Improving Physics Representations in Tropical Cyclone Models: The Issues and Challenges

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Purpose of this presentation:

Advocate using a coherent dynamic paradigm to improve physics representations in TC models.

Presented at Shanghai Meteorological Bureau/Shanghai Typhoon Institute, Shanghai, China, 20 December 2012

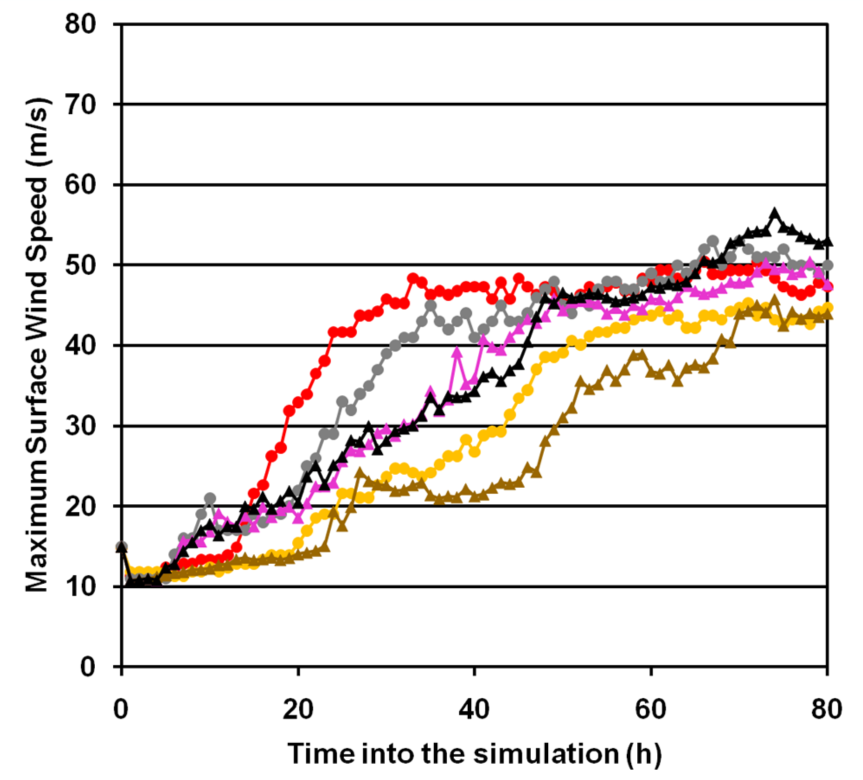
How do we improve physical representations in TC models to get clouds better simulated?

Outline

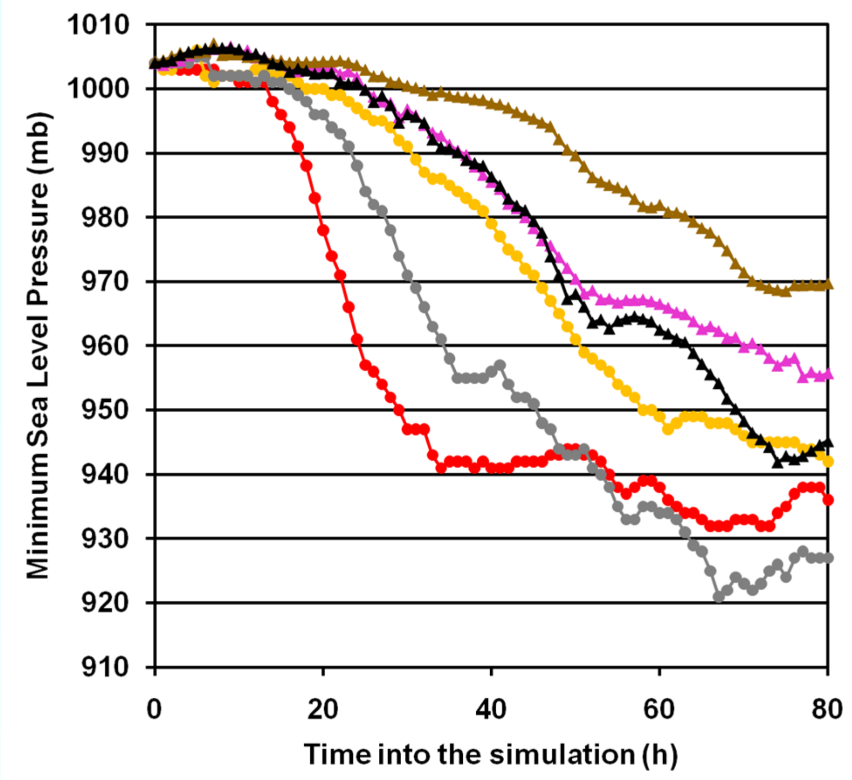
1. **Physics representations in TC models: Synergy of cloud physics, subgrid dynamics, air-sea interaction, radiation, etc., and the dynamic core**
2. **Highlighted issues and challenges in**
   - **a. Cloud microphysics parameterization**
   - **b. Parameterizations of subgrid-scale mixing and PBL schemes**
   - **C. Radiational physics**
3. **Summary**

Sensitivity to Convective Parameterization Scheme Options

Max. Surface Wind Speed (m/s)

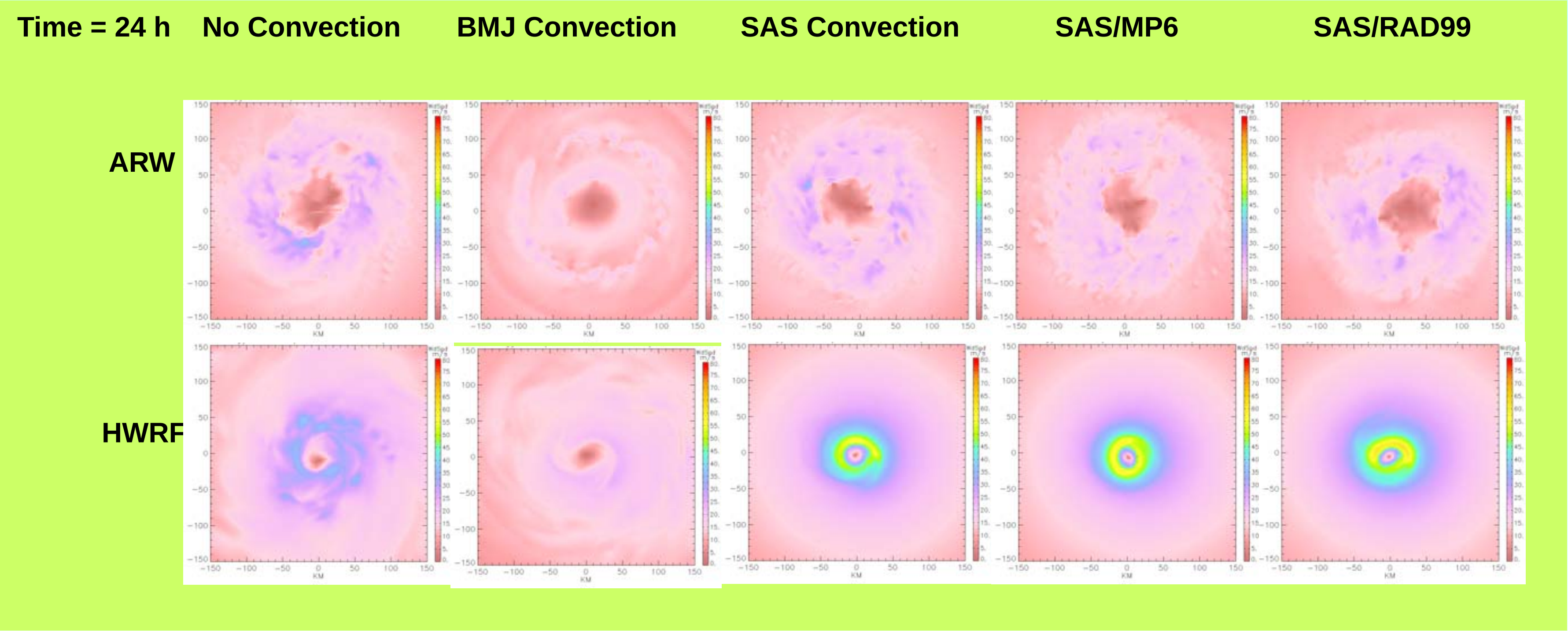


Min. Sea-level Pressure (mb)

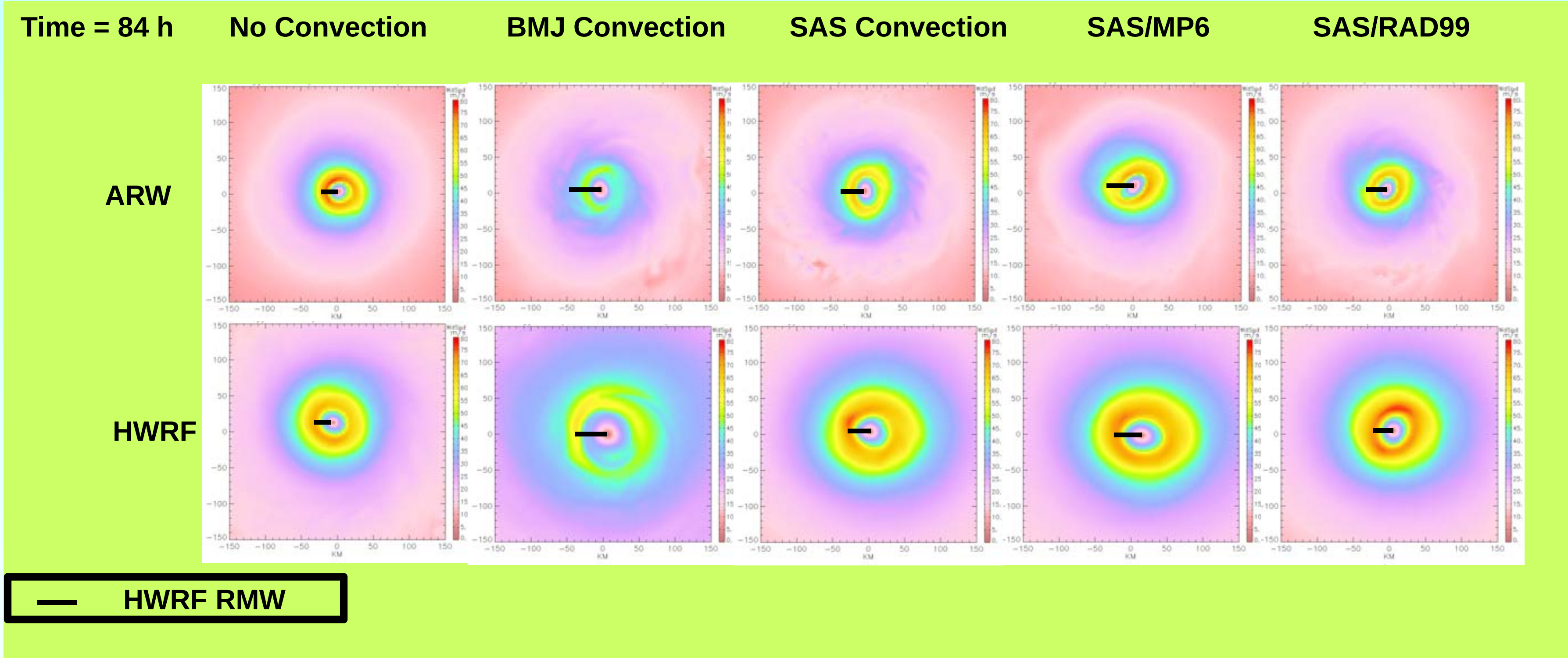


Magenta Triangles: ARW SAS
Brown Triangles : ARW BMJ
Black Triangles : ARW None
Red Circles: HWRF SAS
Yellow Circles: HWRF BMJ
Gray Circles: HWRF None

Sensitivity of Storm Structure to Physics Parameterizations: 850m mb Wind Speed at T=24h



Sensitivity of Storm Structure to Physics Parameterizations: 850m mb Wind Speed at T=84h



Summary

Issue:

Performance of the physics package is model-dependent.

Challenge:

A combination of observational analysis and theoretical understanding is needed to determine an "improved" operational physics configuration for a given operational dynamic core.

The Problem of parameterizations of subgrid mixing and PBL schemes in TC models

Reynolds-averaged Navier–Stokes equations: Basis for parameterizing 3-D subgrid mixing

- Grid scale filtering: $\Psi = \overline{\Psi} + \Psi'$ with $\overline{\Psi}(V,t) = \frac{1}{\Delta x \cdot \Delta y \cdot \Delta z} \int_V \Psi(V',t)\, dV'$

  $\overline{\Phi\Psi} = \overline{\Phi}\;\overline{\Psi} + \overline{\Phi'\Psi'}$

  Volume balance approach (Schumann, 1975)

- The filtered equations of motion, e.g., in Boussinesq form

$$\frac{\partial \overline{u}_i}{\partial t} = -\frac{\partial \overline{u}_j \overline{u}_i}{\partial x_j} - \frac{1}{\rho_0}\frac{\partial \overline{\pi}^*}{\partial x_i} - \varepsilon_{ijk} f_j \overline{u}_k - \varepsilon_{i3k} f_3 \overline{u}_{g_k} + \delta_{i3}\frac{g}{\theta_0}\overline{\theta}_v^* - \frac{\partial \tau_{ij}}{\partial x_j}$$

$$\overline{\pi}^* = \overline{p}^* + \frac{2}{3}\rho_0 \overline{e}\,, \qquad \tau_{ij} = \overline{u_i' u_j'} - \frac{2}{3}\overline{e}\,\delta_{ij}\,, \qquad \overline{e} = \frac{1}{2}\overline{u_i'^2}$$

Modified pressure SGS stress SGS TKE

What happened in most NWP model applications…

$$\frac{\partial \overline{u}}{\partial t} = -\overline{u}\frac{\partial \overline{u}}{\partial x} - \overline{v}\frac{\partial \overline{u}}{\partial y} - \overline{w}\frac{\partial \overline{u}}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial x} - f\overline{v} + \mu\nabla^2\overline{u}$$

2nd order

$$-\frac{\partial \overline{u'u'}}{\partial x} - \frac{\partial \overline{u'v'}}{\partial y} - \frac{\partial \overline{u'w'}}{\partial z}$$

horizontal subgrid mixing

Vertical subgrid mixing

$$\frac{\partial \overline{v}}{\partial t} = -\overline{u}\frac{\partial \overline{v}}{\partial x} - \overline{v}\frac{\partial \overline{v}}{\partial y} - \overline{w}\frac{\partial \overline{v}}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial y} + f\overline{v} + \mu\nabla^2\overline{v}$$

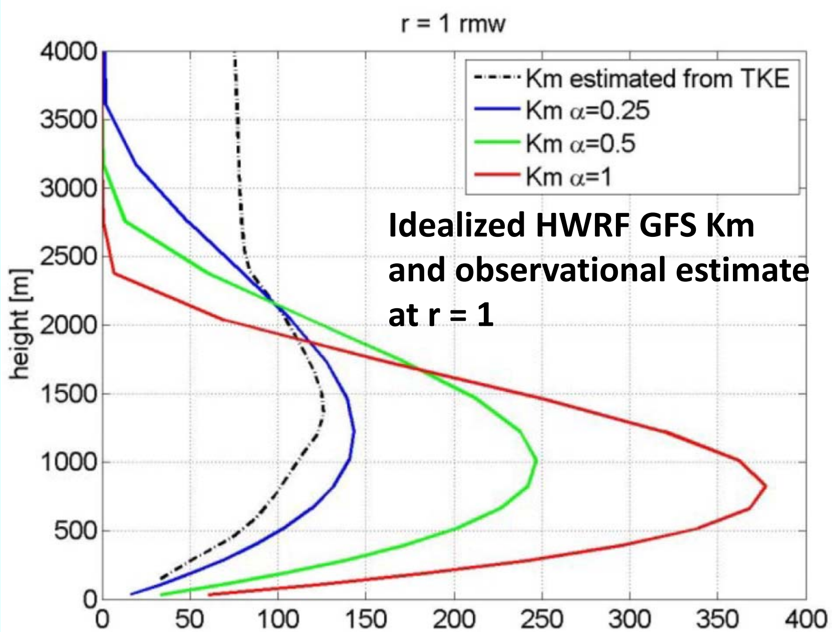
2nd order

$$-\frac{\partial \overline{v'u'}}{\partial x} - \frac{\partial \overline{v'v'}}{\partial y} - \frac{\partial \overline{v'w'}}{\partial z}$$

Horizontal subgrid mixing: resolved strain rate dependent, mostly numerical

Vertical subgrid mixing: stability depend, physically tied with the PBL mixing theory

There is no constraint on the conversion of grid-scale KE to subgrid TKE!



Zhang et al. 2012

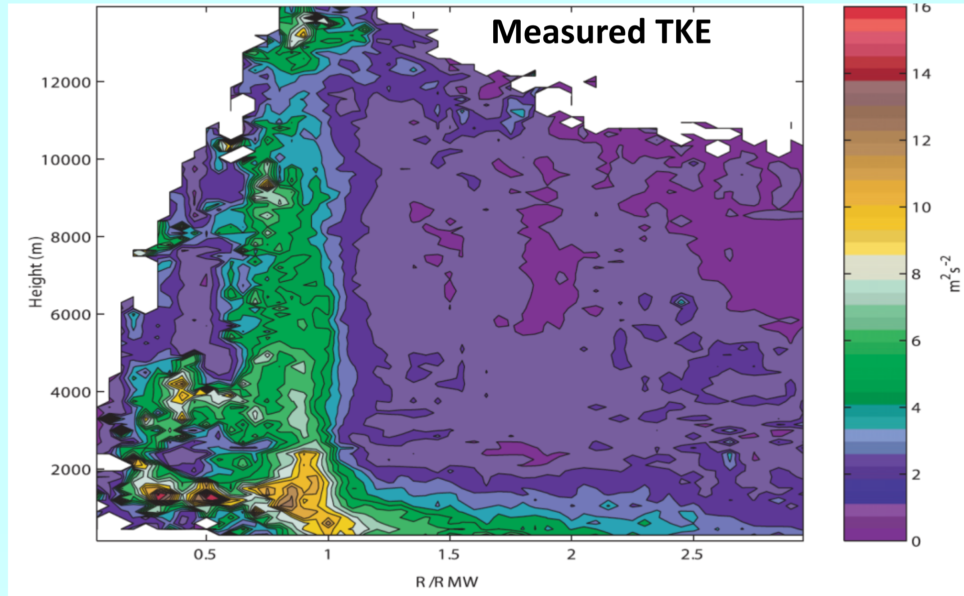
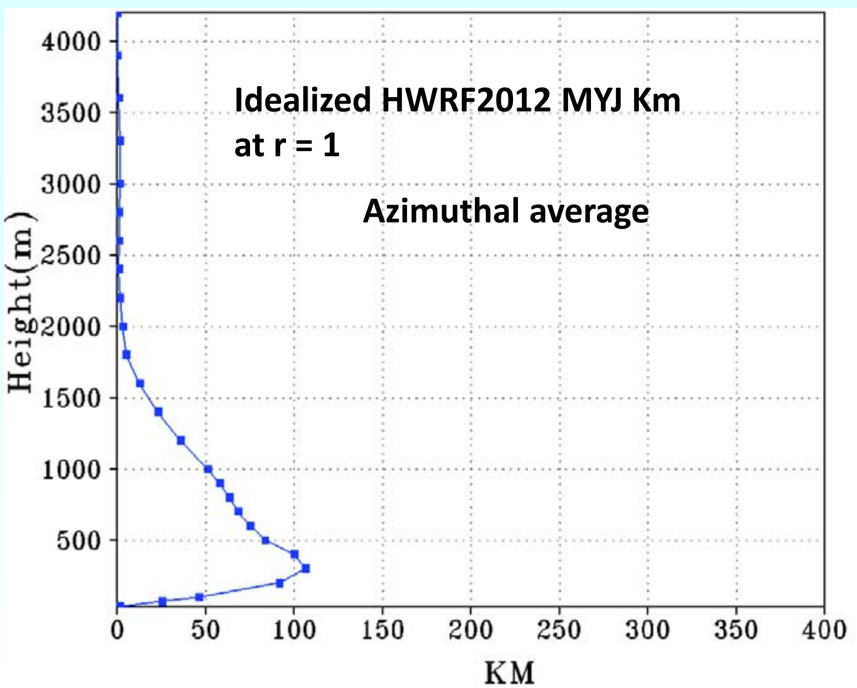
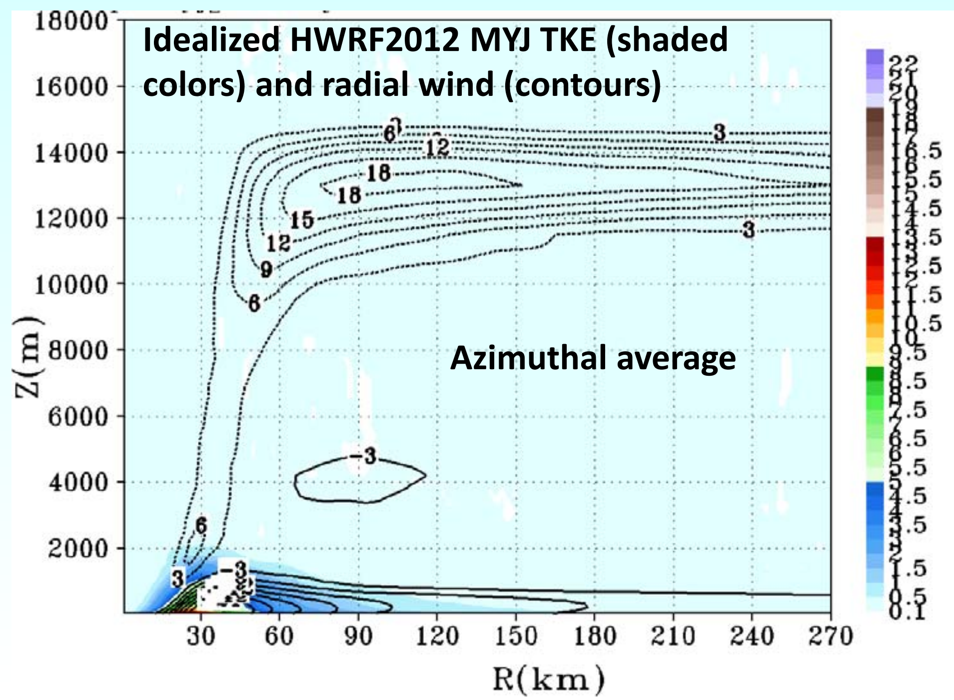


FIG. 7. The *R–Z* mean cross section of TKE for all cases, scaled on RMW.

Lorsolo *et al*. 2010





Constraint on Grid Scale KE and Subgrid TKE Energy Conservation (from G. Tripoli)

$$\frac{\partial k}{\partial t} = \mathbf{V}\cdot\frac{\partial \mathbf{V}}{\partial t}$$

$$= -\frac{1}{\rho}\nabla\cdot(\mathbf{V}\rho k) + \frac{k}{\rho}\nabla\cdot(\rho\mathbf{V}) - \mathbf{V}\cdot(\theta_{vv}\nabla\pi + \mathbf{g}) + \mathbf{V}\cdot(\mathbf{F}^1 + \mathbf{F}^2)$$

$$= -\frac{1}{\rho}\nabla\cdot(\mathbf{V}\rho k) \qquad + S_m^E \qquad + S_h^{PV} \qquad - S_e^{MP}$$

1. flux divergence of k transport.
2. Change in kinetic energy resulting from elastic momentum convergence
3. Conversion from kinetic energy to thermal energy (work term) resulting from the nonhydrostatic pressure velocity correlation.
4. Mechanical production conversion to e (turbulence kinetic energy)

$$\frac{\partial e}{\partial t} = -\frac{1}{\rho}\nabla\cdot(\rho\mathbf{V}e) + F_e^1 + F_e^2 + S_e^{MP} + S_e^{BP} + S_e^{DS} + S_e^{D} + S_e^{BS}$$

1. flux transport. The domain integral of this term produces a net source of *e* only from boundary fluxes
2. Physical turbulence
3. Numerical filter.
4. Mechanical production term
5. Buoyancy production term
6. Turbulence dissipation term- represents the downscale conversion of turbulence kinetic energy to molecular scale kinetic energy.
7. Divergence term
8. Mechanical backscatter production term.

Preliminary results from testing more generalized subgrid mixing scheme in idealized simulations

ARW Model Experiment Setup

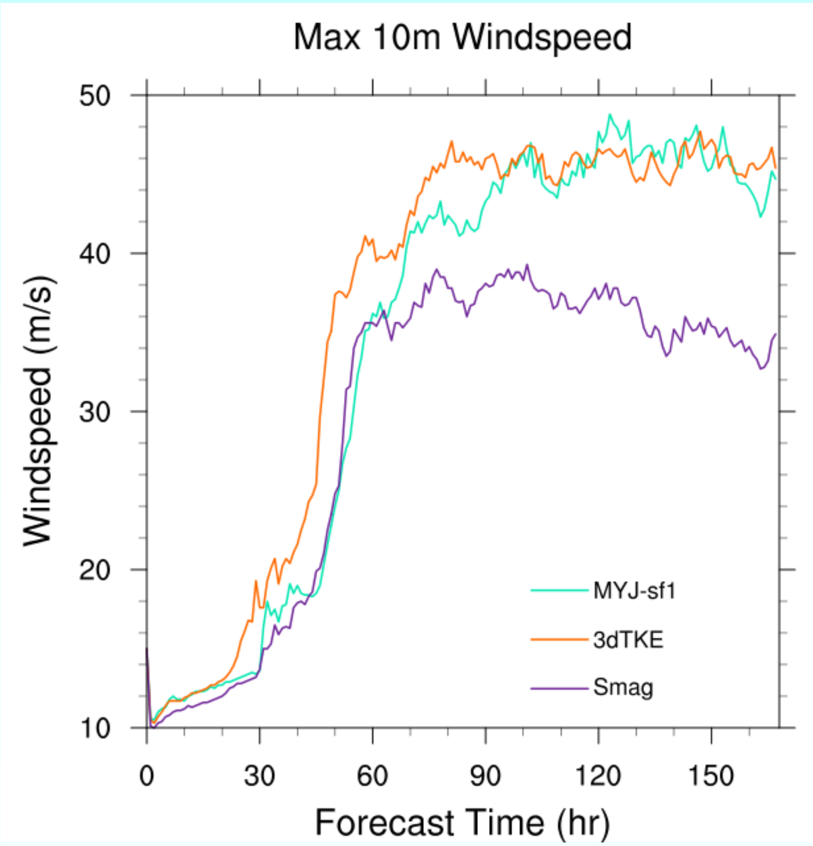
The model is initialized with a weak axisymmetric vortex disturbance in an idealized tropical environment that is favorable for the vortex disturbance to develop into a hurricane. The initial mass and wind fields associated with the weak vortex disturbance are obtained by solving the nonlinear balance equation for the given wind distributions of the initial vortex (Wang 1995, MWR), and the prescribed background thermal sounding and winds.

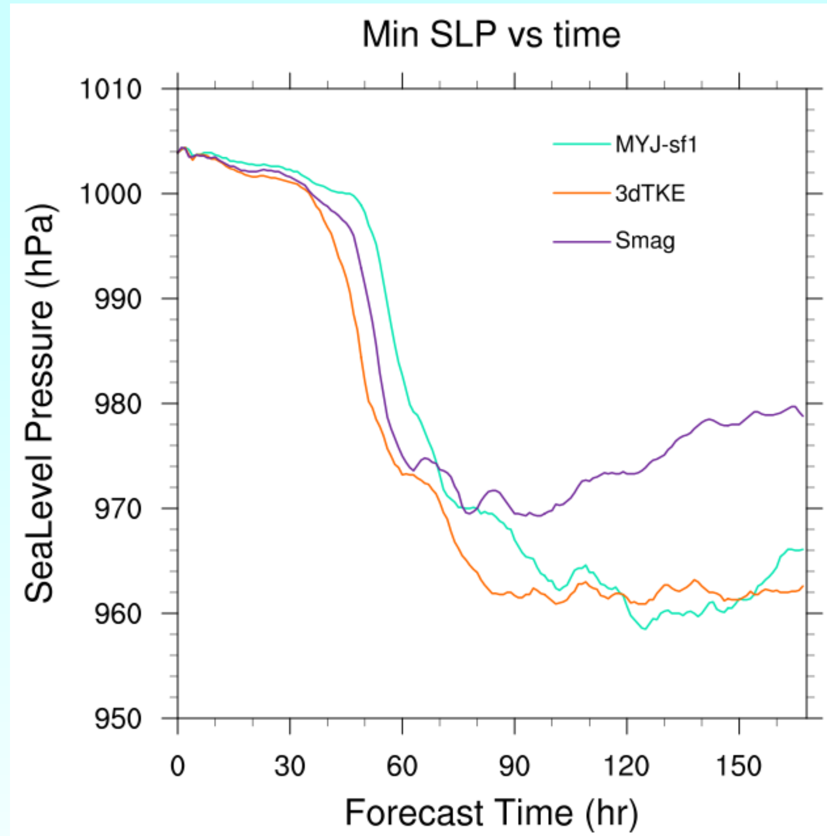
- *f*-plane located at 12.5^{o}N
- The prescribed axisymmetric vortex:
  — maximum surface tangential wind: 15 ms^{-1}
  — radius of surface maximum wind: 90 km
- Quiescent environment thermally corresponding to the Jordan sounding with a constant sea surface temperature of 29 ^{o}C
- Both models are run with 2 domains, a 9 km outer domain with a moving 3-km nest and 43 vertical levels

Table of experiments

Name of Experiments	V-Diff.	H-Diff.	Mixing Length	MP	CU	SFC
Sfclay1_MYJ_FerrSAS	MYJ	Smag+ TKE	L_h=Δs, L_v=kz/(1+kz/Linf) in PBL, and L_v=Δz>PBL	Ferrier	SAS (D1)	MO
sfclay1_stdwrf_FerrierSAS	3dTKE	3dTKE	L_h=Δs, L_v=Δz	Ferrier	SAS (D1)	MO
ssfclay1_mag_FerrierSAS	Smag	Smag	L_h=Δs, L_v=Δz	Ferrier	SAS (D1)	MO
Sfclay1_FerrSAS_cm1mods -linf100	3dTKE	Smag	L_h=Δs, Linf=100 L_v=kz/(1+kz/Linf)	Ferrier	SAS (D1)	MO
sfclay1_FerrSAS_10Lh_linf 100	3dTKE	3dTKE	L_h=10*Δs, Linf=100 Lv=kz/(1+kz/Linf),	Ferrier	SAS (D1)	MO
sfclay1_FerrSAS_0.1Lh_linf 100	3dTKE	3dTKE	L_h=10*Δs, Linf=100 L_v=kz/(1+kz/Linf)	Ferrier	SAS (D1)	MO

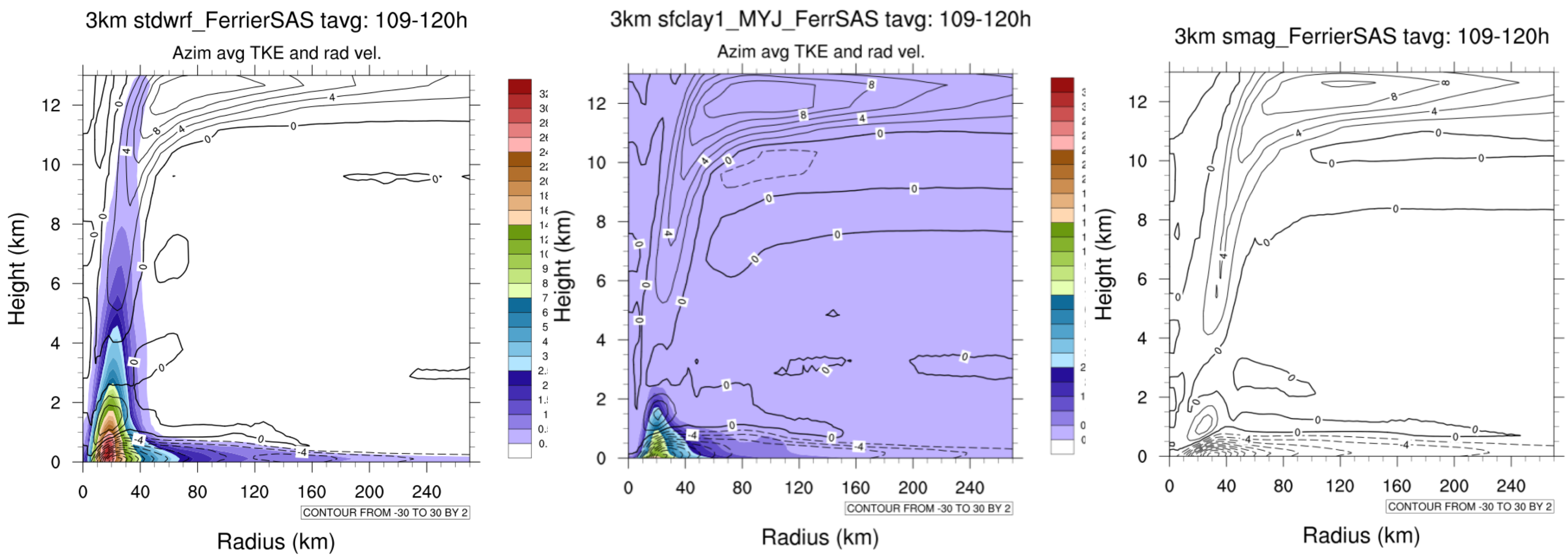
Sensitivity to Diffusion Option (same surface layer scheme)





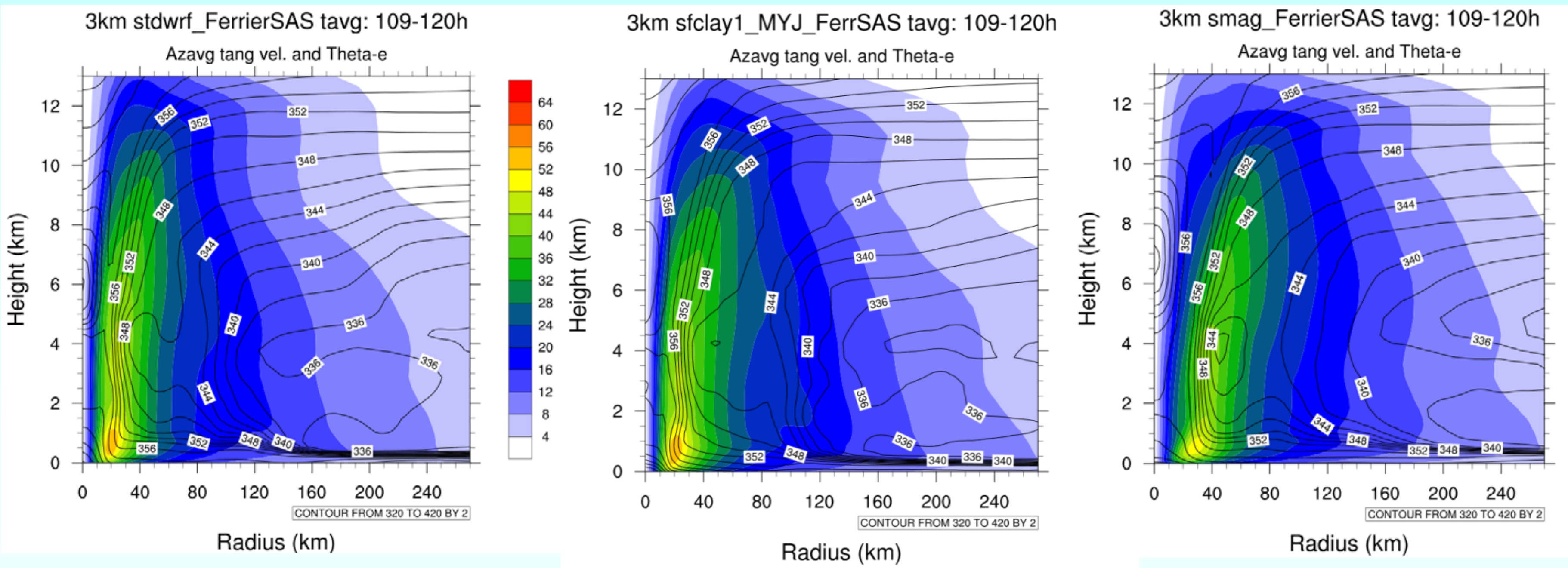
Sensitivity to Diffusion Option

Azimuthally averaged TKE and radial velocity



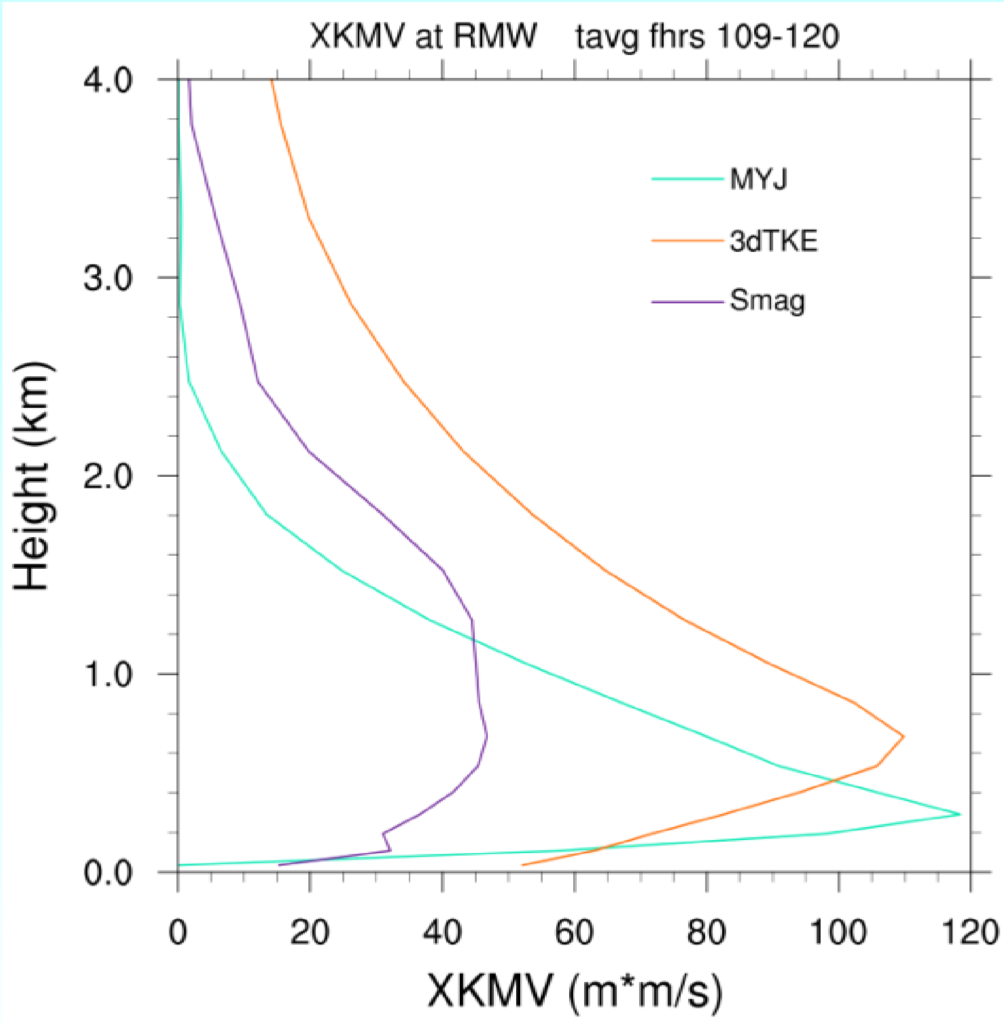
Sensitivity to Diffusion Option

Azimuthally averaged tangential wind speed and θ_e



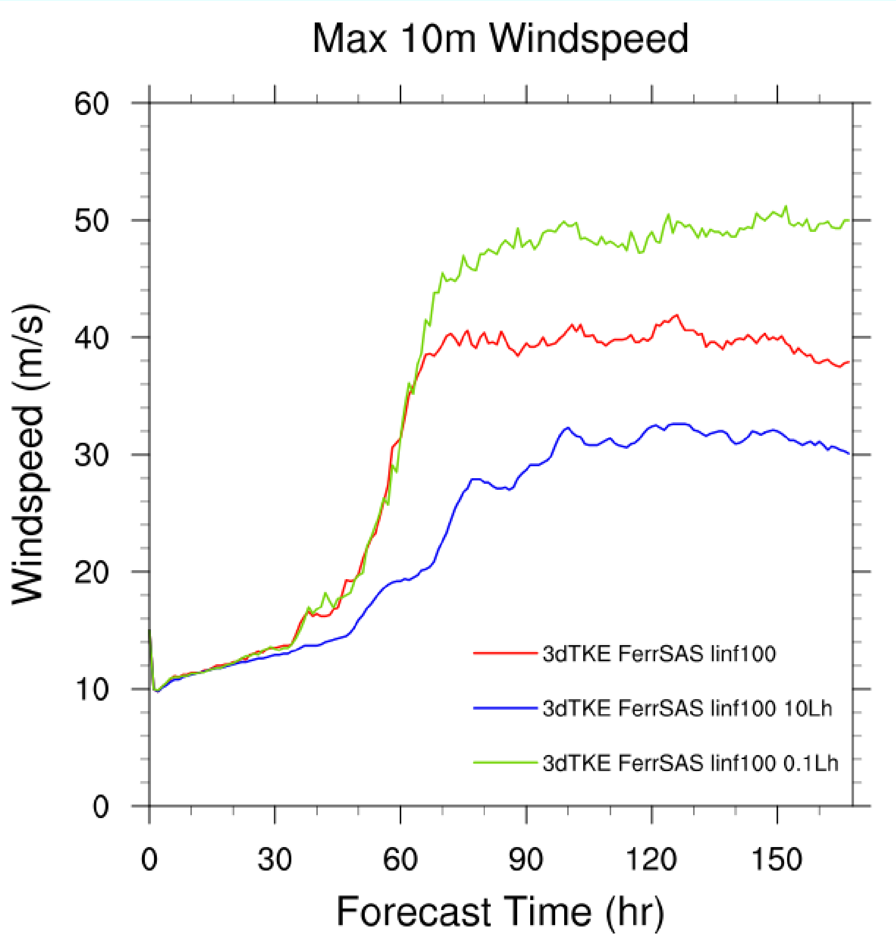
K Profiles at RMW

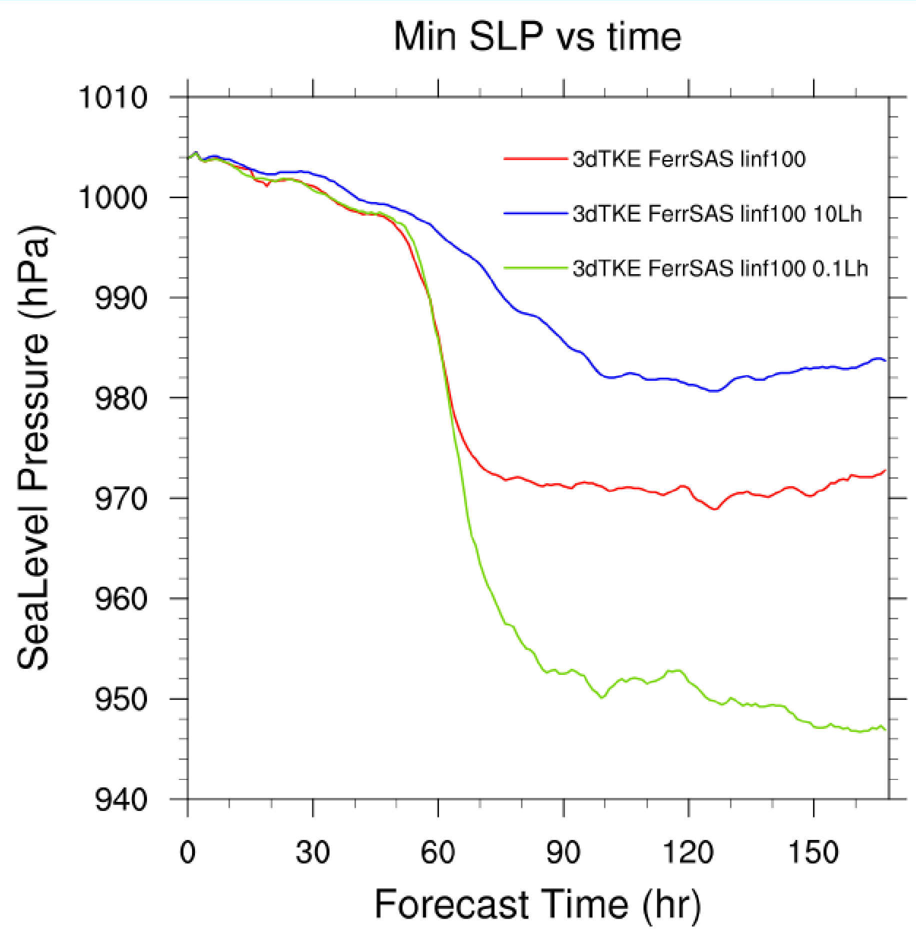
Varying diffusion options



L_h sensitivity

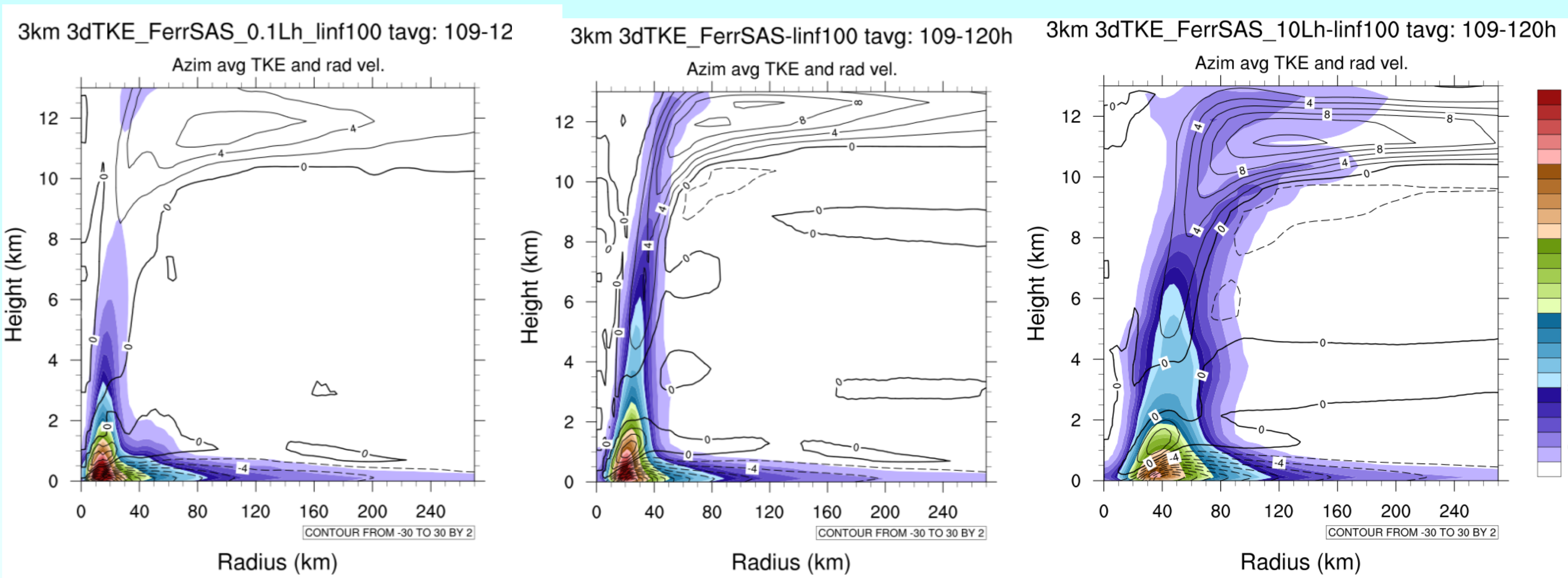
L_v =kz/(1+kz/Linf), Linf=100





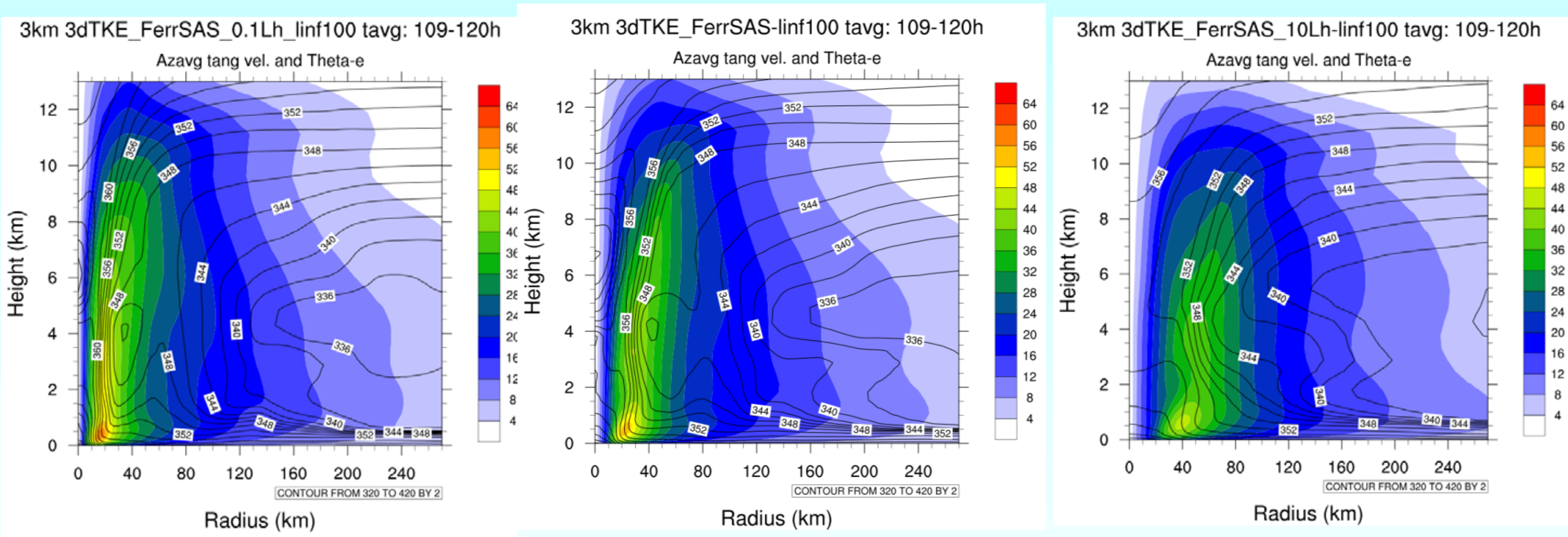
L_h sensitivity: $L_v = kz/(1+kz/Linf)$, Linf=100

Azimuthally averaged TKE and radial velocity



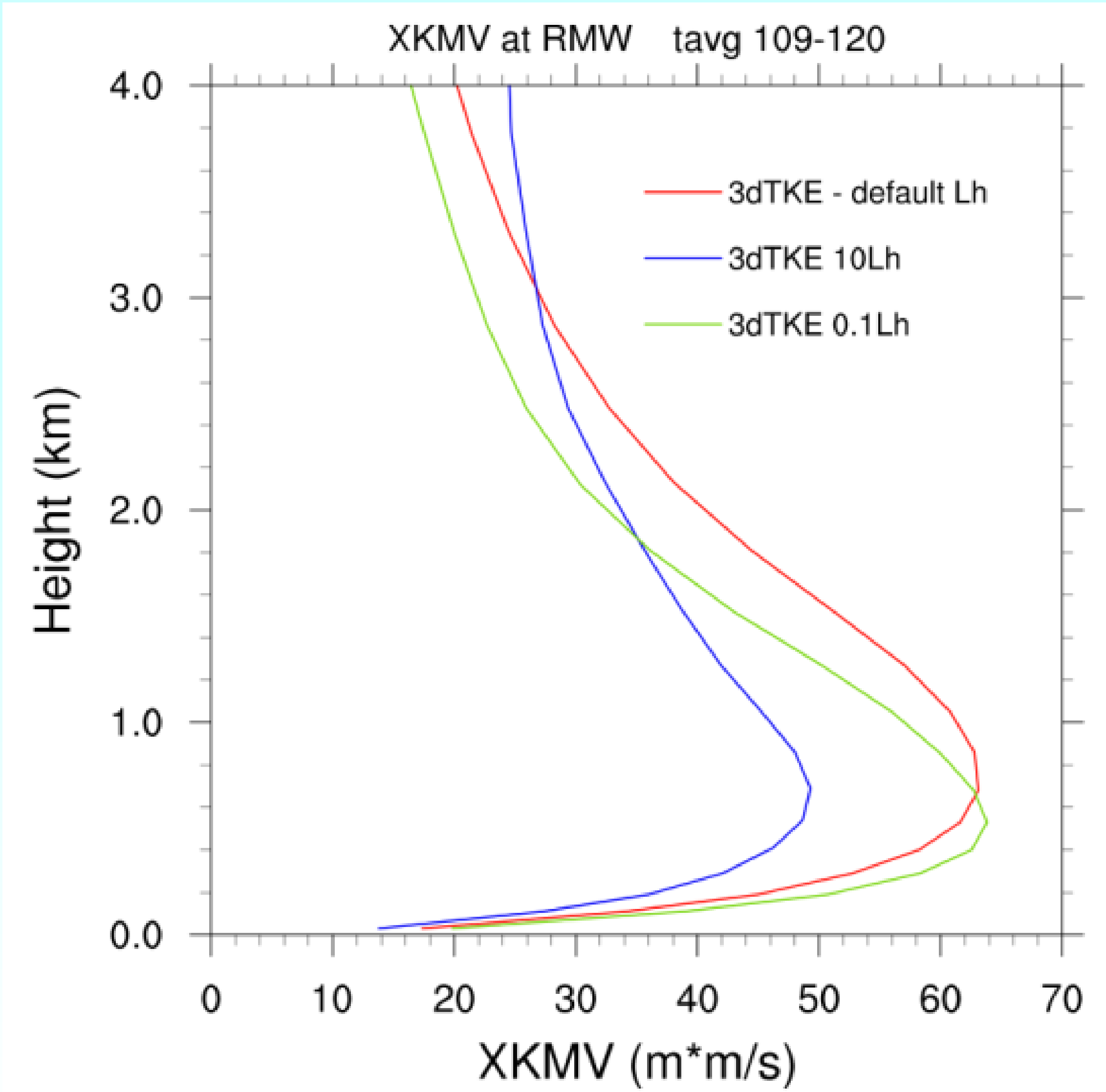
L_h sensitivity: L_v =kz/(1+kz/Linf), Linf=100

Azimuthally averaged tangential wind speed and Θ_e

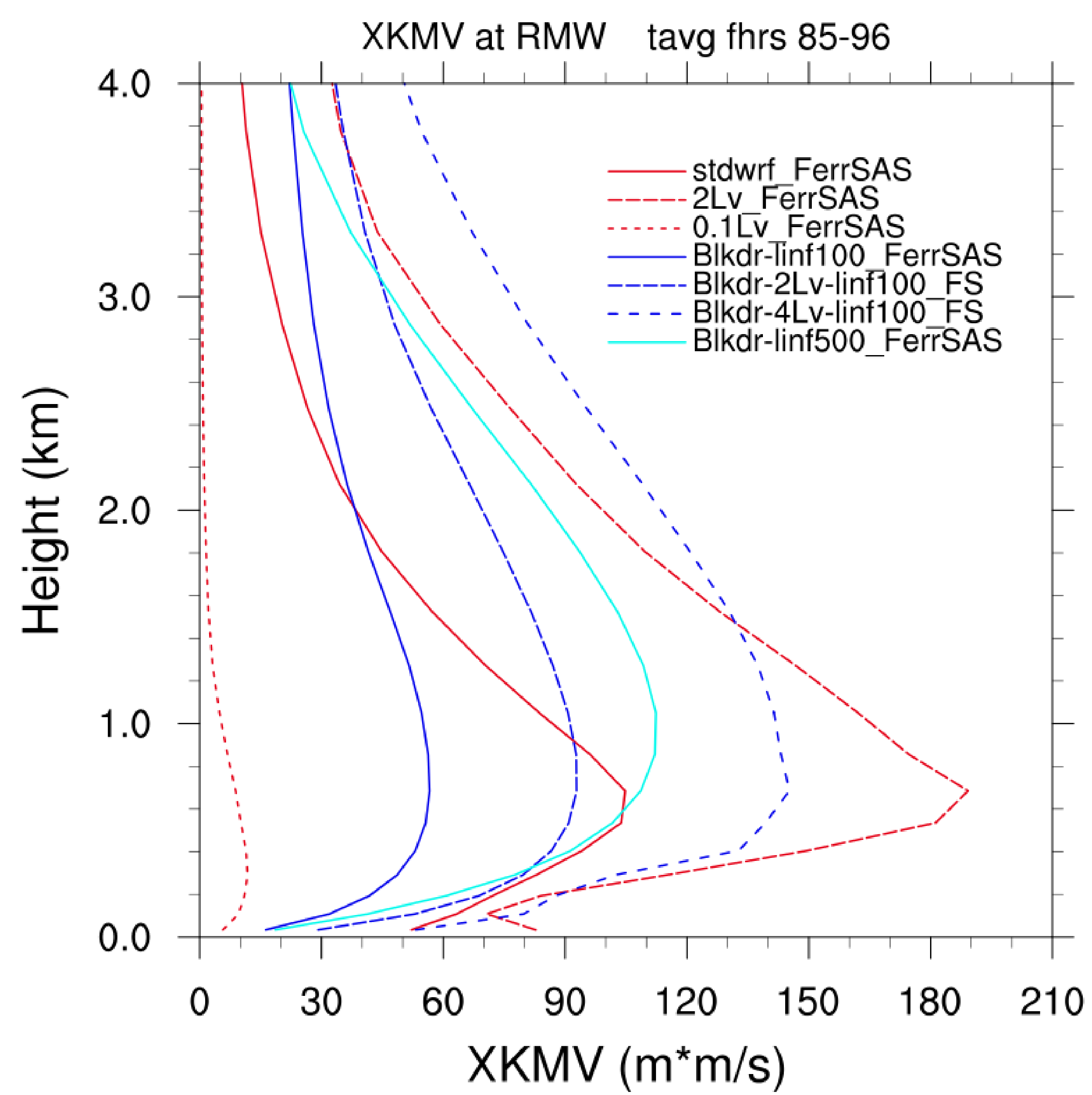


K Profiles at RMW

Varying horizontal diffusion



K Profiles at RMW: Varying Lv



Summary

Issue:

The conventional parameterizations of subgrid turbulent mixing in NWP models are based on the H-V scale separation when horizontal grid spacing is much greater than the scale of PBL depth. No constraint in KE to TKE conversion.

There is need for justification of using the PBL depth as one of the closure parameters.

Challenge:

Coherent parameterizations of 3-D subgrid mixing should be explored as tropical cyclone model resolution continues increasing.

Comparisons of the model parameters describing subgrid mixing should account for the fact that the observational estimate of these parameters is scheme-dependent.

Uncertainties in microphysics schemes in an idealized environment

- The 3 versions of the Ferrier scheme in HWRF2012
- Spectral bin vs bulk schemes in ARW

Multistage Intensification Process of a Weak Vortex into a Hurricane

- **First stage (0 – 18 h): initiation of convective vortices and their aggregation due to the adjustment of initial axisymmetric weak vortex associated with the development of shallow warm clouds to deep clouds of water-ice mixed phase**
- **Second stage (18 h – 36 h): further aggregation of the vortices into a strong TC-like vortex with an organized TC eyewall**
- **Third stage (beyond 36 h): further intensification of the TC-like vortex to the hurricane strength**

Only the preliminary analysis of the first stage is reported here.

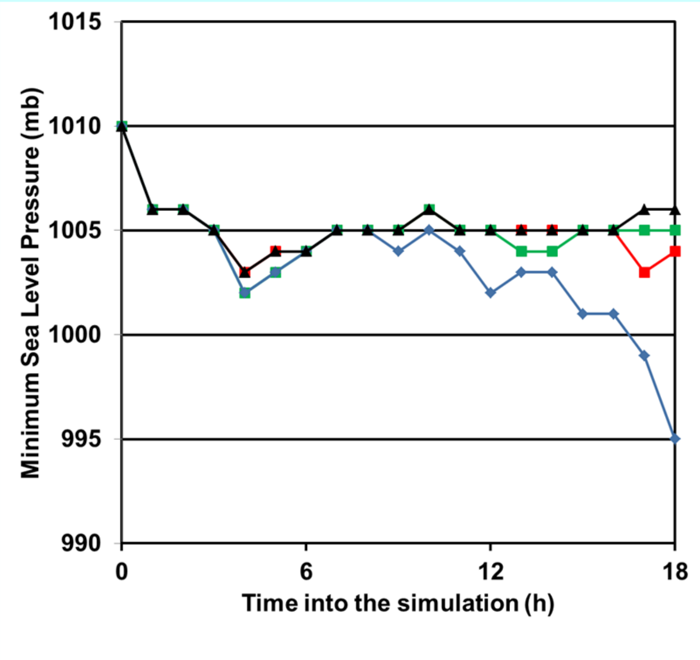
HWRF2012 Model Experiments

Other than microphysics, all experiments use HWRF2012 default physics; the idealized initialization was done the same as in the ARW simulations mentioned previously.

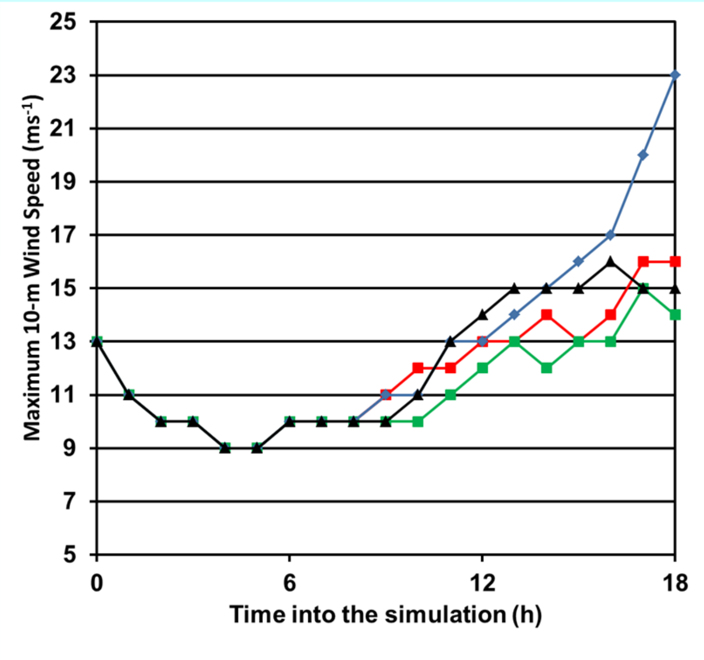
Experiment Name	Microphysics
gfsgfdl_hwrffer	Default HWRF2012 microphysics
gfsgfdl_mp5-etanew	Microphysics option #5- uses subroutine module_mp_etanew.F
gfsgfdl_mp95-etaold	Microphysics option #95- uses subroutiine module_mp_etaold.F
gfsgfdl_hwrffer-mod	Default HWRF2012 microphysics with modifications to replace the rate of collection of cloud water by rainwater with that from module_mp_etanew.F

First-Stage Intensity Differences Made by Different MP schemes

Minimum sea-level pressure

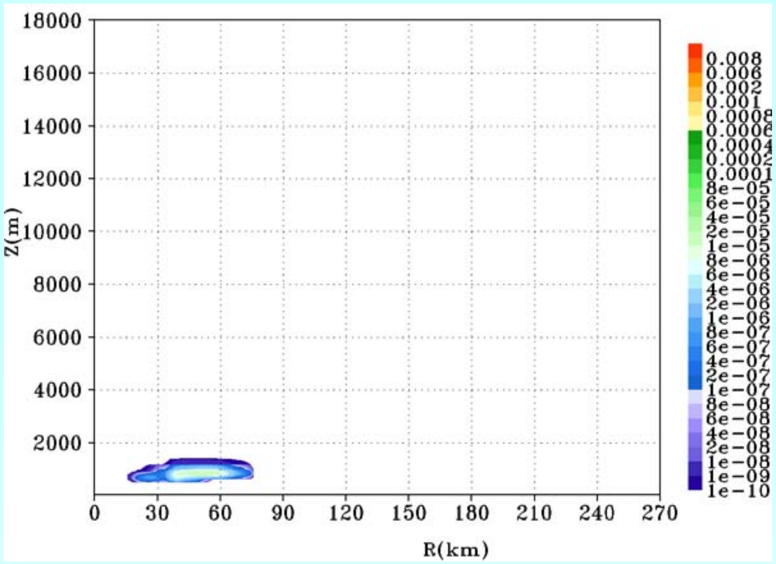


Maximum 10-m wind speed

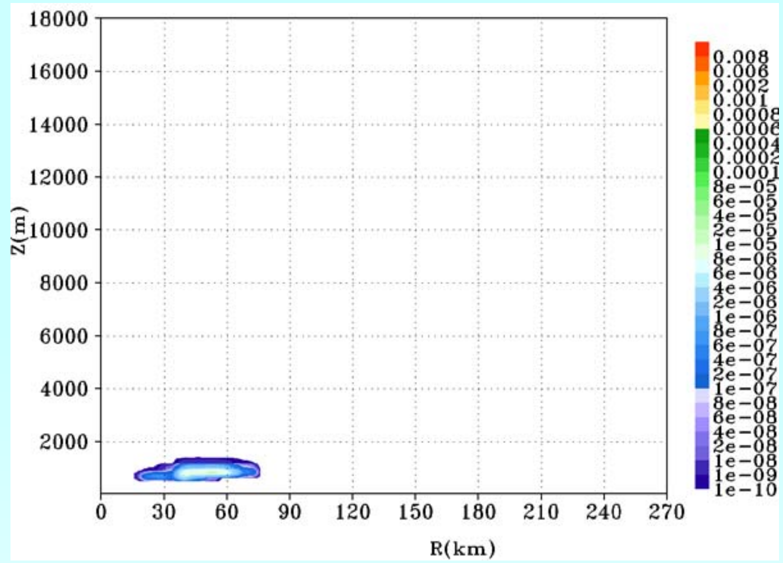


Azimuthally averaged QCLD valid at hour 4

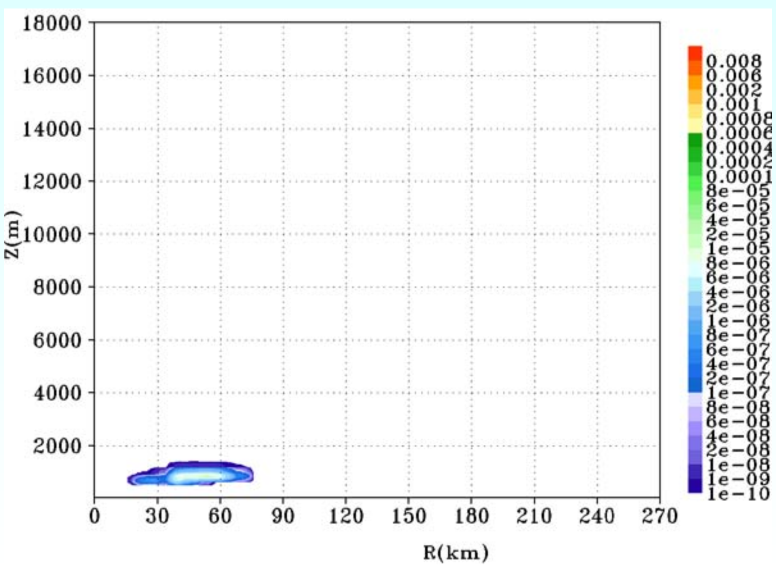
GFSGFDL-HWRFFER



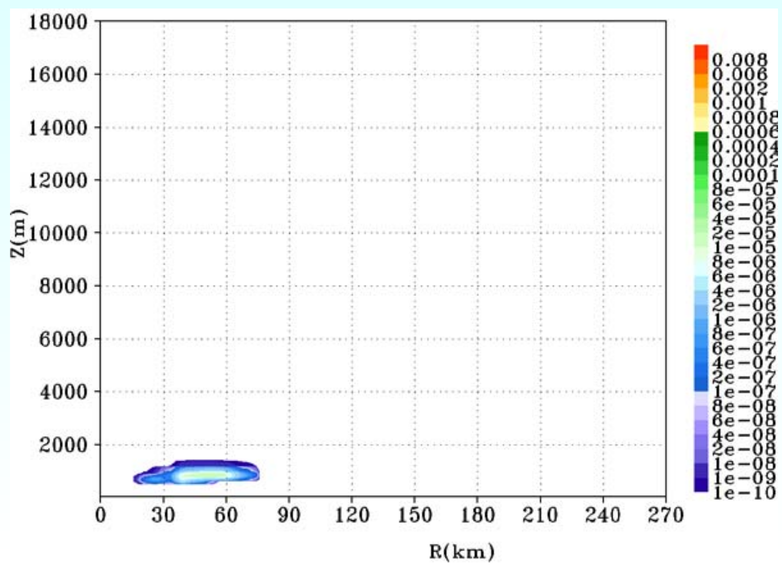
GFSGFDL-MP5-ETANEW



GFSGFDL-MP95-ETAOLD

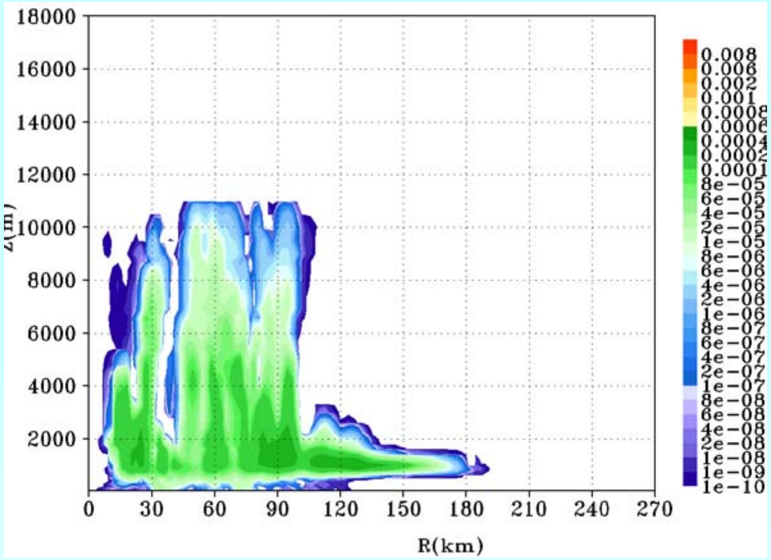


GFSGFDL-HWRFFER-mod

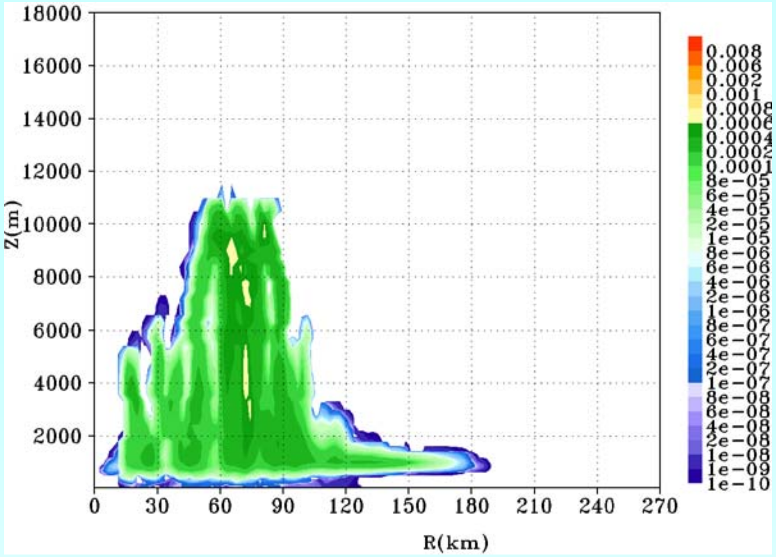


Azimuthally averaged QCLD valid at hour 12

GFSGFDL-HWRFFER



GFSGFDL-MP5-ETANEW



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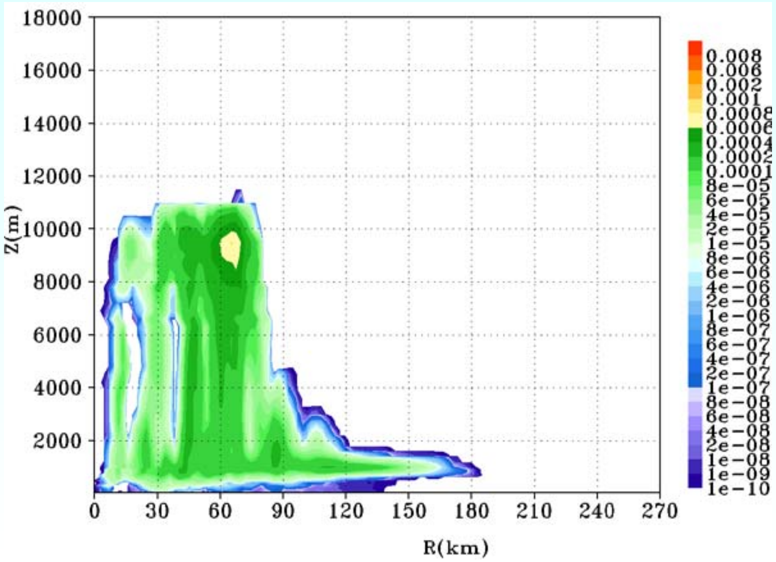
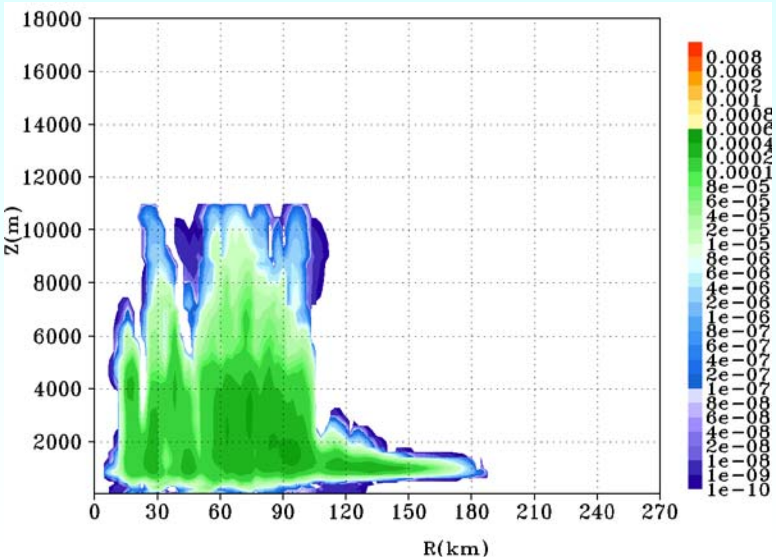
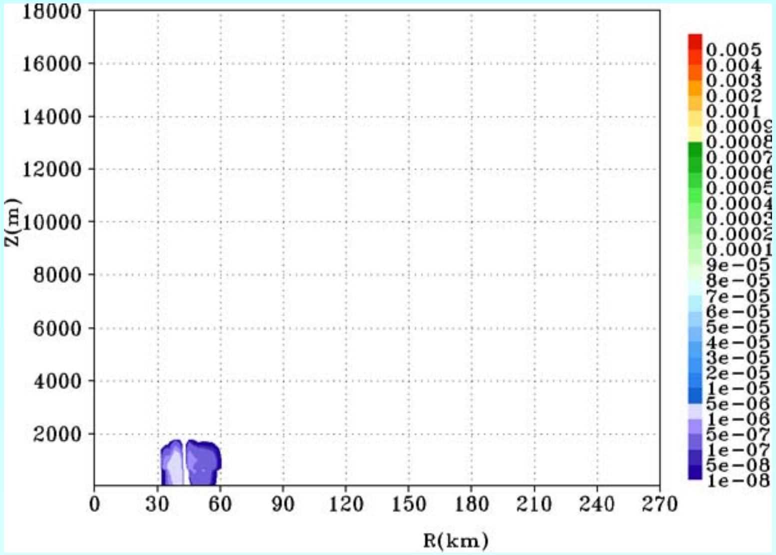


GFSGFDL-HWRFFER-mod

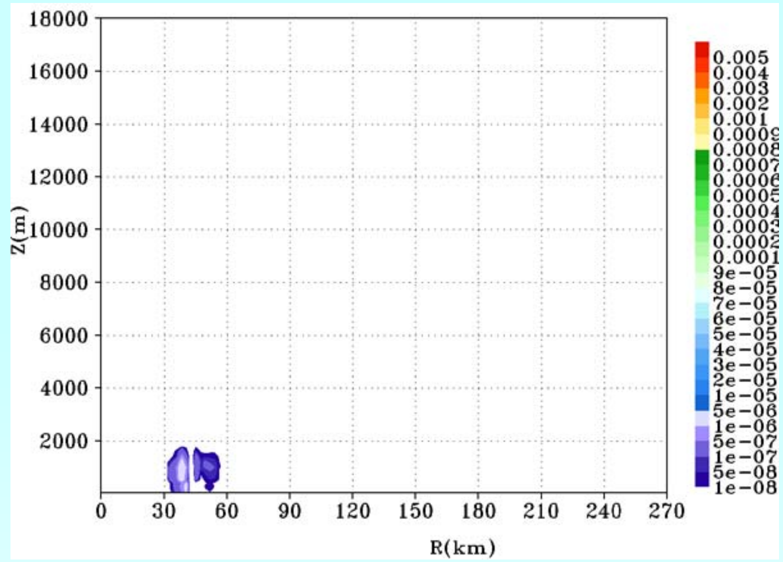


Azimuthally averaged QRAIN valid at hour 6

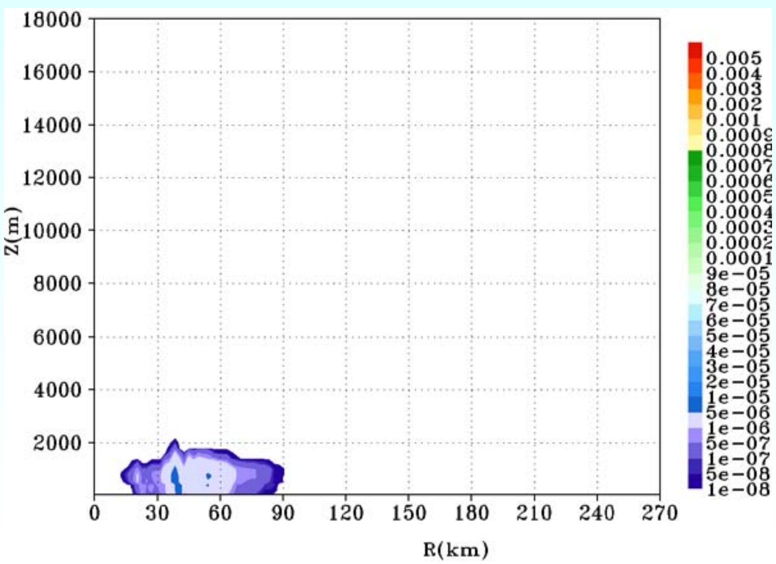
GFSGFDL-HWRFFER



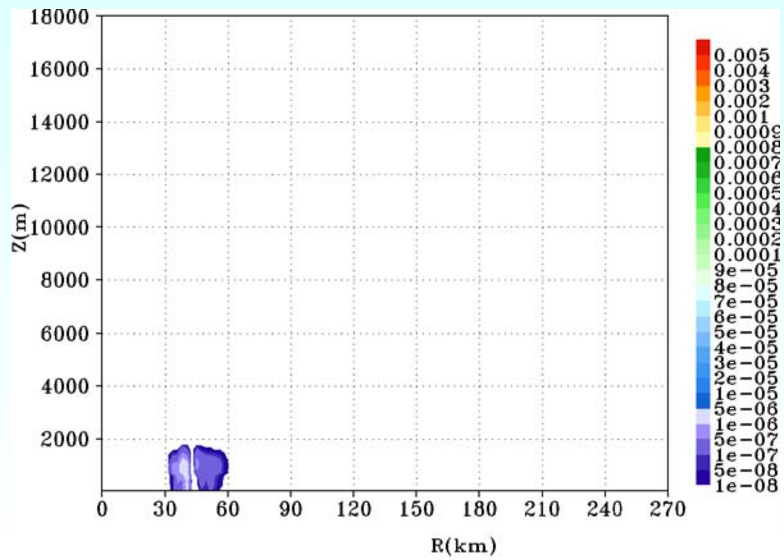
GFSGFDL-MP5-ETANEW



GFSGFDL-MP95-ETAOLD

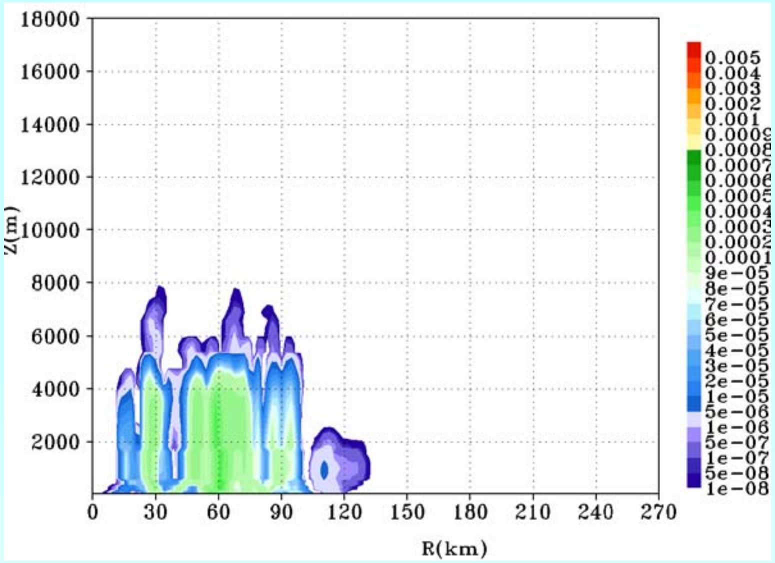


GFSGFDL-HWRFFER-mod

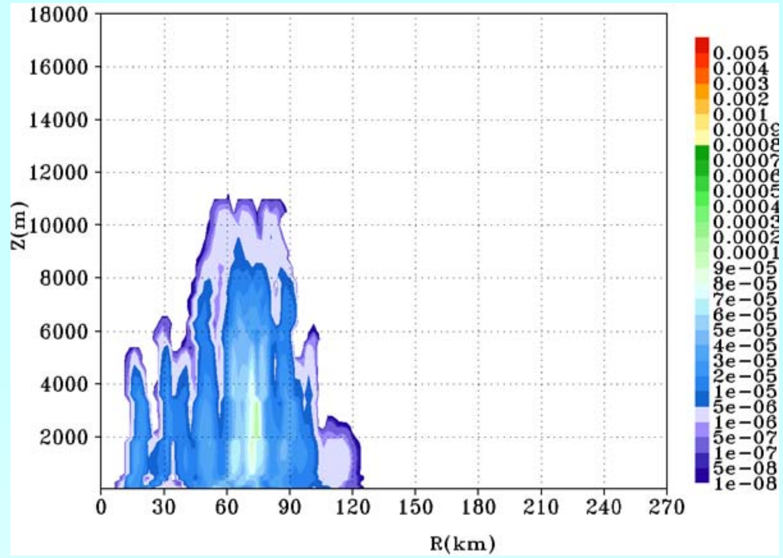


Azimuthally averaged QRAIN valid at hour 12

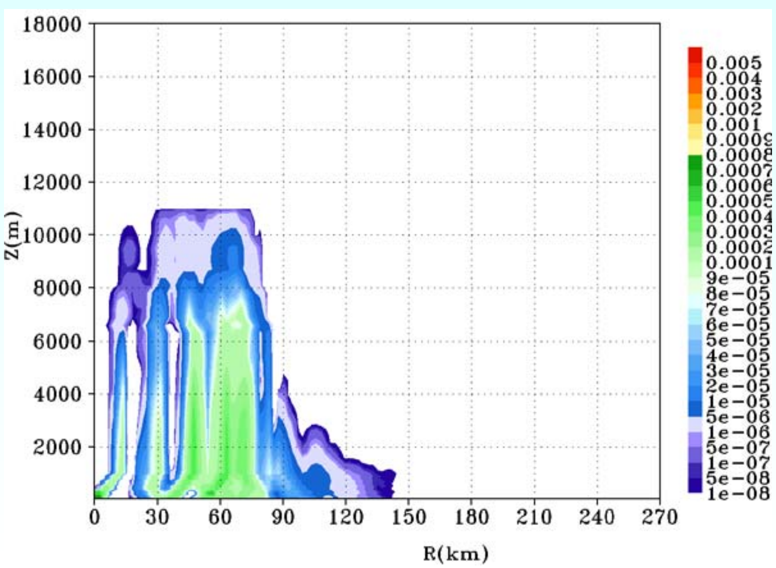
GFSGFDL-HWRFFER



GFSGFDL-MP5-ETANEW



GFSGFDL-MP95-ETAOLD



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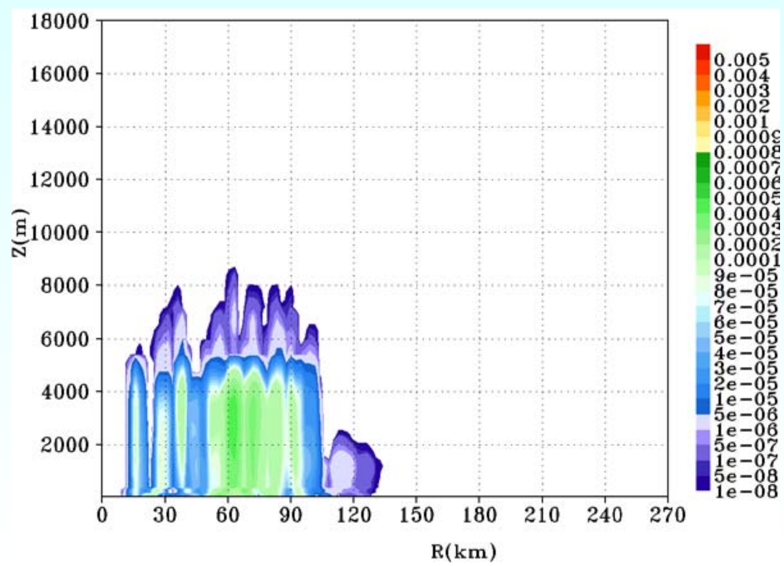
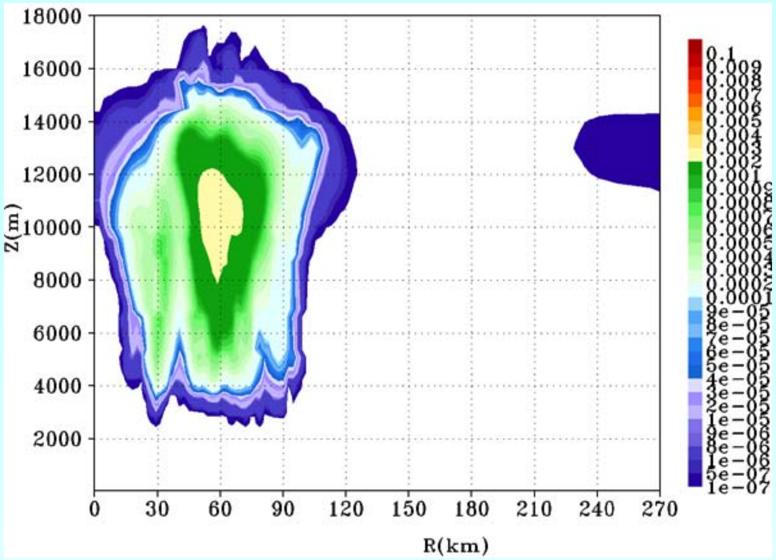
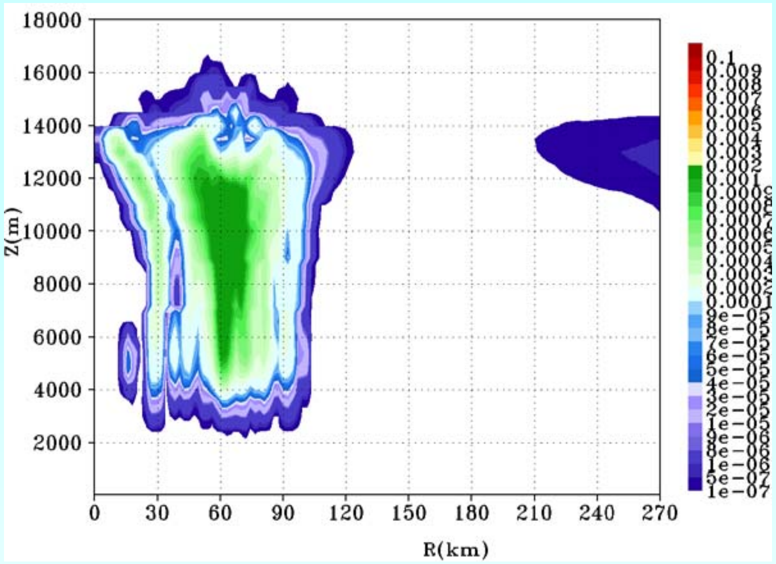


Azimuthally averaged QICE valid at hour 12

GFSGFDL-HWRFFER



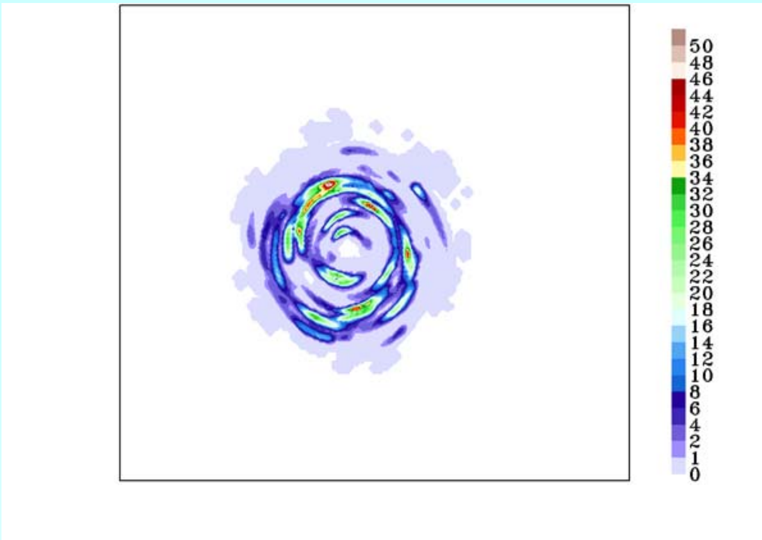
GFSGFDL-HWRFFER-mod



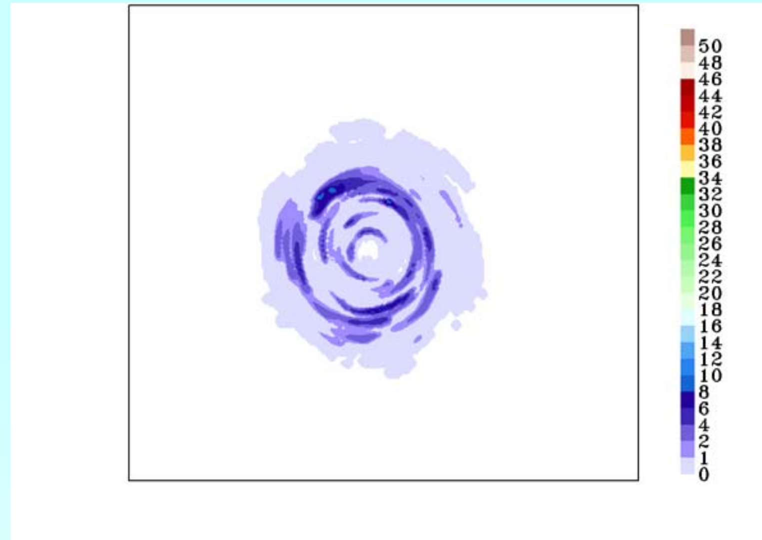
The differences highlight the challenge we are facing in using observations of just one hydrometeor species, such as cloud ice, to verify the MP scheme. How do we discern whether the differences in one hydrometeor species is caused by deficiencies in the formulations of the other hydrometeors?

Accumulated precipitation (mm) valid at hour 12

GFSGFDL-HWRFFER



GFSGFDL-MP5-ETANEW



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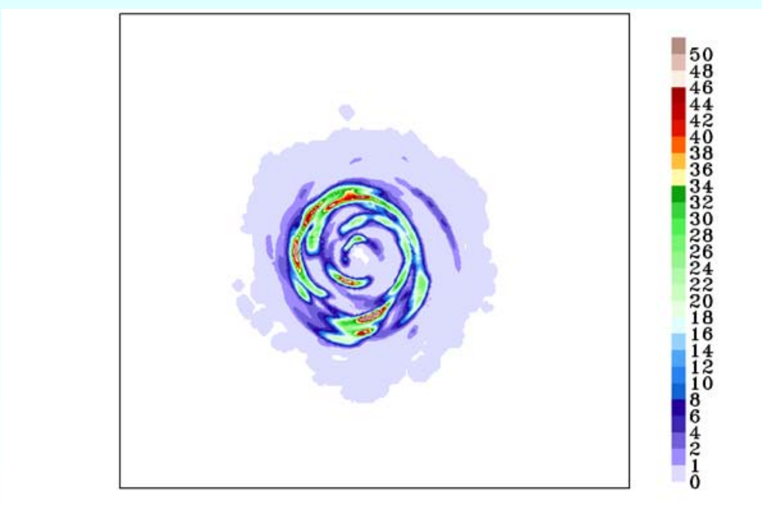
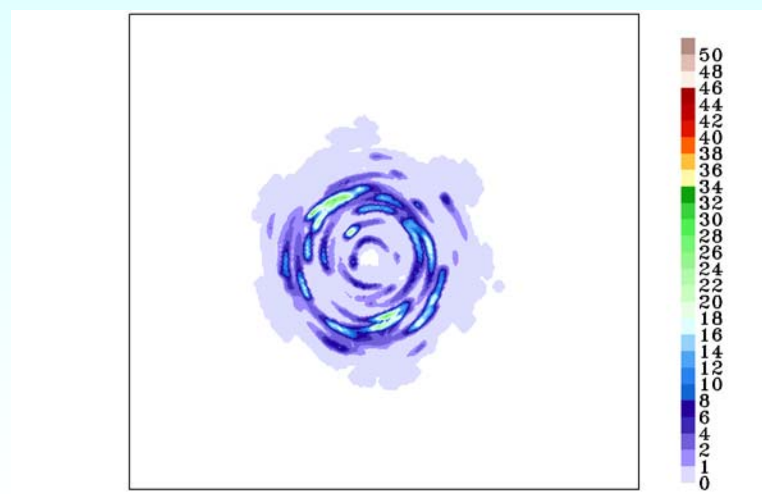


GFSGFDL-HWRFFER-mod



Summary

Issue:

There are great uncertainties in the rates of conversion/accretion for various hydrometeors, significantly affecting the intensification dynamics.

Challenge:

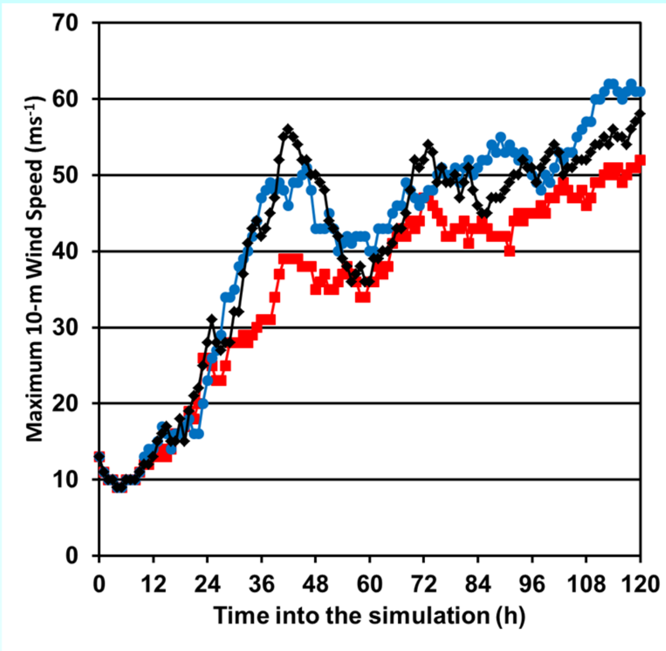
There is a needed to evaluate microphysics schemes of various complexity on an equal footing using observations in order to address the question of how much accuracy is sufficient for operational TC models and to what degree we can achieve such an accuracy.

There is a need for observations of more than one hydrometeor species (including precipitation) to be used for evaluating and improving operational MP schemes.

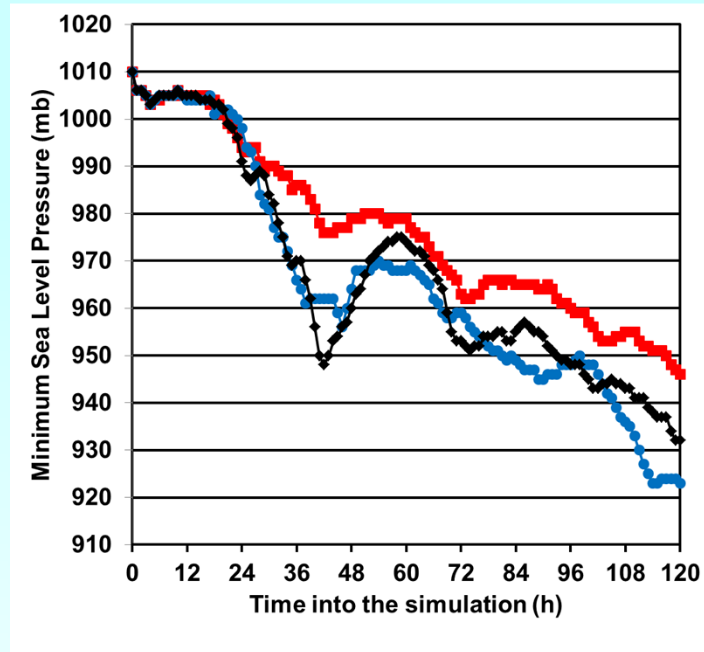
Uncertainties in shortwave and longwave radiation schemes in an idealized environment

Experiment Name	Longwave scheme	Shortwave scheme
gfsgfdl_hwrffer	Default HWRF2012 Longwave radiation	Default HWRF2012 Shortwave radiation
gfsgfdl_hwrffer_lw4sw98	Longwave=RRTMG	Default HWRF2012 Shortwave radiation
gfsgfdl_hwrffer_lw4sw2	Longwave=RRTMG	Shortwave=Goddard

Maximum 10-m wind speed



Minimum Sea Level Pressure



gfsgfdl_hwrffer

gfsgfdl_fer_lw4sw98

gfsgfdl_hwrffer_lw4sw2

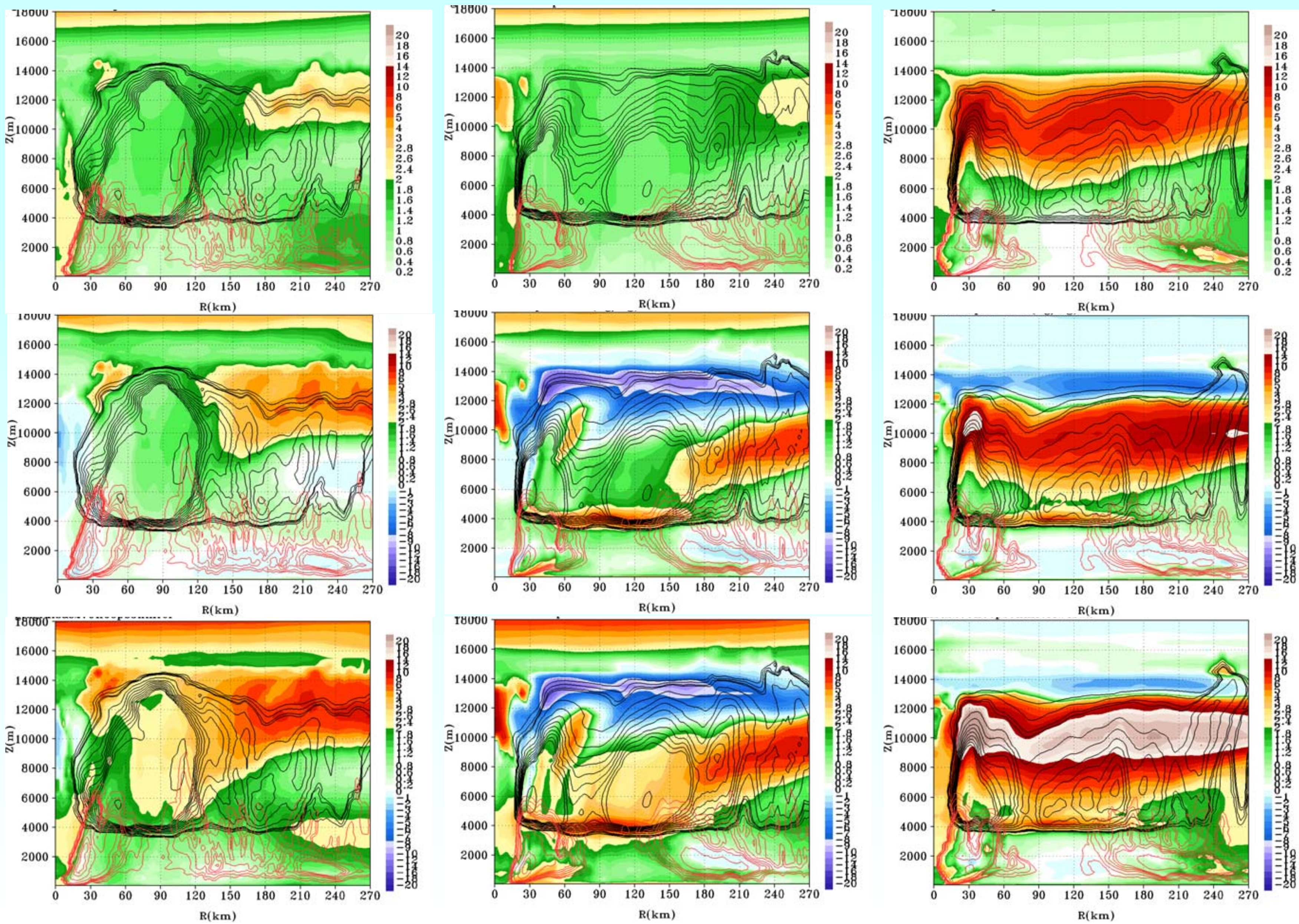
Radiational heating (K/day)/QICE (black contours) and QCLD (red contours) at 54 h

gfsgfdl_hwrffer | gfsgfdl_hwrffer_lw4sw98 | gfsgfdl_hwrffer_lw4sw2

SW

LW

Total



Summary

Issue:

Radiation-cloud interaction tends to destabilize cloudy layers, which regulates the intensification of deep convection in the TC inner core.

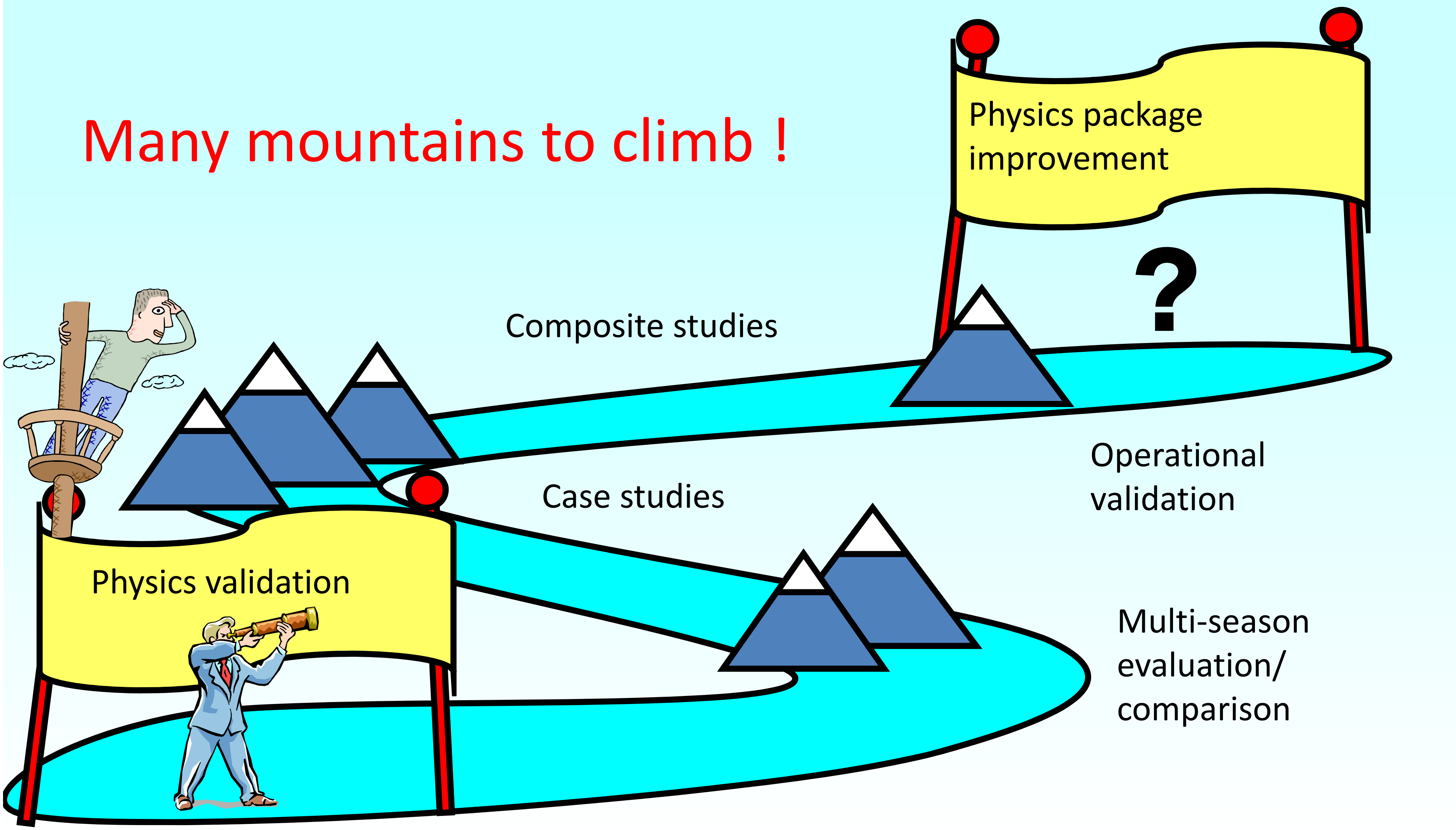
However, great uncertainties exist in the microphysical details of the cloud specification required by radiative transfer schemes (a problem shared by models from GCMs for climate simulations to NWP models on various scales).

Challenge:

More observations of cloud-radiation interaction processes in tropical cyclones are needed for model evaluation.

How much accuracy is enough?

The path to improved physics package in tropical cyclone models…




Questions for discussion?