Almost Resolving Convection but not quite...Challenges for Convective Parameterizations

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Special acknowledgements for development and providing slides go to:

Saulo Freitas (NASA), Hannah Barnes (young scientist at GSL)

Structure of talk

1. Some basics on convective parameterizations
2. Background on gray-scale issues, why is there a problem?
3. Some examples of early and current ideas on what to do on gray-scales
4. Are we done?
5. What are we working on with the Grell-Freitas (GF) scheme

The parameterization problem

- What do we do when we parameterize?
  - We know of a process that is important for model simulation but cannot be resolved explicitly
  - We express the effect that this process would have in terms of other variables and processes that the models simulate
- What is necessary to be able to parameterize?
  - A good physical understanding of the process
  - Scale separation

Do we have a good physical understanding of the process ?

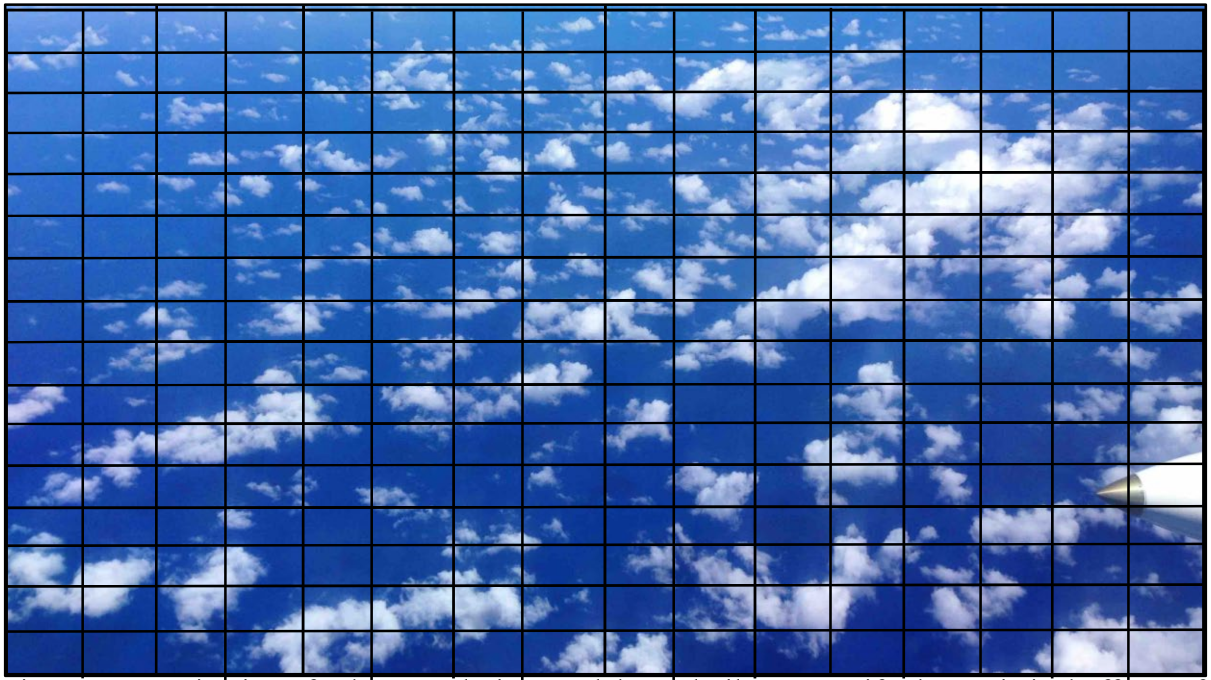
Convection and clouds are very complex, multiscale processes

and also are beautiful (to a meteorologist, or a weather geek!)

What do we need to know when we try to parameterize convection?

1. Where will the convection be, and how strong will it be (closure and trigger functions)
   - Examples of closures used in parameterizations: stability closures, quasi-equilibrium closures, moisture convergence closures, non-resolved forcing, vertical velocity, trigger functions,….
2. How will convective clouds modify the environment
   - What does the cloud look like? Plume? Bubble? Where does the air inside the cloud come from? Entrainment? Detrainment? Lateral Mixing? What physical processes are important in the cloud? Condensation, evaporation? How important are downdrafts? How does the surrounding air respond? What does the mass flux look like?
3. Can scale separation be guaranteed?
   - Convection spans many scales - deep, congestus, shallow, organized – What to do if/when the model can resolve some of the convection?
4. For some modeling applications: Atmospheric composition interactions, aerosols in microphysics, aqueous phase chemistry, scavenging from tracers

Scale Separation and Convective Parameterizations



Convective parameterizations for low-resolution models are built to quantify the statistical effects of all clouds in the grid box with the approximation that the clouds cover a small area of each grid-cell.

However, at high resolution:

- Some grid cells might be almost filled by the convective drafts
- Convective transports might occur on grid-scale
- Forcing and triggering may have to be different

Is there agreement on how to parameterize these beautiful designs from Mother Nature?

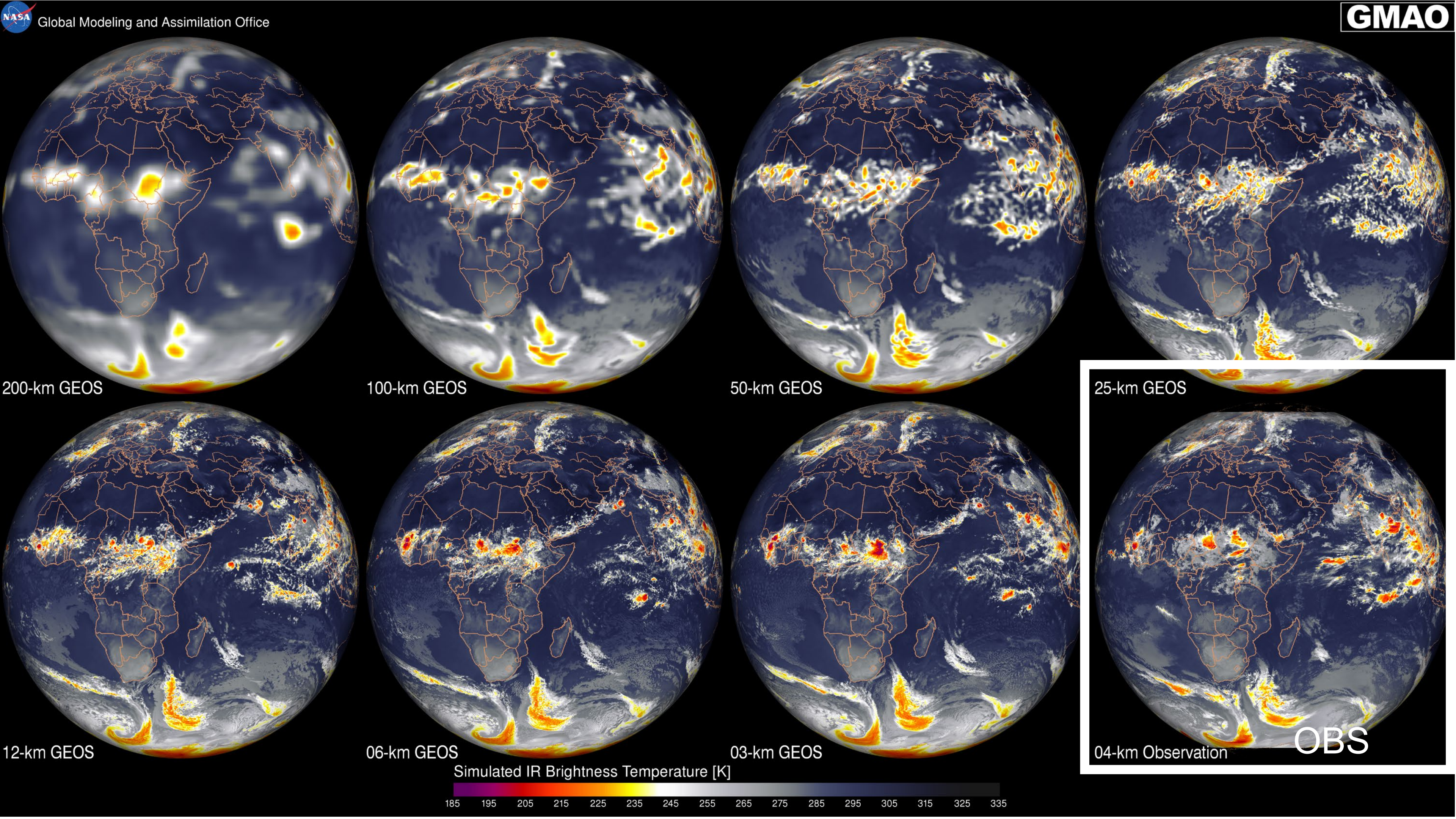
<u>Absolutely NOT!</u>

- Challenges in convective parameterizations are enormous
- Proper treatment of convection in the tropics is extremely important for longer range global forecast skill
- Scientists have worked on these challenges for over 50 years
- Currently more challenges are being added rather than resolved, one of them is the gray-scale question

Finer and finer resolution in NWP models makes scale-awareness (gray-scale issues) a fairly new but very important challenge

Gray-scales = resolutions where there is a mix between being able to resolve convection and having to parameterize it (1km < dx < 15km)

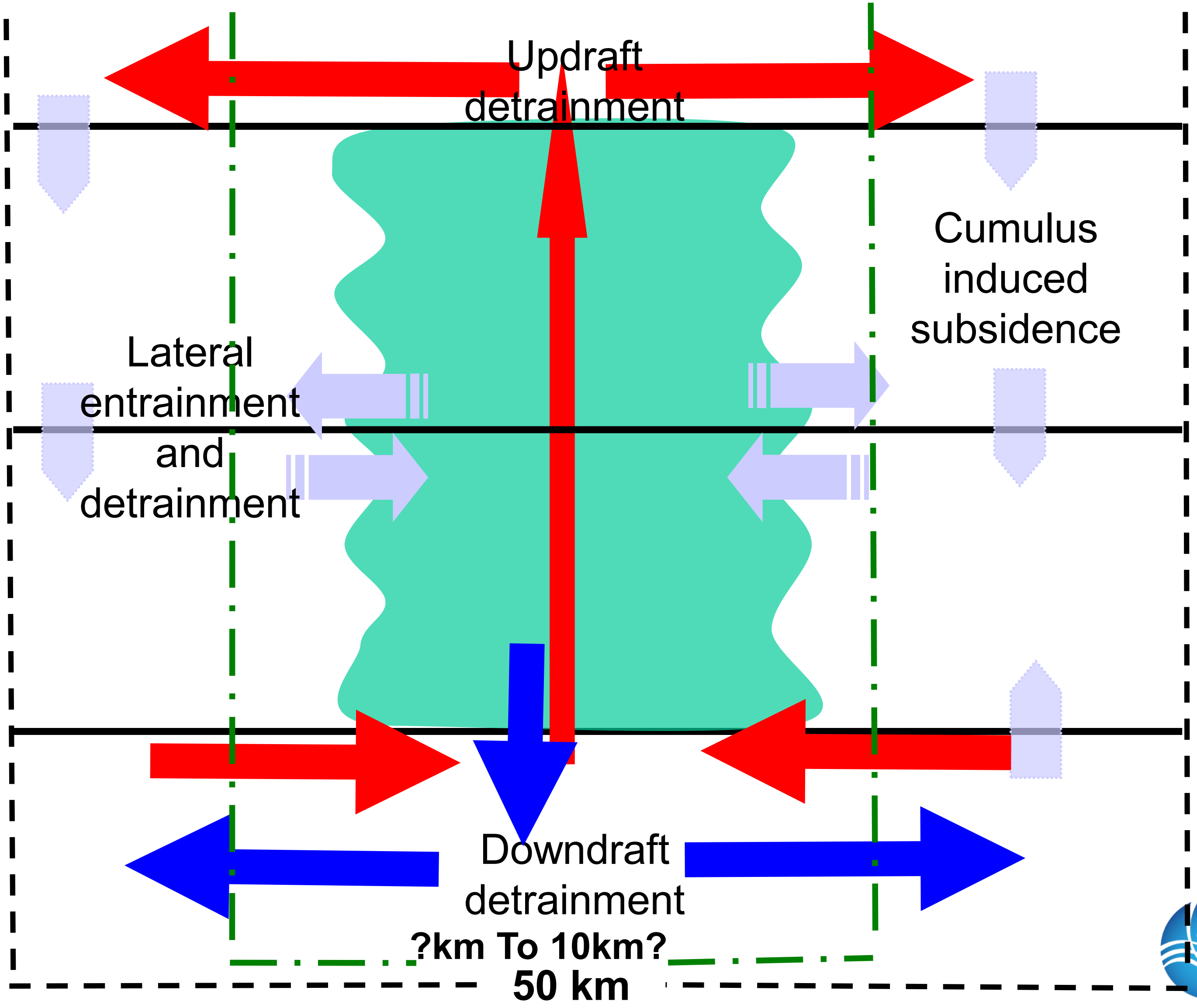
Do we need gray scale resolutions? DYAMOND runs – 40 day simulations (Freitas et al, 2020)



Gray scale resolutions are here to stay (till after my retirement)

- Need simulations on gray scales to more realistically represent cloud and precipitation fields
- Convective systems start looking more realistic at dx < 6 km

Simplified conceptual idea of how a convective cloud may be seen in a parameterization



Obvious problems – with respect to the commonly used conceptual picture

- Mass detrainment at top of cloud and surface (from downdrafts) and compensating subsidence
  - Have by far the strongest effect on the resolved scales
  - Could well be mostly out of the grid box with dx < 10km
- The finer the resolution, the worse the assumption that every feedback is within the same grid box

What may happen physically in the model simulations with full impact convective parameterization

- Subsidence may have strong heating and drying effect
  - May keep the explicit scheme from becoming active
  - Strong diffusive effect, flow will become too viscous for model to simulate the dynamics of explicit convection that may be resolvable (this "viscous" effect has also been found by other scientists in PBL/LES applications)
- Another problem – probably caused by the oversimplified conceptual picture - that is sometimes observed: Parameterized convection may be stuck over area of forcing (such as mountains), may not move with flow as dynamically simulated convection would
- Very little chance to catch organization of cloud clusters

Common problems if no convective parameterization is used

Convection spans many scales, a dx of 4km for example would give an effective resolution of > 20km, not good enough for explicit simulation

1. With no convective parameterization, convection may take too long to develop
2. Once it develops it may be too strong

For operational forecasting it depends on the application: for medium-range or S2S applications, results are quite often worse if no convective parameterization is used. For storm-scale severe weather forecasting, not using a CP may be preferred

Operational Centers are more and more applying gray-scale resolutions in their models

Three approaches are currently being used

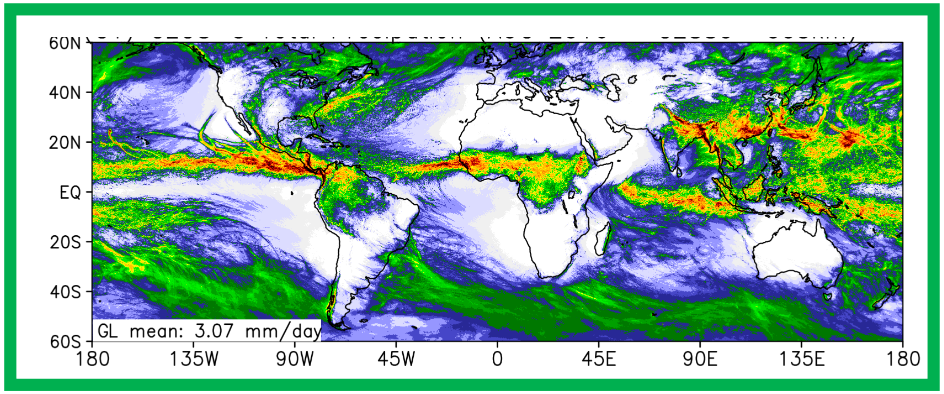
1. Convective parameterizations are being used without any modifications on gray-scales, because of “better” results
   - Who cares where the subsidence hits? As long as we conserve mass….and it rains…parameterizations are inherently inaccurate anyway
2. No convective parameterization is being used because of “better” results
   - Doesn’t look right to use them, parameterizations are inherently inaccurate anyway
3. Scale aware convective parameterizations are being used because of “better” results
   - Sort of an ensemble average of (1) and (2) ??

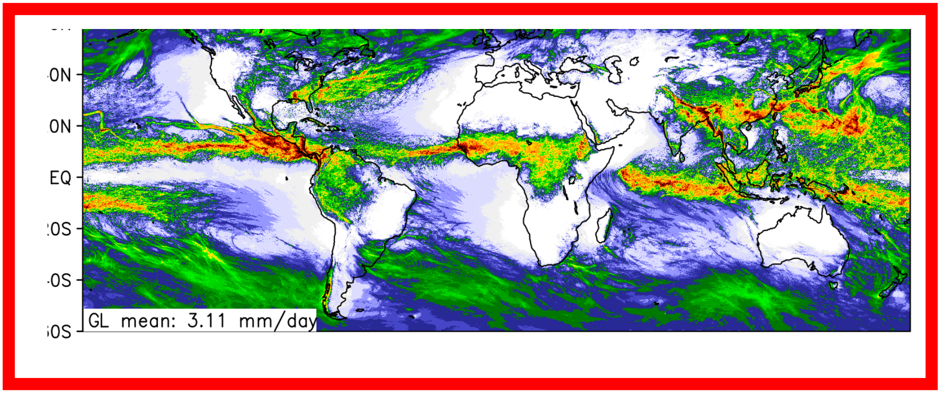
August 2016 precipitation mean (mm day^{-1}) as estimated by GPCP and GPM (panels A1 and A2). The remaining panels show the GEOS GCM simulated total precipitation. Horizontal resolution is approximately 3km

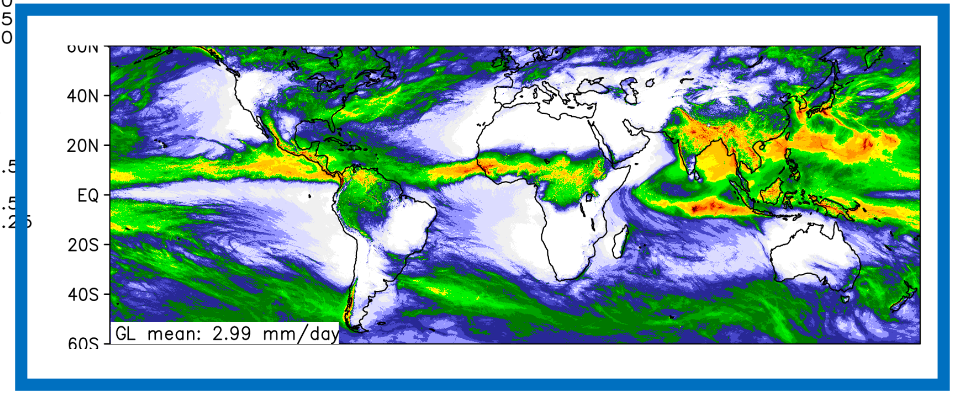
🟩 **Scale-aware GF**

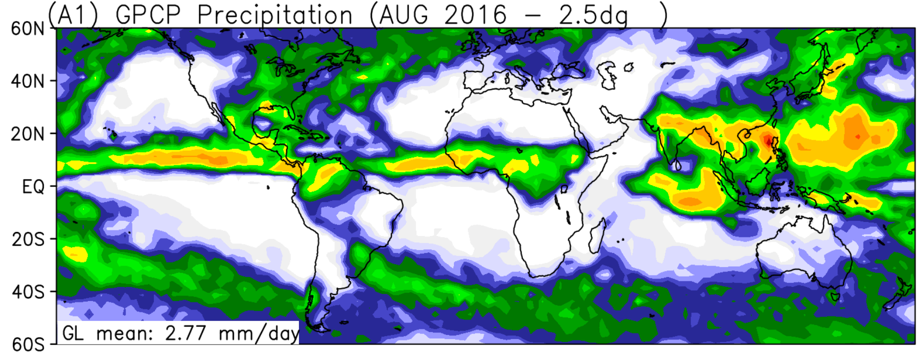
🟥 **No CP**

🟦 **GF w/o scale aware**

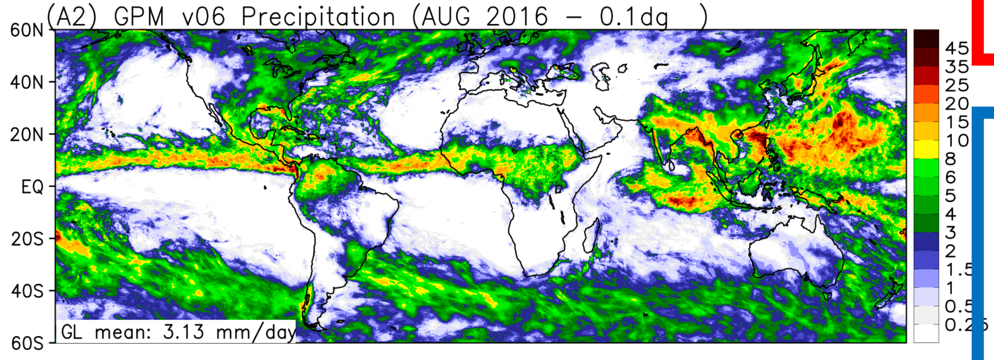








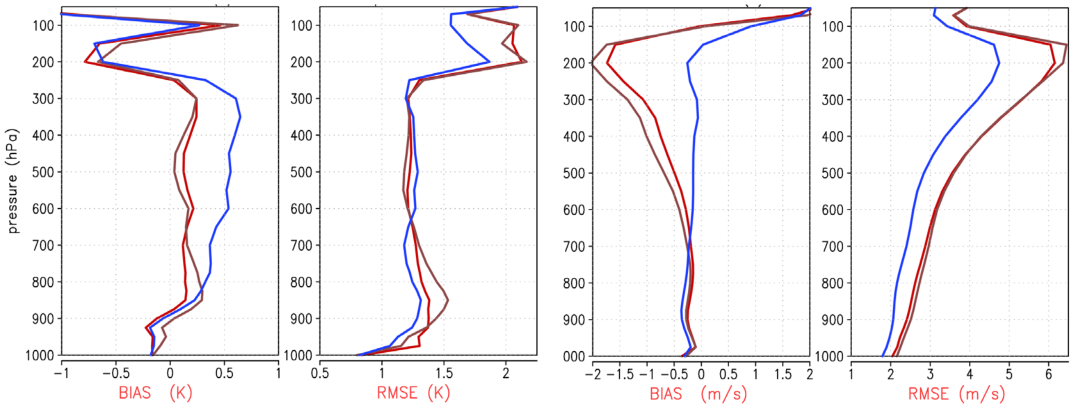
(A1) GPCP Precipitation (AUG 2016 – 2.5dg)



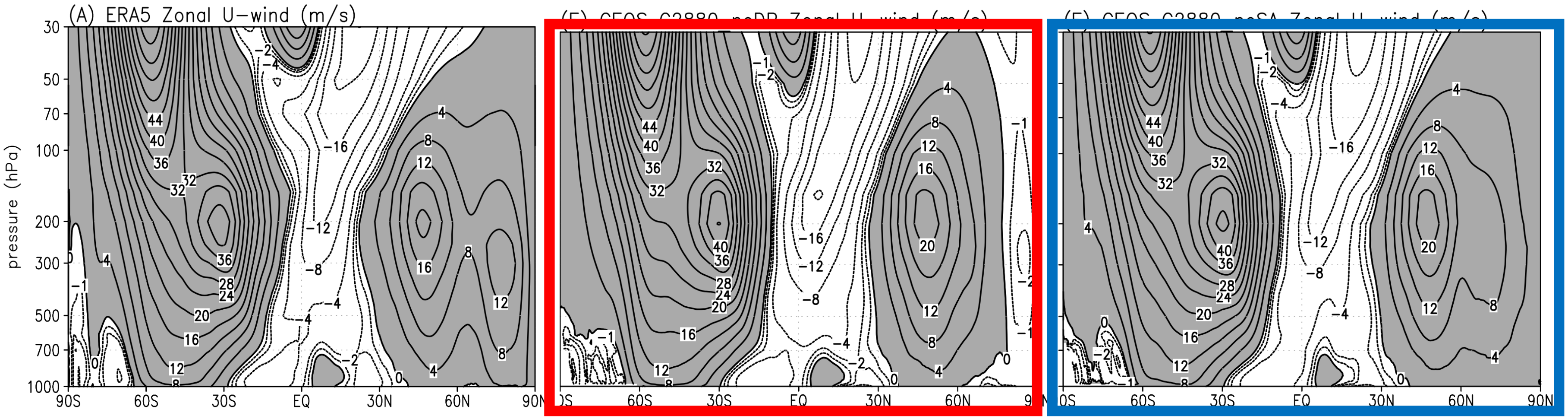
(A2) GPM v06 Precipitation (AUG 2016 – 0.1dg)

Freitas, S. R., Putman, W. M., Arnold, N. P., Adams, D. K., & Grell, G. A. (2020). Cascading toward a kilometer-scale GCM: Impacts of a scale-aware convection parameterization in the Goddard Earth Observing System GCM. *Geophysical Research Letters*, 47, e2020GL087682.

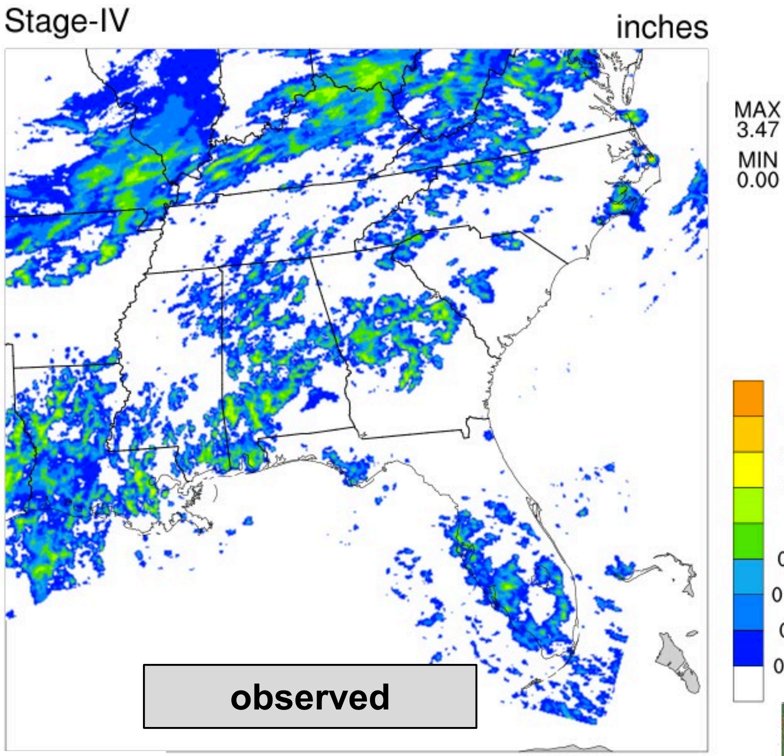
40 day simulation, August 2016, dx~3km, 72 levels, comparisons to ERA5 analysis for a run without a convective parameterization, one with **GF without scaling (!)** and one with scaling



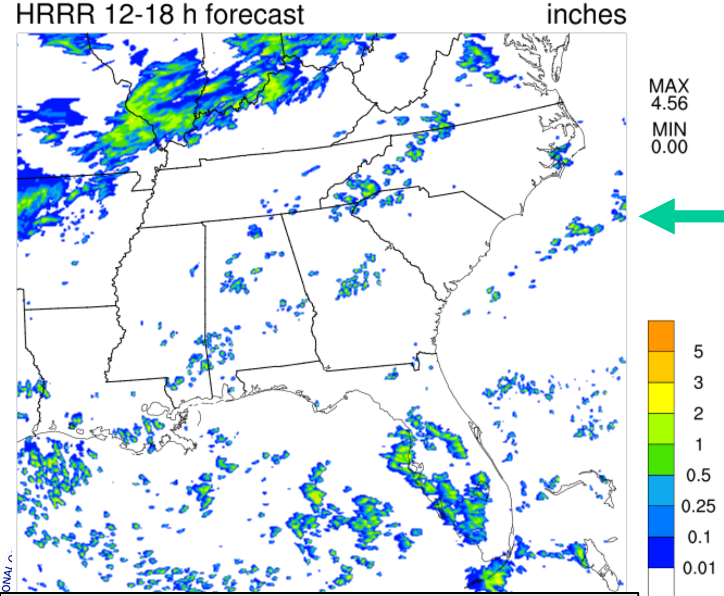
As above, but displaying averaged zonal U-wind



Best results – when looking at long range skill – for runs with full convective parameterization! **Worst for run without any parameterization!**



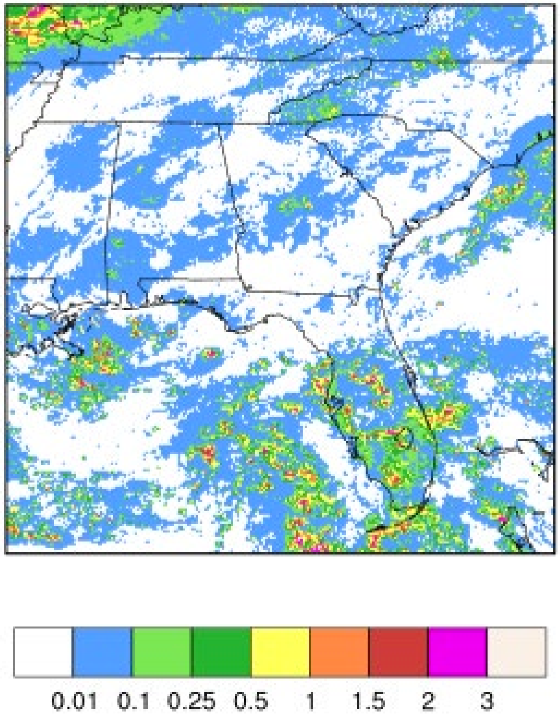
observed



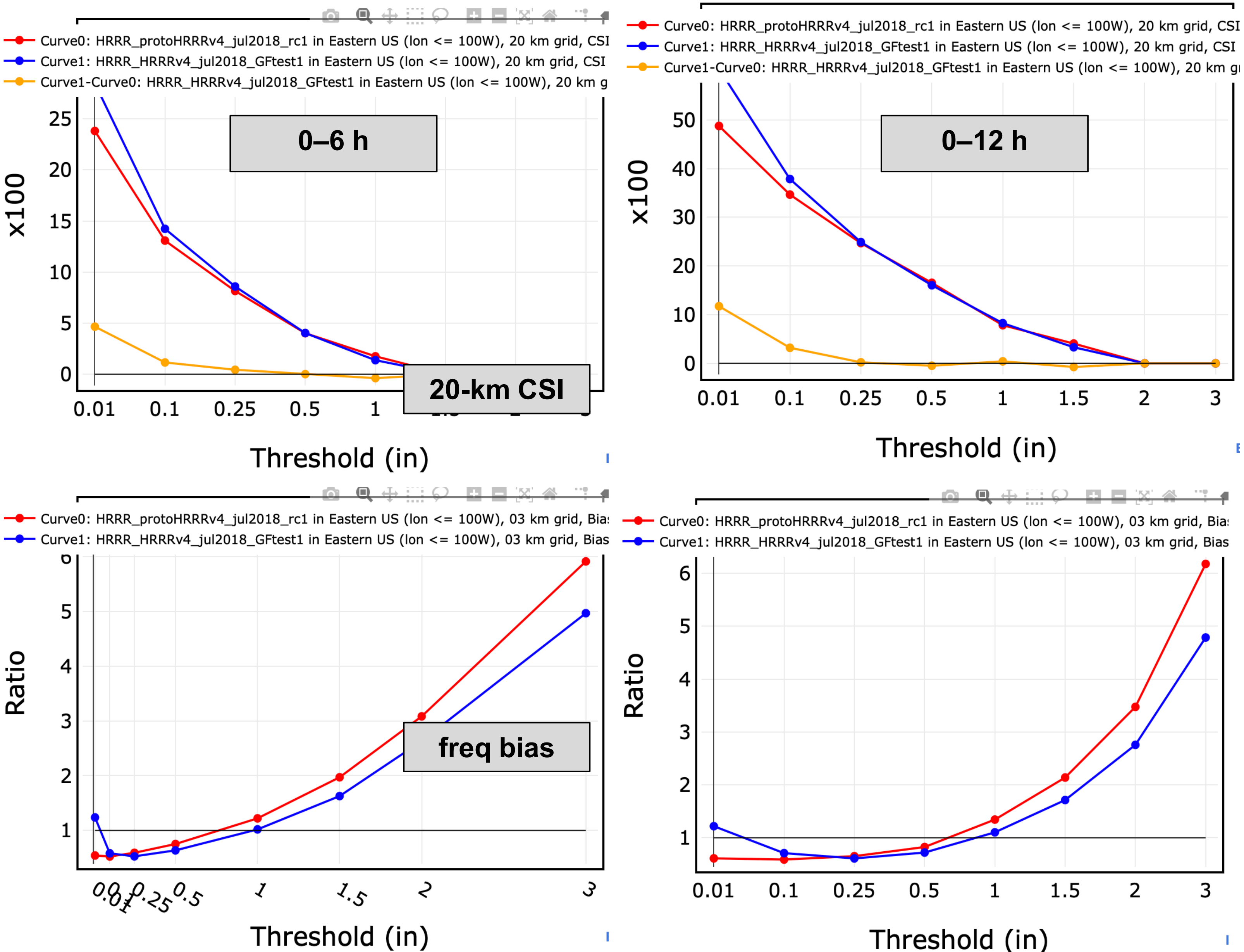
HRRRv4 forecast (“cu_physics = 0”)

No CP

With scale-aware GF.
Threshold at 0.6



Red curve: no convective parameterization used



0–6 h

0–12 h

20-km CSI

freq bias

precipitation
East CONUS: 8–9 Aug 2018

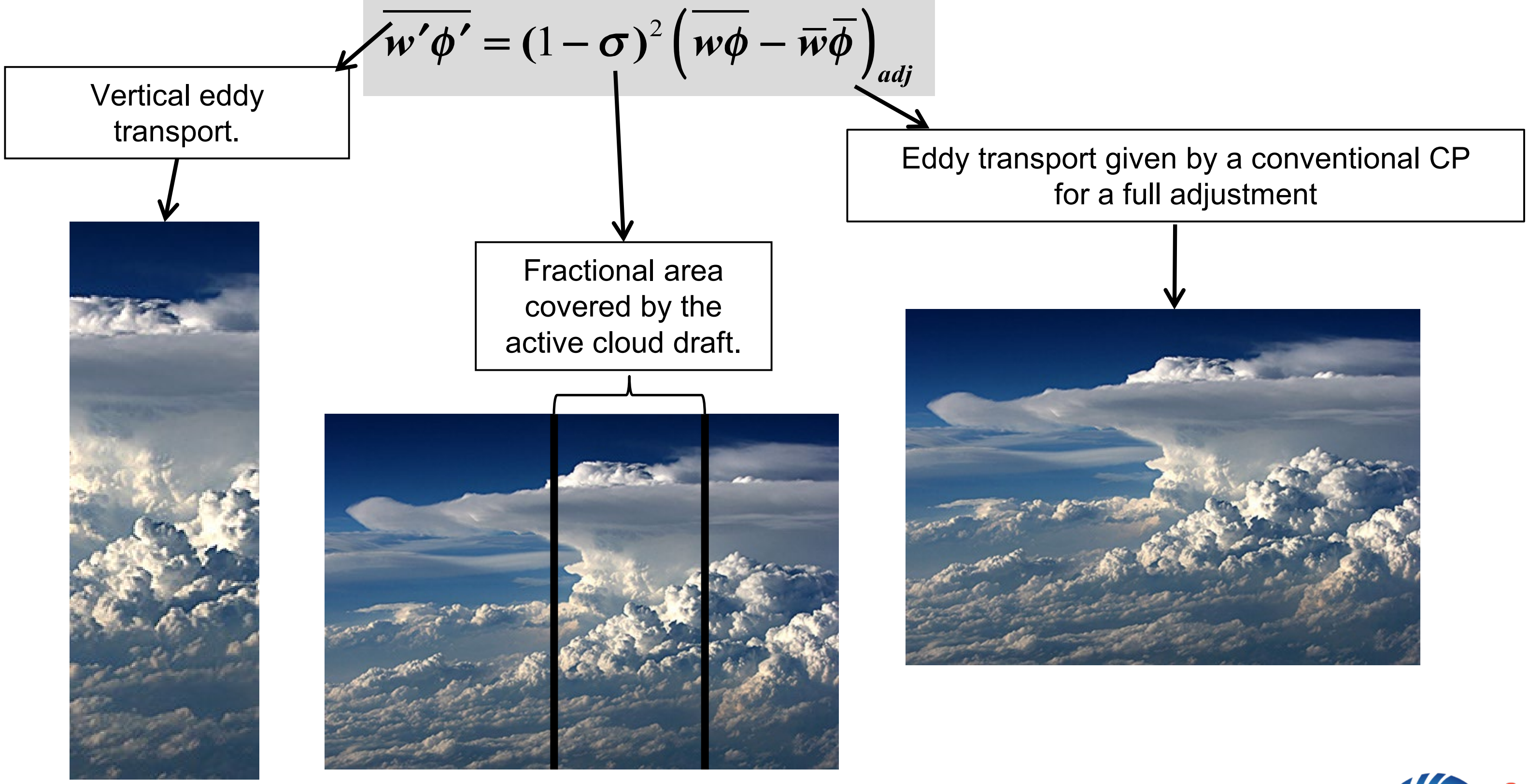
Some historic attempts to address these problems with modifications in parameterizations

1. UKMET office in 80’s attempt to let the convective parameterization only do transport of mass – so no compensating subsidence – no known publication
2. Kuell and Bott (2007, QJRM) – as in (1) but claim success.
    - (1) and (2) can only be done in non-hydrostatic models, (2) at least existed in an experimental version of the operational model that is used by the German weather service
3. Super parameterization approach (Grabowski and Smolarkiewicz 1999 and/or Randall et al 2003,….) – using a 2d CRM inside the non cloud resolving model
4. Gerard et al (2009, MWR) – prognostic equations for σ and w_c
5. Applying the parameterization over a range of grid points - we did this in a version of the Grell scheme (G3, Grell and Freitas, 2014, ACP)
6. Arakawa et al 2011 by relaxing the σ requirement and defining a relaxed adjustment – now used in some way or the other in many different approaches

(1), (2) - in contrast to (6) – may not be consistent with the derived eddy flux equations, but are purely based on the conceptual ideas from Figure 1. (5) appears to work for constant grid spacing, but requires communication across grid points and cannot easily and smoothly transition for irregular grids. (6) offers a smooth transition, but is it really the way to go?

Arakawa's approach

- A scale-aware parameterization is built on top of a conventional parameterization:
    - at low resolution, the conventional parameterization dominates,
    - at high resolution, the parameterization gives way to the microphysics scheme.
- Arakawa et al (2011) proposed the following equation for the vertical eddy transport that includes the scale dependence through the σ parameter:



$$\overline{w'\phi'} = (1-\sigma)^2 \left(\overline{w\phi} - \bar{w}\bar{\phi}\right)_{adj}$$

Vertical eddy transport.

Fractional area covered by the active cloud draft.

Eddy transport given by a conventional CP for a full adjustment

$(1-\sigma)^2$ is simply a scaling factor!

More on Arakawa's approach

$$(1-\sigma)^2$$

Many attempts exist to put some sort of physics in this scaling factor that have some or no dependence on the fractional area coverage. All of them have some sort of success giving a smooth transition – in particular important for irregular grids

But problems do remain!

More on historic attempt (6), scaling the tendencies:

ECMWF

Convective adjustment time scale is proportional to convective overturn time

$$\tau = \frac{H}{\bar{w}_{\mathrm{up}}}\alpha_x = \tau_{\mathrm{c}}\alpha_x$$

The scaling factor α_x was empirically determined by the German Weather Service, where the massflux maximizes at 8km dx, and then converges to zero as resolution increases

$$\alpha_x = 1 + 1.66\frac{dx}{dx_{\mathrm{ref}}}, \quad dx_{\mathrm{ref}} = 125 \times 10^3 \text{ m} \quad dx \geq 8 \times 10^3 \text{ m}$$

$$\alpha_x = 1 + \left(\ln\left(\frac{10^4}{dx}\right)\right)^2, \quad dx < 8 \times 10^3 \text{ m}$$

More on historic attempt (6), scaling the tendencies:

The Scale-Aware Tiedtke Scheme (Wei Wang):

- Define a scaling factor to modify convective adjustment time scale following Zheng et al. 2016:

$$Scaling = \left(1 + ln\frac{15}{\Delta x}\right)^3$$

- Limit mid-level convection to unsaturated atmospheric conditions;
- Scale coefficient for conversion from cloud water to rain water.

Scale aware KF scheme (MSKF) uses a similar approach

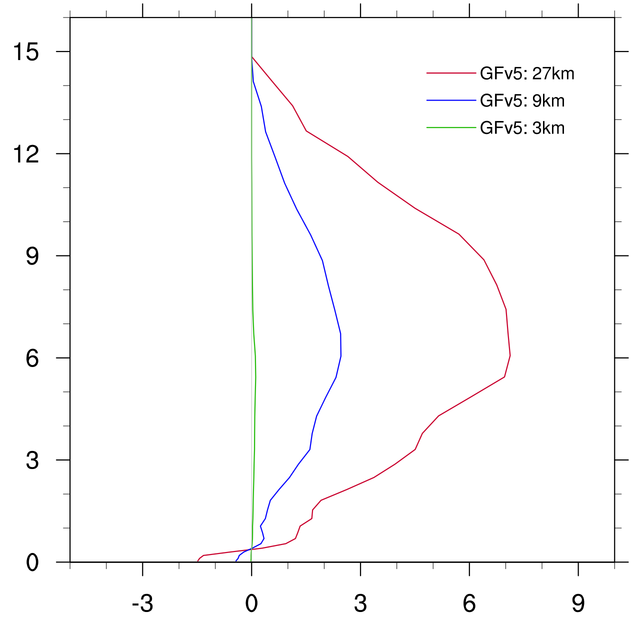
More on historic attempt (6), scaling the tendencies: GF

- GF tries to determine the fractional area coverage. GF tried several approaches, including also estimating updraft vertical velocity, but the only one that so far was working was to use the entrainment relationship to calculate σ.

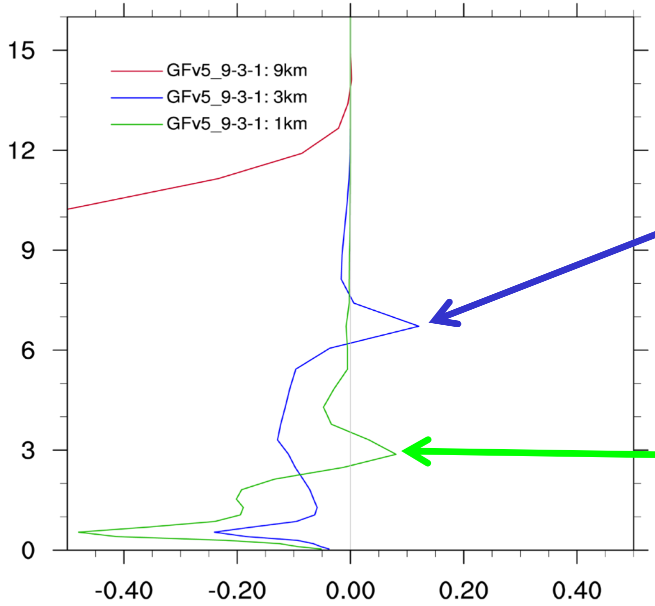
$$\lambda = \frac{.2}{r}$$

- Where λ is the initial entrainment rate assumed to characterize the PDF for normalized mass flux for deep convection. GF does not allow σ to go past a certain threshold σ_{th}.
- The larger the threshold, the faster convergence goes to zero.
- To avoid a too quick turnoff of the tendencies, GF changes the initial entrainment rate when the threshold is hit - leads to a decrease in cloud size

Idealized 3d tropical cyclone simulation



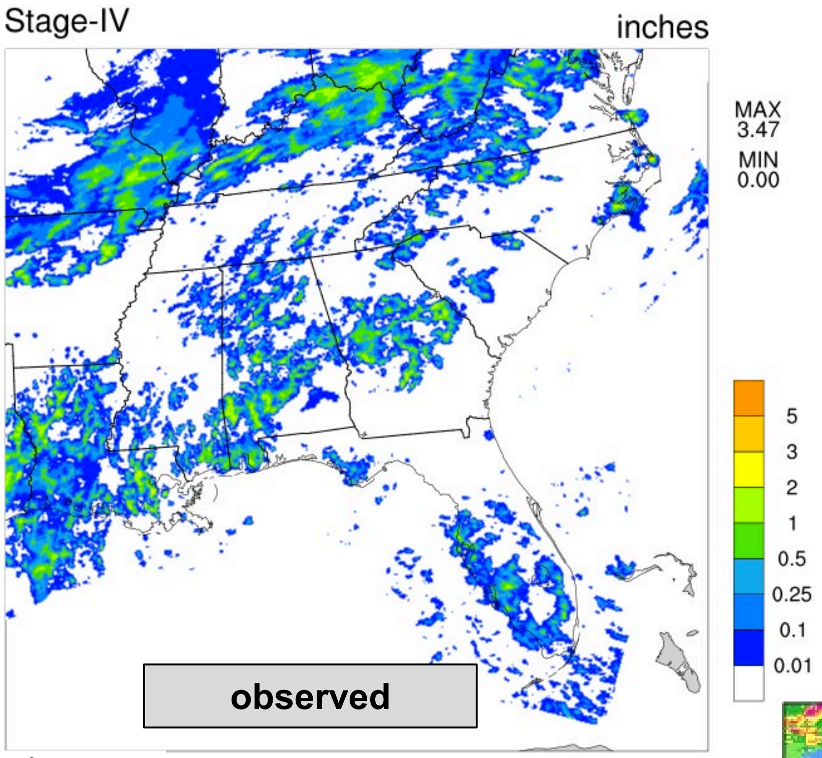
Heating profiles from convective parameterization for idealized tropical cyclone simulations at 27km, 9km, and 3km



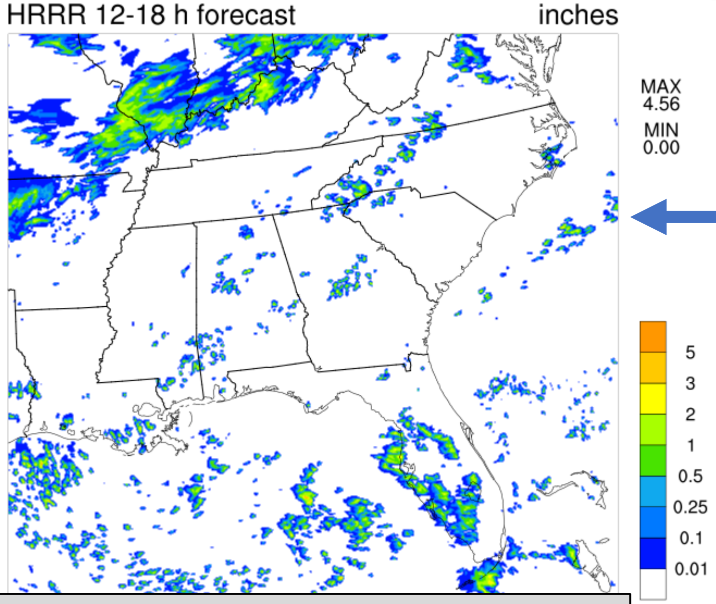
Average cloud top at 7km

Average cloud top at 3km

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



observed



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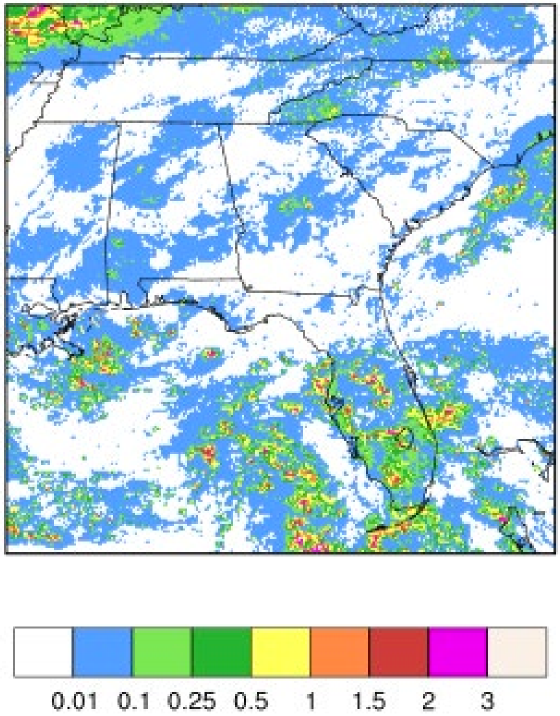


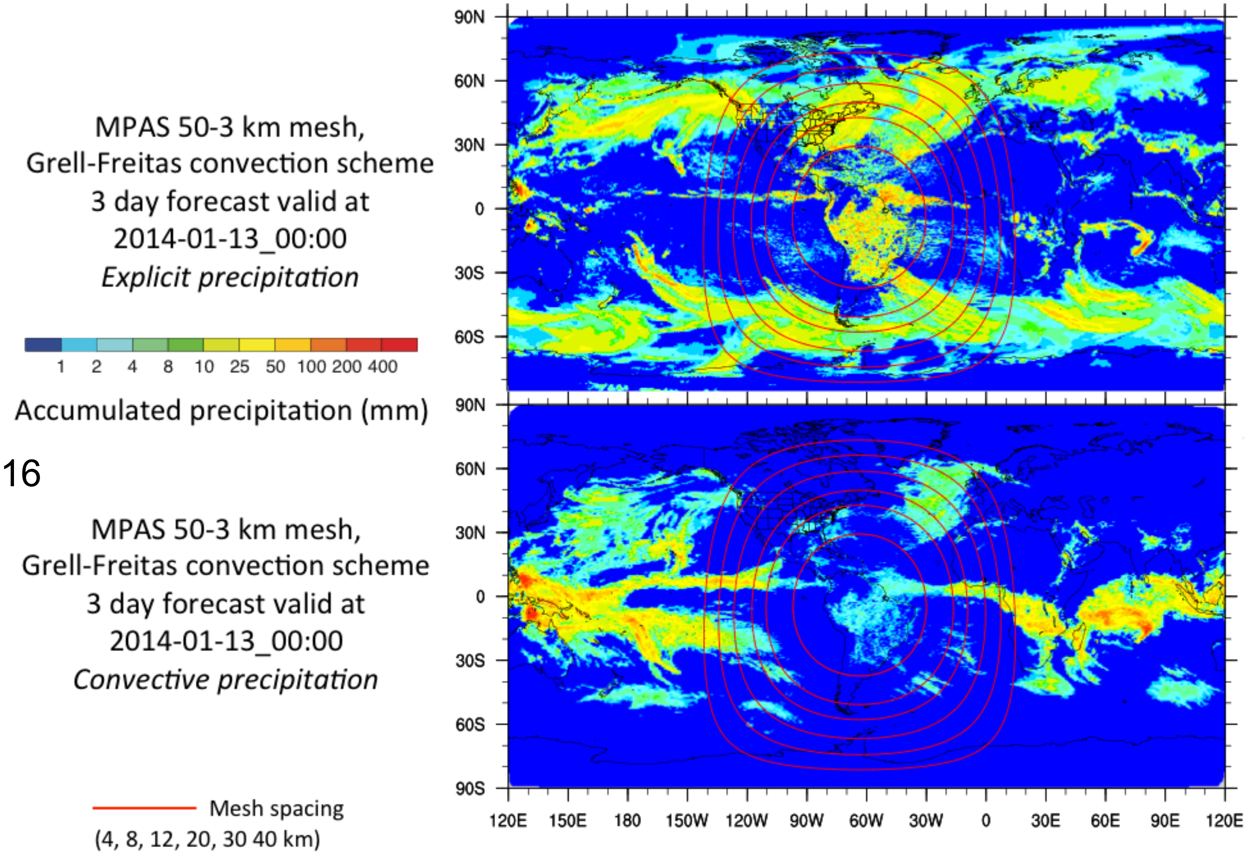
What to do for applications that reach to cloud resolving scales?

- To understand physical processes with very strong relation to convection, we should stay away from convective parameterizations, and adjust resolution so the simulated process is fully resolved ($dx \leq 1$km)
- For operational applications it is usually not feasible to fully resolve convection
  - Scaling is somewhat unphysical, convection is not restricted to just one grid box (an assumption in all scaling approaches)
  - An answer may be to consider impacts on neighboring grid points
  - There could be a mixture between scaling and 3d applications of CP's
  - There could be a dependence on the type of forcing
  - Stochastic approaches may also help some
  - The physically most realistic approach would be mix between 3d application and scaling
- It's in the tropics where proper scale awareness application may be most important!

Some aspects that we are trying to address in the Grell-Freitas (GF) scheme

GF is a scale-aware scheme, the first to successfully apply the Arakawa approach

Fowler et al. 2016



MPAS 50-3 km mesh,
Grell-Freitas convection scheme
3 day forecast valid at
2014-01-13_00:00
Explicit precipitation

MPAS 50-3 km mesh,
Grell-Freitas convection scheme
3 day forecast valid at
2014-01-13_00:00
Convective precipitation

The original paper (ACP, 2014) also describes the 3D approach from the predecessor (G3 scheme, was used operational in RAP, was replaced by GF)

What is new with convective parameterization development in GF?

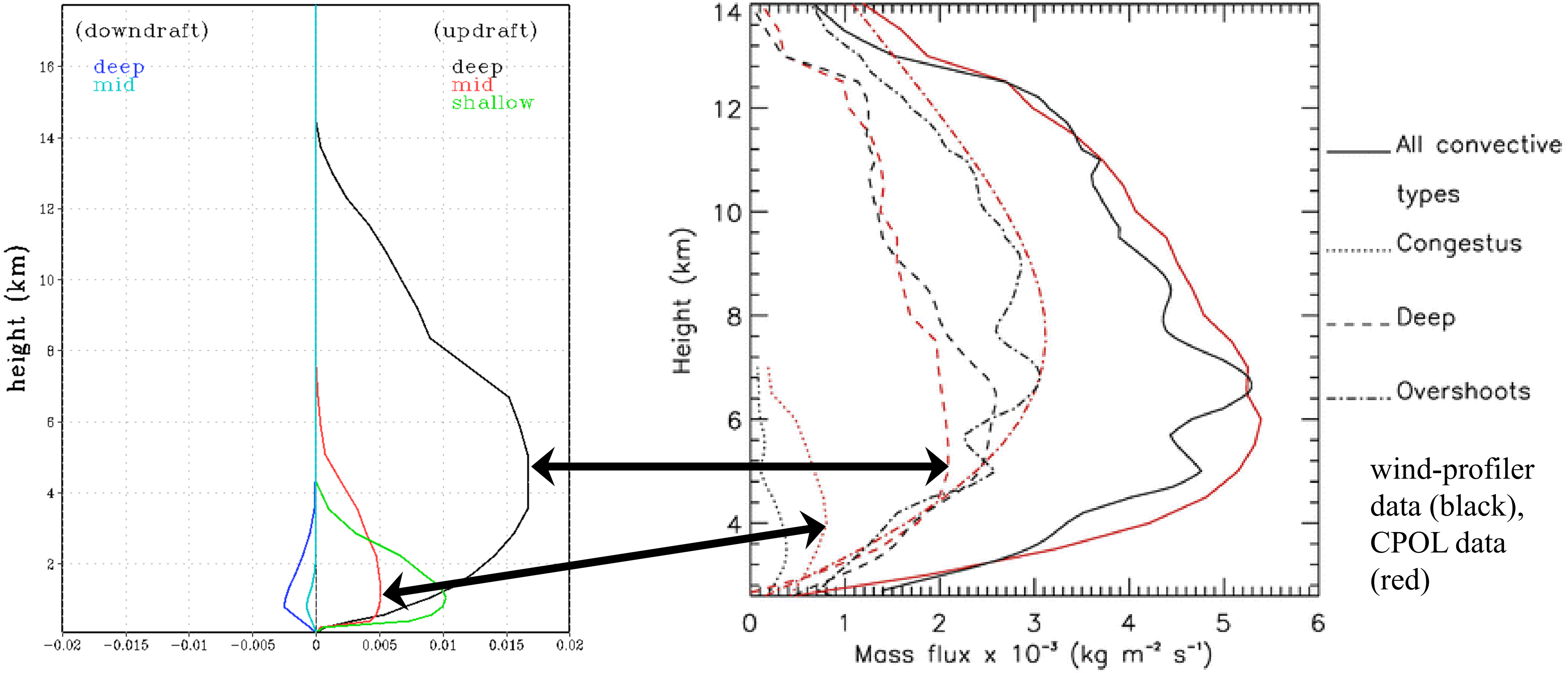
- Mass flux is a very important parameter in convective parameterizations
- Much work has been spent on making assumptions about what entrainment and detrainment rates should be, which are key in determining the vertical mass flux distribution. This is used by many different parameterizations (also SAS and previous versions of my schemes)
- We decided on a different approach – coming from the other side….
    - In GF the average statistical properties from deep convective plumes are determined by a characteristic cloud size and a PDF that determines the vertical mass flux distribution
    - Entrainment and detrainment then follow from the mass flux distribution
    - Level of maximum mass flux determined by stability profile
- Three pdf’s (deep, congestus, shallow convection) are used

PDF's for deep and congestus convection

TWP-ICE single column model versus observations

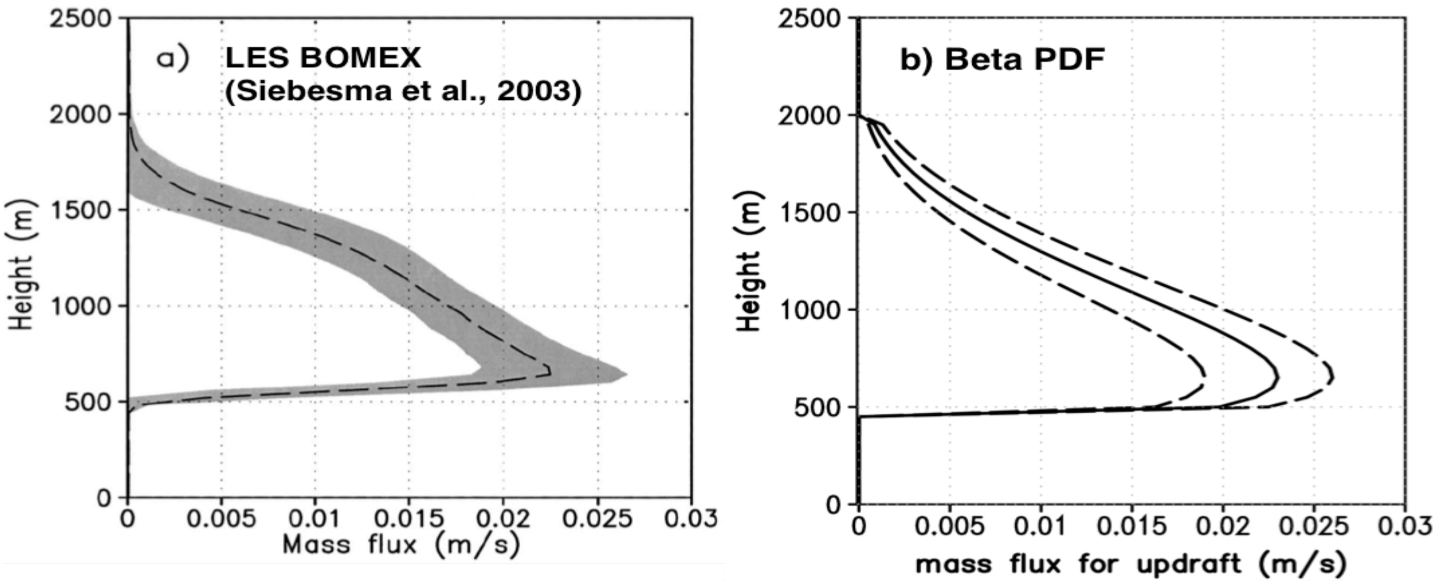
SCM model results for nomalized mass flux PDF, deep, shallow, and downdraft mass fluxes

From "The Estimation of Convective Mass Flux from Radar Reflectivities" (JAMC, Kumar et al. 2019)



wind-profiler data (black), CPOL data (red)

PDF for Shallow Convection Plume



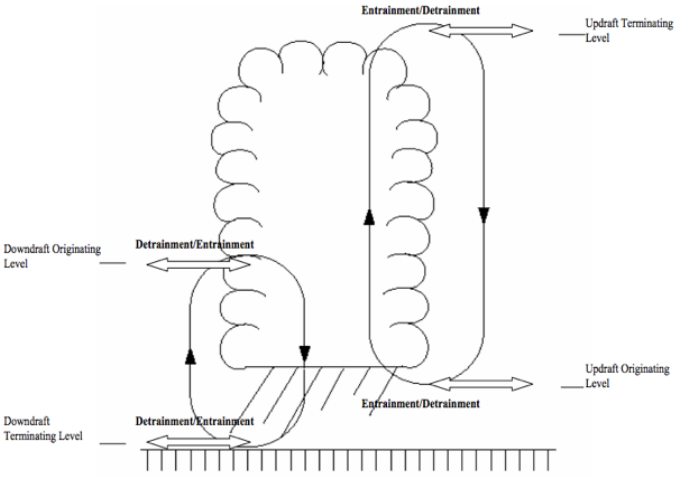
On the left, mass flux profile of shallow convection from a large eddy simulation (LES). On the right, a representation of the mass flux profile within the GF parameterization scheme using a PDF

More new developments in the GF parameterization

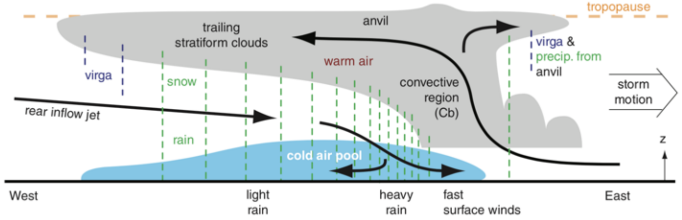
- Cloud water detrainment now proportional to mass detrainment and incloud cloudwater/ice mixing ratio (proportionality constant is a tuning factor)
- Memory is used to influence PDF’s, cloud water detrainment
- Below cloud base evaporation is optional in particular for shallow convection
- Changed subsidence terms for clw/ice to avoid negative mixing ratios (upstream with positive definite choice)
- Double moment microphysics tendencies included
- Cloud movement and downdraft cold pool advection is being tested
- Aerosol interactions are being evaluated

Storm Motion in convective parameterizations (H. Barnes, Haiqin Li)

- Unless forcing moves, parameterized convection will not move, no matter what upper level winds or downdrafts do
- Downdrafts are one mechanism that can foster convective propagation, new development, and organization
- This work tries to use the downdrafts represented in GF to foster storm propagation with mean upper level winds

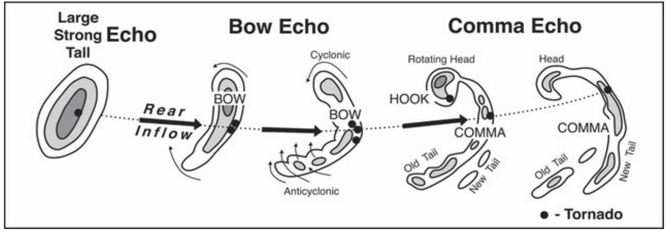


Mesoscale Convective Systems



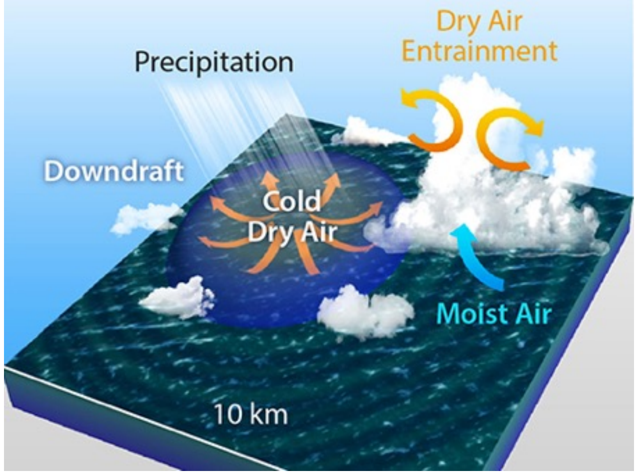
https://www.eoas.ubc.ca/courses/atsc113/flying/met_concepts/04-met_concepts/04a-Tstorm_types/index-mcs.html

Squall Lines



Wakimoto et al., 2006

Cold pools



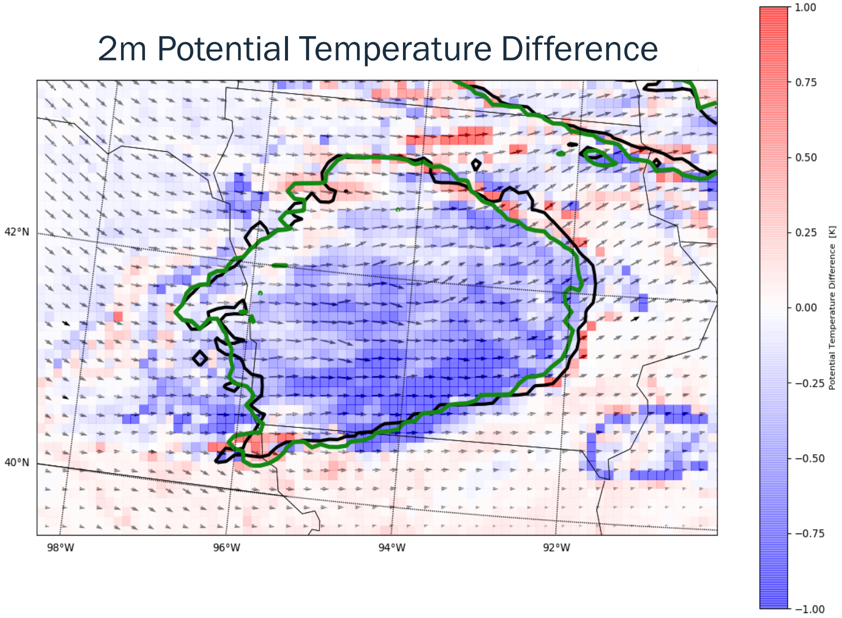
Zhe et al., 2015

Storm Motion in GF: Results

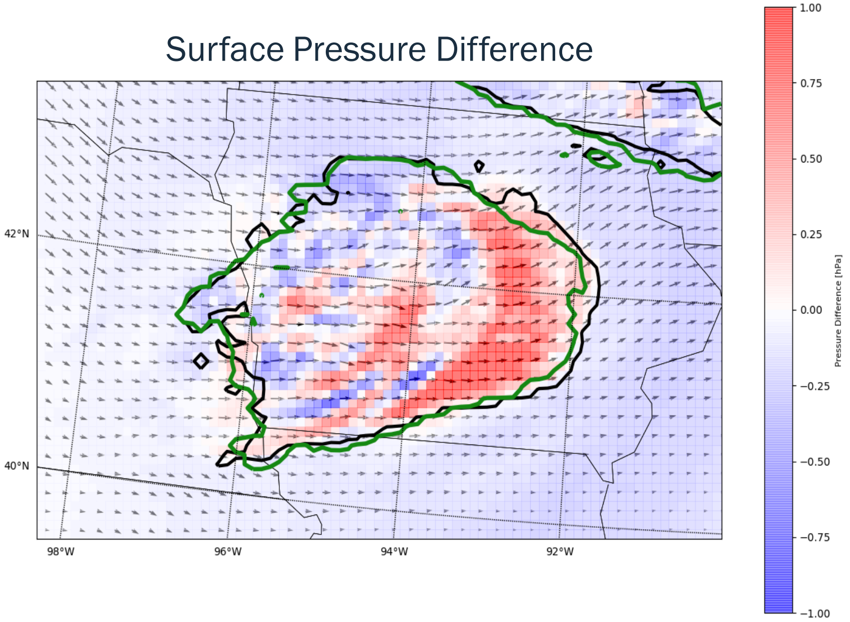
Difference Maps

Shading: Advection – No Advection, Green: No Advection, Black: Advection

2m Potential Temperature Difference



Surface Pressure Difference



The simulation with advection has a stronger cold pool and larger surface pressure perturbations.

The differences depend much on winds at steering level, also horizontal resolution

Number Concentrations in GF: Motivation

- Potential problem when using the parameterization with double moment microphysics scheme is inconsistency
  - Cumulus parameterizations are most often single-moment
  - Creates artificial modification of the particle size distribution that is fed into the microphysics scheme
  - Can impact model performance

- Developed a simple, inexpensive, diagnostic method to output cloud water and cloud ice number concentrations from GF
  - Cloud water approximation based on:
    - Cloud water mixing ratio from GF
    - Water-friendly aerosol characteristic
  - Cloud ice approximation based on:
    - Cloud ice mixing ratio from GF
    - Ice size – temperature relationship

  - Methodology made to be consistent with the aerosol-aware Thompson Microphysical Parameterization

Grell et al., 2018

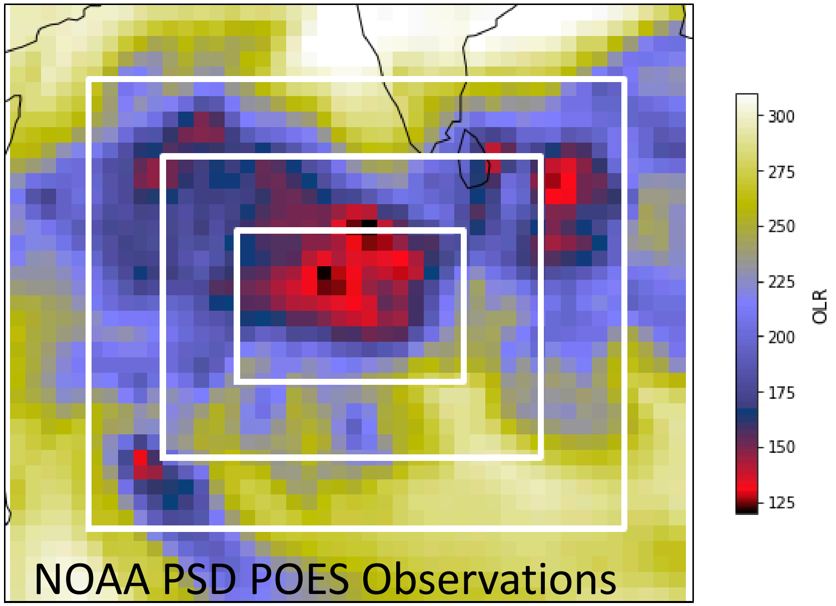
Very inexpensive method! Created by H. Barnes in collaboration with Greg Thompson

WRF simulations comparing to field experiment

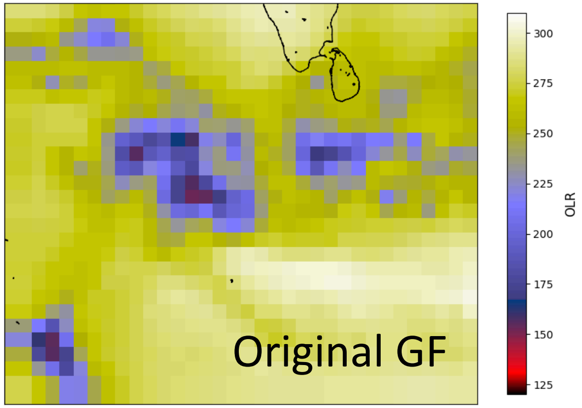
Daily Average OLR

1 deg resolution 23 November 2011

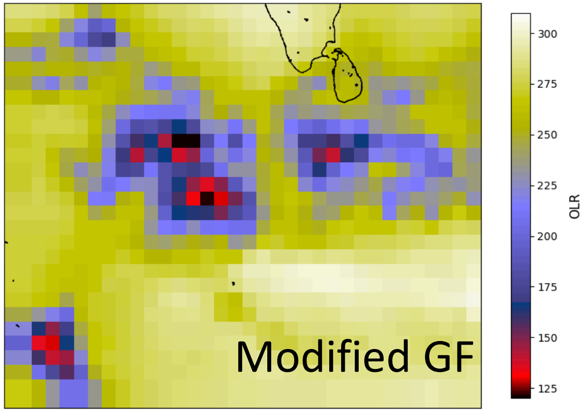
Daily Mean Interpolated OLR from NOAA PSD
23 November 2011



Daily Average GF Orginial OLR
23 November 2011



Daily Average GF Modified OLR
23 November 2011



This approach is now also used in UFS (when using Thompson microphysics)

Currently receiving much attention at operational NWP centers: Aerosols

A Working Group for Numerical Experimentation (WGNE) was established to look at

- Aerosol impacts on numerical weather prediction
- Interaction with radiation (direct and semi-direct effect),
- Interaction with clouds (indirect effect)
- Impact on data assimilation

Phase 2 is currently looking at the impacts of aerosols in more detail as well as their impact on sub-seasonal to seasonal predictions

Aerosol awareness in GF

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

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

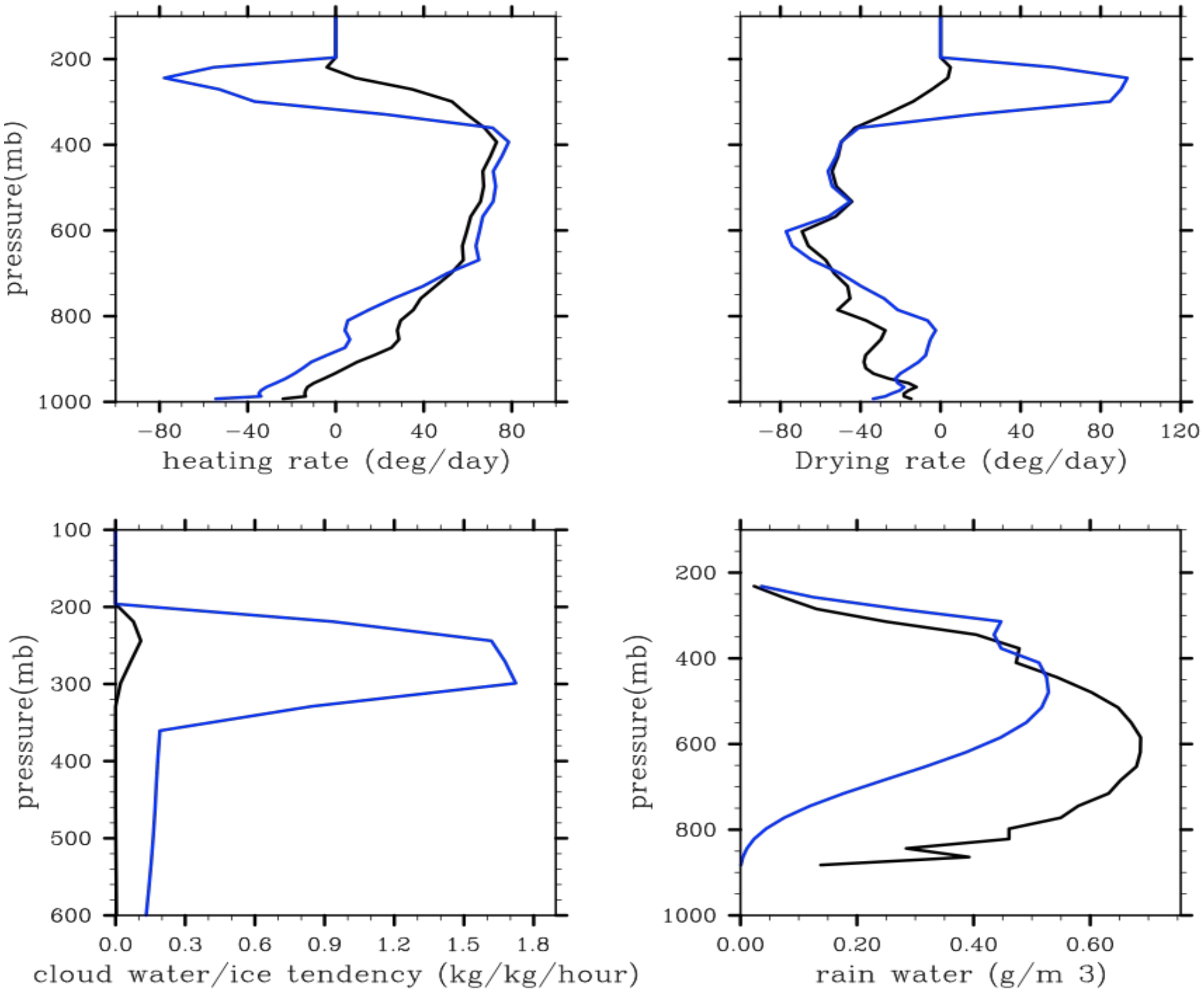
Change 2: Modified evaporation of raindrops (Jiang and Feingold) based on empirical relationship

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

Change 3: Implementing scavenging through memory (H. Barnes)

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

Turning on aerosol-awareness in the GF convective parameterization



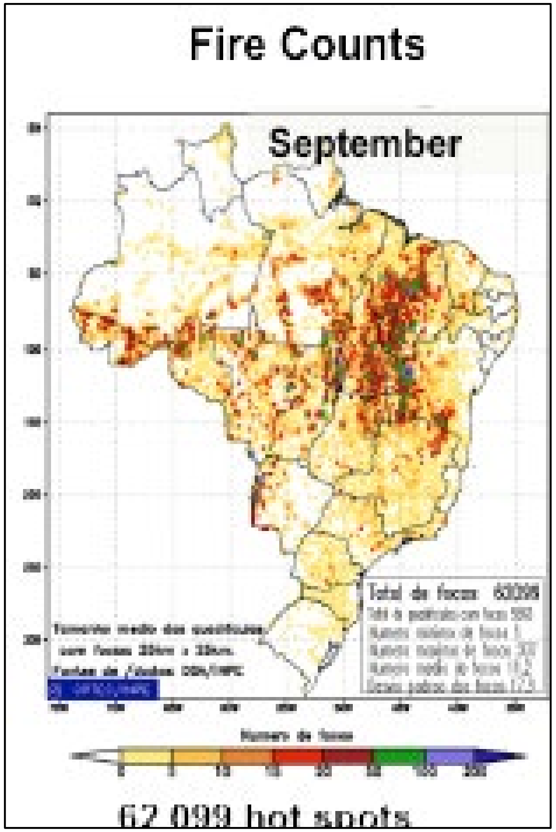
Polluted (AOD=1.)

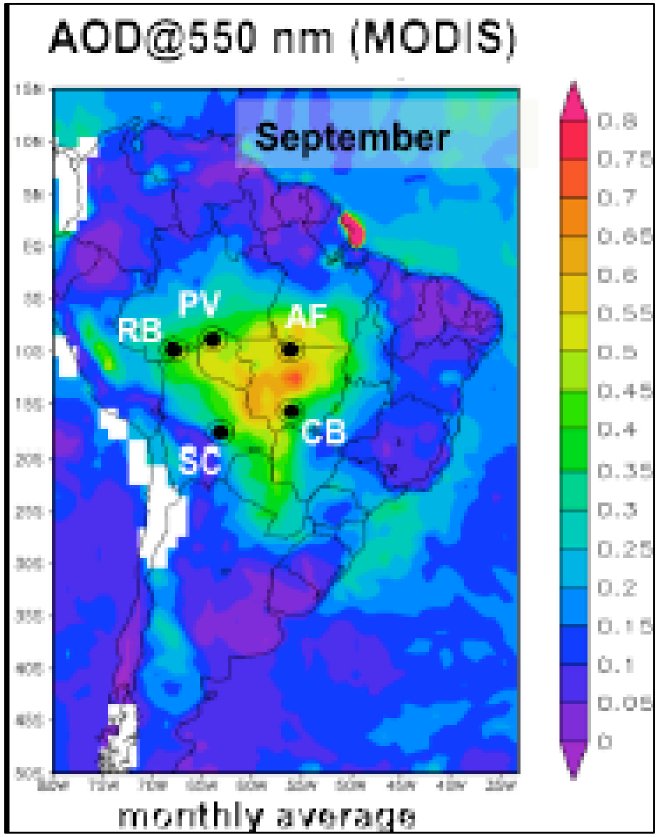
clean (AOD=.01)

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 downdraft, leading to less drying in and just above the boundary layer, but stronger cooling in lowest levels

Phase I tests to evaluate aerosol impact on NWP (WRF-Chem, but also global modeling systems)



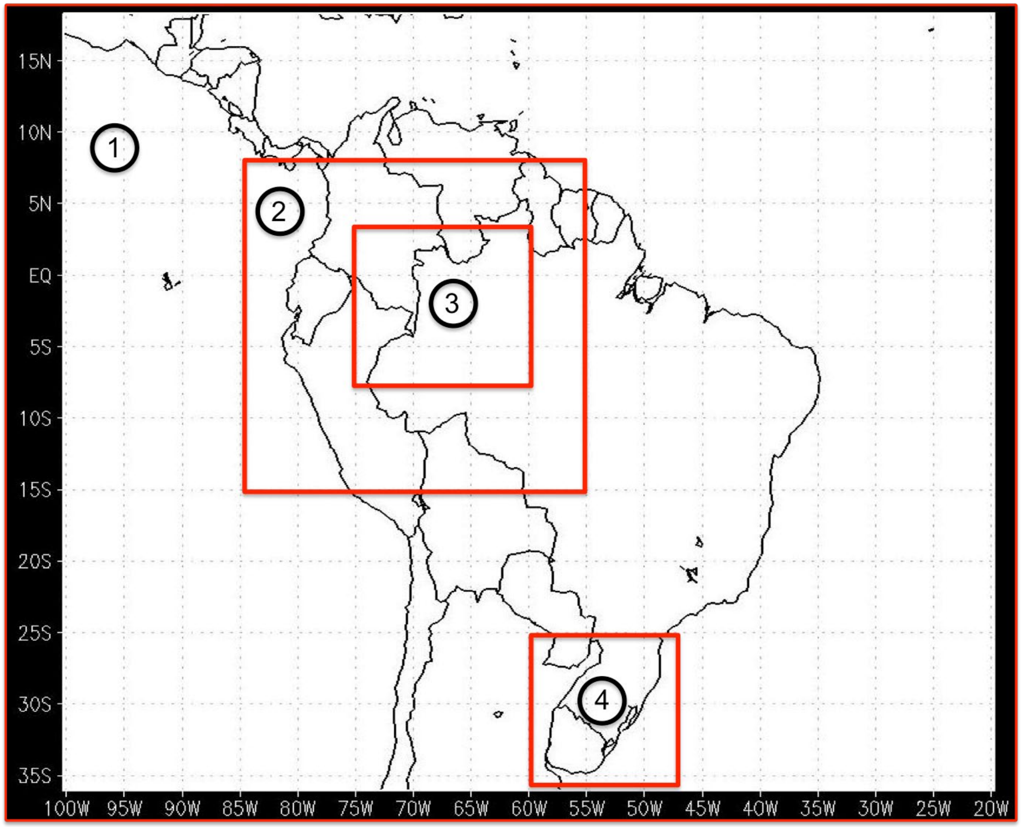


Field experiment case from September 2012 provided the background for complex physics/chemistry simulations to look at aerosol impacts for regional predictions

WRF-Chem domains

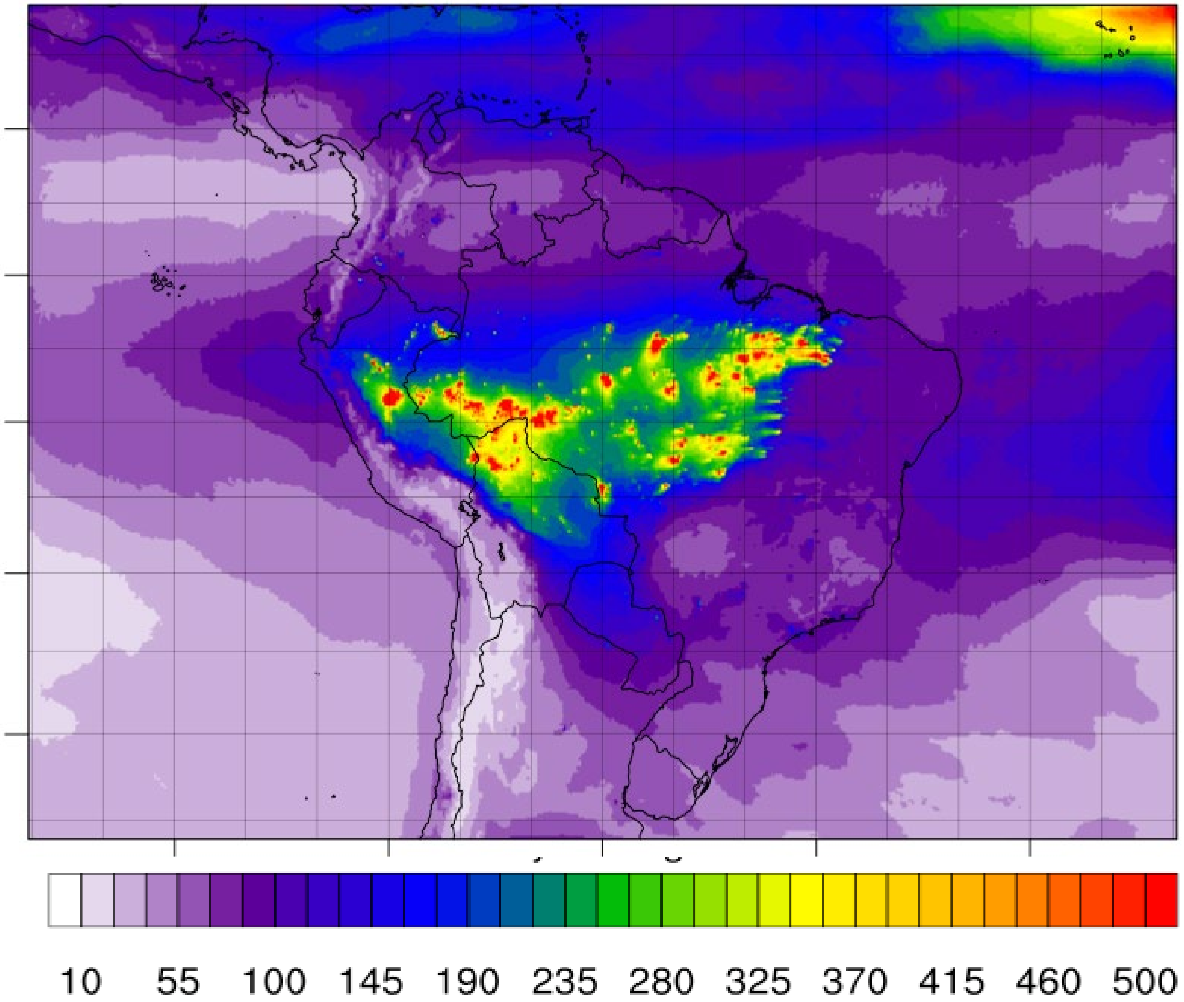
Model was run with gas-phase chemistry, modal aerosols, aqueous phase chemistry, and double moment microphysics

Very expensive, not possible in operations



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

WRF-Chem runs, dx=15km, averaged total burden PM25 distribution (20 runs, each 72 hours), convection permitting simulations over NE Brazil and Columbia (1.7km dx)

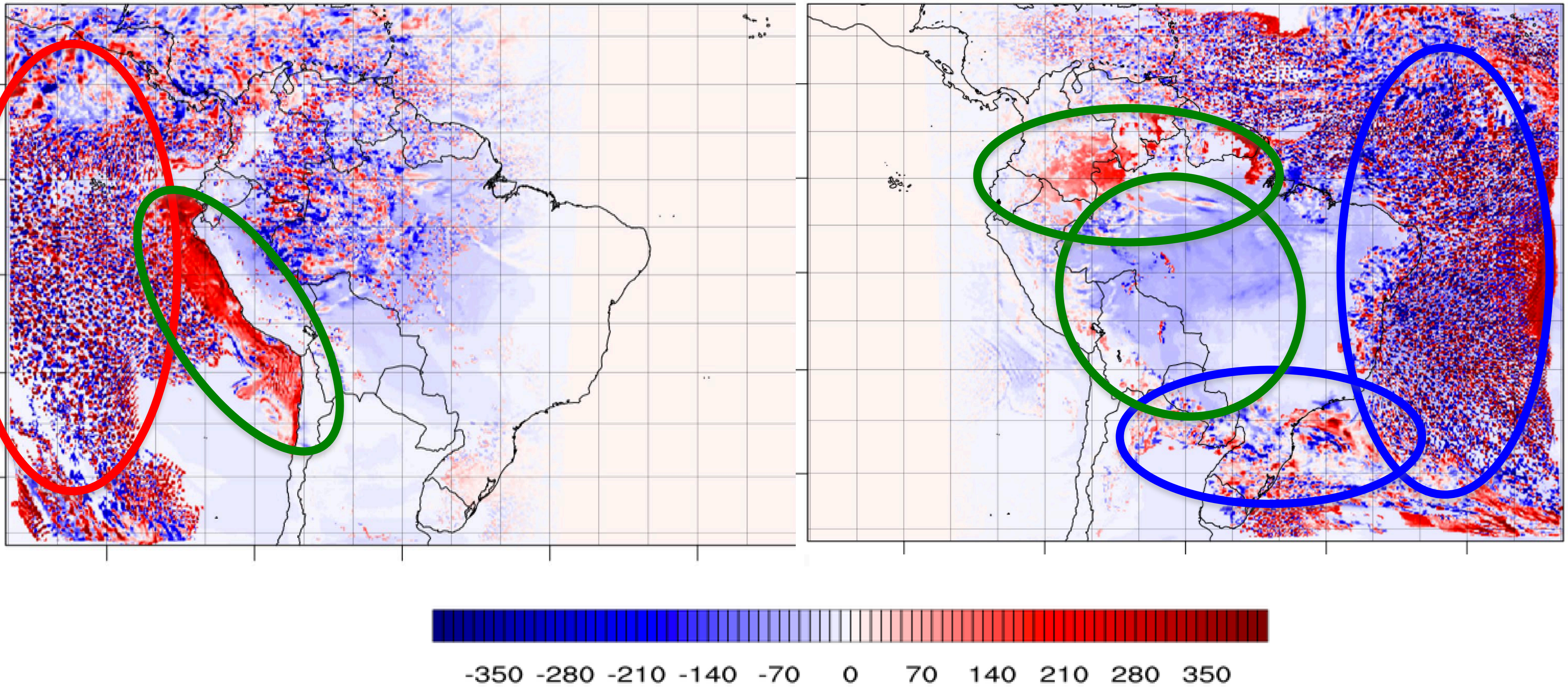


Systematic and random SW differences (Chem – Met) (almost every run, 20 runs, 3-day forecasts)

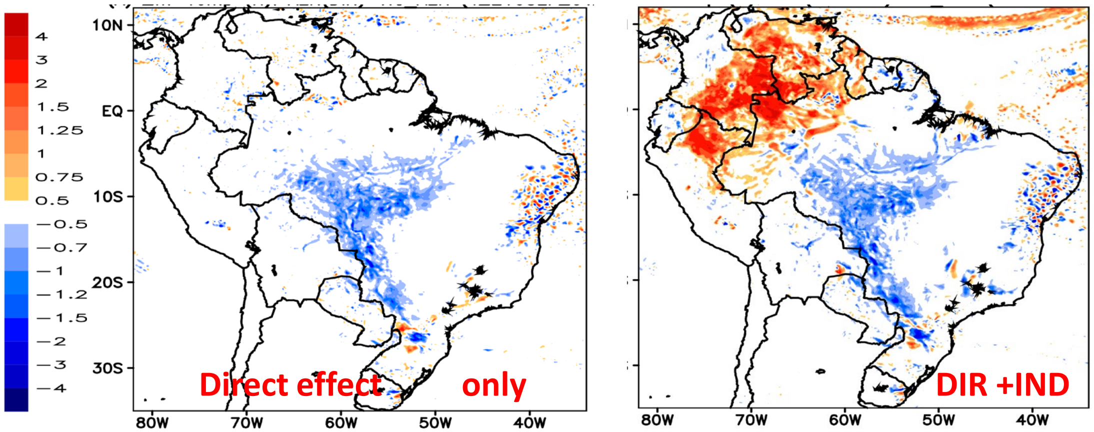
Random changes, cloudy, different
location of clouds, not interesting,
usually less SW radiation reaching the ground

Apparently random changes, interesting
systematic change in almost every run at this
point

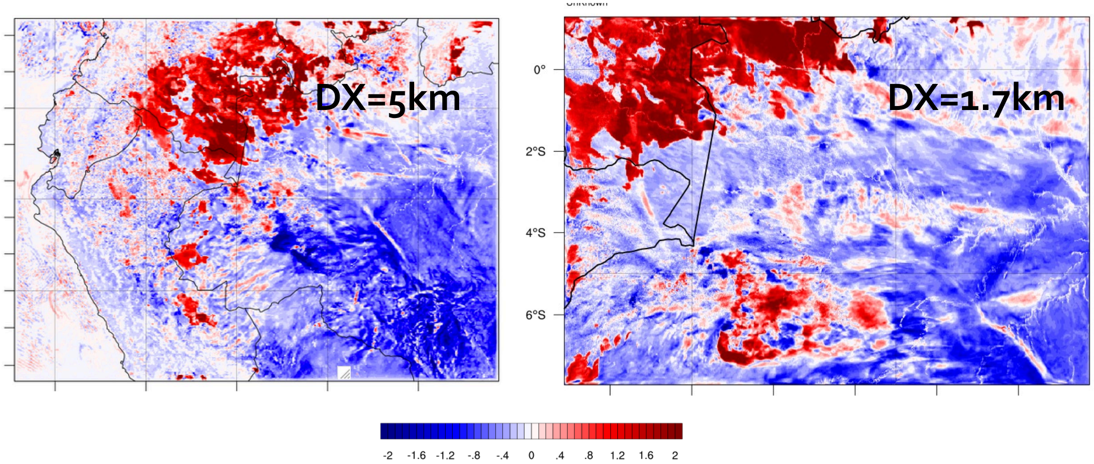
Systematic effect of high aerosol concentrations



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



Convection permitting simulations

In summary: Convective parameterizations have been causing headaches for more than 50 years, and they might just continue to do so for a long time to come

Much interesting work is going on in the world, mostly related to :

- **Scale-awareness!**
- **Forcing, or what controls strength and location of convection?**
  - Stability closures, w closures, moisture convergence, trigger functions
- **How much sophistication in parameterized clouds?**
  - Microphysics consistency, aerosol interaction processes, memory
- **What processes need to be realistically represented for feedback?**
  - Up/downdrafts, radiation coupling, clw/ice detrainment (interaction with microphysics), interaction with other physics parameterization
- **Should convection be represented with single plume, ensemble of plumes, PDF representing plumes?**
- **How can we implement memory impacts and organization?**
  - Interesting work currently happening as you hear this talk
  - Scavenging of aerosols, downdraft cold pool movement
- **Where is stochastics most important/necessary?**
  - Forcing, PDF representing plumes, microphysical processes
- **Can we use machine learning in a physical meaningful way?**
  - PDF representing plumes ?

Thank you!   Questions?

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