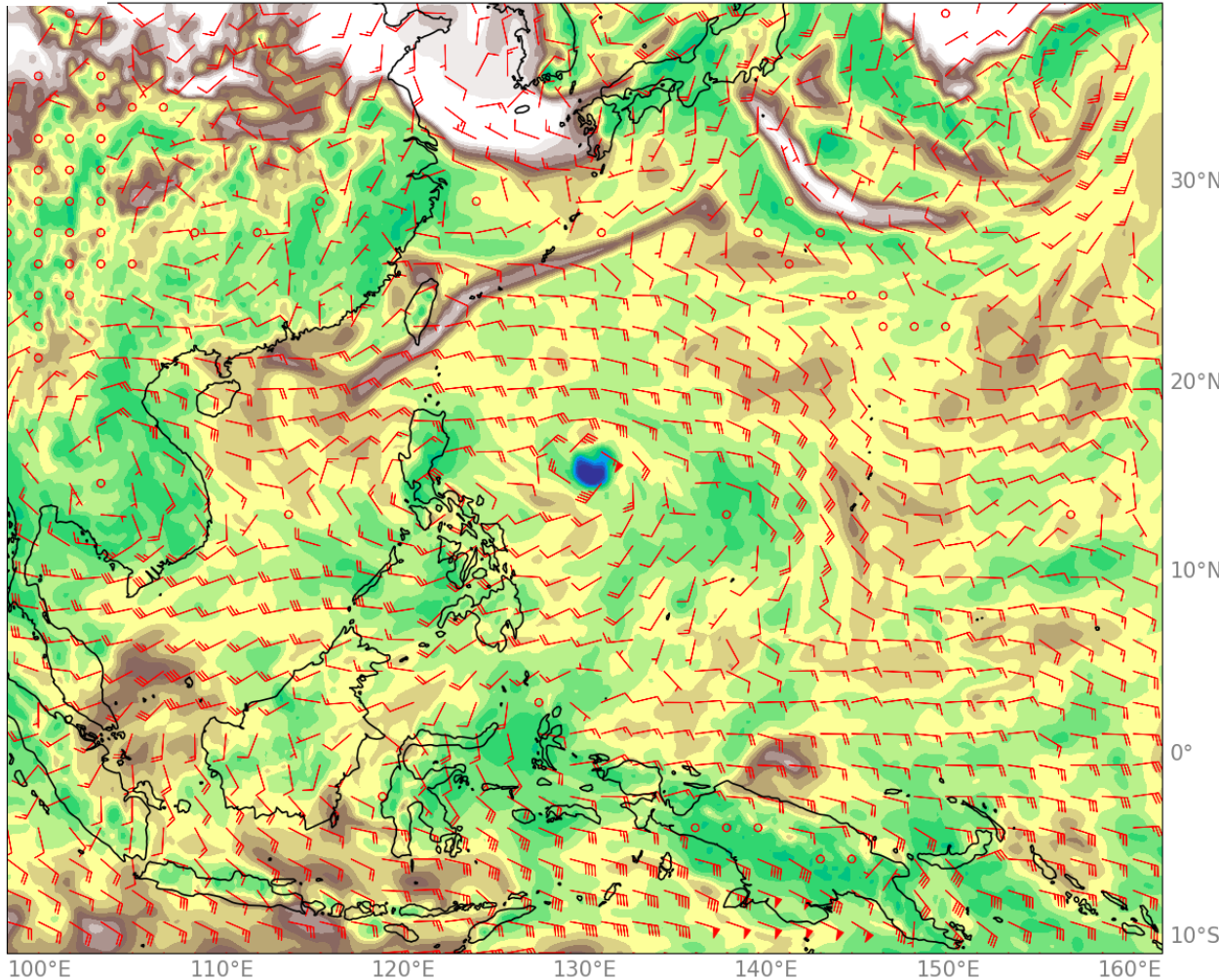
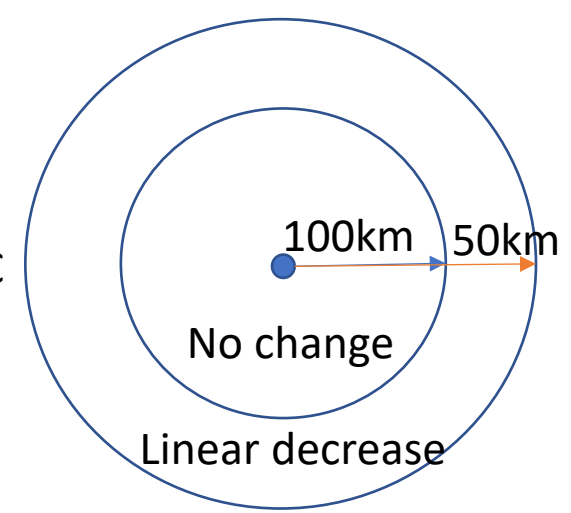


Model run ("cruel" run) set-up

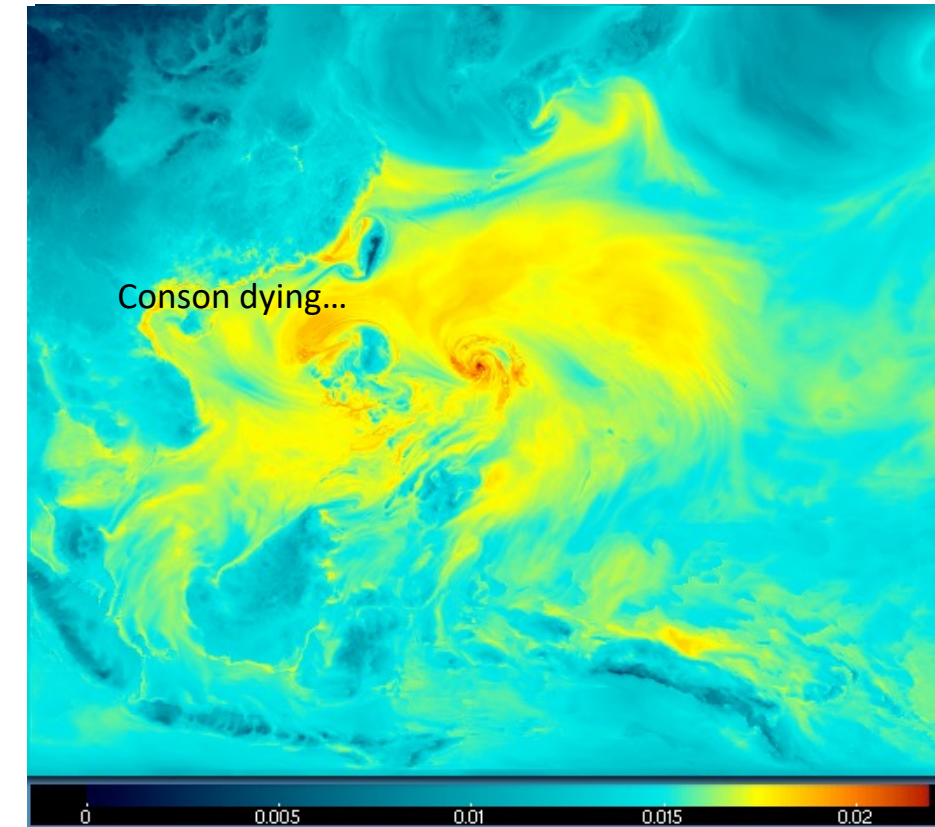
Both initial and boundary RH condition changed
Other fields almost untouched,

Gentle Run 850 Wind Barbs (m/s) and Relative Humidity (Shading) at 2021-09-08-12

Within 100km of the center: Maintained
Dry rate =25% outside of 150km from the TC
Buffer zone of 50km for linear decreasing



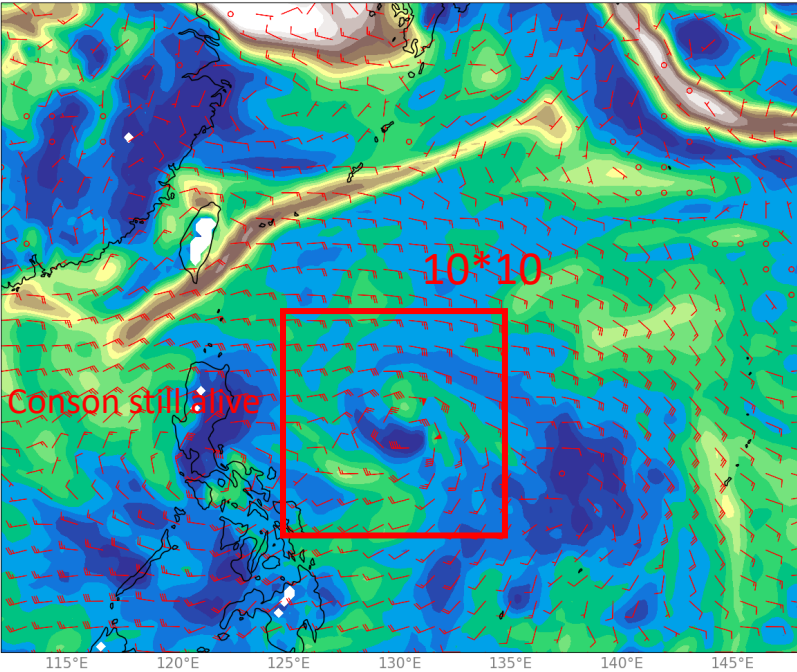
Water Vapor (g/kg)



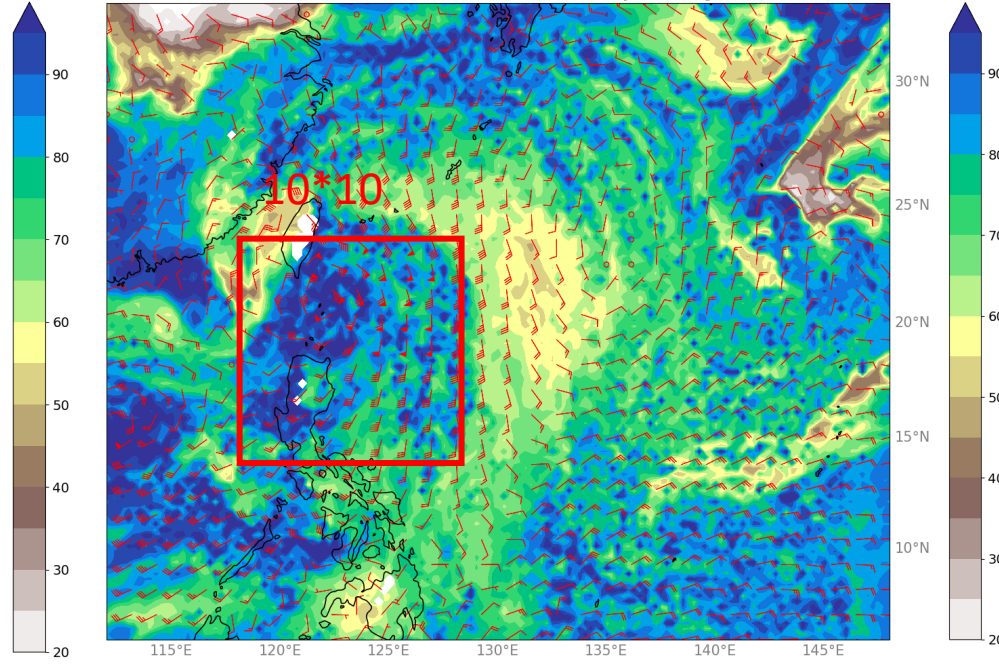
Both initial and boundary RH condition changed
Other fields almost untouched,

Model run (“gentle” run) set-up

Normal Run 850 MB Wind Barbs (m/s) and Relative Humidity (Shading) at 2021-09-08T12

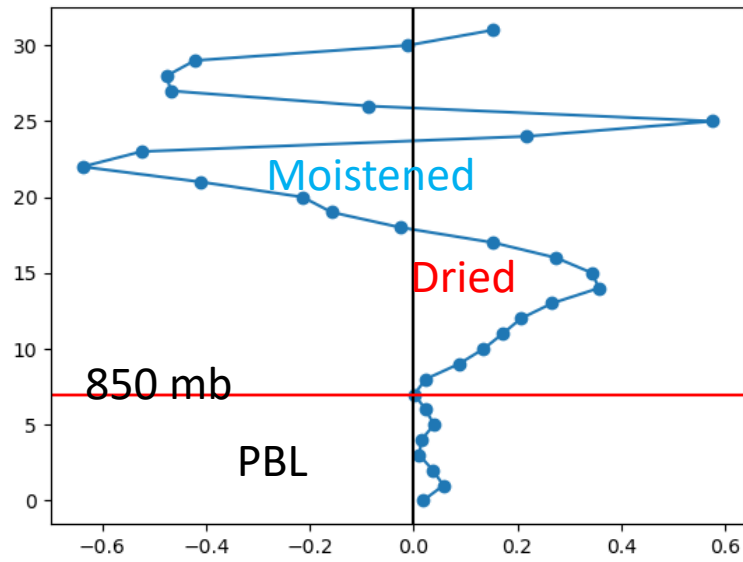


Normal Run 850 MB Wind Barbs (m/s) and Relative Humidity (Shading) at 2021-09-11T00



08-12Z mean:
Central Lon +5/-5
Central Lat +5/-5

11-00Z mean:
Central Lon +2.5/-7.5
Central Lat +2.5/-7.5



Dry rate is determined by normal run’s 11-0Z – 08-12Z on every input level

Integrate over height: not much difference

However, the vertical structure is different

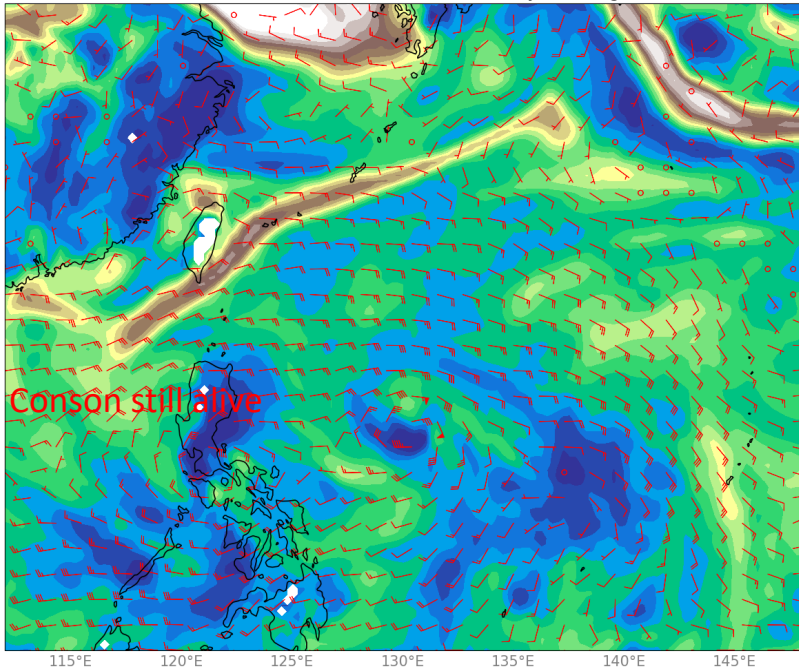
Slightly more humid boundary layer + More moist mid-level + Drier upper-level

Dry rate (level) = $[(11-0Z - 08-12Z)/11-0Z]$ % outside of 150km from the TC
Buffer zone of 50km for linear decreasing

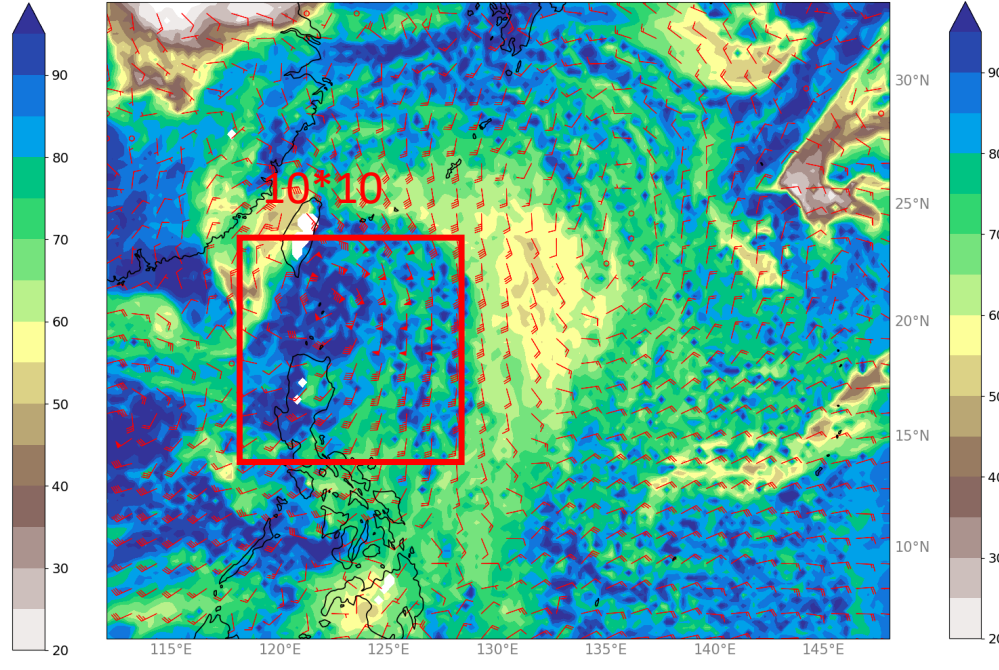
Both initial and boundary RH condition changed
Other fields almost untouched,

Model run (“gentle” run) set-up

Gentle Run 850 MB Wind Barbs (m/s) and Relative Humidity (Shading) at 2021-09-08T12

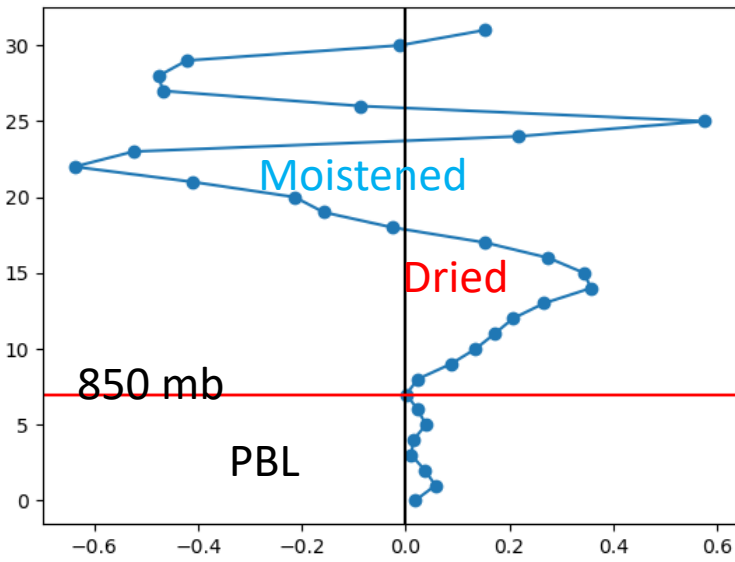


Normal Run 850 MB Wind Barbs (m/s) and Relative Humidity (Shading) at 2021-09-11T00



08-12Z mean:
Central Lon +5/-5
Central Lat +5/-5

11-00Z mean:
Central Lon +2.5/-7.5
Central Lat +2.5/-7.5



Dry rate is determined by normal run's 11-0Z – 08-12Z on every input level

Integrate over height: not much difference

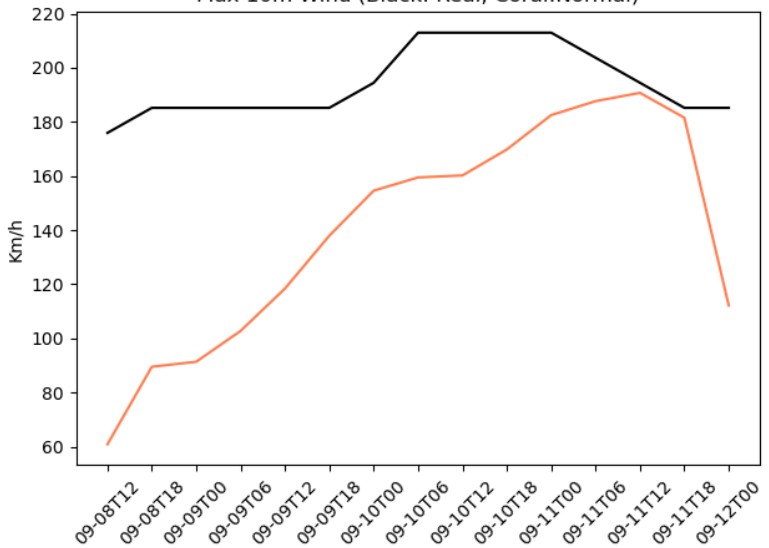
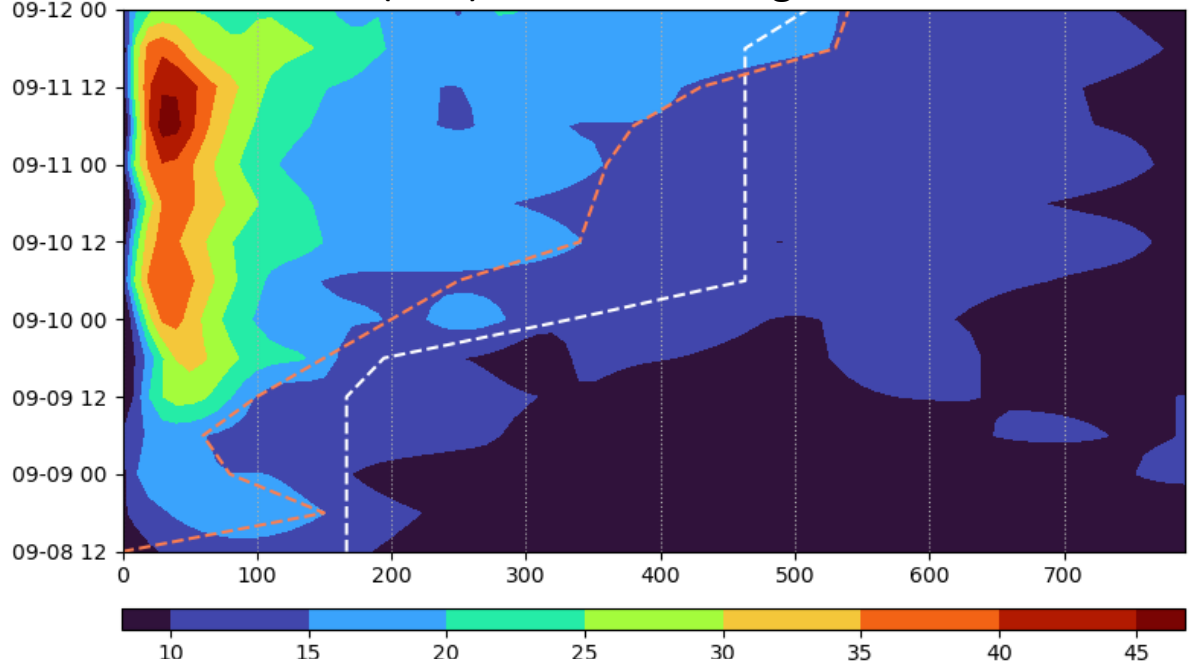
However, the vertical structure is different

Slightly more humid boundary layer + More moist mid-level + Drier upper-level

Dry rate (level) = $[(11-0Z - 08-12Z)/11-0Z]$ % outside of 150km from the TC
Buffer zone of 50km for linear decreasing

Model run (normal run) results

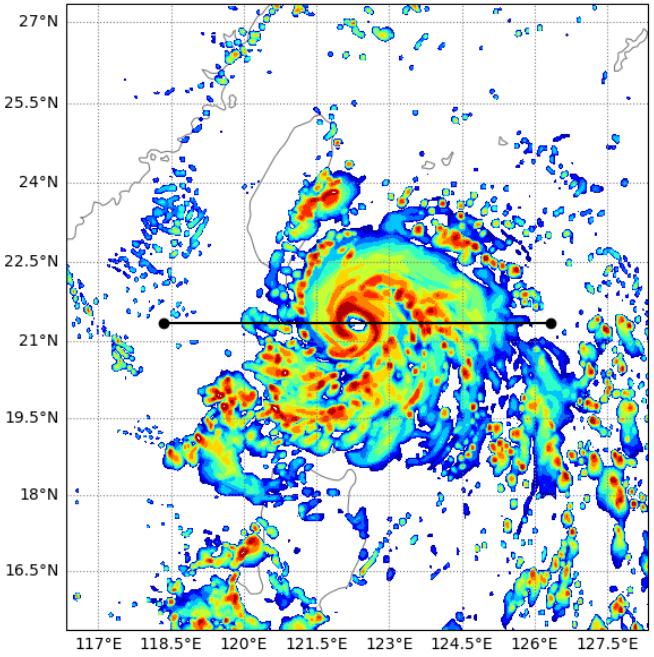
Wind (m/s) Hovmoller Diagram of the East Radii



White dashed line:
Real 30 knot Radii
Coral Dashed line:
Normal run 30 knot radii

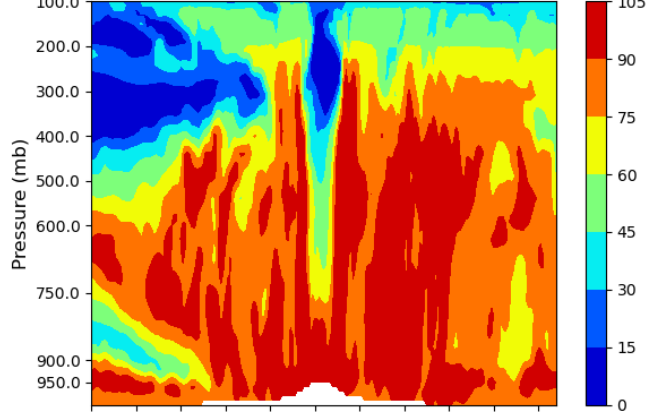
Black line:
Real max wind
Coral line:
Normal run max wind

Maximum Reflectivity (dBZ)

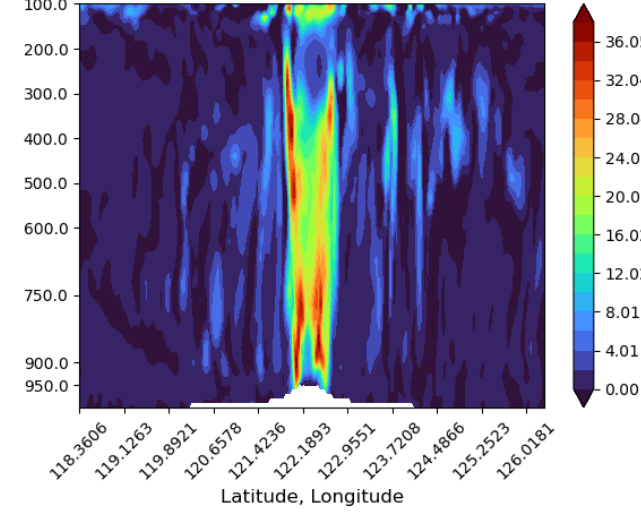


Plenty of outer rainbands!

Cross-Section of Relative Humidity

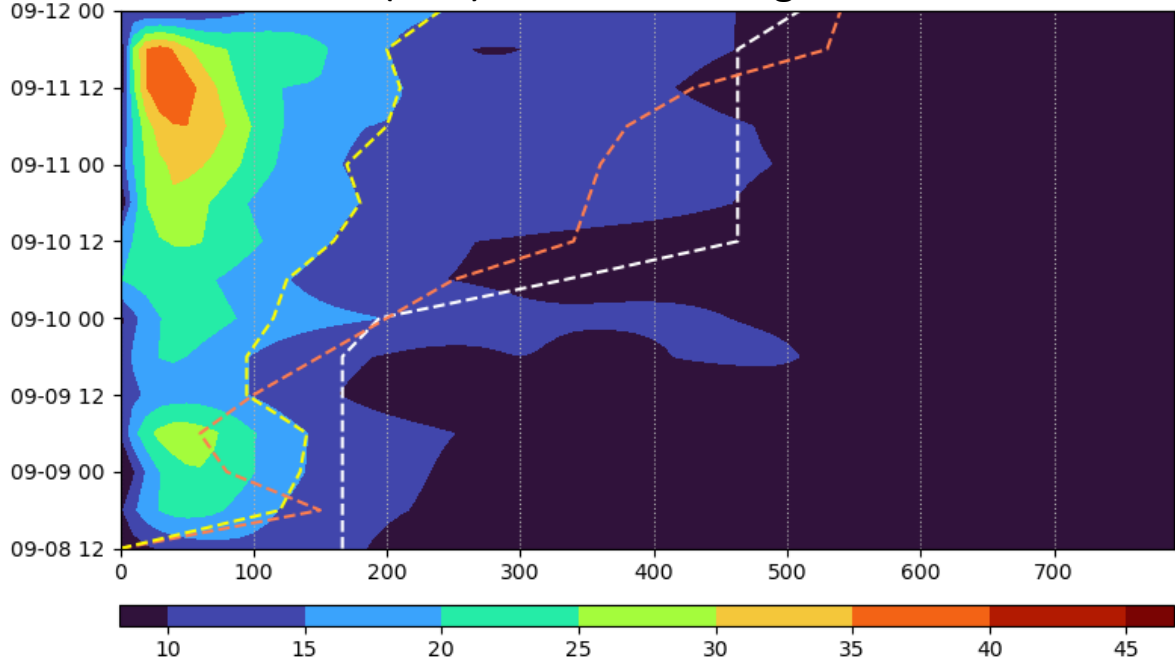


Cross-Section of Potential Vorticity (PVU)

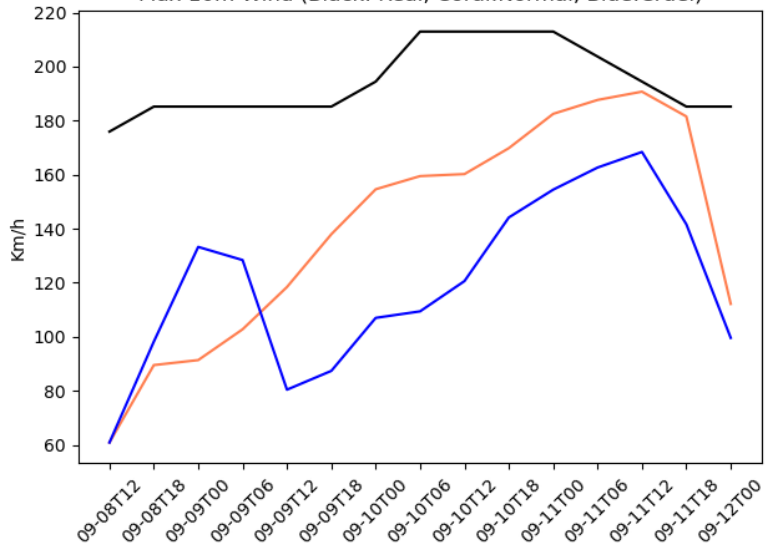


Model run (cruel run) results

Wind (m/s) Hovmoller Diagram of the East Radii



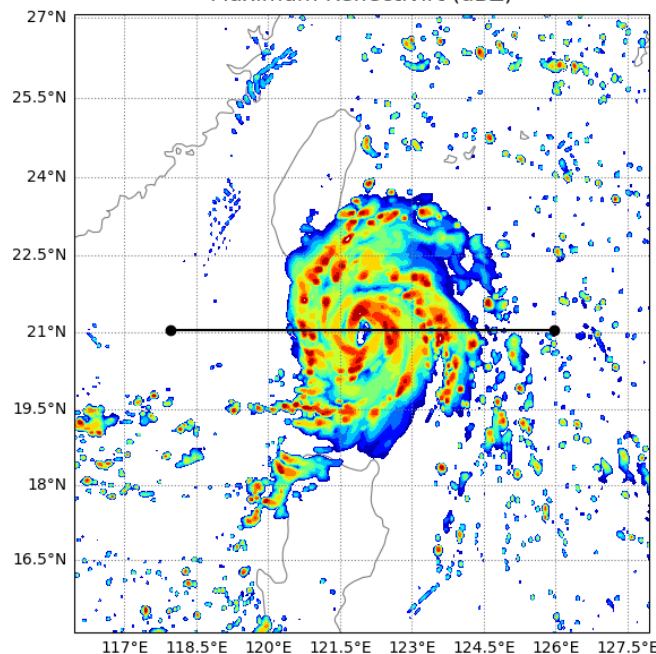
Max 10m Wind (Black: Real, Coral:Normal, Blue:Cruel)



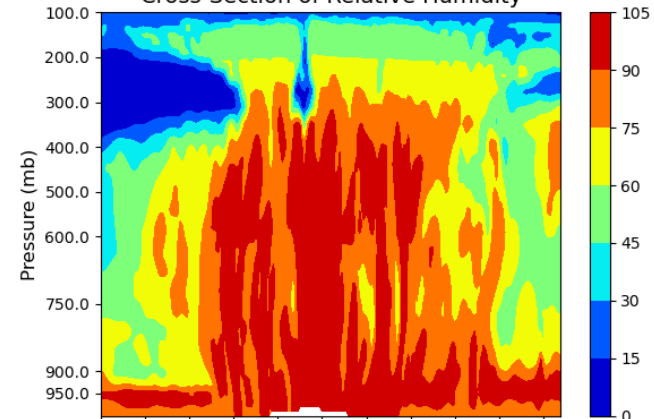
Yellow dashed line:
Estimated Cruel run
30 knot wind radii

Blue line:
Cruel run max wind

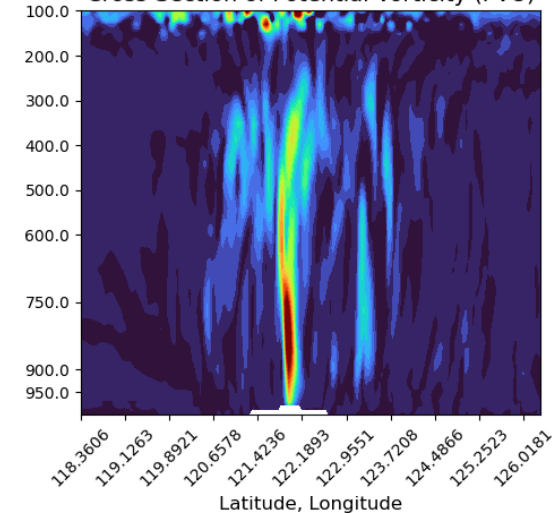
Maximum Reflectivity (dBZ)



Cross-Section of Relative Humidity

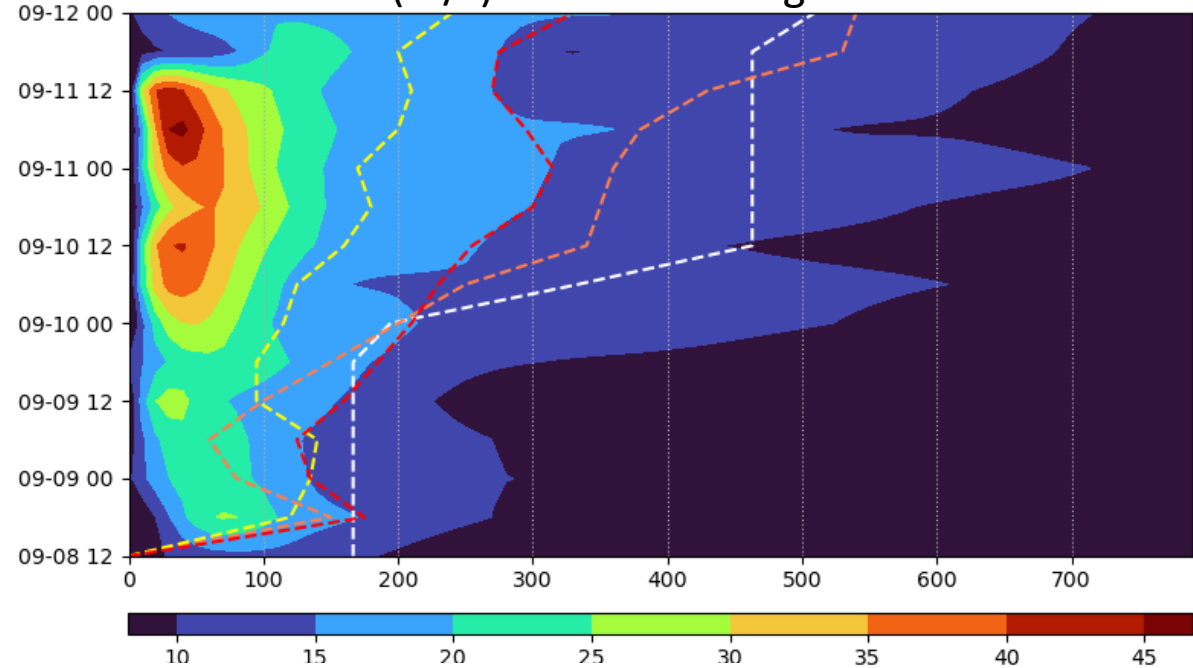


Cross-Section of Potential Vorticity (PVU)

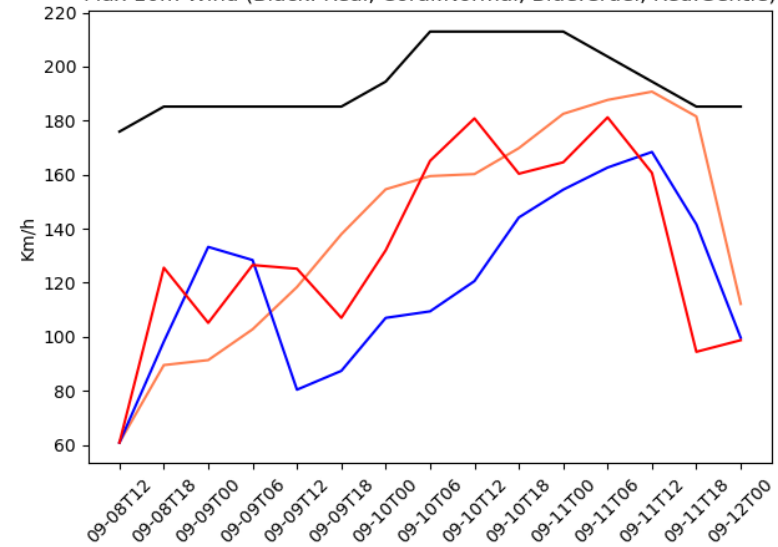


Model run (gentle run) results and comparison

Wind (m/s) Hovmoller Diagram of the East Radii

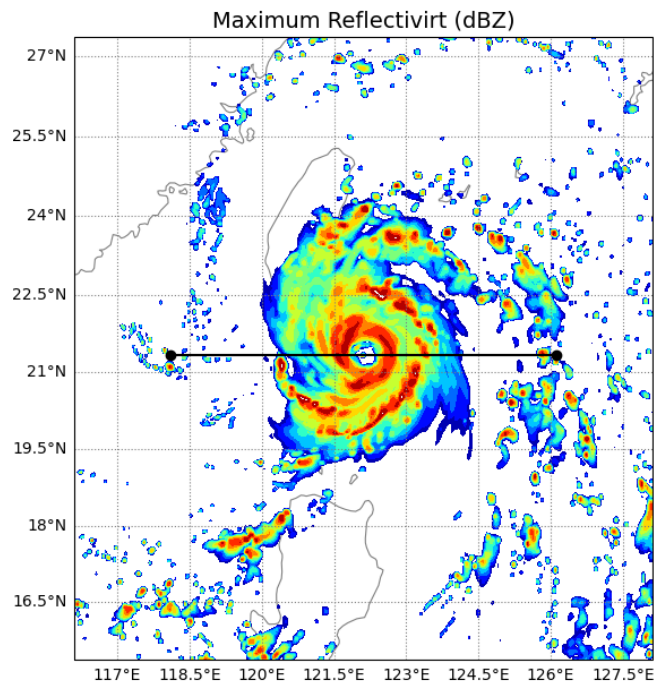


Max 10m Wind (Black: Real, Coral:Normal, Blue:Cruel, Red:Gentle)

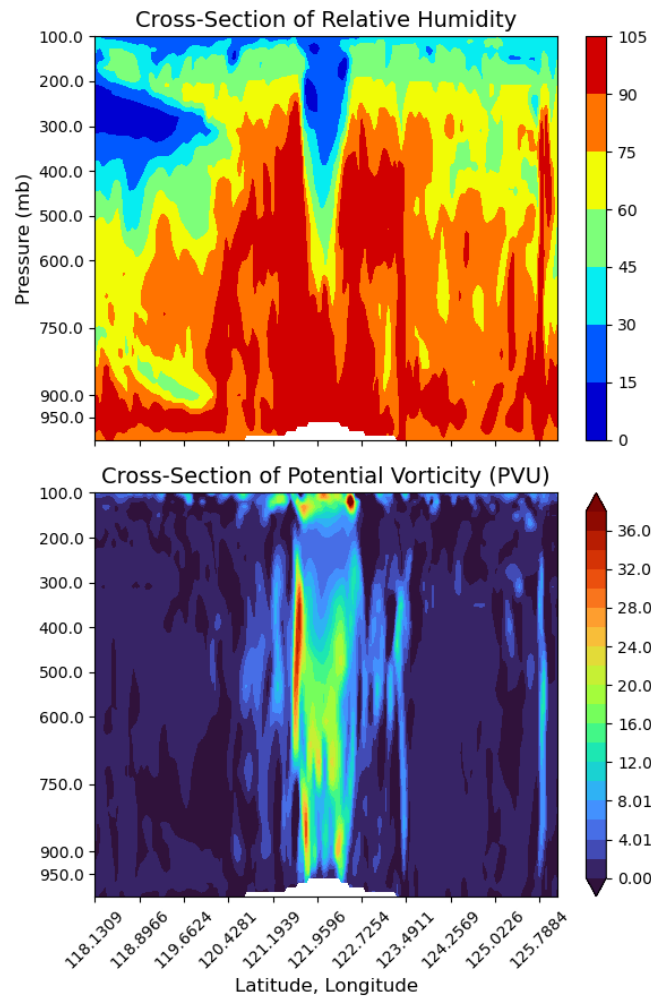


Red dashed line:
Estimated gentle run
30 knot wind radii

Red line:
Gentle run wind



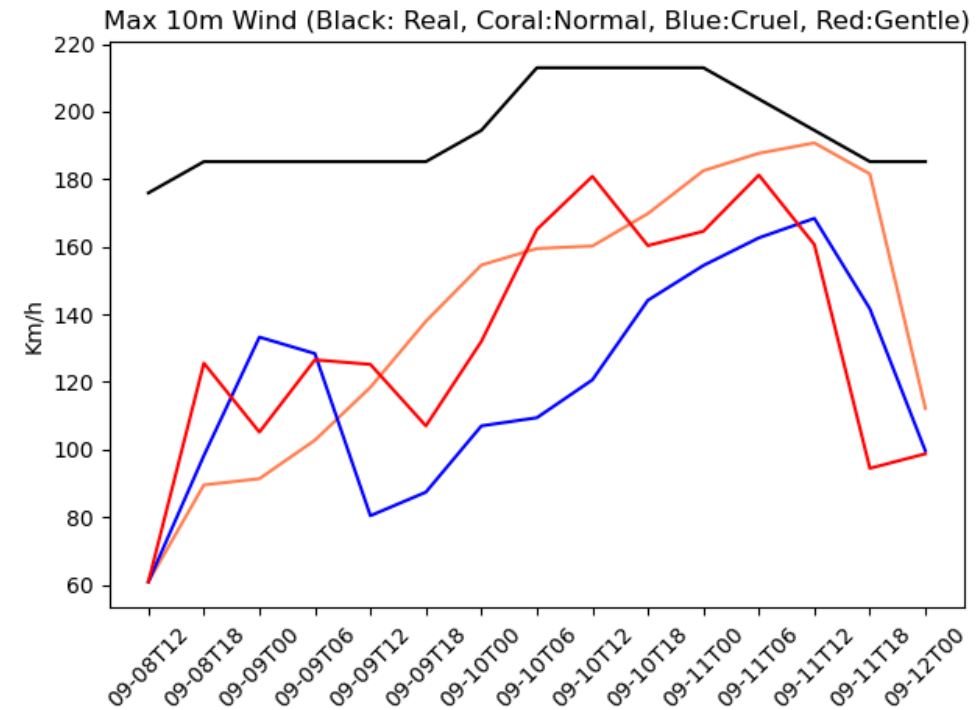
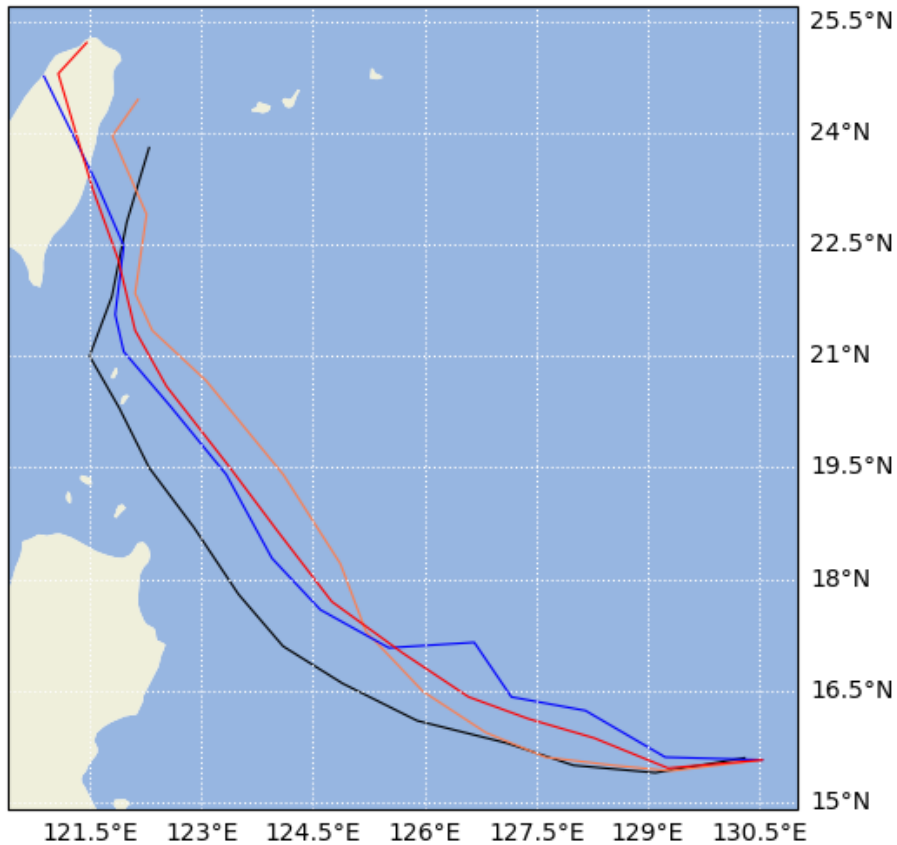
Wider eyewall,
narrower rainbands
compared to normal



- Normal run has the largest enlargement growth rate
- Cruel and gentle run has the similar growth rate despite gentle run's larger final size.
- Early-stage size growth might be sensitive to other systems nearby

More comparisons...

Tracks (Black:Real, Coral:Normal, Blue:Cruel, Red:Gentle)



- **10m maximum wind's** difference match the size's difference.
- Underestimation of ERA5 might cost additional spin-up time and lower peak intensity. So, winds generally grow with sizes.
- **Tracks** are generally in good agreement except for the last day, Cruel and gentle run hit land. Generally north shift (Fujiwhara effect?)
- The early-stage difference: it might be affected by the existence of the other two systems.
- RE- stage difference: Note that size and intensity can affect TC's movement. It Looks like the faster the RE, the north of the track.

Remarks

- The cruel run proves that a favorable environmental humidity is very important to TC growth in general, but we don't know to what extent.
- Despite unchanged initial PV field or slightly changed total available water vapor, the gentle run does not repeat the RE growth rate in the normal run, and its growth rate is nearly identical to the cruel run.
- Outer-PV is associated with TC's rainbands and additional circulations.
- Gentle run has the similar rainband width as in the cruel run but has the widest eyewall associated with wider inner-PV.
- Environmental RH in the boundary layer may not induce TC RE (But mid-level humidity does).
- The start-off stage's fields can also significantly alter the final result. In this case, the two other systems' intensities and locations.
- Recall those "vertical terms" in the PV budget equation: Vertical advection/divergence, Vertical cumulus mass flux convergence, Vertical differential of radiation...
- Infer that those "vertical terms" are as important, if not more, as the "horizontal terms".
- Which says, vertical structure of humidity can potentially affect the vertical structure of convection/precipitation, and distribution of clouds, which can in turn, determines the PV budget and the TC size growth.

Future work

- More cases to be examined. Due to the disturbances in the initial condition, Chanthu case might not be very straightforward. And to determine a threshold for “Rapid Enlargement” for case selection.
- How does RE affect TCs’ tracks?
- Full analysis of the wind radii
- Full analysis of each term in the PV budget equation, and determine the dominant factors contributing to TC RE (Both for inner eyewall expansion, and outer rainbands growth)
- Maybe consider running idealized cases.

Thank you! And citation...

- Chan, K. T., & Chan, J. C. (2016). Sensitivity of the simulation of tropical cyclone size to microphysics schemes. *Advances in Atmospheric Sciences*, 33, 1024-1035. Chan, K. T., & Chan, J. C. (2016). Sensitivity of the simulation of tropical cyclone size to microphysics schemes. *Advances in Atmospheric Sciences*, 33, 1024-1035.
- Hill, K. A., & Lackmann, G. M. (2009). Influence of environmental humidity on tropical cyclone size. *Monthly Weather Review*, 137(10), 3294-3315.
- Park, J., Cha, D. H., Lee, M. K., Moon, J., Hahm, S. J., Noh, K., ... & Bell, M. (2020). Impact of cloud microphysics schemes on tropical cyclone forecast over the western North Pacific. *Journal of Geophysical Research: Atmospheres*, 125(18), e2019JD032288.
- Stull, R. B. (2015). *Practical meteorology: an algebra-based survey of atmospheric science*. University of British Columbia.
- Yang, D. S., & Krishnamurti, T. N. (1981). Potential vorticity of monsoonal low-level flows. *Journal of Atmospheric Sciences*, 38(12), 2676-2695.
- Zhang, C., & Wang, Y. (2018). Why is the simulated climatology of tropical cyclones so sensitive to the choice of cumulus parameterization scheme in the WRF model?. *Climate Dynamics*, 51(9-10), 3613-3633.