Why are Tropical Cyclones so Weak in Canadian NWP?

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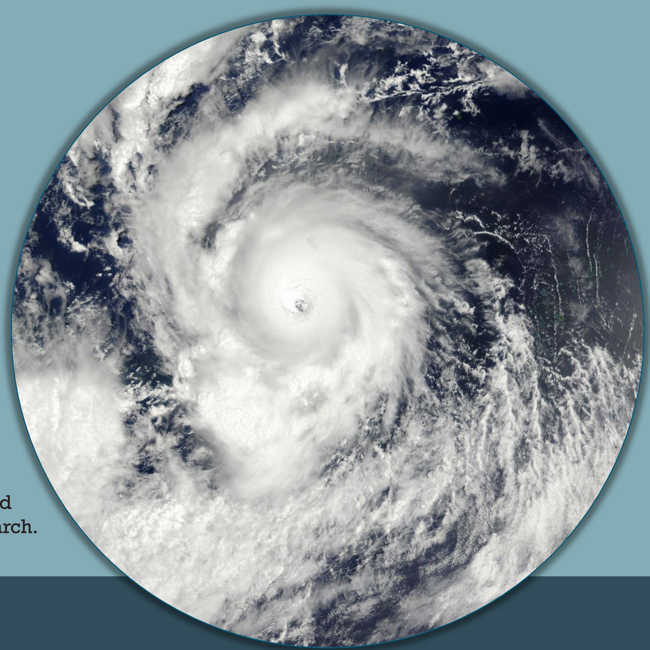

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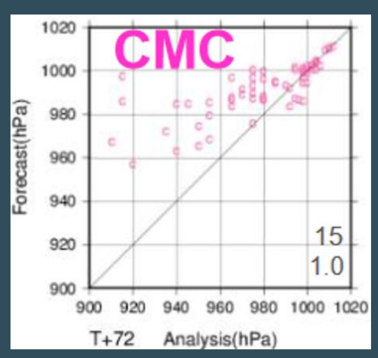
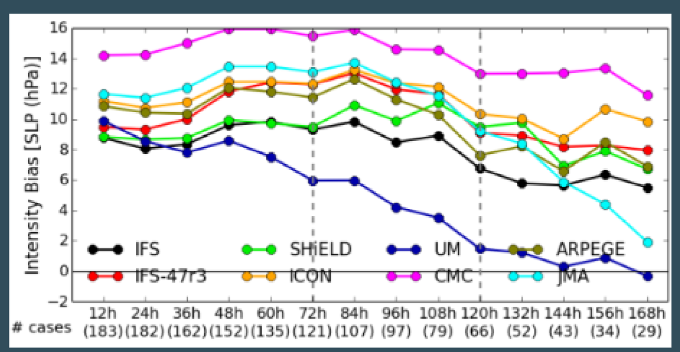
Background

The Canadian Global Environmental Multiscale (GEM; Girard et al. 2014) model suffers from a weak-intensity bias for tropical cyclones (TCs), despite a recent upgrade to the physics of the global NWP system that reduced false alarms (McTaggart-Cowan et al. 2019). This bias is evident in routine verification, annual TC reports to WGNE and the DIMOSIC project (Magnusson et al. 2022).



Central pressure forecast vs. best track scatter plot for 72 h West Pacific in 2020 (Hiroaki and Masashi 2021).



Central pressure bias wrt best track for TCs in global NWP systems (GEM: pink) participating in DIMOSIC (Chen 2022).

This systematic error was assumed to be related to the relatively coarse resolution of the global forecast system; however, there was no improvement with the transition from 25 km to 15 km grid spacing…

Experimental Design

An idealized TC test case is constructed to reduce the dimensionality of the problem:

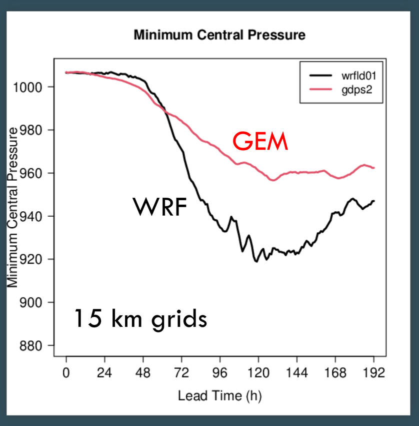
- Jordan tropical sounding with a ~28°C SST aqua-channel (based on Nolan 2011)
- Balanced weak (<5 ms^{-1}) westerly shear on an f-plane at 20°N
- Initially dry axisymmetric vortex with a ~10 ms^{-1} near-surface circulation

The initial perturbation develops into a TC in an environment with a potential intensity (Emanuel 1988) of ~900 hPa and 75 ms^{-1}. The dominant processes involved are adiabatic dynamics (dynamical core), boundary layer turbulence, and condensation (grid-scale and convective parameterization in the 15-km configuration).

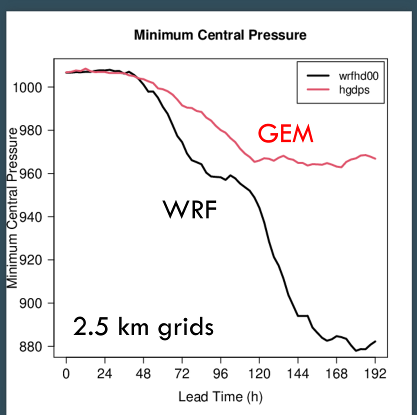
A set of WRF simulations are used as references because of the system's proven ability to accurately depict TC intensity and structure. WRF simulations use only the parameterizations for relevant processes, while GEM tests use various configurations.

Reproducing the Systematic Error

In the 15-km GEM configuration (equivalent of the operational Global NWP system), the TC never undergoes rapid intensification and reaches only a 957 hPa central pressure. Winds are equally weak, barely exceeding 40 ms^{-1} (Category-1 hurricane). This is entirely consistent with the documented weak-TC bias.



Central pressure evolution in 15-km simulations from WRF (black) and GEM (red).



Central pressure evolution in 2.5-km simulations from WRF (black) and GEM (red).

The results from the baseline 2.5 km convection-permitting integrations are more surprising. The WRF simulation generates a very intense TC with a central pressure <890 hPa and winds >85 ms^{-1}. The TC in GEM is **weaker** in the high-resolution simulation than in the 15 km configuration: minimum central pressure >960 hPa although winds peak near 50 ms^{-1}.

Increasing Resolution will **not** fix the weak-TC error.

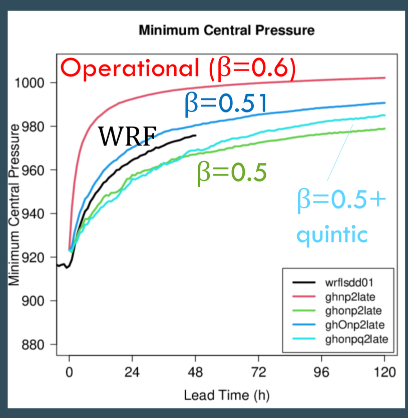
A large set of tests have been run to identify leading-order sensitivities to the representation of relevant physical processes, **all with little effect**:

- **Surface exchanges**: adjustment of the Charnock-based roughness estimate, elimination of surface layer stability functions for the near-neutral TC case, implementation of WRF roughness length, explicit flux application in atmosphere
- **Boundary layer turbulence**: changes to mixing length estimate, adoption of an alternate boundary layer scheme, removal of boundary layer stability functions, implementation of WRF (YSU) boundary layer scheme
- **Condensation**: replacement of operational condensation scheme with the P3 microphysics scheme, application of conservation corrections, implementation of Kessler-type warm rain scheme

Assessing the Model's "Dissipation"

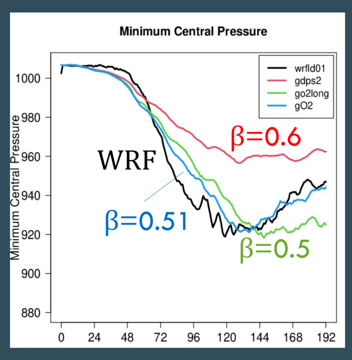
The numerics of the dynamical core may be "dissipating" variance and reducing kinetic energy. However, it cannot be isolated using the standard initialization because no TC develops without physical forcings. Instead, a dynamics-only configuration is initialized with the 144h WRF forecast, so that the strong TC spins down through:

- Vertical realignment of the vortex in the sheared flow
- Internal dynamical processes (e.g. vortex Rossby waves)
- **The effects of numerical dissipation**



The operational GEM configuration is much more dissipative than the WRF reference. Removing off-centering (β=0.5) in the semi-Lagrangian scheme dramatically reduces spin-down (Reed and Jablonowski 2012), with a value of β=0.51 producing a decay rate that closely matches WRF. The idealized TC and full-system tests confirm intensification.

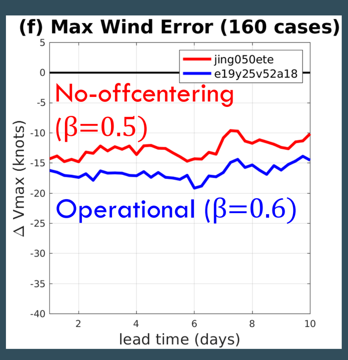
Central pressure spin-down evolution in 15 km simulations as annotated.



Central pressure evolution in 15 km simulations as annotated.

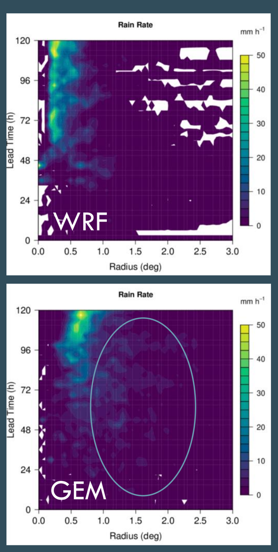
But removing off-centering dissipation only increases intensity at 15 km – not 2.5 km

Wind speed bias for 2019 Northern Hemisphere tropical cyclones in the global model.

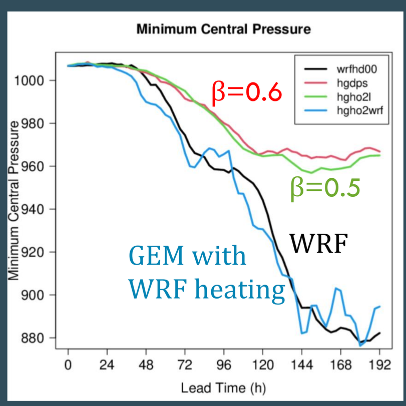


Possible Impacts of Physics Coupling

Rainfall rates in the 2.5 km GEM simulation are as large as those of WRF, indication that sufficient diabatic heating is available to the system. However, heating in WRF occurs inside the radius of maximum wind where it can effectively reduce the TC scale and increase angular momentum in the eyewall.



Hovmoller diagrams of azimuthally averaged rainfall rates in WRF (top) and GEM (bottom) 2.5 km integrations.



Central pressure evolution in 2.5 km integrations configured as described in the annotations.

A GEM simulation constrained using WRF heating rates in a storm-relative coordinate shows that GEM can represent the primary circulation given well-structured heating.

Despite sufficient heating in the 2.5 km GEM simulations, poor structure seems to limit TC intensity

Conclusions

What we know

- TCs in GEM are weak
- Sensitivity to physics is limited
- Off-centering should be minimized
- Results at 15 km are promising

What we think we know

- A problem beyond off-centering affects the 2.5 km model
- Heating is not structured for deepening
- Possible relation to vertical motion response to heating

What we know we don't know (yet)

- How to determine whether the dynamics responds correctly to heating
- **How to fix the 2.5 km system!**

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