Kelvin Waves and Tropical Cyclogenesis: Insights from MPAS Simulations of Tropical Storm Victor (2021)

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Background

What is known

- Tropical cyclone (TC) formation ("genesis") remains a formidable forecast challenge, and much is unknown about the process[1]
- Convectively-coupled Kelvin waves (CCKWs) have been shown to increase the likelihood of TC genesis[2,3,4]
- The direct link between CCKWs and mesoscale TC genesis processes is still unknown, may be due to environmental changes by CCKWs[2,3,5]

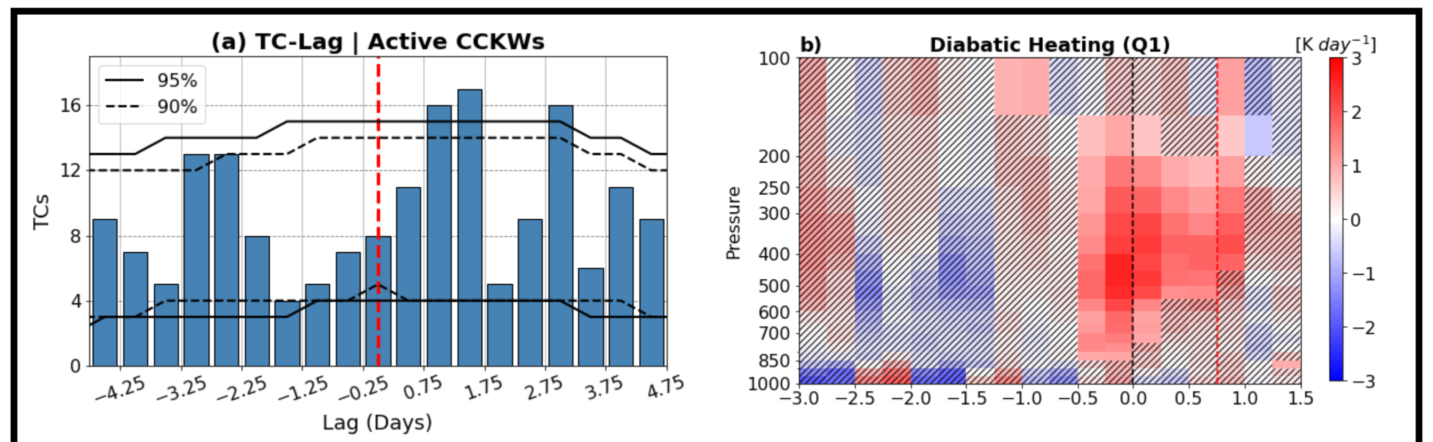


Figure 1: (a) Number of TC genesis events, binned in time relative to passing active CCKW phases (day 0). (b) Composite of apparent diabatic heating for 33 CCKW passages that resulted in TC genesis in the 0.75 – 1.75 day lag window. Day 0 is the time of CCKW passage.

In ERA5 data, Lawton et al. (2023, *in prep*)[4] find **an increase in TC genesis 0.75– 1.75 days** following active CCKWs, alongside **increases** in **moisture and convection**

Goals of MPAS Simulations

We utilize the Model for Prediction Across Scales – Atmosphere (MPAS-A) to simulate Tropical Storm Victor (2021) and investigate the following:

1. **The mesoscale and convective processes leading to genesis and potential connections to the active CCKW phase**
2. **A method to remove CCKWs and their impacts from a simulation**

Model Configuration and Methodology

Case Selection and Model Details

Tropical Storm Victor (2021)

- Tropical Storm Victor was a typical, if weak, TC genesis case in Eastern Atlantic
- Reanalysis indicates that Victor formed 0.75 to 1 day following active CCKW
- MPAS-A can realistically simulate CCKWs, especially with resolved convection[6,7]
- *Good opportunity to study CCKW-TC relationship and marginal TC genesis*

Simulations

- High resolution: 15km/3km, mesh shown on right
- Other controls: 15km uniform, 30km uniform (not shown here)
- CCKW removal: 30km uniform, CCKWs removed from initialization

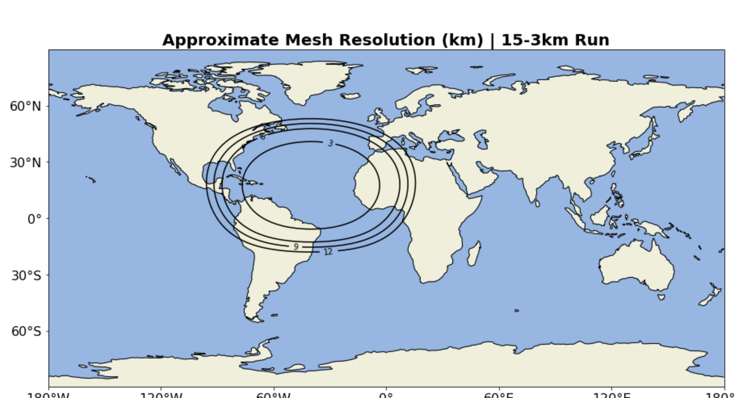


Figure 2: Approximate mesh resolution for the 15/3km MPAS simulation.

Simulation Settings

- All initialized on 9-24-2021 from ECMWF IFS data; allows CCKW evolution
- *Scale-aware* Tiedtke convective parameterization
- MPAS "mesoscale reference" with Thompson microphysics and MYNN BL

Wave and TC Identification

Tracking AEWs

- Use method and existing output of L22[6]; tracks using 700-hPa curvature vorticity

CCKWs

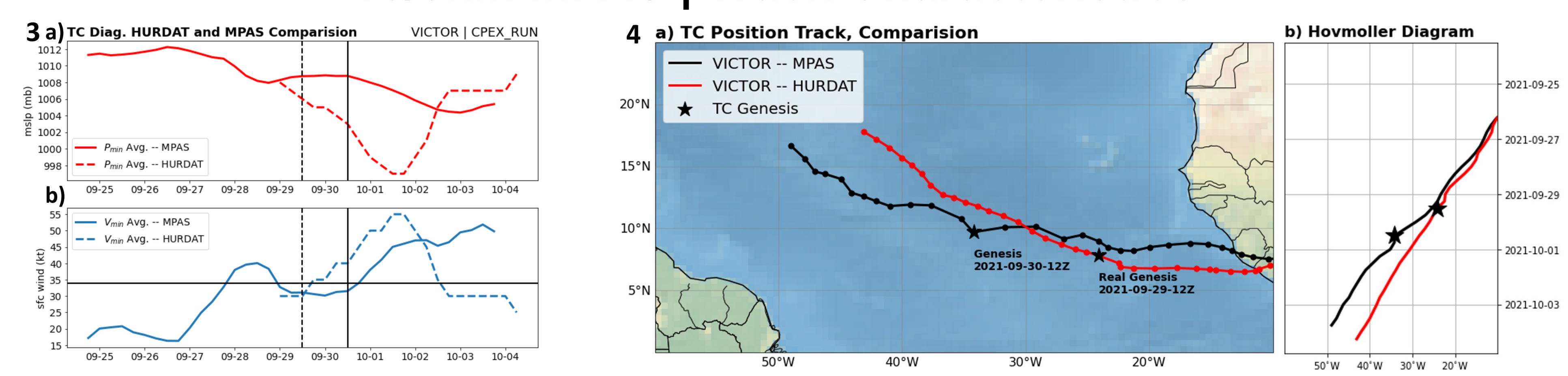
- WK99[8] Kelvin-Filtering: 1-14 wavenumber, 2.5-20 days, 8-90m equivalent depth
- Filtering combines ERA5 (wind fields) or GridSat-B1 data with MPAS output due to short simulation lengths, so could be some inherent spatiotemporal overlap

TC Genesis

- Algorithm looks for MSLP falls, closed contours for 24-hr; we confirm subjectively
- TC vortex tracked separately, combined with AEW track 24-hr pre-genesis

High Resolution Results (15/3km Simulation)

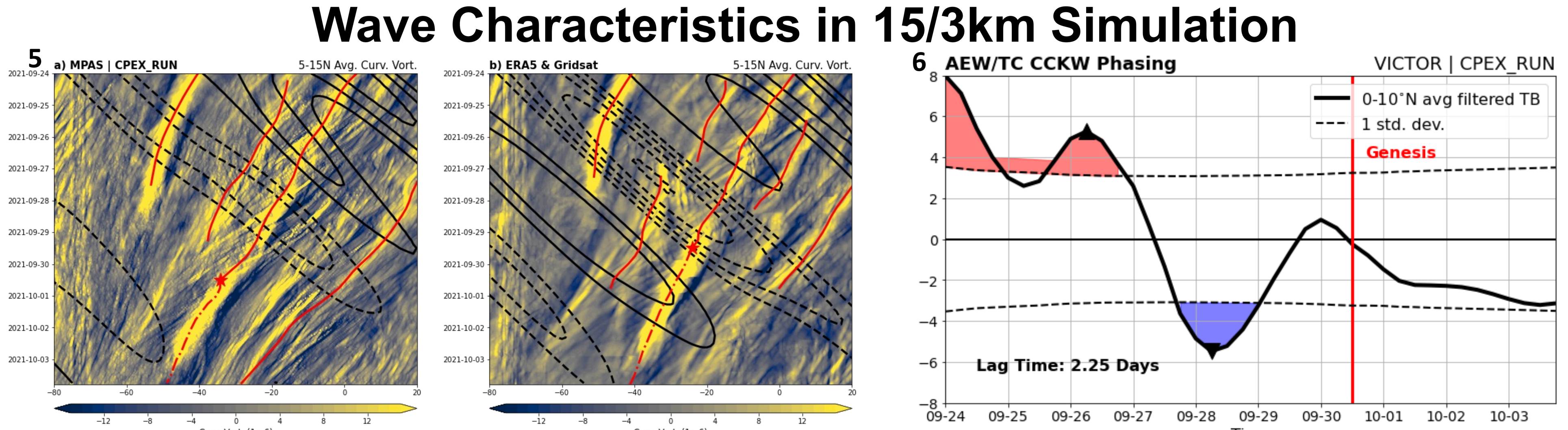
15/3km MPAS | Track Characteristics



Figures 3 and 4: (3a) Minimum pressure, compared between MPAS simulation (3-hourly rolling mean, solid) and HURDAT database (dashed). (3b) As in 3a but for maximum wind speed at 10m. Comparison of MPAS (black) and HURDAT (red) AEW and eventual TC track in longitude-latitude space (4a) and longitude-time space (4b).

- **Simulated TC genesis is determined to be at 9-30-21-12z;** 1 day later than and to the west of HURDAT
- Minimum pressure and maximum **wind speeds are less intense in MPAS simulation than in reality**
- Simulation **comes very close to brief TC genesis during active CCKW on 9-28**; could complicate interpretation

Wave Characteristics in 15/3km Simulation

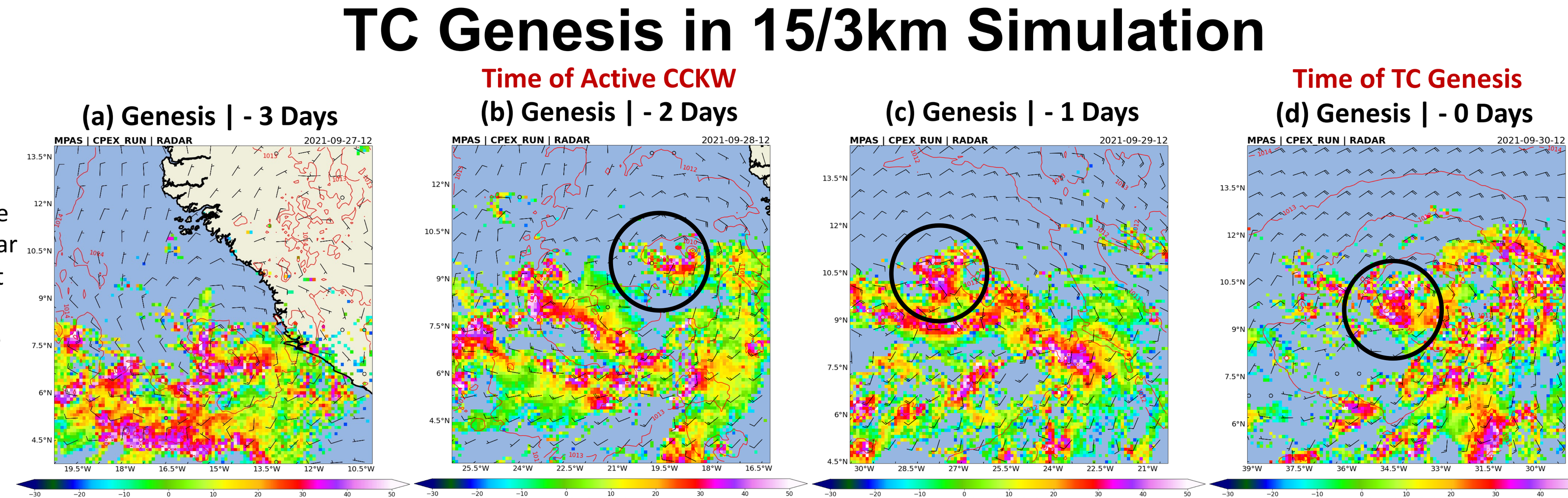


Figures 5 and 6: (5) Hovmöller diagrams showing 5-15°N average 700hPa curv. vort. (shading), Kelvin-filtered brightness temp. (T_b) contours (dashed negative, solid positive, std. dev. starting at 1 and 0.5 spacings), and overlain AEW (red) and TC genesis (dot-dash) tracks for MPAS (5a) run and ERA5/GridSat-B1 (5b). (6) 0-10°N average Kelvin-filtered T_b at tracked longitude of AEW/TC.

- 15km/3km MPAS simulates **a vigorous CCKW in both convective and dynamical fields**
- However, **CCKW is weaker in simulation than reality**, in both active and (mostly-absent) suppressed phase
- MPAS depicts **AEW strength and propagation similarly to ERA5**, but does have an accelerated pre-Victor AEW
- CCKW-TC genesis **lag time in MPAS is greater than ERA5/GridSat-B1**, partially due to delayed TC genesis

TC Genesis in 15/3km Simulation

Shading is the simulated radar reflectivity at 1km; **red contours** are MSLP; **wind barbs** are of 10m wind



Closed isobars and **surface circulation** at time of TC genesis; however, cyclone is asymmetric

Figure 7: Evolution of 1km reflectivity (shading), mean sea-level pressure (MSLP, contours), and 10m wind barbs in the 15-3km MPAS simulation following the pre-Victor AEW through TC genesis. The times are (a) 12z on 9-27-21, (b) 12z on 9-28-21, (c) 12z on 9-29-21, and (d) 12z on 9-30-21. The CCKW passage occurring around panel (b).

- As AEW moves off Africa, there is offshore propagating squall and other convection south of the AEW trough
- Beginning two days prior to genesis, a prominent **mesoscale convective vortex (MCV; black circle) rotates around the AEW trough** and becomes the center of the incipient TC vortex
- **Convective activity** at and north of the AEW trough appears **to increase at time of the CCKW passage;** this can be seen visually in Fig. 7 and in the Fig. 8a convective coverage diagram

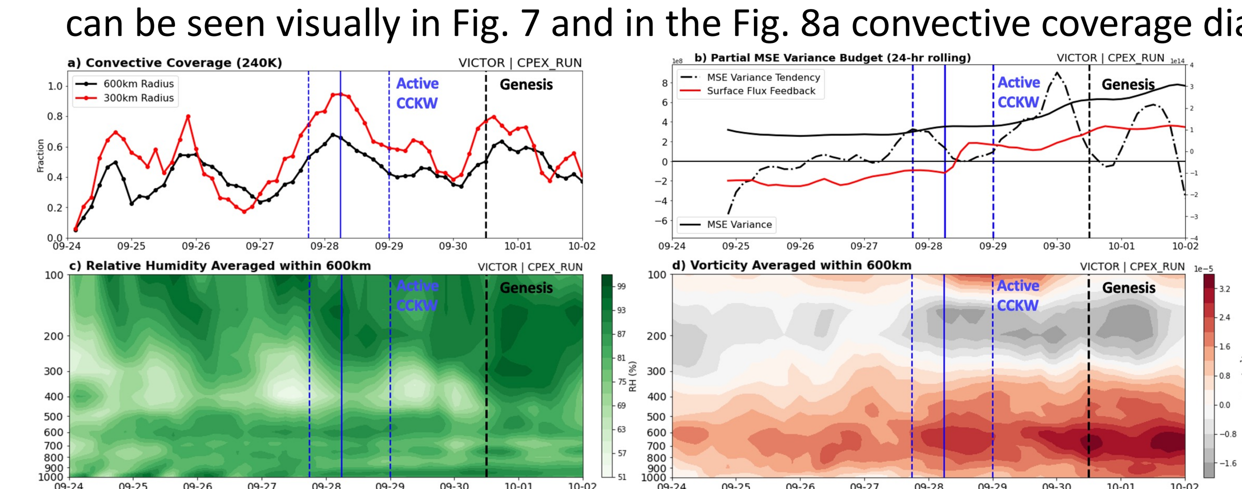


Figure 8: Evolution of area-computed fields surrounding the AEW/TC in the MPAS simulation of Victor. (a) is convective coverage (%), (b) shows a partial moist static energy (MSE) budget, (c) is relative humidity, and (d) is relative vorticity.

- ML RH, LL cyclonic vorticity, and UL anticyclonic vorticity **increase *temporarily* at time of CCKW**
- **Matches literature[6]**; but failed early TC genesis (Fig. 3) is confounder
- Partial MSE variance budget shows **increased convective aggregation** (MSE variance) and **surface flux feedbacks** during TC genesis

CCKW Removal (30km Simulation)

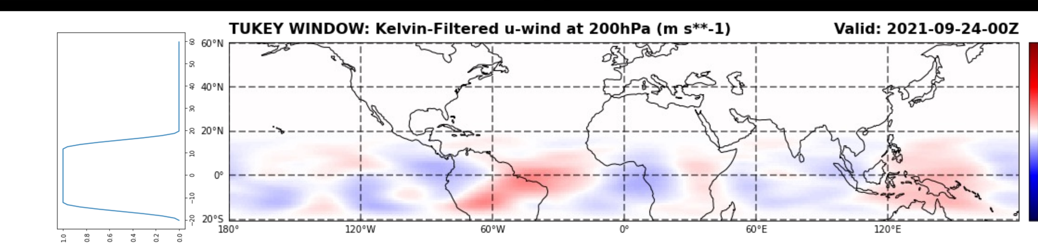


Figure 9: Retained 200hPa u-wind at initialization after application of Kelvin filtering and Tukey window.

CCKW Removal Process

- Filter one month of IFS wind data (u,v; all model levels) *prior to model initialization* in the Kelvin-band using the WK99 technique
- Kelvin-filtered wind is then subtracted out from original IFS data at initialization time, but only within a 20°S – 20°N Tukey window (Fig. 9) to confine to tropics
- New simulation (30km) is initialized with this new IFS data

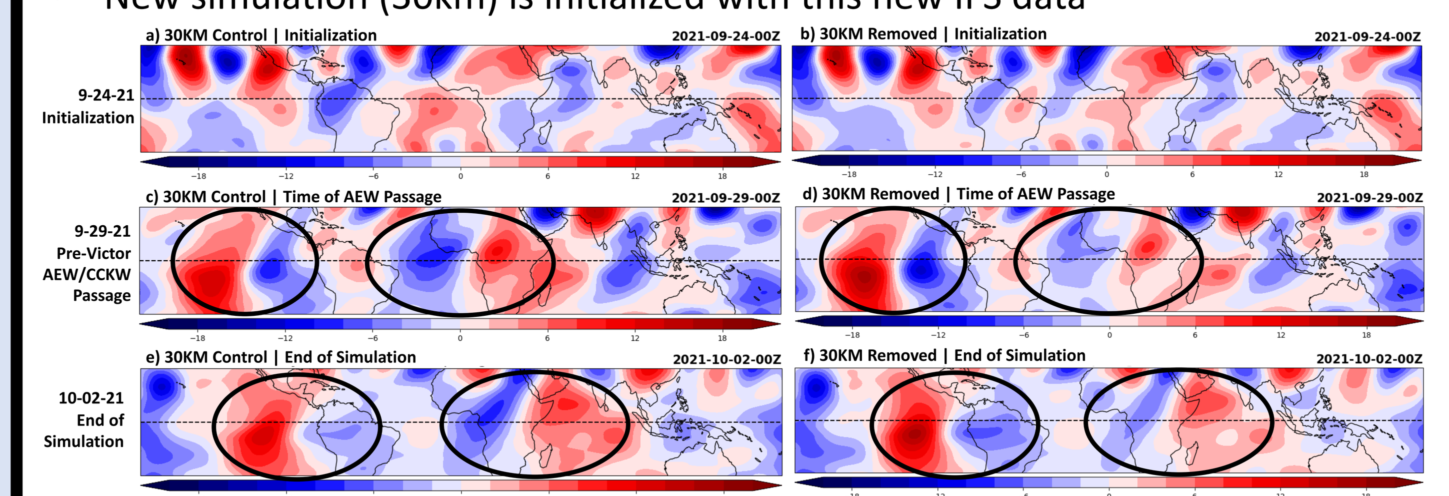


Figure 10: Progression of Kelvin-filtered, 200hPa velocity potential (VP) for the 30km control (left column) and the CCKW removed simulations (right column). Chosen times correspond to initialization (a-b), AEW-CCKW passage (c-d), and the end of the runs (e-f).

Results | Control versus CCKW removal (30km uniform)

- Filtering shown above uses the *CCKW-removed IFS data* (not original IFS or ERA5) with model results appended; resulting signals should be due to the growth of Kelvin-band disturbances and *not* overlap from previous data
- **CCKW of interest is significantly weaker** in the removed simulation, but not gone entirely
- However, **a Pacific CCKW** develops and **is stronger** in the CCKW-removed simulation!
- One possibility: removing CCKWs from the initialization will not prevent their growth in model, so the **stronger Pacific CCKW** could be **compensating** for the **weaker Atlantic CCKW**
- Some support for this, as **Hadley cell** is generally similar between both (within 4%)

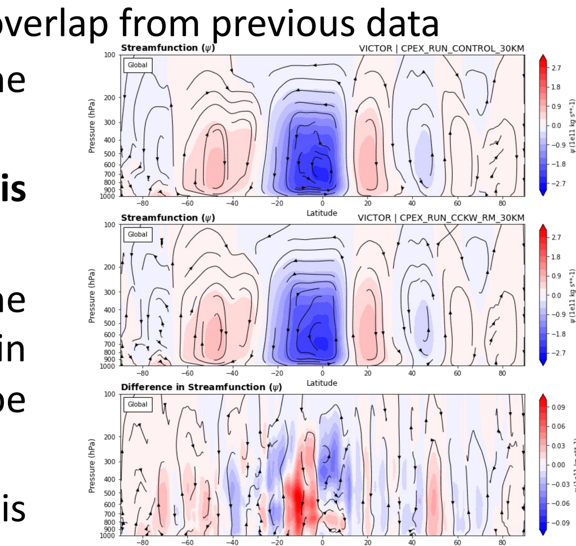


Figure 11: Global stream function: top is control, middle is CCKW-removed, bottom is middle – top.

Conclusions and Future Work

Summary

- High resolution (15/3km) MPAS simulation depicted a mostly accurate CCKW, closer to reality than lower resolution simulations (30km, 15km; not shown)
- Timing and progression of environmental changes prior to TC genesis matches previous studies on CCKWs and AEWs/TCs
- CCKW removal worked *decently*, but could not prevent the growth of CCKW-band disturbances after initialization

Future Work

- Expand analysis of convective processes pre-TC genesis; mass flux profiles, etc.
- High-resolution simulations with CCKW-removed -- what happens to TCs?

References and Acknowledgments

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