Deep, middle, low, and dx: almost resolving convection but not quite...

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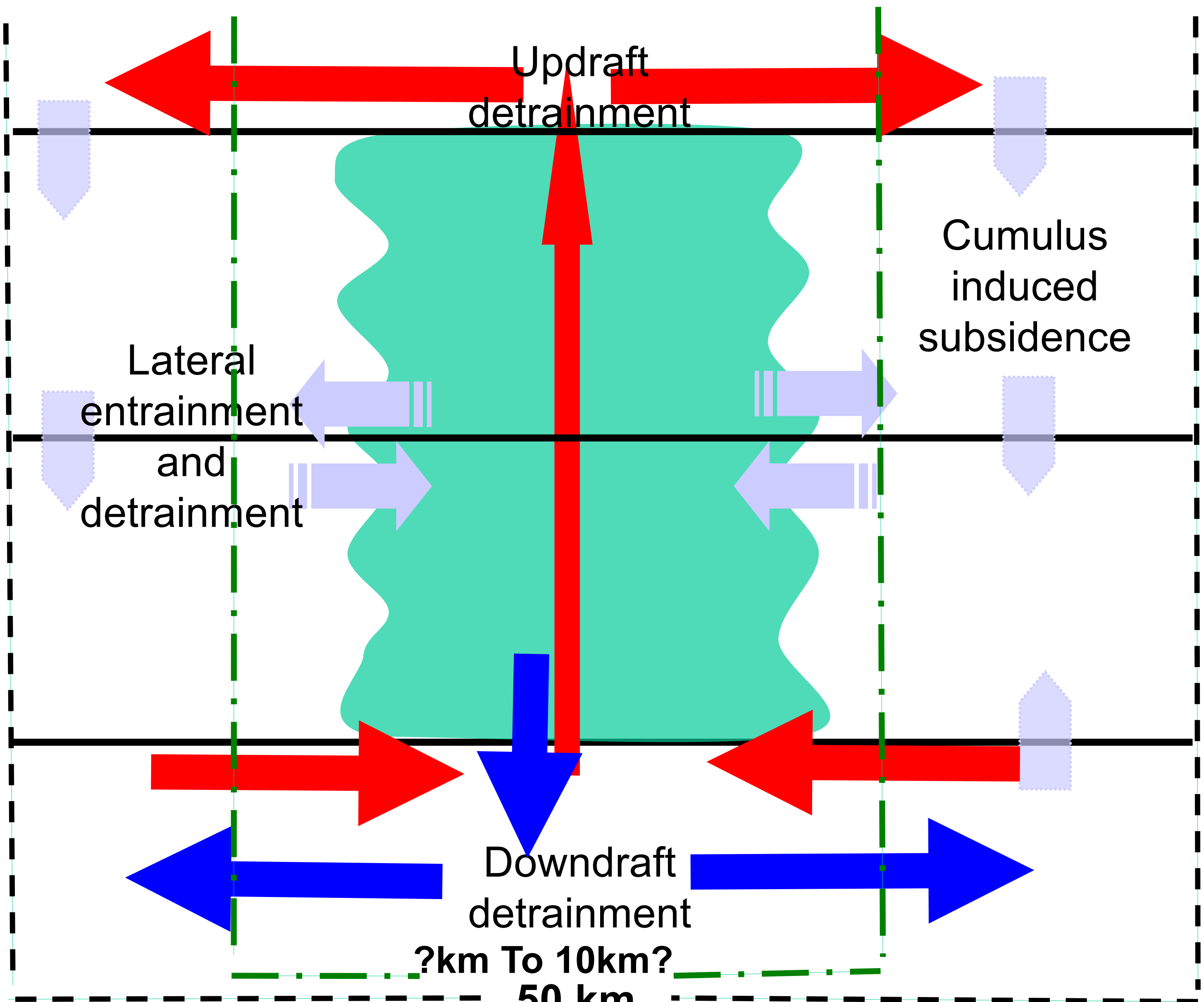
Structure of talk

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

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



Obvious problems – with respect to the commonly used conceptual picture (Figure 1)

- 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 better the resolution, the worse the assumption that every feedback is within the same grid box

Other way to look at the problem: simple derivation of vertical eddy transport

assuming

$$\overline{\psi} = \sigma \psi_c + (1-\sigma)\widetilde{\psi}$$

$$\overline{w} = \sigma w_c + (1-\sigma)\widetilde{w}$$

$$\overline{w\psi} = \sigma w_c \psi_c + (1-\sigma)\widetilde{w}\widetilde{\psi}$$

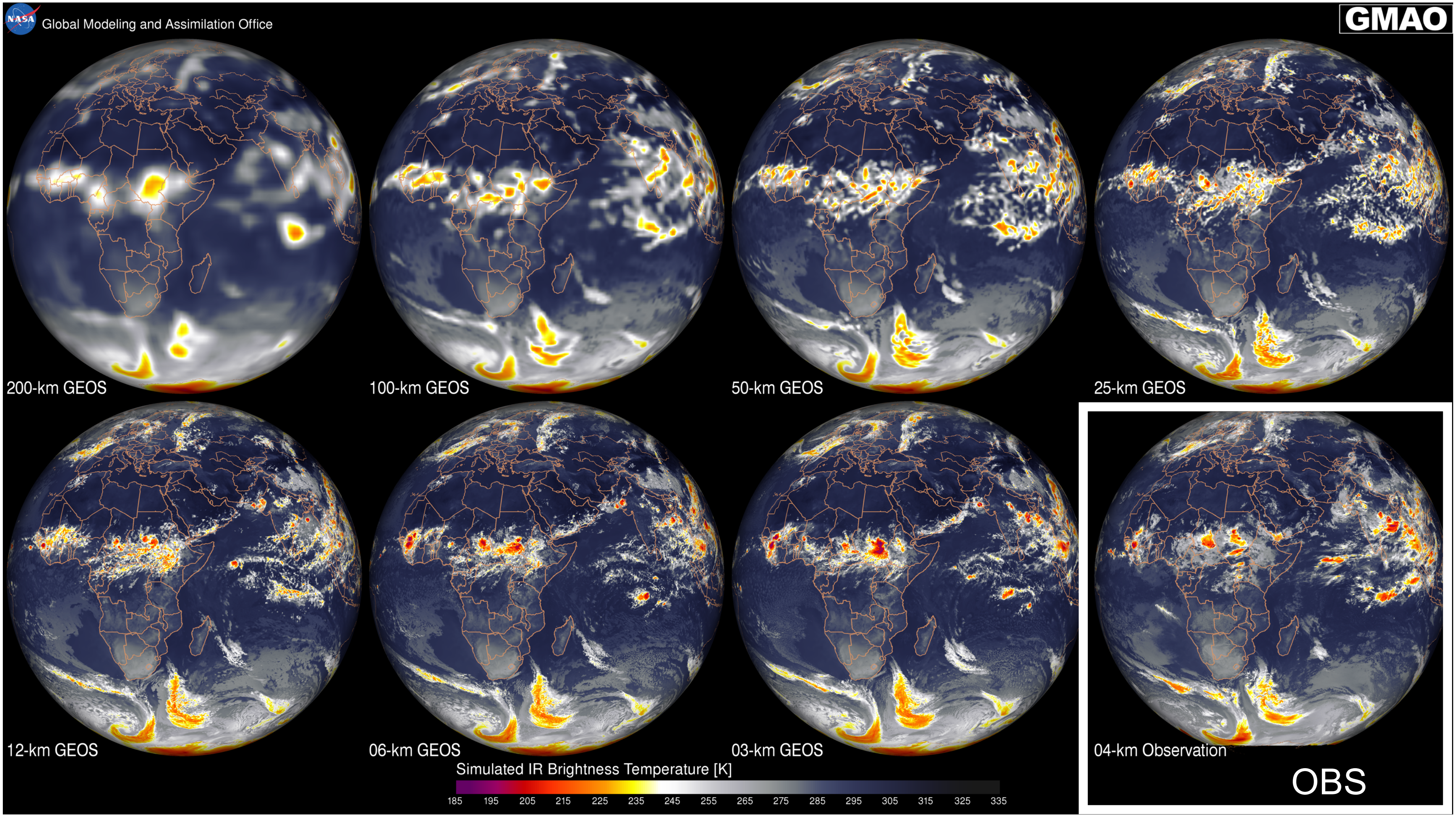
One gets

$$\overline{w\psi} - \overline{w}\,\overline{\psi} = \frac{\sigma}{1-\sigma}(w_c - \overline{w})(\psi_c - \overline{\psi})$$

With σ<<1 and w_c>>ŵ

$$\rho\left(\overline{w\psi} - \overline{w}\,\overline{\psi}\right) \approx M_c\left(\psi_c - \overline{\psi}\right)$$

Do we need gray scale resolutions?



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

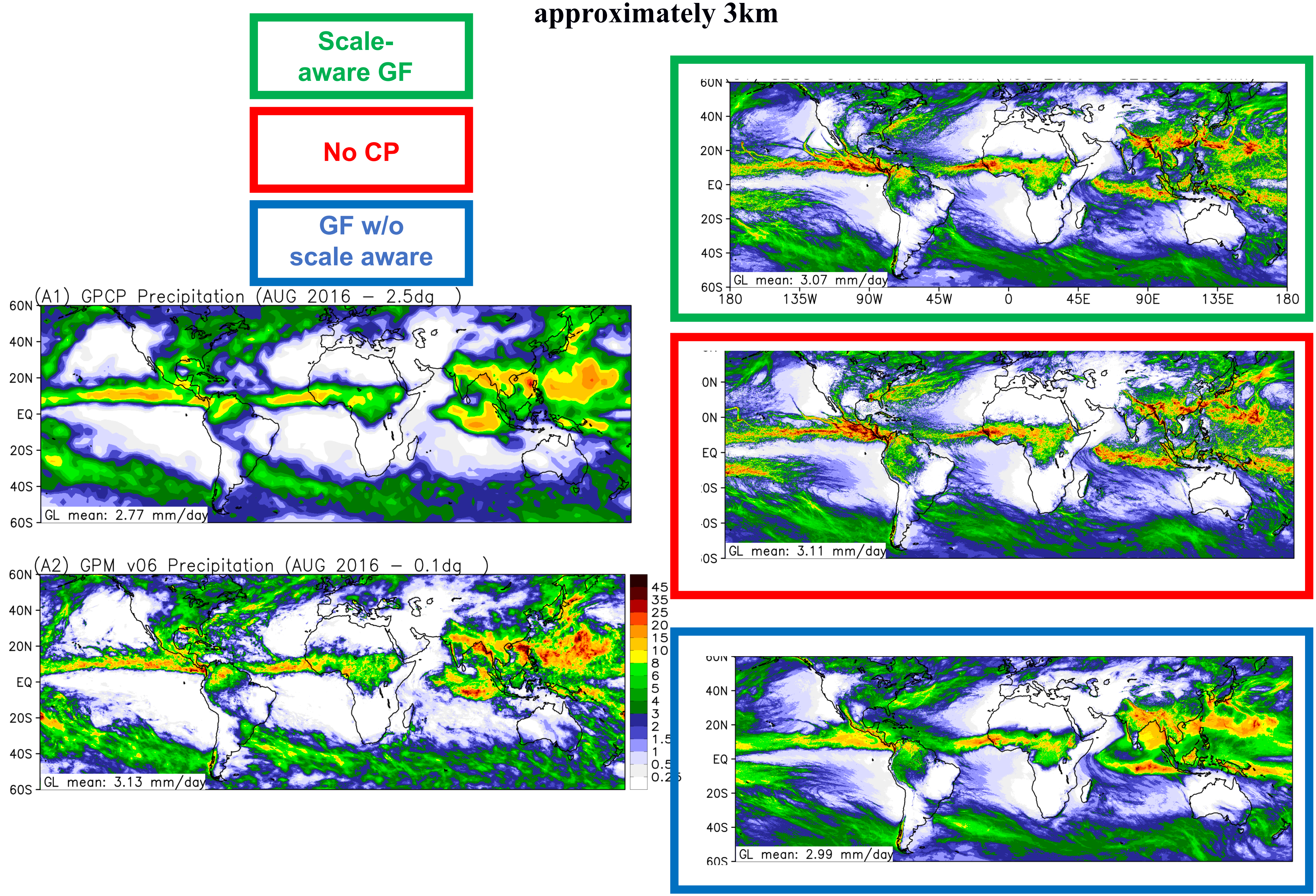
WRF MPAS

We need gray-scale resolutions, so what!

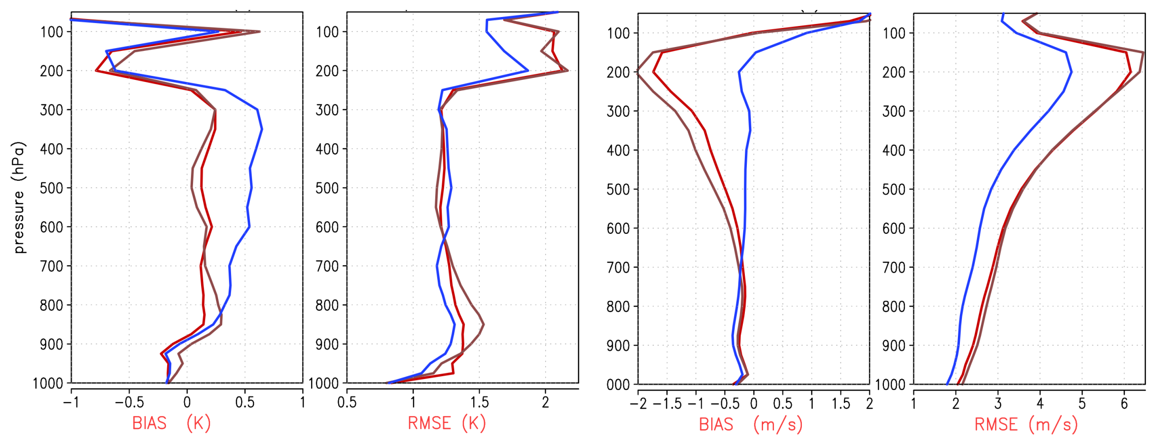
There are 3 approaches being used

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, 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).

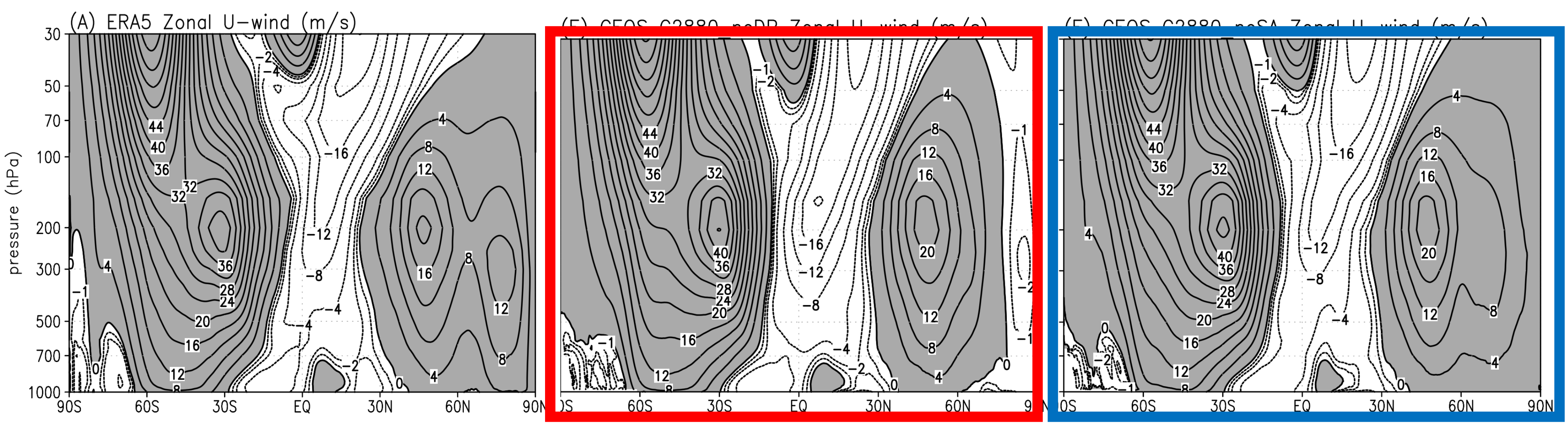
August 2016 precipitation mean (mm day^{-1}) as estimated by GPCP and GPM (panels A1 and A2). The remaining panels show the GEOS GCM simulated total precipitation. Horizontal resolution is approximately 3km



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!**

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

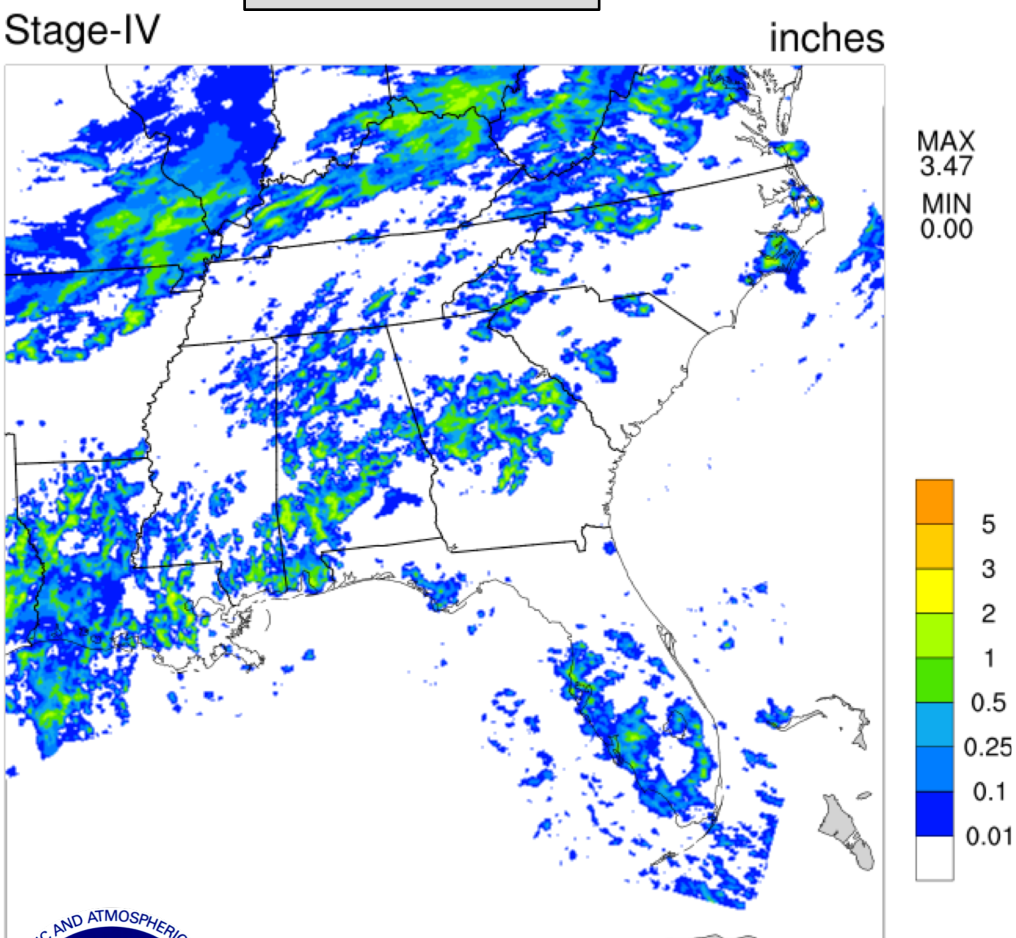
Convection spans many scales, a dx of 4km for example would give an effective resolution of > 20km, not good enough for explicit simulation

1. With no convective parameterization, convection may take too long to develop
2. Once it develops it may be too strong
3. For operational forecasting it depends on the application: if (1), (2), or long range results are important - results are quite often worse if no convective parameterization is used. For storm-scale severe weather forecasting (1) and (2) are not the most important and not using a CP maybe preferred

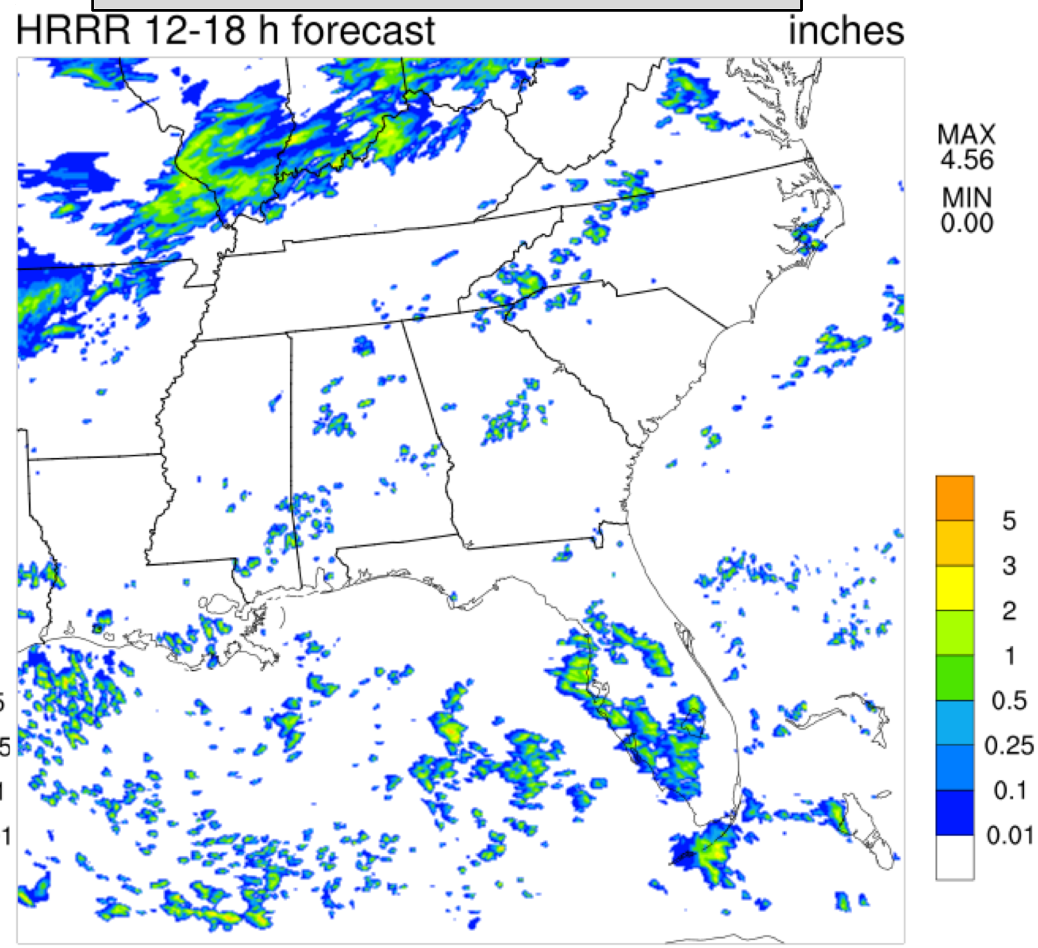
No convective parameterization in the HRRRv4

6-h accumulated precip
ending 0000 UTC UTC 08 Aug 2018

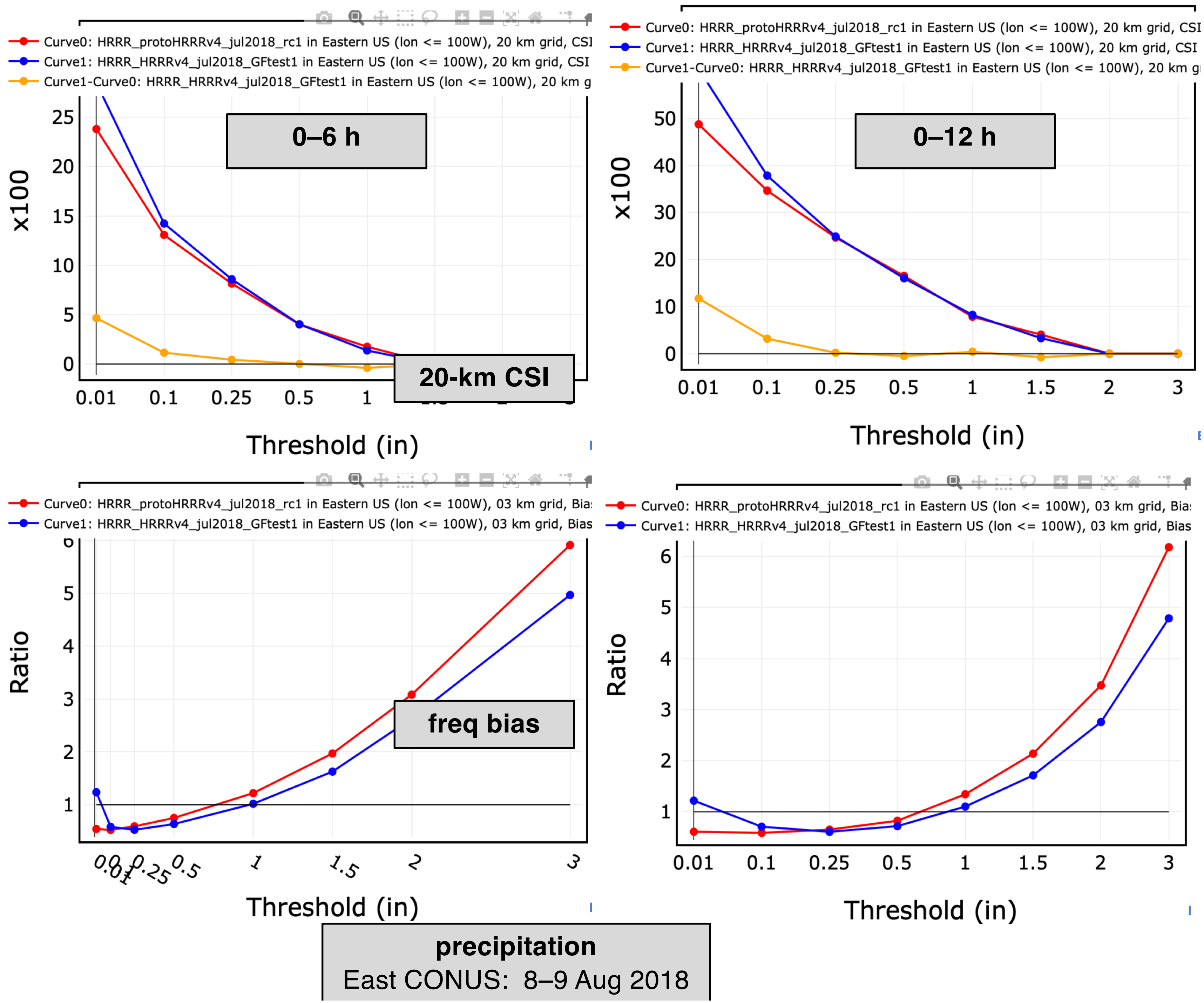
observed



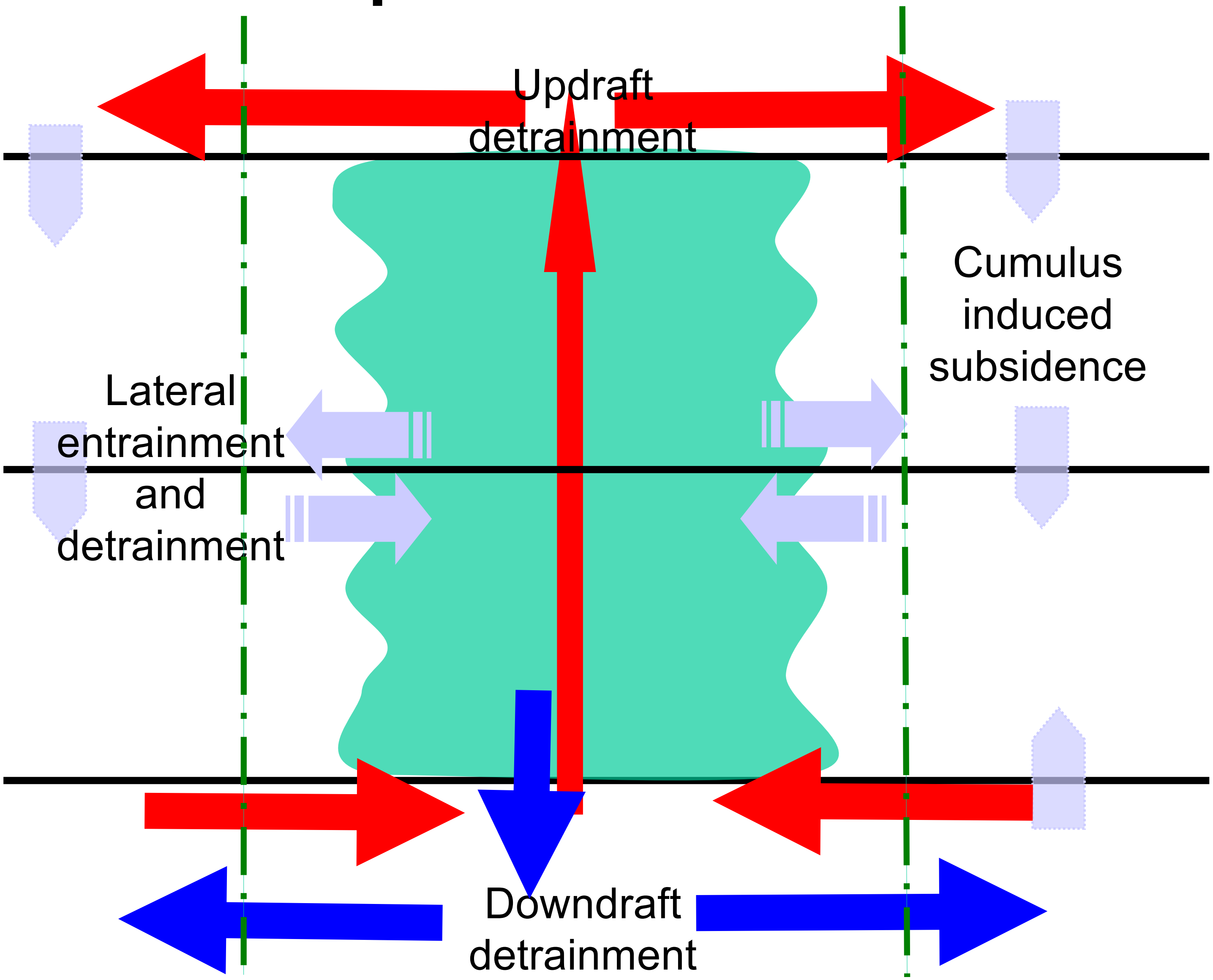
HRRRv4 forecast ("cu_physics = 0")



Red curve: no convective parameterization used



Coming back to the simplified conceptual idea of how a convective cloud may be seen in a parameterization



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 (maybe a very simplified version of (3))
5. Applying the parameterization over a range of grid points (such as in G3 scheme)
6. Arakawa et al 2011 by relaxing the σ requirement and defining a relaxed adjustment – now used in some way or the other in may different approaches

(1), (2) - in contrast to (6) – may not be consistent with the derived eddy flux equations, but is 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?

More on (6): simple derivation of vertical eddy transport

assuming

$$\overline{\psi} = \sigma \psi_c + (1-\sigma)\tilde{\psi}$$

$$\overline{w} = \sigma w_c + (1-\sigma)\tilde{w}$$

$$\overline{w\psi} = \sigma w_c \psi_c + (1-\sigma)\tilde{w}\tilde{\psi}$$

One gets

$$\overline{w\psi} - \overline{w}\,\overline{\psi} = \frac{\sigma}{1-\sigma}(w_c - \overline{w})\left(\psi_c - \overline{\psi}\right)$$

With σ<<1 and w_c>>ŵ

$$\rho\left(\overline{w\psi} - \overline{w}\,\overline{\psi}\right) \approx M_c\left(\psi_c - \overline{\psi}\right)$$

More on historic attempt (6):

Arakawa et al., 2011 simply define a setup that will lead to convergence to an explicit solution and get

$$\overline{w\psi} - \bar{w}\bar{\psi} = (1-\sigma)^2(\overline{w\psi} - \bar{w}\bar{\psi})_{adj}$$

Arakawa et al. define σ as the fractional area covered by all convective clouds in the grid cell. $(\overline{w\psi} - \bar{w}\bar{\psi})_{adj}$ **is simply the tendency if the parameterization would be applied without any scale-awareness.**

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

More on historic attempt (6):

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

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 such as may be used in MPAS (Laura Fowler’s talk is next).

But problems 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 the converges to zero as resolution increases

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

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

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 un-saturated atmospheric conditions;
- Scale coefficient for conversion from cloud water to rain water.

Scale aware KF scheme (MSKF) uses a similar approach, L. Fowler will give a few more details about what is done in MSKF

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.

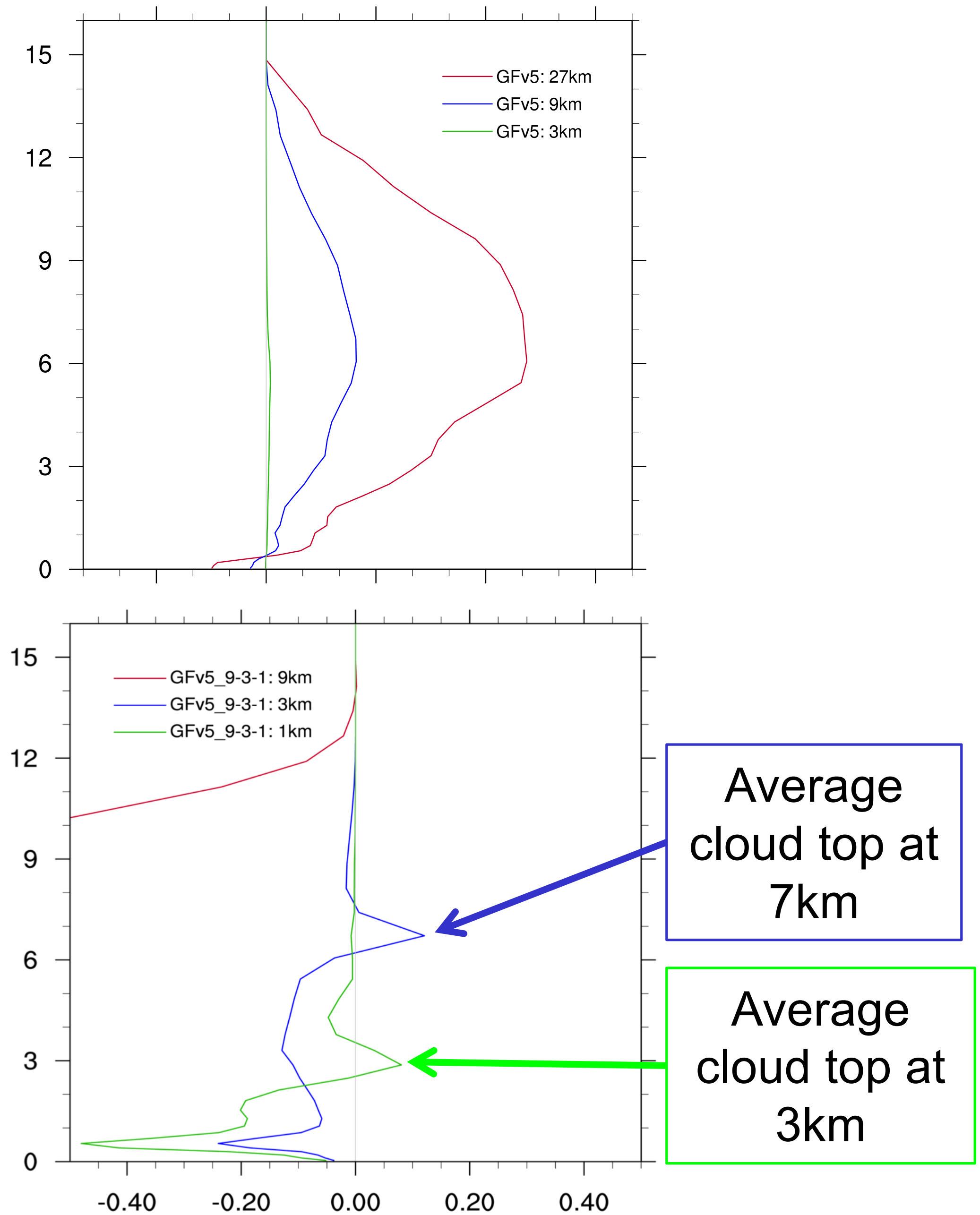
$$\lambda = \frac{.2}{r}$$

- 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}. WRF and/or MPAS used .7 or .9.

- 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

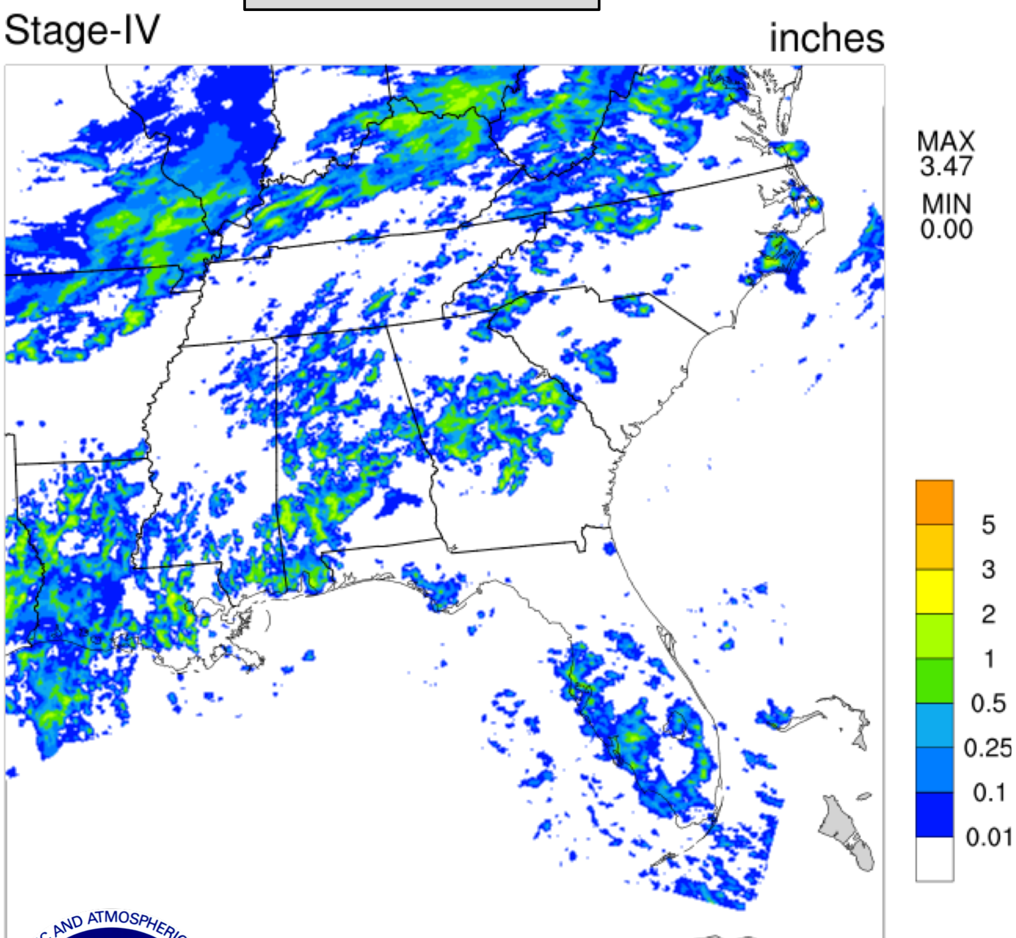


Heating profiles from convective parameterization for idealized tropical cyclone simulations at 27km, 9km, and 3km

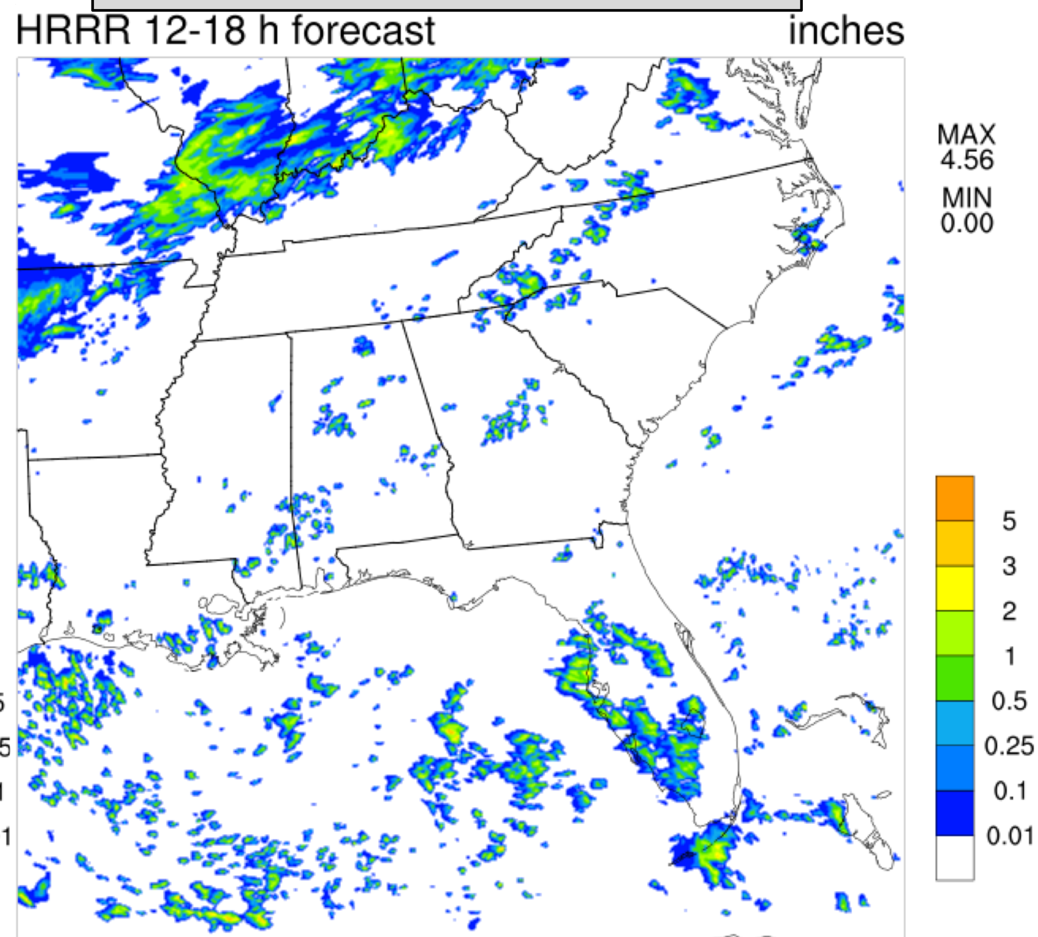
Drying profiles from convective parameterization for idealized tropical cyclone simulations at 3km and 1km (!) resolution

Where the scaling fails, at least in the original implementation is in areas with very light forcing

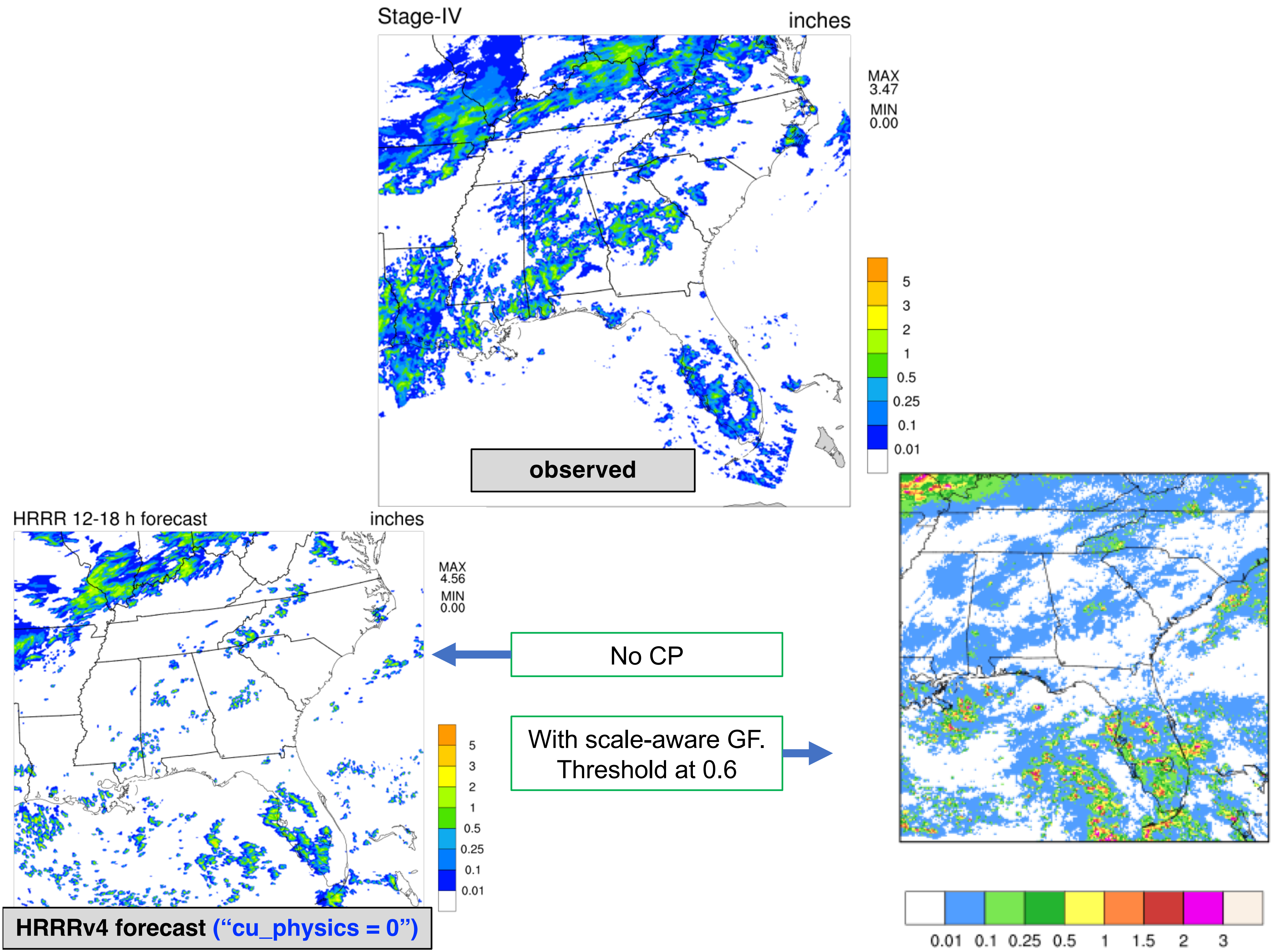
observed



HRRRv4 forecast (“cu_physics = 0”)

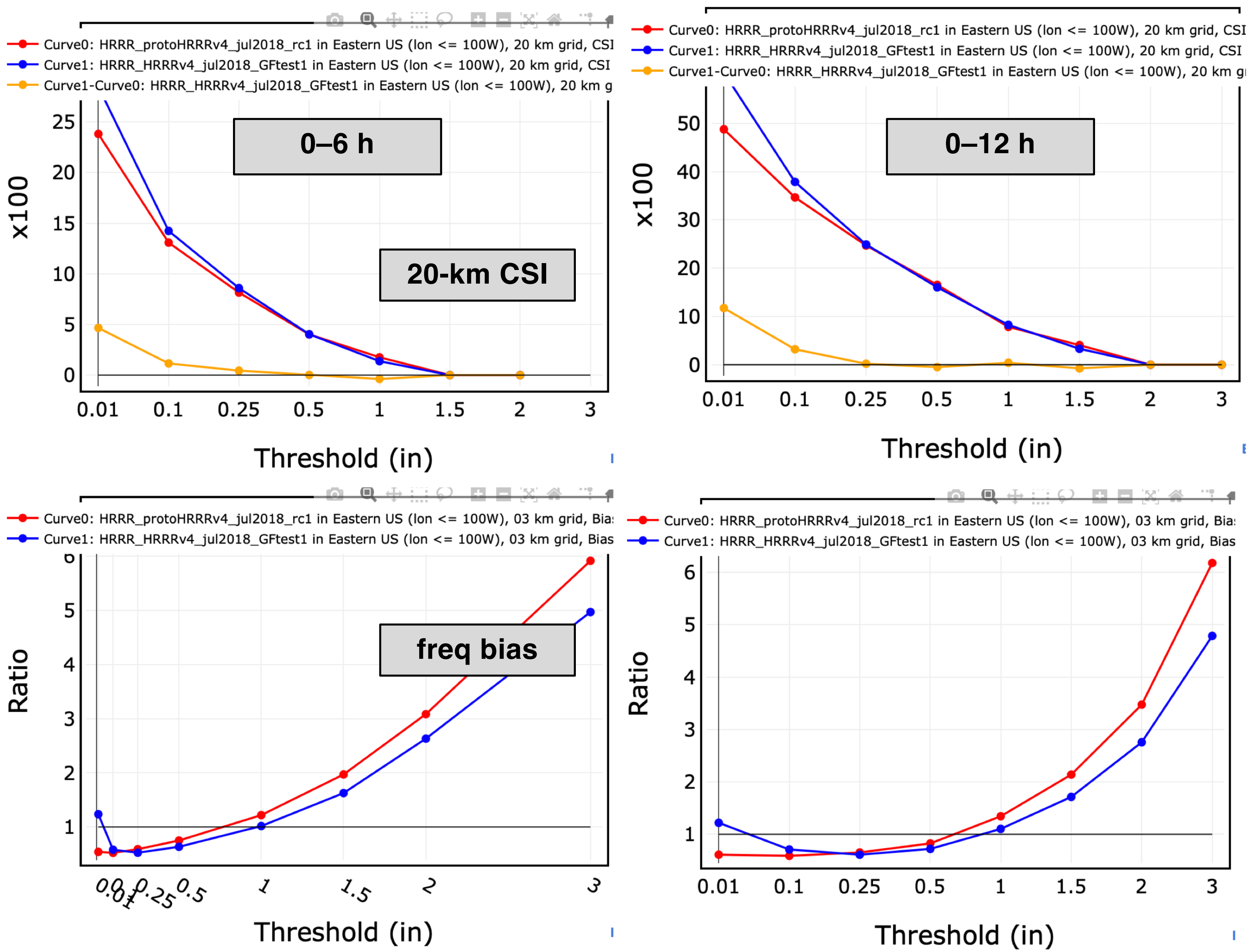


6-h accumulated precip ending 0000 UTC UTC 08 Aug 2018


Stage-IV
inches
MAX 3.47
MIN 0.00
5
3
2
1
0.5
0.25
0.1
0.01
observed
HRRR 12-18 h forecast
inches
MAX 4.56
MIN 0.00
5
3
2
1
0.5
0.25
0.1
0.01
HRRRv4 forecast ("cu_physics = 0")
No CP
With scale-aware GF.
Threshold at 0.6
0.01 0.1 0.25 0.5 1 1.5 2 3

Red curve: no convective parameterization used

precipitation
East CONUS: 8–9 Aug 2018



What should we do when running WRF and/or MPAS 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 ≤ 1km)
- Although it may be the best choice to fully resolve convection, it is usually not feasible
  - Try using schemes that are available in WRF and/or MPAS, use what works best for you (may also depend on other physics that are used) but keep the limitations (gray scales and conceptual figure) in mind
- If nothing helps you could develop and/or implement a new approach:
  - Convective parameterization development might drive you insane, or it might feed you for many years to come!!

Here are some ideas for you young developers, including some interesting new ideas

Challenges for convective parameterizations

- **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**
  - Updrafts/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 ?

What is new with convective parameterization (Grell and Freitas, GF) development?

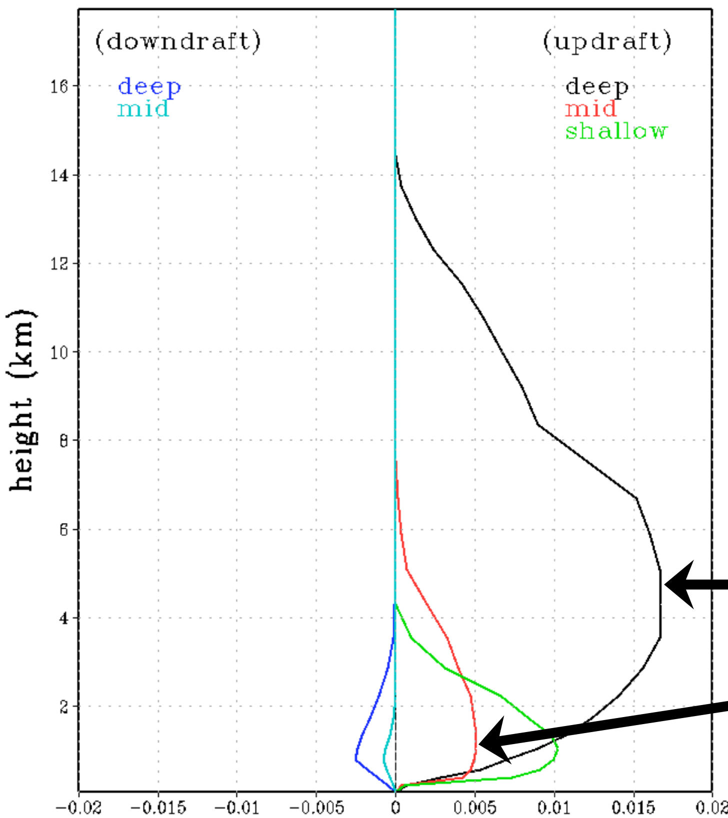
- A pdf describes the vertical mass flux distribution, meant to represent the average of deep convective plumes
  - Will determine average entrainment/detrainment profiles
  - Level of maximum mass flux determined by stability profile
- Three pdf’s (deep, congestus, shallow convection)
- Cloud water detrainment now proportional to mass detrainment and incloud cloudwater/ice mixing ratio (proportionality constant is a tuning factor)
- Below cloud base evaporation is optional (shallow does not have downdrafts)
- Double moment microphysics tendencies
- Changed subsidence terms for clw/ice to avoid negative mixing ratios (upstream with positive definite choice)

Experiments with use of memory to influence PDF’s, cloud water detrainment, aerosol dependence

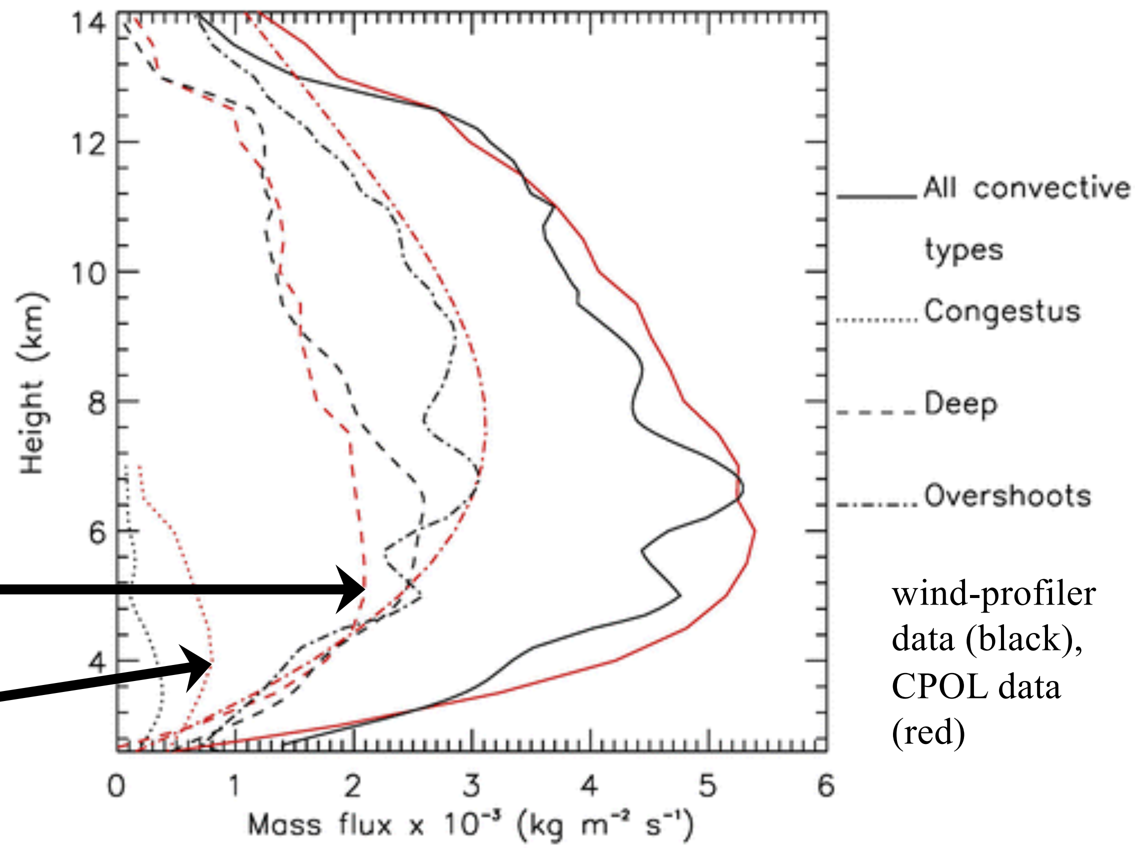
Work with HRRR: stochastics is an option (maybe the Cellular Automata scheme), or turning off scaling for special type of light forcing, or going back to G3

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)

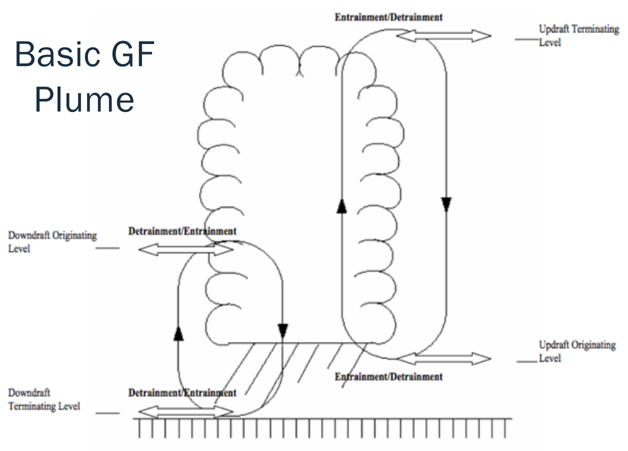


wind-profiler data (black), CPOL data (red)

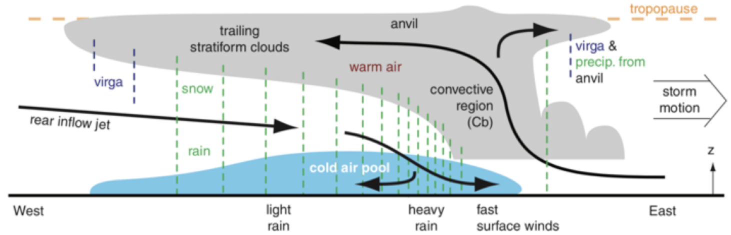
Storm Motion in GF: Motivation

- Downdrafts are one mechanism that can foster convective propagation and organization
- GF already simulates downdrafts
  - This work tries to use the downdrafts represented in GF to foster storm propagation

Basic GF Plume

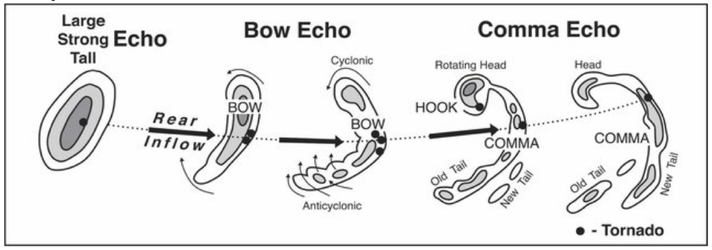


Mesoscale Convective Systems



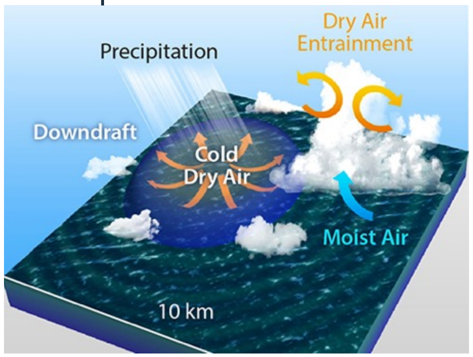
https://www.eoas.ubc.ca/courses/atsc113/flying/met_concepts/04-met_concepts/04a-Tstorm_types/index-mcs.html

Squall Lines



Wakimoto et al., 2006

Cold pools

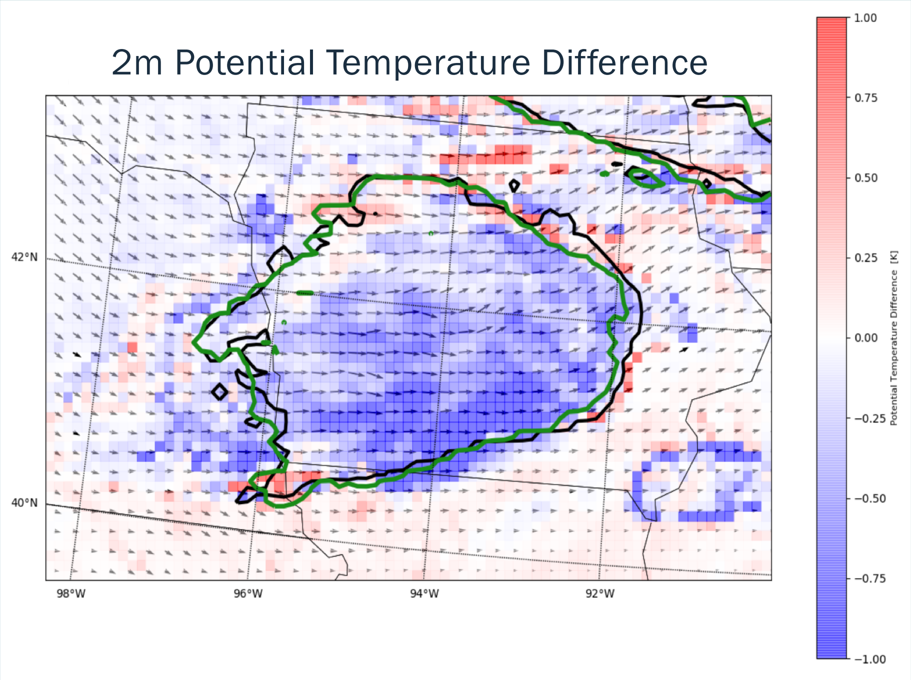


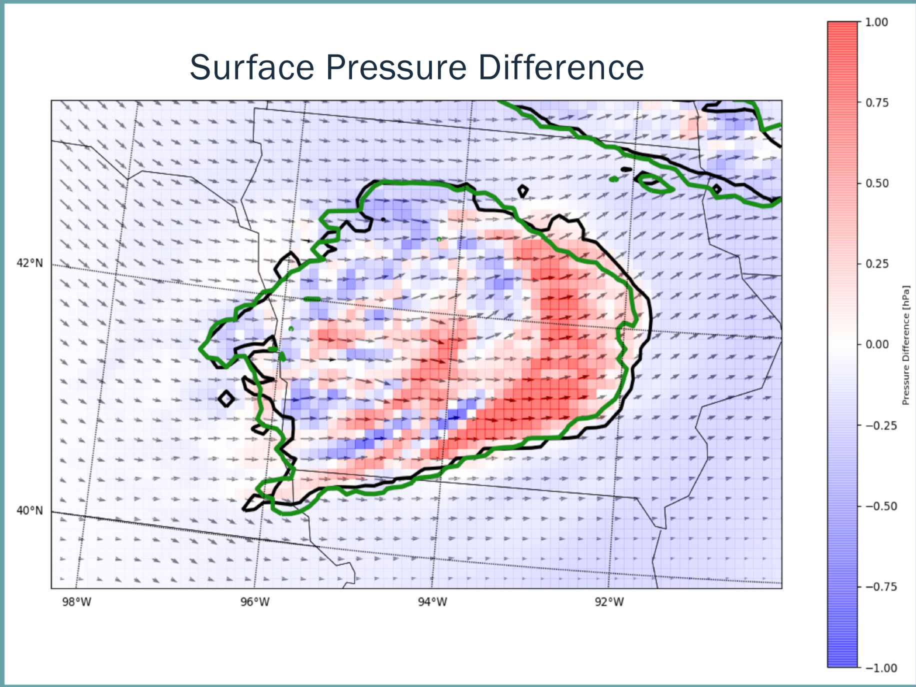
Zhe et al., 2015

Storm Motion in GF: Results

Difference Maps

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





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

Thank you!   Questions?

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