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A Highly Configurable Vortex Initialization Method for Tropical Cyclones

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1. Introduction

Tropical cyclones continue to pose a significant forecast challenge for numerical weather prediction models, and vortex initialization is one of the factors in improving forecast accuracy. In the most basic (yet still practical) approach, a synthetic or "bogus" hurricane-like vortex can be generated and inserted into a model's large-scale environment.

Kurihara et al. (1993) argued that the synthetic vortex should possess three properties to minimize dynamic adjustment and false spin-up/spin-down:

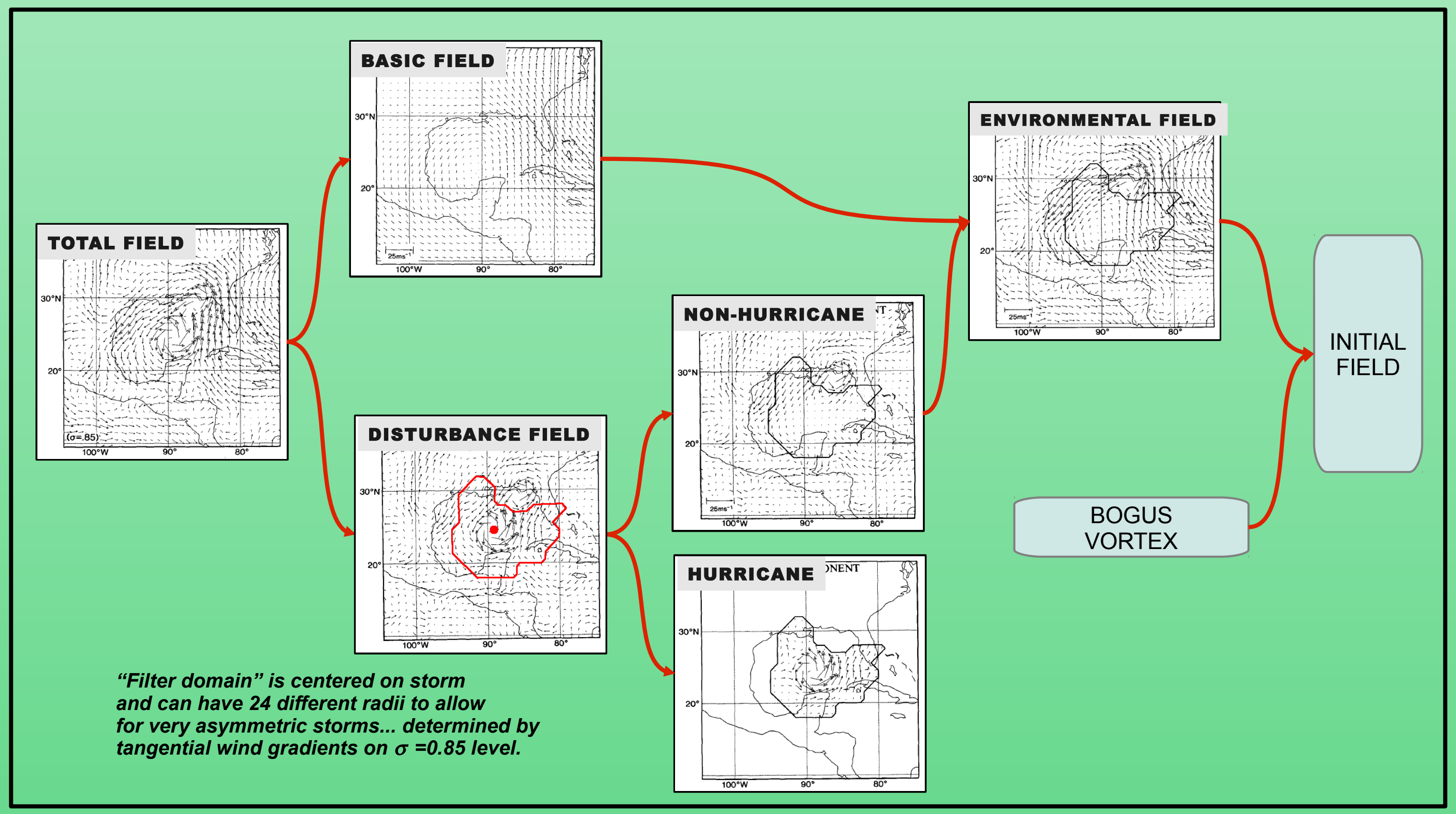
- *structural consistency*
- *resemblance to the "real storm"*
- *compatibility with the numerical model*

To ensure these qualities are enforced in the generation of tropical cyclone-like flows for model initialization, three general techniques, that work together or alone, have been developed: 1) data assimilation, 2) dynamic initialization, and 3) vortex bogusing.

This methodology provides an efficient vortex bogusing scheme with many configurable parameters. A more detailed description and results can be found in Rappin et al. (2013).

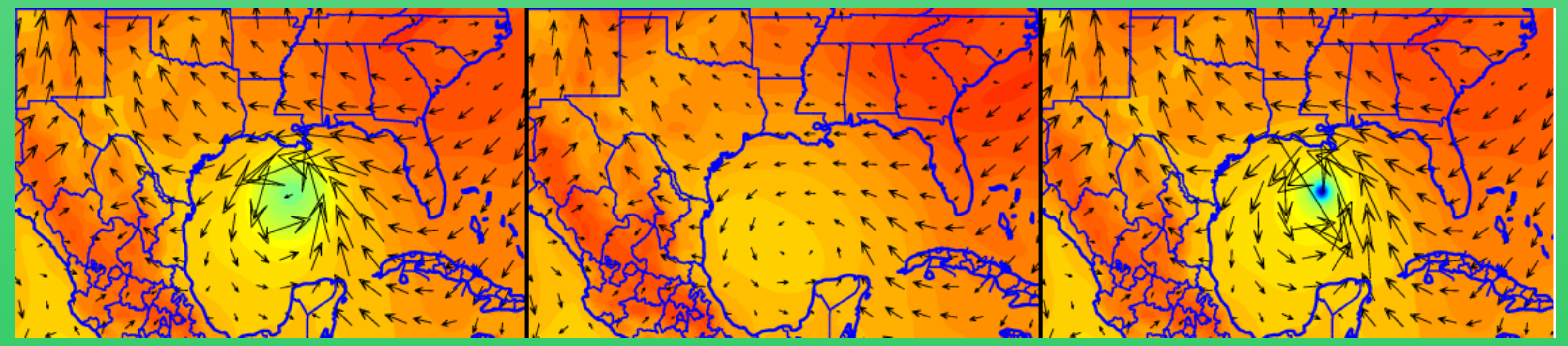
2. Vortex Removal & Addition

The vortex removal technique closely follows that designed by GFDL (Kurihara et al. 1993, Kurihara et al. 1995). The figure below shows a flow diagram of the process, beginning with a model's initial analysis. (Hurricane Florence 1988, from Kurihara et al. 1995).



"Filter domain" is centered on storm and can have 24 different radii to allow for very asymmetric storms... determined by tangential wind gradients on σ =0.85 level.

In this framework, a moist, axisymmetric vortex is created and inserted into the model's background environment in a dynamically consistent fashion. The radial and vertical structure can be specified, and a secondary circulation can also be generated. Below is an example of the "total", "environmental", and "initial" fields (wind vectors and perturbation hydrostatic pressure). (Hurricane Lili 2002, from Rappin et al. 2013).



3. Configurable Parameters

A primary advantage of this technique is that many of the parameters that control the vortex removal and addition processes are easily adjustable. In the current version of the code (in Matlab and Fortran 90), there are approximately two dozen parameters the user can change. Some options depend on other options being set, but examples include:

- Storm center location (model-based or best-track)
- Radial structure (Mod-Rankine or Willoughby dual-exponential)
- Vertical structure (Gaussian decay or Emanuel)
- Secondary circulation (Emanuel or none)
- Boundary layer flow scheme (Foster similarity or Gaussian decay)
- Boundary layer depth
- Boundary layer eddy diffusivity
- Radius of maximum wind
- Storm depth
- Outflow temperature
- Radius of tropical storm winds
- Tangential wind decay exponent
- Gaussian decay rate constants
- Moisture enhancement

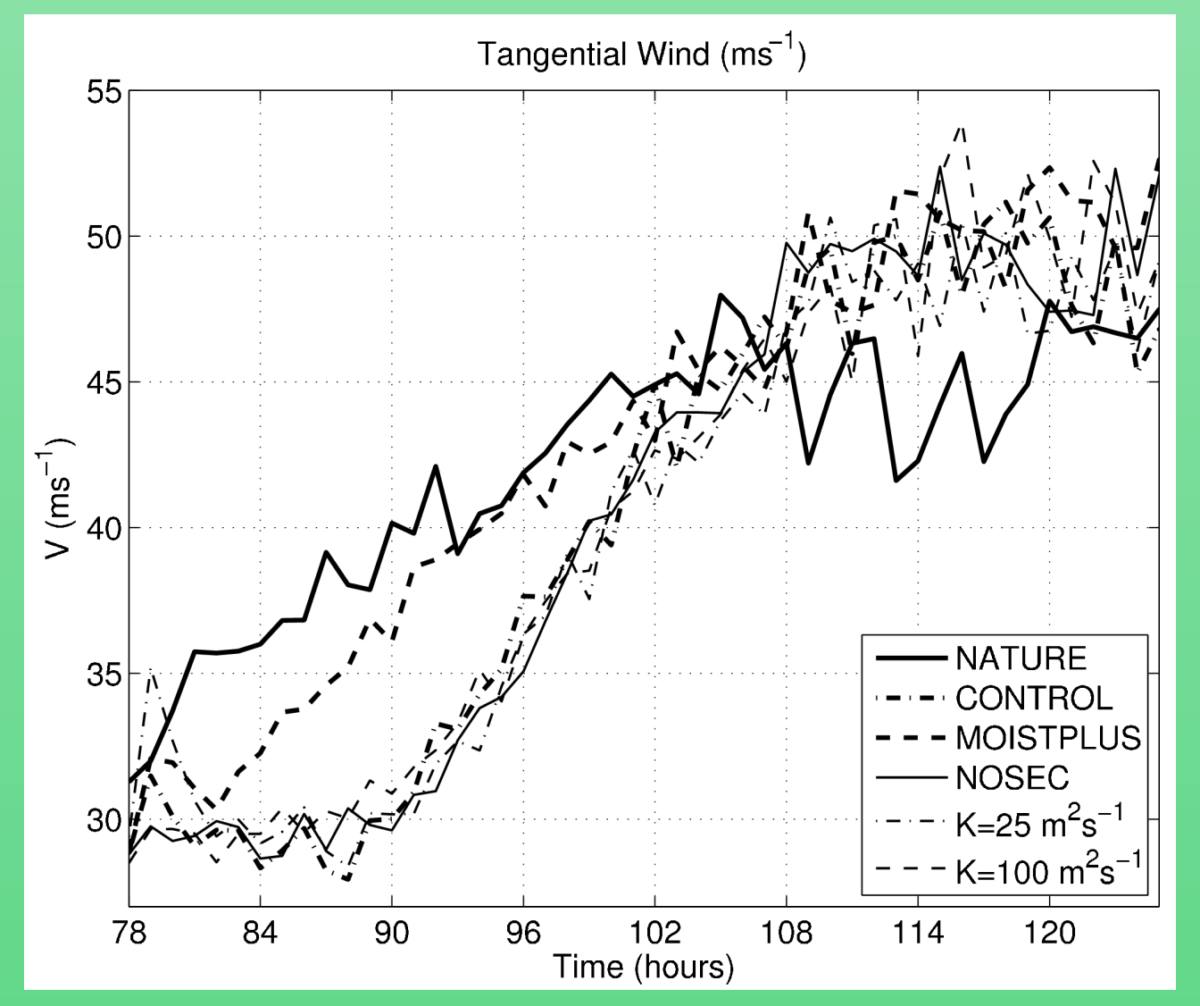
4a. Model Experiments: Intensity

All simulations performed use the WRF 3.1.1 model with 27/9/3km nested grids. Details on the various radiation, convection, microphysics, etc parameterizations and schemes can be found in Rappin et al. (2013).

Setup of experiments on Hurricane Bill 2009:

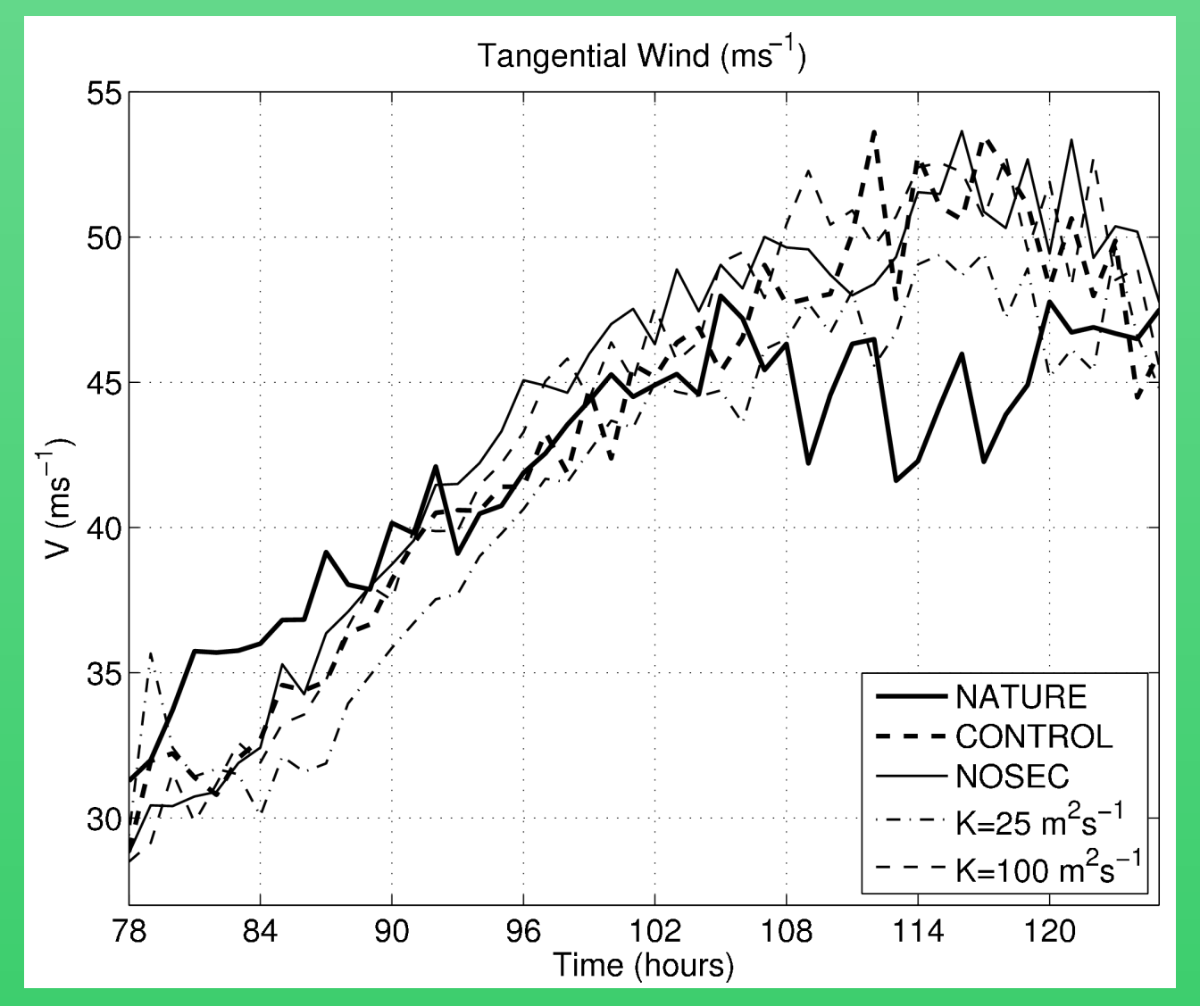
- Nature run (**NATURE**: no bogusing)
- Control run *(**CONTROL**: default bogus vortex)*
- Initial moisture enhancement *(**MOISTPLUS**: +10% RH at RMW)*
- Influence of initial unbalanced secondary circulation *(**NOSEC**: U,W=0)*
- Varying eddy diffusivity value *(**K25**: 0.45*CTRL, **K100**: 1.8*CTRL)*

In all cases, the track forecast was very similar, and is not shown. The intensity forecasts (azimuthally averaged maximum tangential wind at lowest model level ~ 100m) are shown here. All synthetic vortex initializations shown here were conducted at 78 h into the nature run.



The MOISTPLUS run is the only one that does not suffer from a significant initial adjustment period of vortex spin-down.

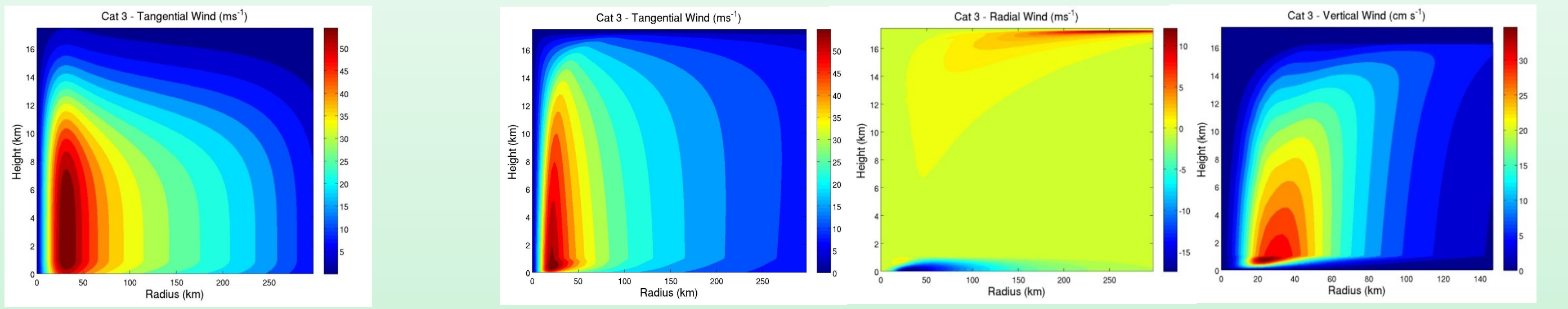
To further demonstrate the effect of enhanced moisture on initial adjustment, all experiments were rerun but with 15% higher RH in the inner core.



With inflated inner core moisture, regardless of secondary circulation and eddy diffusivity value, the adjustment time is greatly reduced.

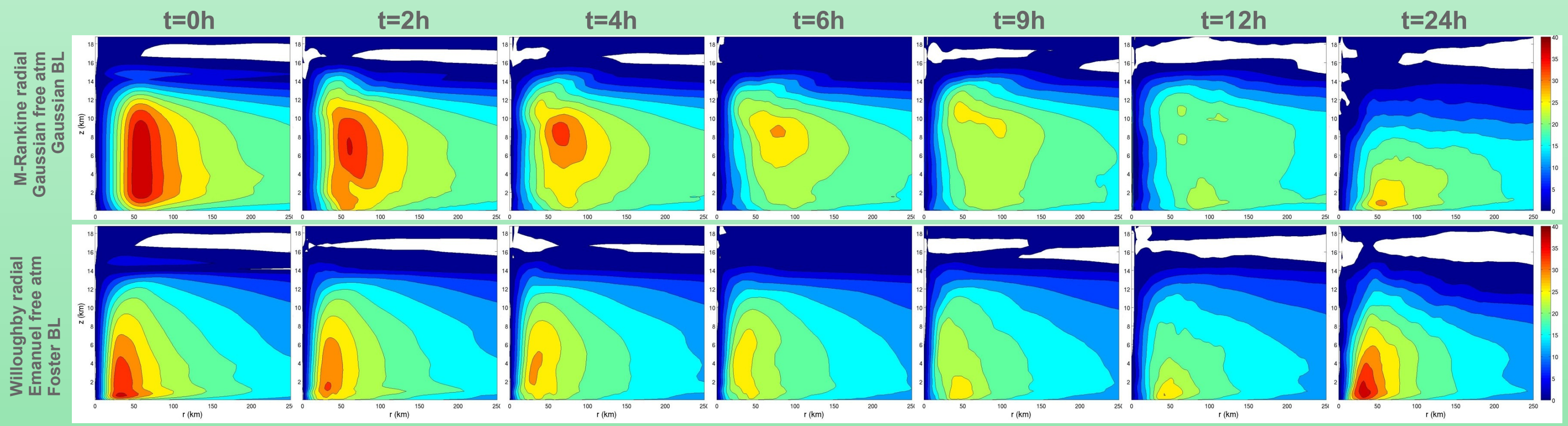
4b. Model Experiments: Structure

The vortex structure can also be tuned. It can be as simple as a modified Rankine profile in the radial and Gaussian decay above and below the boundary layer in the vertical with no secondary circulation, to something as complex as a Willoughby (2006) dual-exponential profile in the radial with Emanuel (1986) steady-state free atmosphere and Foster (2009) nonlinear similarity model in the boundary layer with a mass and momentum conserving secondary circulation in the vertical – and almost any combination in between.



Vertical cross-sections from the simplest and most complex idealized vortices this methodology can create. a) modified-Rankine radial profile with Gaussian decay vertical profile above and below the boundary layer. No secondary circulation. b-d) tangential, radial, and vertical winds from a Willoughby radial profile with Foster boundary layer and Emanuel free atmosphere. Full secondary circulation generated.

The structural evolution of the two bogus vortices when used as an initial condition in WRF is fairly diverse. In this series of figures, a vortex modeled after Hurricane Bill 2009 -- using both formulations described above -- is created and inserted into the background environmental flow. While the structure is noticeably different, the track forecasts (not shown) are nearly identical.



5. Applications

The Fortran 90 version of the code runs ~150x faster than the original Matlab version, and is therefore suited for research as well as quasi-operational purposes.

- Idealized simulations, sensitivity studies
- Test observing strategies in OSSEs
- Basic plug-and-play vortex in bogusing schemes
- A step in dynamic initialization schemes
- Ensemble of bogus vortices for data assimilation schemes

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