The Grell-Freitas scale- and aerosol aware stochastic convective parameterization: development as well as global and regional applications

Georg A. Grell

With slides from: Saulo R. Freitas, Joseph Olson, Jian-Wen Bao, E. Grell, I. Jankov, P. Marrapu, B. Skamarock, L. Fowler, Steven E. Peckham

Structure of talk

- Basic details of Grell-Freitas convection scheme (as of 2014)
- Scale-awareness (RAP, WRF-Hurricane simulations, fresh from the press HWRF simulation)
- Scale-awareness global (MPAS)
- New implementations for HIWPP (as of May 2015)
- Stochasticism
- More improvements when using within GFS physics: Using a few more SAS “features” (as of last week)
- Next
- Aerosol-awareness experiments (WGNE working group)

Motivation

1. NWP and Air Quality modeling on better and better resolutions: need for scale and aerosol aware convective parameterization
   - Use stochastic parameterization
   - Including transport of chemical compounds,
   - Including aerosol interactions
2. Improve predictive skill
   - Convection permitting
     - Hurricane track and intensity forecasts
     - Short range weather forecasting
   - Range of scales (hydrostatic to convection permitting
     - Medium range NWP
     - Seasonal predictions
3. Special additional intention for talk here at EMC: possibly get some ideas on further development and applications especially with respect on how GF schemes interacts with other physics in GFS physics package

Grell-Freitas Convective Param

- **Scale-aware/Aerosol-aware (Grell and Freitas, 2014, ACP)**
  - Stochastic approach adapted from the Grell-Devenyi schem
    - Originally many parameters could be perturbed
    - In 2014 version only 2 were kept (closures and capping inversion threholds)
  - Scale awareness through Arakawa approach (2011) or spreading of subsidence
  - Aerosol awareness is implemented with empirical assumptions based on a paper by Jiang and Feingold
  - Separate shallow scheme also exists with modifications by Joe Olson

The scale awareness: Our adaptation of Arakawa's approach

1. Define fractional coverage (σ) = area covered by active updraft and downdraft plume
2. Define very simple relationship between σ and entrainment rate (which is related to radius of plume) – but any other approach may easily be used
3. Initial entrainment rate determines when σ is becoming important (when scale awareness kicks in),
   - Maximum allowable fractional coverage determines when scheme transforms itself to a shallow convection parameterization
   - This effect can be turned off

Aerosol awareness

Change 1: Change constant autoconversion rate to aerosol (CCN) dependent Berry conversion

$$\left(\frac{\partial r_{rain}}{\partial t}\right)_{\substack{\text{autoconversion}\\ \text{Berry, 1968}}} = \frac{(\rho r_c)^2}{60\left(5+\frac{0.0366\ CCN}{\rho r_c m}\right)}$$

Change 2: Modified evaporation of raindrops (Jiang and Feingold) based on empirical relationship

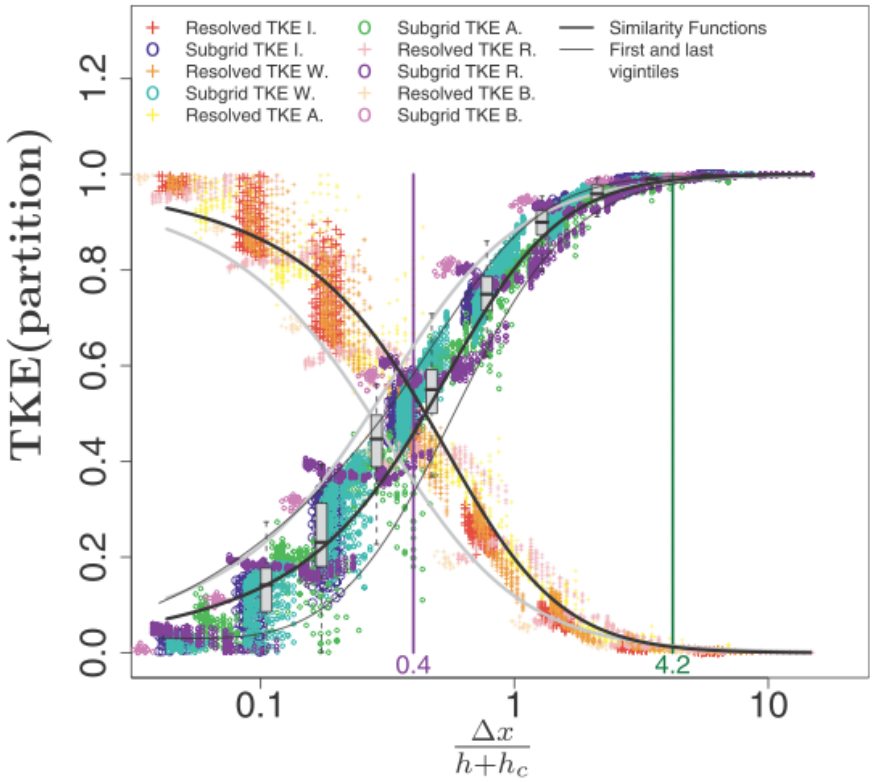
$$PE \sim (I_1)^{\alpha_s - 1}(CCN)^{\zeta} = C_{pr}(I_1)^{\alpha_s - 1}(CCN)^{\zeta}$$

Change 2 introduces a proportionality between precipitation efficiency (**PE**) and total normalized condensate (**I_1**), requiring determination of the proportionality constant **C_{pr}**

Tapering of Shallow-Cu Scheme

- **Based off of Honnert et al. (2011, JAS):**
  - ✧ TKE partition in the entrainment layer

Figure 5 (a) $0.85 \leq \frac{z}{h} \leq 1.1$



- **Other methods are/will be tested (i.e., Shin and Hong 2013, JAS).**

Aerosol awareness

How do we get CCN?

1. **Most sophisticated approach:**
   directly from complex model results (WRF-Chem)
2. **Simplest approach:**
   from observed Aerosol Optical Thickness (AOT) at 550 nm (global or regional analysis), following Rosenfeld et al. (2008) and Andreae et al (2008), using

$$AOT = 0.0027\, CCN^{-0.643}$$

3. **Or anywhere in between – depending on complexity of model setup**

The dependency introduced through precipitation efficiency

- can have a strong effect on downdrafts, but is
- limited by other environmental conditions (e.g., if the precipitation efficiency is already very low, it cannot get much lower, and vice versa)

Improving WRF Physics to Better Perform Across a Wide Range of Spatial Scales

Joseph Olson and Georg Grell

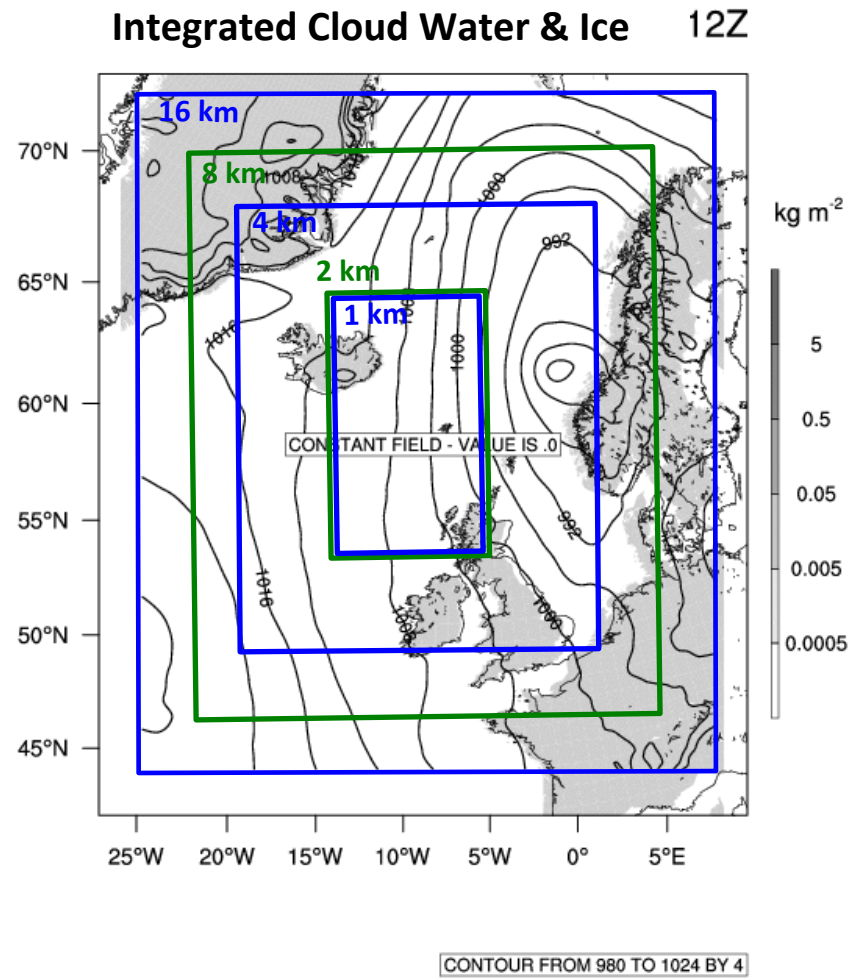
Test Case: Grey Zone Project

Organized by the U.K. Met Office with many participants from around the world.
Cold-air outbreak case over N. Atlantic.
Primarily shallow-cumulus regime with very little deep convection.

Grey Zone Project to test scale awareness

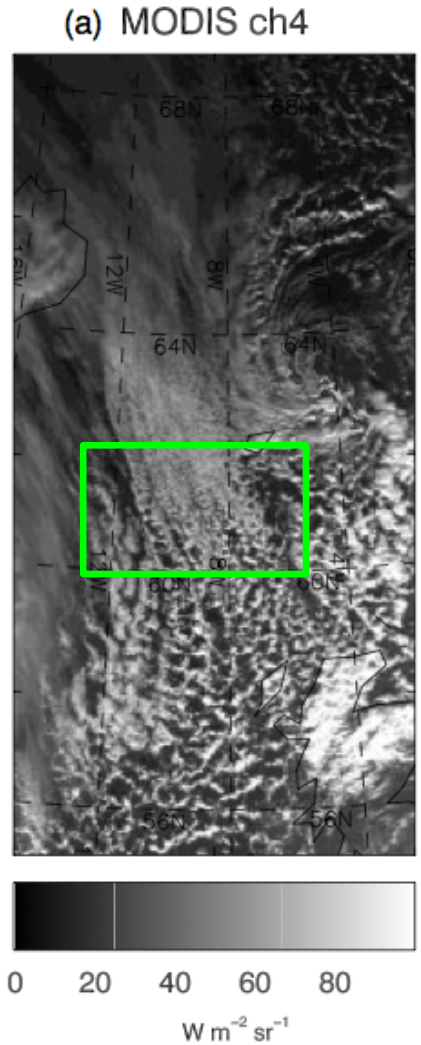
The Grey Zone Project (headed by UK Met Office) aims to systematically explore convective transport and cloud processes in NWP models at resolutions ranging from 1 to 16 km.

- For each set of the LAM simulations (at grid spacings of 1, 2, 4, 8, 16 km), two permutations were run:
  1. GF deep-cu scheme **OFF** GF shallow-cu scheme **OFF**.
  2. GF deep-cu scheme **ON** GF shallow-cu scheme **ON**.
- 36 hour simulations are done using ECMWF analyses beginning at 12 UTC 30 Jan 2010, and used every 6h to generate LBCs for the coarsest domains.
- Two set of 1-way nested domains are used:
  - 16-4-1 km grids
  - 8-2 km grids

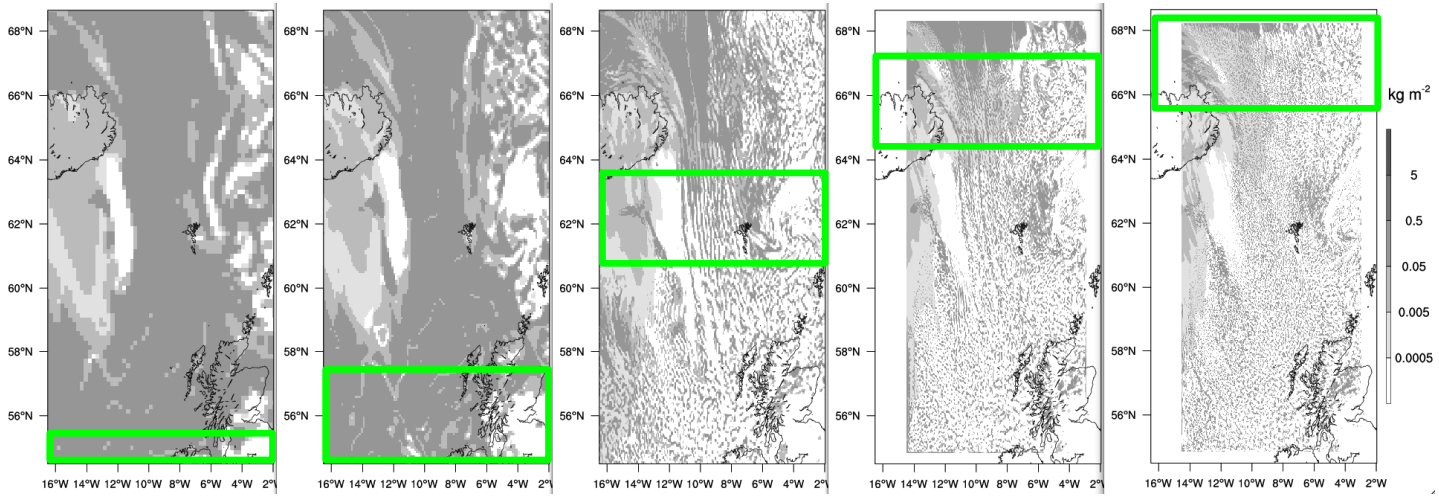


Final results after some improvements in the PBL (MYNN-Olson) scheme

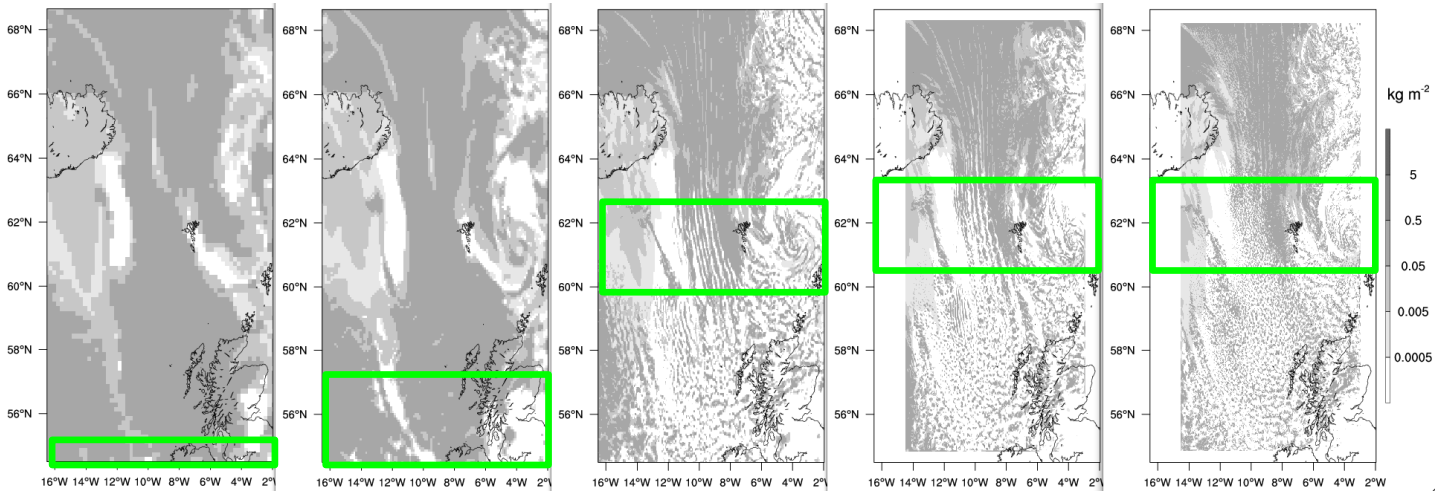
Δx = 16 km Δx = 8 km Δx = 4 km Δx = 2 km Δx = 1 km



Cu off, ShCu off, 51 levels (Control)



Cu on, ShCu on, 63 levels, with PBL mods



Above figure taken from Field et al (2013).

MPAS
Model for Prediction Across Scales

Variable Resolution Tests using the Grell-Freitas Convection Scheme

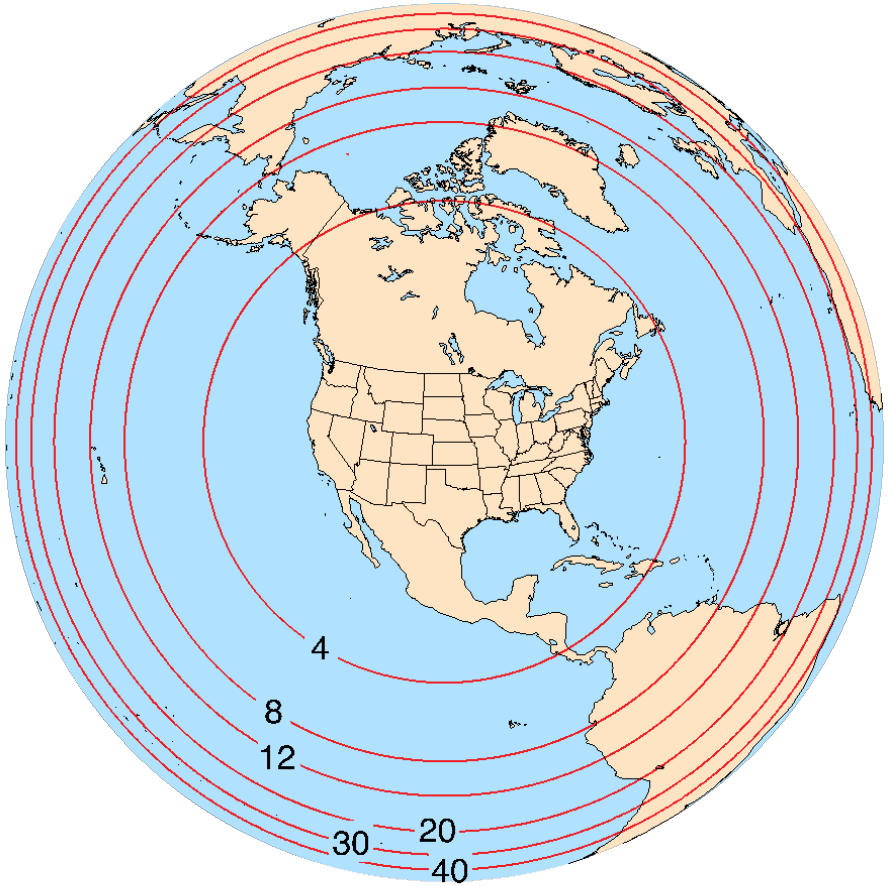
(Laura Fowler, Bill Skamarock, GF group)

MPAS mesh:

50 – 3 km variable resolution.
CONUS is the 3 km region.
Very smooth transition to the 50 km region.

MPAS Physics:

- WSM6 cloud microphysics
- Grell-Freitas convection scheme
- Monin-Obukhov surface layer
- YSU PBL
- Noah land-surface
- RRTMG lw and sw.

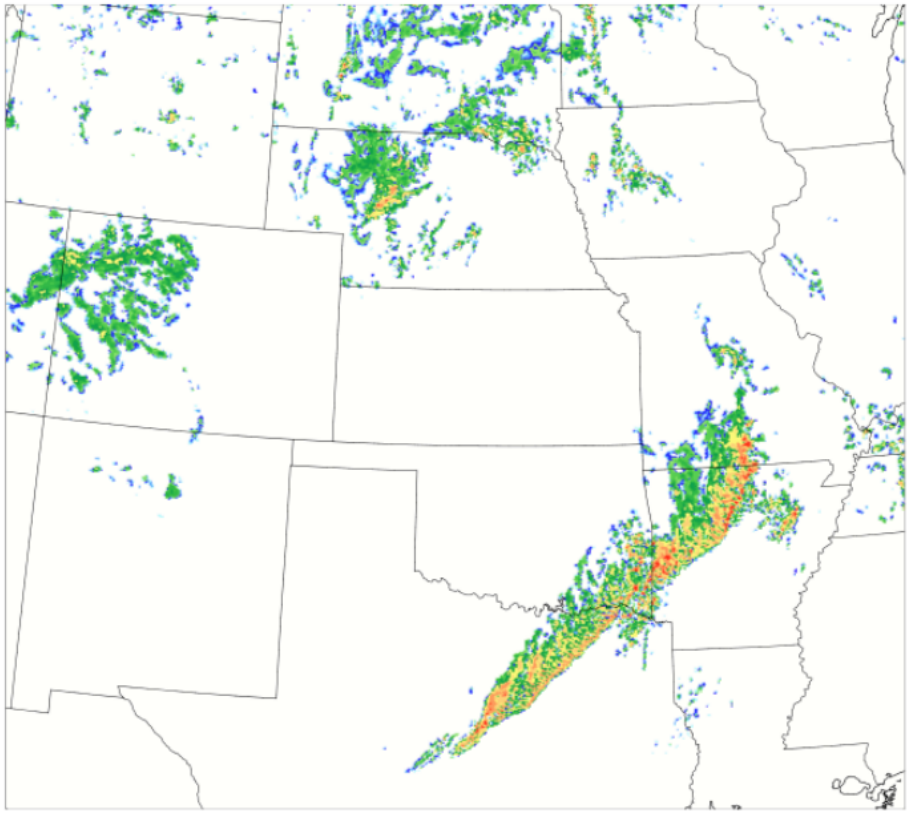


3-50 km mesh, Δx contours 4, 8, 12, 20, 30, 40
approximately 6.85 million cells
68% have < 4 km spacing

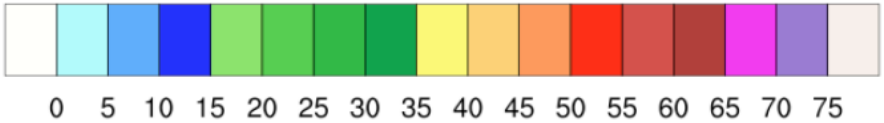
MPAS
Model for Prediction Across Scales

Hazardous Weather Testbed
Spring Experiment 2015
Forecasts Results from MPAS

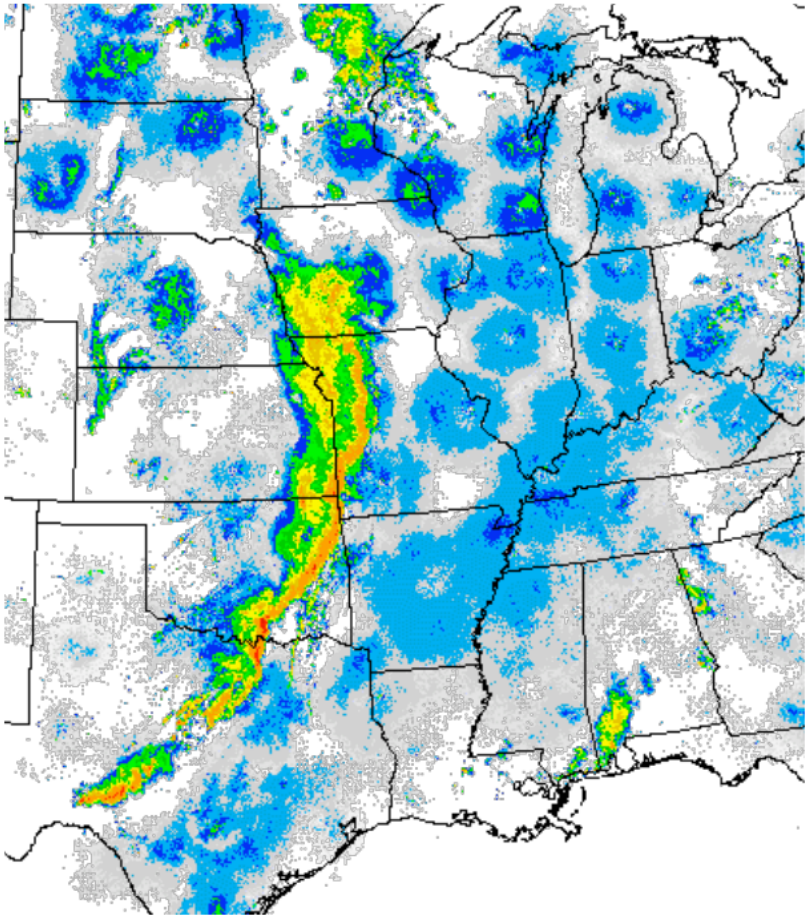
MPAS 50-3km 30h fcst
Init: 2015-05-16_00:00:00 UTC Valid: 2015-05-17_06:00:00 UTC
1km AGL reflectivity [dBZ]



NCAR



Reflectivity, NOAA SPC archive
valid 2015-05-17 06 UTC



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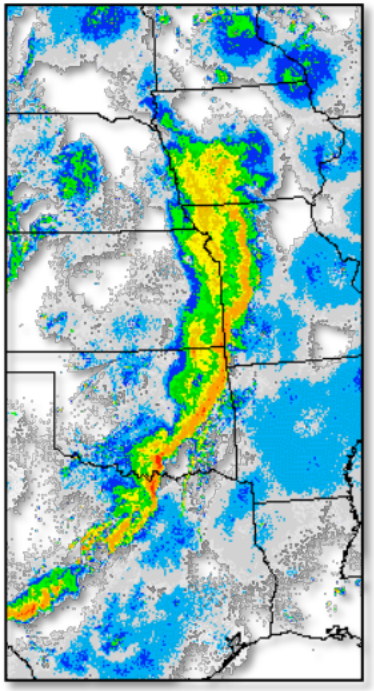
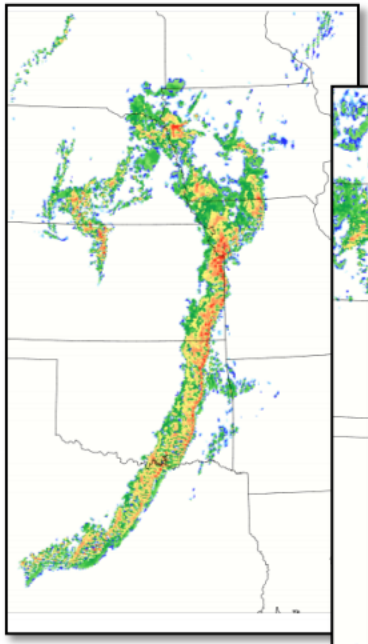
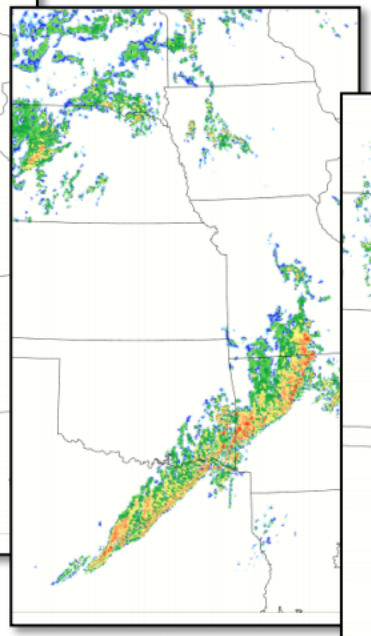


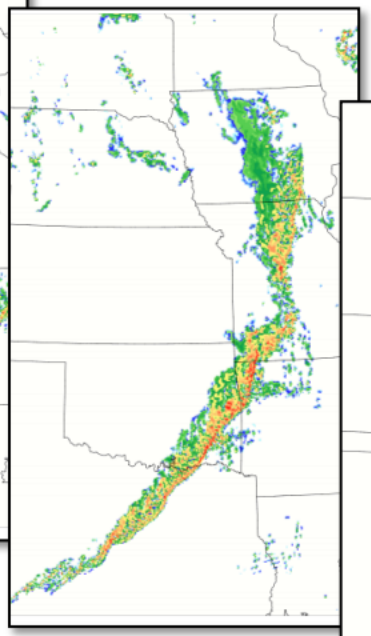
6 h forecast



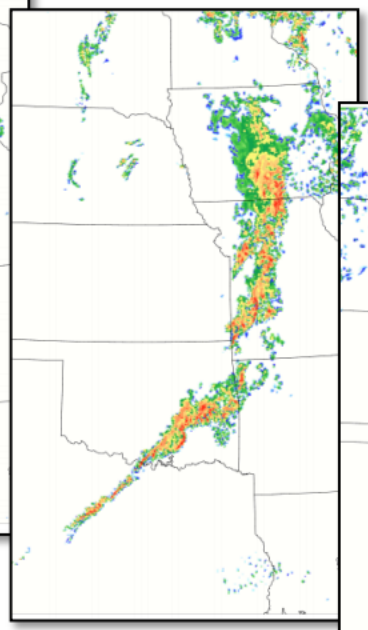
30 h forecast



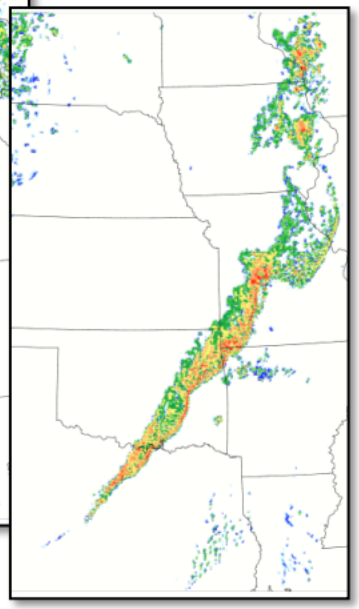
54 h forecast



78 h forecast



102 h forecast

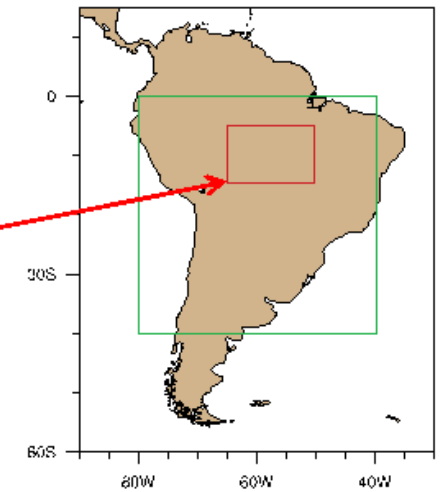


1 km AGL reflectivity
Forecasts valid 2015-05-17 6 UTC

MPAS results for South America runs

Variable Resolution Tests with the Grell-Freitas Convection Scheme

MPAS 50-3 km mesh, Grell-Freitas convection scheme
10-13 January 2014 forecasts, 3-day average heating rates



no parameterization
GF, no scale-awareness
scale-aware GF

CONVECTIVE HEATING RATE (K day^{-1})

(from the GF scheme)

GRID-SCALE HEATING RATE (K day^{-1})

(explicit, from the microphysics)

Tropical Cyclone scale awareness fully 3d simulations

Model setup for full 3d idealized tests

- A prescribed weak axisymmetric vortex:

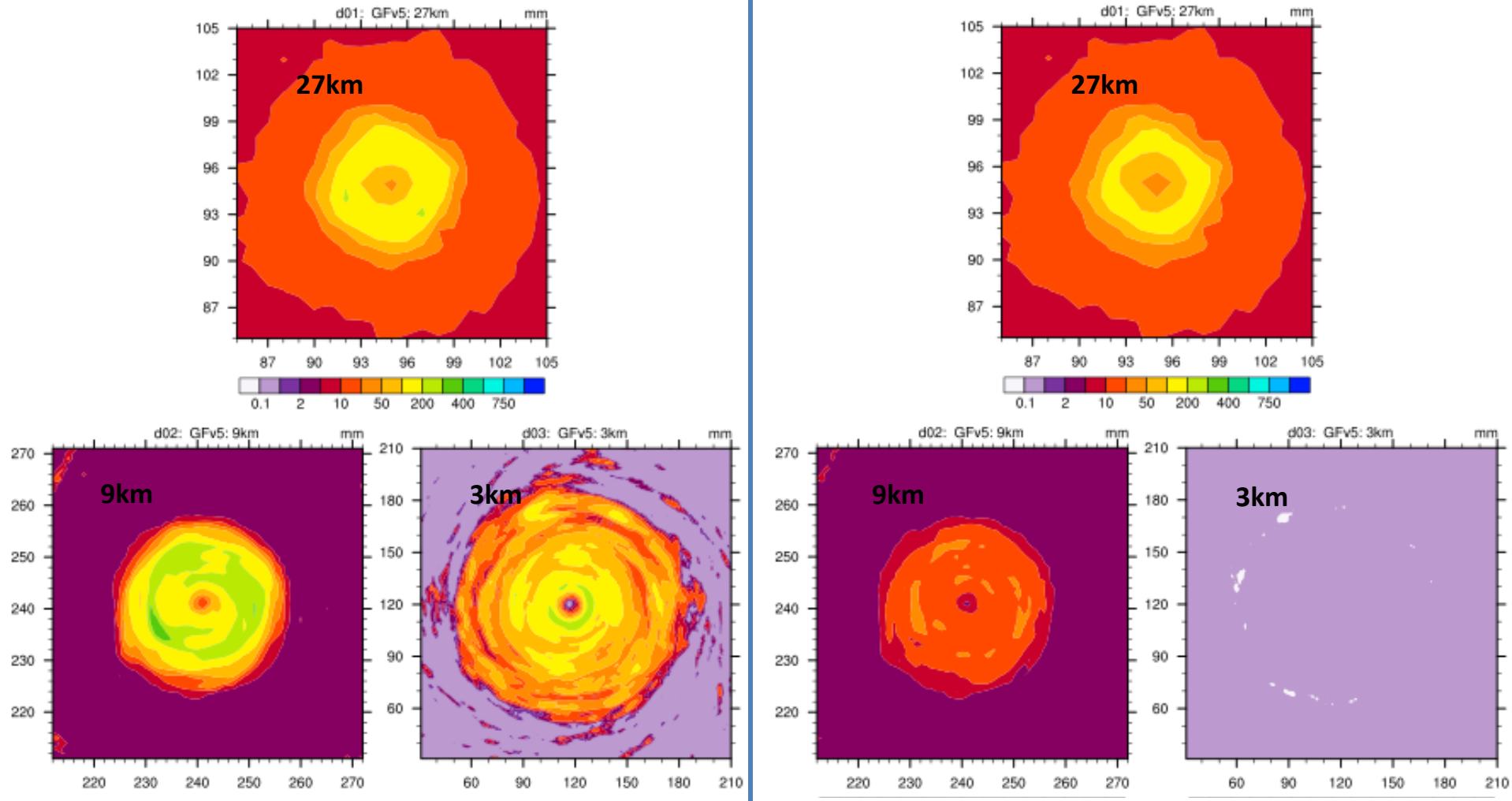
  — maximum surface tangential wind: 15 ms^{-1}

  — radius of surface maximum wind: 90 km
- 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)
- Idealized environment thermally corresponding to the Jordan sounding with a constant sea surface temperature of 29ºC (favorable for hurricane development)
- *f*-plane located at 12.5ºN
- 4 different resolutions are used, 27-9-3-1km. There is no 2-way interaction. 43 vertical levels

All experiments use a Monin-Obukhov surface layer, the unified Noah land-surface model, modified 3dTKE mixing

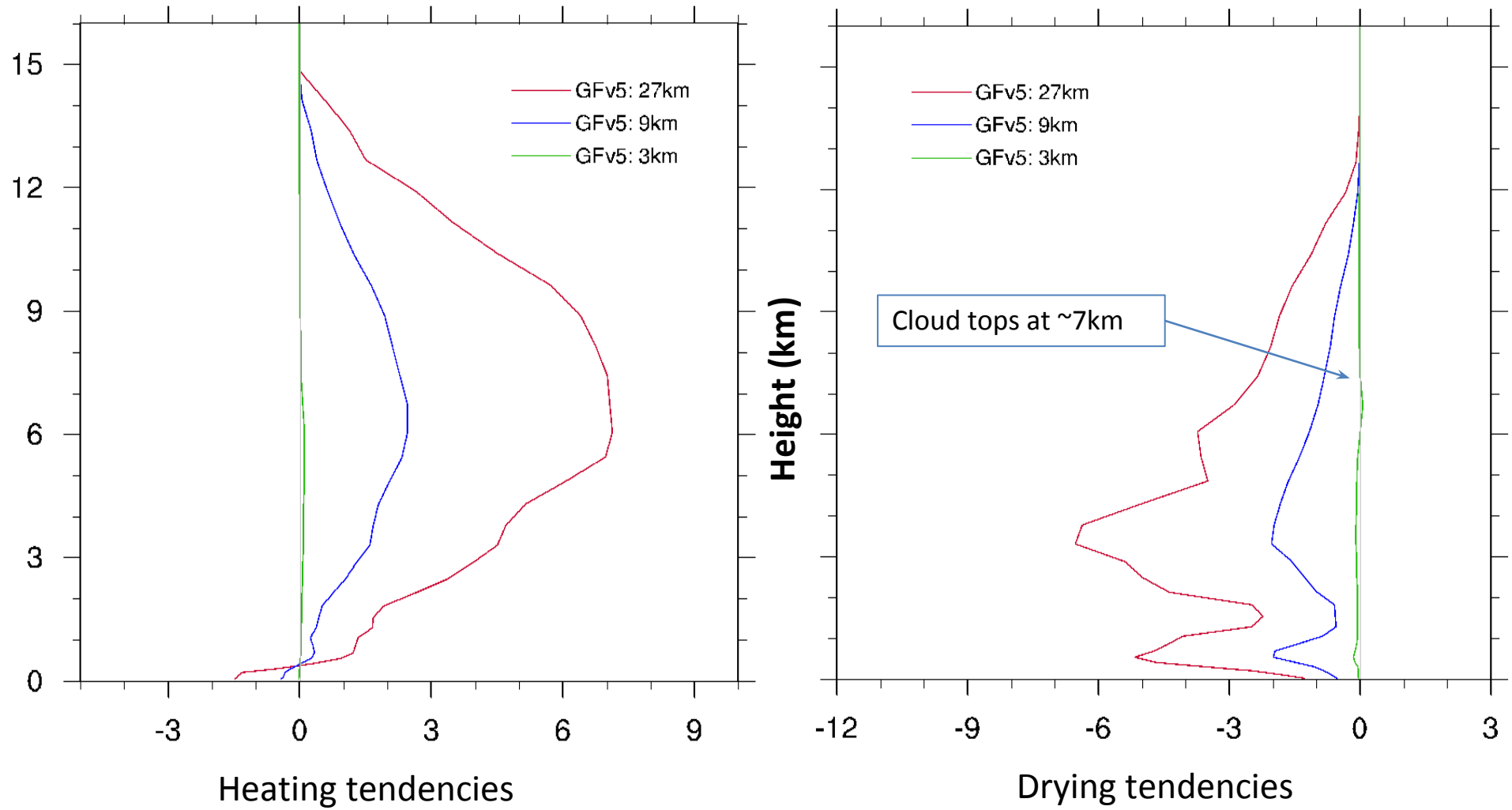
total precipitation

convective precipitation

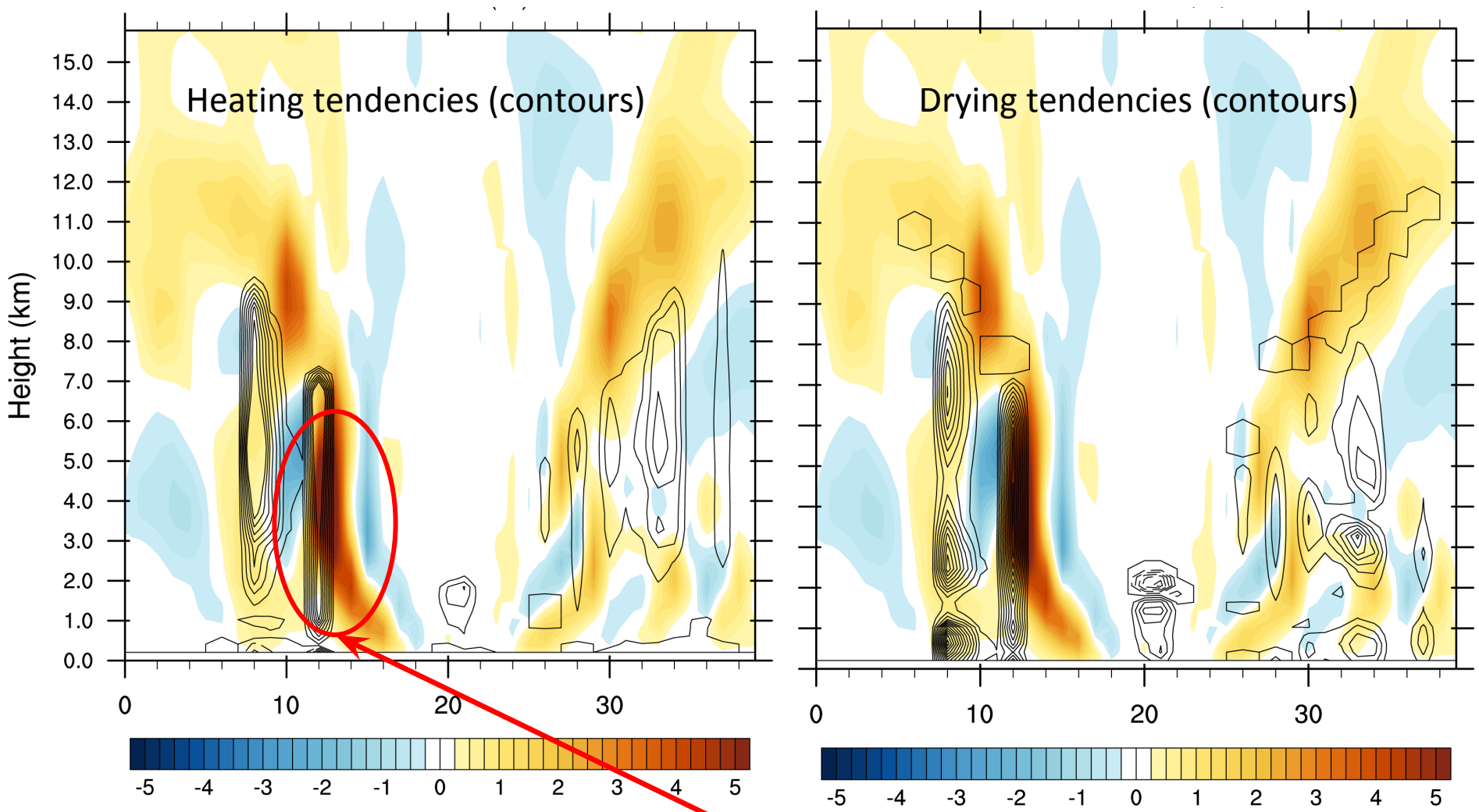


Early stage of storm development

Heating and drying tendencies at 36hr (deg/day) – averaged inner part of 3km domain



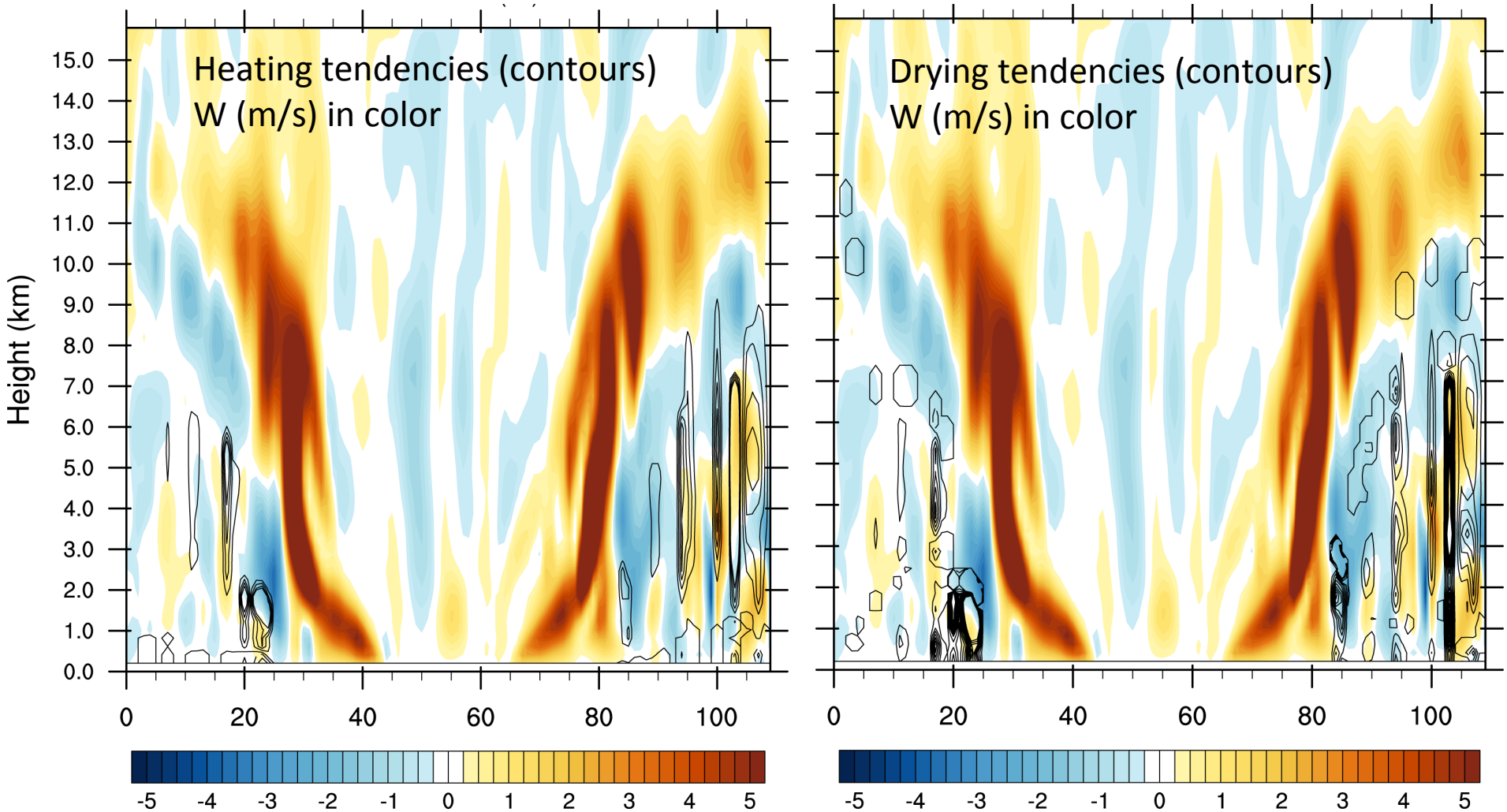
Crossection through center of storm, **dx=3km**, vertical velocity in color (m/s)



Parameterization can not handle tilt, could be a significant problem if tendencies would not be so miniscule

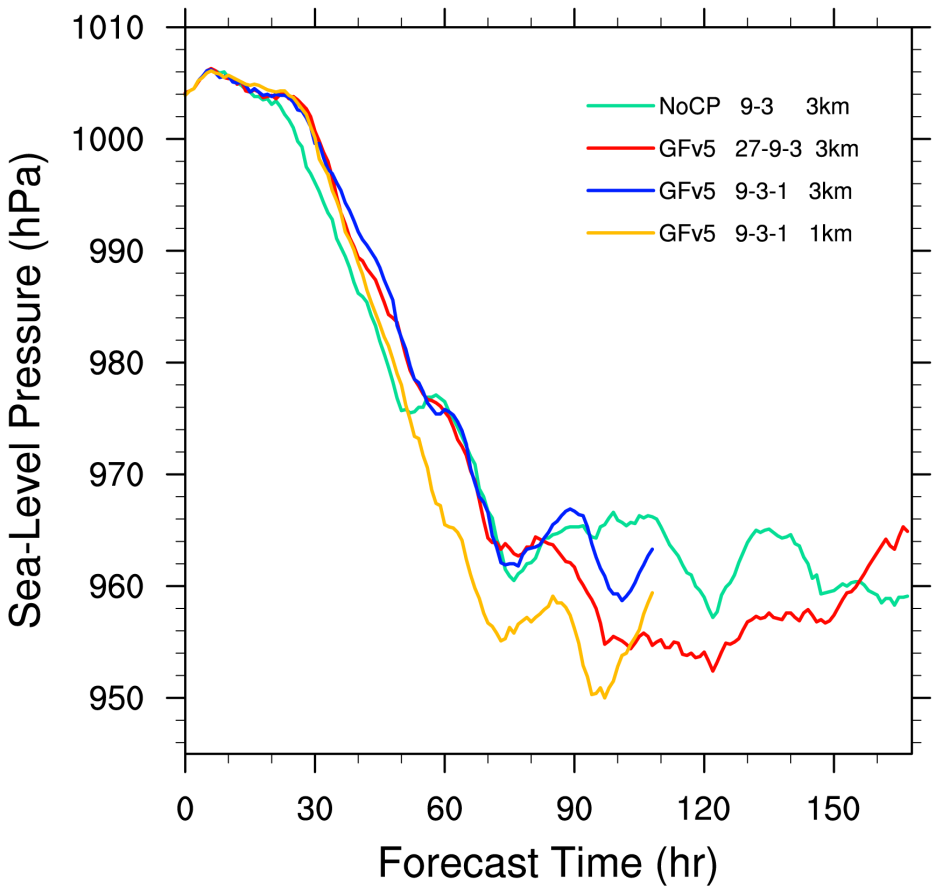
Adding a 1km resolution simulation

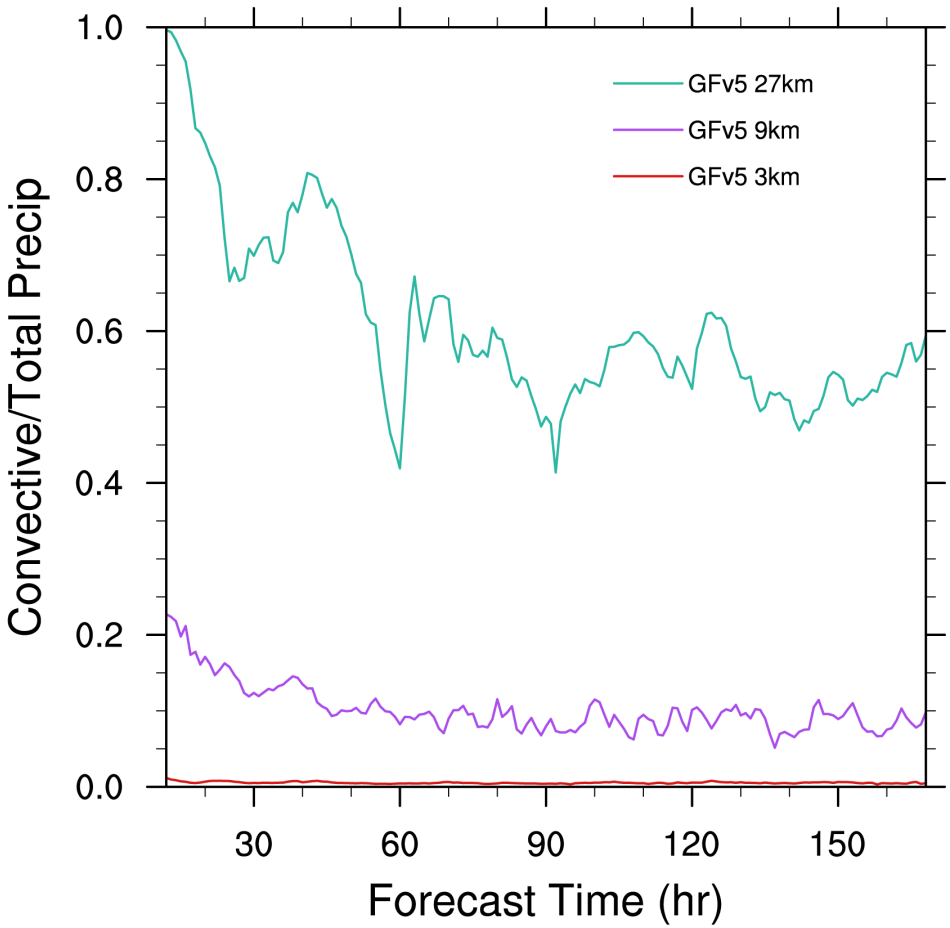
Cross-section through center of storm, **dx=1km**, vertical velocity in color (m/s)



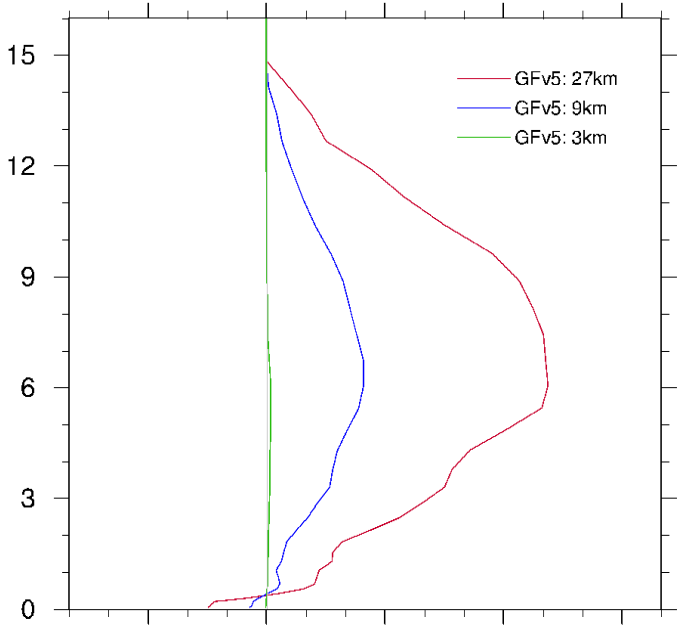
Actually looks better on dx=1km!

Domain averaged (3km resolution domain) precipitation rate (mm/h) and fraction of convective to total rain

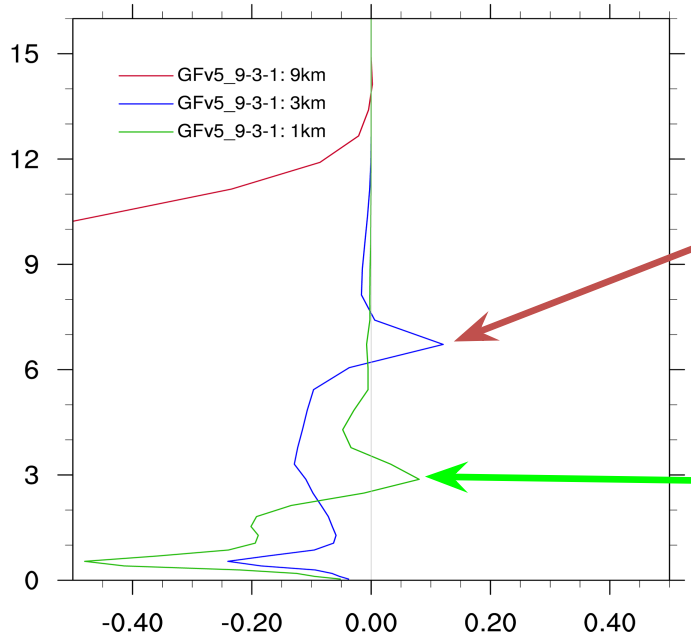




Idealized 3d tropical cyclone simulation



Heating profiles from convective parameterization for idealized tropical cyclone simulations at 27km, 9km, and 3km



Average cloud top at 7km

Average cloud top at 3km

Drying profiles from convective parameterization for idealized tropical cyclone simulations at 3km and 1km (!) resolution

Scale-awareness seems to work fine with the very simple Arakawa (2011) approach, as well as other very simple assumptions to estimate a fractional coverage.

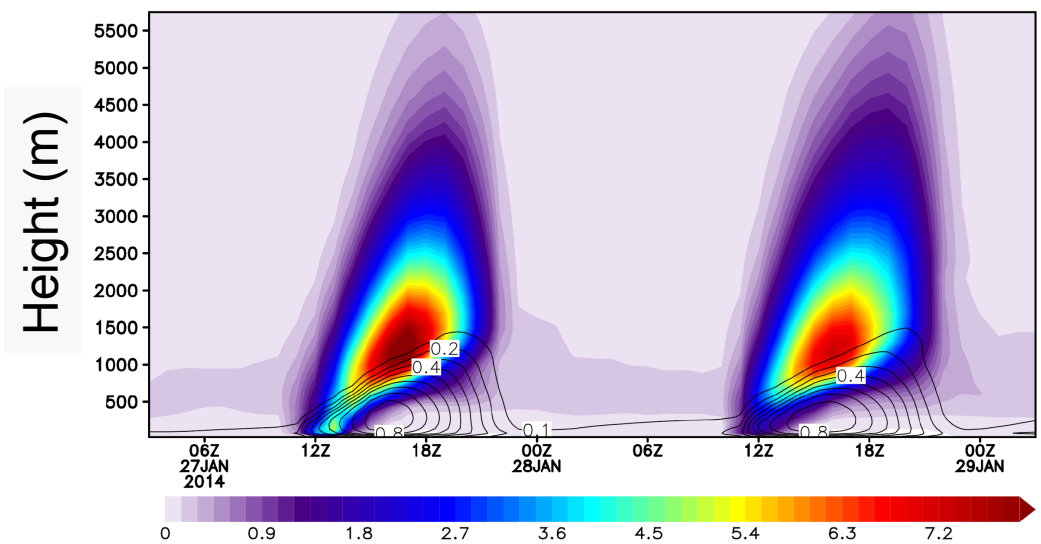
Recent new "HIWPP" implementations

1. Momentum transport (as in SAS or ECMWF)
2. Additional closure for deep convection: Diurnal cycle effect (Bechtold)
3. Mass conserving transport completed for shallow scheme
4. Mass conserving transport for deep currently being tested
5. Additional closures for shallow convection (including the SAS shallow convection closure, and one from Renno and Ingersoll, JAS 1996)
6. PDF approach for normalized mass flux profiles was implemented (fitting LES modeling for shallow convection and allows easy application of stochastic perturbation of vertical heating and moistening profiles)
7. GF scheme was fully immersed into GFS 2012 and 2015 physics (replacing the call to SAS deep and/or shallow schemes)
8. Rain evaporation (by parameter choice) after tendency calculations

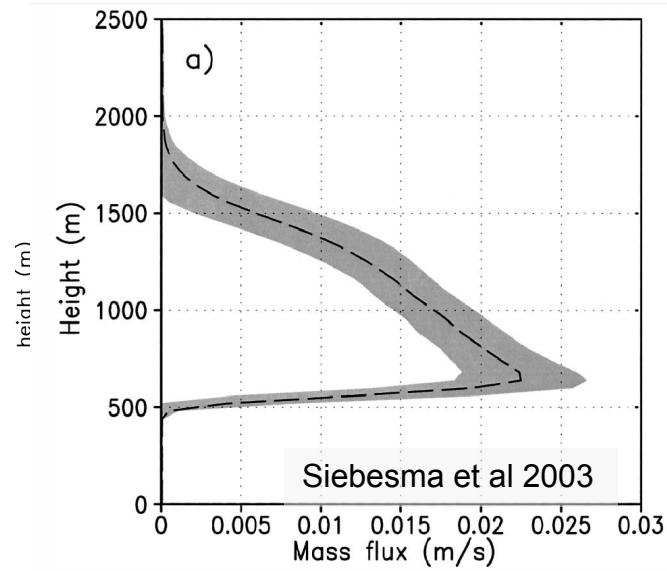
Shallow Convection Scheme

- Non-precipitating
- Transport of moisture, heat and tracers
- Mass flux profile given by a Beta PDF
- Three closures – BLQE (Raymond, 1995), W*(Grant, 2001) and convection as natural heat engine (Rennó and Ingersoll, 1996).

Diurnal cycle of shallow convection and diffusion in PBL



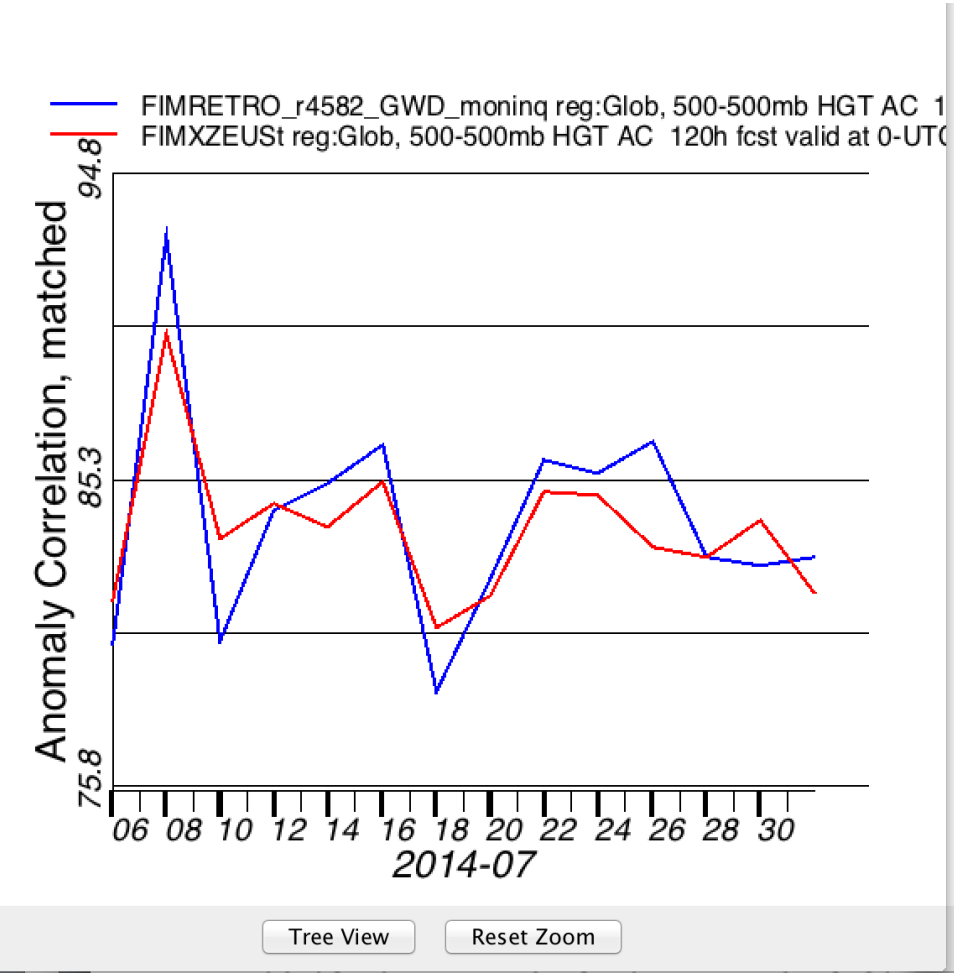
updraft mass flux: shaded
TKE: contour

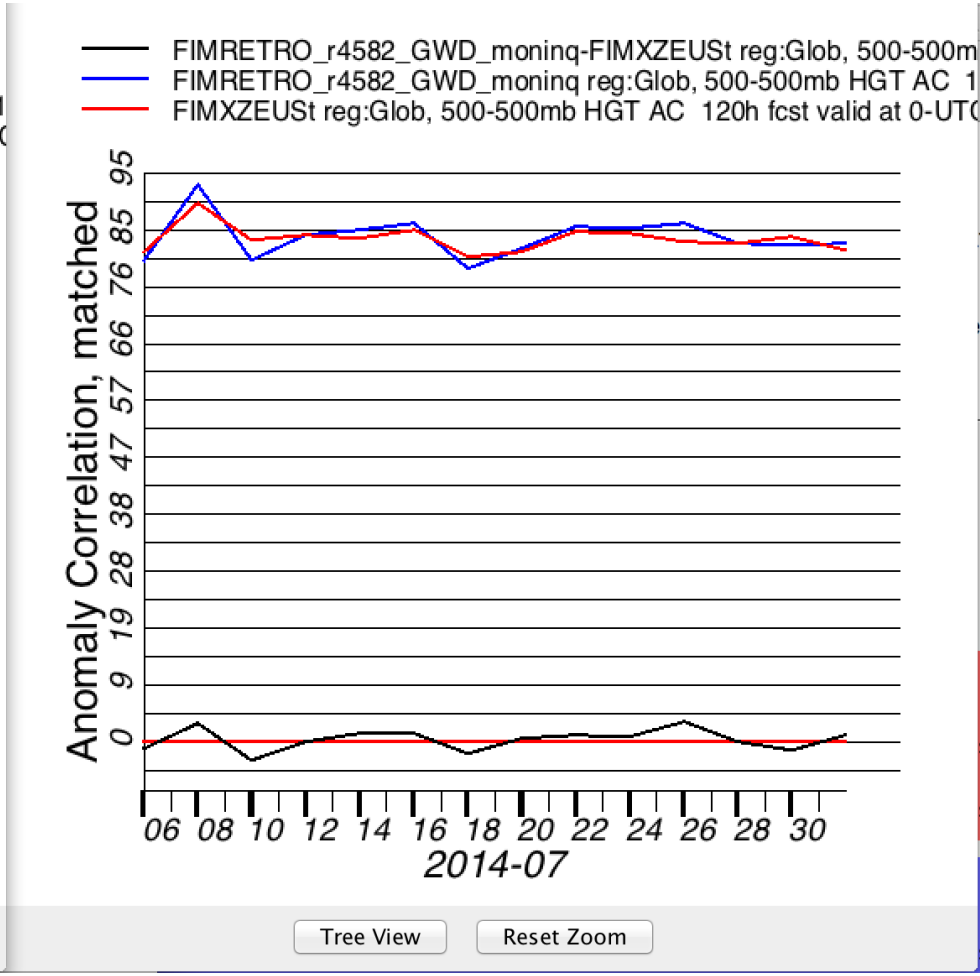


- Similar with LES
- Sharp increase, peaking just above boundary layer
- Smooth decrease above

So, with all those changes, where are we now for the global model?

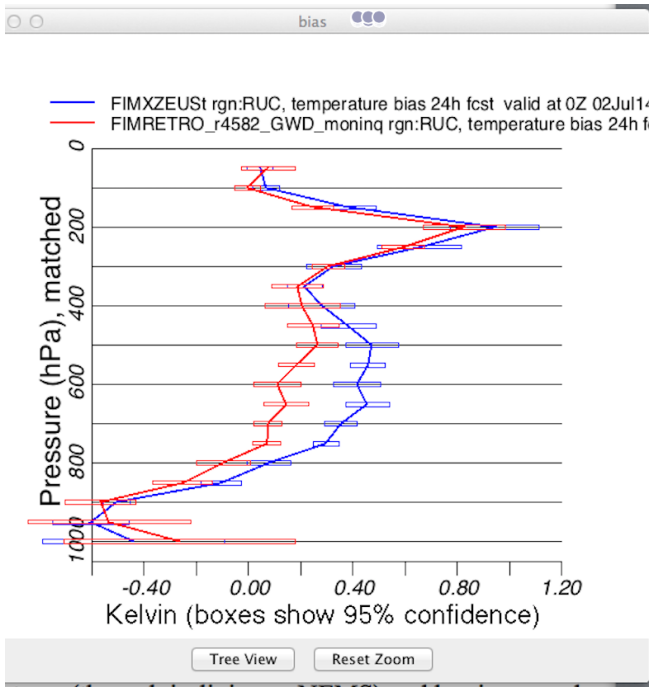
120hr height anomaly correlations as of latest HIWPP meeting (May 2015) - close



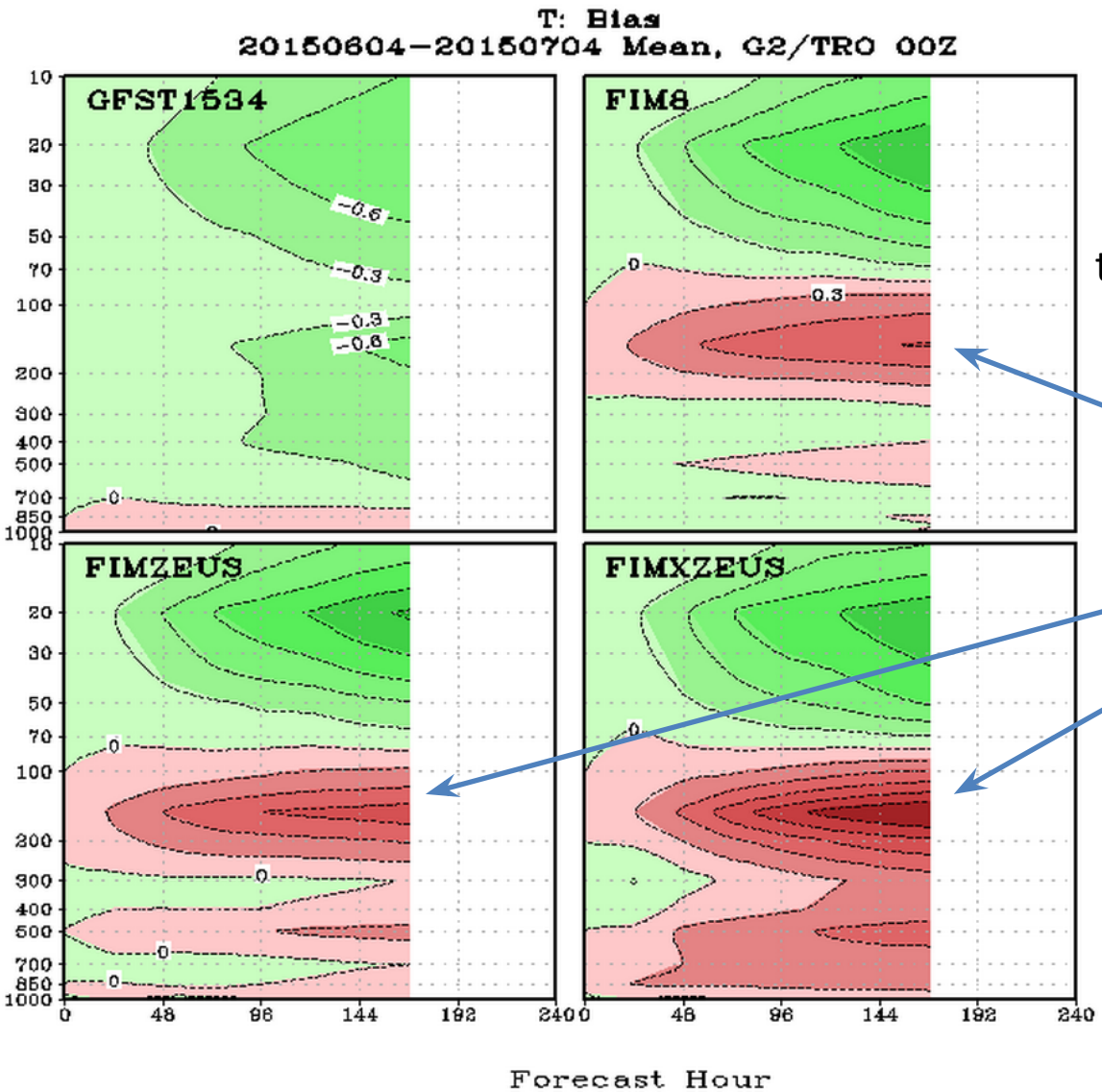


Remaining **problem** to solve

- What is responsible for positive temperature bias?
  - This was the reason for implementing SAS rain evaporation



  - Take a detailed look at momentum transport

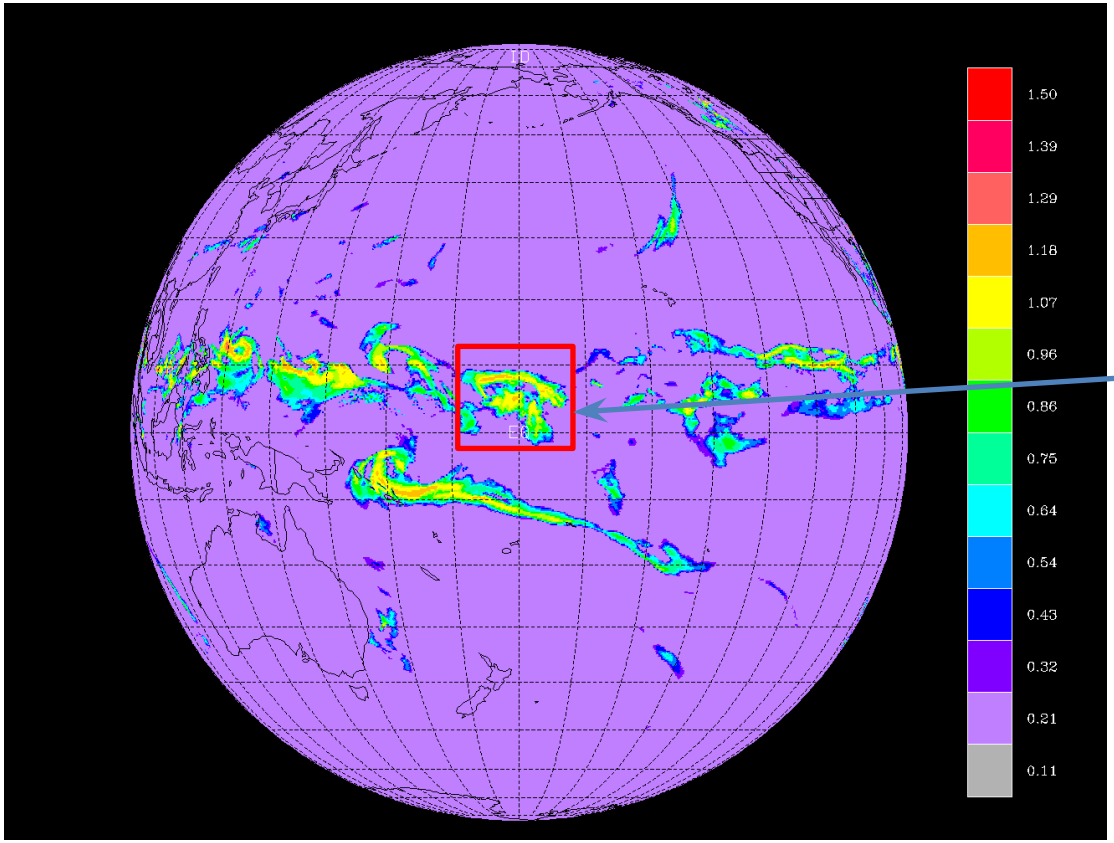


In tropics: temperature bias in both GFS physics versions, but worse when using GF – yet heating tendencies are actually smaller in GF!

T-Bias

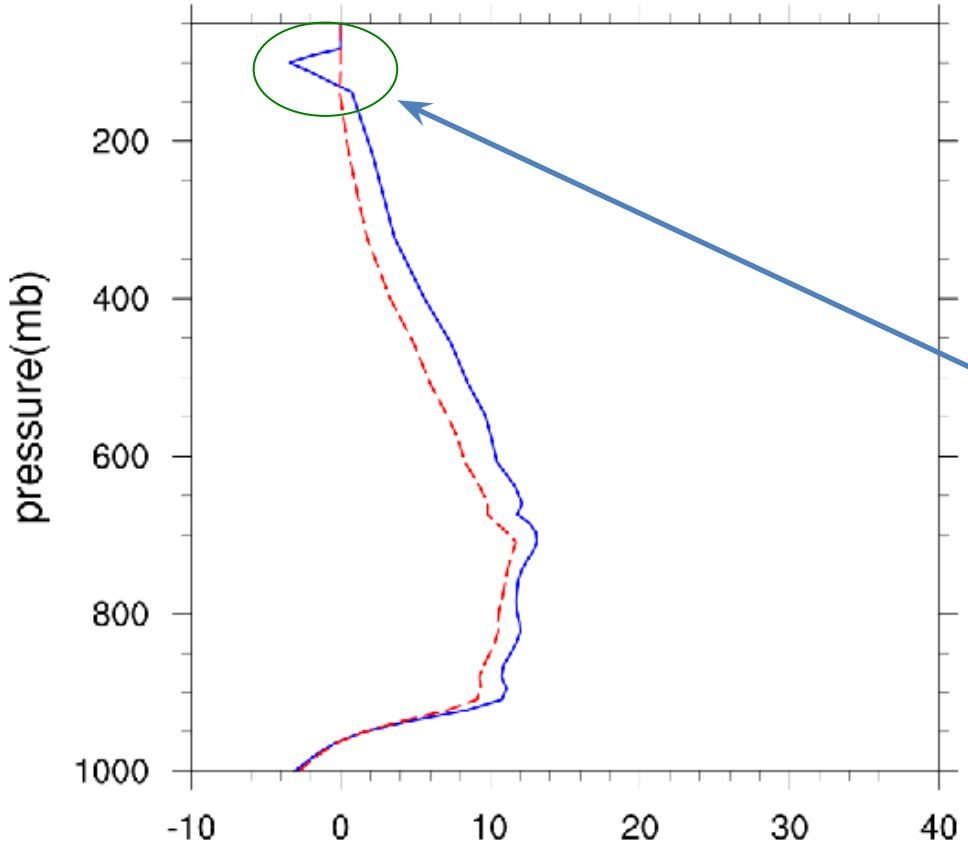
First look at upper level T-bias: overshooting tops (is also used in SAS) as an option?

Next slides are from FIM simulations at about 30km resolution, using GFS 2015 physics and T1534 GFS initial conditions



Vertical profiles of physics tendencies over 10x10 degree average, 24hr into the forecast

Vertical profiles of temperature tendencies from GF scheme allowing significant overshooting to see impact clearly!

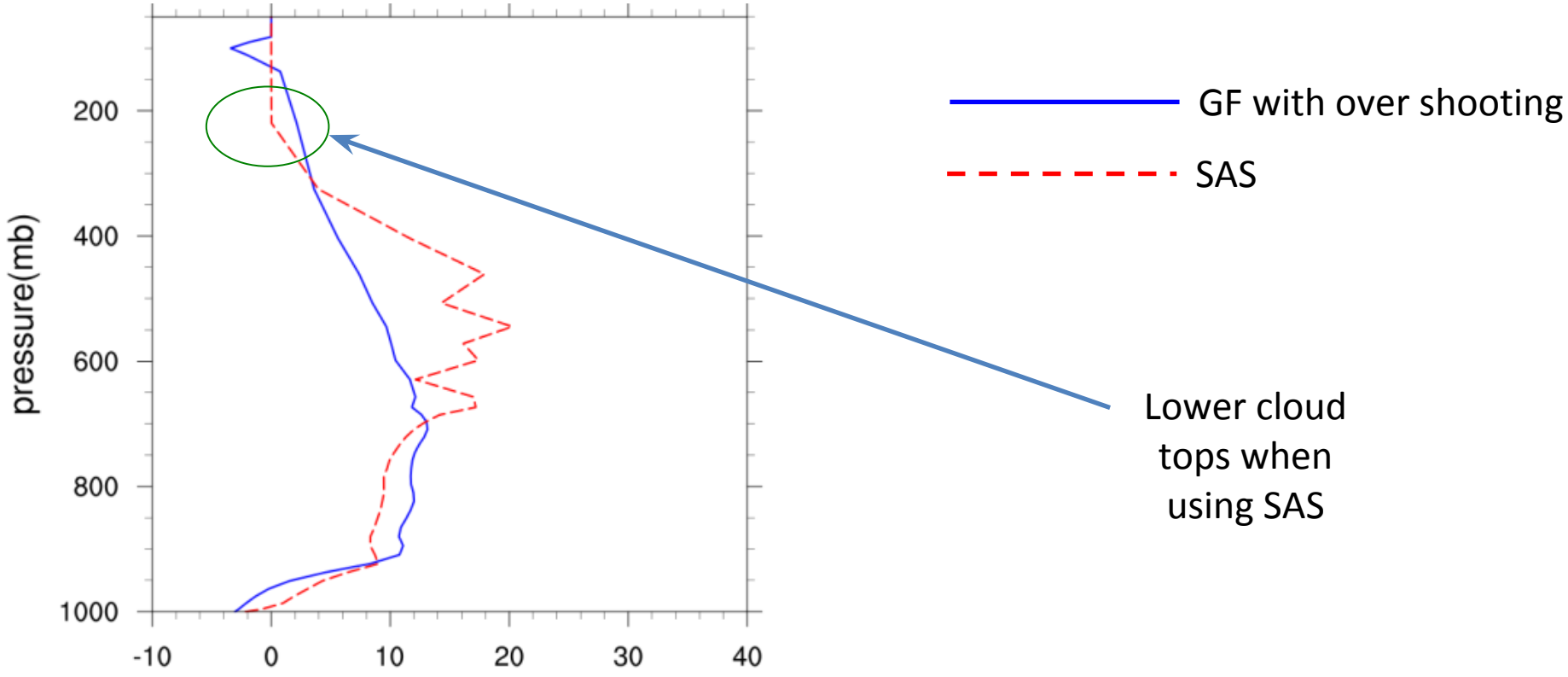


GF with over shooting

GF no over shooting

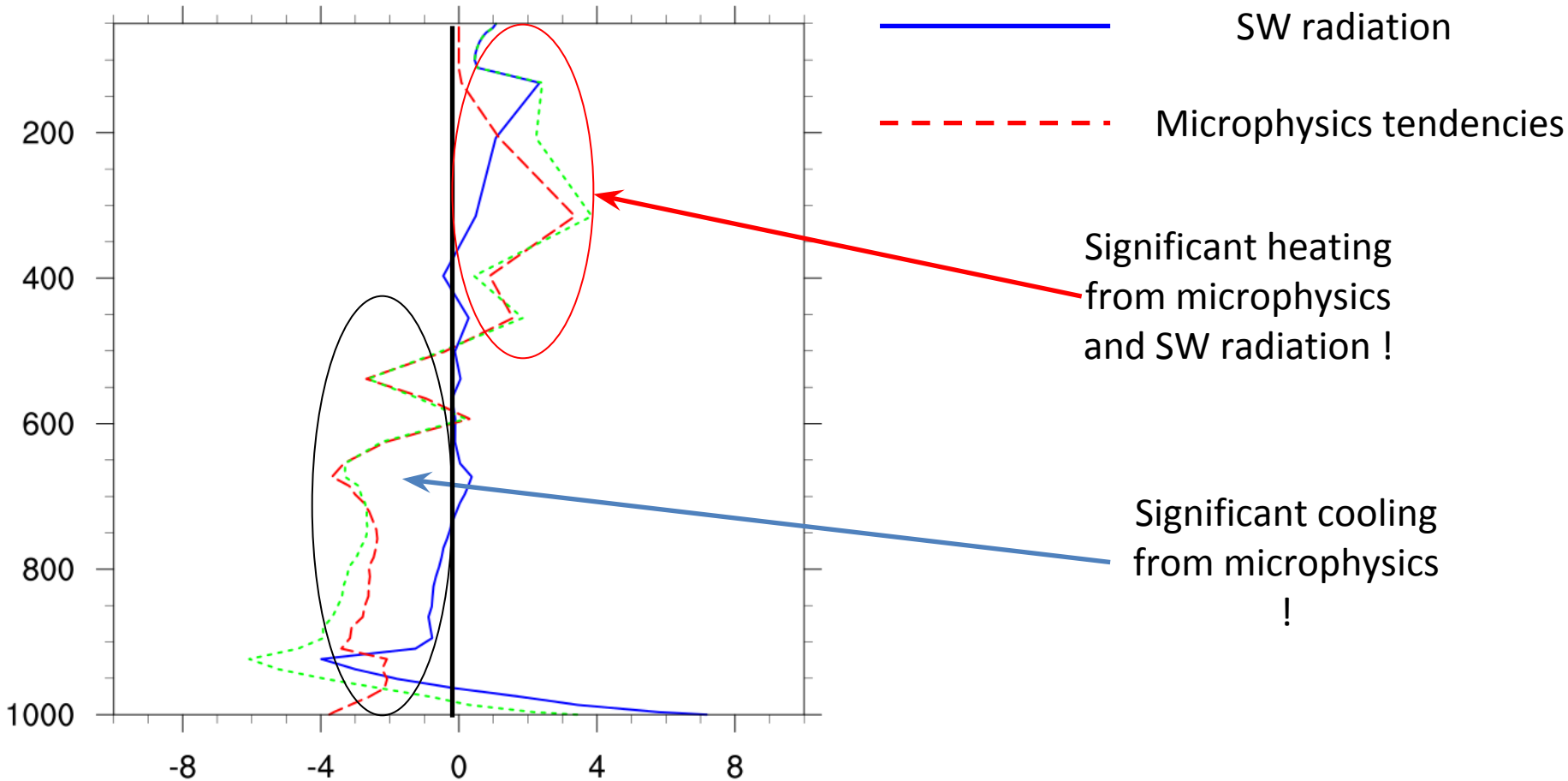
Cooling, but initial version higher than wanted – easy to modify

Vertical profiles of temperature tendencies from GF and SAS scheme over 10x10 degree average, 24hr into the forecast

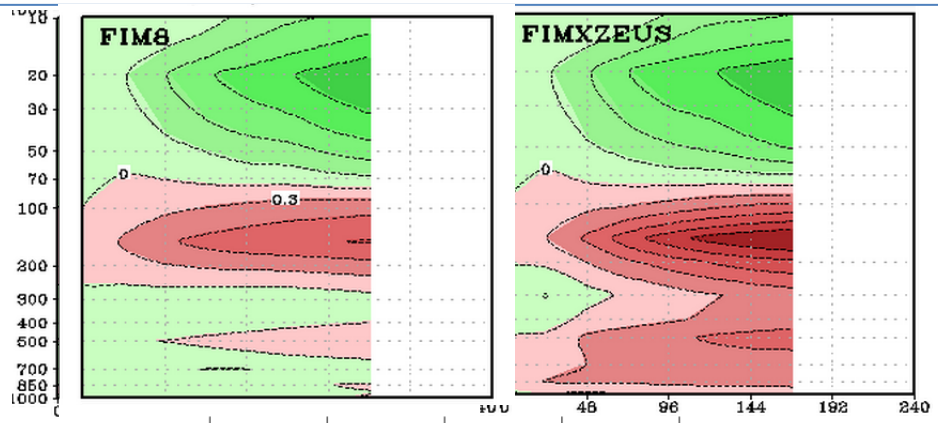


Moving on to lower levels heating bias : differences must be caused by interaction with microphysics or radiation

Vertical profiles of temperature tendencies from GFS physics over 10x10 degree average, 24hr into the forecast

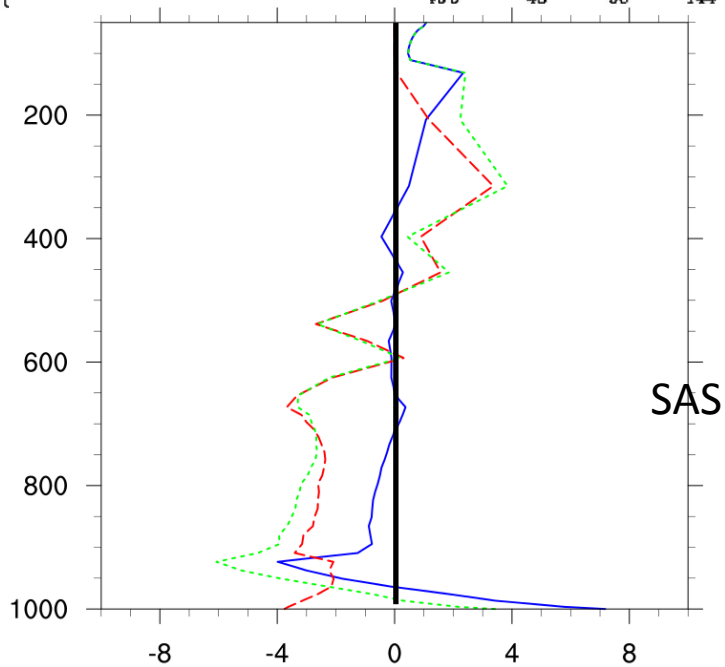


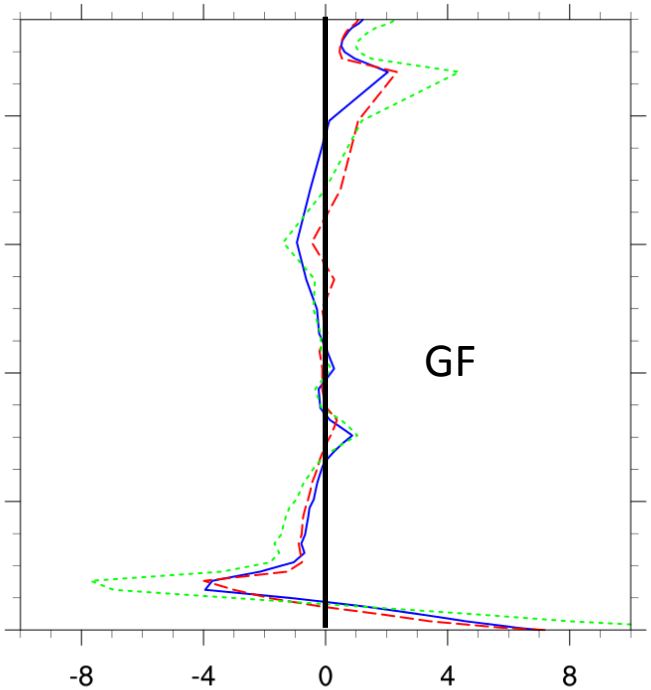
Vertical profiles of microphysics nd SW radiation temperature tendencies when using SAS (left) and GF (right) over 10x10 degree average, 24hr into the forecast



SW radiation

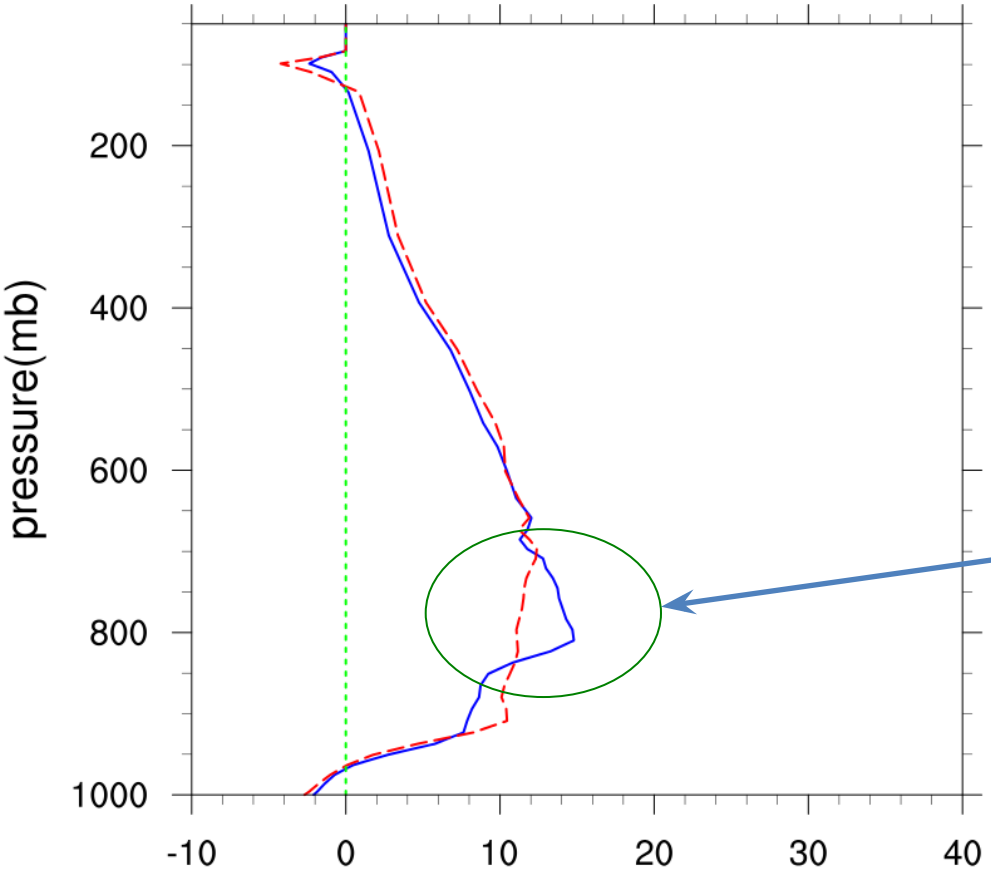
Microphysics tendencies





Vertical profiles of temperature tendencies from GF scheme over 10x10 degree average, 24hr into the forecast with different formulation of clw detrainment.

In SAS: detrainment is formulated similar to what is done with the autoconversion parameter, making this much more tunable and independent of mass detrainment.

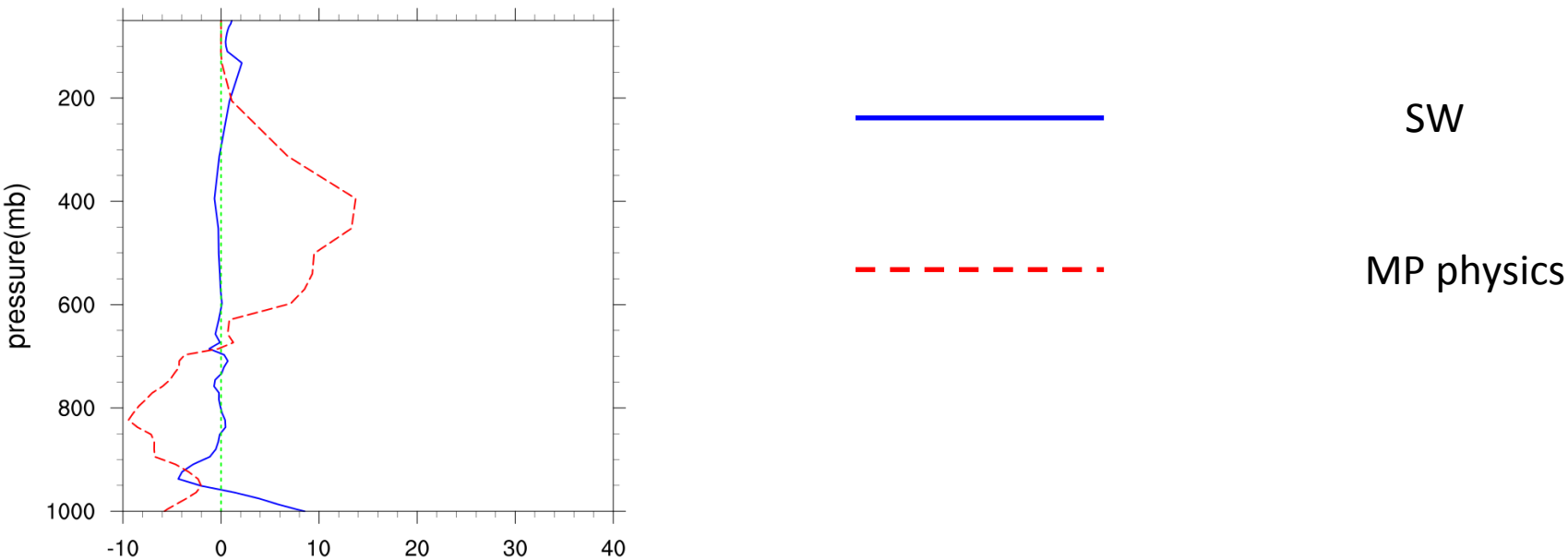


GF with over shooting

GF with different clw detrainment and overshooting

For tendencies coming from GF, not very large differences..

Microphysics and SW radiation tendencies when using arbitrary clw detrainment (similar what is done in SAS



Next we will

- **Redo retro-runs with 2015 GFS physics, GF and T1534 resolution**
- **Compare to MP tendencies from different microphysics scheme (started looking at Greg Thompson's aerosol aware scheme within the GFS physics)**
- **Take a detailed look at momentum transport**

Stochastic Parameter Perturbation in GF Scheme

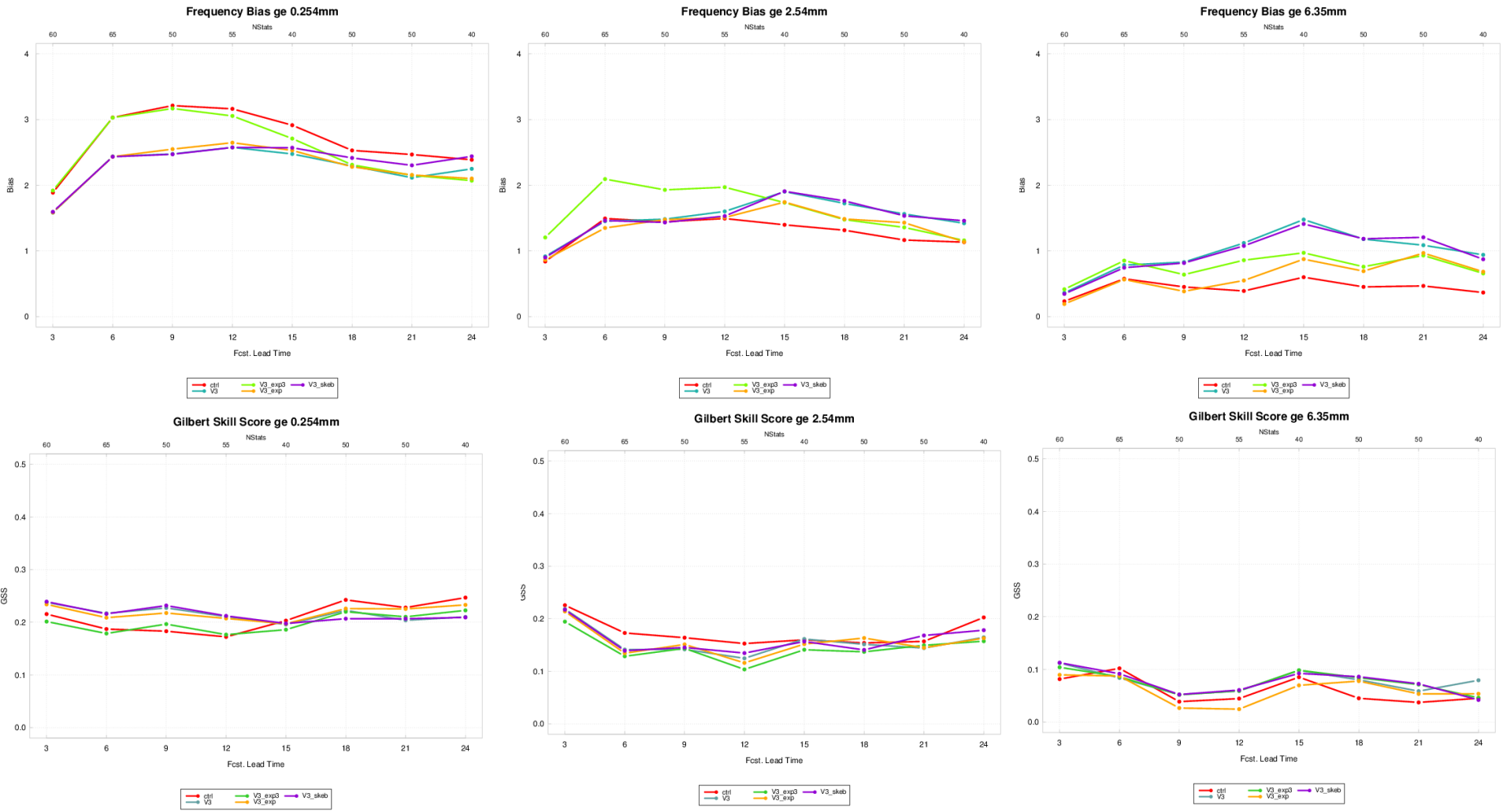
- For stochasticism
  - Starting to work with Judith Berner's approach (Stochastic Kinetic Energy Backscatter scheme (SKEBS) but currently restricted to WRF) – Isidora Jankov
    1. Apply directly to closure assumptions – for location and strength of convection)
    2. Apply to skewness of vertical mass flux PDF's (an easy way to significantly alter **vertical** heating and drying profiles
  - Plan is to try for forecast improvements or ensemble data assimilation

Comparison of performance between mixed physic and stochastically perturbed parameters ensembles

Experiment design

- Regional RAP model simulations
- Can be transferred to FIM, GFS, MPAS, HWRF, or other NGGPS core for testing on global domains
- 14 day period 15-31 May, 2013, 24 hr simulations
- Focus on convective Grell-Freitas parameterization
- Analysis of simulated precipitation was performed against Stage IV data, and for other standard variables (tmp., height, wind) against NDAS analysis
- All verifications performed over CONUS
- The control run, expensive mixed physics ensemble includes two versions of Arakawa-Schubert (AS) scheme, Betts-Miller-Janjic (BMJ) and Grell Freitas (GF) convective parameterizations - **ctrl**
- Stochastically perturbed parameter ensemble experiments (using only one run!):
  - Stochastically perturbed closures-**V3**
  - SKEBS scheme was added to closure perturbations – **V3_skeb**
  - In addition to the closure perturbations entrainment rate was perturbed – **V3_exp**
  - Stochastically perturbed max capping inversion –**V3_exp3**
- Performance of the mixed physics ensemble, V3, V3_exp and Ve_exp3 in terms of simulated precipitations was evaluated

Ensemble Mean Frequency Bias and Gilbert Skill Score



Ctrl – mixed physics ensemble

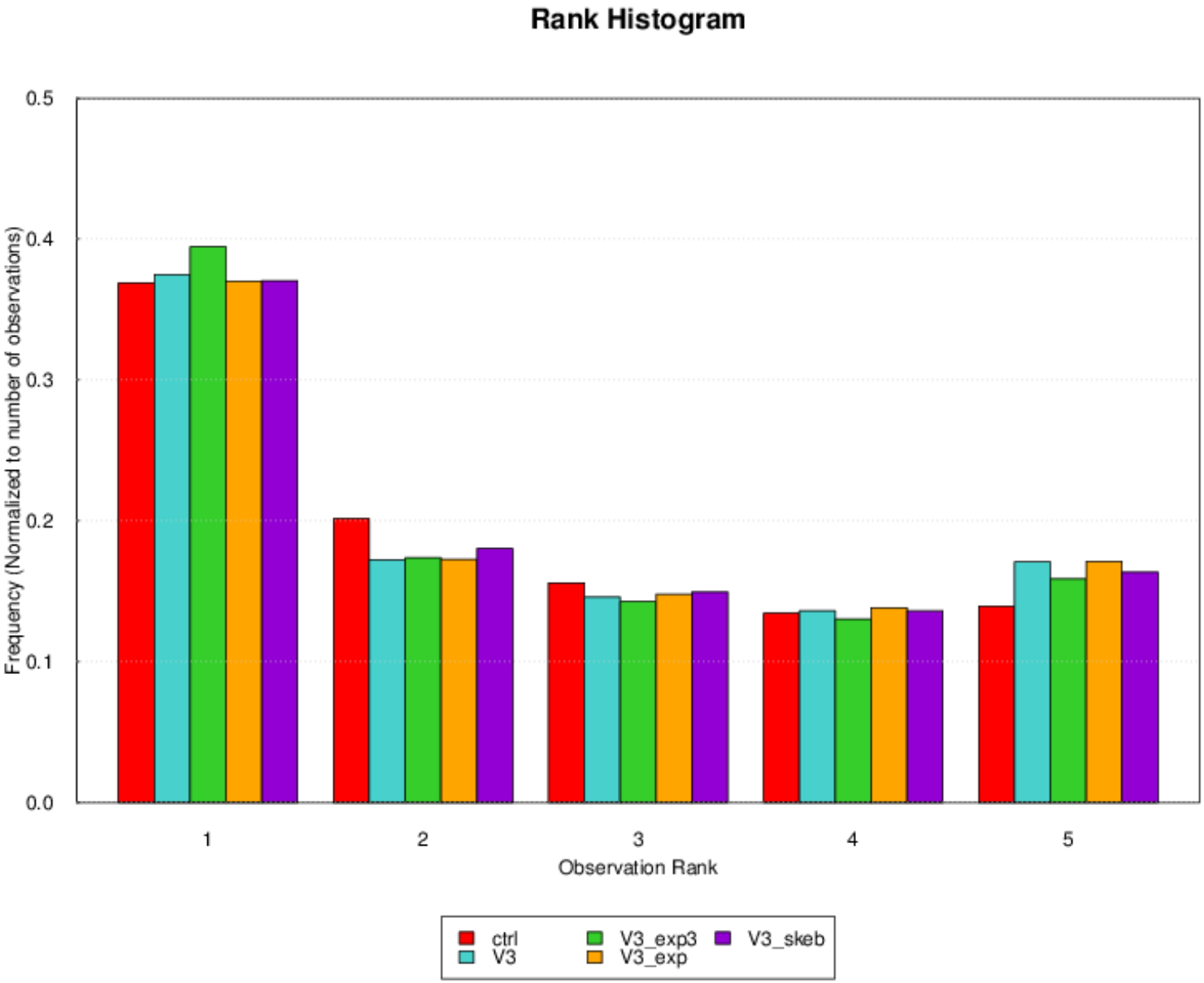
V3 – perturbed closures

V3_exp3 – perturbed max inversion capping

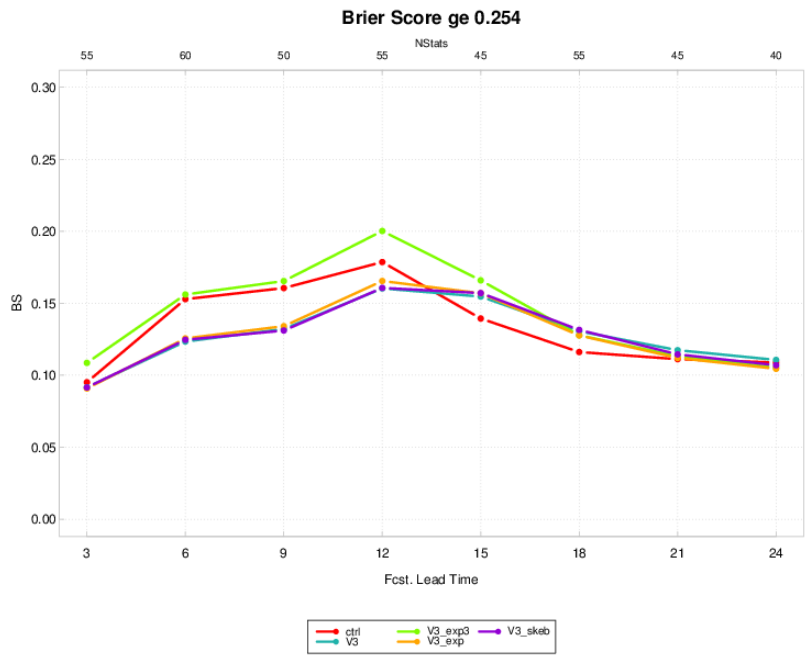
V3_exp – +perturbed closures + entrainment rate

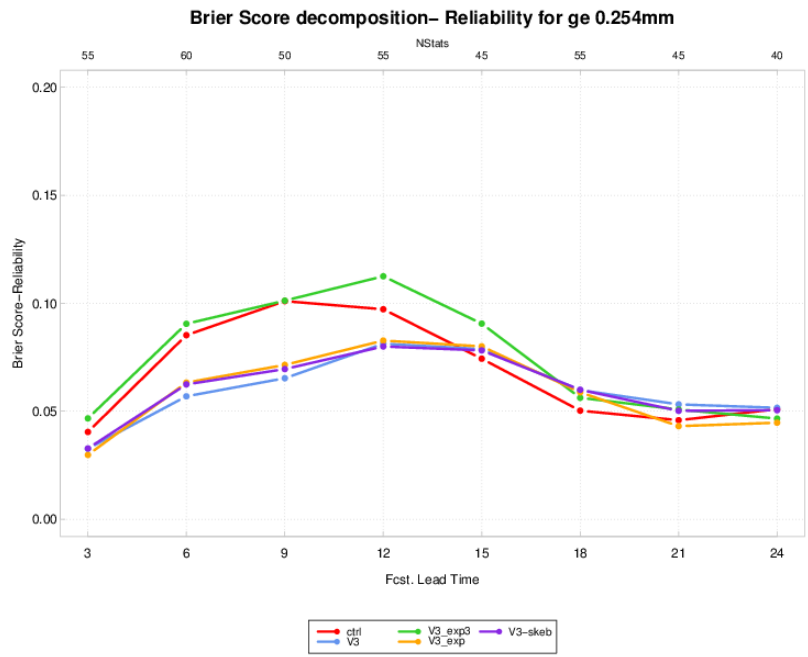
V3_skeb - perturbed closures +skeb

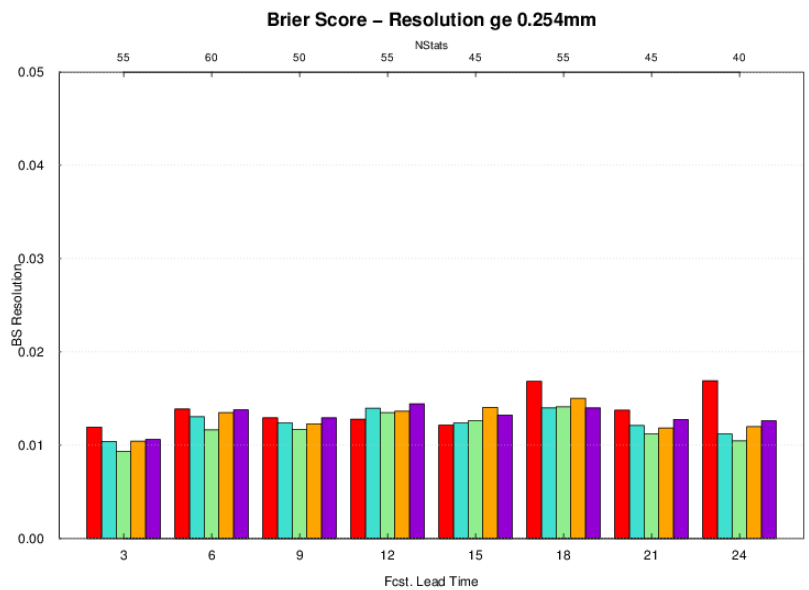
Ensemble Statistics



Brier Skill and its decomposition to Reliability and Resolution

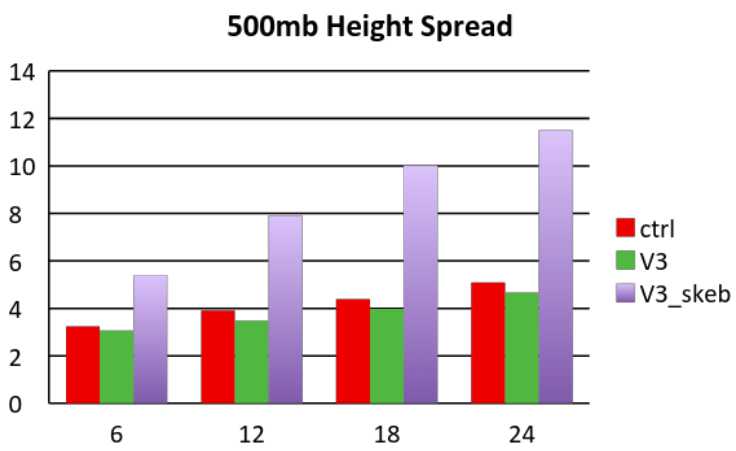


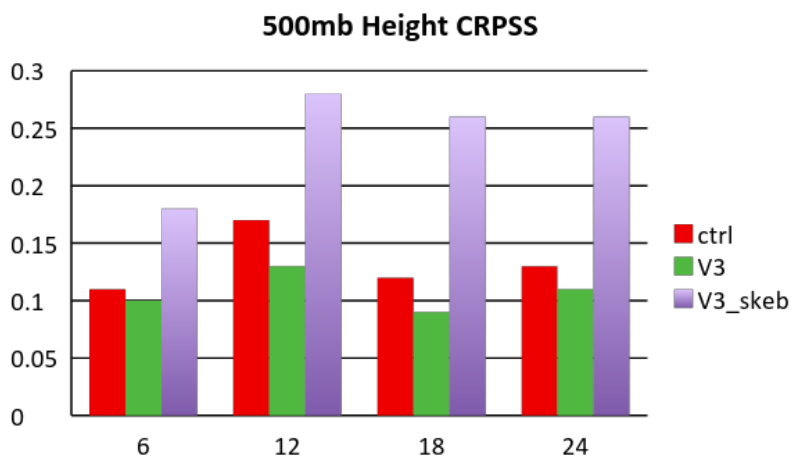


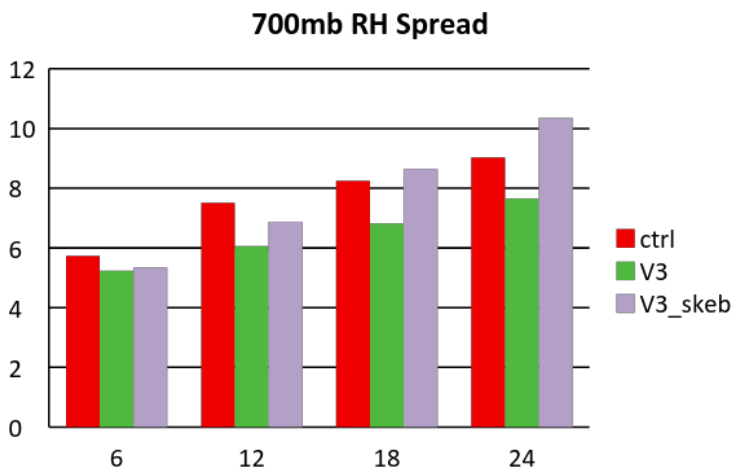


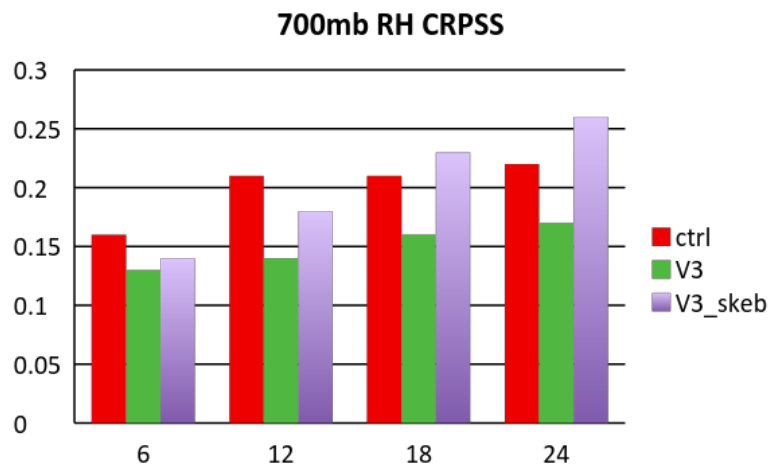
Brier Score (smaller better)
Resolution part of BS (larger better)
Reliability part of BS (smaller better)

Combination of stochastic physics and SKEB impact on standard variables

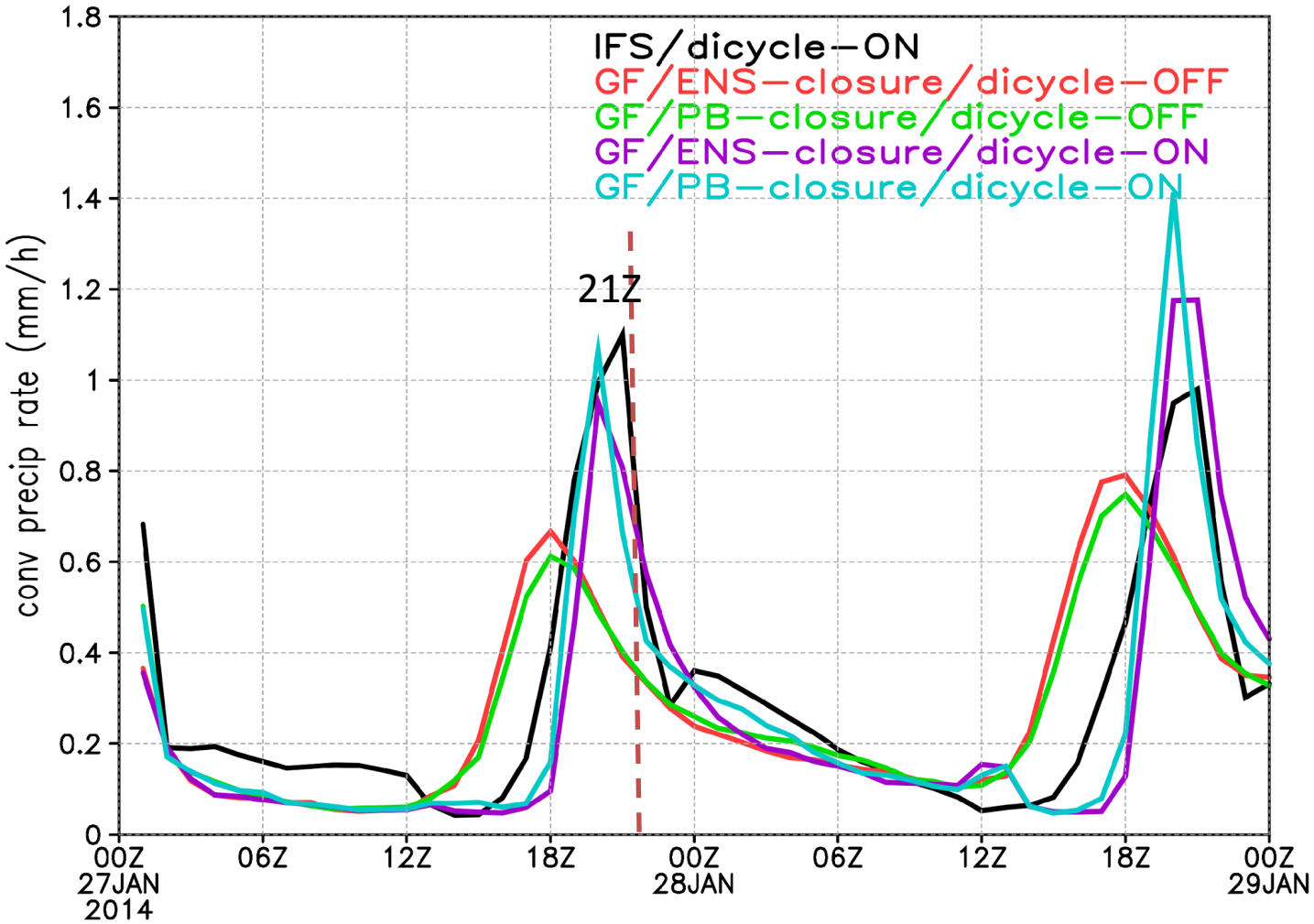






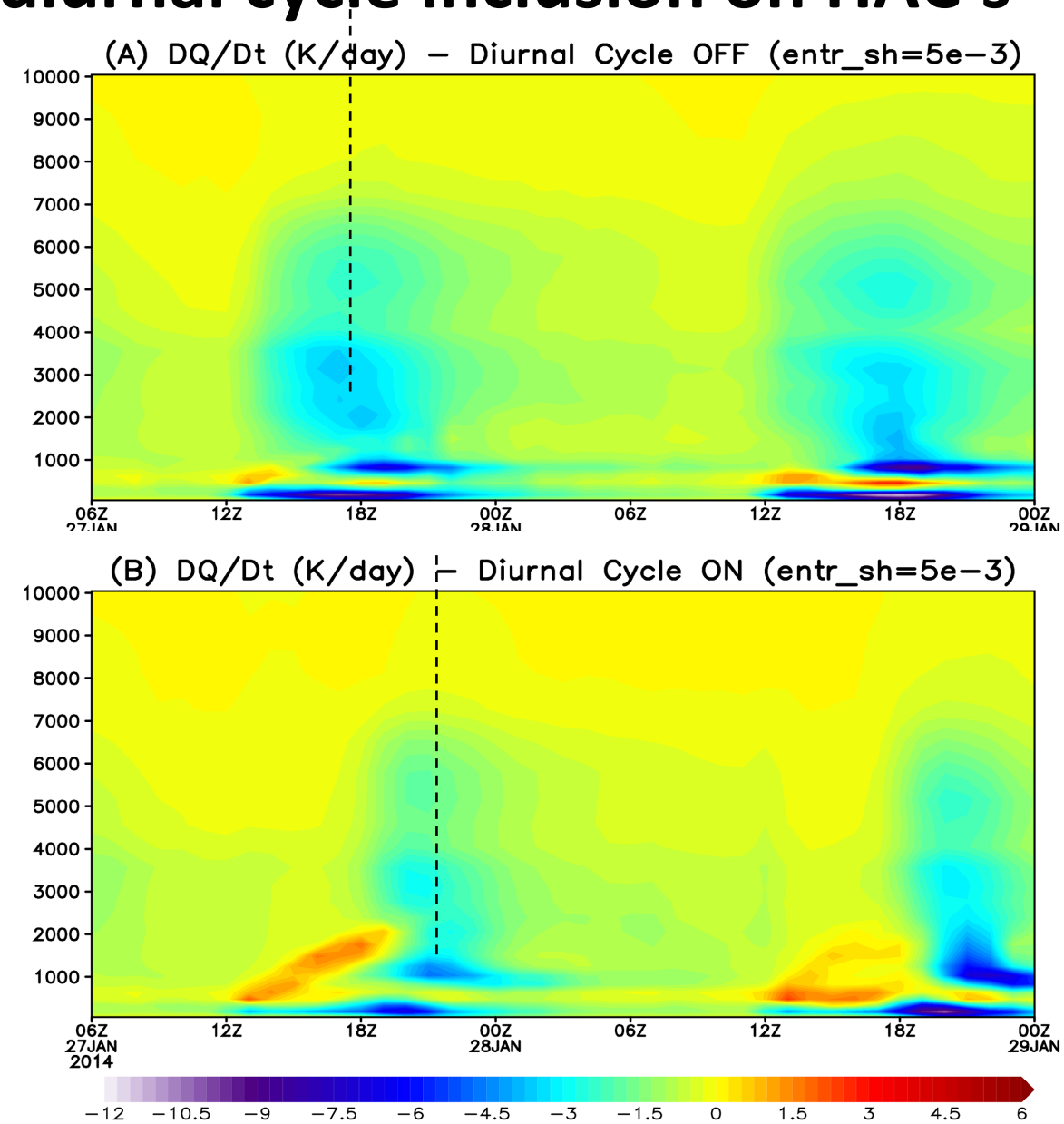


Ongoing experiments: (1) Evaluate impact of diurnal cycle inclusion on HAC's (FIM) and precip scores (RAP)

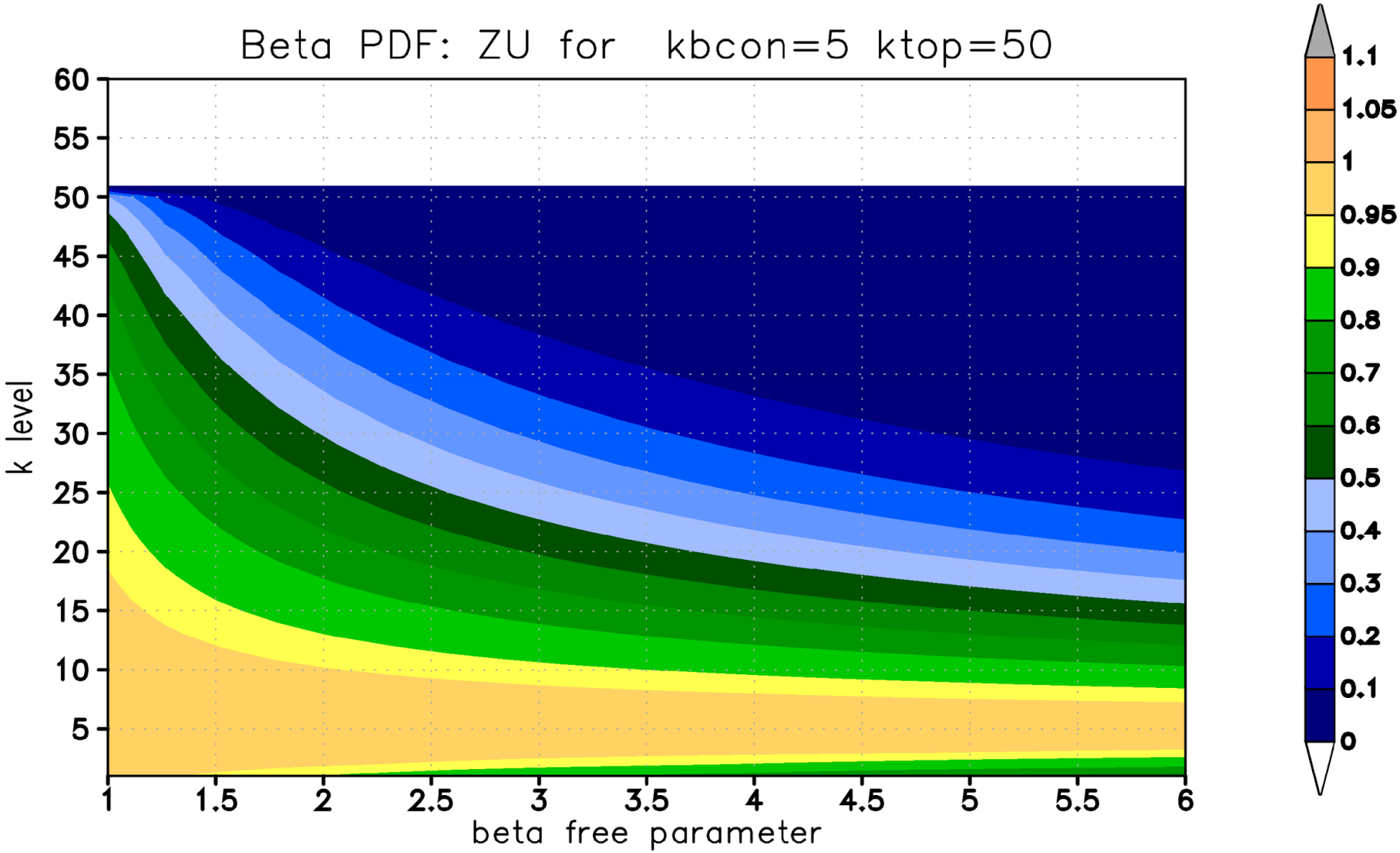


Conv prec rate (mm/h) from cumulus parameterization (area average over Amazonia domain)

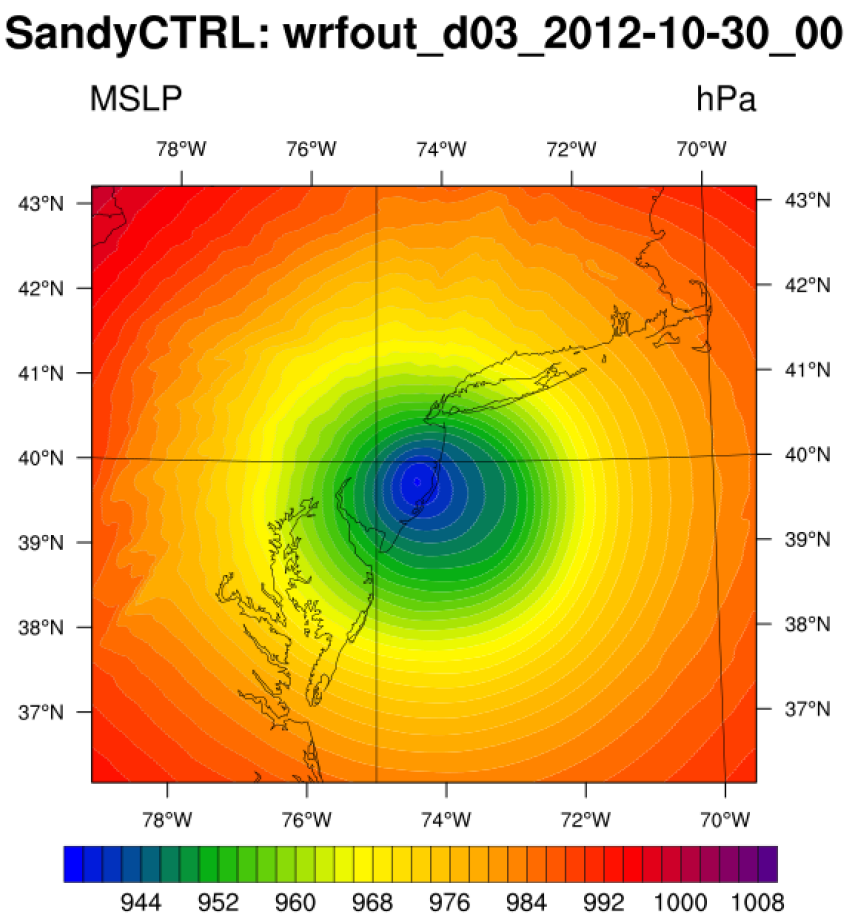
Ongoing experiments: (1) Evaluate impact of diurnal cycle inclusion on HAC's

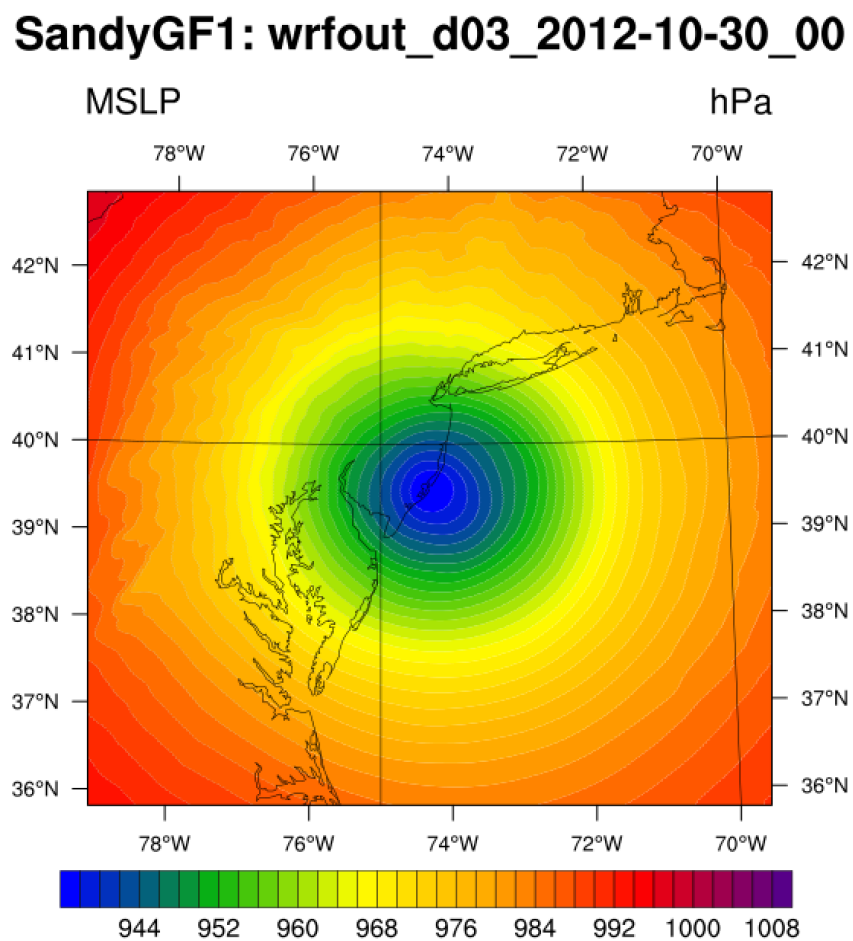


(2) Evaluate impact of stochastically perturbing vertical mass flux PDF's



Currently under way: Initial tests within HWRF, 27-9-3km resolution simulations of Hurricane Sandy





Currently receiving much attention at operational NWP centers: Aerosols

Interaction with radiation (direct and semi-direct effect), clouds (indirect effect), and impact on data assimilation

Result: Working Group for Numerical Experimentation (WGNE) for aerosol impacts on numerical weather prediction

Second and third test case selected to evaluate aerosol impact on NWP (WRF-Chem, but also global modeling systems)

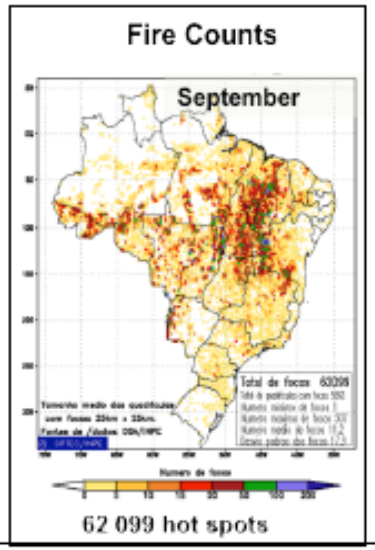
Case 3: Extreme biomass burning smoke in Brazil – the SAMBBA case

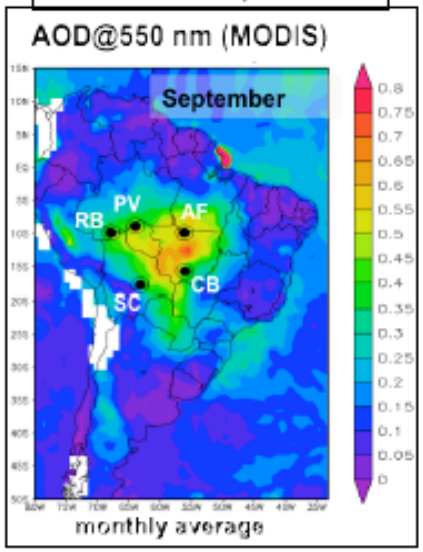
Experiment set-up

- Aerosol effects: forecast with and without interactive aerosols, including direct and indirect effects.
- Ideally four experiments should be performed:

Experiment	Direct effect	Indirect effect	Direct + indirect effects	No aerosol interaction
1	X			
2		X		
3			X	
4				X

- Duration and time period: 10 days, 05-15 September 2012
- Length: minimum of 3 days forecasts from the 00UTC or 1200UTC analysis with and without interactive aerosols.
- Center of the model domain (for limited area models): 60^0 W, 10^0 S
- Model configuration should be compatible with the configuration of the operational system used currently for NWP.
- Initial and boundary conditions for meteo fields can be provided upon by ECMWF (eg MACC) for the limited area models.



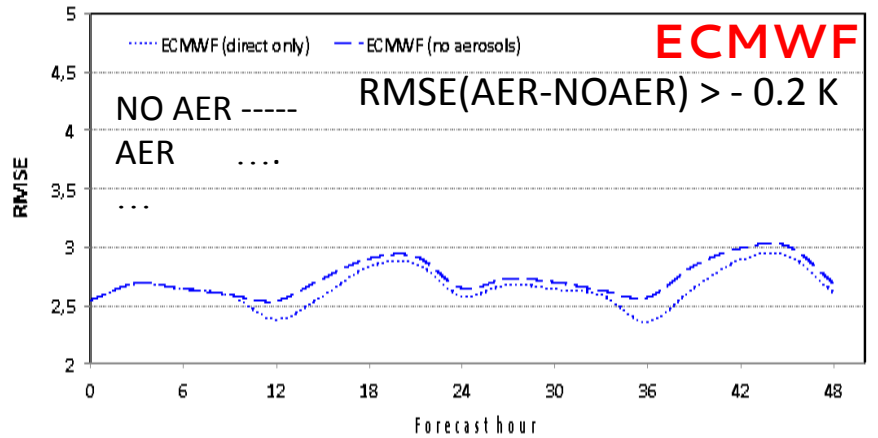


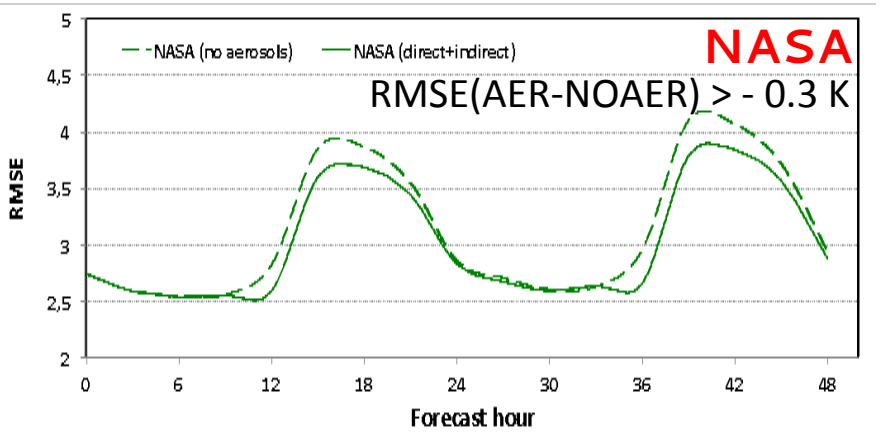
Our planned Methodology for WGNE testcases

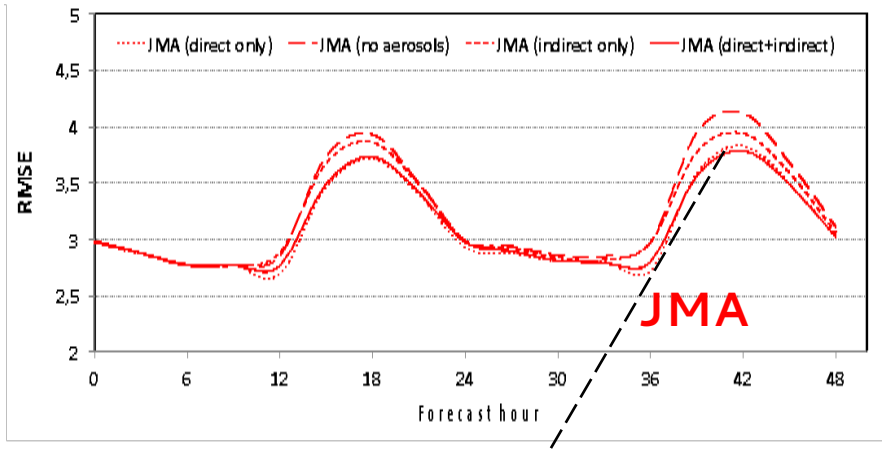
1. Aerosol impacts on NWP: Use more sophisticated cloud resolving simulations, then decrease complexity and resolution to what is used in operational systems
2. How different are simple, lower resolution simulations from complex simulations? Observations?
3. Many studies of indirect effect use resolutions that require convective parameterizations. Unless the CP includes aerosol interactions, conclusions are at best suspect.
4. Conclusions are also suspect with a CP that includes aerosol interactions – unless we can show agreement with cloud resolving simulations

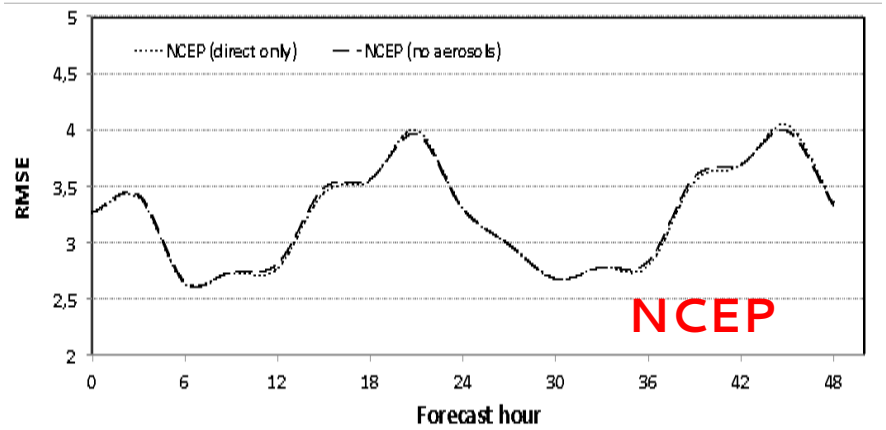
Can we even believe in cloud resolving simulations? – Hopefully strong signals will tell us something..

RMSE: 2-m Temperature









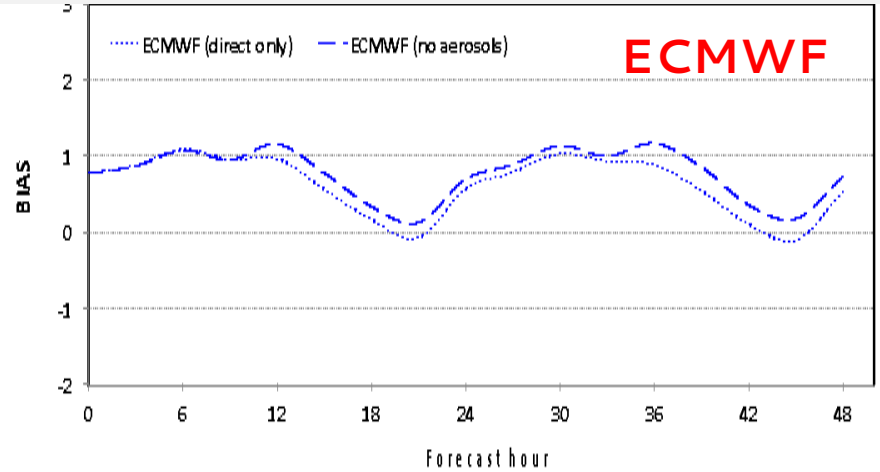
4.12 – no interaction
3.94 – indirect only
3.83 – direct only
3.79 – IND + DIR

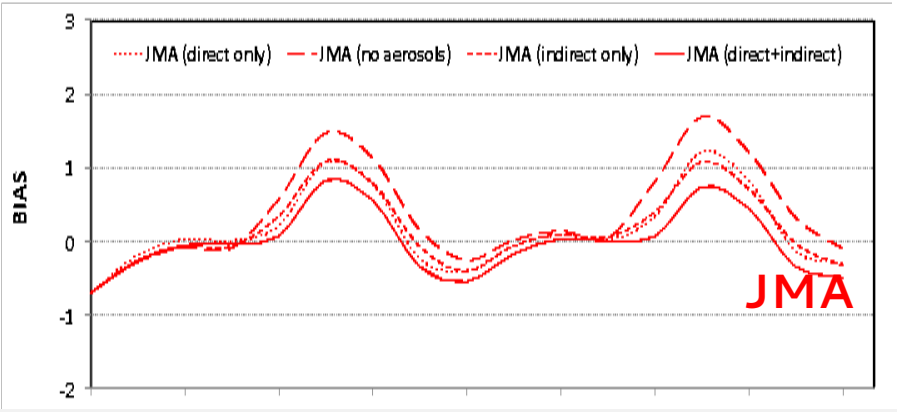
- ECMWF, NASA, JMA: Consistent and significative RMSE reduction
- NCEP : negligible change
- JMA : RMSE reduction increases with the aerosol treatment complexity

ECMWF and JMA use climatologies for no aer run

BIAS: 2m Temperature

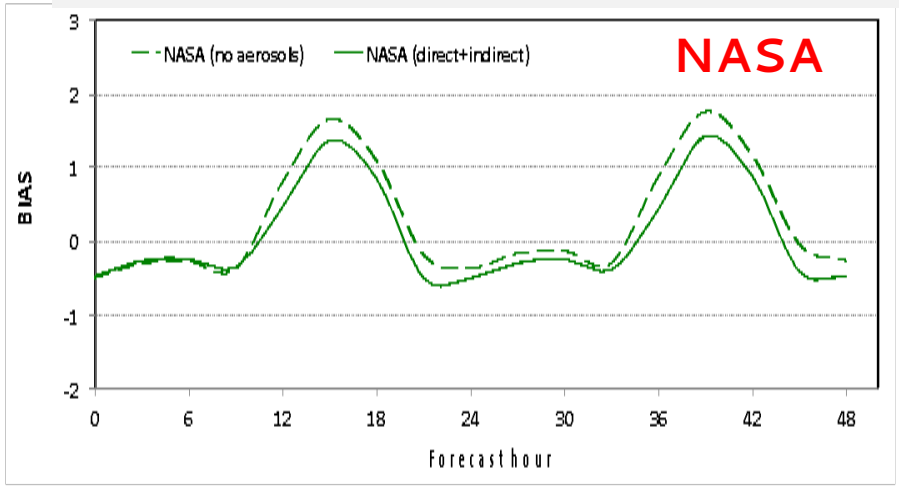
Comparing to no direct effect: Consistent bias reduction

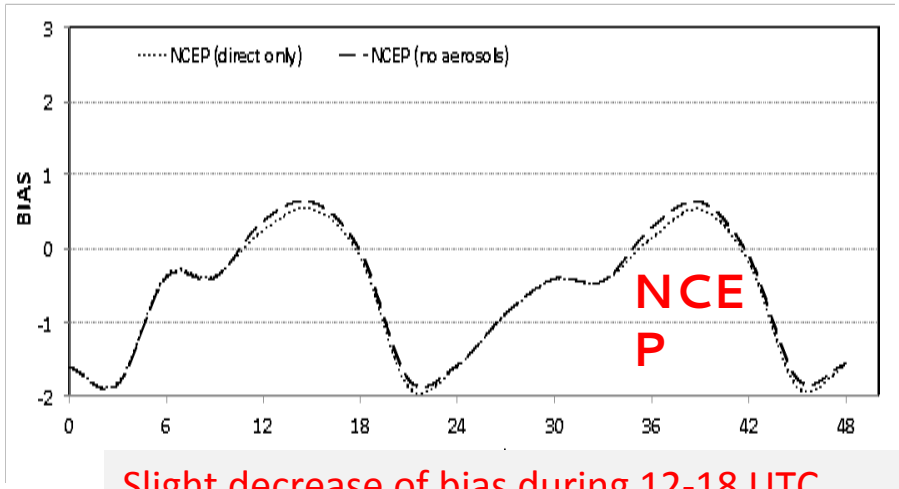




Consistent bias reduction with increasing aerosol treatment complexity during the day, with a slight increase* during the night.
(*) Absolute value

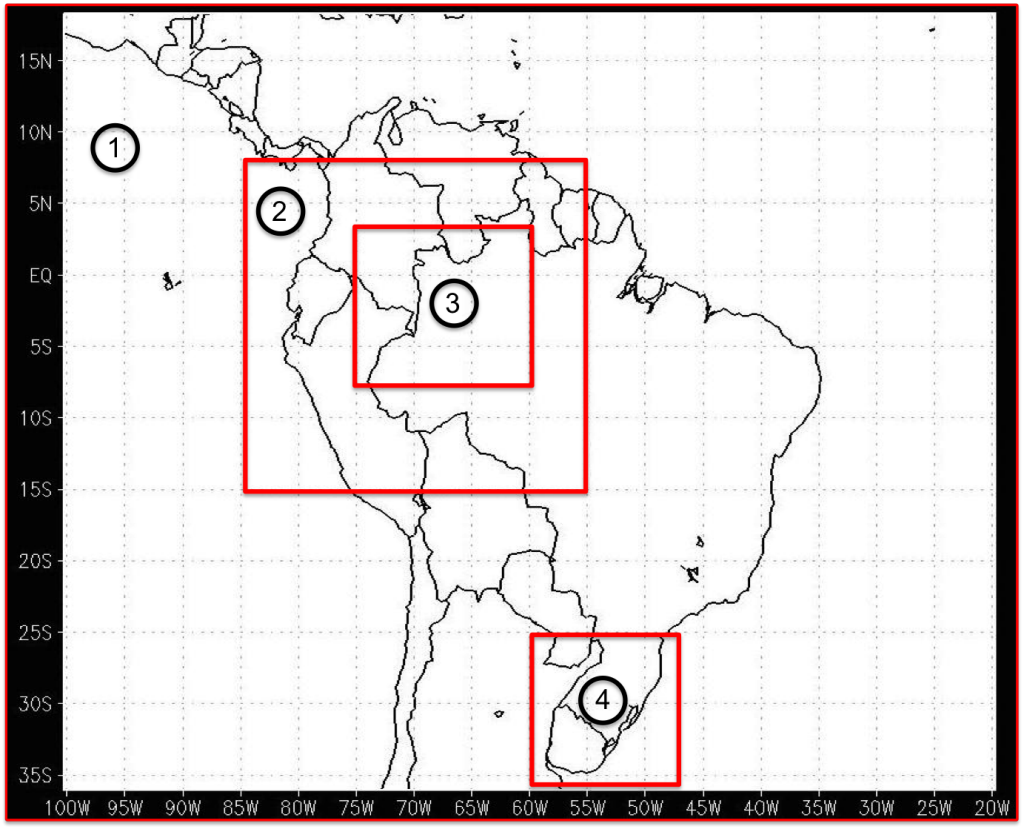
Comparing to no aerosols: bias decreases during the day, but increases* at night





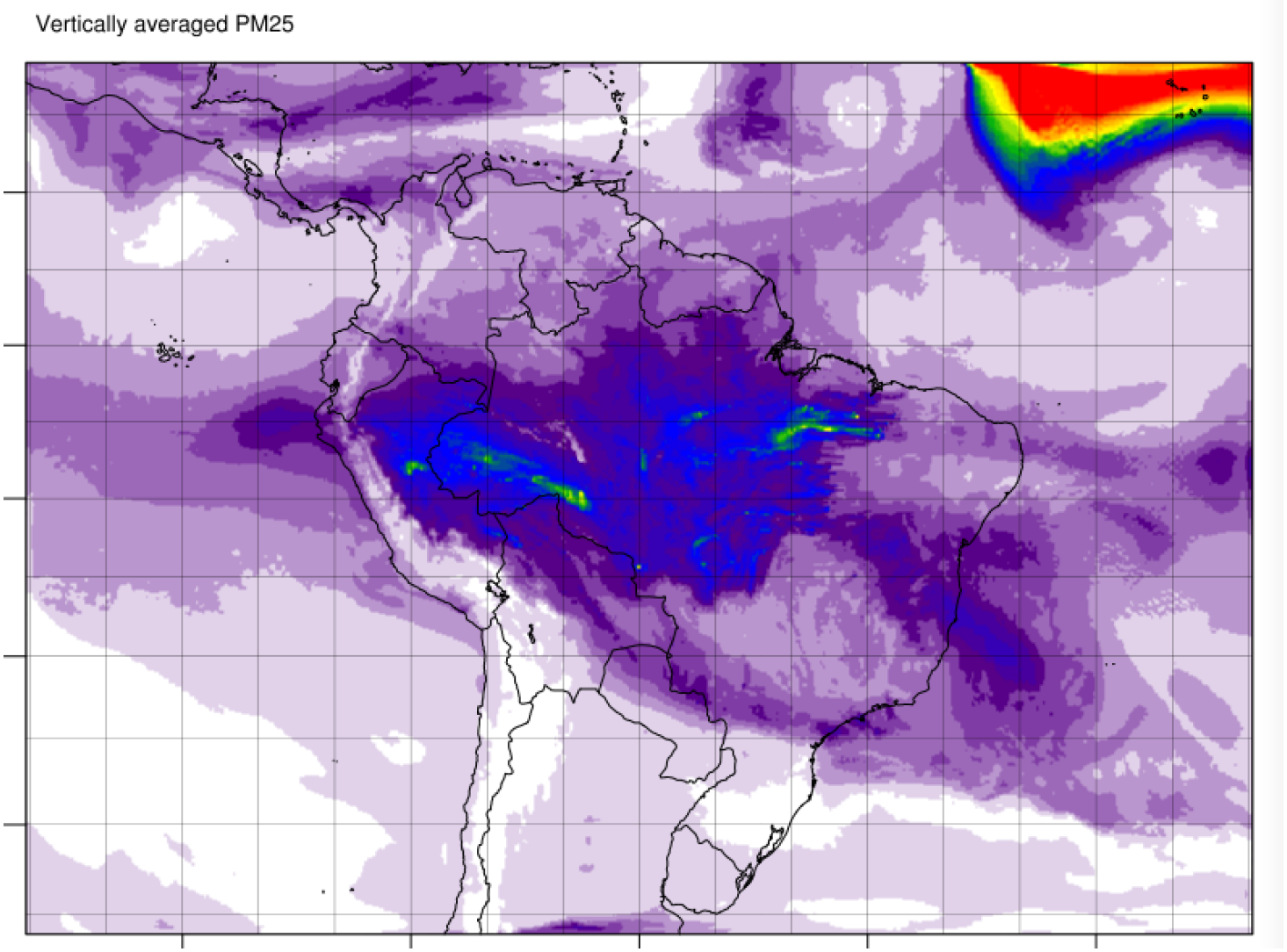
Slight decrease of bias during 12-18 UTC

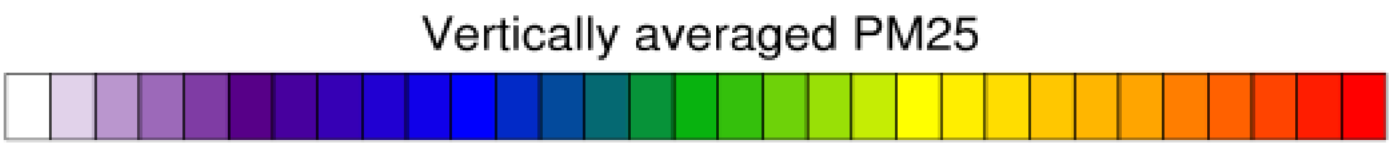
WRF-Chem domains



Domain	Resolution	Grid Size
1 (South America)	15km	590 * 420
2 (North Brazil)	5km	586 * 439
3 (North Brazil)	1.67km	847 * 595
4 (South Brazil)	5km	276 * 276

Typical vertically averaged PM25 distribution





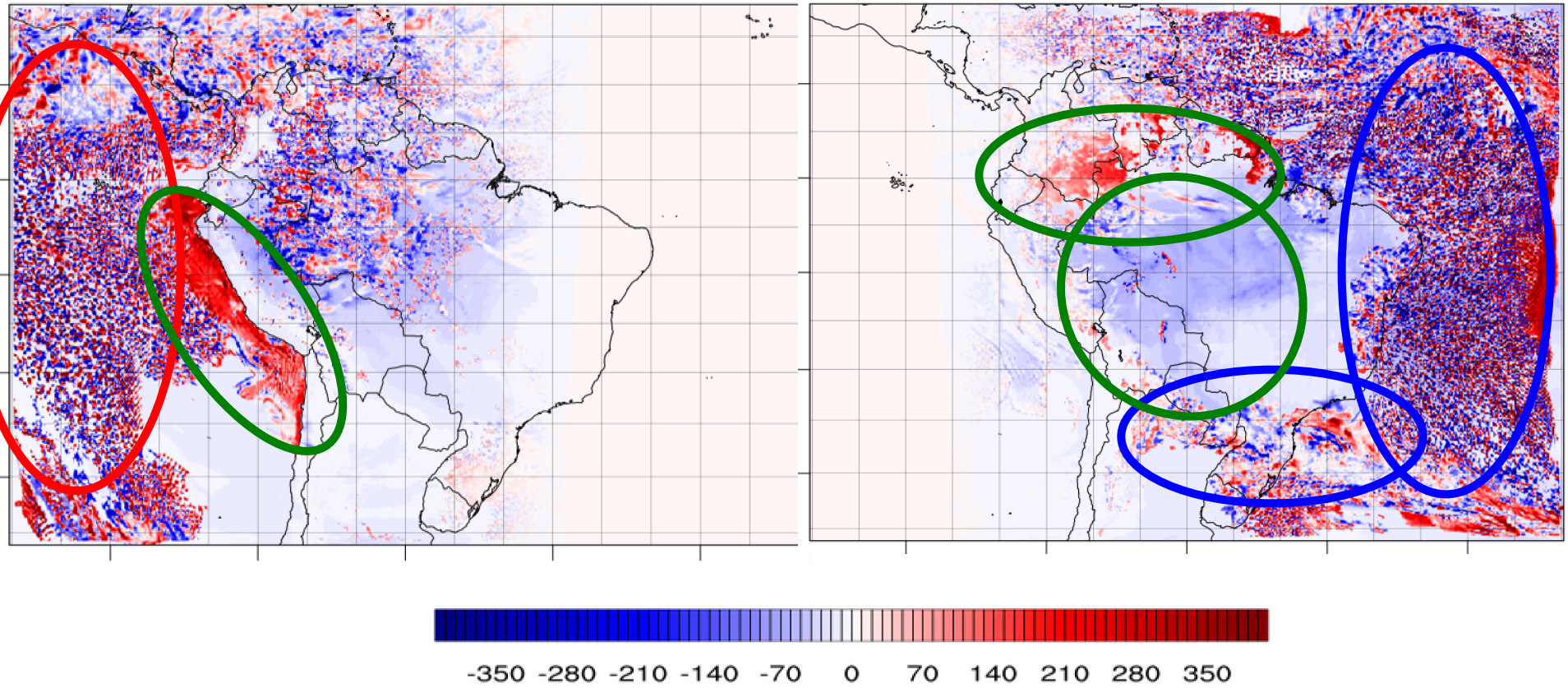
Systematic and random SW differences (Chem – Met) (almost every run, 20 runs, 3-day forecasts)

Random changes, no clear pattern

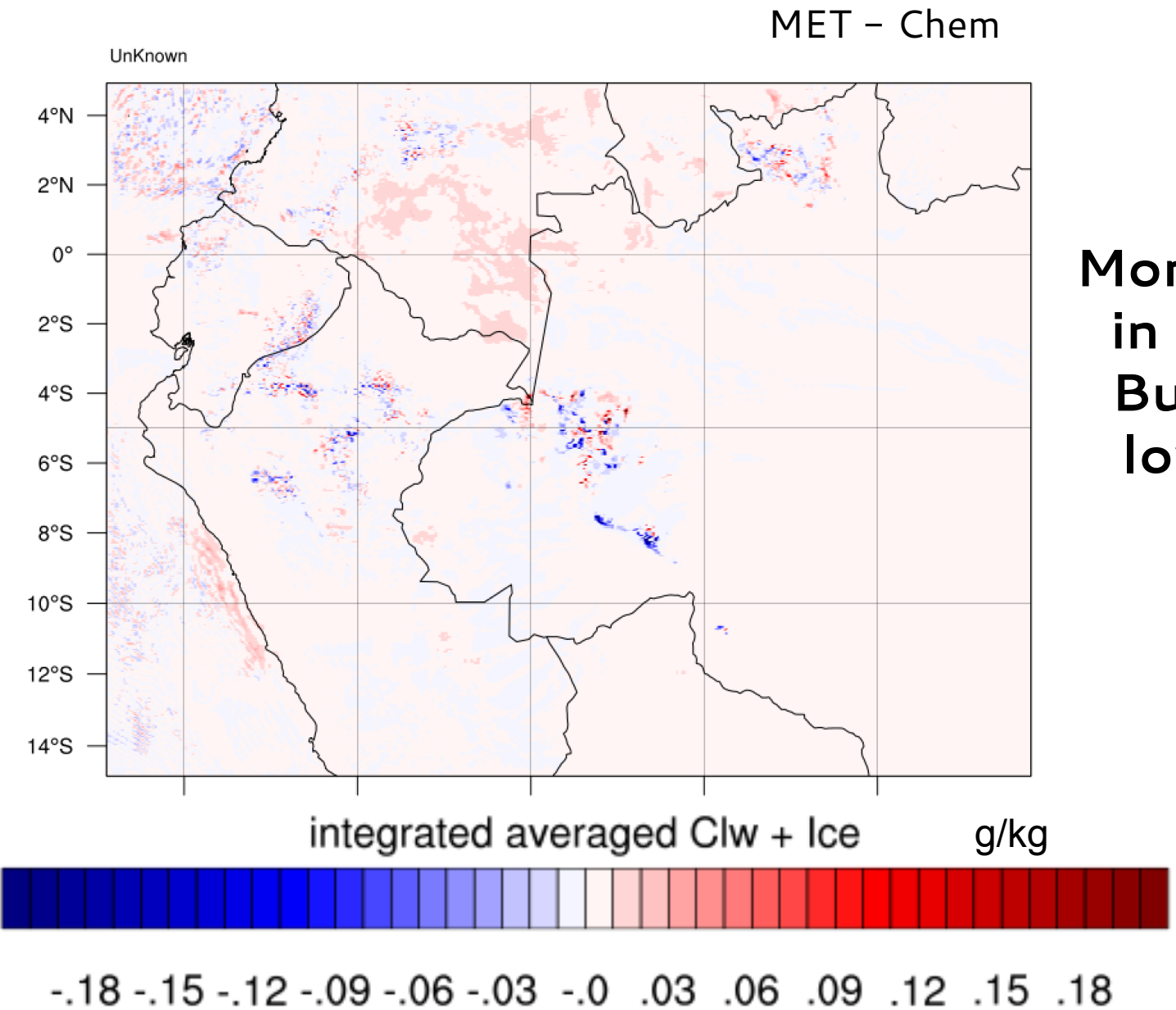
Systematic differences, almost every run

Appears to be mostly cloudy, usually less SW radiation reaching the ground

Systematic differences, almost every run, but not always, usually less SW radiation reaching the ground



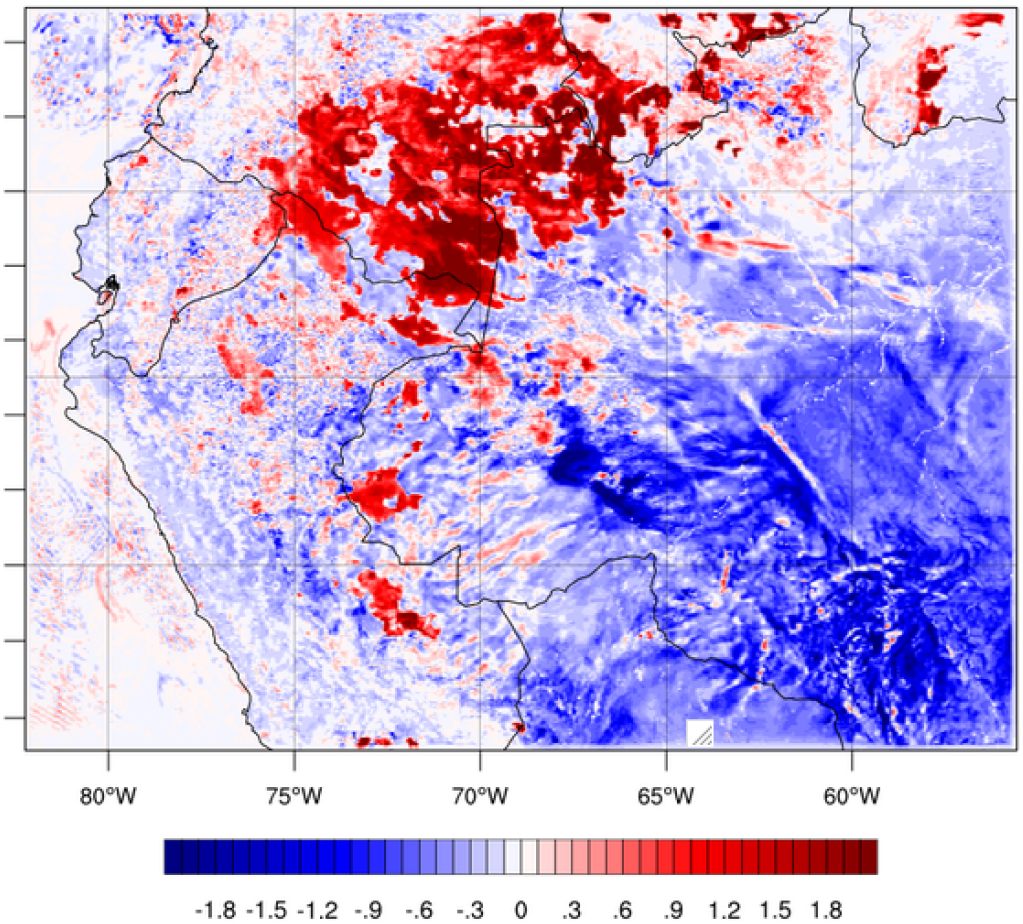
Differences in integrated cloud water and ice concentrations, 36 hour simulations starting Sep 9, 12Z. DX=5km, displayed is Sep 10, 12Z



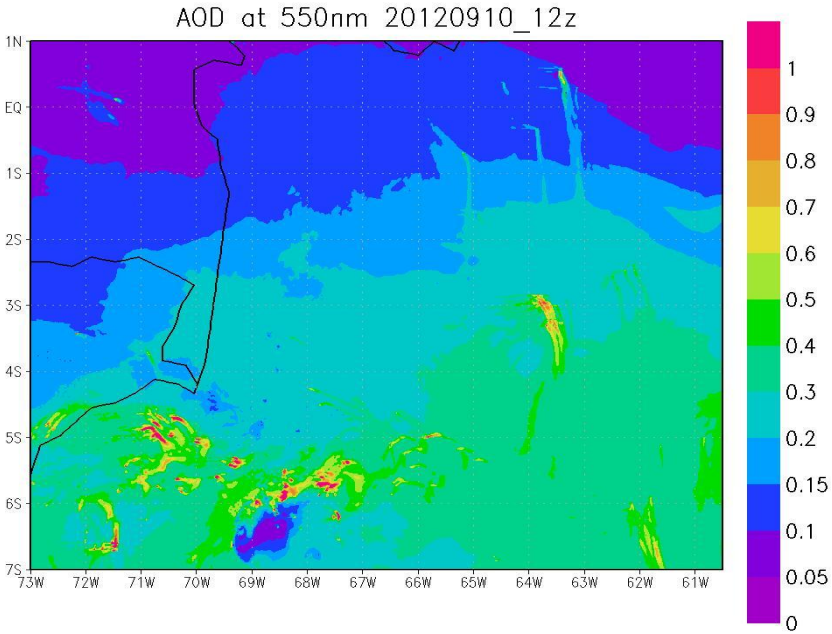
More cloudwater in the met run! But only in the lowest levels!

Results from 5km resolution simulation, T2m differences, CHEM - MET

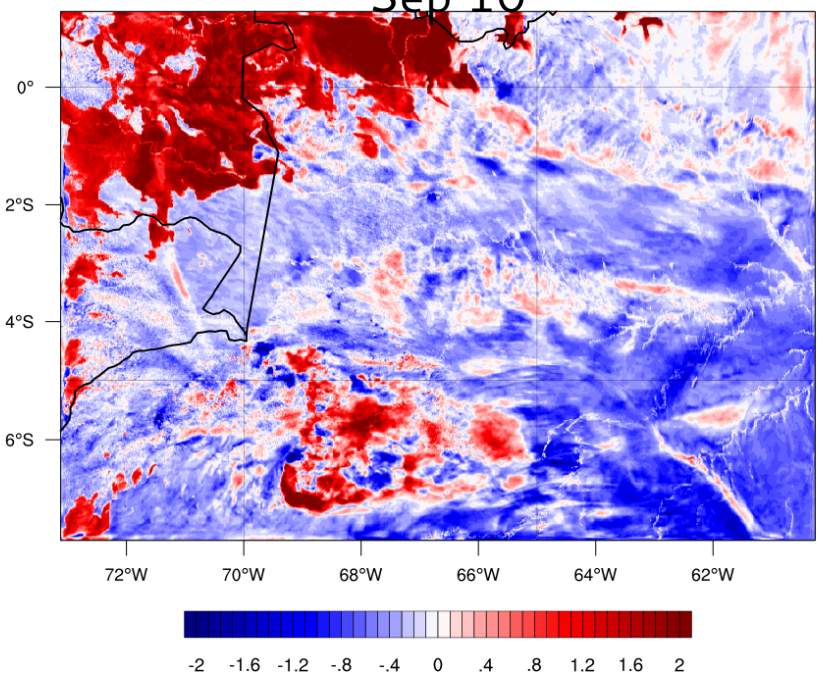
Sep 10, 12Z

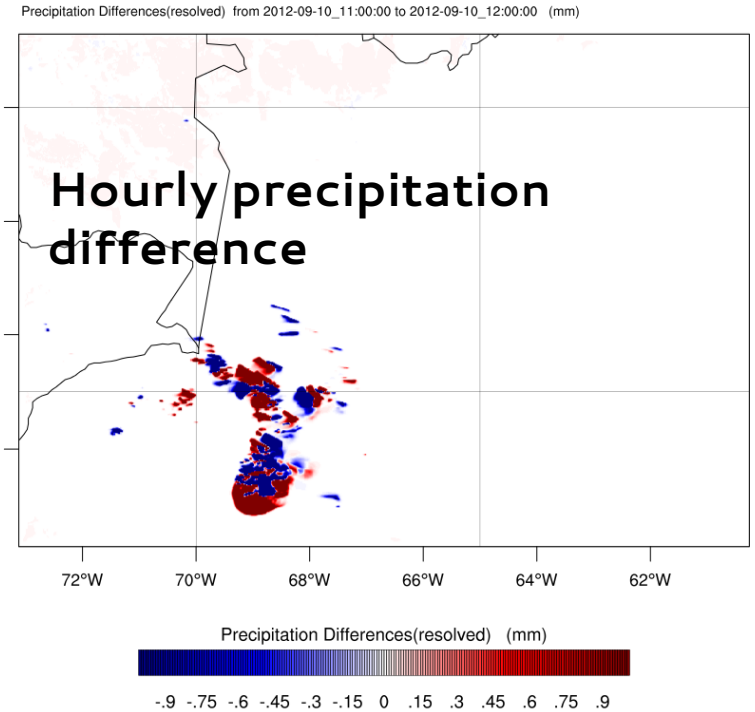


Next: 1.7km resolution, convection: WRF-Chem simulation over 30hr period, initialized at 18Z, Sep 9



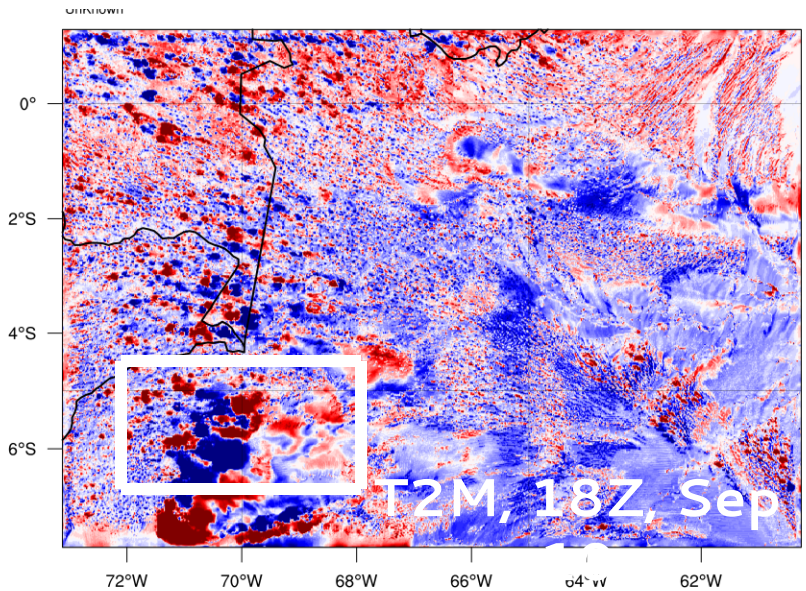
T2M differences, Chem-Met, 12Z, Sep 10

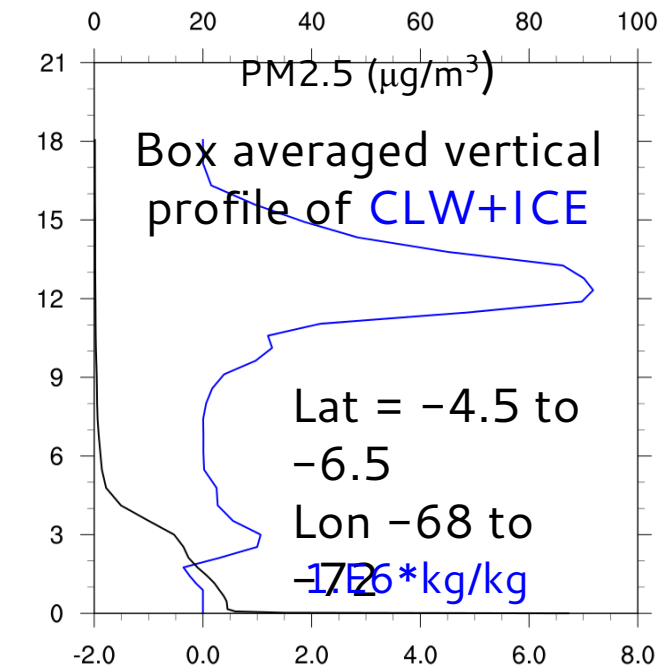




Low level clouds in NE corner do not exist in run with indirect effect included...

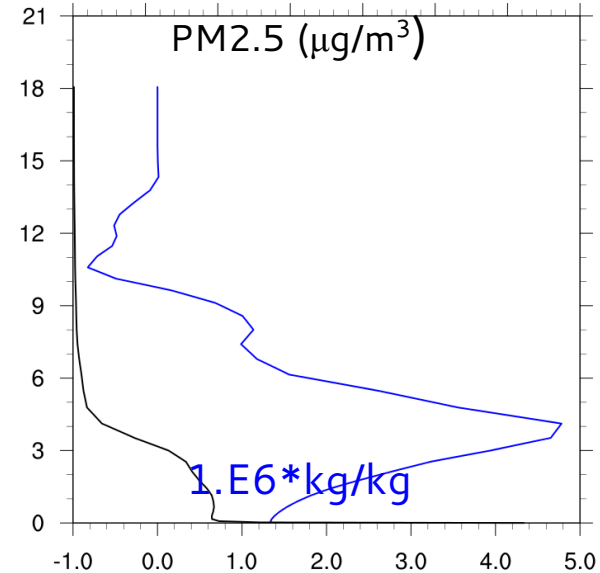
Averaging in areas with significant convection



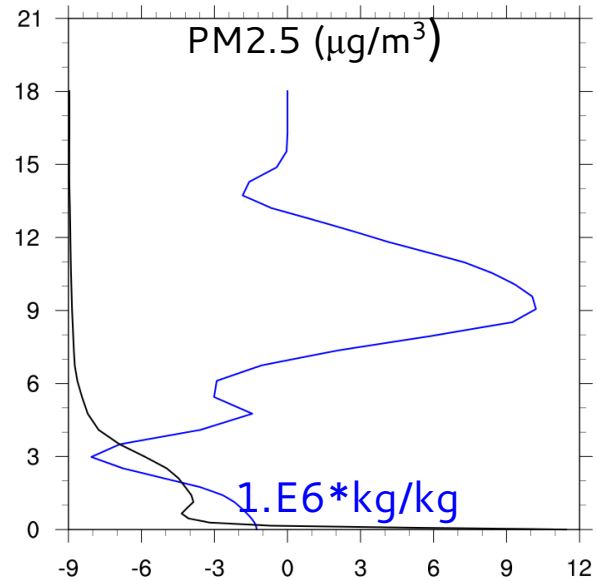


RNW unpredictable: Convection has different strength

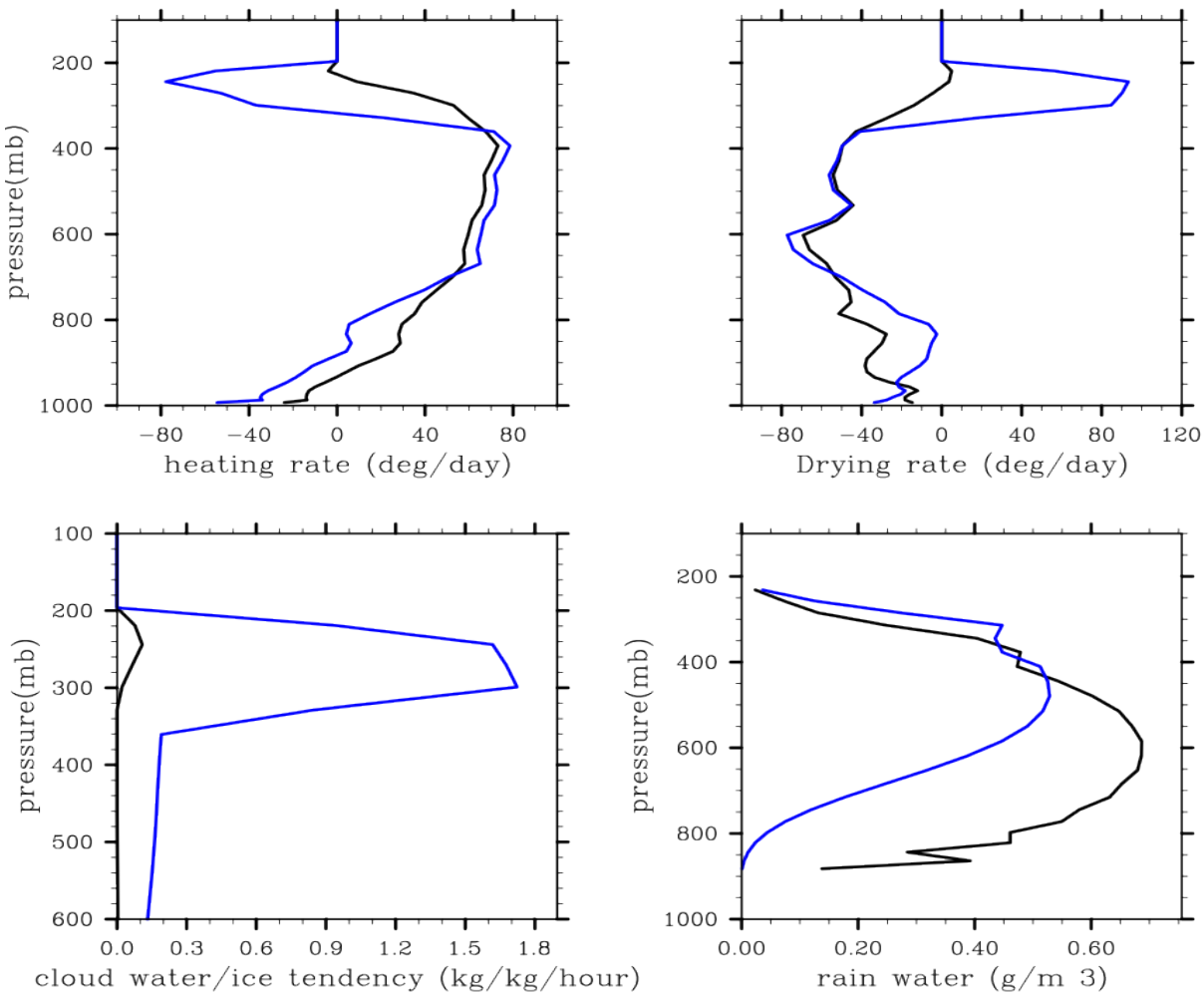
CLW and ICE appear to have a signal



RNW+SNOW at different locations



So what if you try this with aerosol-awareness turned on in the GF convective parameterization



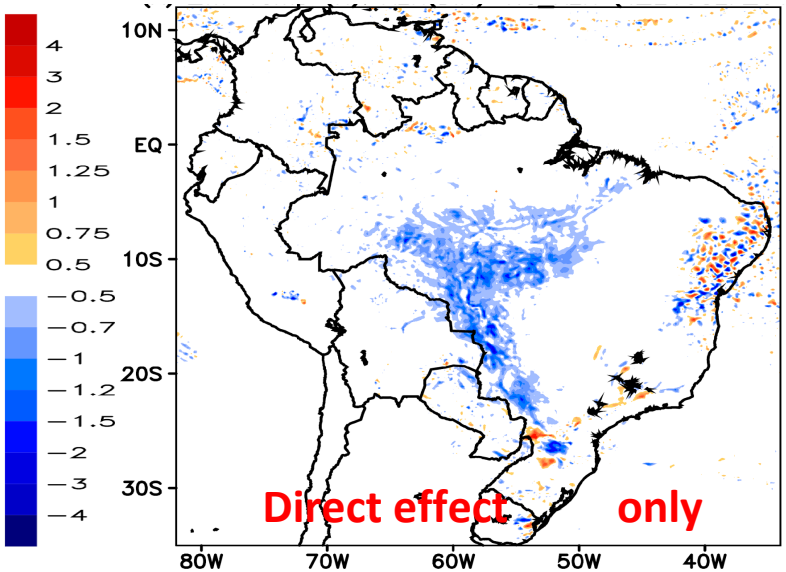
Polluted (AOD=1.)

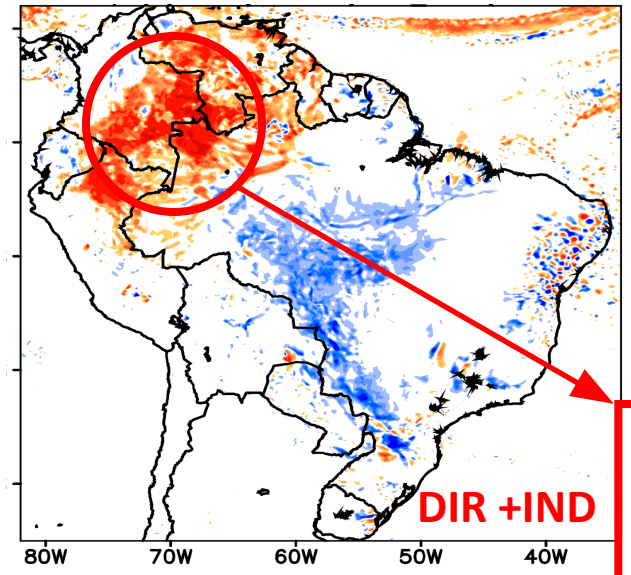
clean (AOD=.01)

Previous 1-d tests

- much more detrainment of cloud water and ice at cloud top
- less suspended hydrometeors, especially in lower part of parameterized clouds
- stronger downdrafts. Leading to less drying in and just above the boundary layer, but stronger cooling in lowest levels

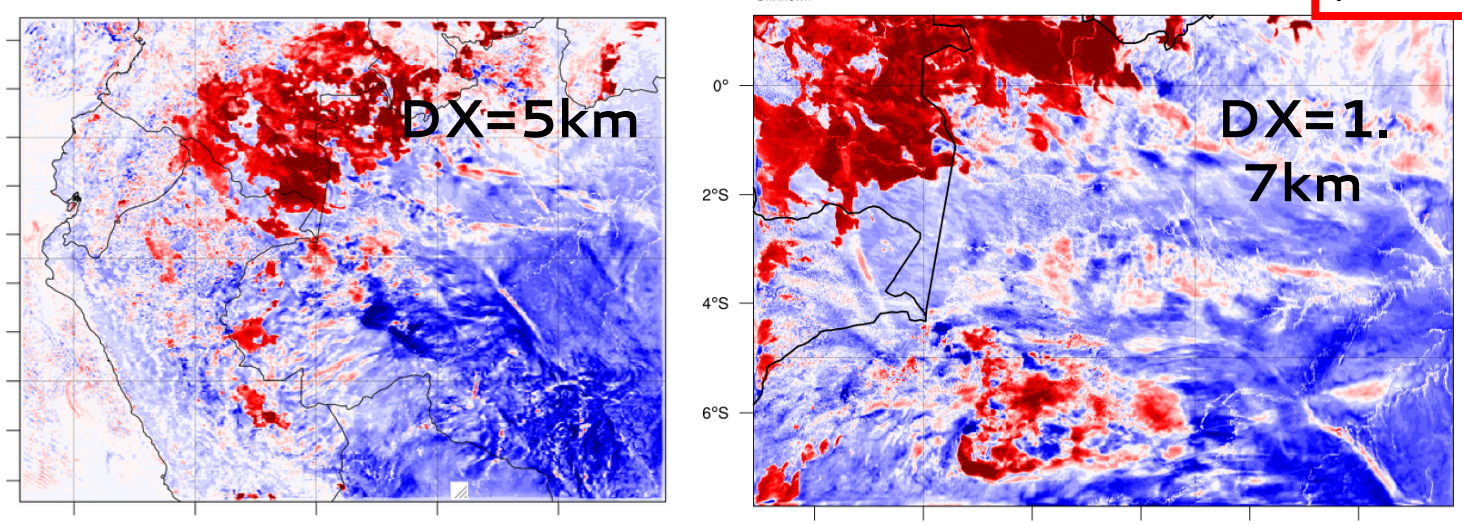
T2M difference fields, September 10, 1200UTC- mid-morning. Positive (red) is warmer compared to MET – simulation with convective parameterization



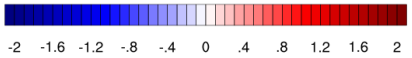


Using convective parameterization with and without aerosol awareness

Why should this be related to convective parameterization?



Convection permitting simulations



Aerosol tests – initial conclusions

- Tropical environments may be the most likely to see an impact – **signal strength also very important (very low or very high AOD)**
- Strength of convection at this point, and with our model setup, may be difficult to correlate to aerosols
- Initial results for aerosol aware convective parameterization indicate more tests needed
  - Shallow convection
  - Use CCN from model
- 3d impacts will depend on environmental conditions
  - Because of the dependence of precipitation efficiency on wind shear and subcloud humidity in addition to CCN, impacts in middle latitudes may be much more mixed

Aerosol tests – ongoing and future work

- More simulations are currently being done with dx=1.7km, also over the mid latitude domain in southern Brazil
- We will also test simpler chemistry modules and microphysics schemes with a focus on:
  - Thompson aerosol aware microphysics would be much less expensive approach and will be used operationally at NCEP on regional scales
  - GF scheme can run with observed AOD (no chemistry at all necessary)
  - How simple can we go and still compare well to the complex simulations
- We are planning on testing the impact on NWP within a global modeling system (FIM, http://fim.noaa.gov), also for seasonal predictions using FIM-iHYCOM-Chem
- Experiments with stochasticism (J. Berner)