Improving cloud and solar radiation forecasts in the RAP/HRRR forecast systems

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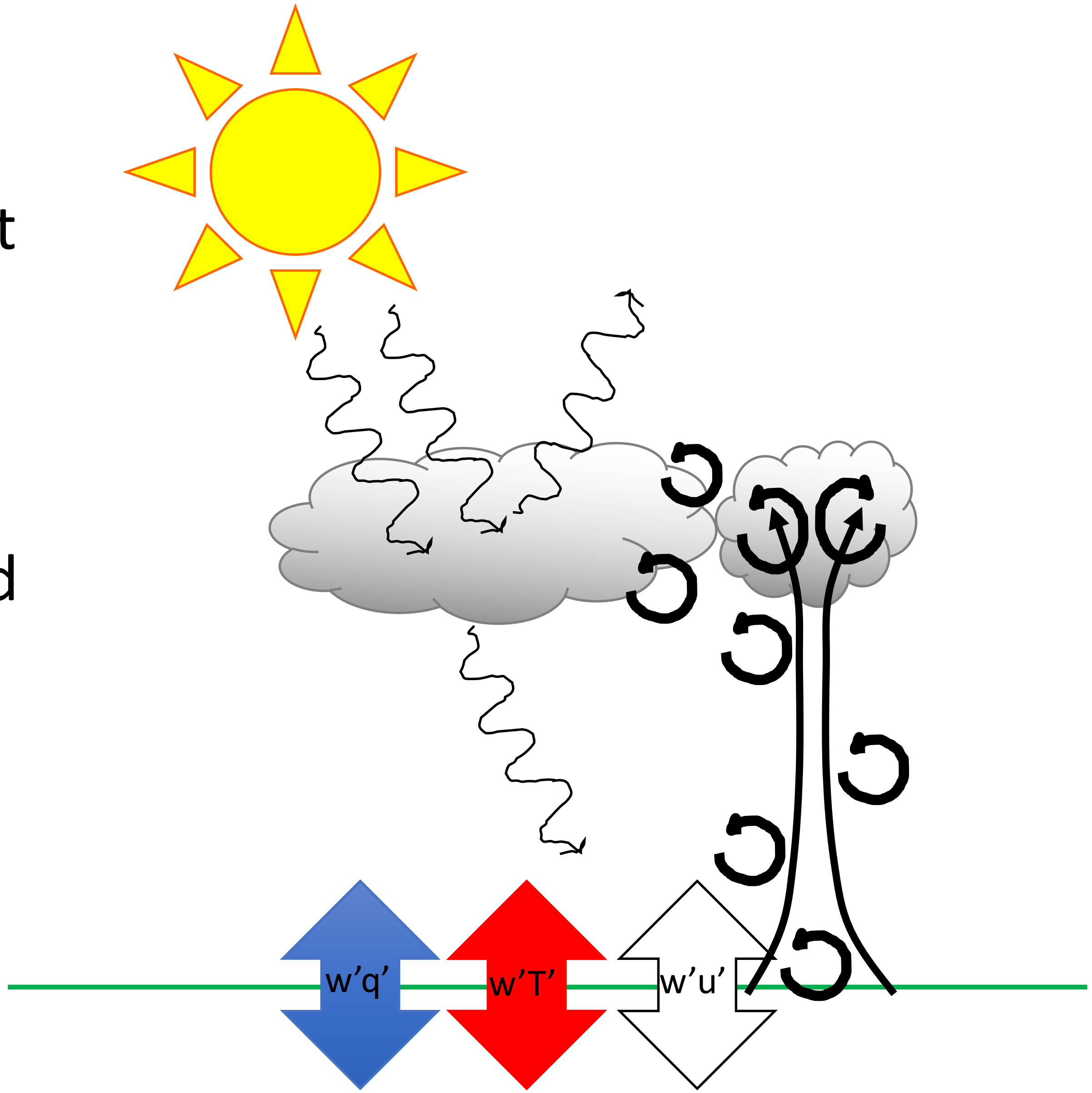
Outline

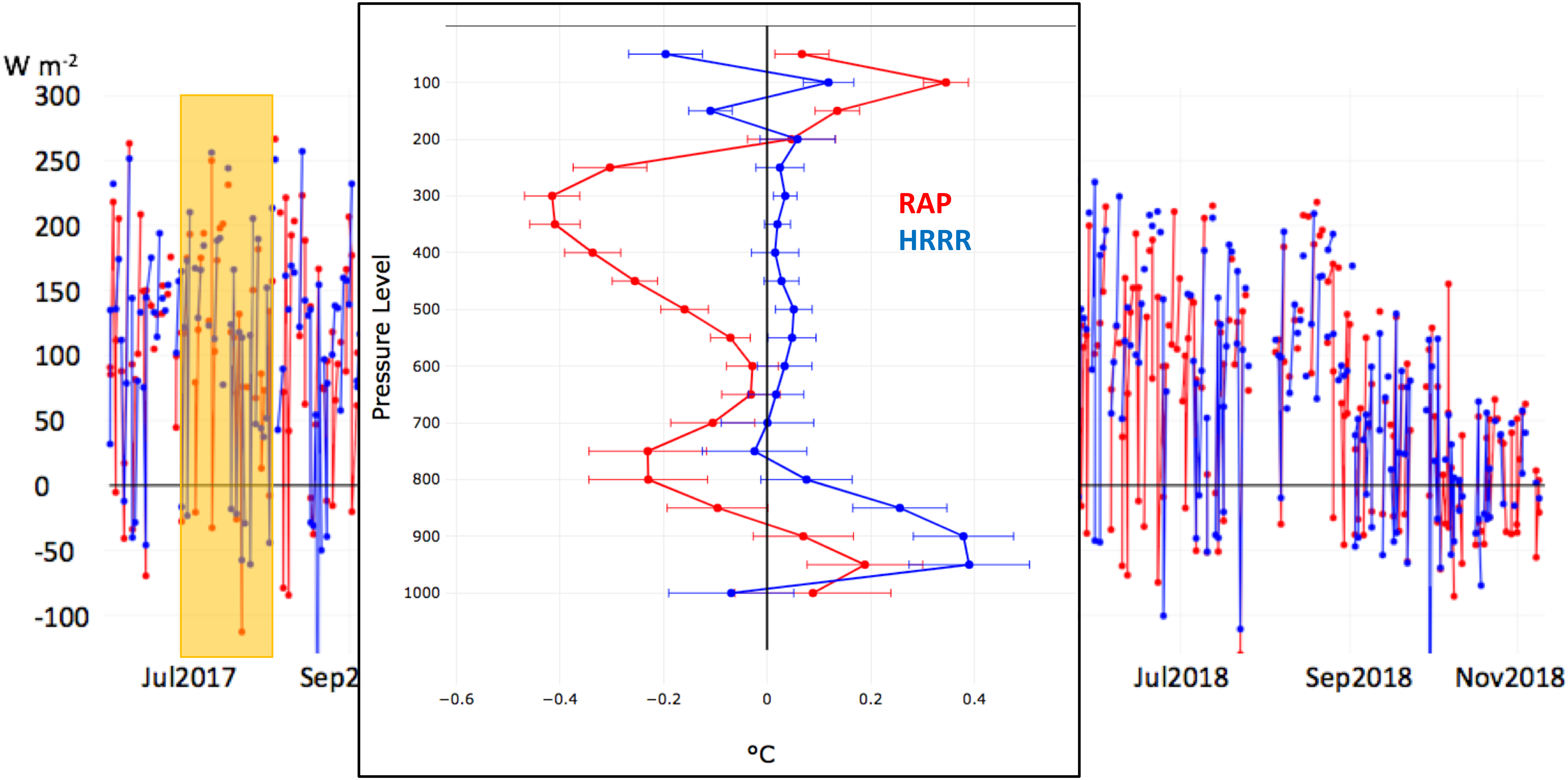
- Motivation
- Overview model development for improved subgrid-scale (SGS) clouds and the interaction with the radiation scheme
- Summarize improvements
    - Downward shortwave radiation at the surface
    - Cloud ceilings
- The consequence of improving primary model physics biases:
    - Low-level cold bias
- Subsequent work to alleviate the low-level cold bias

Motivation

- Cloud-Radiation interactions are primary physical processes that can dictate the climate of a model forecast
- As a primary physical process, any systematic biases can result in incorrect forcing of other processes, such as surface fluxes, turbulence, and convection.



History of Solar Radiation Biases in RAP/HRRR

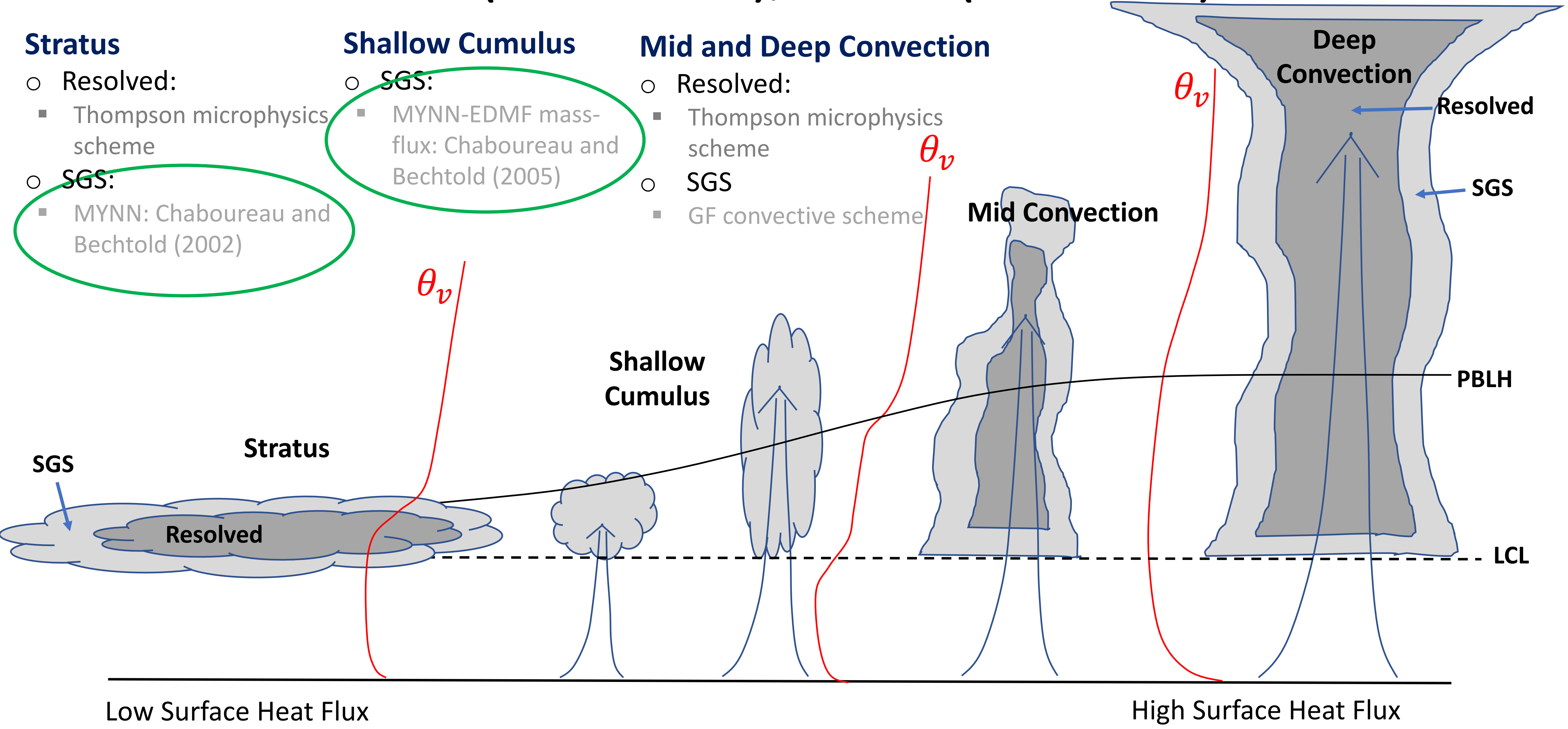


Resolved and Subgrid-Scale (SGS) Clouds in the RAP (Δx=13km)/HRRR (Δx=3km)

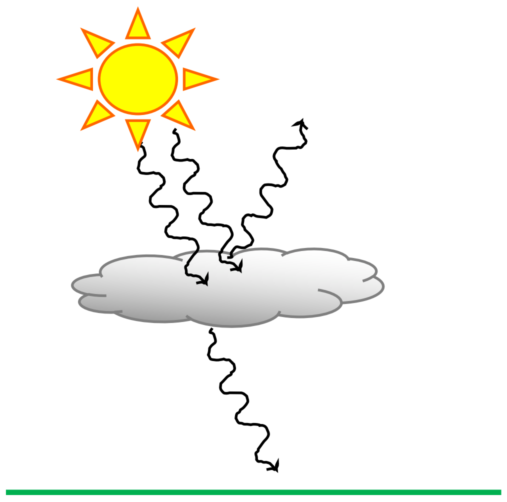
Stratus
- Resolved:
  - Thompson microphysics scheme
- SGS:
  - MYNN: Chaboureau and Bechtold (2002)

Shallow Cumulus
- SGS:
  - MYNN-EDMF mass-flux: Chaboureau and Bechtold (2005)

Mid and Deep Convection
- Resolved:
  - Thompson microphysics scheme
- SGS
  - GF convective scheme



Modifications to SGS Cloud Components



Important subgrid scale (SGS) microphysical/macrophysical quantities for interaction with the radiation scheme (changes noted in red):

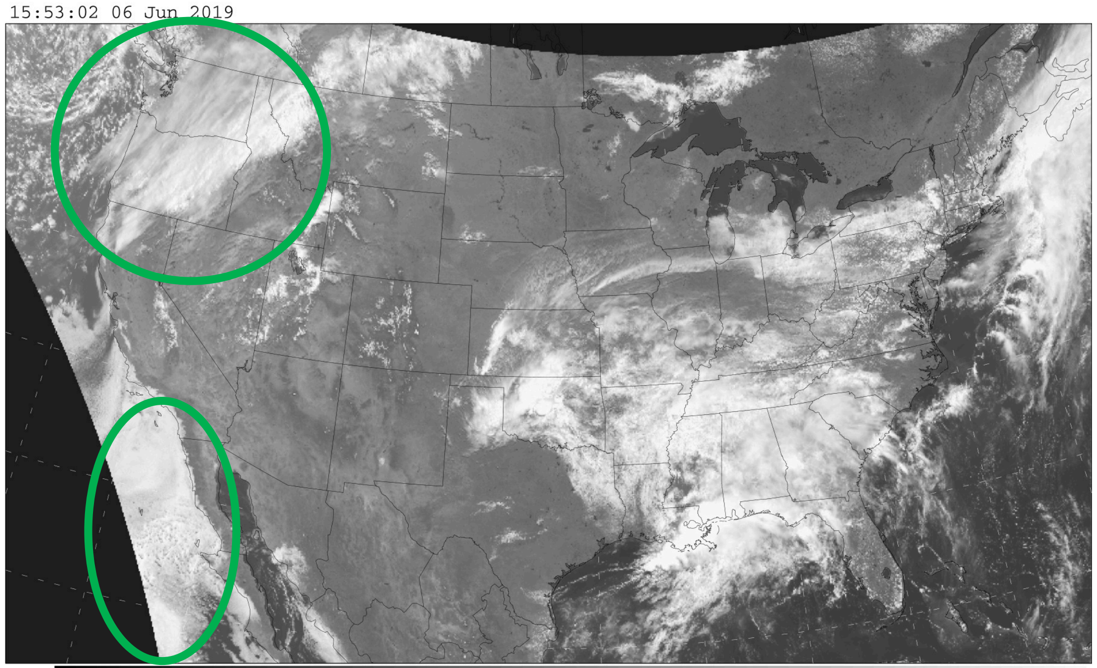
- SGS Mixing ratio (q_c *and* q_i):
  - Non-convective q_x: Chaboureau and Bechtold (2002) (removed constraints)
  - Mass-flux scheme: stronger mass-flux → deeper penetration → better areal coverage
- SGS Cloud fraction (A_{cf}):
  - Non-convective: Chaboureau and Bechtold (2002) (reduced, except for high RH)
  - Convective: Chaboureau and Bechtold (2005)
  - No longer use Xu-Randall (1996) cloud fraction (icloud = 1) – only use MYNN SGS clouds
- SGS cloud water/ice effective radii (r_e):
  - Water: Turner et al. (2007, BAMS)
  - Ice: Mishra et al. (2014, JGR)

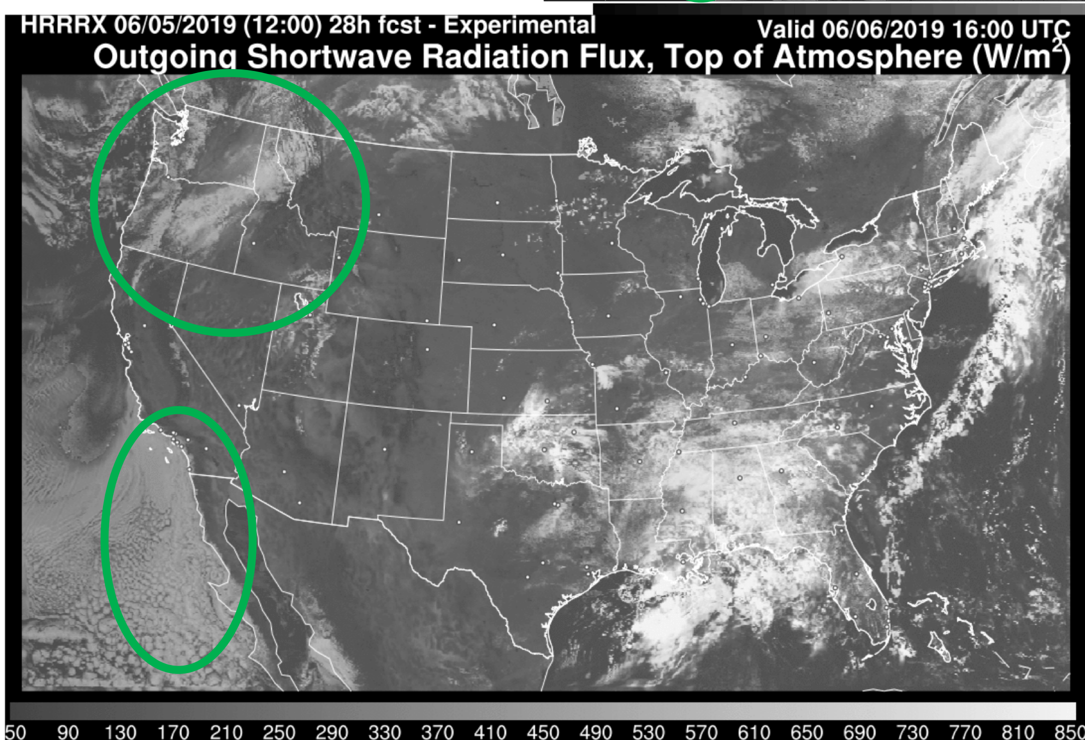
Comparison of SW-up at top of atmosphere

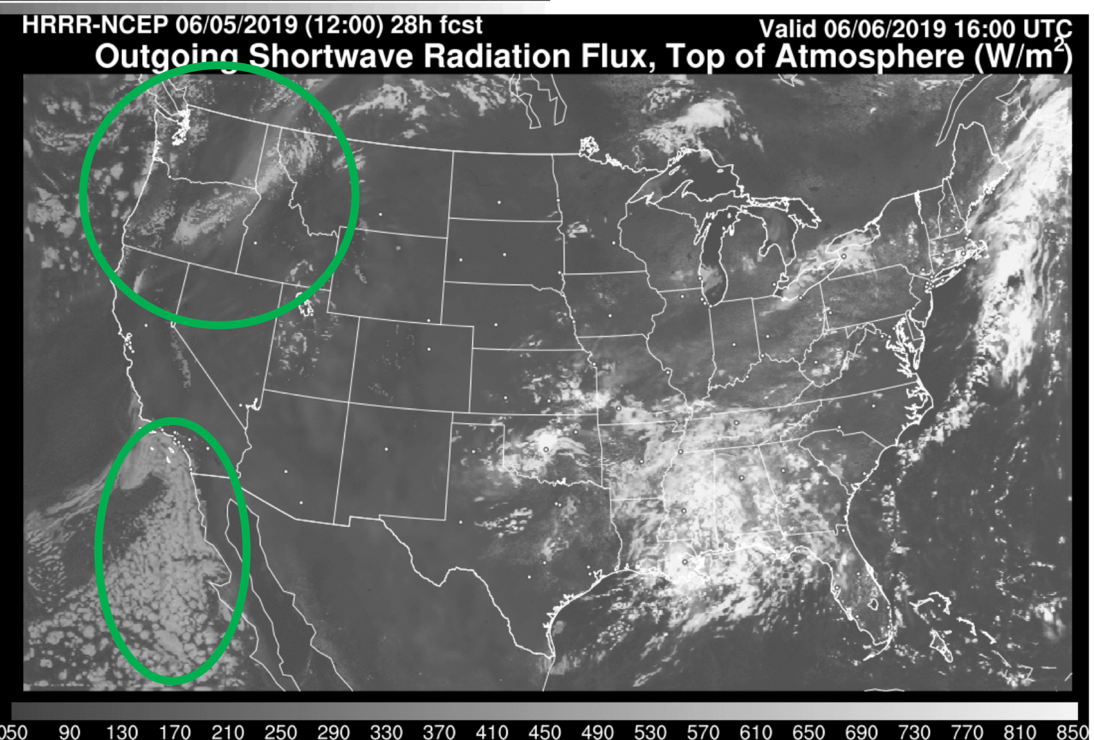
16 UTC 06 June 2019

Initialized 12 UTC 05 June
Fcst hr 28:

GOES-16 combined (ch1, 2, 3) visible albedo



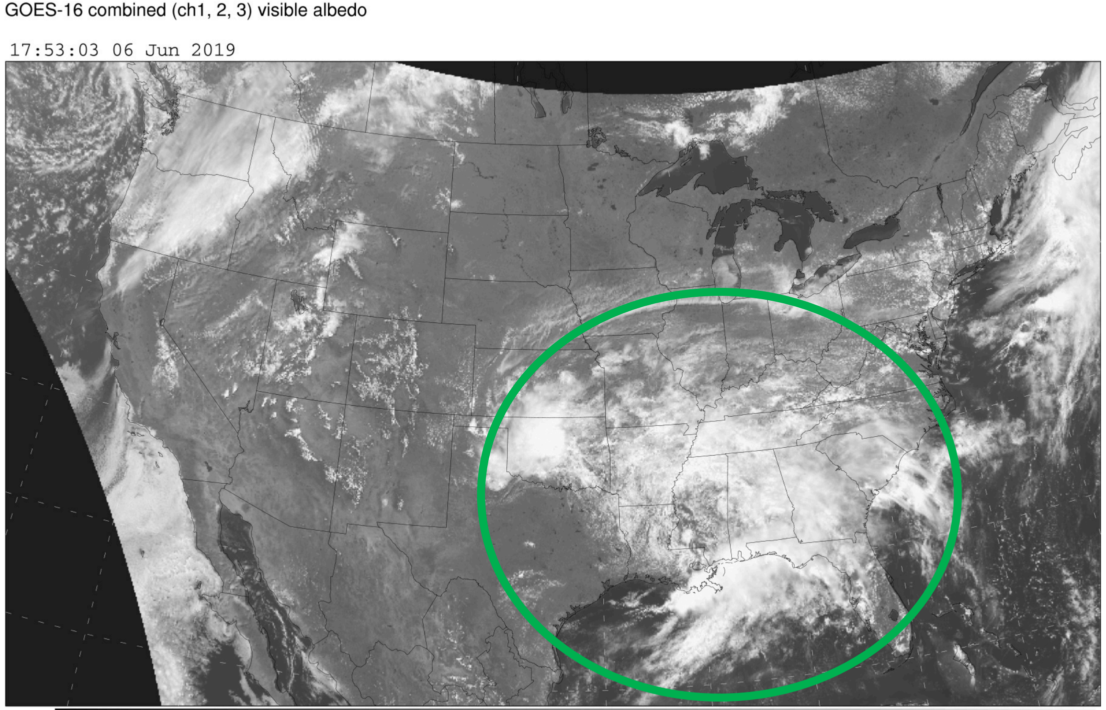


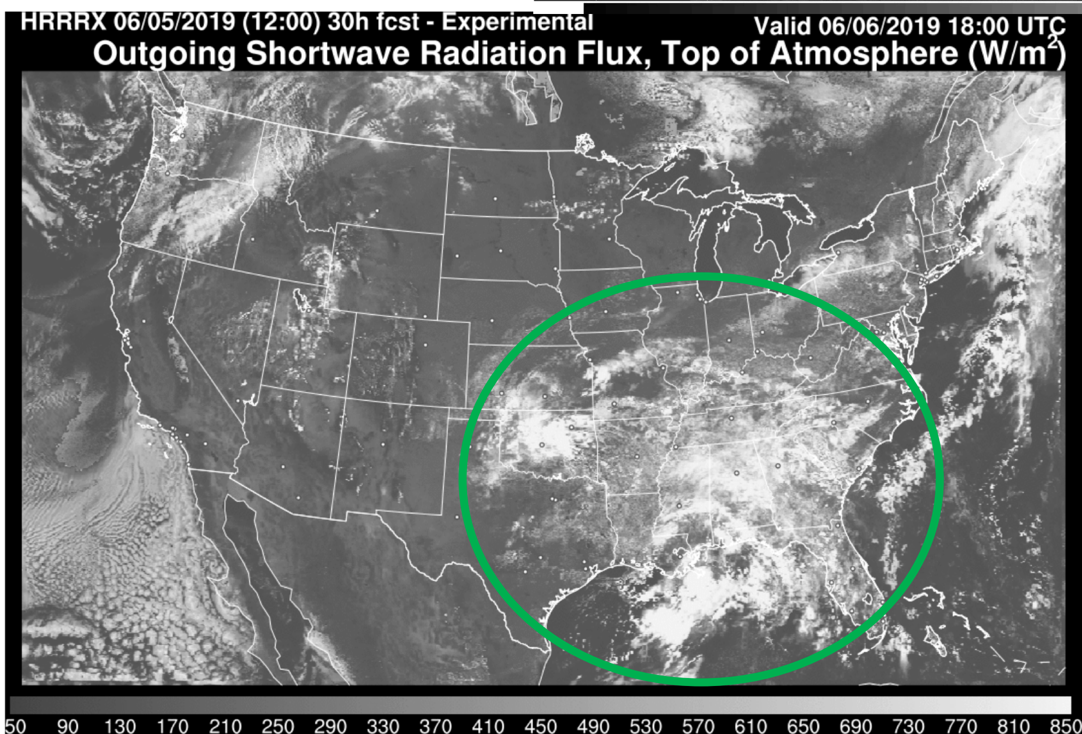


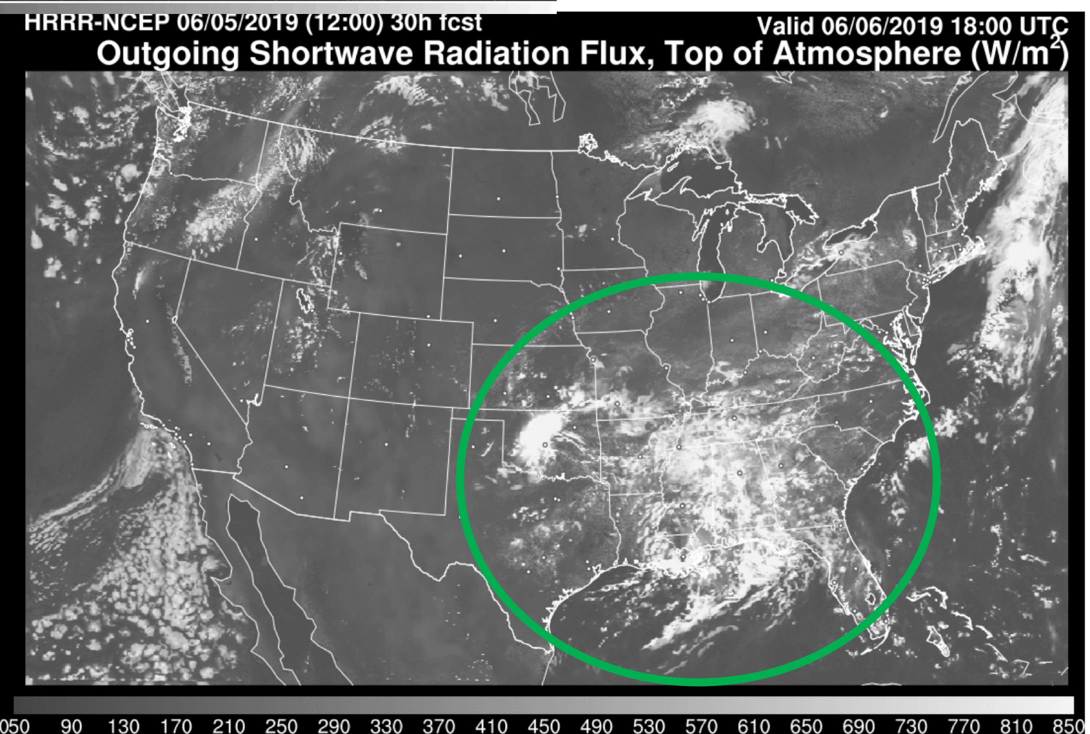
Comparison of SW-up at top of atmosphere

18 UTC 06 June 2019

Initialized 12 UTC 05 June
Fcst hr 30:



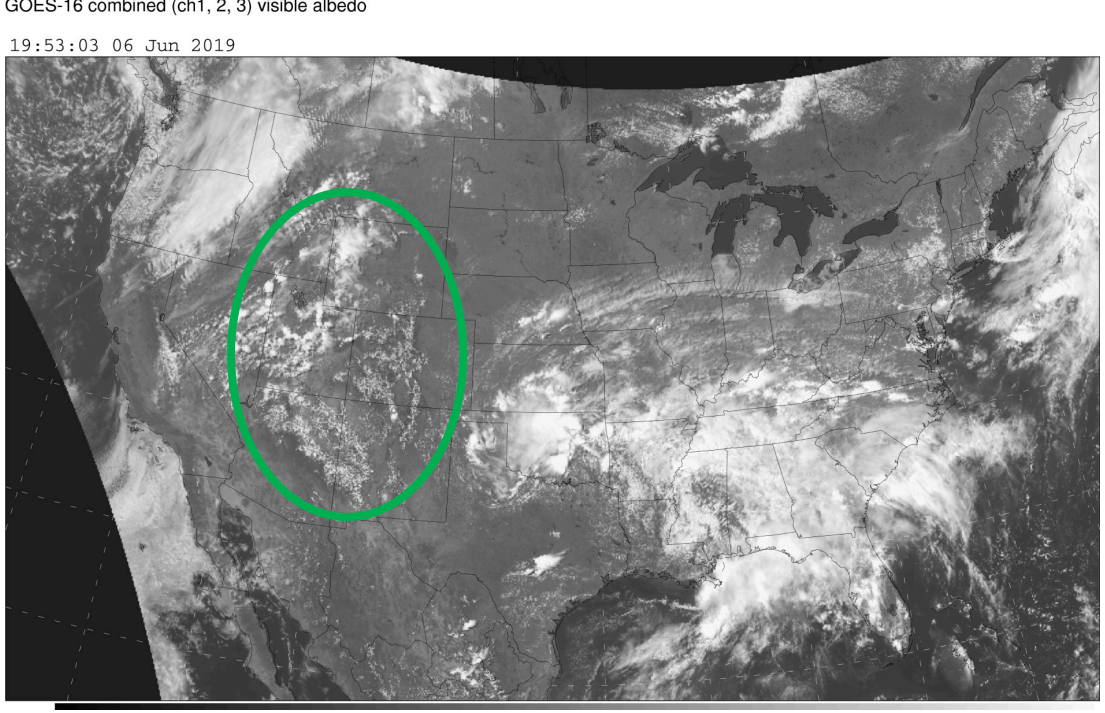


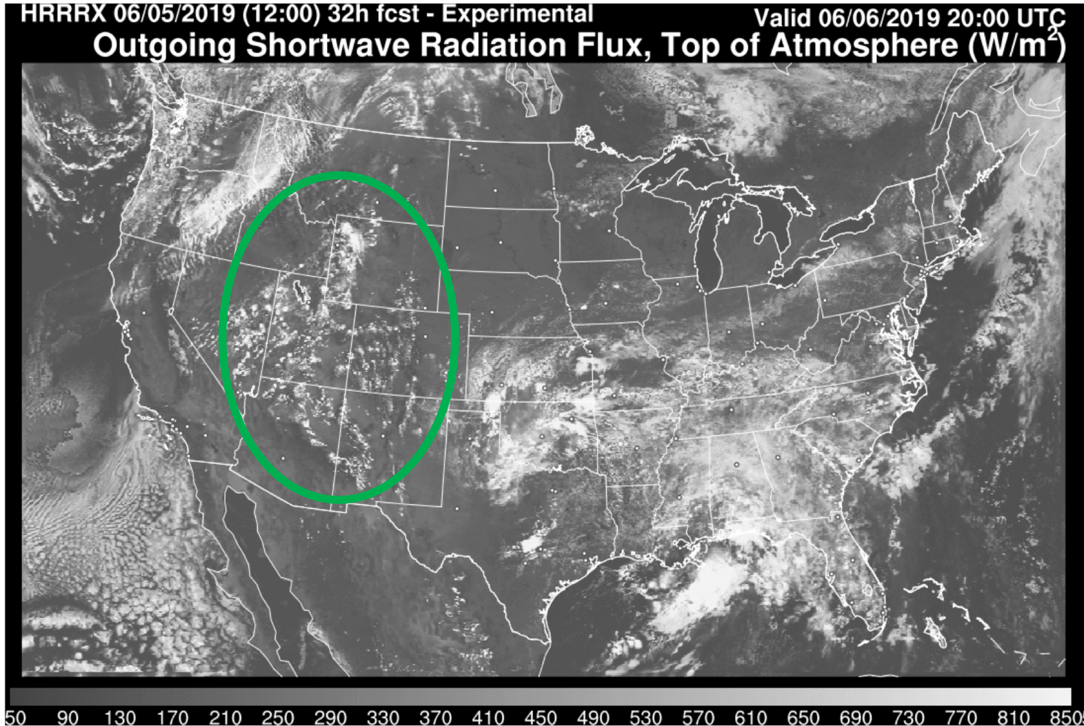


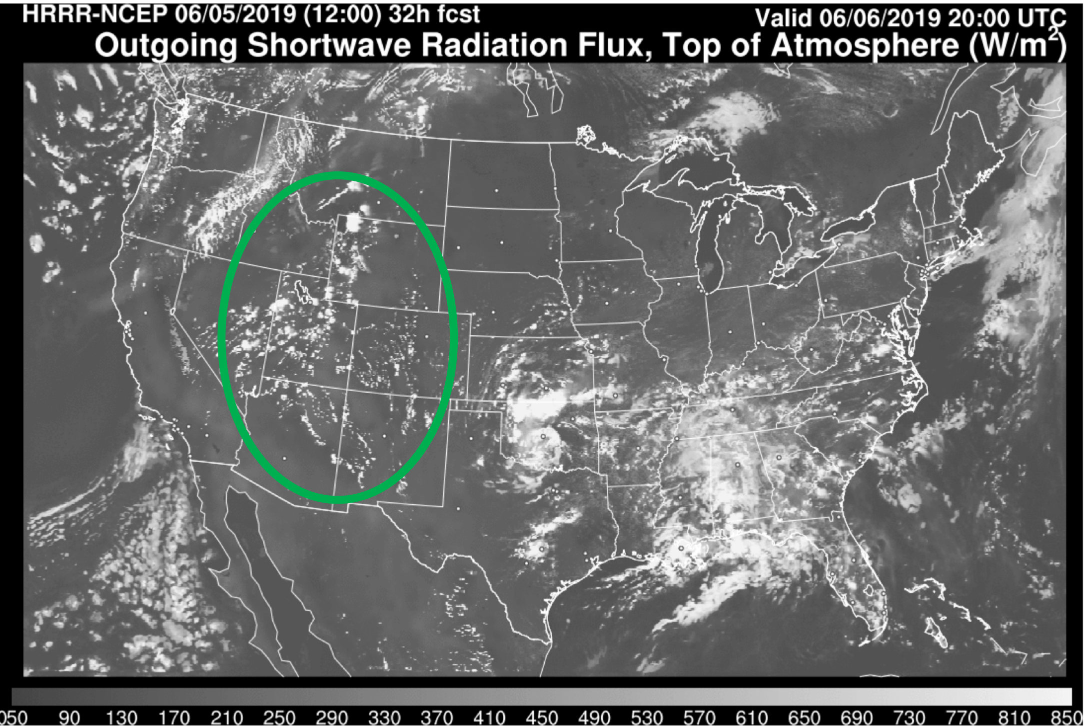
Comparison of SW-up at top of atmosphere

20 UTC 06 June 2019

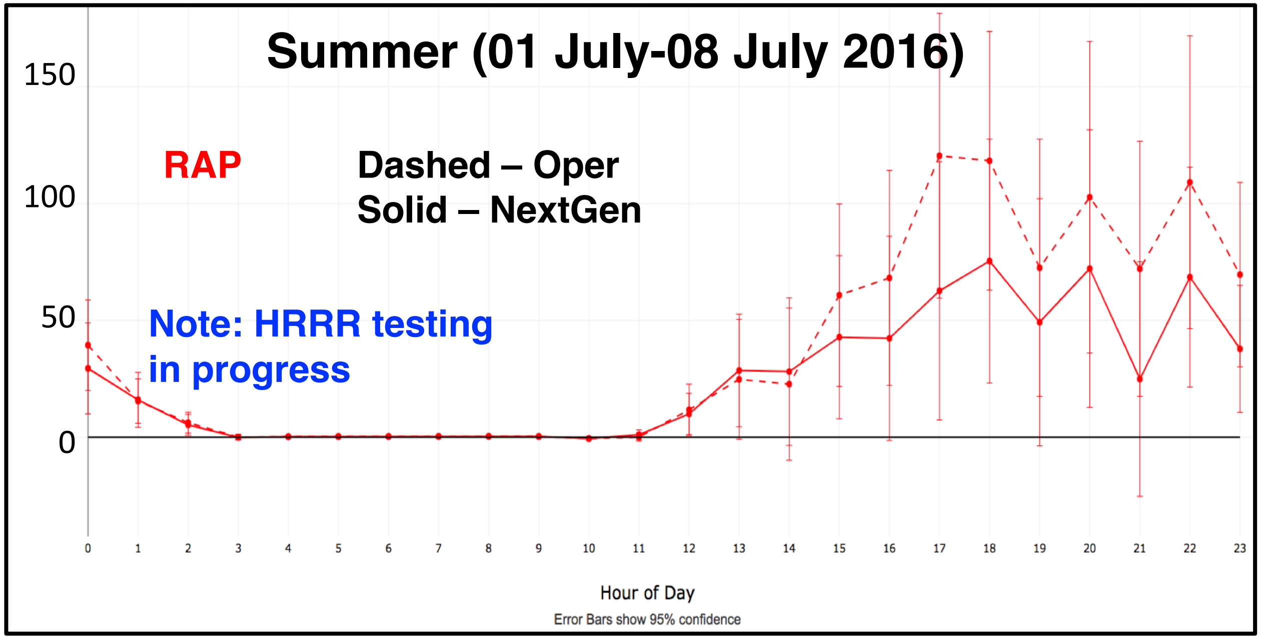
Initialized 12 UTC 05 June
Fcst hr 32:

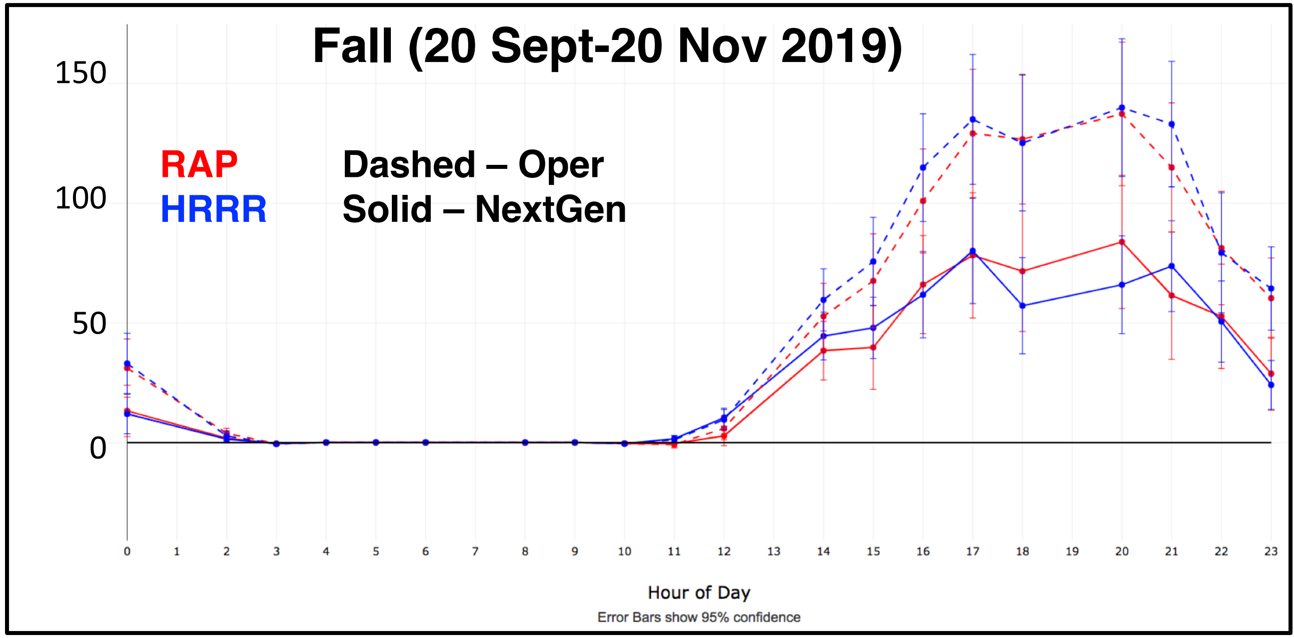


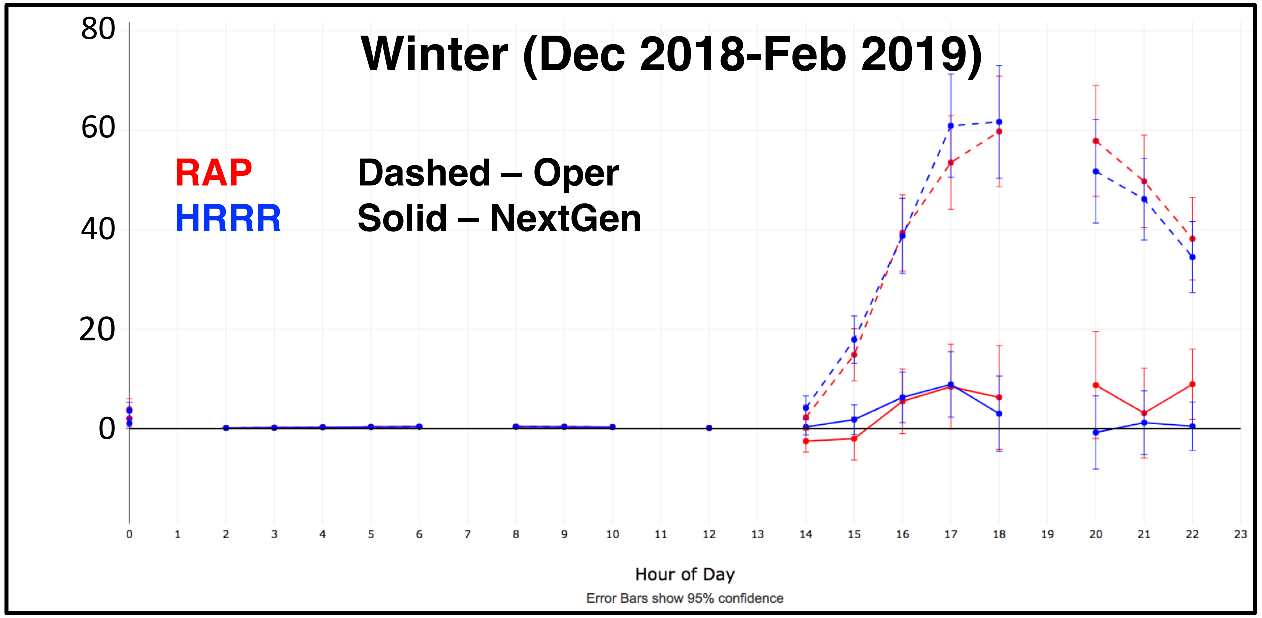


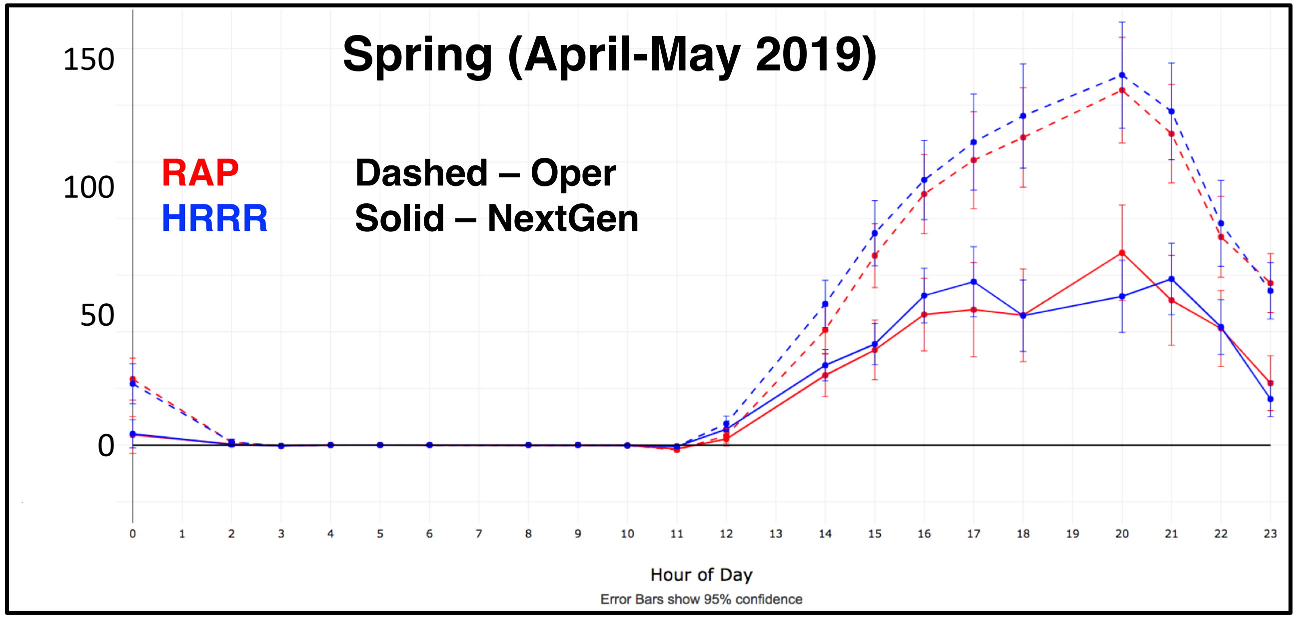


Diurnal Mean Surface GHI (W m^{-2}) | 12-h bias









Ceiling Diagnostic Algorithm in the RAP and HRRR

Legacy Diagnostic:

For each grid column, ceiling is diagnosed where:

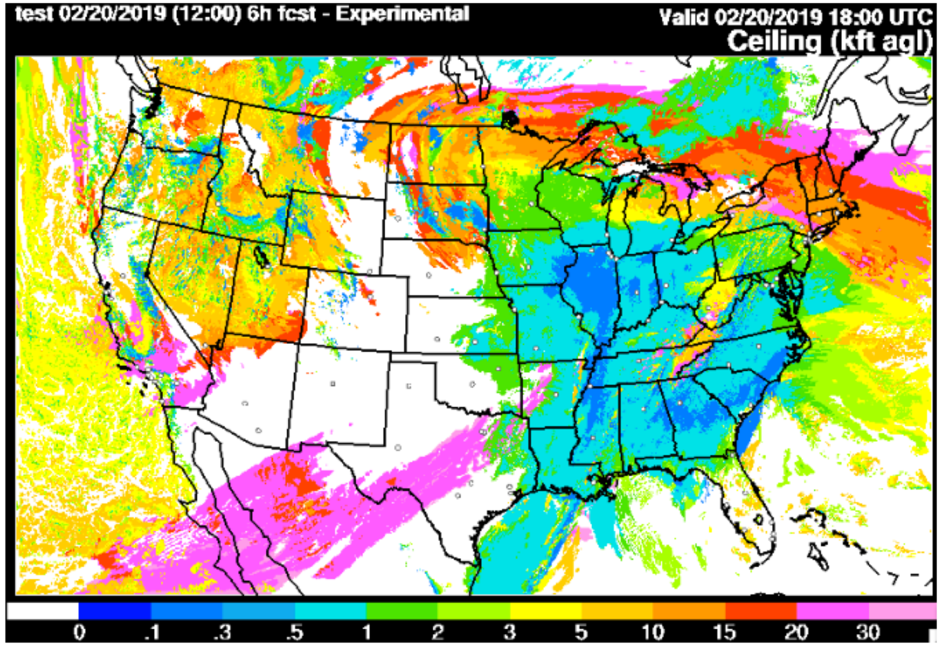
- ~~grid-scale $q_c + q_i > 10^{-6}$ kg kg^{-1}, or~~
- ~~grid-scale RH at PBL top > 95%~~

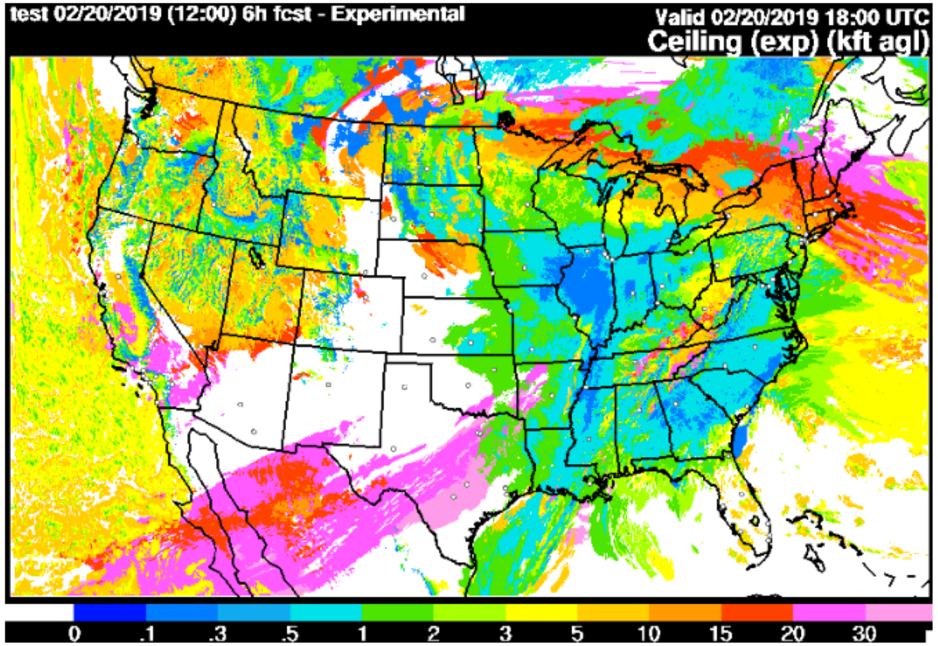
Experimental New Algorithm

New Experimental Diagnostic:

- MYNN cloud fraction > 0.5

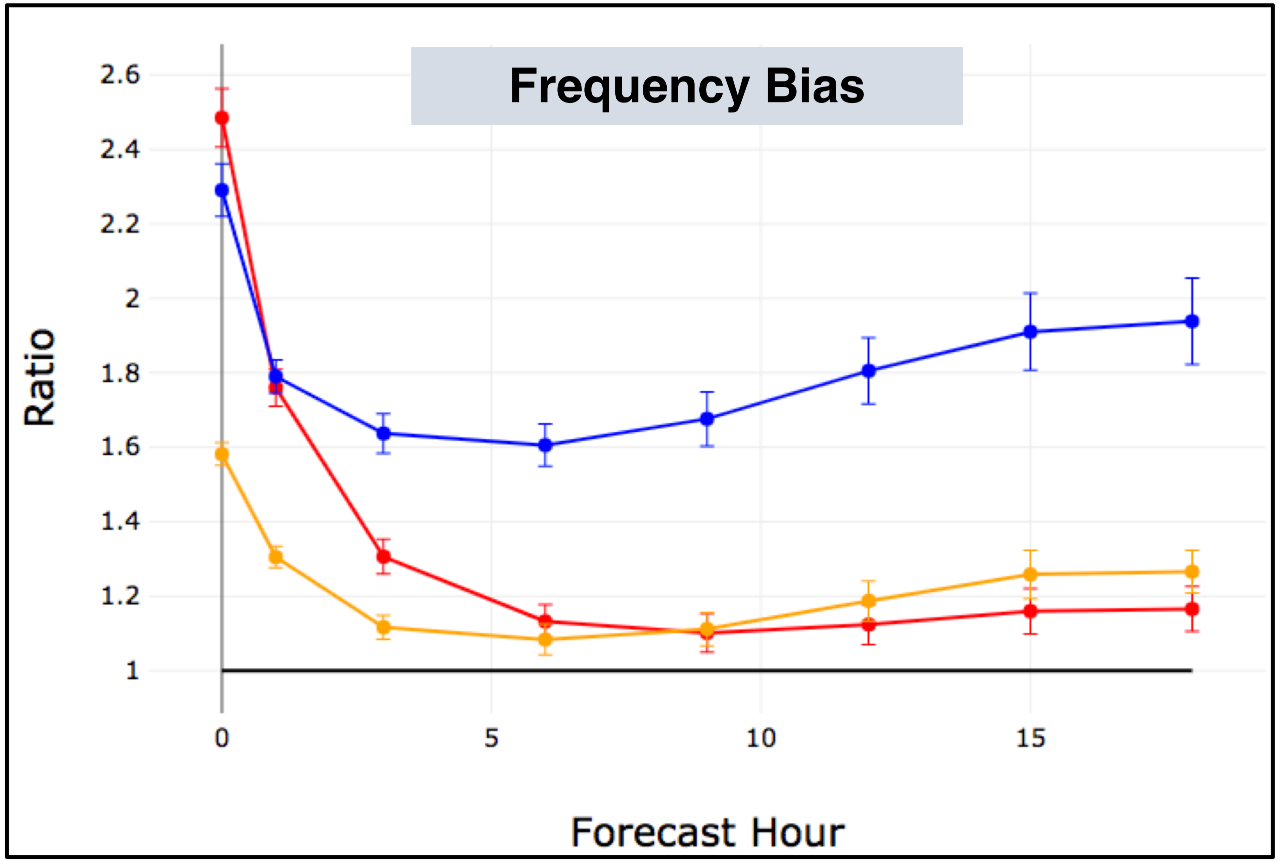
- **Thin, surface-based cloud layers (< ~80 m deep) are disregarded**
- **If grid-scale snow is present, the diagnosed ceiling is lowered**

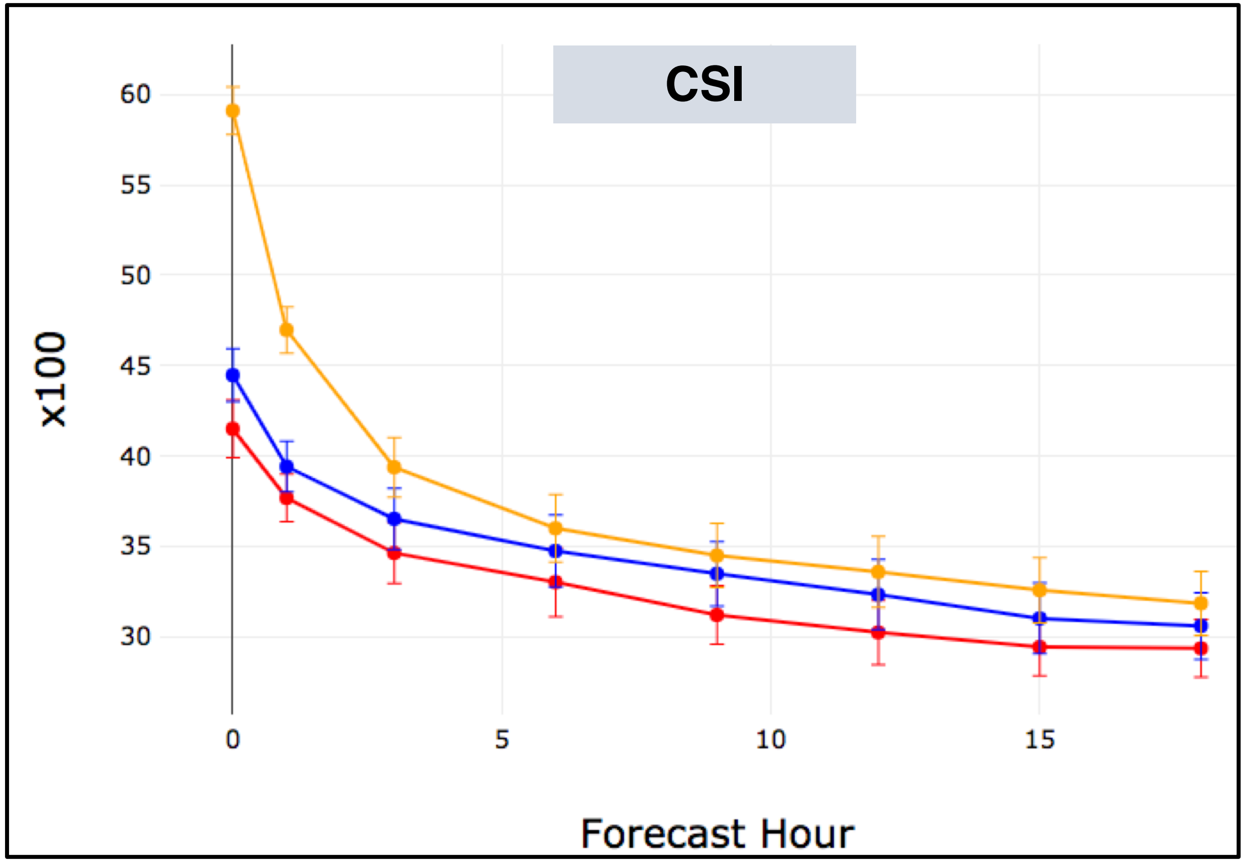




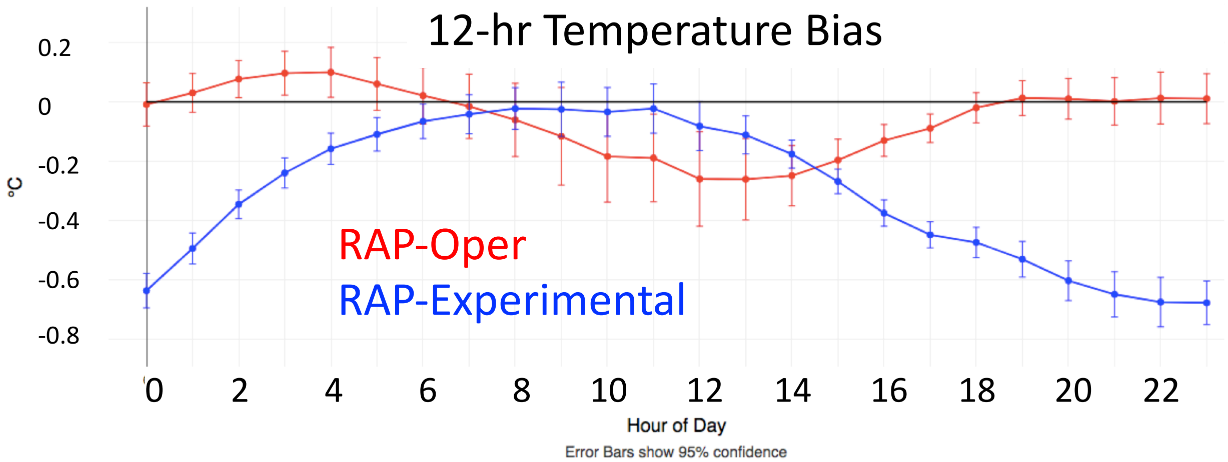
HRRR 1000-ft ceiling "dieoff" (E CONUS): 15 Mar – 5 Jun 2019

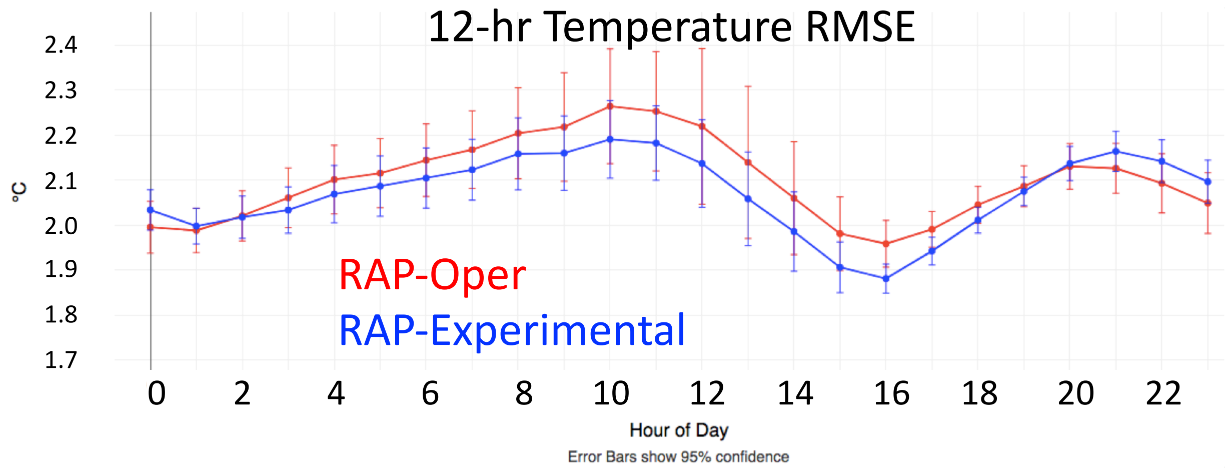
HRRRv3 – Legacy diagnostic
HRRR Exp – Legacy diagnostic
HRRR Exp - Experimental diagnostic

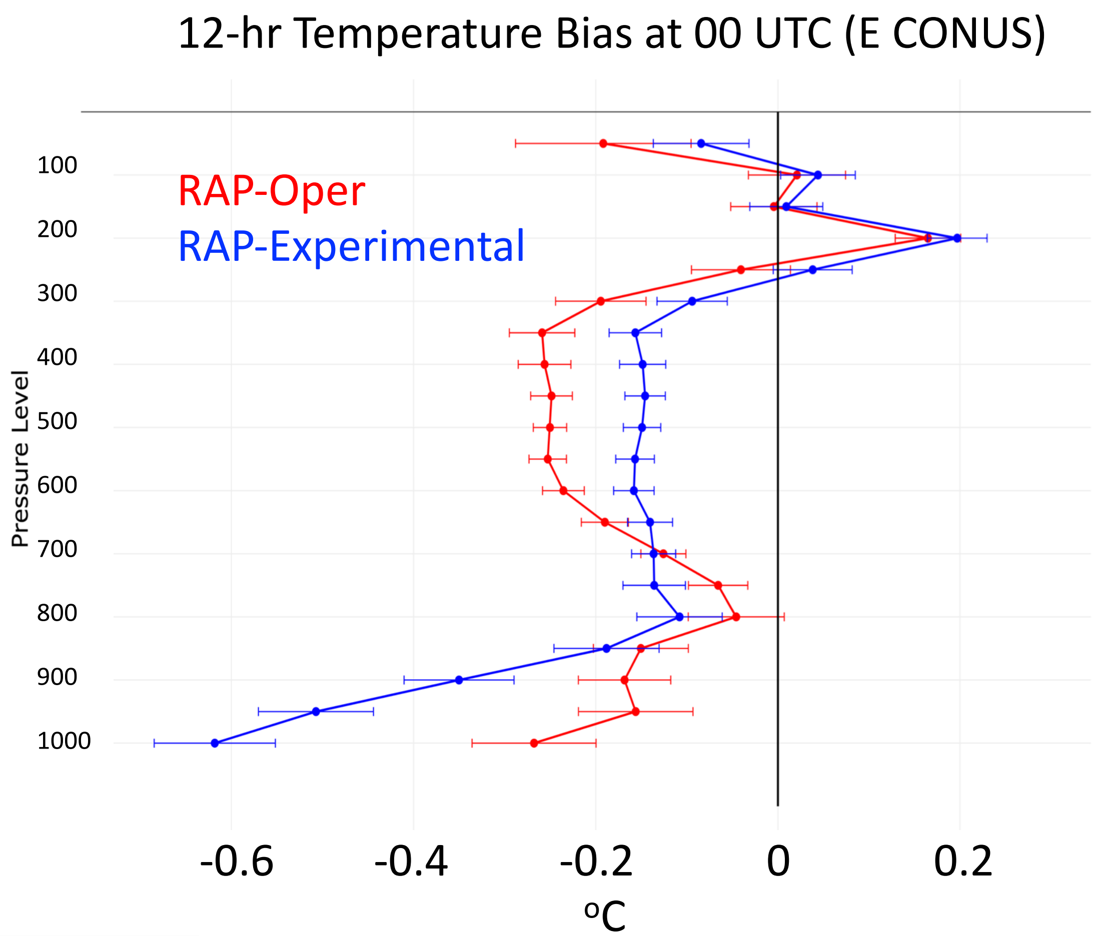




New Temperature Bias Characteristics (Oct–May)







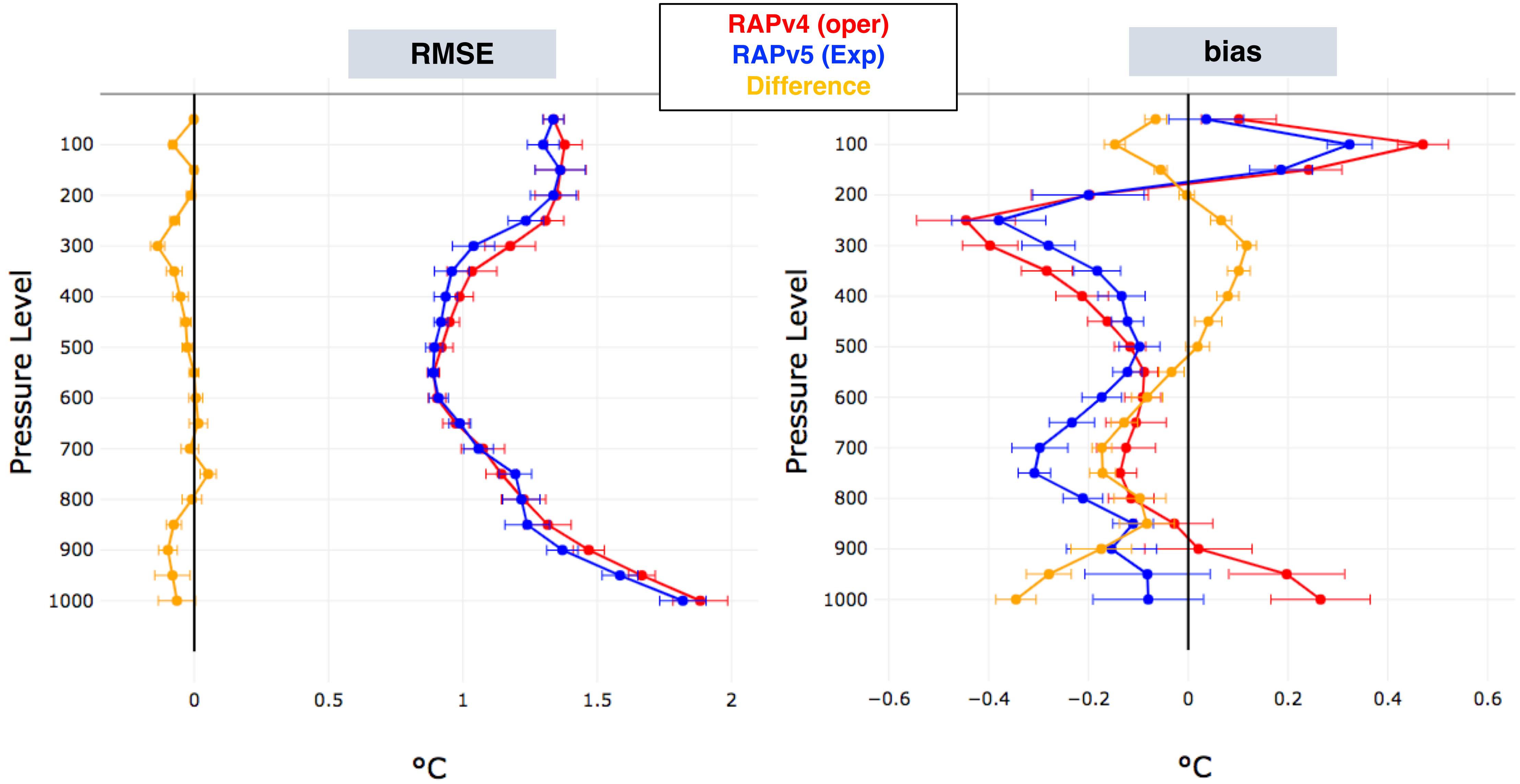
Changes to MYNN-EDMF to combat cold bias

(All changed made for both RAP and HRRR)

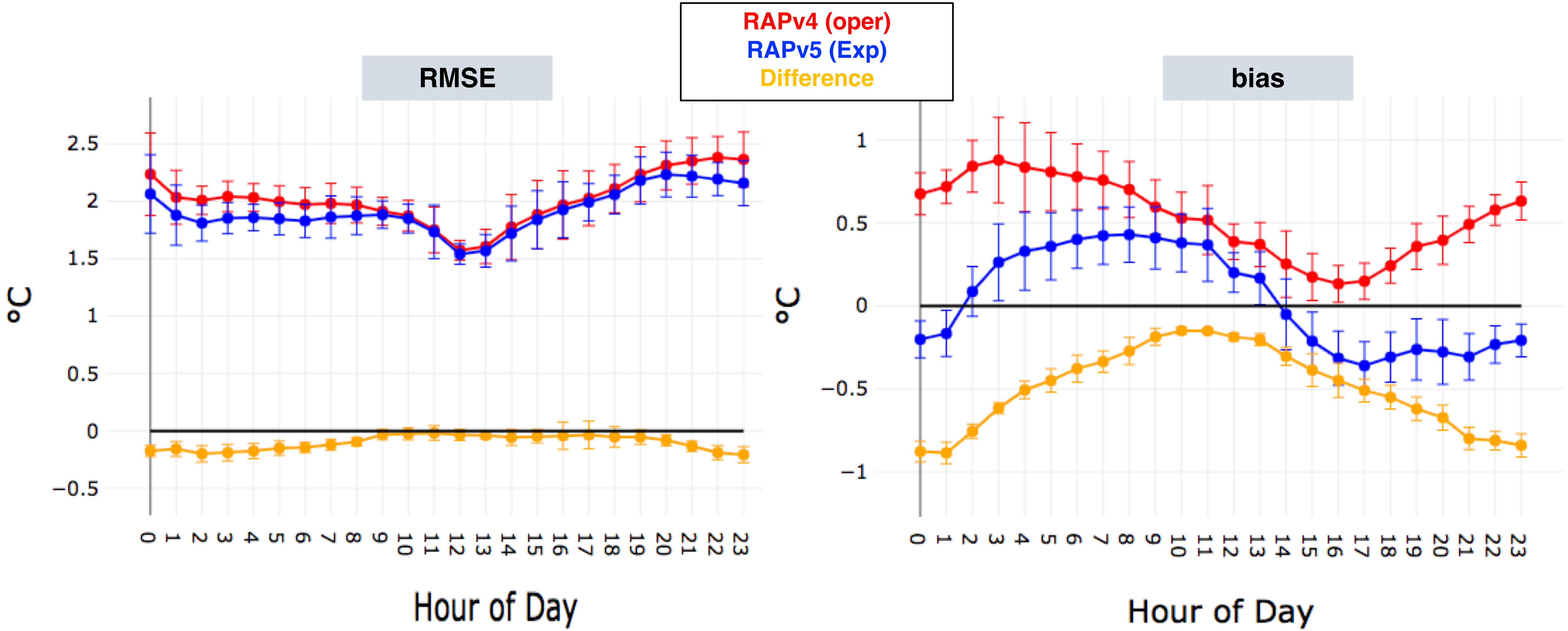
Approximate contribution to warming 12 hr fcst:

- **Mixing length:** — ~ +0.1 to +0.2 C (daytime only)
  - Increased the turbulent mixing
- **Added TKE cycling:** — ~ +0.1 C (in 0-3 hr fcst)
  - No longer re-spinning up the TKE every hour
- **Added dissipative heating (similar to Han and Bretherton 2019):** — ~ +0.1 C
- **Added buoyancy flux functions (Bechtold and Siebesma 1998):** — ~+0.1 to +0.2 C (mostly over water)
- **Surface layer scheme:** — ~ +0.1 to +0.2 C (daytime only)
  - Switched to exact calculation of z/L (from diagnostic mapping of $Ri_b \rightarrow z/L$)
  - Increased C_{zil} from 0.075 to 0.085

RAP 18-h Temperature: 1–13 July 2016



RAP 12-h 2-m Temperature (E CONUS): 1–13 July 2016



Summary

- Improvements to the mixing ratio, cloud fraction, and effective radii further improve downward shortwave radiation forecasts
  - Bias is reduced by about 50% compared to current operational RAP/HRRR
  - RMSE is also reduced by about 10% (not shown)
- Subgrid clouds are also useful for detecting cloud ceilings
- However, improved SW-down forecasts result in near-surface cold bias
  - Increased diffusion help to alleviate the new cold bias, but more work is needed…
- These modifications will be in next operational upgrade of RAP and HRRR
  - Some are already in v4.1, but more commits are coming…
- Further improvement to solar forecasts will probably need:
  - Detailed regime-stratified verification (ShCu, StratoCu, etc)
  - Further research: exponential random cloud overlap, aerosol interaction, subgrid-scale precipitation processes, and cloud PDFs using higher-order moments

Extra Slides

Assembling the SGS Cloud Components for Radiation

Non-radiation physics:

Thompson Microphysics:

- Resolved q_c, q_i, q_s, q_r, etc
- Effective radii r_e

Grell-Freitas Convection:

- SGS q_c and q_i

MYNN-EDMF:

- SGS q_c and q_i
- SGS cloud fraction

In radiation driver:

- SGS q_c and q_i are added to the resolved q_c and q_i when $q_c = q_i = 0$

Using icloud = 1:

- Cloud fractions are obtained from Xu and Randall (1996) X X X X X

↓

- MYNN SGS q_c and q_i are added when the resolved q_c and q_i:
  - $q_c <$ 1e-6 kg kg^{-1} and
  - $q_i <$ 1e-8 kg kg^{-1}
- Use MYNN SGS cloud fractions

→

SGS effective radii, r_e:

- Water: Turner et al. (2007, BAMS)
- Ice: Mishra et al. (2014, JGR)

↓

RRTMG SW and LW

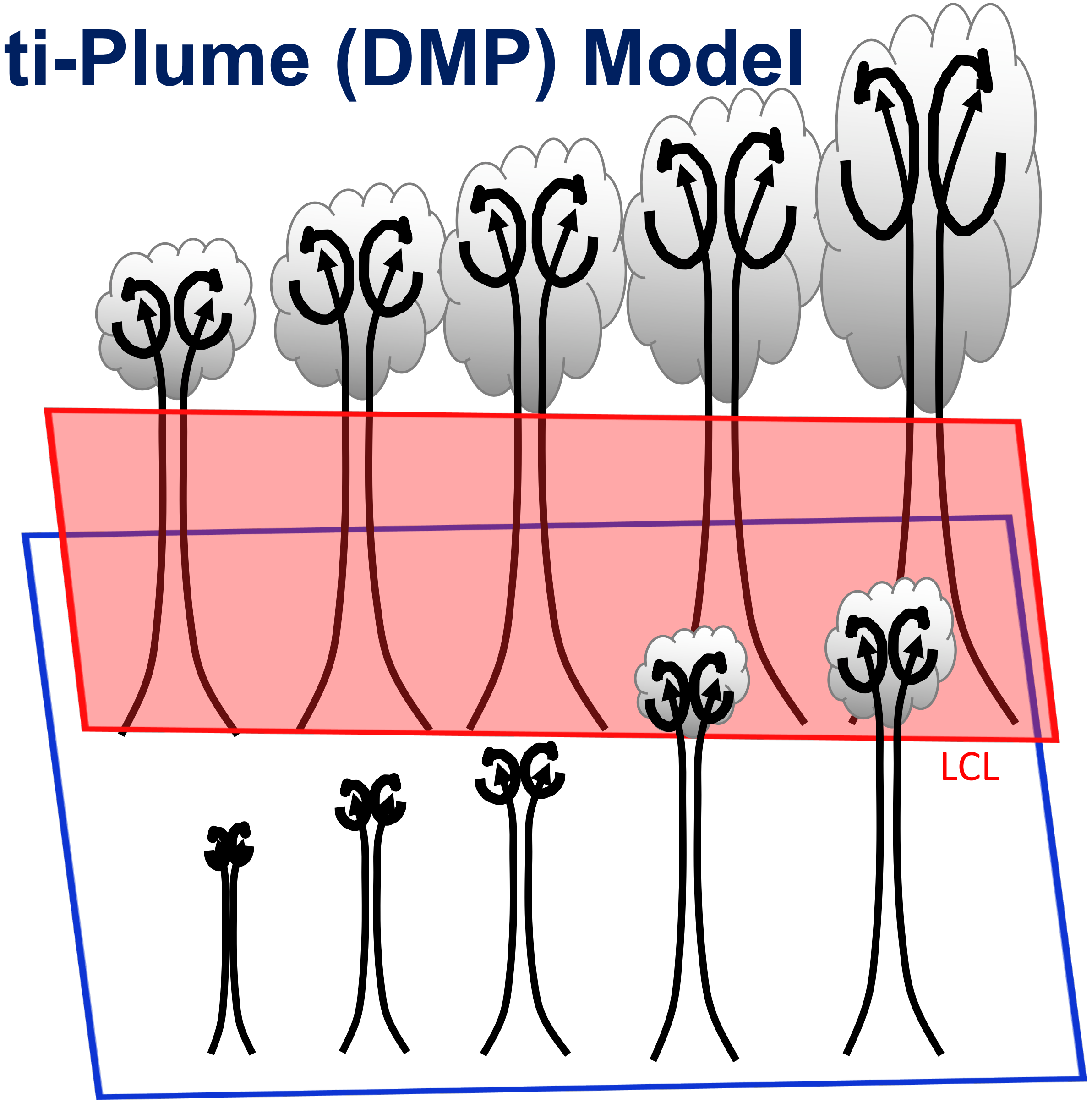
↓

Restore original q_c and q_i

MYNN-EDMF: Dynamic Multi-Plume (DMP) Model

An explicit representation of turbulent transport associated with convective plumes of various sizes, following **Neggers (2015, JAMES)** and **Suselj et al. (2013, JAS)**.

- Total maximum number of plumes possible in a single column: 10.
- Diameters (ℓ): 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1000 m.
- Lateral entrainment varies for each plume $\propto (w\ell)^{-1}$.
- Plumes condense only if they surpass the lifting condensation level (LCL).
- Plumes are only active when:
  - Superadiabatic in lowest 50 m.
  - Positive surface heat flux
- Plume number control:
  - Width of largest plume < MIN(1.2*∆x, 1000)
  - Width of largest plume < MIN(PBLH, 1000)
  - Width of largest plume < MIN(cloud ceiling height, 1000)



More info: Olson, Joseph B., Jaymes S. Kenyon, Wayne M. Angevine, John M . Brown, Mariusz Pagowski, and Kay Sušelj, 2019: A Description of the MYNN-EDMF Scheme and the Coupling to Other Components in WRF–ARW. NOAA Technical Memorandum OAR GSD, 61, pp. 37, https://doi.org/10.25923/n9wm-be49.

Chaboureau and Bechtold subgrid cloud fraction: stratus & convective components

Stratus Component

The subgrid variability of the saturation deficit, s, is expressed in terms of the total water and liquid water temperature:

$$\sigma_{s-strat} = c_\sigma l \left(\bar{a}^2 \left(\frac{\partial \overline{r_w}}{\partial z}\right) - 2\bar{a}\bar{b}C_{pm}^{-1}\frac{\partial \overline{h_l}}{\partial z}\frac{\partial \overline{r_w}}{\partial z} + \bar{b}^2 C_{pm}^{-2}\left(\frac{\partial \overline{h_l}}{\partial z}\right)^2 \right)^{1/2}$$

Where c_σ is a tuning constant, l is the mixing length, and *a* and *b* are thermodynamic functions arising from the linearization of the function for the water vapor saturation mixing ratio.

Convective Component

The subgrid variability of the saturation deficit is proportional to the mass-flux, *M*:

$$\sigma_{s-conv} \approx M \frac{(s^c - s^e)}{w_* \rho_*} \approx \alpha\, M f(z/z^*)$$

Where α is a constant of proportionality (≈5E-3) and f is a vertical scaling function, set to f=$\bar{a}^{-1}$.

Combined saturation deficit variance →

$$\sigma_{s-conv} = \sqrt{\sigma_{s-strat}^2 + \sigma_{s-conv}^2}$$

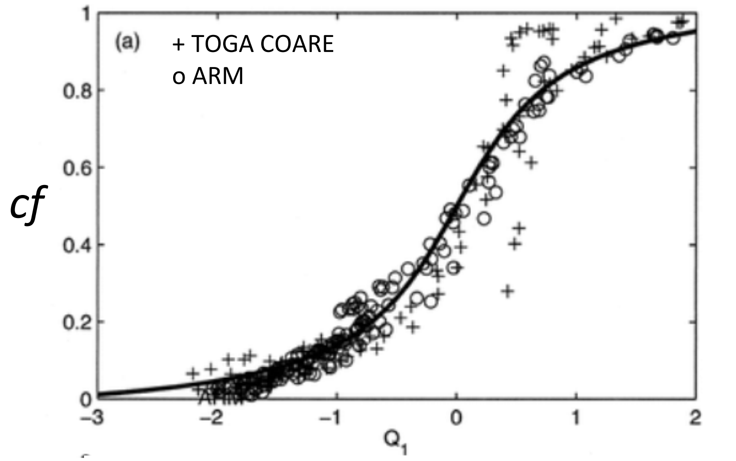
$$\bar{a} = \left(1 + L \frac{\partial r_{sat}(T_l)}{\partial T} \Big/ C_{pm}\right)^{-1} \qquad \bar{b} = \bar{a}\frac{\partial r_{sat}(T_l)}{\partial T}$$

Normalized saturation deficit →

$$Q_1 = \bar{a}(\overline{r_w} - r_{sat}(\overline{T_l}))/\sigma_{s-x}$$

Subgrid cloud fraction →

$$cf = MAX\{0, MIN[1, 0.5 + 0.36ATAN(1.55Q_1)]\}$$



Taken from Chaboureau and Becthold (2002, JAS)