REDUCING A TROPICAL CYCLONE WEAK-INTENSITY BIAS IN A GLOBAL NWP SYSTEM

Ron McTaggart-Cowan, David S. Nolan, Rabah Aider, Martin Charron, Jan-Huey Chen, Jean-François Cossette, Stéphane Gaudreault, Syed Husain, Linus Magnusson, Abdessamad Qaddouri, Leo Separovic, Christopher Subich and Jing Yang

Hurricane Milton as seen from the ISS at 1340 UTC 8 October 2024 (NASA JSC, ISS)

OUTLINE

- **Weak TCs in Canadian guidance:** comparison to forecasts from other global producing centres reveals a weak-intensity bias
- **Hierarchy of models:** dimensionality reduction allows us to focus our diagnostic efforts on individual components of the global system
- **Root cause analysis:** source of the weak-intensity bias is identified as a numerical misalignment of the pressure gradient force vector
- **Solution:** significant reduction in off-centering of the time-stepping scheme yields numerical dissipation that resembles the WRF reference
- **Conclusion:** importance of model hierarchy and dry dynamics for TCs

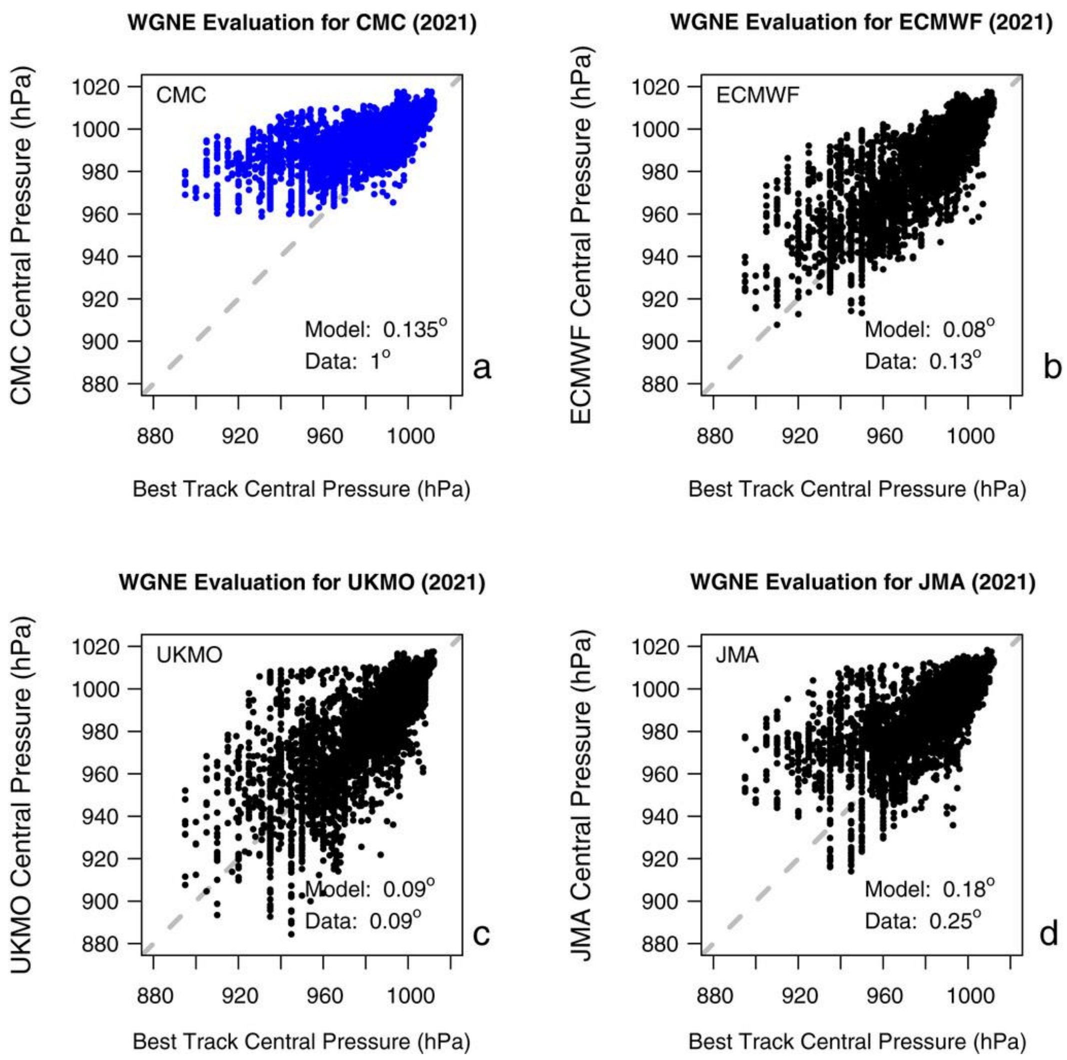
WEAK TC INTENSITY IN GLOBAL PREDICTIONS

The Japan Meteorological Agency does annual tropical cyclone evaluation (Yamaguchi et al. 2017) for the WMO's Working Group on Numerical Experimentation (WGNE).

Predicted TCs from the Canadian Meteorological Centre (CMC) global model (GDPS) rarely have central pressures below 960 hPa:

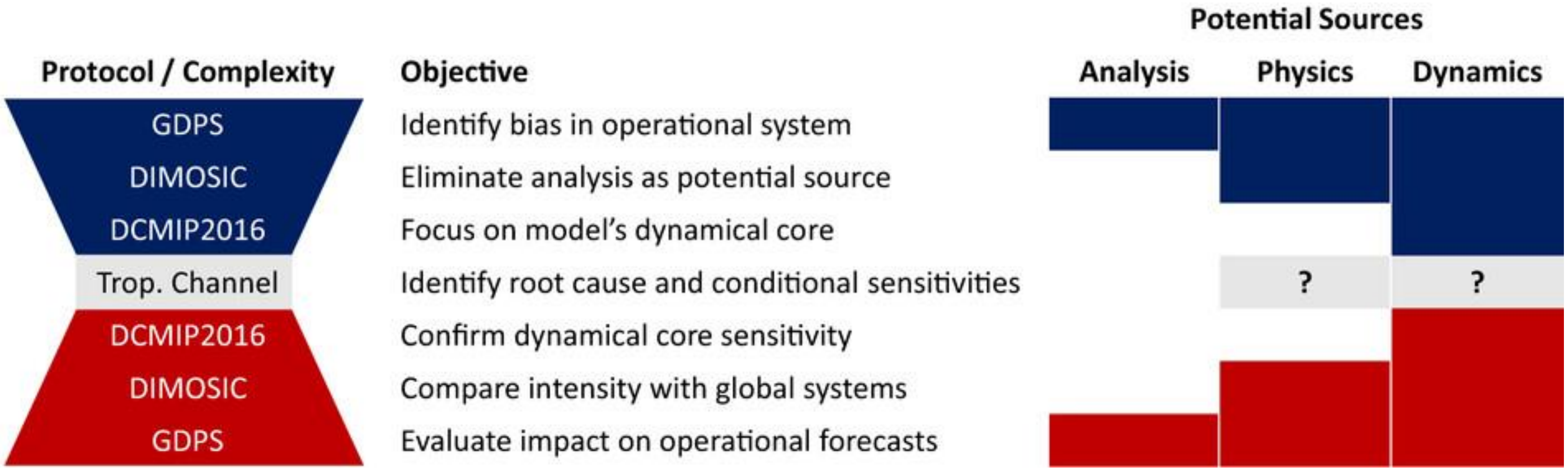
- CMC data are retrieved on a 1° grid
- Consistent with internal CMC evaluations

With 15 km grid spacing, the GDPS should be able to better represent TC intensity (Davis 2018).



Observed (x-axis) and forecast (y-axis) central pressures for 2021 tropical cyclone 72-h forecasts in global NWP systems as identified in the panels (courtesy of Masashi Ujiie).

HIERARCHY OF MODELS



A hierarchical system development approach employs a set of experimental protocols with differing levels of complexity (Frassoni et al. 2023).

Each protocol allows us so narrow down potential sources of error within the highly complex global analysis and prediction system.

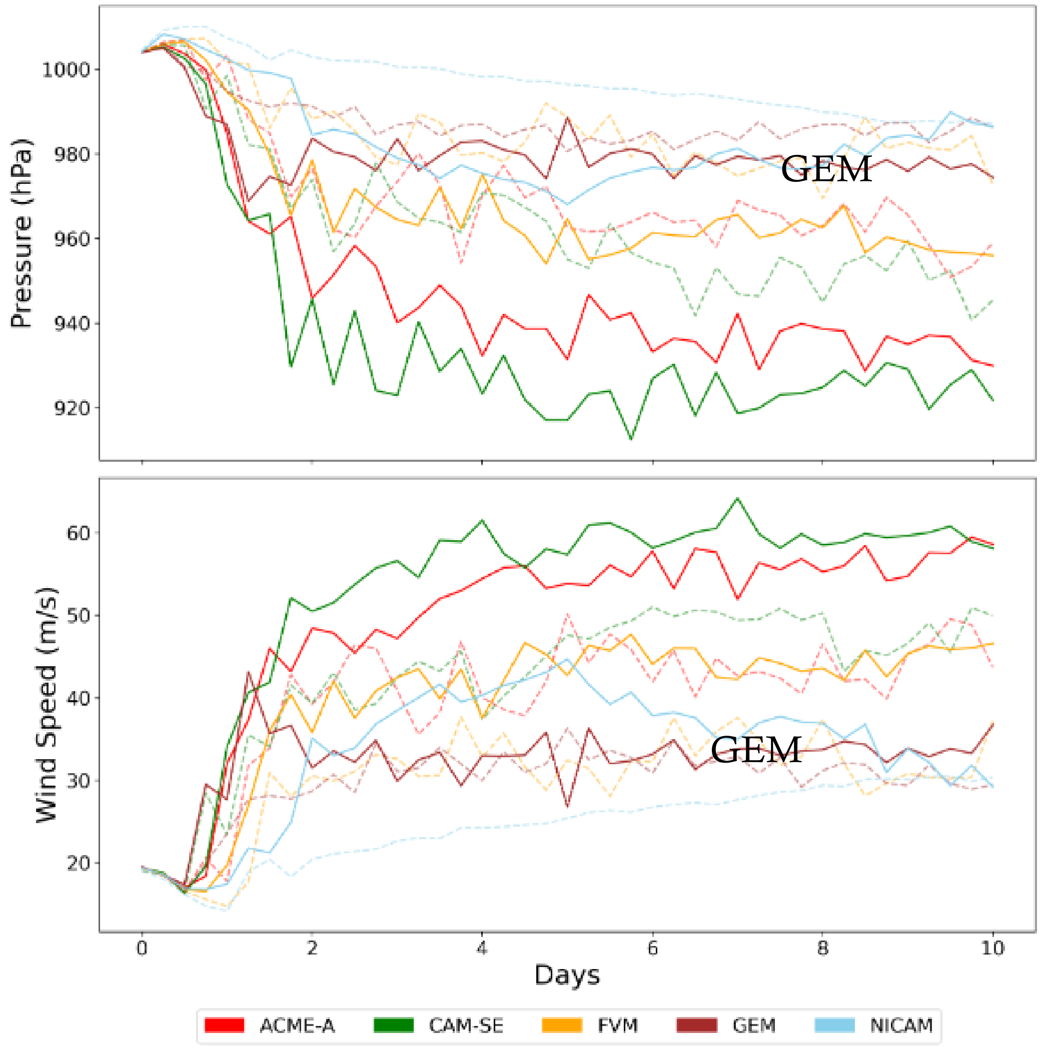
THE DCMIP PROTOCOL

The Dynamical Core Model Intercomparison Project (DCMIP2016) includes a semi-idealized tropical cyclone test case with simplified physics (Reed and Jablonowski 2012; RJ12).

The range of solutions is surprisingly large.

The Canadian Global Environmental Multiscale (GEM) dycore has a weak bias consistent with operational GDPS guidance.

RJ12 hypothesize that semi-Lagrangian interpolation and “decentering” **may reduce intensity in models like GEM**.



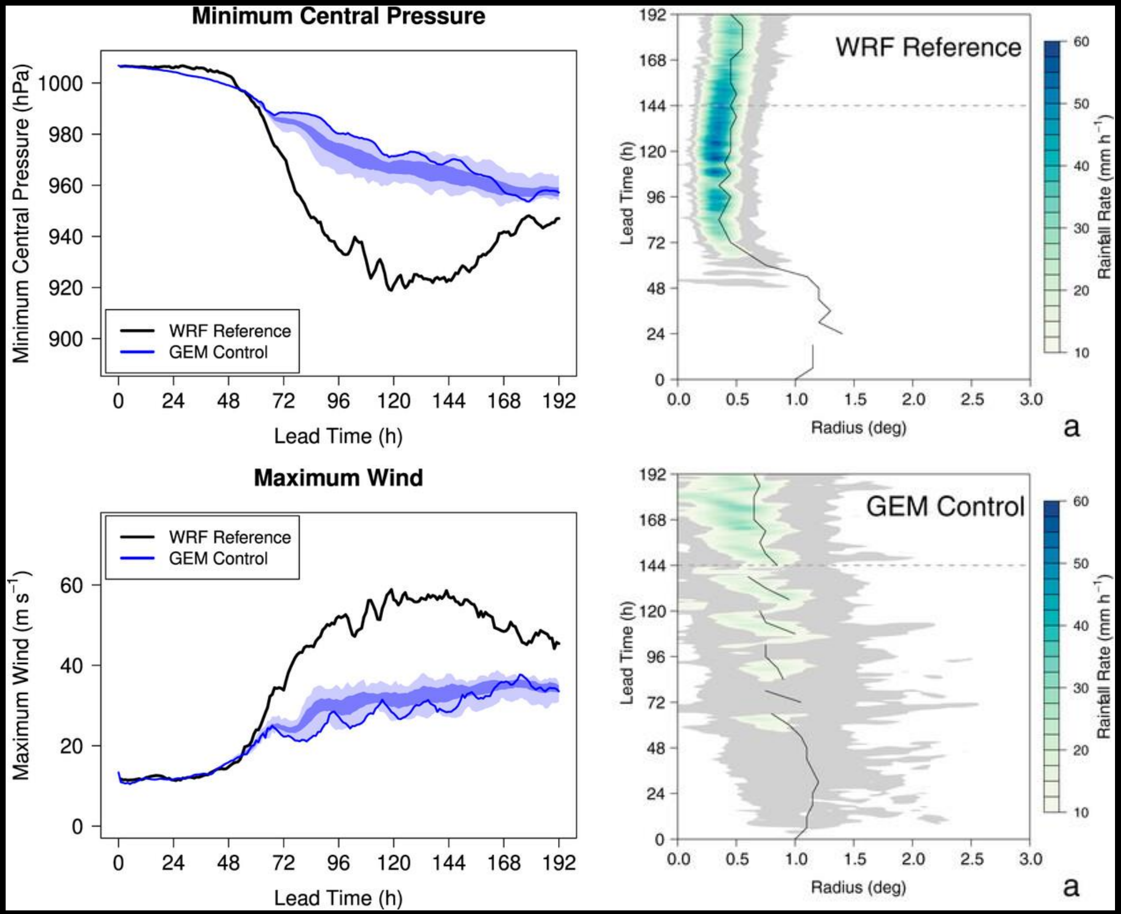
Central pressure (top) and maximum near-surface wind speed (bottom) in 50-km (dashed) and 25-km (solid) configurations (Willson and Coauthors 2024).

A SEMI-IDEALIZED TC TEST CASE

The Nolan (2011) tropical channel configuration initialized with a weak vortex but potential intensity of 75 ms^{-1} (900 hPa)

A 15-km WRF Reference simulation builds to a strong TC, while the GEM Control barely reaches Category-1 intensity.

Weak convection inside the eyewall fails to build intensity and contraction in GEM, with repeated eyewall replacements starving the core of high-θ_e inflow.

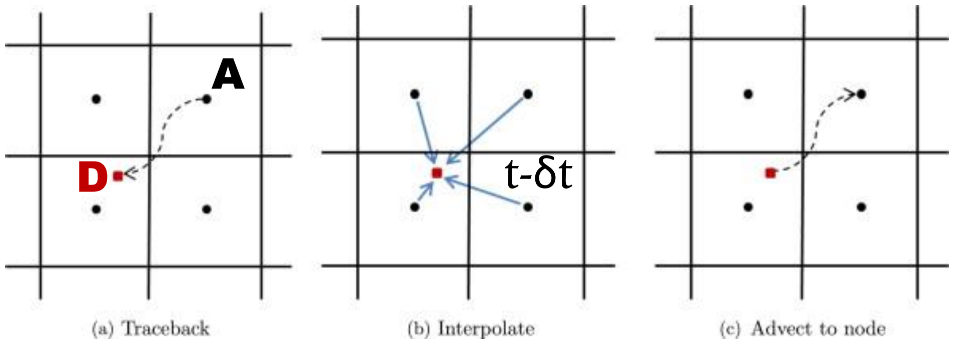


Central pressure (top-left) and wind speed (bottom-left) in the WRF Reference and GEM Control as labelled. The right-hand column shows azimuthal mean rainfall rate (shaded) and radius of maximum wind (RMW; black line).

TIME INTEGRATION IN GEM

GEM uses iterative implicit time stepping with semi-Lagrangian advection to advance the primitive equations.

This technique has been adopted by other centres because it is stable for long time steps: ECMWF, Met Office, Meteo-France, CMA etc (Bennachio and Wood 2016).



Schematic of semi-Lagrangian advection (Verma et al. 2014).

The governing equations for variable F_i can be expressed through forcings G_i,

$$\frac{dF_i}{dt} + G_i = 0$$

which can be discretized in time and space,

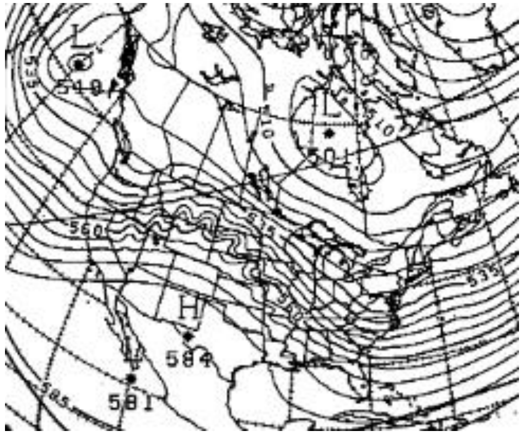
$$\frac{F_i^A - F_i^D}{\delta t} + bG_i^A + (1-b)G_i^D = 0$$

to compute the tendency of F_i between the departure (D, t-δt) and arrival (A, t) points.

Here b is a numerical “off-centering” parameter that maintains Crank-Nicholson second-order accuracy for b=0.5 (centered).

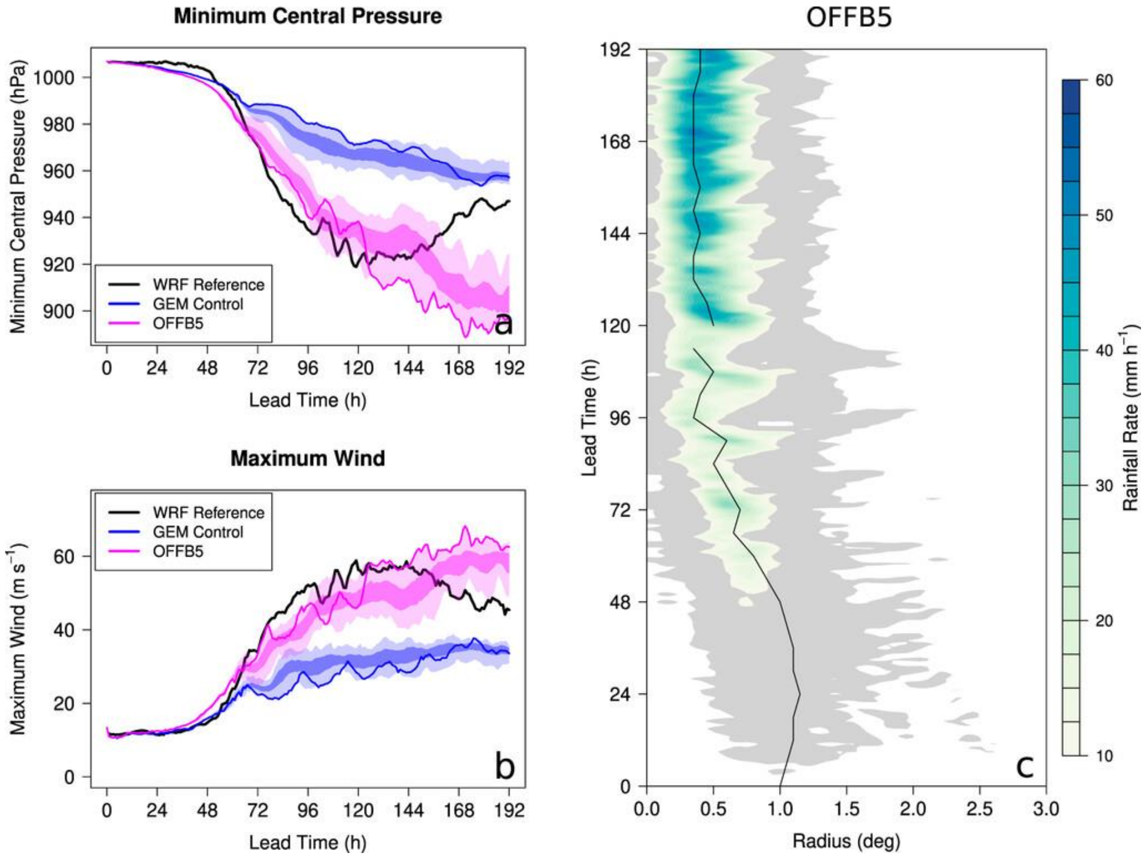
SENSITIVITY TO MODEL DYNAMICS

All operational GEM configurations use b=0.6, favouring the implicit solution to eliminate "orographic resonance".



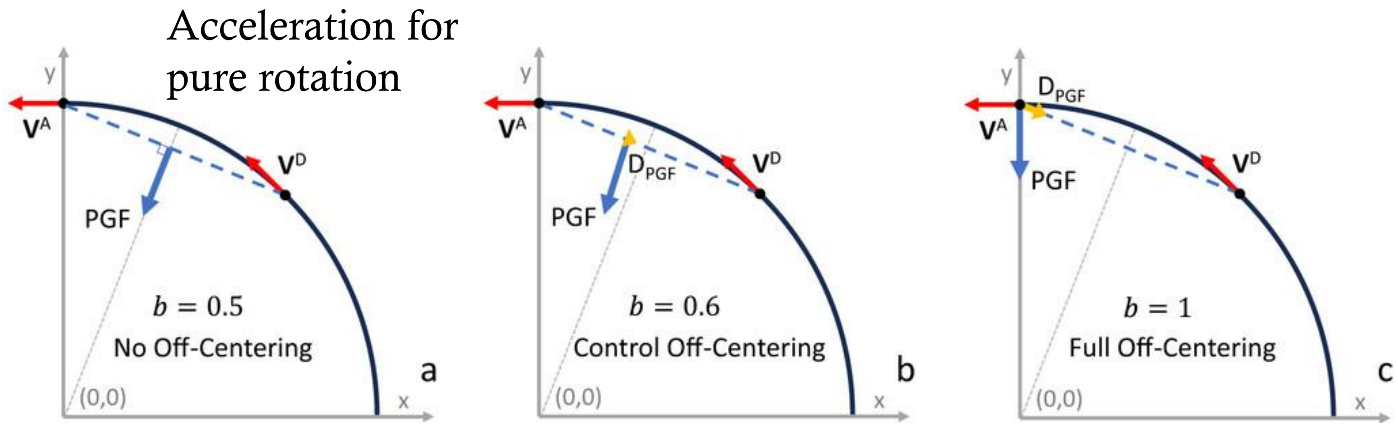
North American 500 hPa heights in a 48 h forecast valid at 1200 UTC 14 February 1979 (Rivest et al. 1994).

The impact of removing off-centering (b=0.5) on the TC is enormous.



Central pressure (top-left) and wind speed (bottom-left) in the WRF Reference and GEM simulations as labelled. The right-hand column shows azimuthal mean rainfall rate (shaded) and radius of maximum wind (RMW; black line) in OFFB5 (b=0.5; no off-centering).

NUMERICAL DRAG



The pressure gradient force (PGF) controls acceleration of a parcel rotating around the storm centre.

Off-centering (b>0.5) means that the PGF is computed further along the back-trajectory.

A component of the PGF opposes the flow in addition to incompletely rotating the wind vector when b>0.5

Semi-Lagrangian discretization of momentum equations:

$$\frac{\boldsymbol{V}^A - \boldsymbol{V}^D}{\delta t} = \underbrace{-bR_d(T_v\nabla\ln p)^A}_{\text{“Arrival” PGF}} - \underbrace{(1-b)R_d(T_v\nabla\ln p)^D}_{\text{“Departure” PGF}} + \cdots$$

weight increases with off-centering (b)

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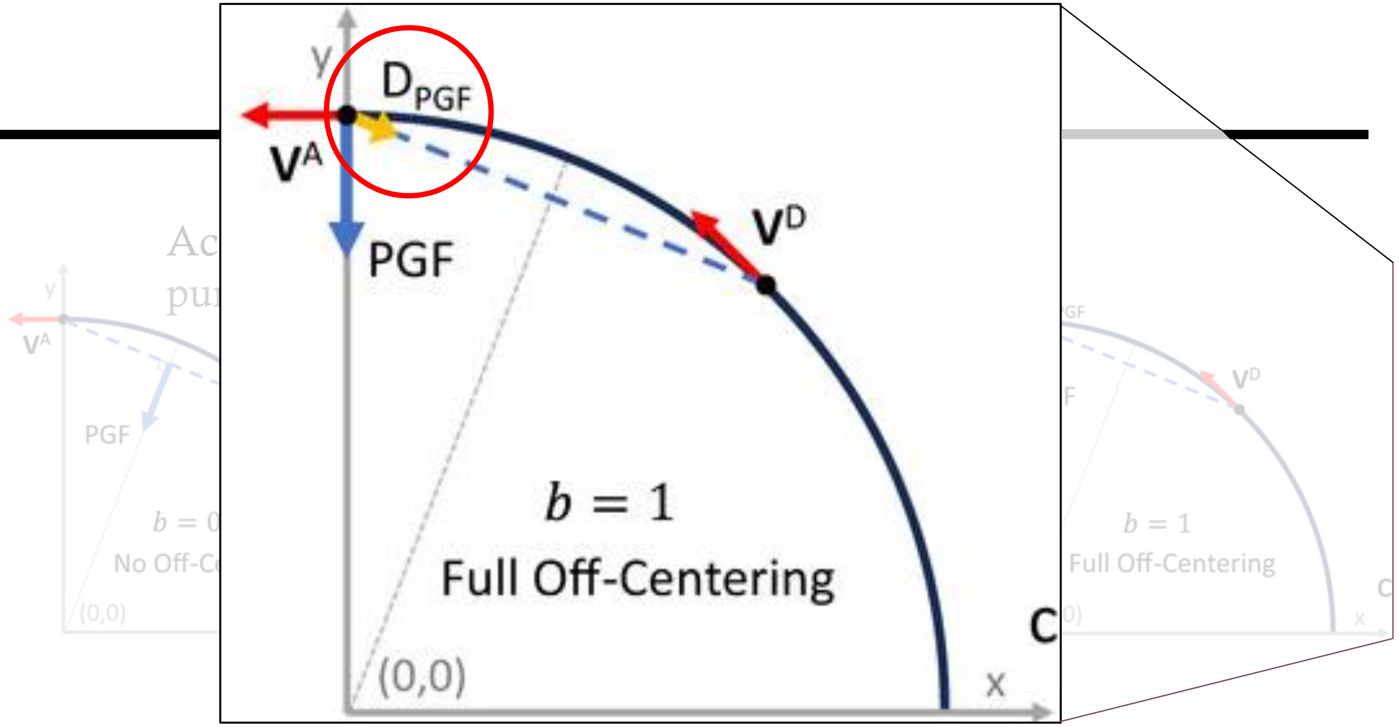

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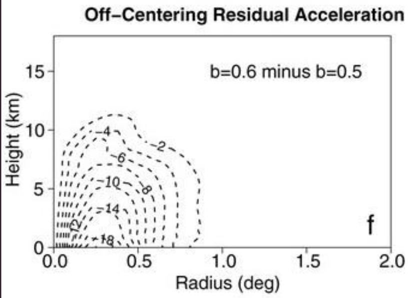
weight in-creases with off-centering (b)

TANGENTIAL WIND BUDGET

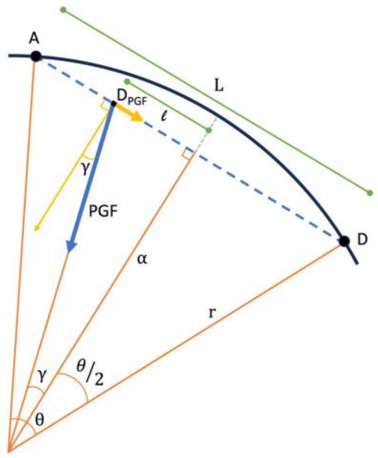
$$\frac{\partial \bar{v}}{\partial t} = -\bar{u}(\bar{\zeta} + f) - \bar{w}\frac{\partial \bar{v}}{\partial z} - \overline{u'\zeta'} - \overline{w'\frac{\partial v'}{\partial z}} + D_T$$

Gradient Balance

Numerical Drag (Residual)



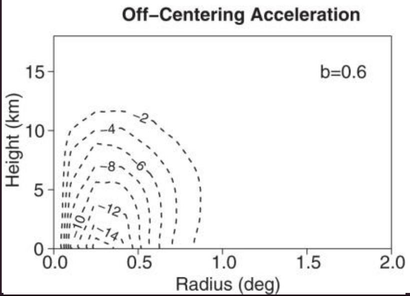
Numerical drag induced by off-centering (b=0.6), diagnosed by piggybacked run (Grabowski 2014)



Geometric derivation of PGF error acceleration

$$D_{PGF} = -\frac{\chi(\frac{v^2}{r} + fv)}{\sqrt{1 + \chi^2}}$$

$$\chi = 2(b - {}^{1}/_{2})\tan({}^{v\delta t}/_{2r})$$



Numerical drag diagnosed from PGF misalignment for b=0.6.

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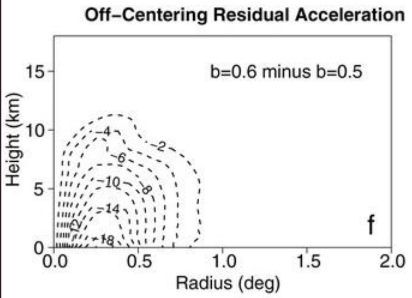

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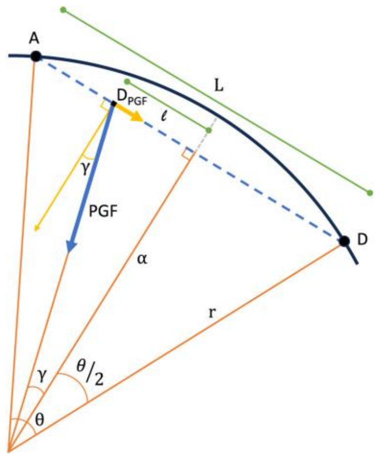

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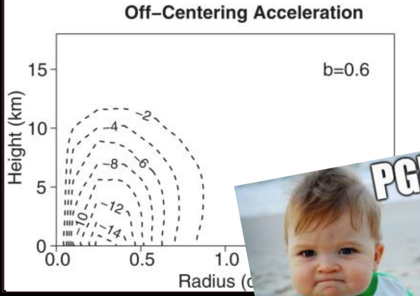

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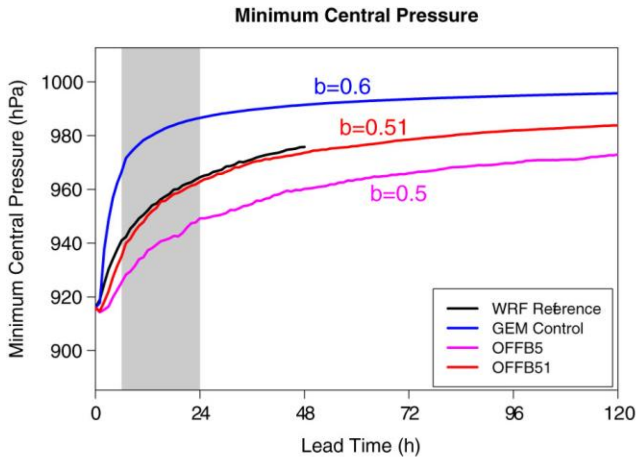
A NUMERICAL SOLUTION

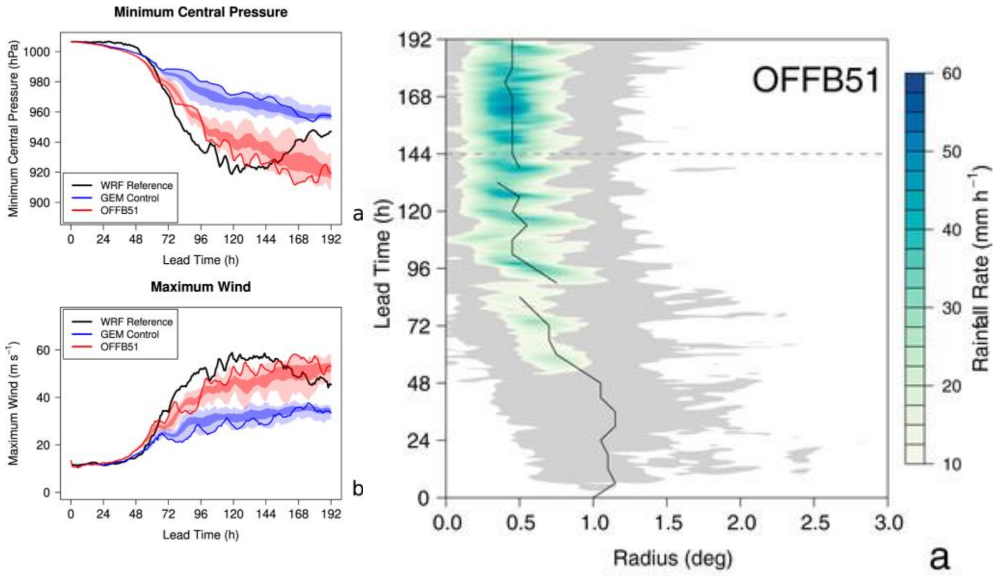
The spin-down of a mature TC in the adiabatic, inviscid dynamics is used to constrain off-centering.

With b=0.51, GEM dissipation matches the WRF reference.

Reduced off-centering in the tropical channel test results in a TC that matches the WRF reference intensity despite a broad eyewall an inward-propagating bands.



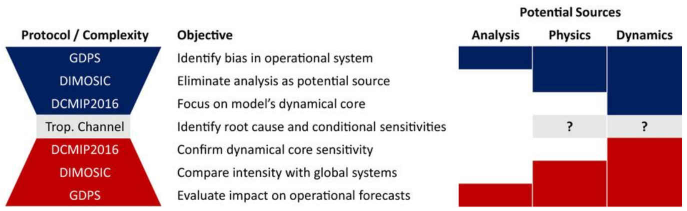
Spin-down dynamical core test



Central pressure (top-left) and wind speed (bottom-left) in the WRF Reference and GEM simulations as labelled. The right-hand column shows azimuthal mean rainfall rate (shaded) and radius of maximum wind (RMW; black line) in OFFB51 (b=0.51).

INCREASING SYSTEM COMPLEXITY

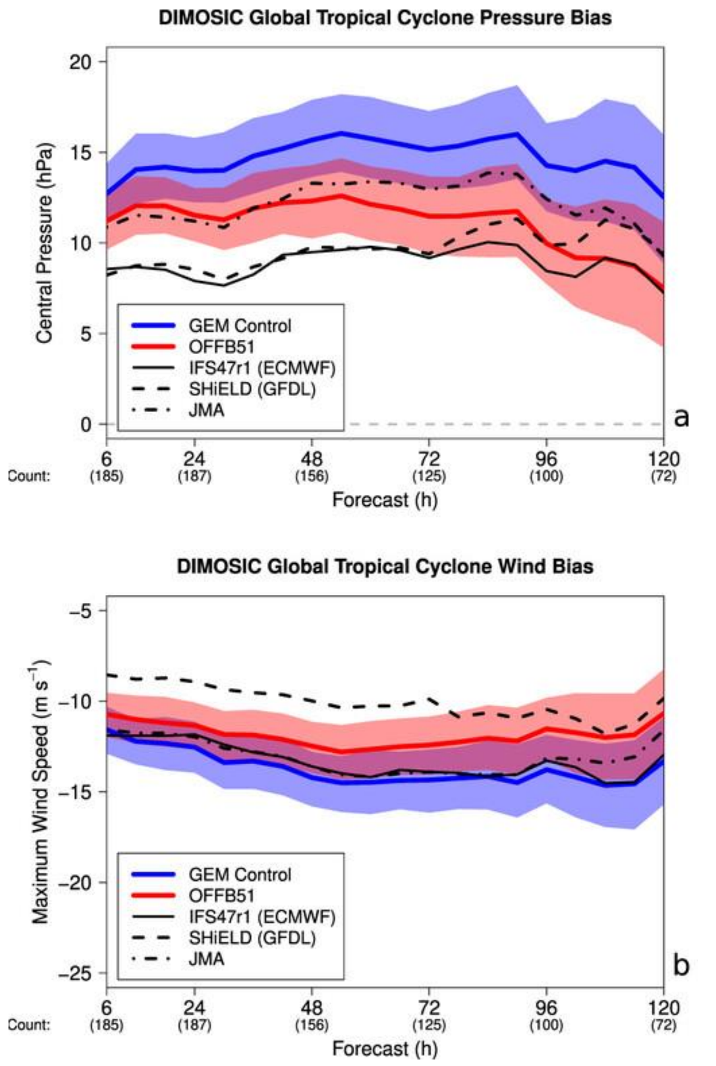
Moving back up the hierarchy of complexity confirms that excessive off-centering affects more complete configurations.



The DIMOSIC protocol (Magnusson et al. 2023) isolates forward models by initializing with ECMWF analyses:

- A 50-km exchange grid leads to underprediction by all models.

Tropical cyclone intensity is significantly increased with b=0.51, with biases more in line with other NWP models.



DISCUSSION

The source of an important tropical cyclone intensity bias has been identified in operational Canadian NWP guidance.

Reduction of numerical off-centering reduces dissipation in the dynamical core to a level comparable to equivalent models.

Use of low-order systems for model development:

- Facilitates root-cause analysis
- Quantifies conditional sensitivities in model components
- Avoids potential for introduction of compensating errors

Ongoing development will reformulate the GEM dynamical core to eliminate the need for off-centering, changes that could be adopted by other semi-Lagrangian models.

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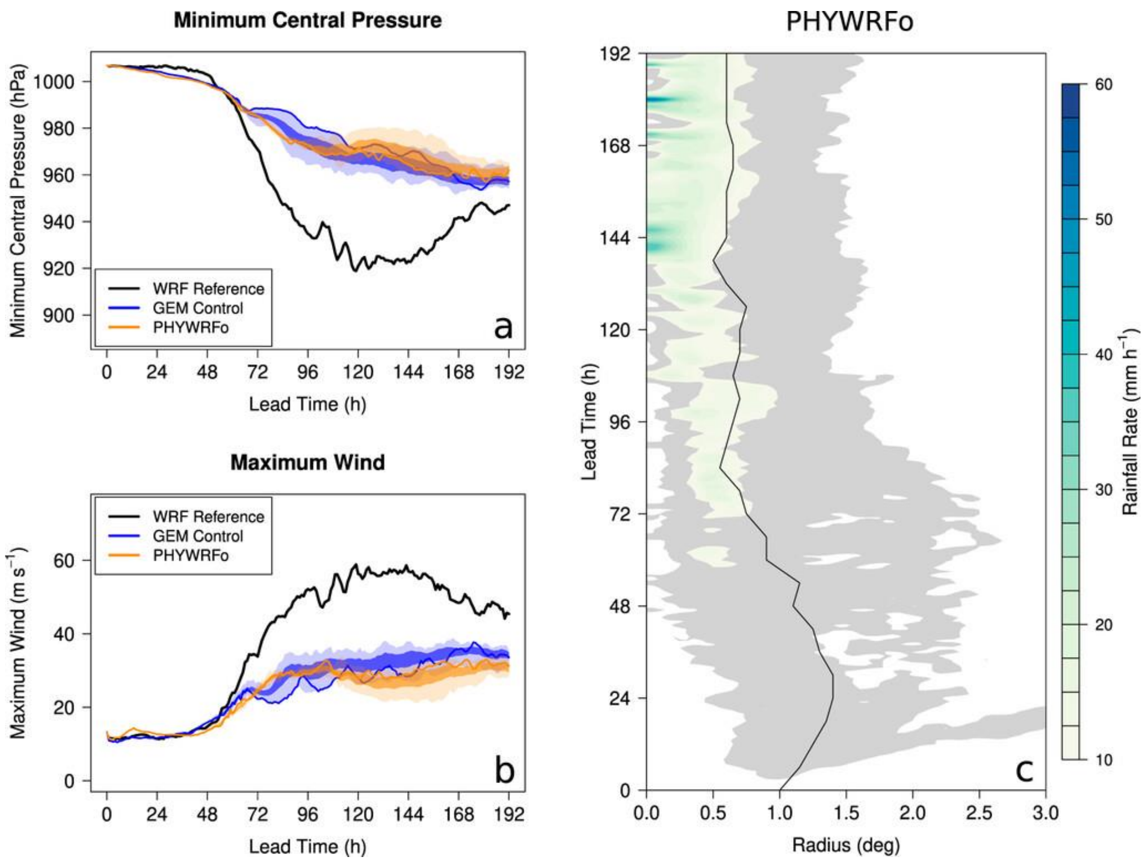
SENSITIVITY TO MODEL PHYSICS



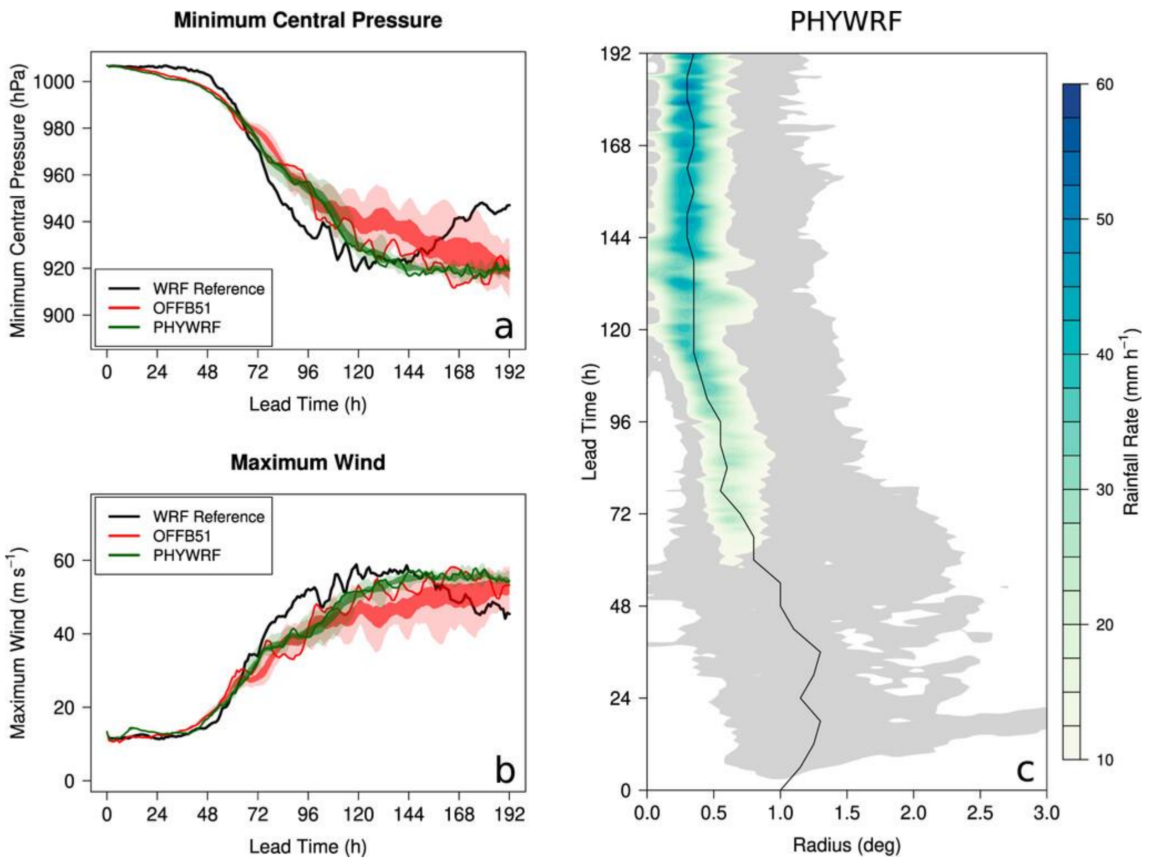
The relevant physics parameterizations are unified with the WRF Reference:

- The YSU boundary layer scheme is introduced in GEM
- Kain-Fritch deep convection
- Sensitivity to microphysics is generally small

Eyewall replacement cycles disappear.

Convection is focused inside the RMW but does not promote significant development.

CONDITIONAL PHYSICS SENSITIVITY



Adopting WRF-type physics leads to a significantly stronger TC with more stable evolution in time.

Dominant rainbands are replaced by a strong eyewall and secondary circulation (not shown) with convection concentrated just inside the RMW.

This sensitivity to model physics is conditional on a dynamical core that does not suffer from excessive 3D drag.

HIERARCHICAL SYSTEM DEVELOPMENT

Confirm a TC weak-intensity bias that exceeds resolution limits in the operational global model (GDPS).

Confirm significant bias reduction in higher-complexity systems

Exclude analysis as potential source

Identify dynamical core as potential source

Exclude model physics as potential source

Identify conditional sensitivity to physical parameterizations

Root-cause analysis identifies off-centering in the dynamical core as the bias source

Confirm off-centering sensitivity via geometric analysis and in shallow water model.

System Complexity

Progress Towards Solution