An Overview of the MYNN-EDMF Turbulence Scheme in the RAP/HRRR Forecast Systems

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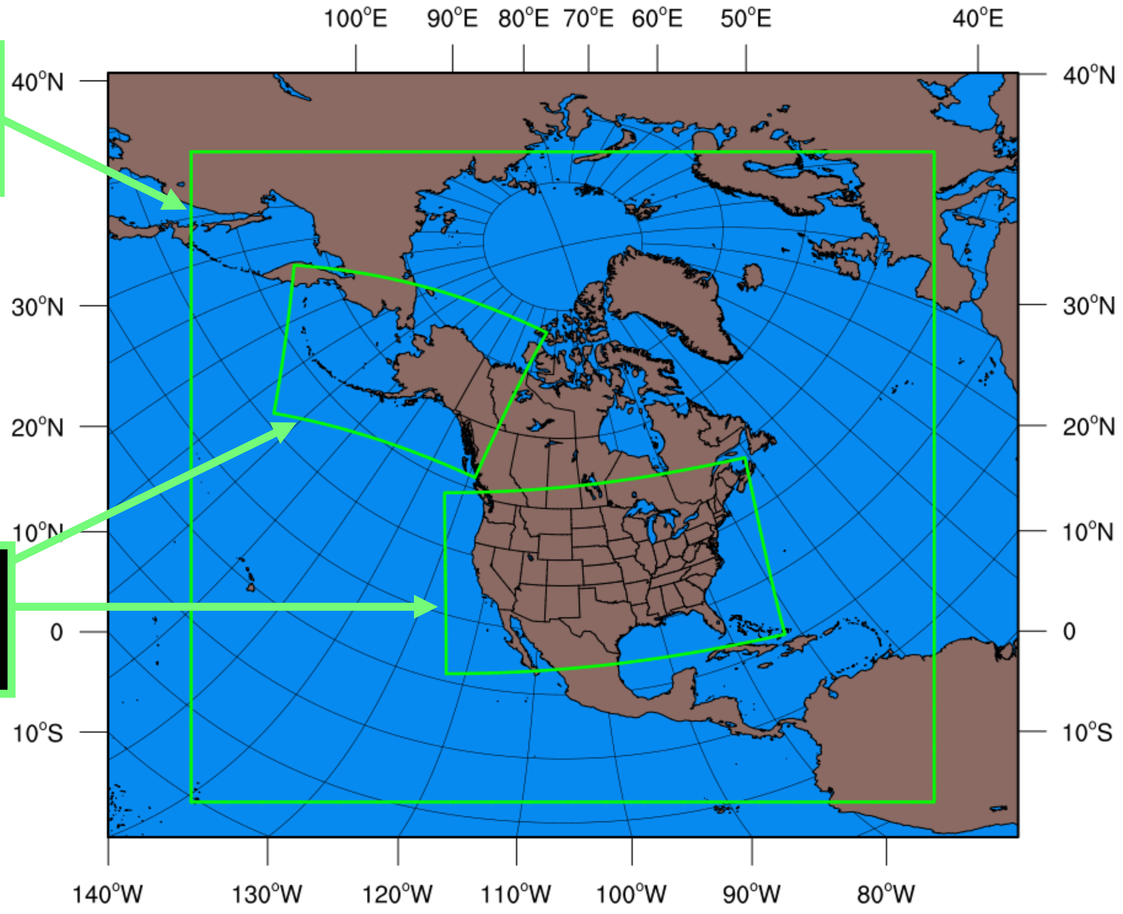
The MYNN-EDMF is the turbulence scheme in the operational RAP/HRRR Model Forecast Systems

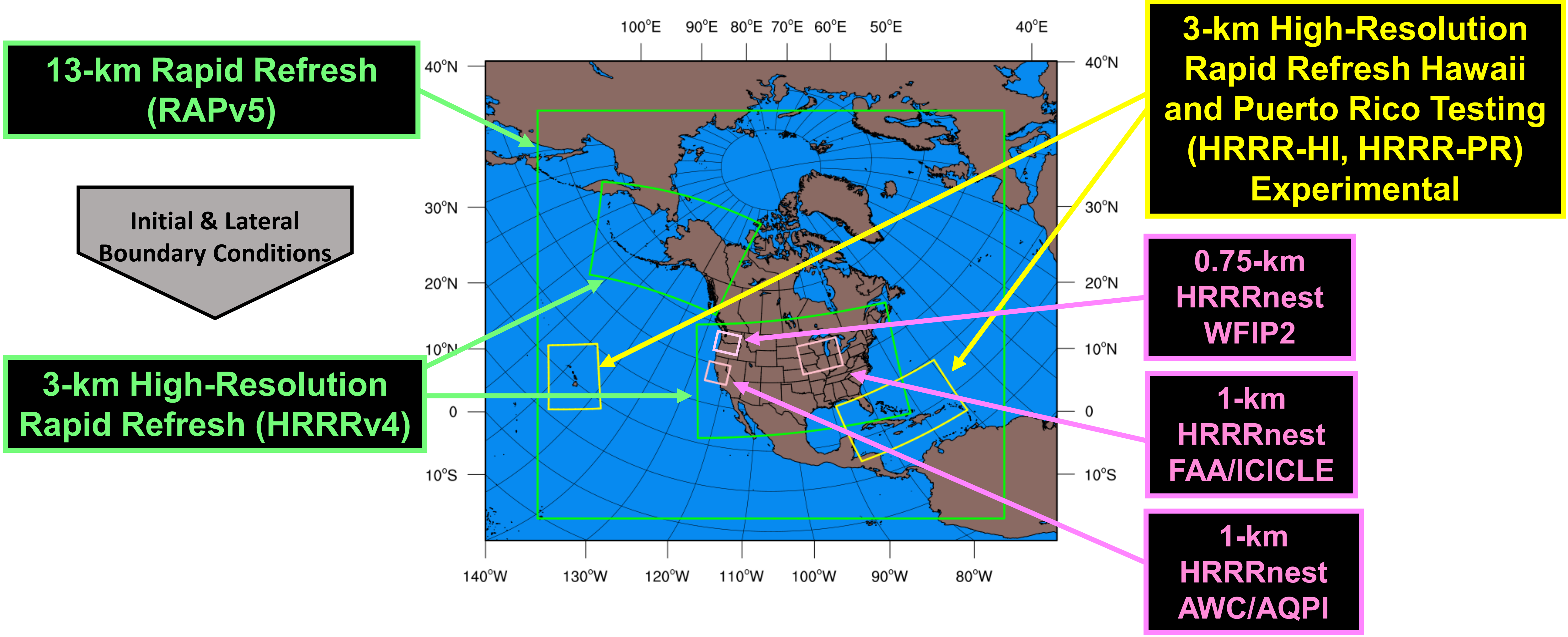
13-km Rapid Refresh (RAPv5)

Initial & Lateral Boundary Conditions

3-km High-Resolution Rapid Refresh (HRRRv4)



As well as the RAP/HRRR experimental products



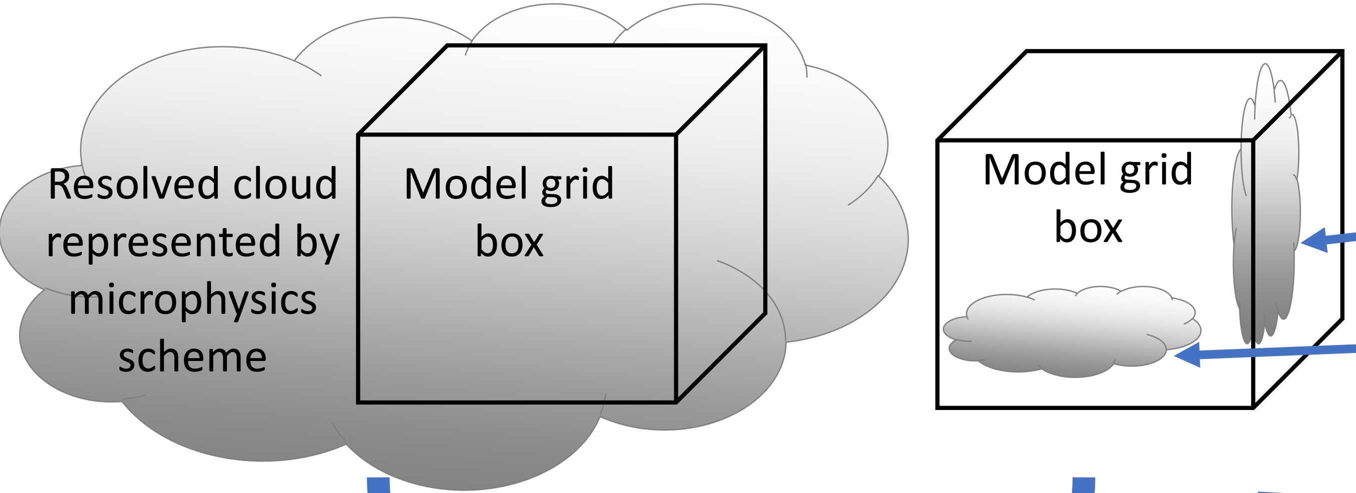
An Overview of the MYNN-EDMF Turbulence Scheme

- **Implemented into WRF-ARW, MPAS, and FV3 (CCPP) models.**
- **Has been used in NOAA's operational RAP and HRRR forecast systems since 2014**
- **Main features of the Mellor-Yamada-Nakanishi-Niino (MYNN) include:**
  - **Eddy Diffusivity-Mass Flux (EDMF) scheme**:

$$\overline{w'\phi} = -K\frac{\partial\bar{\phi}}{\partial z} + M(\phi_u - \bar{\phi})$$

    - **Eddy Diffusivity**: turbulent kinetic energy (**TKE**)**-based** with option to run at **level 2.5 or 3.0 closure** (level 3 has non-local counter-gradient term)
    - **Mass Flux**: Spectral multi-plume model
  - **Moist-turbulent mixing scheme**:
    - Uses θ_{li} [$= \theta - (\theta/T)(L_v/c_p)q_l - (\theta/T)(L_f/c_p)q_i$] and q_w ($= q_v + q_l + q_i$), are used as thermodynamic variables
    - Uses a cloud PDF to consistently represent **subgrid-scale (SGS) clouds,** their **impact on turbulent mixing,** and the SGS clouds are **coupled to the radiation scheme**
  - **Development regimen**:
    - tuned to a database of LES simulations
    - developed to improve key forecast objectives in the operational RAP and HRRR (case studies & cycled retrospective periods), such as PBL temperature, moisture, winds, ceilings, cloud cover, SW-down, etc
    - extensive single-column model (SCM) testing

Coupling the Mass-Flux, Eddy Diffusivity & Subgrid Clouds



Subgrid clouds represented by:

MYNN-EDMF
a) Mass-flux – Chaboureau and Bechtold (2005) convective cloud PDF.
b) Stratus cloud PDF (Chaboureau and Bechtold 2002) with modifications.

Cloud mixing ratios directly impact the:

- Mixing lengths (Teixeira and Cheinet 2003, BLM).
- TKE (via buoyancy flux, Bechtold and Siebesma 1998).
- Stability functions, $S_{h,m}$ (via buoyancy flux).

$$K_{h,m} = S_{h,m}\,(2*TKE)^{1/2}\,l$$

- Condensing plumes release latent heat, causing plumes to increase mass flux ($M = a_u w$).

Diffusion Solver:

Total fluxes are sum of eddy diffusion and mass-flux:

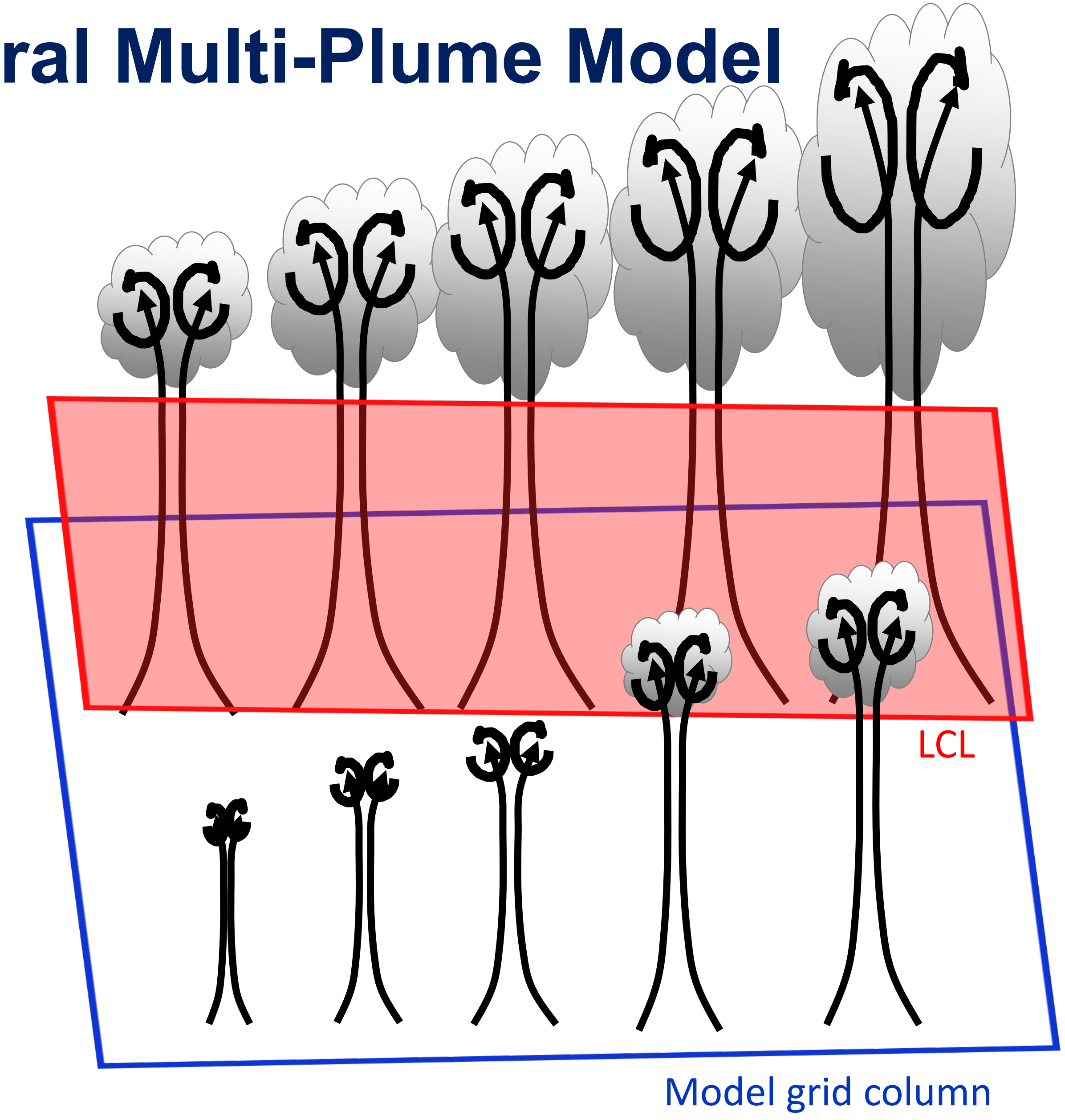
$$\overline{w'\phi} = -K\frac{\partial\bar{\phi}}{\partial z} + M(\phi_u - \bar{\phi})\ ,$$

which mixes and transports θ_{li}, u, v, q_v all cloud species, and chemical species.

MYNN-EDMF: Dynamic Spectral Multi-Plume Model

A **spectral plume model** is used to explicitly represent all plume sizes that are likely to exist in a given atmospheric state, following **Neggers (2015, JAMES)** and **Suselj et al. (2013, JAS)**.

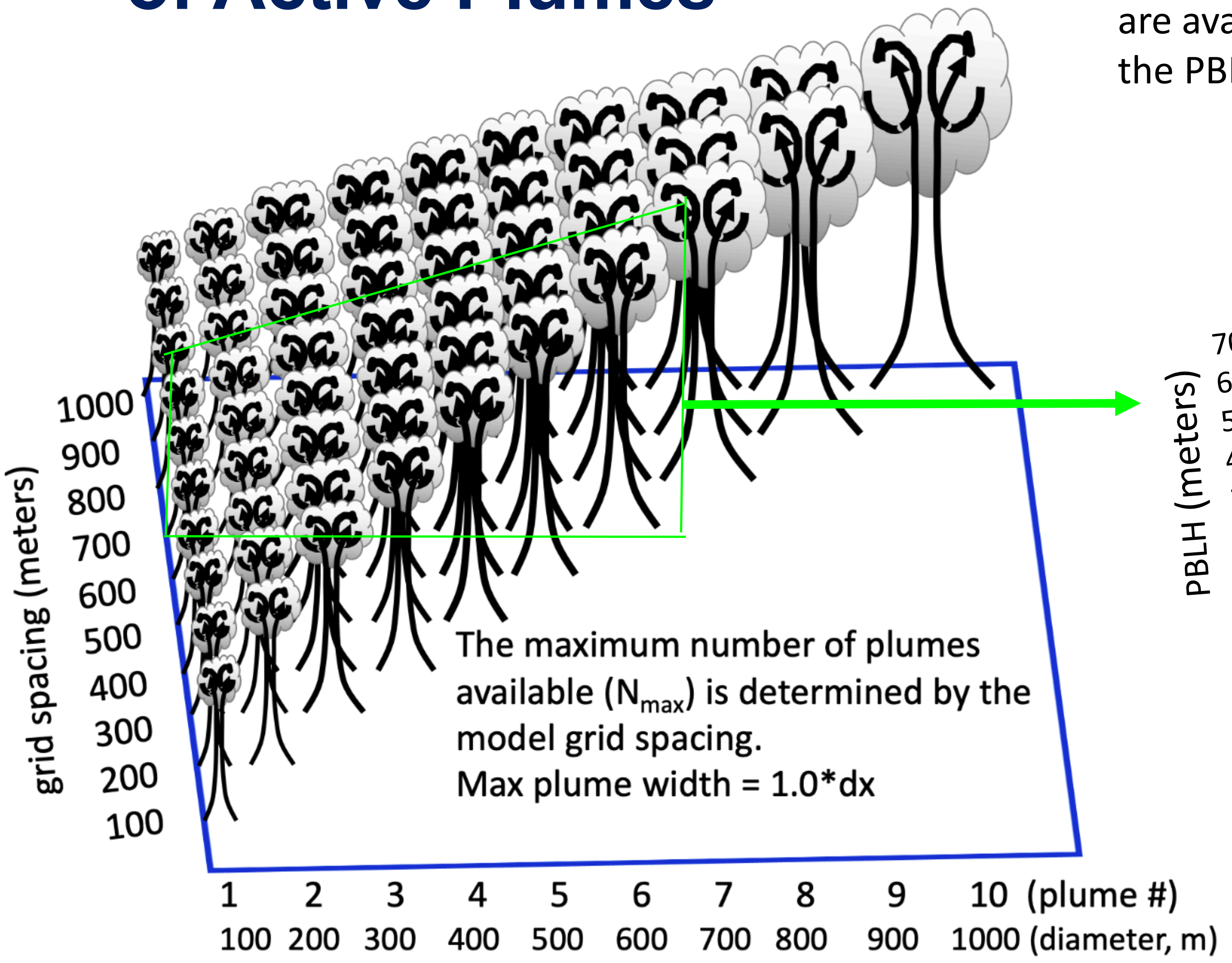
- Total maximum number of plumes possible in a single column: 10.
- Diameters (ℓ): 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1000 m.
- Max plume size is MIN(PBLH, cloud ceiling, $\triangle$x)
- Lateral entrainment varies for each plume $\propto (w\ell)^{-1}$.
- Plumes condense only if they surpass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



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.

Governing the Number of Active Plumes

The number of plumes (N) is further limited by the **PBLH.** For example, at dx = 700 meters, a maximum of 7 plumes are available, but the number od plumes used will grow as the PBLH grows:



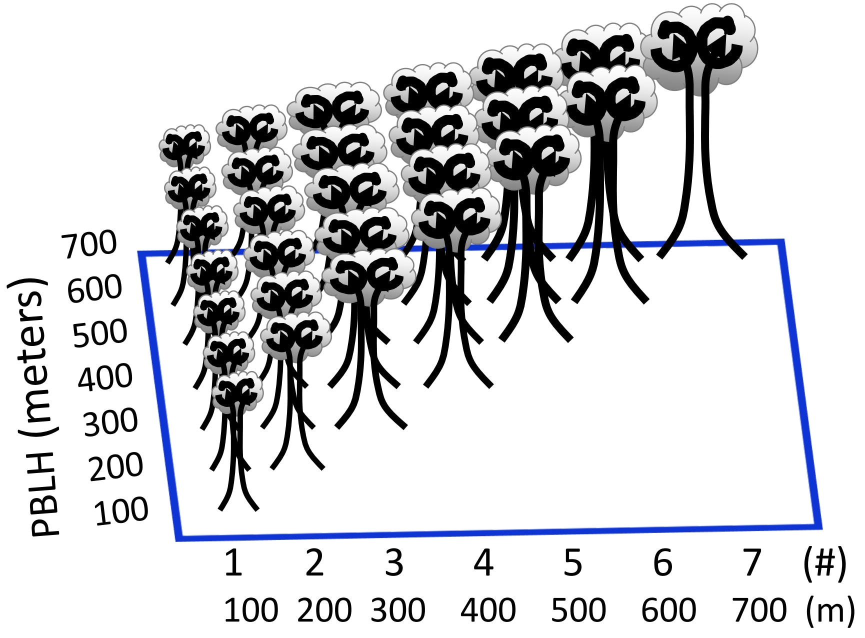


TABLE 2. The position of the scale break in the cloud size densities of the BOMEX, SCMS, and ARM case.

Case	Scale break size (m)
BOMEX	700
SCMS	1050
ARM 1500–1600 UTC	400
ARM 1600–1700 UTC	700
ARM 1700–1800 UTC	1000
ARM 1800–1900 UTC	1100
ARM 1900–2000 UTC	1250

Taken from Neggers et al. 2003, JAS

MYNN-EDMF: Individual Plume Integration

The vertical integration of each plume is performed with an entraining bulk plume model for the variables $\phi = \{\theta_{li}, q_t, u, v, \text{and TKE}\}$ using a simple entraining rising parcel:

$$\frac{\partial \phi_{u_i}}{\partial z} = -\varepsilon_i(\phi_{u_i} - \phi)$$

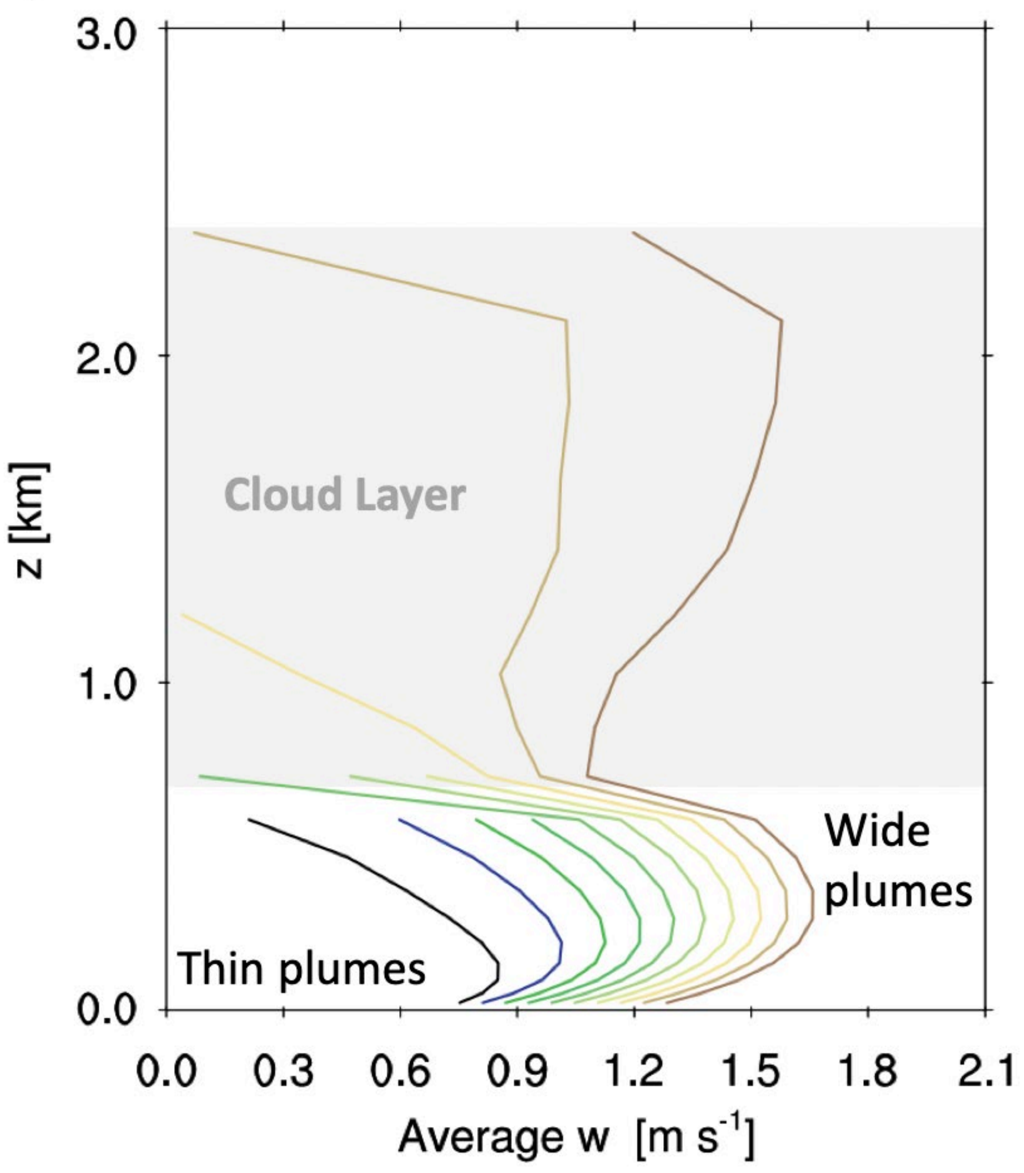
where ε_i is the fractional entrainment rate, which regulates the lateral mixing of the updraft properties, ϕ_{ui}, with the surrounding air, ϕ. The vertical velocity equation uses a form from Simpson and Wiggert (1969), with the buoyancy $B = g(\theta_{v,ui} - \theta_v)/\theta_v$ as a source term:

$$w_{u_i}\frac{\partial w_{u_i}}{\partial z} = -\varepsilon_i a w_{u_i}^2 - bB$$

The only distinguishing aspect to each plume is the entrainment rate ε_i, which is taken from Tian and Kuang (2016):

$$\varepsilon_i = \frac{C_\varepsilon}{w_i l_i}$$

Where l_i is the plume diameter, and $C_\varepsilon = 0.33$.



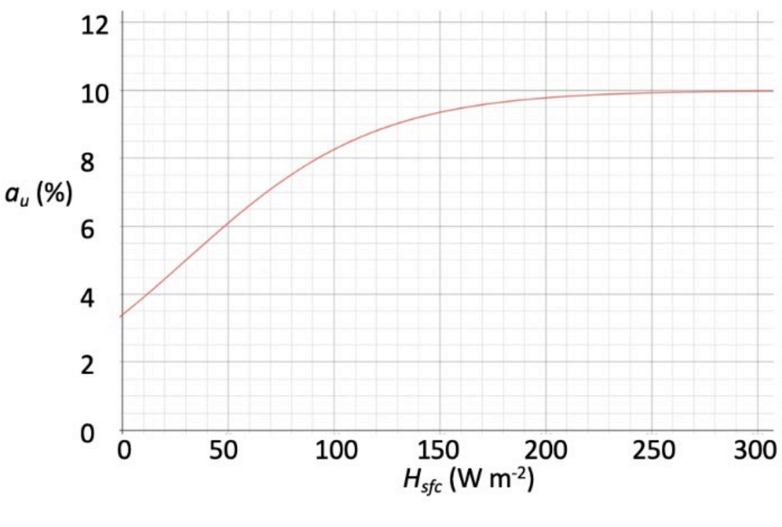
Adapted from Neggers (2015, JAMES)

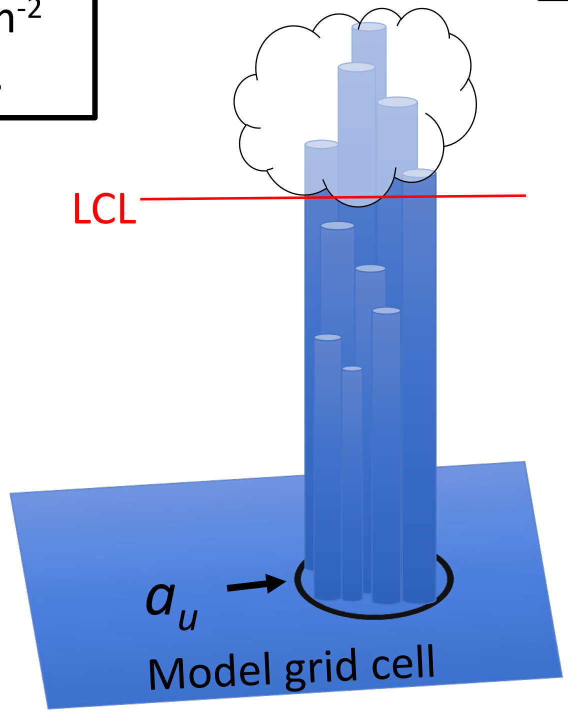
Mapping the contribution of each plume to the total fractional area

The fraction grid area assumed to contain coherent updrafts, a_u (%), is set to be proportional to the surface buoyancy flux (H_{sfc}, W m^{-2}):

$$a_u = 10.0\{0.5\tanh[(H_{sfc} - 30)/90] + .5\},$$

a_u varies between ~10% for H_{sfc} > 200 W m^{-2} and as small as 3-4% for H_{sfc} near 0 W m^{-2}.

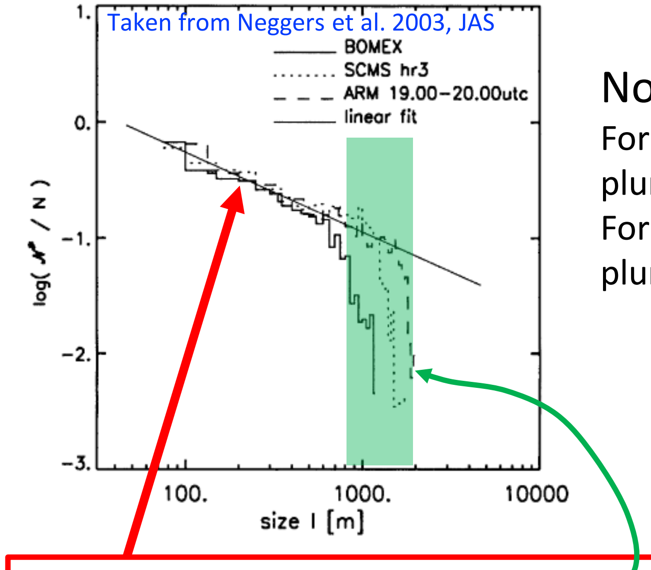




The number density, $\mathcal{N}$, of plume sizes is represented by a power law:

$$\mathcal{N}(\ell) = C\ell^d$$

where C is a constant of proportionality, ℓ is the diameter of the plume, and d is the slope of the power-law relationship. $\mathcal{N}$ effectively weights the contribution each plume size in a_u:



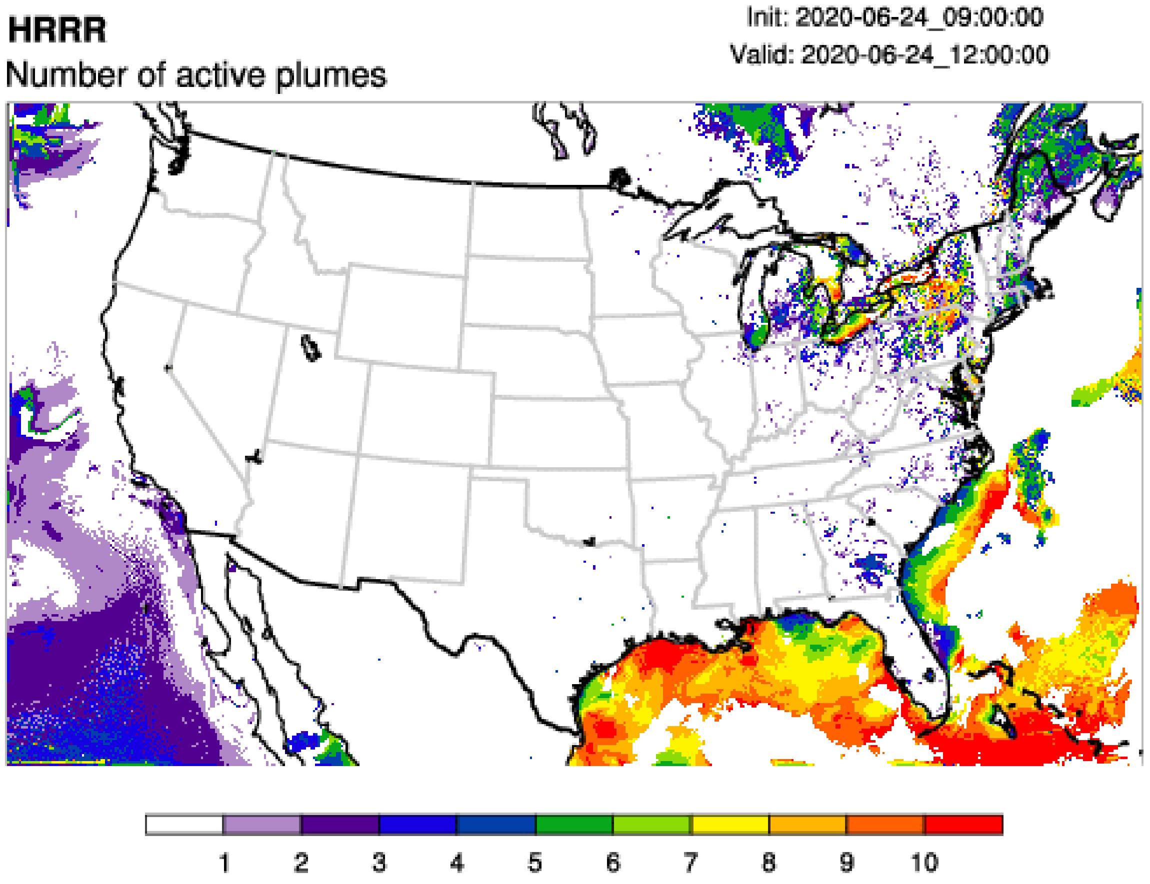
Note:
For d < -2, smaller plumes dominate a_u
For d > -2, larger plumes dominate a_u

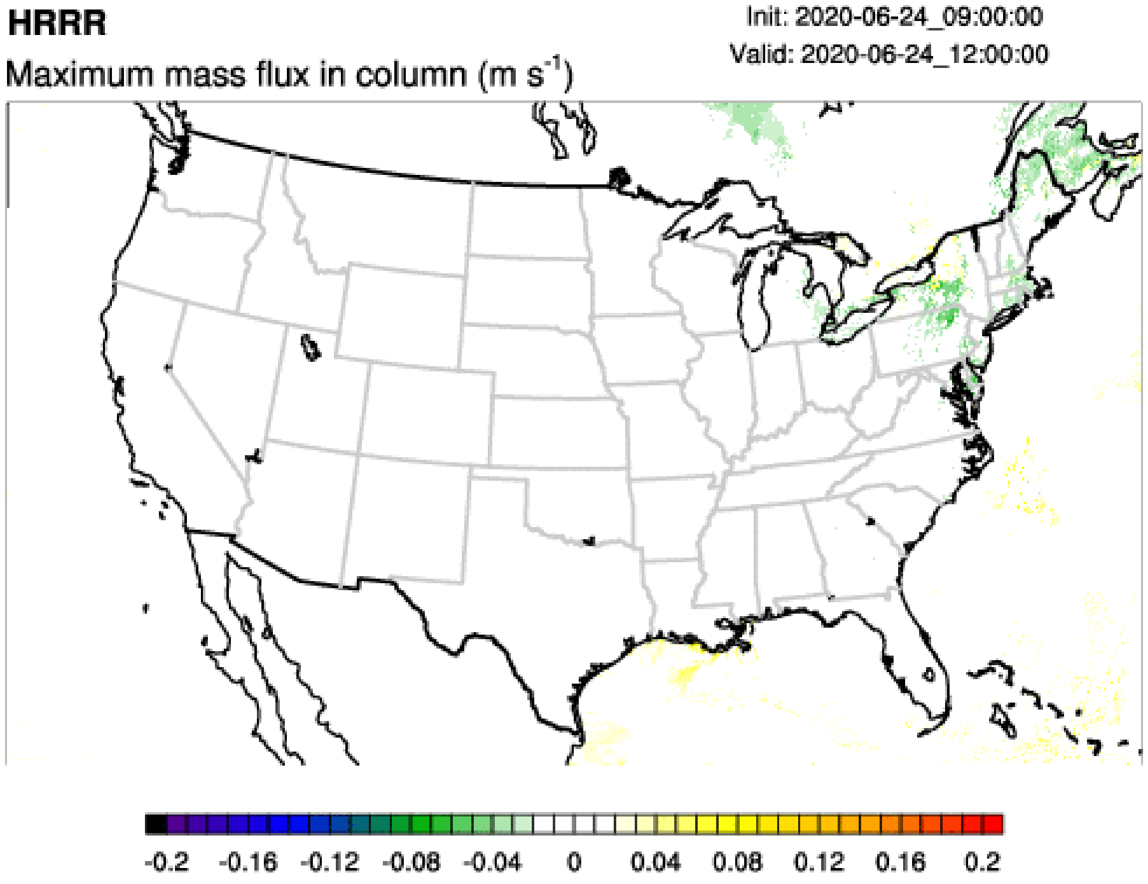
The slope (d) is -1.9 ± 0.3 for the scales below the *scale break*.

Example of Dynamic Spectral Mass-Flux Scheme

HRRR 18-hour forecast

Valid times: 12 UTC 24 June – 03 UTC 25 June 2020





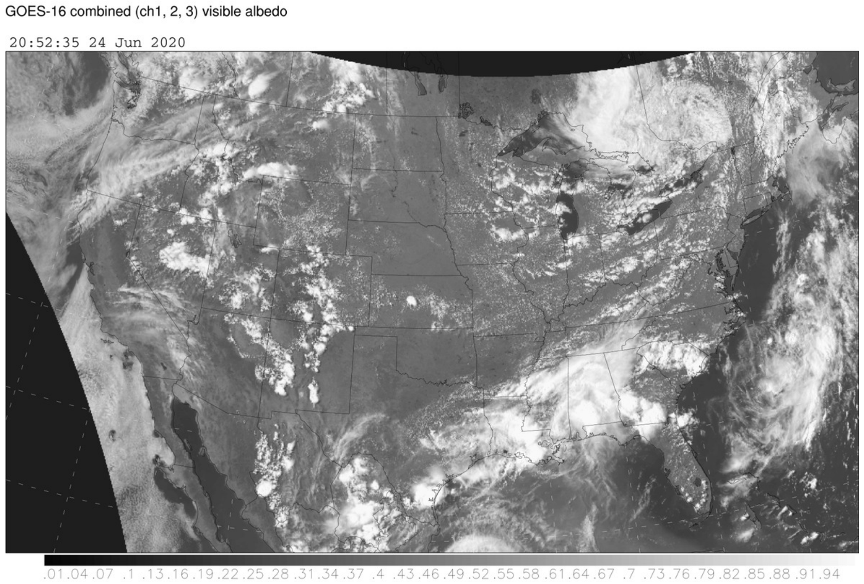
Negative = dry | Positive = condensing

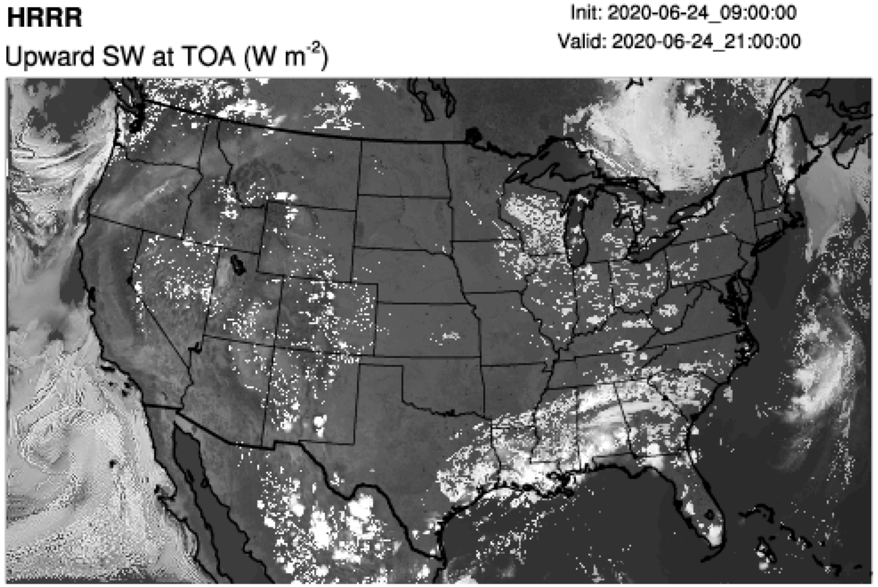
Example Comparison of SW-up at Top of Atmosphere

21 UTC 24 June 2020

Forecast hour 12, Initialized 09 UTC 24 June 2020

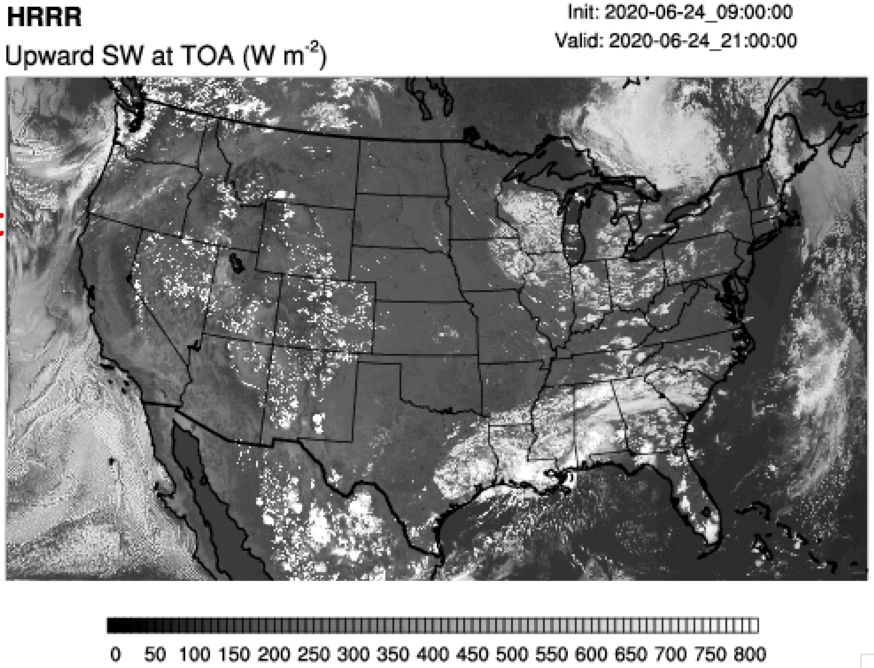
GOES-16 Satellite

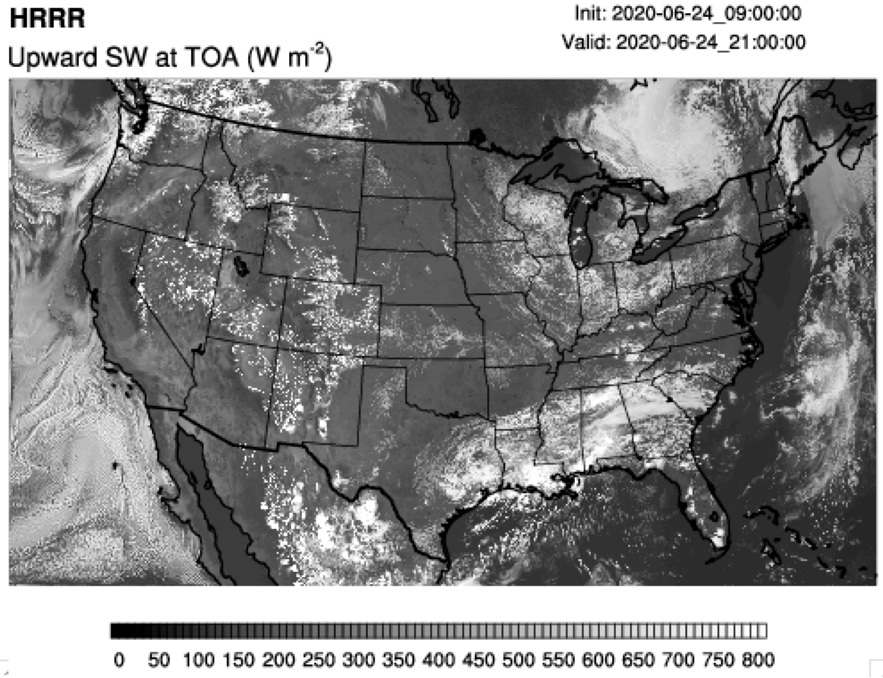




NO SGS Clouds – all clouds are from the Thompson microphysics scheme

Stratus component only

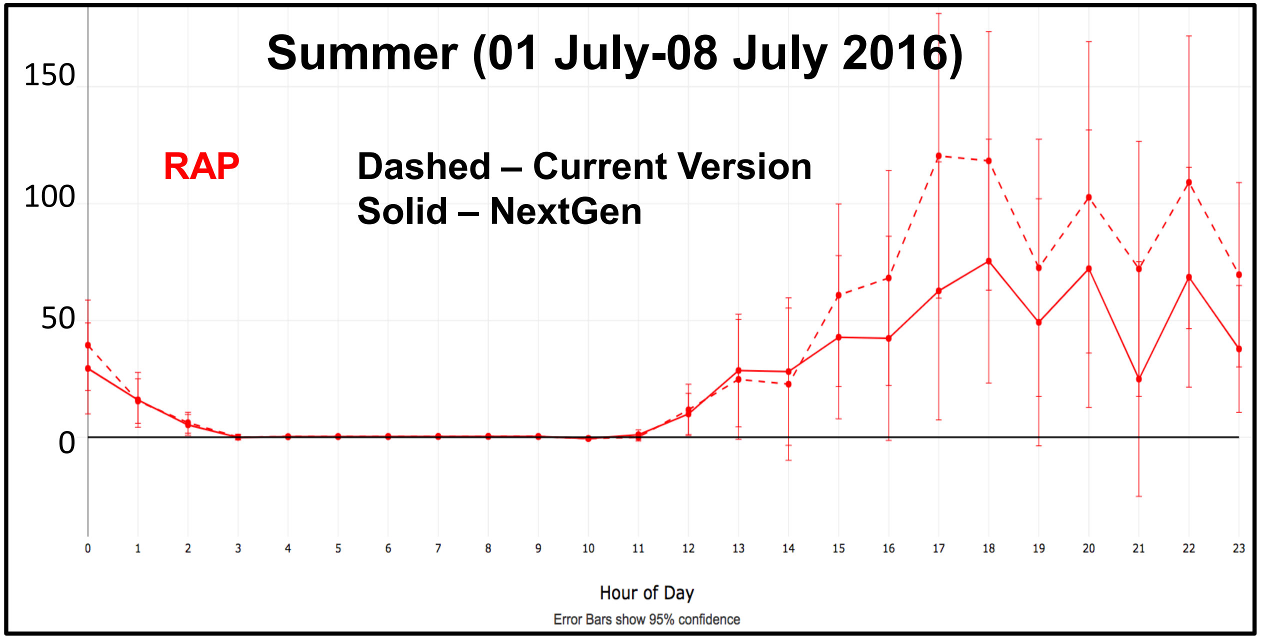


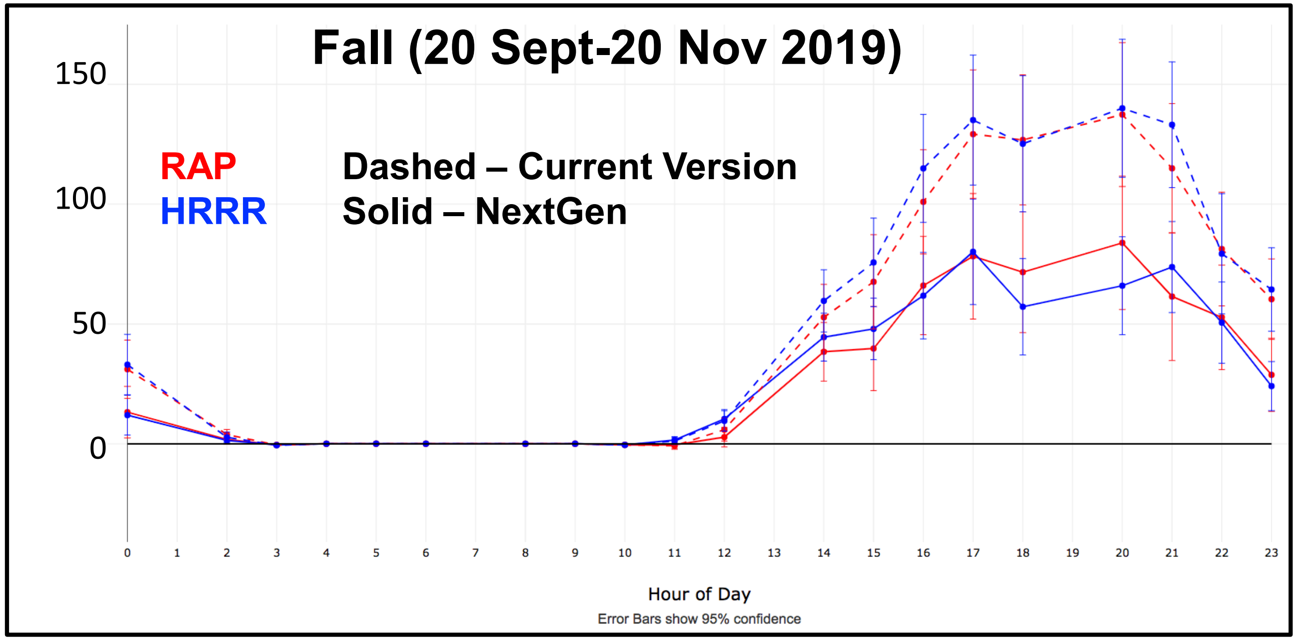


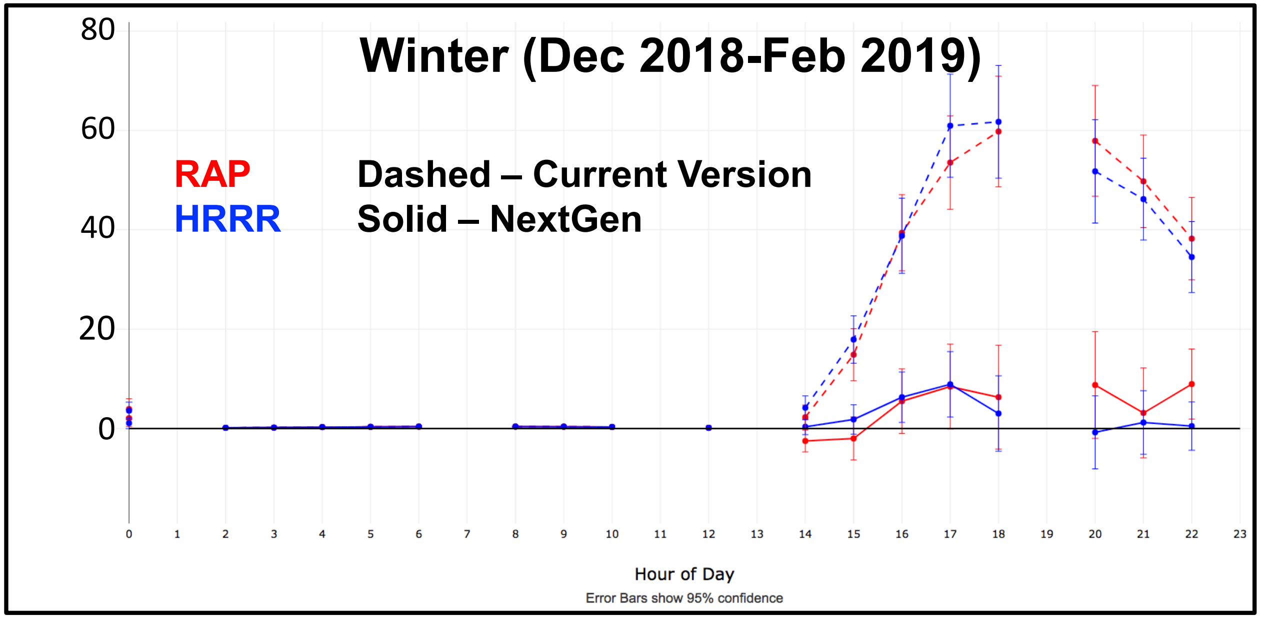
Both Stratus + Mass-Flux components

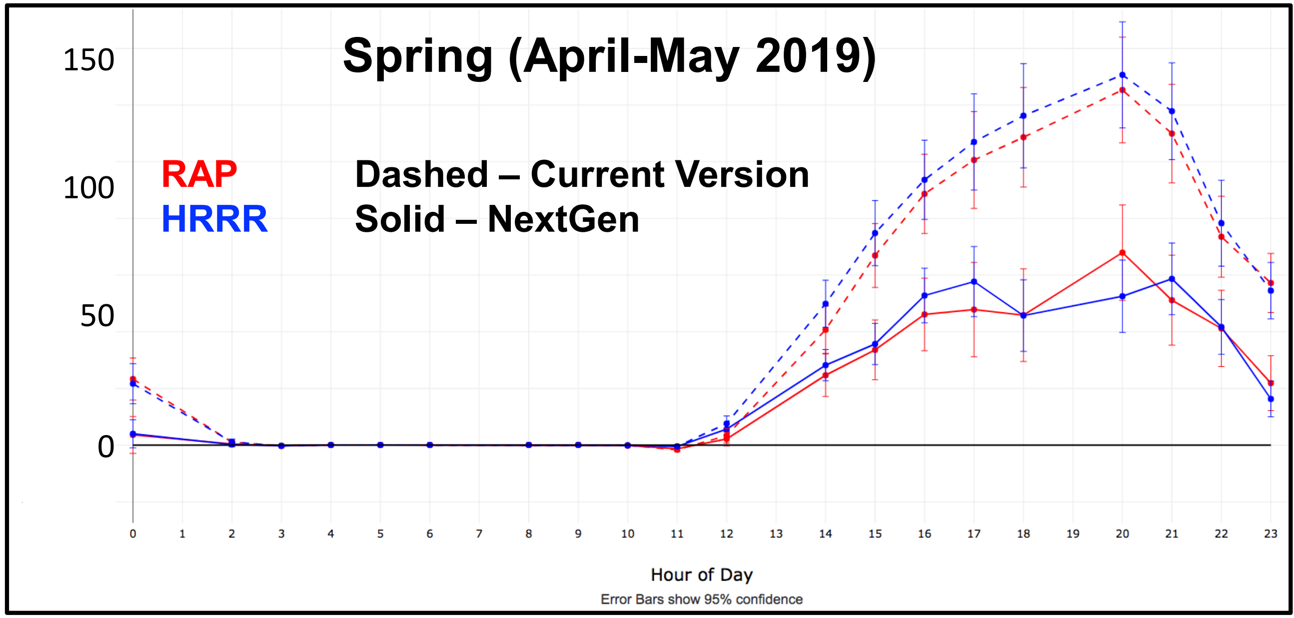
Diurnal Mean Surface GHI (W m-2) – Comparison to GML's SurfRad/SolRad data

12-h bias





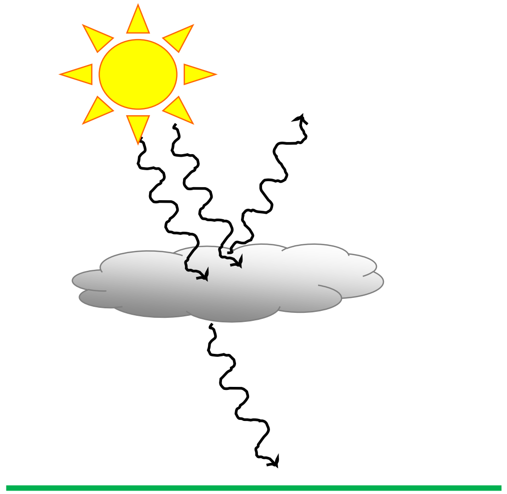




Summary

The MYNN-EDMF has been developed to:

- Handle both local (eddy diffusivity) and nonlocal mixing (mass-flux)
- Include an option to transport chemical species both locally and nonlocally
- Represent all moist-turbulent processes (short of mid- and deep convection)
- Represent all stratus and shallow cumulus for coupling to the radiation scheme



However, biases in downward shortwave radiation remain. The following observations/efforts may help resolve these biases:

- SGS Mixing ratio (q_c *and* q_i)
  - Observations of liquid water path and/or cloud depth
- SGS Cloud fraction (A_{cf})
  - Estimates of cloud cover
  - Variations in cloud fraction with height (cloud-overlap assumptions in the radiation scheme)
- SGS cloud water/ice effective radii (r_e)
- Aerosol impacts
  - AOD
  - Secondary effects are not included in SGS clouds
- Regime-dependent verification of GML's SurfRad/SolRad data
  - Need to better understand where the biases are greatest (upper-level or PBL clouds? Stratus or cumulus clouds? Mid- or deep-convective situations?)

Extra slides

Summary

The MYNN-EDMF is maturing as a complete representation of boundary-layer/cloud physics for use at all scales:

- Much improved representation of clouds (☒ Downward SW, ☒ cloud ceilings, ☒ LWP, ☒ Depth of shallow-cumulus clouds, ☒ Onset/termination of shallow cumulus)
- Much improved representation of moist-turbulent mixing (☒ Turbulence in clouds, ☒ PBLH over land)
- Proven to perform well in the stable PBL (☒ LLJs, ☒ maintenance of shallow stable layers)

High Priority Future (or Ongoing) Research:

- ☒ Tighter coupling to microphysics
- ☒ Incorporate prognostic SGS clouds(?)
- ☒ Incorporate precipitation processes
- ☒ Investigate cloud overlap/effective radii for improved radiation coupling
- ☒ Further investigate convective momentum transport
- ☒ Investigate the use of the level 3.0 version of MYNN
- ☒ Shore up the representation of turbulence in stratocumulus – investigate downdrafts
- ☒ Hurricane forecasting

Ceiling Diagnostic Algorithm in the RAP and HRRR

Legacy Diagnostic:

For each grid column, ceiling is diagnosed where:

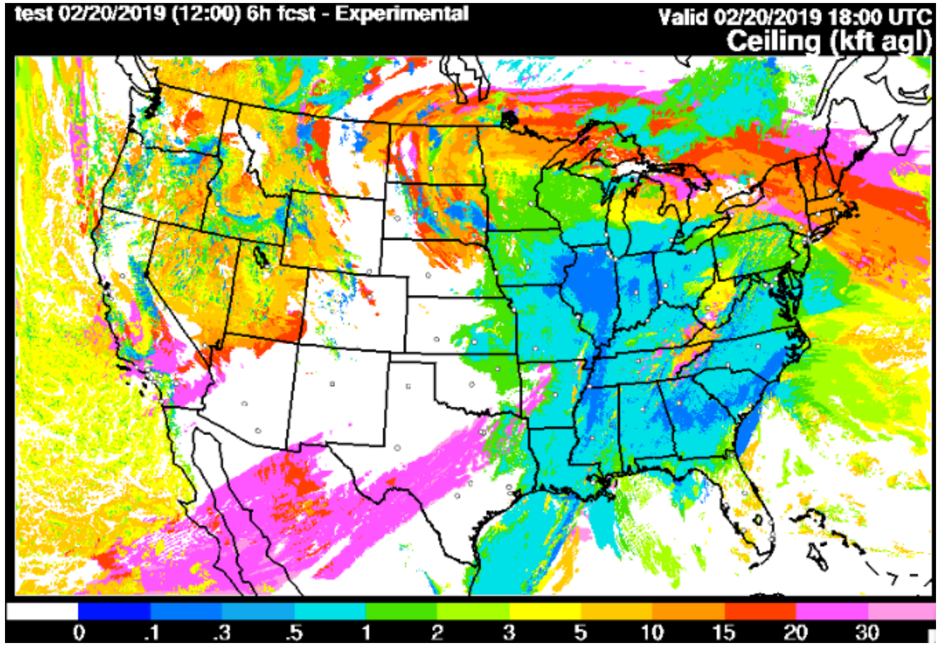
- ~~grid-scale $q_c + q_i > 10^{-6}$ kg kg^{-1}, or~~
- ~~grid-scale RH at PBL top > 95%~~

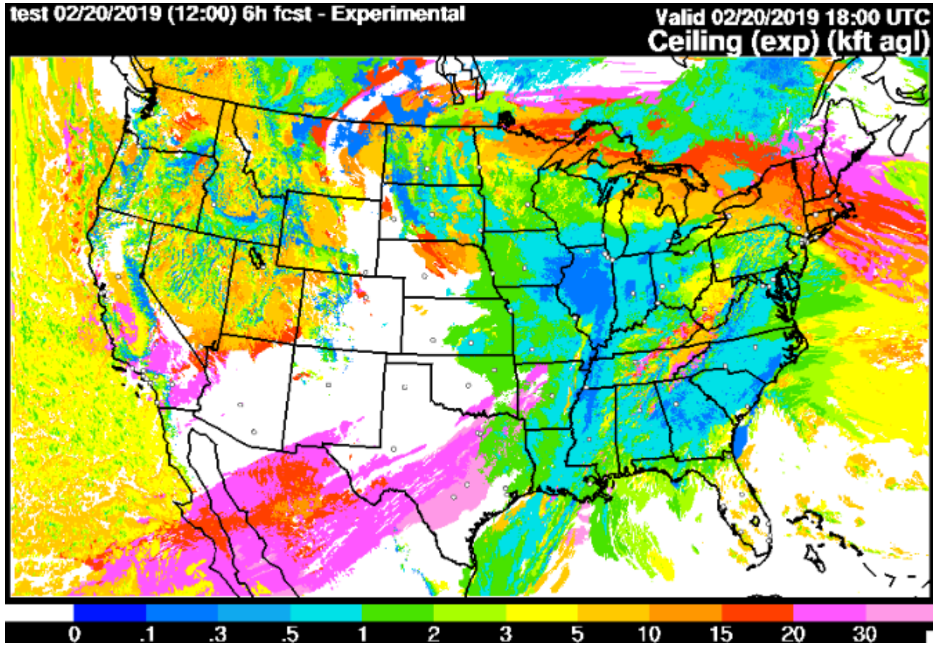
Experimental New Algorithm

New Experimental Diagnostic:

- MYNN cloud fraction > 0.5

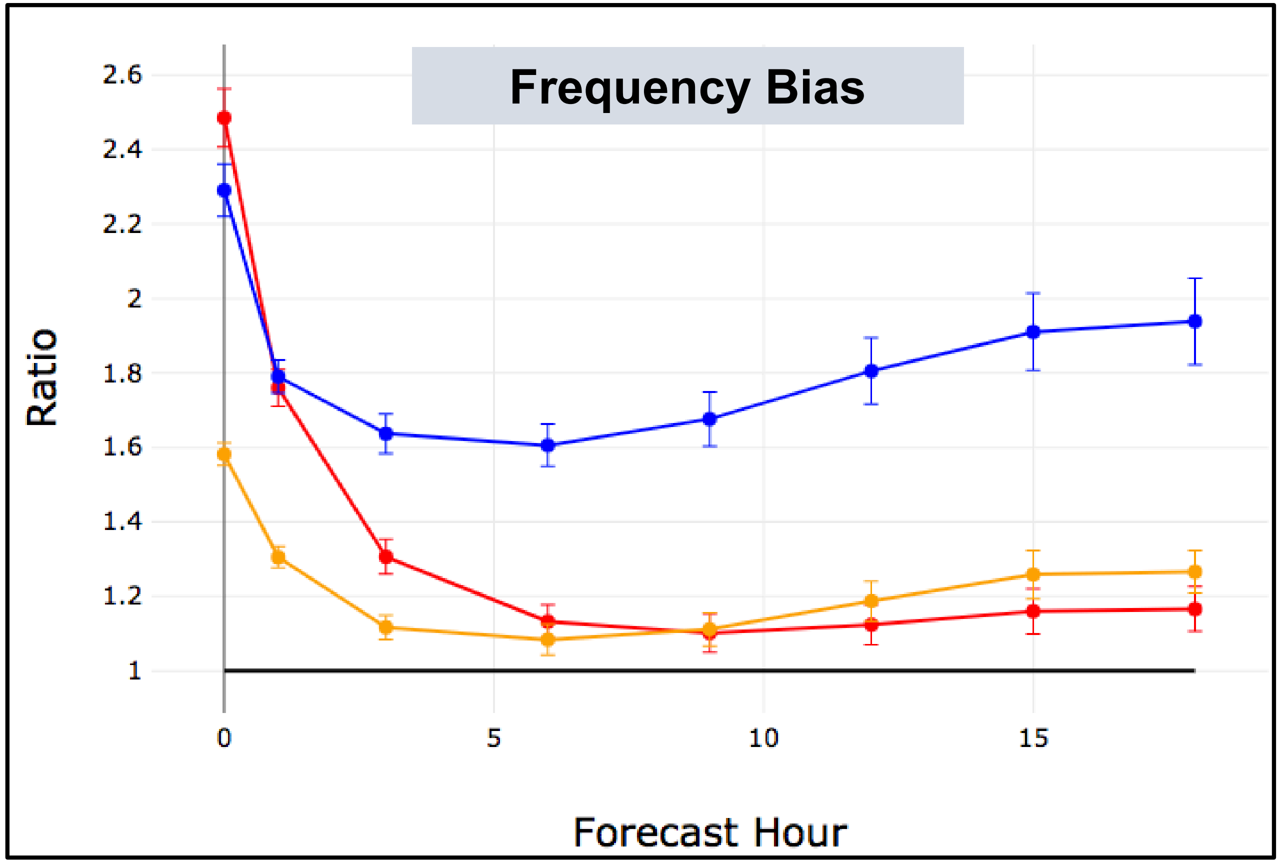
- Thin, surface-based cloud layers (< ~80 m deep) are disregarded
- If grid-scale snow is present, the diagnosed ceiling is lowered

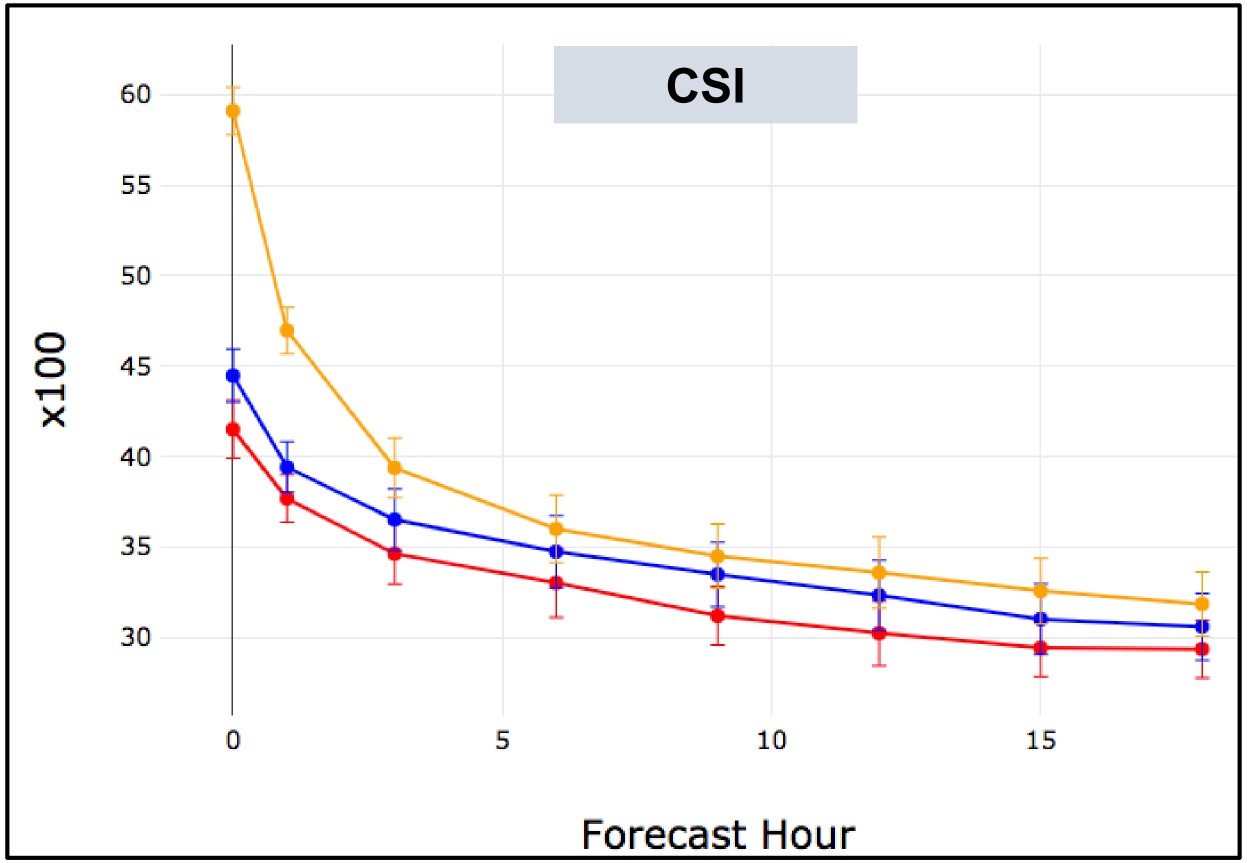




HRRR 1000-ft ceiling "dieoff" (E CONUS): 15 Mar – 5 Jun 2019

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





Features of the MYNN-EDMF

Aspect	Description (bold represents new features)
Order/Type	Eddy diffusivity/**Mass Flux (EDMF).** Eddy Diffusivity is TKE-based (*e-l*) and can run at level 2.5 or 3.0. Mass flus component is a multi-plume scheme with options to transport momentum (default) and TKE (not default).
Variables mixed/ transported	$\boldsymbol{\theta_{li}}$, *qv*, *qc*, ***qi***, *u*, *v*, with options to mix second moments (***qnc*** and ***qni***), aerosols (***qnwfa*** and ***qnifa***), and **any chemical specie**. These variables can also be transported non-locally in the mass-flux component.
Eddy Diffusivity	Mixing lengths have both local (**z-less formulation** for stable conditions) and non-local (for unstable conditions) characteristics, and a surface-stability dependent control of surface layer length scale. **Critical Richardson number has been removed for momentum**.
Additional non-local components	(1) **Dynamic multi-plume mass-flux scheme** only active in unstable conditions; (2) **Top-down diffusion linked to cloud-top radiative cooling**; (3) **explicit downdraft in the works**; (4) Counter-gradient terms for heat and moisture in level 3 mode.
Subgrid Clouds	**Chaboureau-Bechtold (2002, 2005)** stratus and convective components with **temporal decay**. **Coupled to radiation scheme with effective radii** of water droplets following Turner et al. (2007, BAMS) and for ice following Mishra et al. (2014, JGR).
Scale-adaptive	**Mixing lengths transform between mesoscale and LES forms when $\triangle$x = 500 m, while non-local components taper off between $\triangle$x = 600 and 100 m, following Honnert et al (2011). Recently modified (discussed later).**
Stochastic	**Stochastic Parameter Perturbation (SPP) has been implemented for 3 parameters (exchange coefficients K_H and K_M, subgrid clouds, and mass-flux entrainment rates).**
Notes on Coupling	**Subgrid cloud fractions, mixing ratios, and effective radii sent to radiation scheme. Option to transport chemical species.** Input forcing: surface SH and LH over land from LSM; SH and LH over water and u_* (everywhere) from surface layer scheme.
Notes on Solver	**Simultaneous semi-implicit solution in EDMF mode**; otherwise, just implicit solution when run in ED-only mode.

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:

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

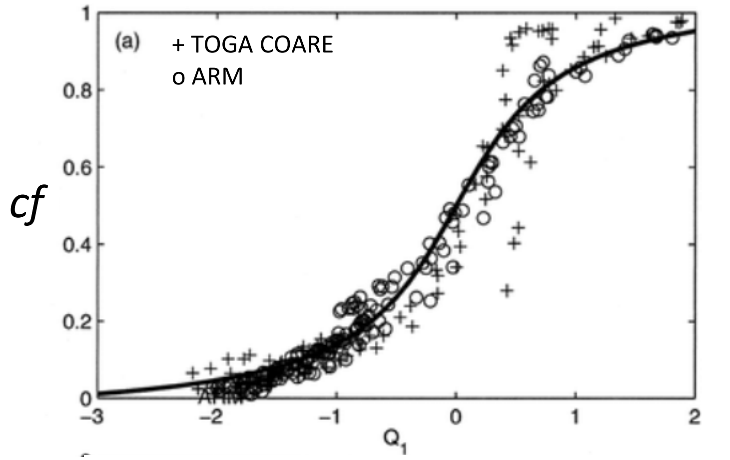
Where α is a constant of proportionality (≈5E-3) and f is a vertical scaling function, set to $f = \bar{a}^{-1}$.

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



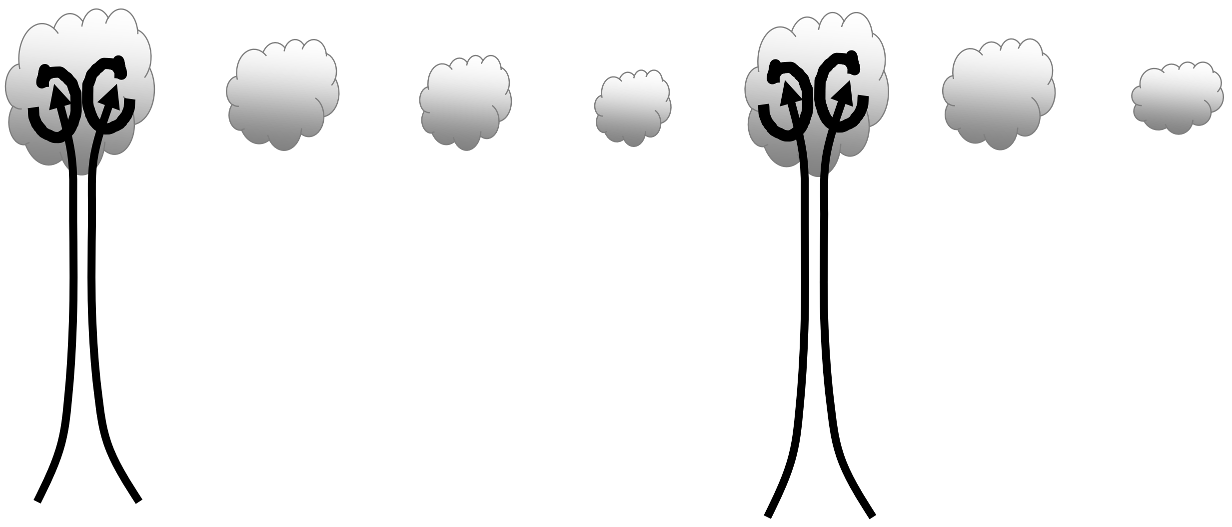
Taken from Chaboureau and Becthold (2002, JAS)

Diagnostic-Decay for Subgrid Clouds

To retain subgrid cloud fraction (*cf*) produced by the mass-flux scheme at later time steps, a diagnostic-decay was implemented:

$$cf = cf - cf_m \frac{\Delta t}{\Delta t_{eddy}}$$

, where cf_m = 0.25 and $\Delta t_{eddy} = 1800\ s$.



NOTE: Need higher rate of decay at high horizontal resolution, limited by the advective timescale, $\Delta t_{adv} = 3\Delta x/U$.

$$\Delta t_{eddy} = MIN(\Delta t_{eddy}, \Delta t_{adv})$$

Time step: n n+ Δt n+2Δt n+3Δt n+4Δt n+5Δt n+6Δt …. etc

Mass-flux scheme is triggered

Mass-flux scheme is re-triggered, *cf* is over-written if $cf_{new} > cf_{old}$