Variability to available planetary boundary layer parametrizations in high-resolution, realistic hurricane simulations

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Background

Theoretical studies of tropical cyclone intensification assume gradient wind balance in the boundary layer in an axisymmetric frame (Schubert and Hack 1982; Shapiro and Willoughby 1982; Bister and Emanuel 1998; Smith 2003; Montgomery et al. 2009). Recently, Smith et al. (2009) showed that from the perspective of azimuthal averaged dynamics, hurricane spin up occurs via two different mechanisms. One of them is within the boundary layer and can not be captured by balanced dynamics.

We explore departures from gradient wind balance in realistic WRF integrations. The simulations differ from each other in the choice of the PBL parametrization. This work aims to be a seminal study of the variability in realistic hurricane integrations given by the PBL parameterizations available today.

Hurricane Jimena (2009)

August 28, 2009 to September 4, 2009: A category 5 hurricane that reached Max. sustained winds of 250 km/h and a minimum pressure of 931 hPa.

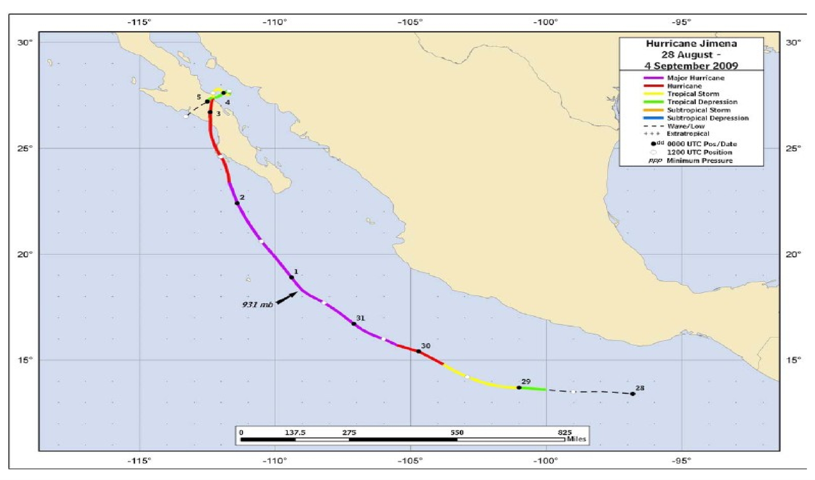


Fig. 1: Path of Hurricane Jimena.

WRF model configuration

- Three domains: 36 km, 12 km and 4 km.
- 54 vertical levels
- GFS analysis and forecasts every 3h used as initial and boundary conditions.
- Four simulations were initialized with a Rankine vortex using different PBL schemes.

Physics options	
Micropysics	WRF Single-Moment 6-class
LW and SW Radiation	RRTMG
Land-surface model	Noah
cumulus	Domains 1 and 2 used Tiedtke

Simulations	PBL schemes
YSU	Yonsei University: Non-local K scheme
MYJ	Mellor-Yamada-Janjic: Prognostic TKE scheme with vertical mixing.
QNSE	Quasi-Normal Scale Elimination: A TKE prognostic scheme
MYNN	Mellor-Yamada Nakanishi and Niino Level 2.5. Predicts sub-grid TKE terms.

Methodology

The simulations were interpolated into a cylindrical grid in order to analyze the agradient force terms in the equation:

$$F_n = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{v^2}{r} + fv$$

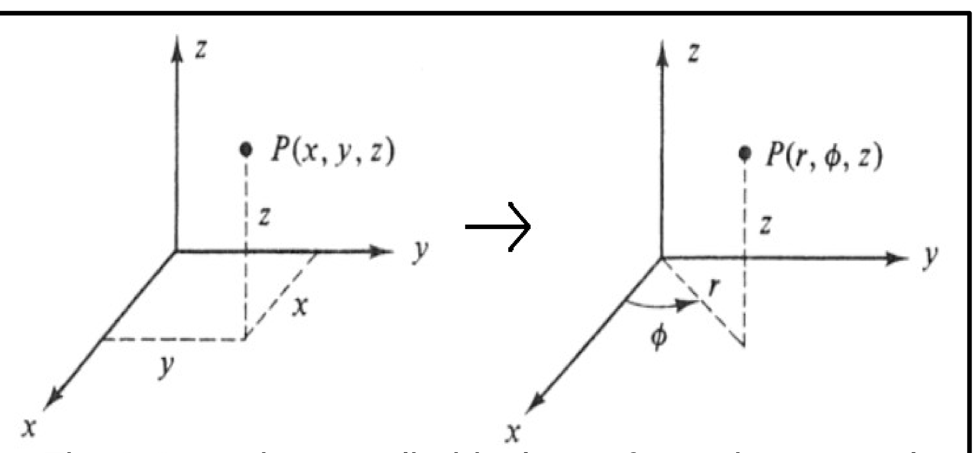
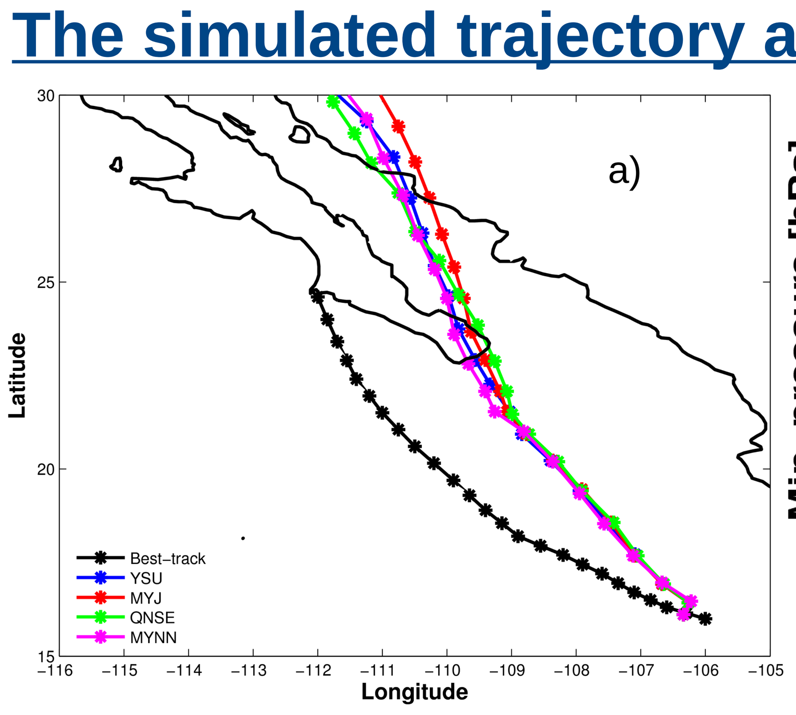
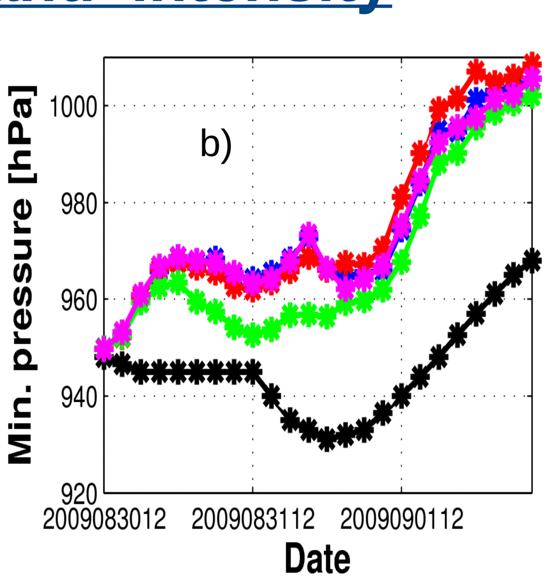
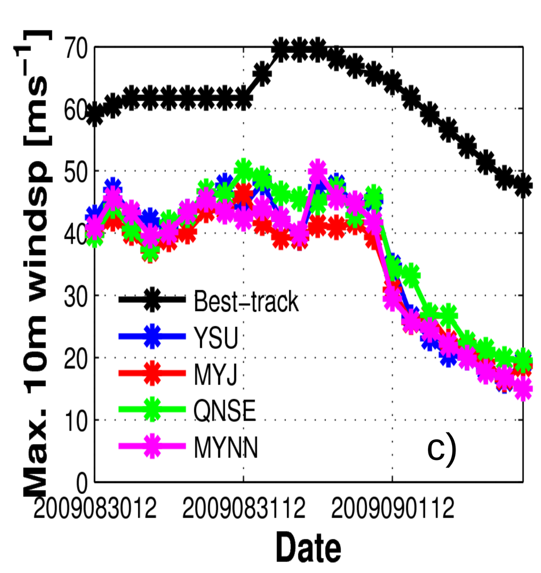


Fig. 2 Cartesian to cylindrical transformation example.

The simulated trajectory and intensity



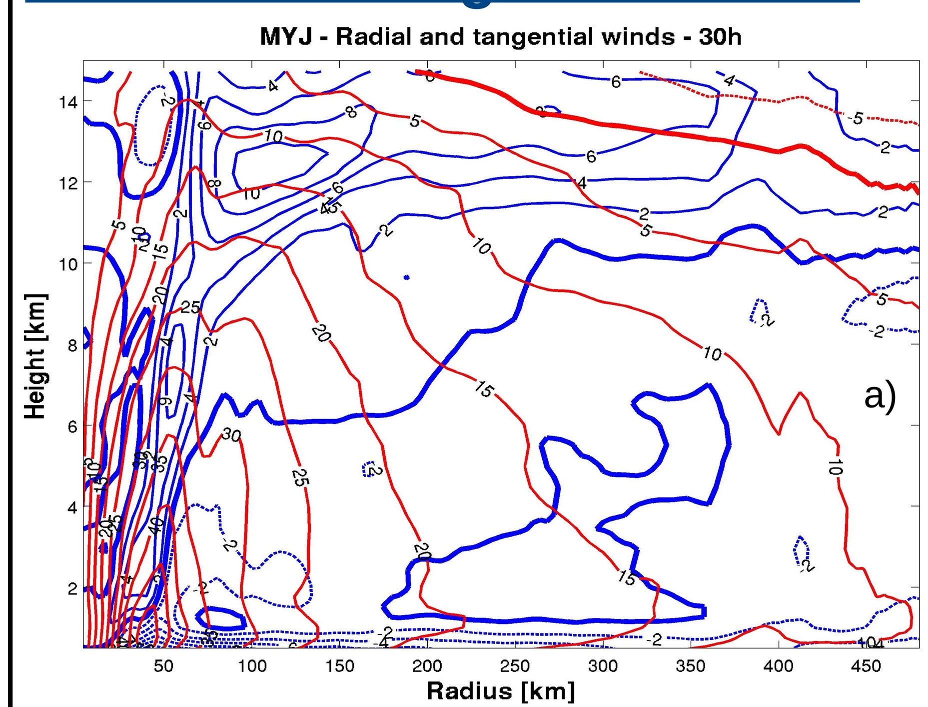


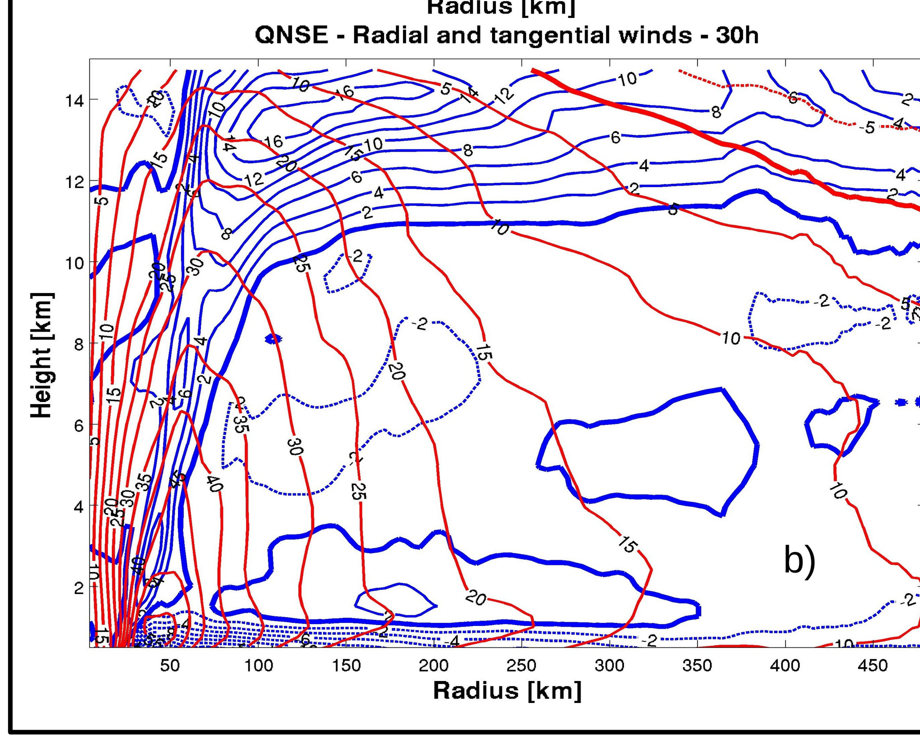


Figs. 3a-c: Comparison between the simulated trajectories, minimum pressures and maximum 10m wind speeds and the best-track for Hurricane Jimena (2009).

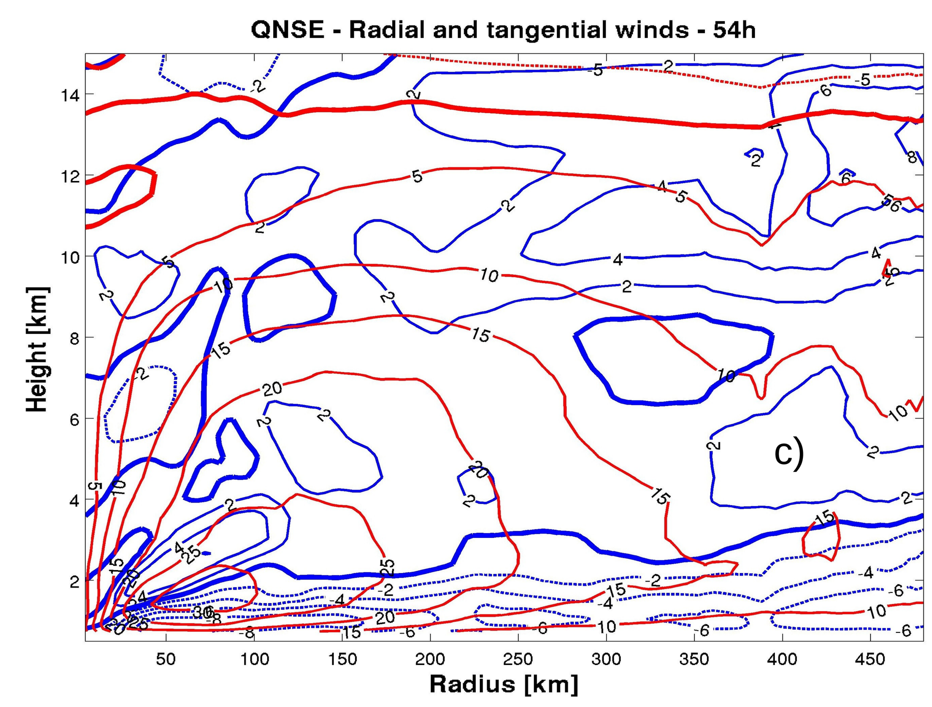
- The simulated trajectories for Jimena agree well with each other in trajectory and punctual measures of intensity. Small differences are shown between them.
- QNSE and MYNN render an integration more in agreement with observations. MYJ differs the most with observations.

Radial and tangential winds



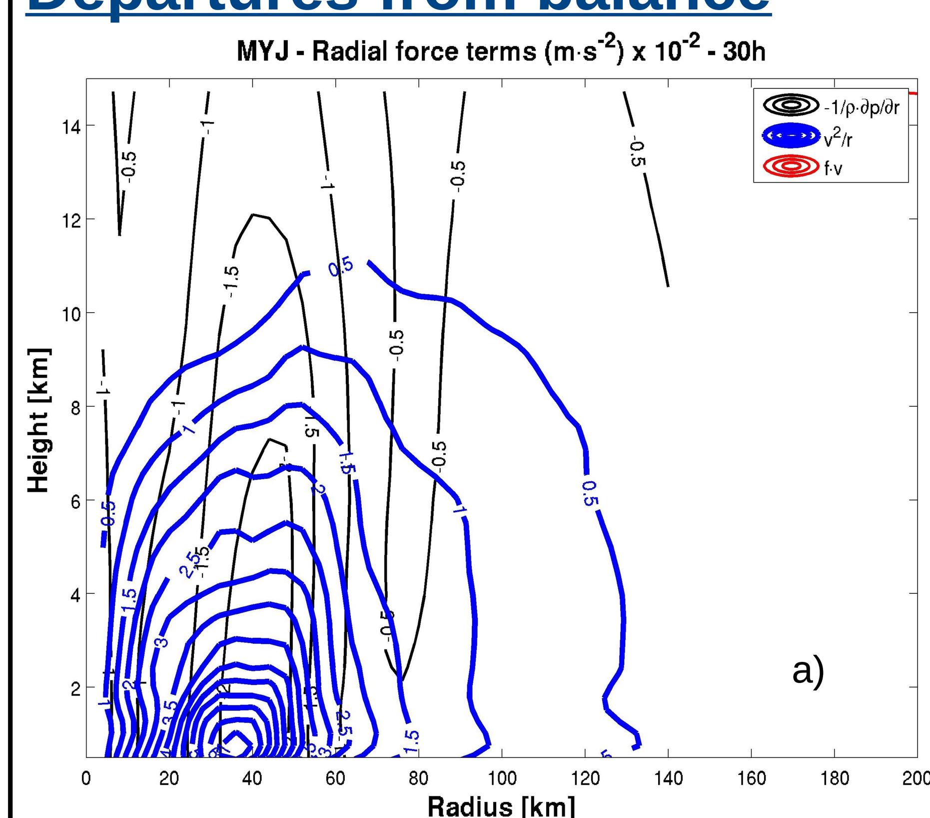


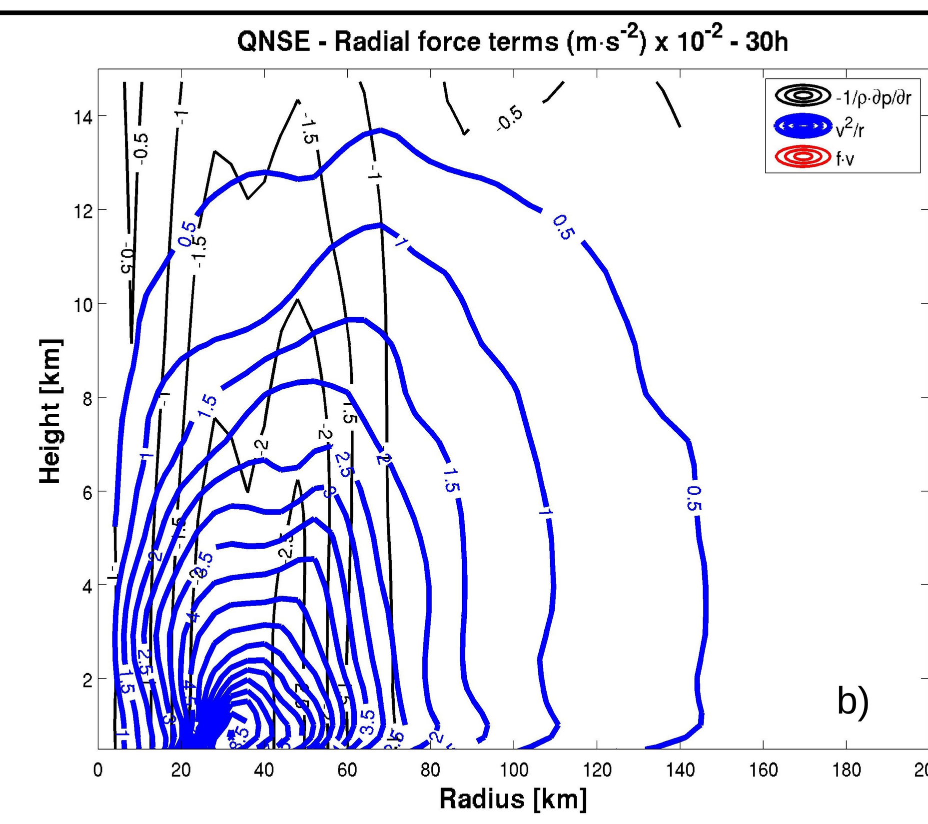
- During intensification the radial inflow is concentrated in a shallower layer, which has been shown in observational and numerical studies (Raymond et al. 1998; Marín et al. 2009).
- All simulations show the maximum tangential winds located within the boundary layer (i.e. within the region of strong radial inflow). This is particularly clear during intensification, where the inflow is located at lower levels than during decaying. The maximum tangential wind is located near the boundary layer top during decaying.



Figs. 4a-c: Height-radial cross sections of tangential (red lines) and radial winds (blue lines) for MYJ and QNSE simulations at 30h and 54h of forecast.

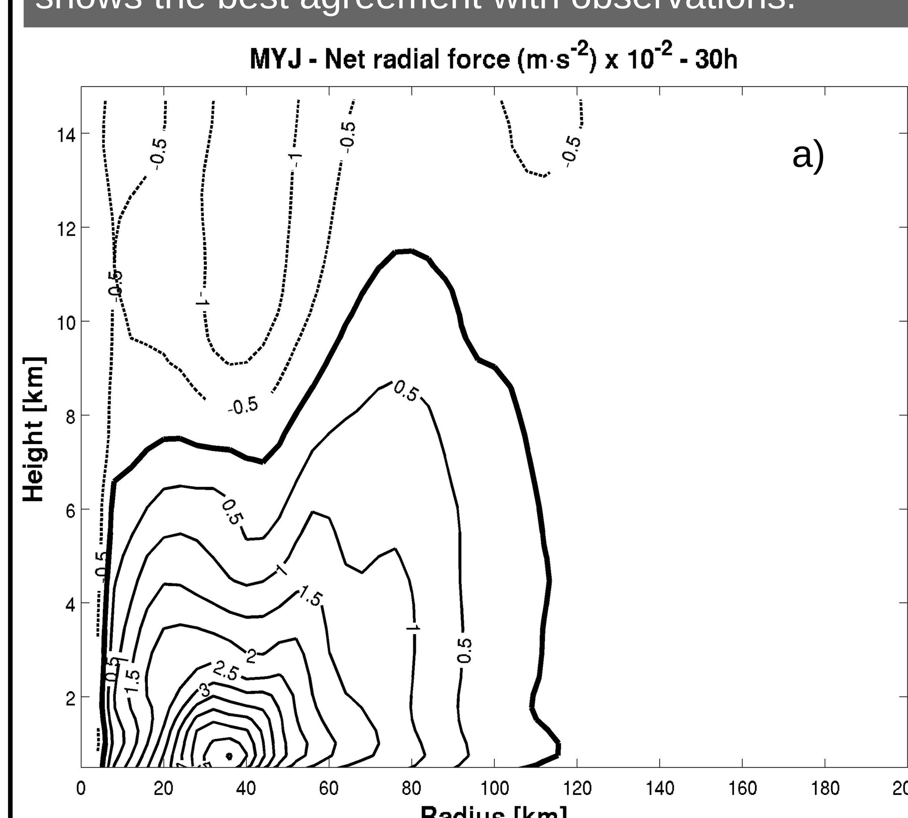
Departures from balance

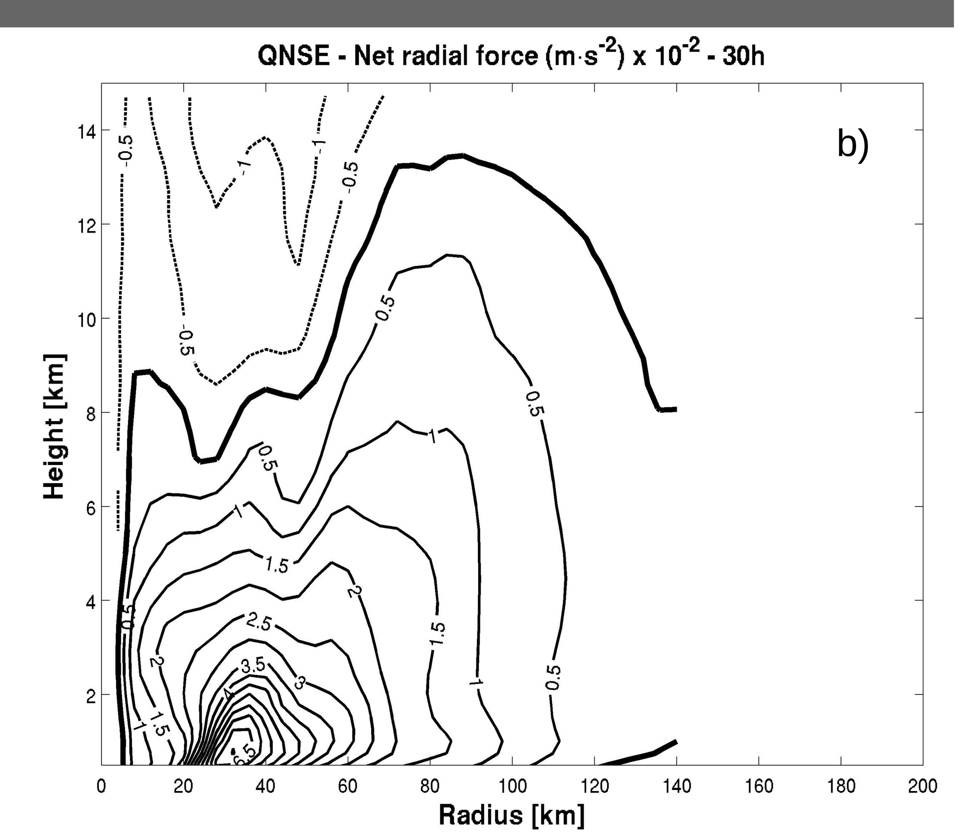




Figs. 5a,b: Height-radial cross sections of radial pressure gradient (black lines), centrifugal (blue lines) and Coriolis (red lines) forces at 30h of simulation for MYJ and QNSE.

- The pressure gradient force and centrifugal force dominate over the whole domain. The centrifugal force dominates in the inner-core region and its maximum values are within the boundary layer.
- Larger values of the centrifugal force in the boundary layer are shown in the QNSE simulation, which shows the best agreement with observations.





Figs. 6a,b: Heigth-radial cross sections of the net radial force (F_n) for MYJ and QNSE simulations at 30h.

Positive F_n values indicate supergradient flows in the inner-core region with maximum values near the surface in the boundary layer during intensification. A more intense hurricane is associated with a larger departure from gradient wind balance in the boundary layer as shown by QNSE simulation.

Conclusions

- Large departures from balance occur in the inner-core region during intensification associated with a strong radial inflow, which concentrates in a shallow layer of the atmosphere. Stronger radial inflows are related to more intense hurricanes.
- The better this process is reproduced by the simulation, the better its agreement with observations.

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