Implementation of an implicit-explicit vertical advection scheme in WRF-ARW for CAM NWP

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Outline

- Why is this important?
- Current approaches to improve efficiency
- Shchepetkin's solution

- Simple examples
- 27 April 2011 tests
- Timings and conclusions

Motivation

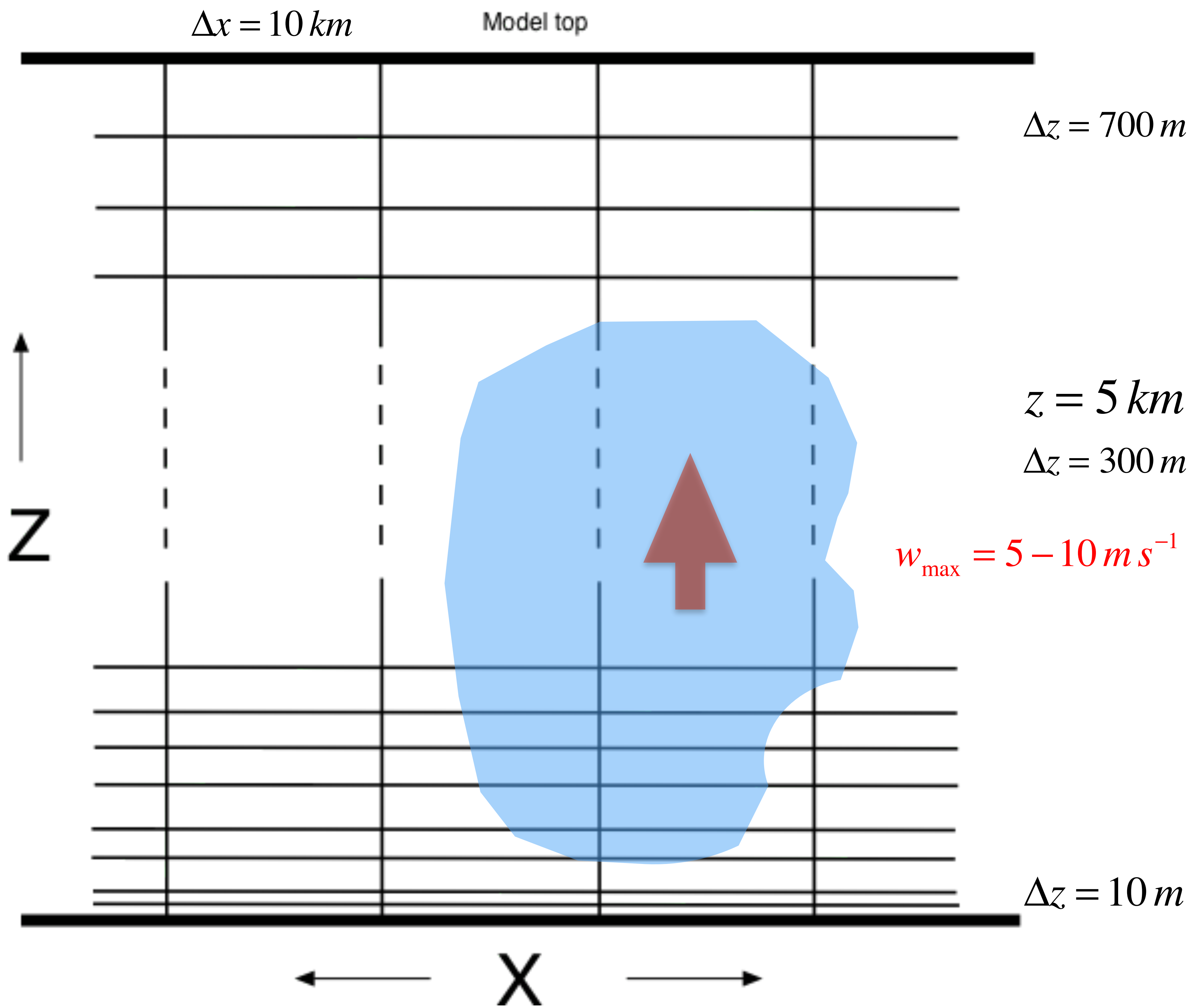
Mesoscale model resolution

$$CFL_h = \frac{u\Delta t}{\Delta x} \sim 1$$

$$w \ll u$$

$$CFL_z = \frac{w\Delta t}{\Delta z} \ll 1$$

time step not impacted by convective updrafts



Motivation

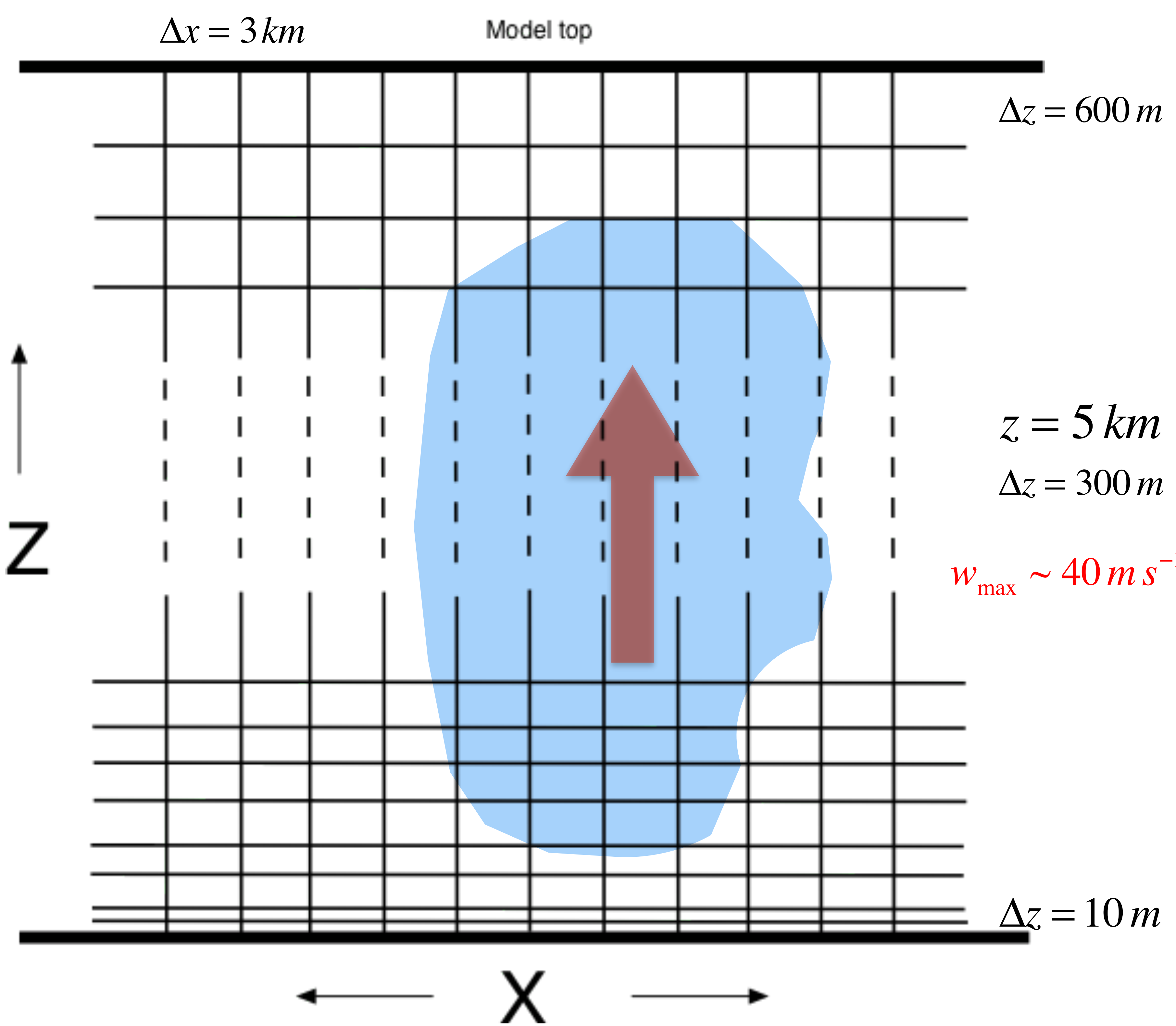
CAM model resolution

$$CFL_h = \frac{u\Delta t}{\Delta x} < 1$$

$$w \approx u$$

$$CFL_z = \frac{w\Delta t}{\Delta z} \sim 1$$

time step now controlled by vertical CFL from convective updrafts



Current Status

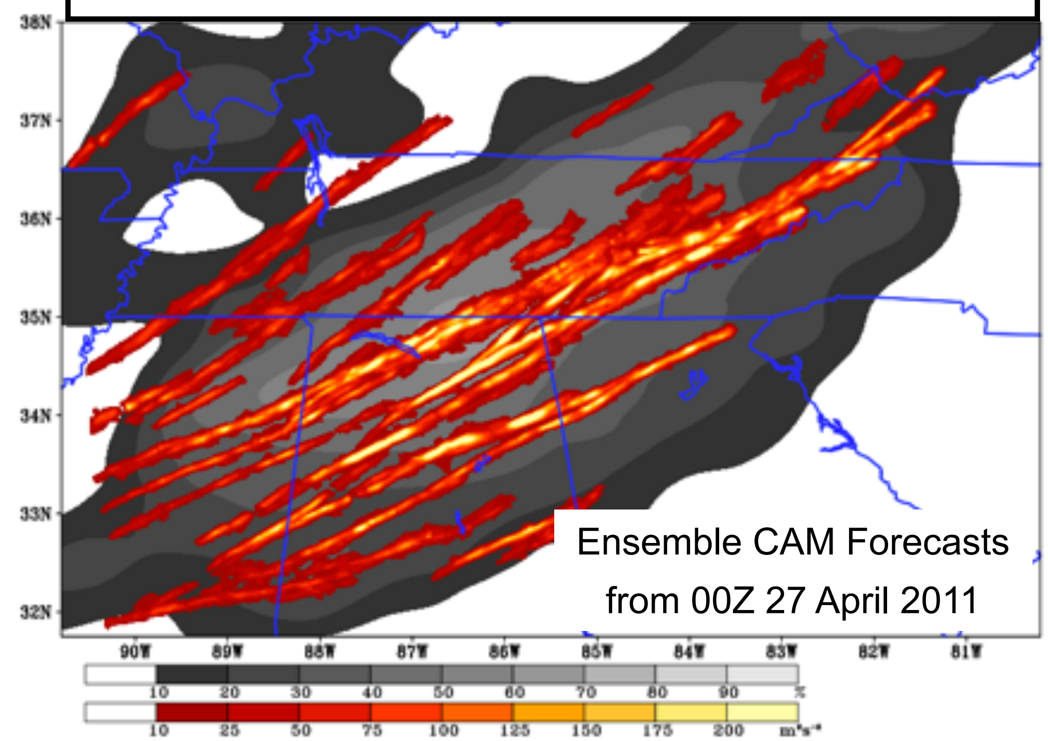
- Current CAMs time steps are limited by *W-CFL*
  - e.g., HRRR config: dx = dy = 3km, 60 levels
  - Anisotropic grids - aspect ratios dx/dz > 5
  - Supercells: max W's ~40 m/s [**yes, even at 3 km res!**]
    - a few grid points **limit** the time step for entire domain!
  - **For operational NWP - even small speedups (5-10%) can be important!**

- Strategies currently available to increase time step in WRF
  - W-Filter: Rayleigh damping the vertical velocity when w-cfl > 1.2
  - W-Filter: **Limit the latent heat release term from physics (MP_TEND)**

Test Case

- 00Z 27 April 2011: Supercell tornado outbreak in southern US
- Extremely strong convection - good test case!!
- **Stability test: 24 hour integration**
  - **~02Z: Strong convection in N and E Texas and LA**
  - After 18Z: Large number of supercells develop in MS and move into N AL.
- **Model configuration**
  - 1601x1201 (3 km res) with 51 vertical levels
  - Thompson microphysics (non-aerosol aware)
  - MYNN
  - Initialized from NAM

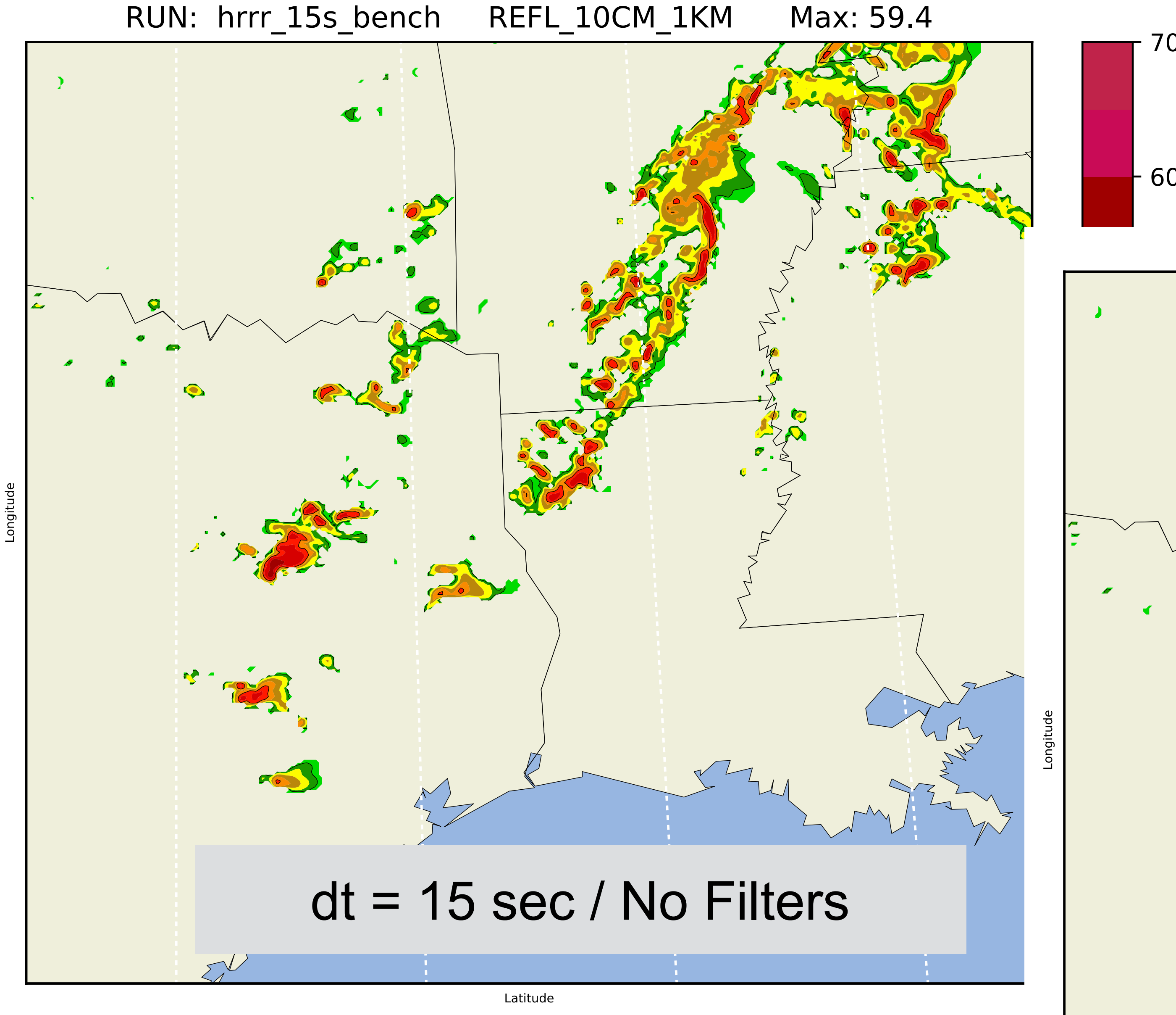
24 hour ensemble fcst of UH

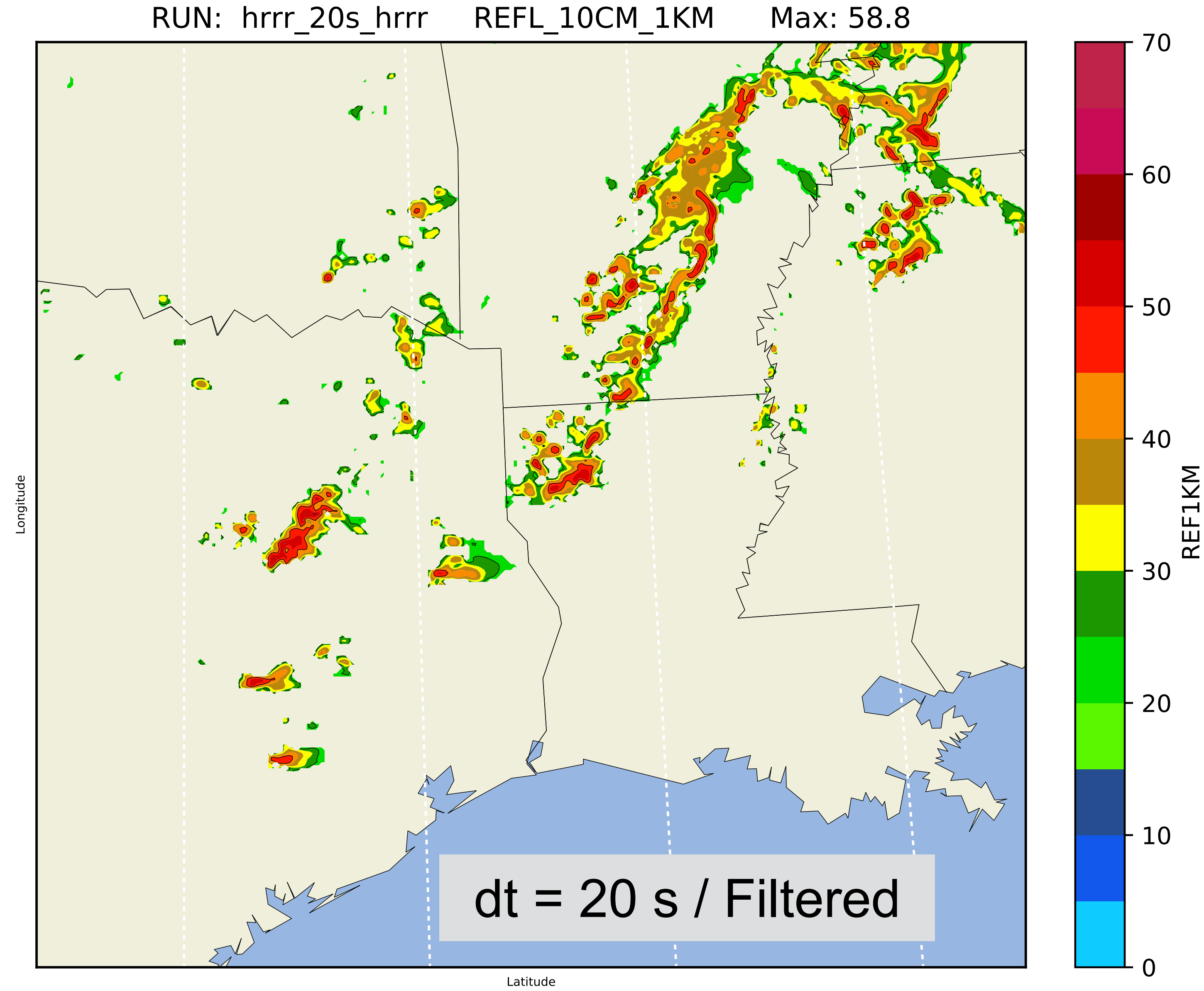


Impact of Filters…

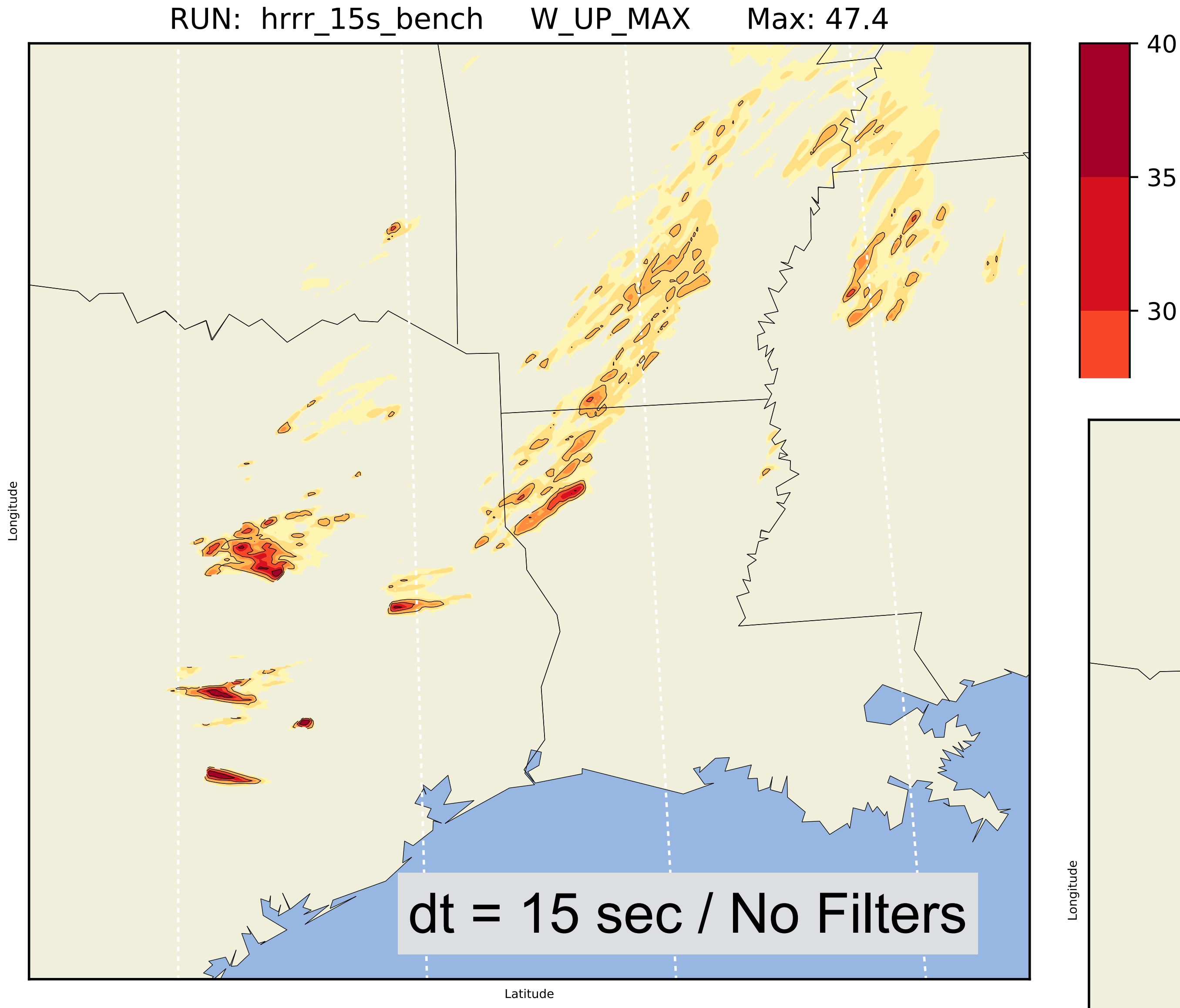
- Test 27 April 2011 case using a HRRR-like configurations.
- No vertical velocity filters (no w_damp, no mp_tend_lim)
  - Maximum stable time step: dt_{max} = 15 sec
  - Max W > 45 m/s
- Both vertical velocity filters on: (w_damp on, mp_tend_lim ~ 0.07)
  - Maximum stable time step: dt_{max} = 20 sec
  - Max W < 30 m/s, reduction in most intense storms by ~40%
- Vertical transport of water substance and latent heat are also reduced!
- This approach is currently used in HRRRv3 (but hopefully not in v4!)

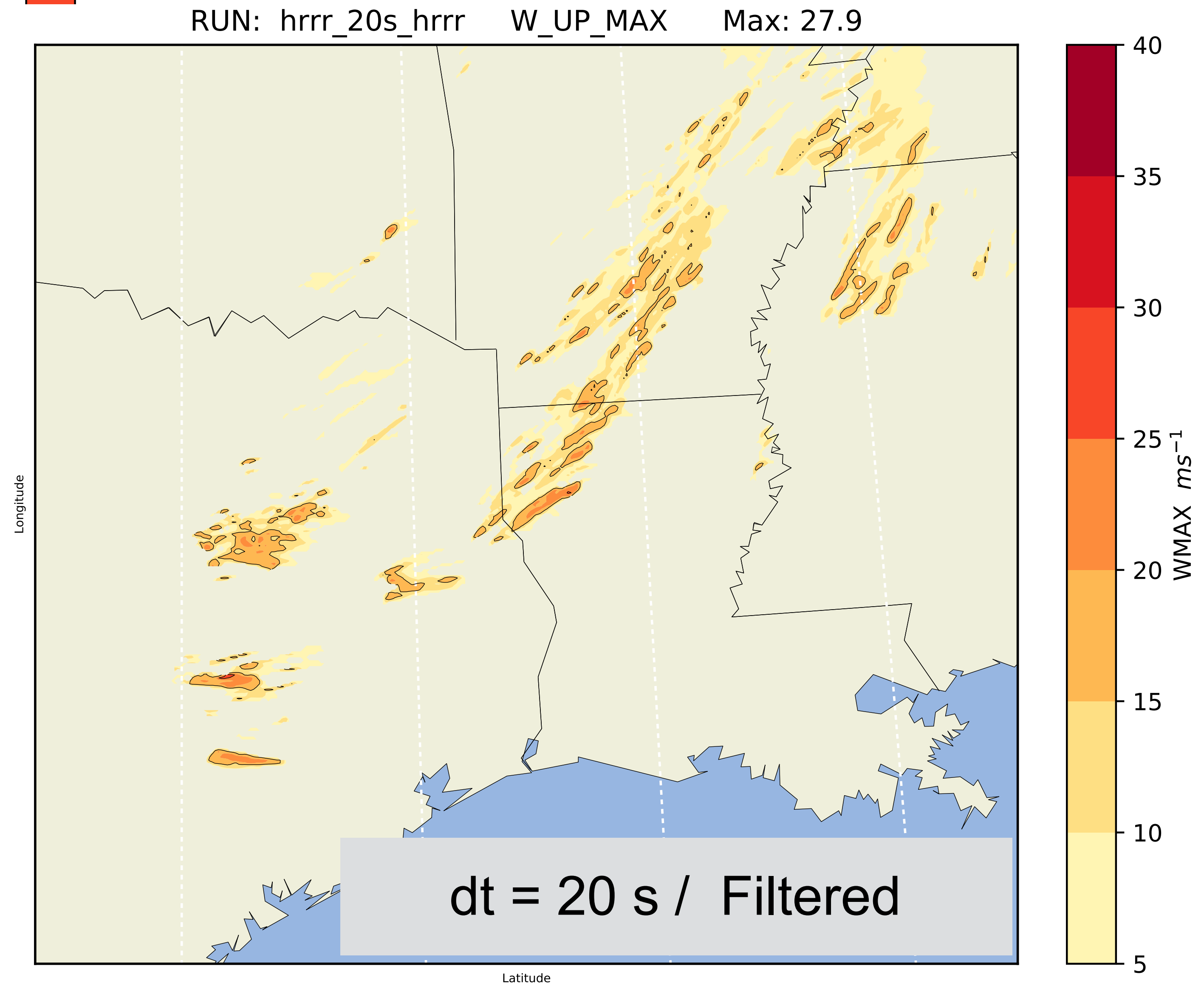
27 April 03Z 1 KM REF





27 April 03Z 1 hour Max Updraft





Spring Exp (2017) CAM Updraft Statistics

Max Column W for hours 18-26 (21 days)

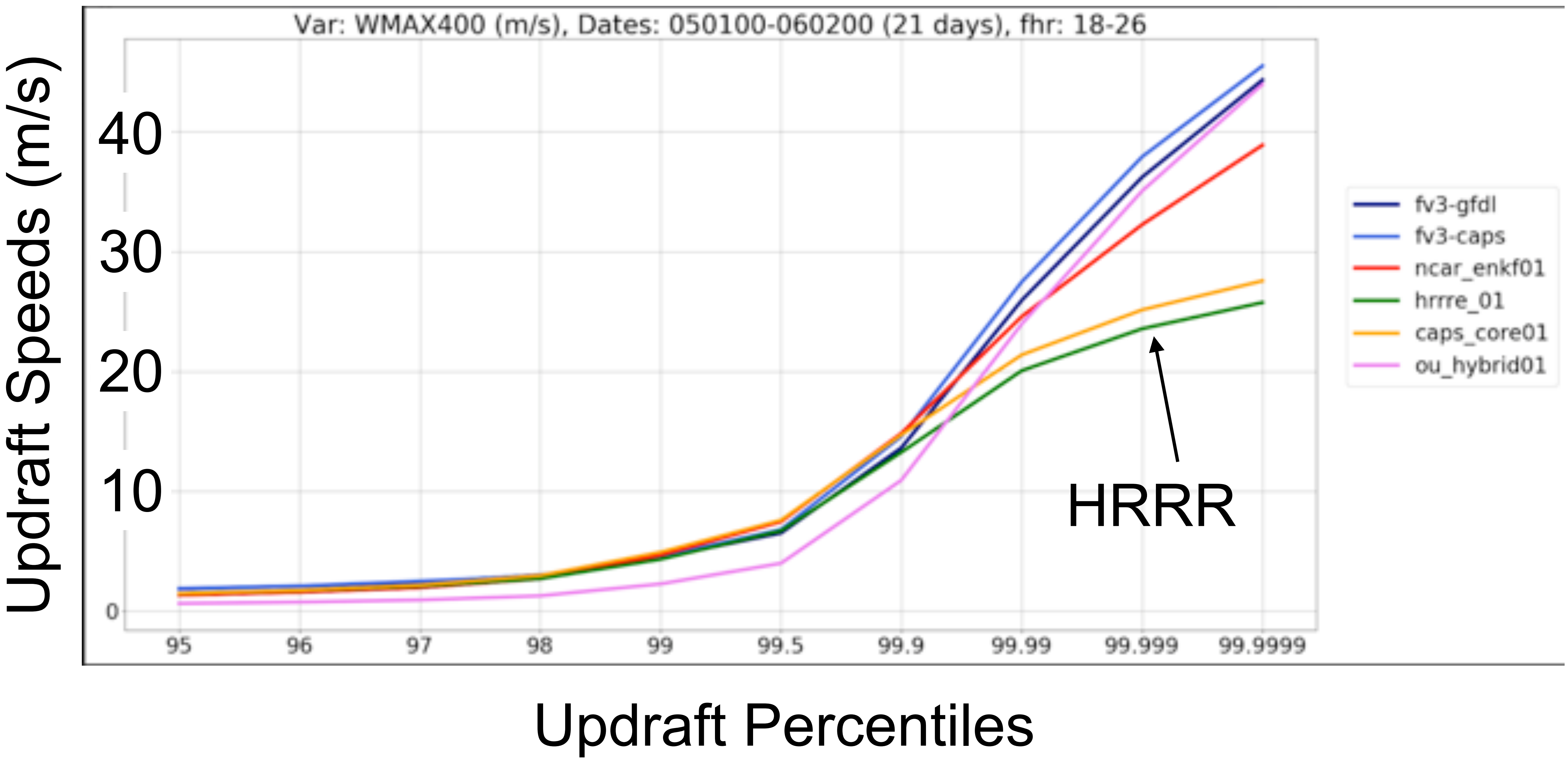


Figure courtesy of C. Potvin

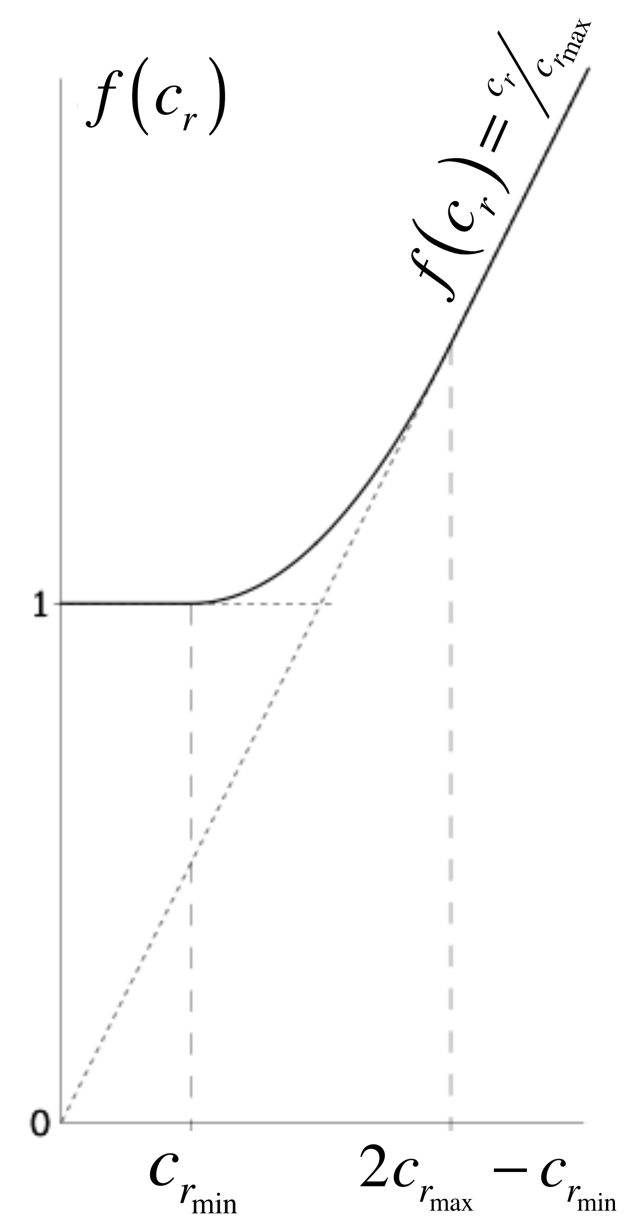
Shchepetkin's Solution

Shchepetkin 2015: An Adaptive, Courant-number-dependent Implicit Scheme for Vertical Advection in Oceanic Modeling. Ocean Modeling ***91,*** *pp. 38-69.*

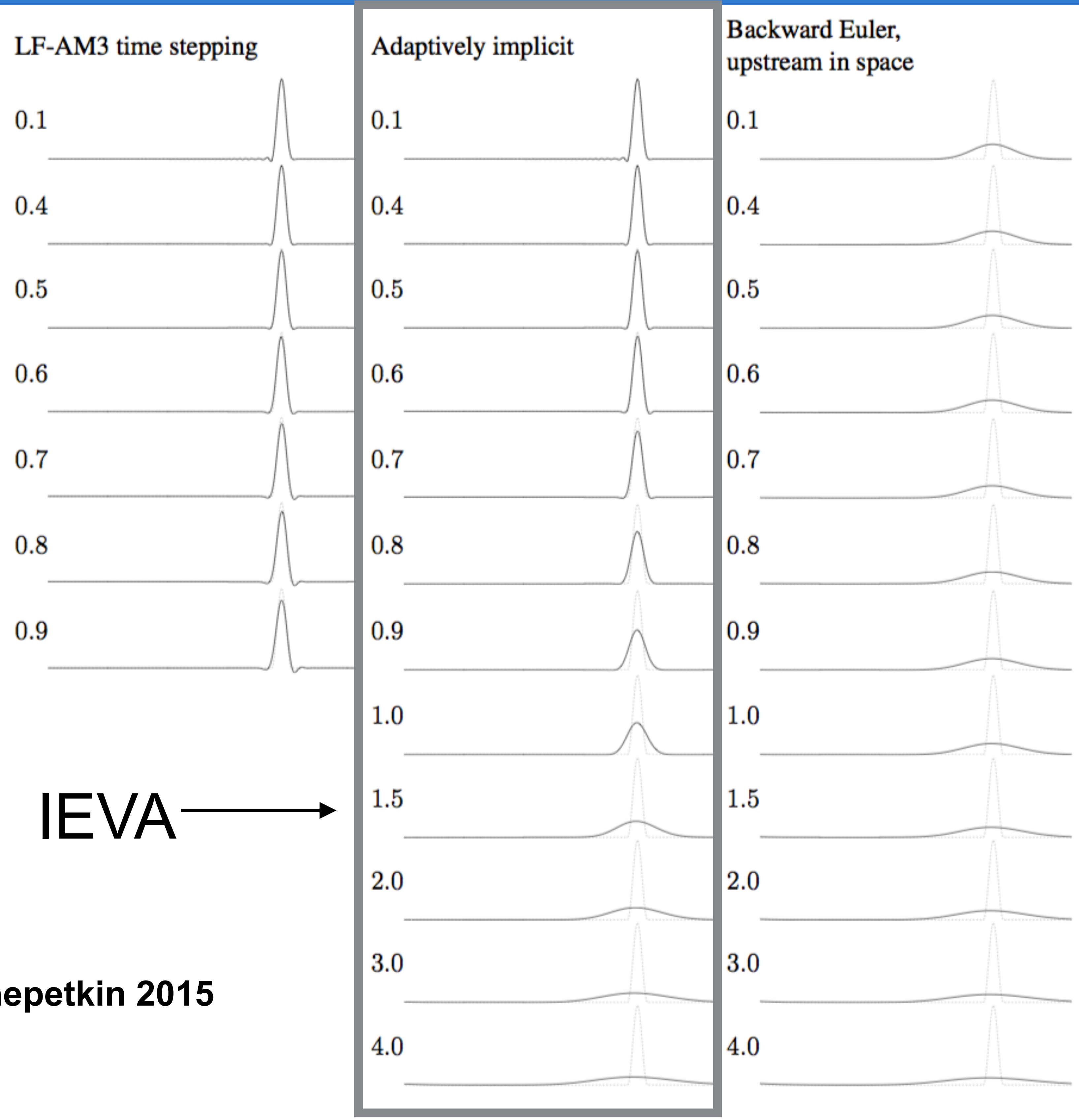
- CAM time-step limitation due to local W-CFL similar in ROM ocean model simulations when horizontal resolution increases
- Large and transient W's in small regions (oceanic fronts) limited the size of time step for entire ROM's simulation *(sound familiar?)*
- His solution:
  - Break the vertical velocity into 2 fields based on the vertical courant number
  - Almost all of the transport will use the standard **Explicit** scheme, except…
  - where W-CFL > 1, do part of transport **Explicitly**, and the rest **IMPLICITLY**

IEVA Algorithm

- Compute local vertical courant number at each grid point
- Choose critical courant number from linear theory
  - for RK3 5th order w-advection: $w\_cr_{critical} = 1.1$
- Divide w-field into explicit and “implicit” pieces
  - the labels refer the actual transport (explicit or implicit).
  - $w_{ex}(i,k,j) = dz/dt * \mathrm{Min}(\, w\_cr(i,k,j),\ w\_cr_{critical}\,)$
  - $w_{im}(i,k,j) = w(i,k,j) - w_{ex}(i,k,j)$
- The “normal” RK3 algorithm is used with the w_{ex} field.
- An Euler-backward (implicit) with upwind fluxes uses the w_{im} field to do the implicit piece of the transport



Simple Advection Tests

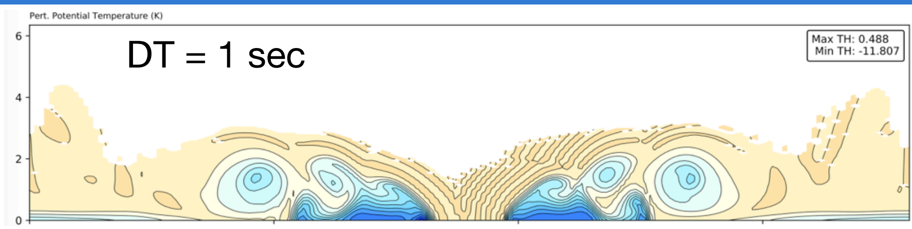


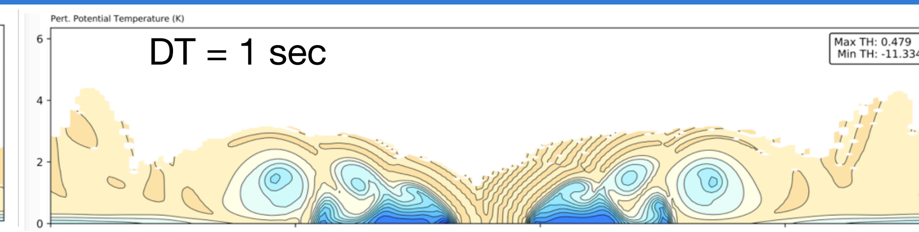
from Shchepetkin 2015

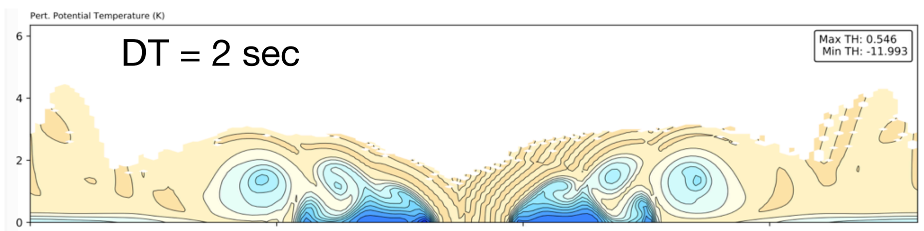
Translating Downburst with $\frac{\Delta x}{\Delta z} = 4$

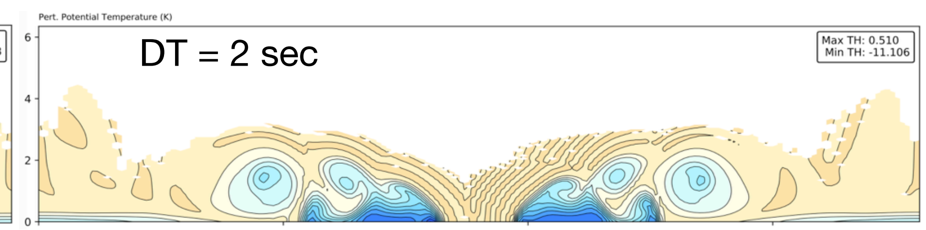
RK3

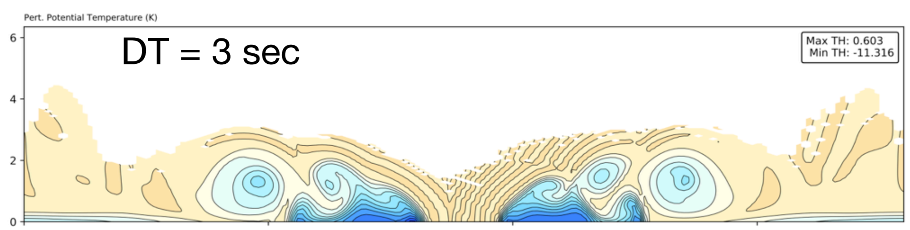
RK3-IEVA

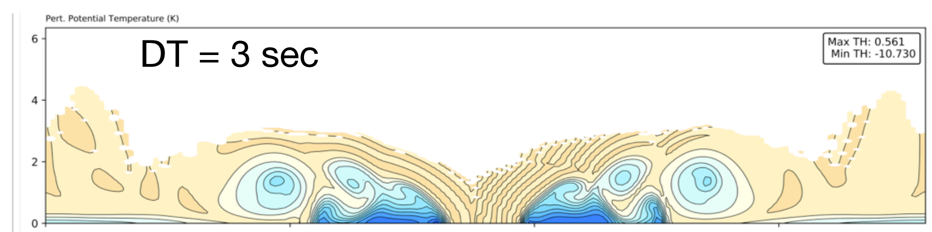




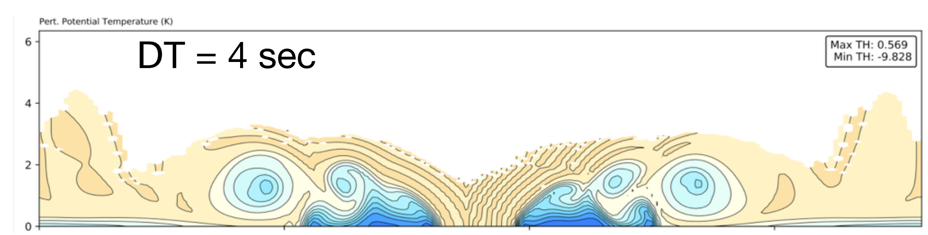








UNSTABLE



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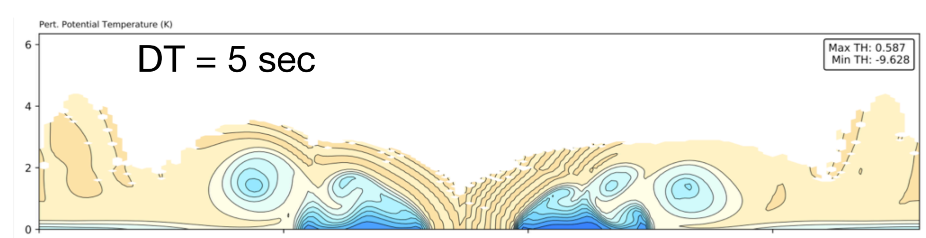

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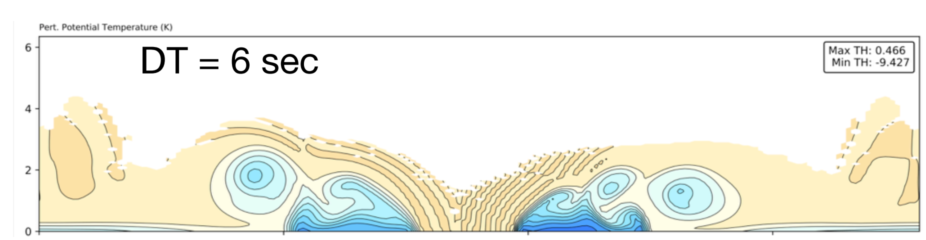

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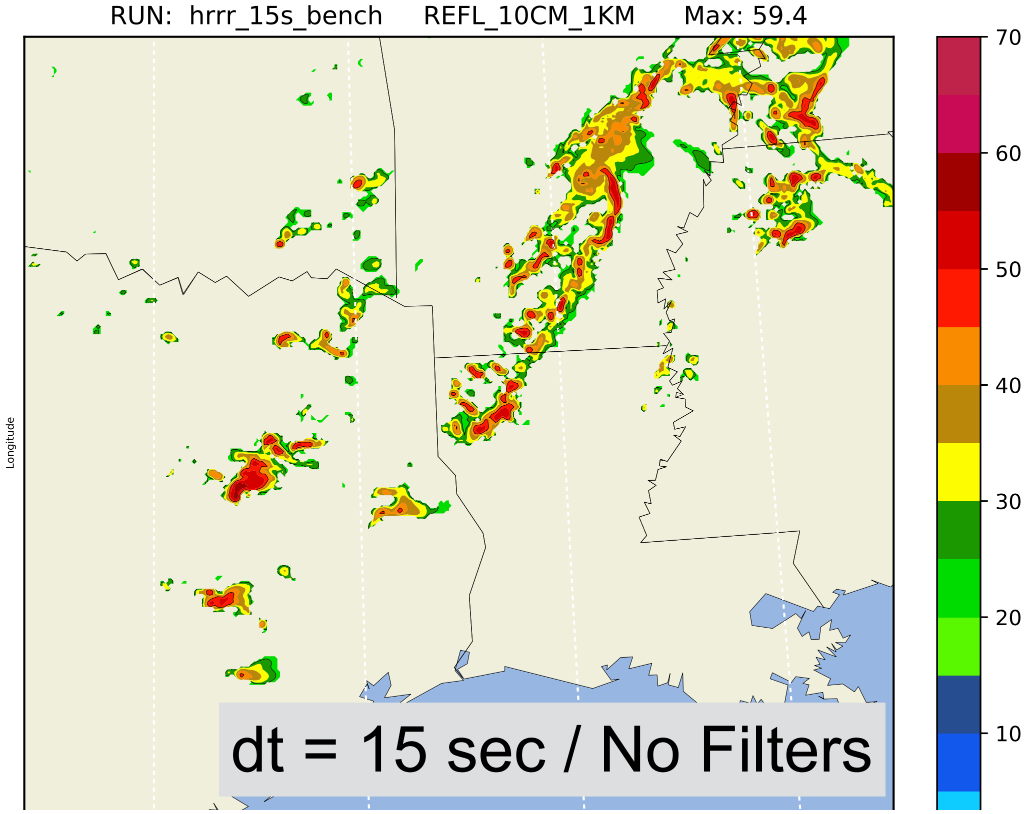

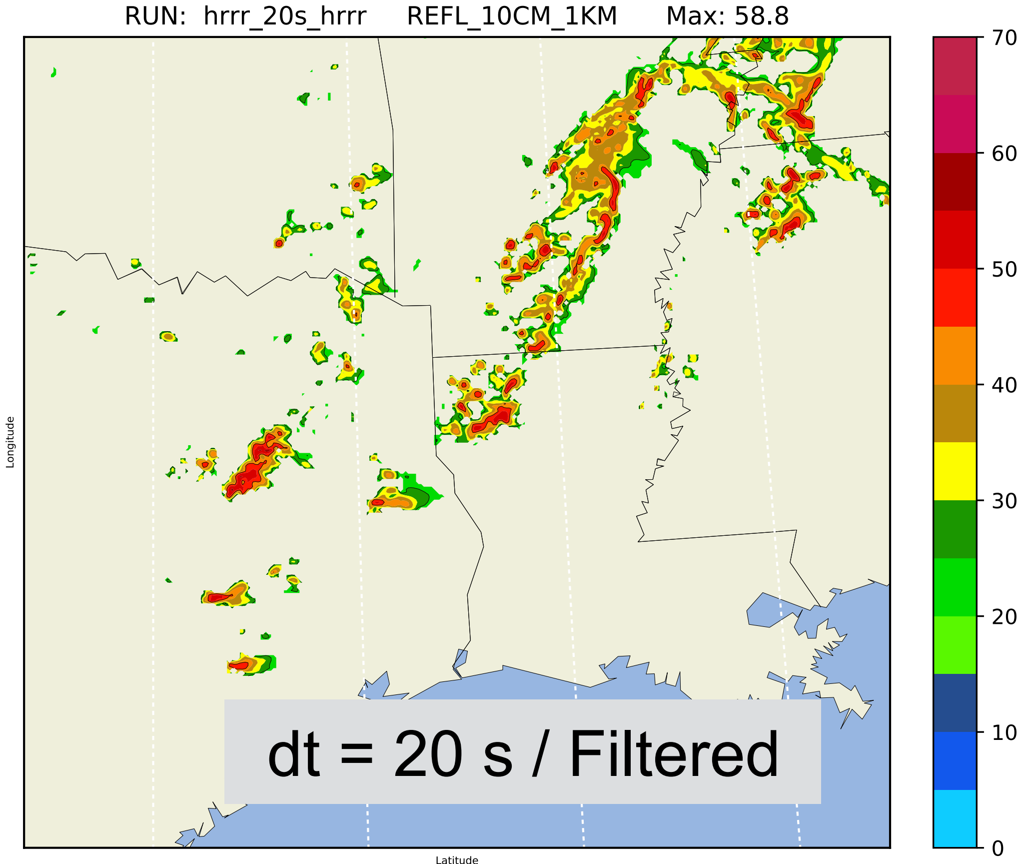

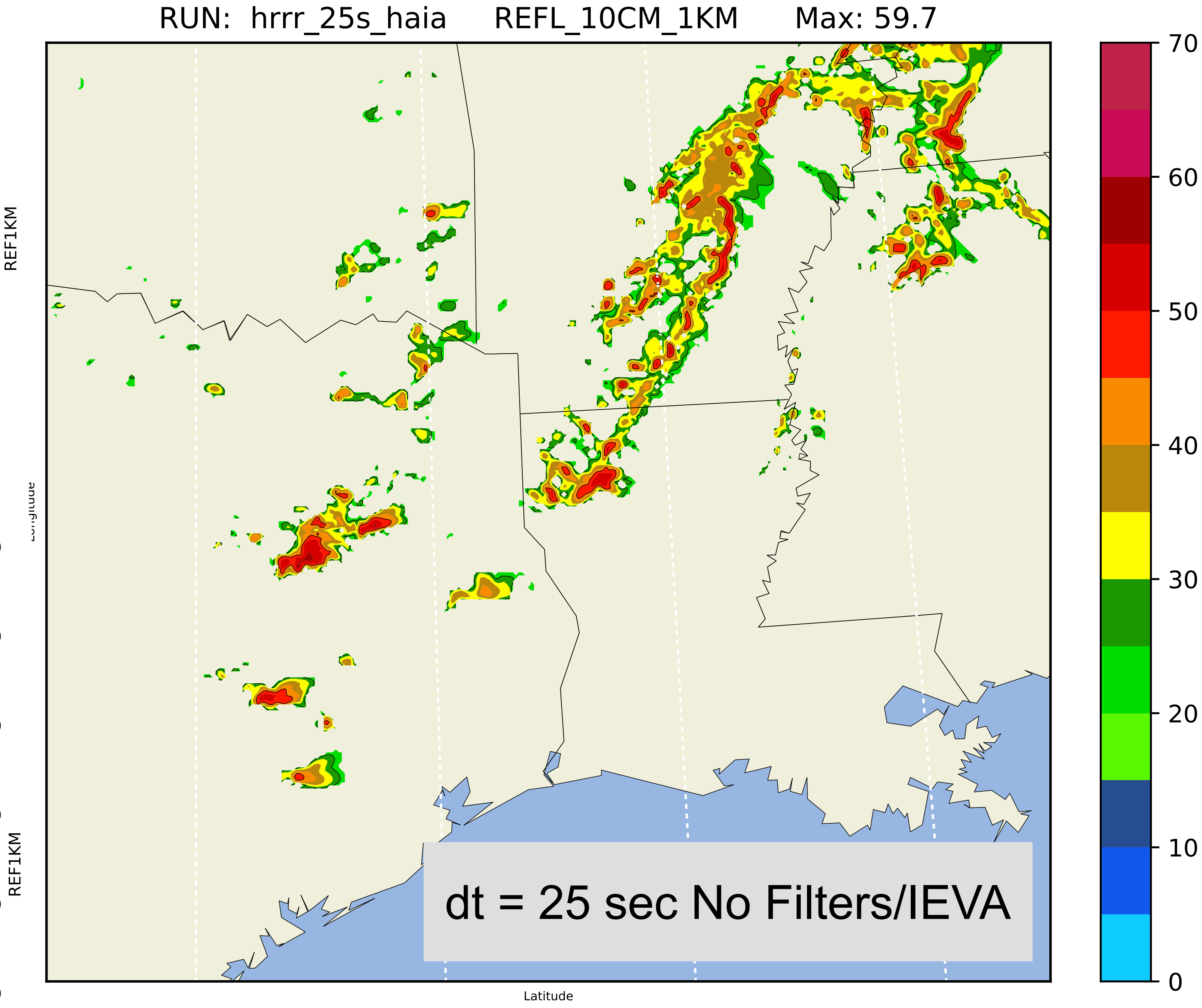

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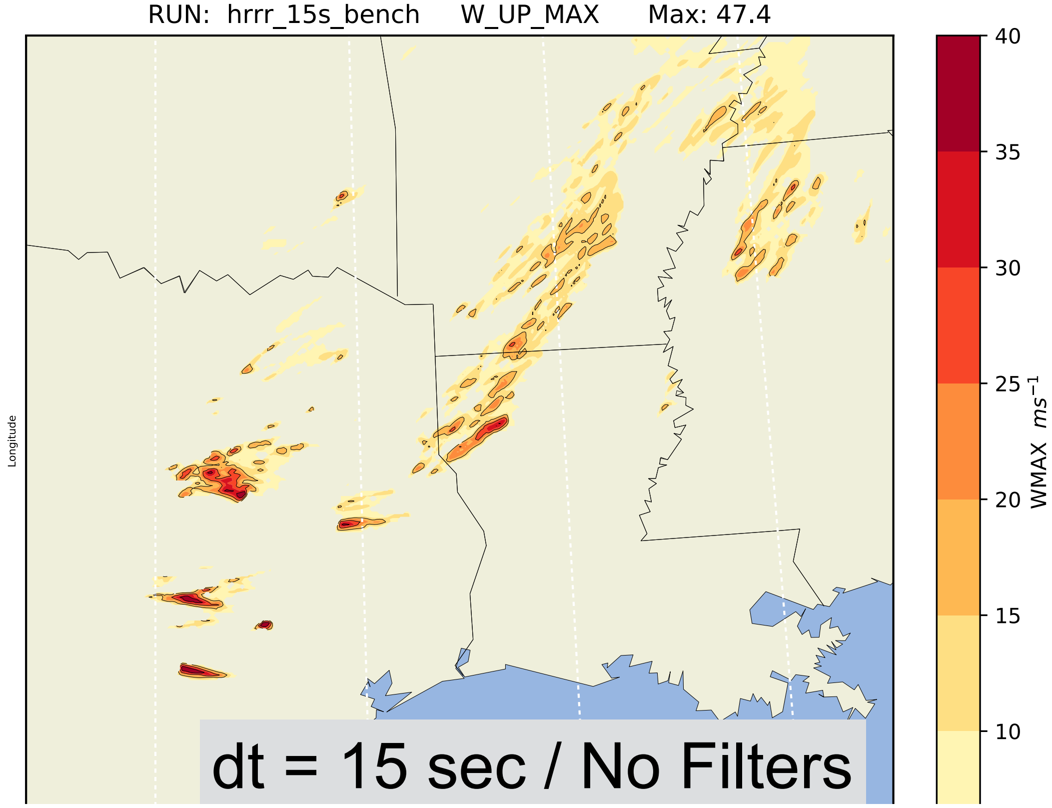
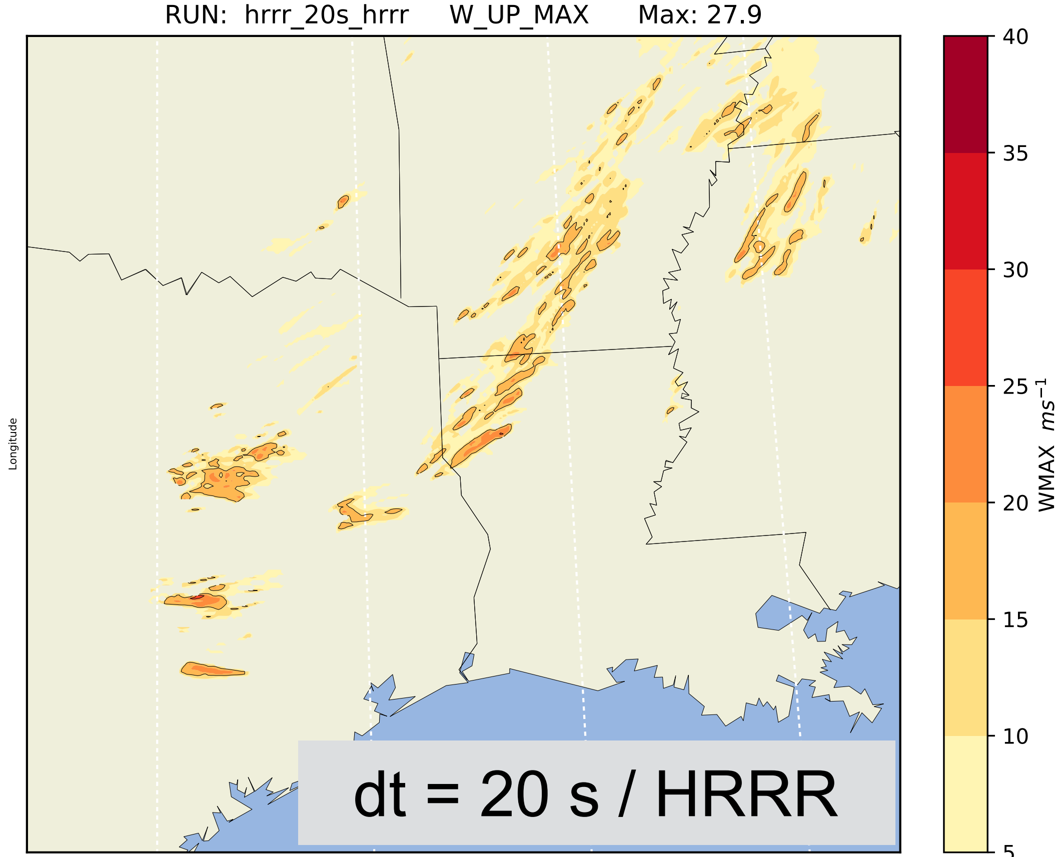
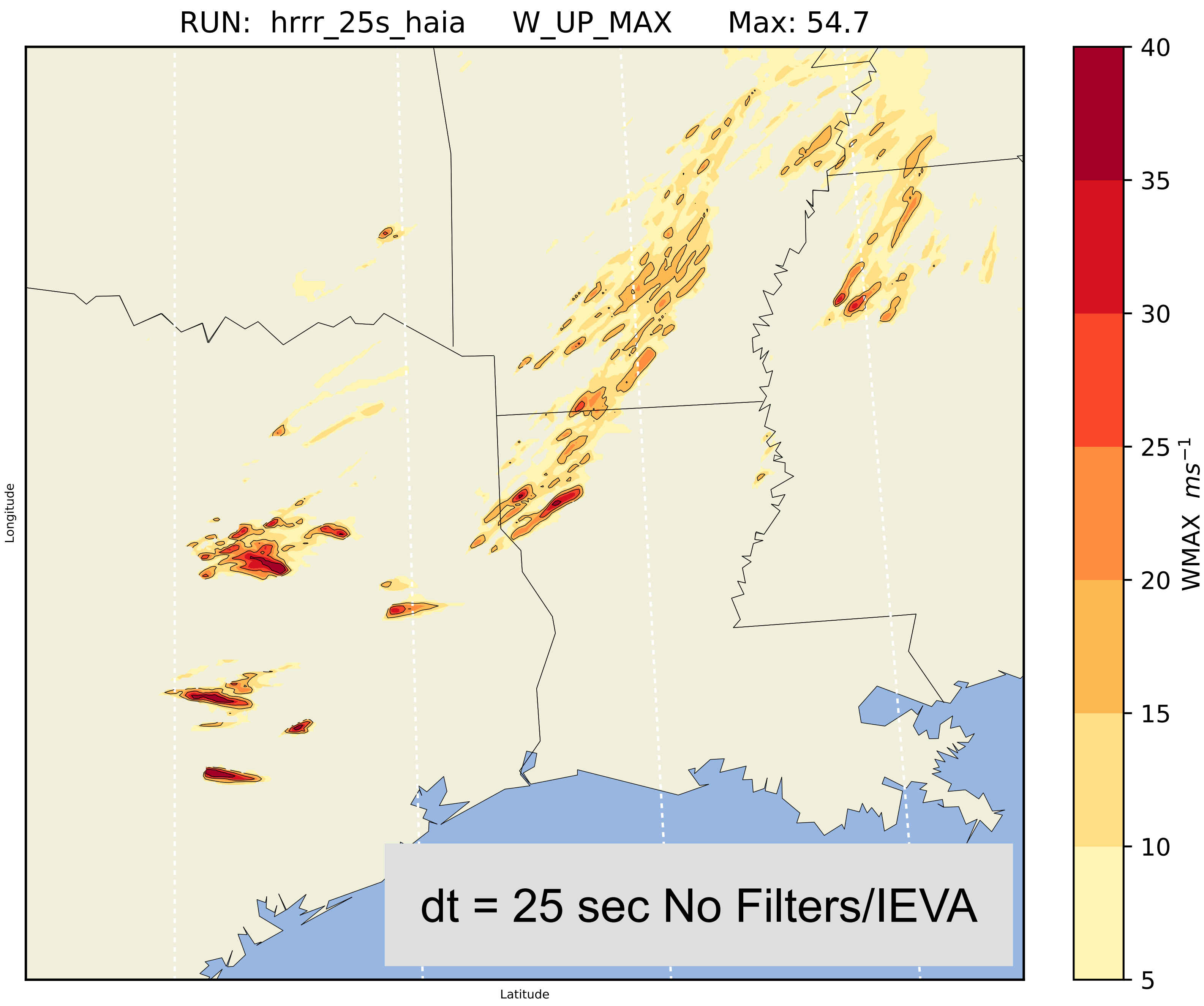


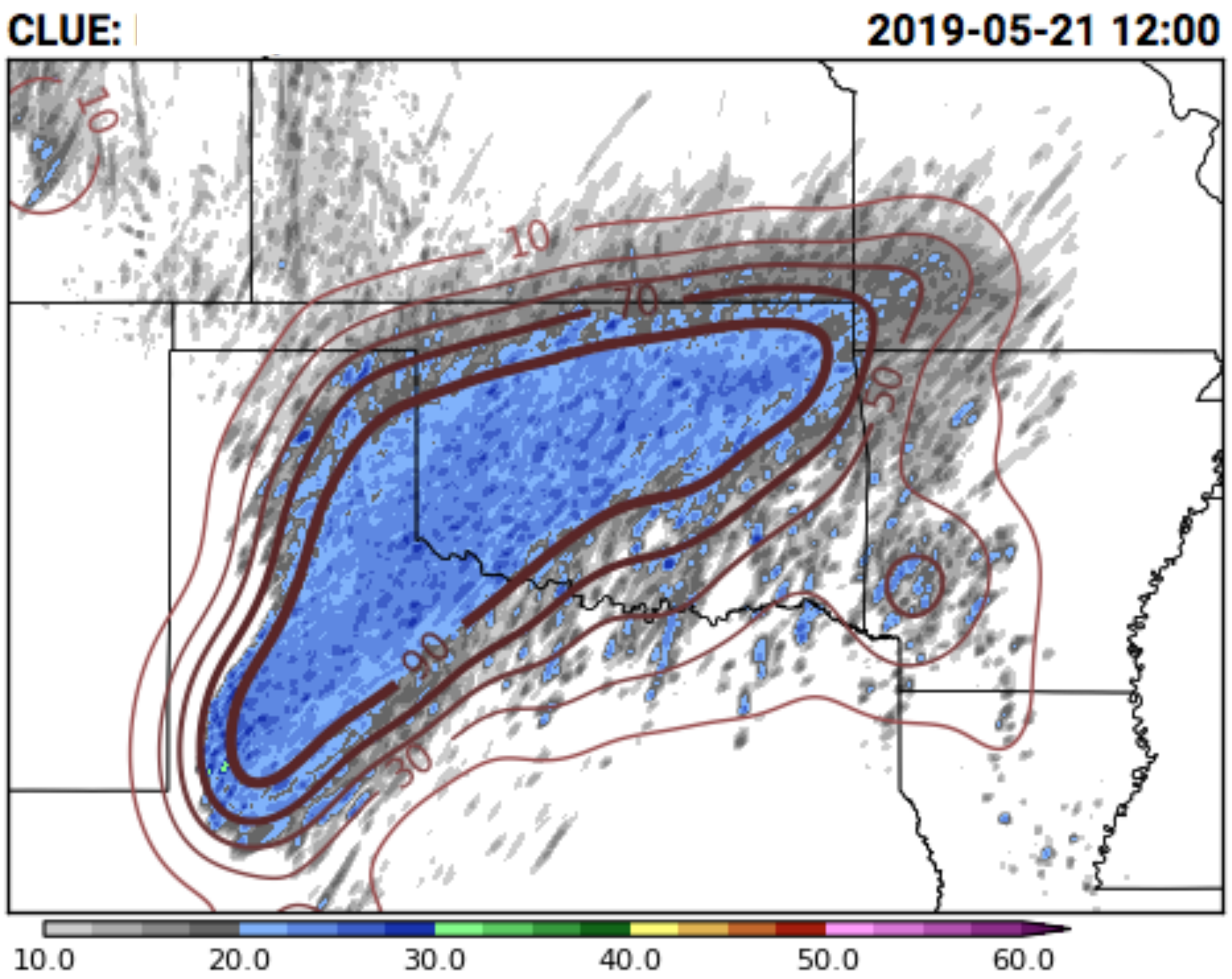




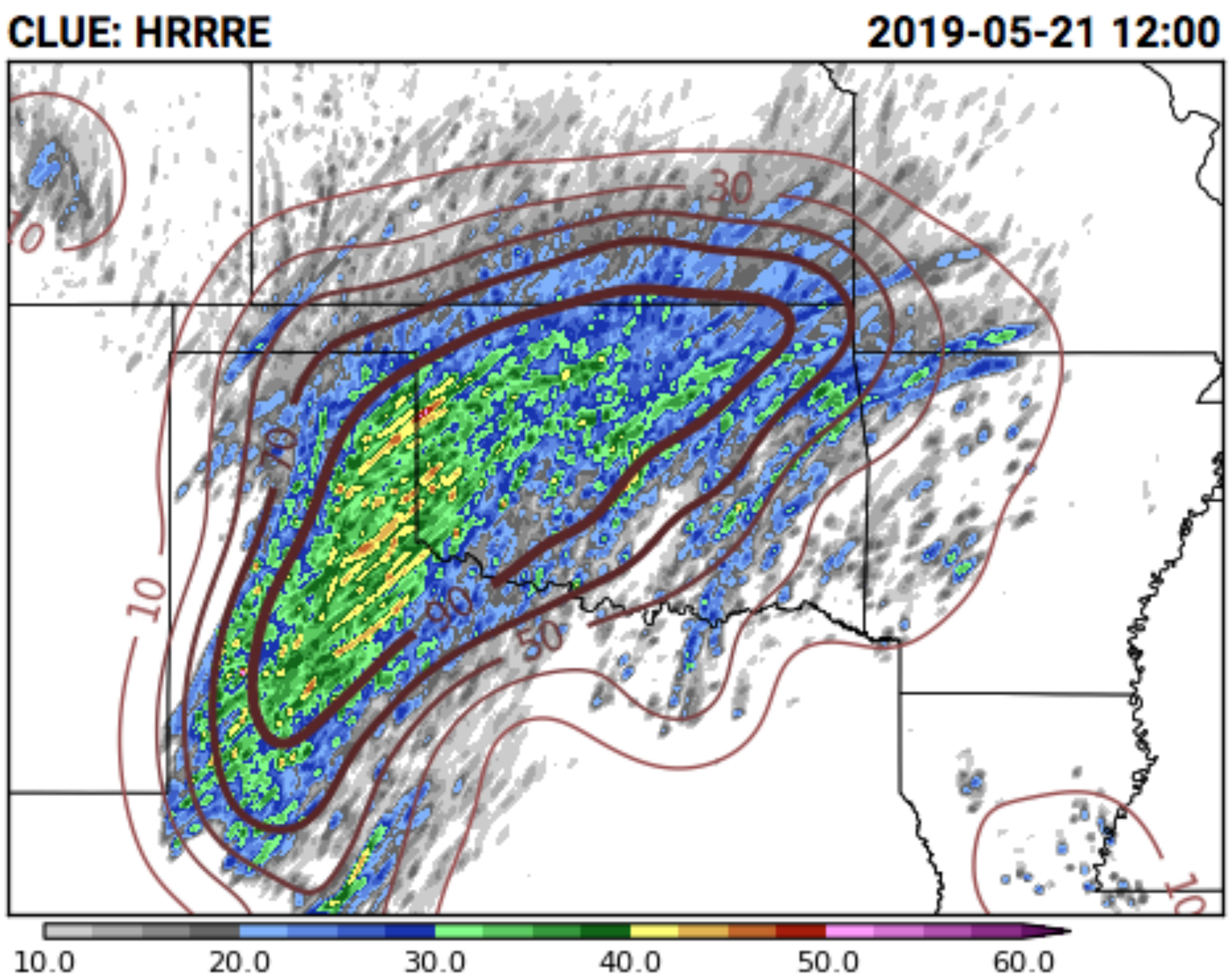
"HRRRe" vs HRRRe + IEVA in 2019 Spring Forecast Experiment

Max Column W for 36 hours (05/20/19)

Filtered



NO Filters



WRFv4.1 Timings

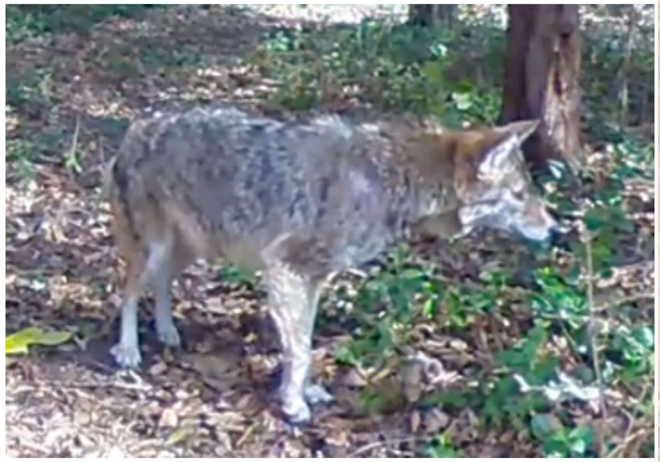
- Timings from 3 hour runs 00Z-03Z 27 April
  - I/O omitted
  - 960 cores
  - 3 runs for each configuration on Cray XC
  - NSSL 2-moment microphysics

Time step (dt in secs)	HRRR 20	IEVA 20	IEVA 24
Run1	519	544	456
Run2	522	543	454
Run3	519	543	455
Avg	**520**	**543**	**455**
Speed relative to HRRR	1.0	1.04	**0.88**
Notes		Overhead is 4%	Max Theoretical Speedup 0.833

IEVA Summary

- **Adapted the Shchepetkin (2015) adaptive implicit-explicit vertical advection scheme into WRF Runge-Kutta framework (WRFv 3.8, 3.9, 4.1)**
- **IEVA can be used to remove existing w-filters in WRF, permitting more realistic vertical velocities while using a larger time step.**
- **IEVA can be shown to <u>consistent</u> and <u>conservative</u> for transport**
- **For NWP, testing shows time step can be increased by 20-25%**
    - **Speed up** for run relative to current HRRR config is **10-15%**
    - Extra cost comes from solving a tridiagonal system for each column/state variable
    - Implementation could be made to be somewhat faster
    - Physics schemes may have to be “hardened” to accurately use larger time steps
        - Ted Mansell had to improve NSSL 2-mom ice interactions not to over deplete for larger time steps (run with dt = 30 sec for some limited domain test runs)
- **IEVA will be (hopefully) used in the 2020 HRRRv4 implementation.**

Questions?



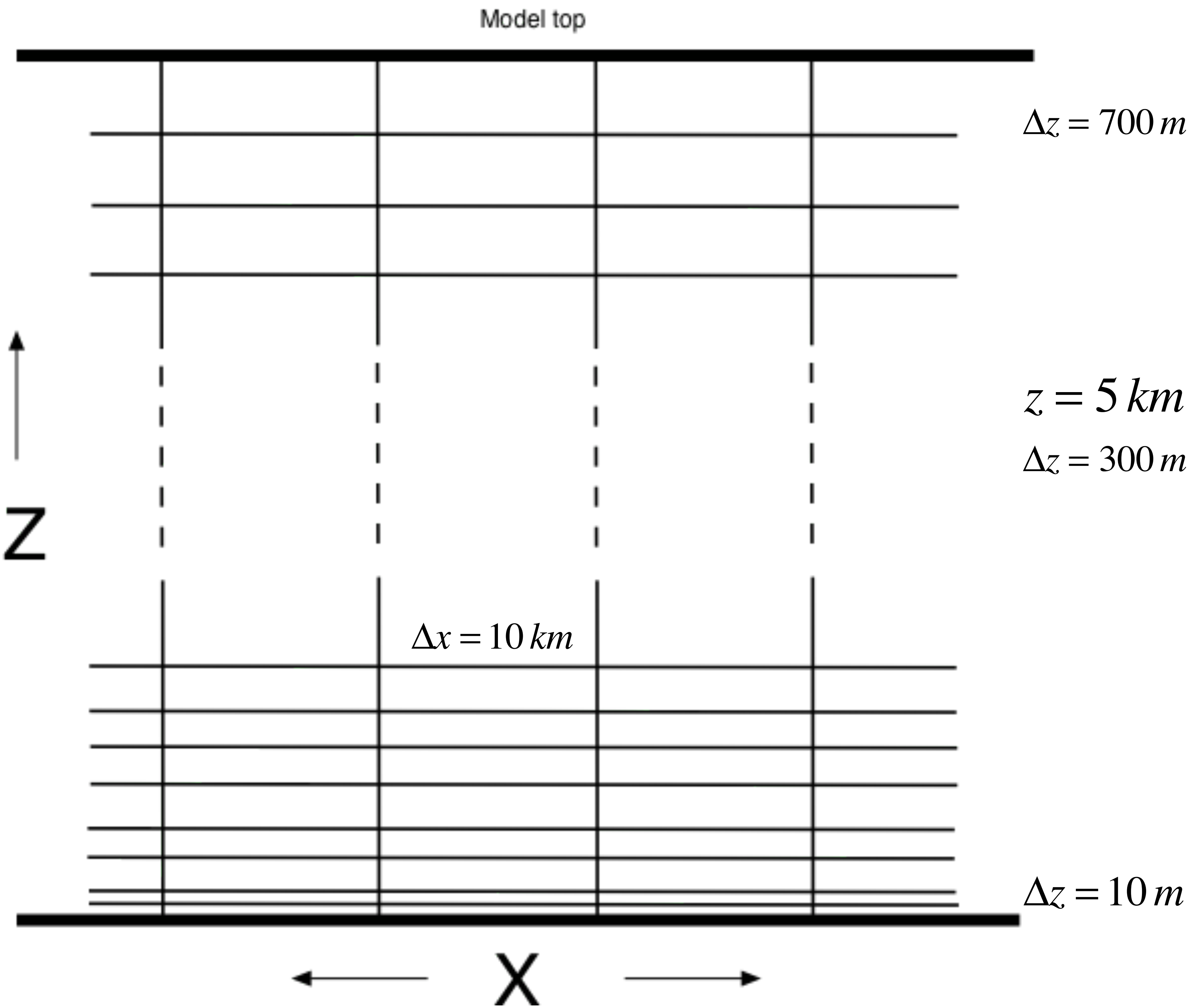
Special Thanks

Bill Skamarock

Corey Potvin

Ted Mansell

Motivation


Model top
$\Delta z = 700\,m$
$z = 5\,km$
$\Delta z = 300\,m$
Z
$\Delta x = 10\,km$
$\Delta z = 10\,m$
X

Motivation

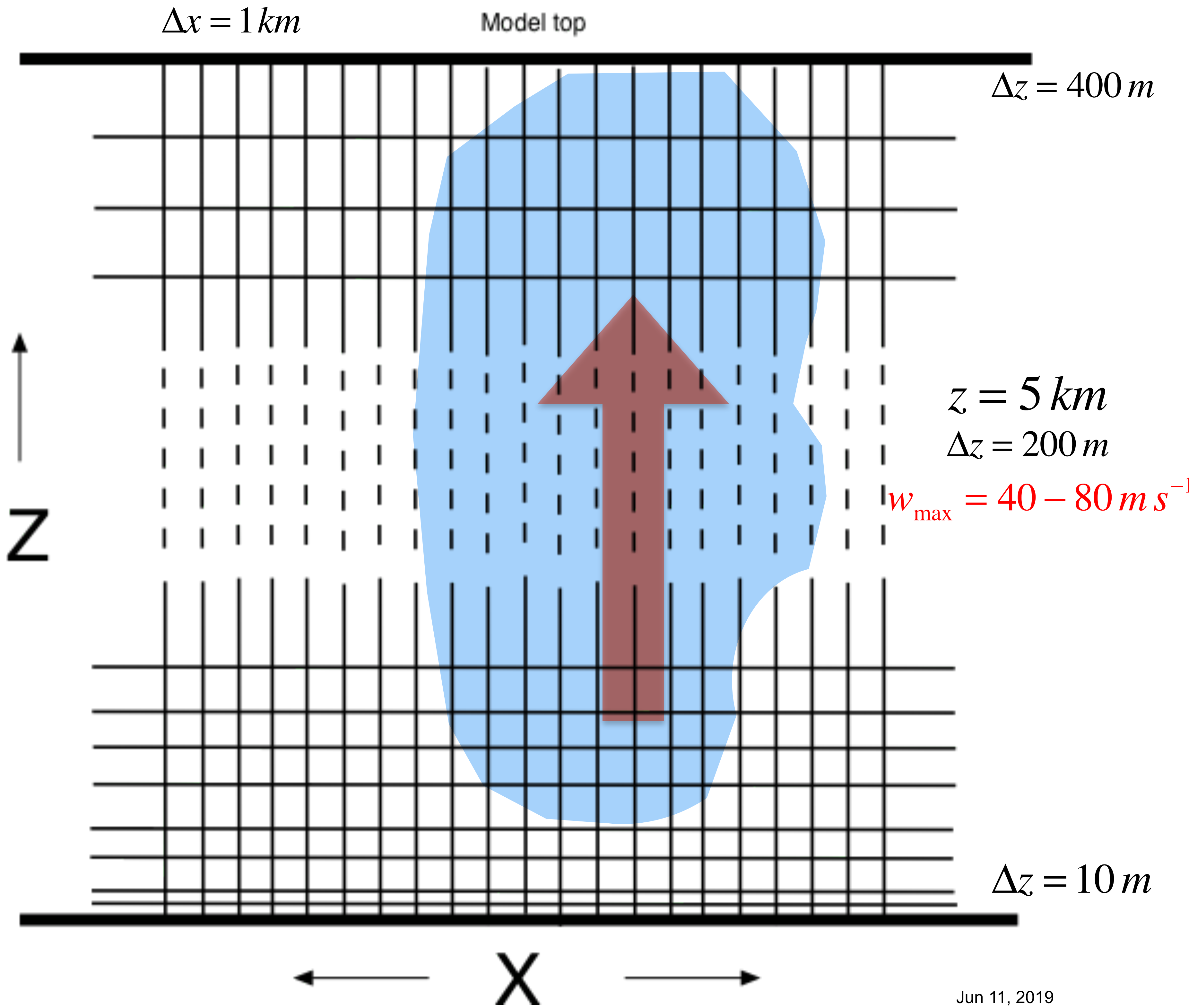
High-Res model resolution

$$CFL_h = \frac{u\Delta t}{\Delta x} \sim 1$$

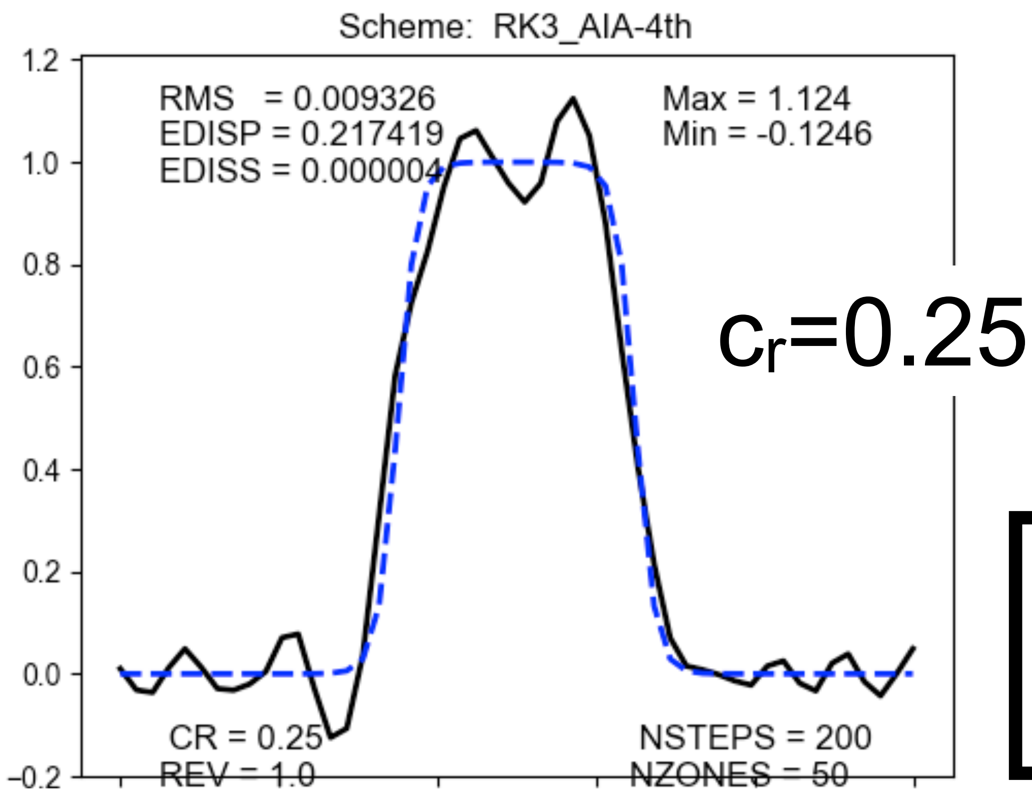
$$w \geq u$$

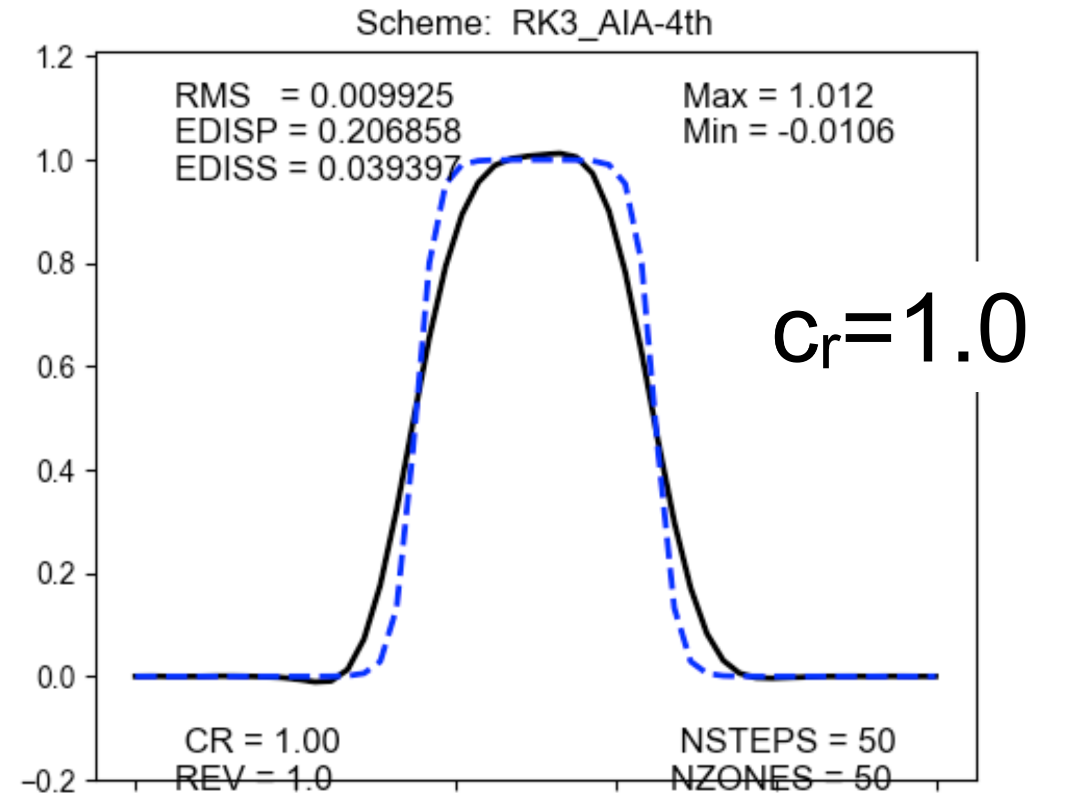
$$CFL_z = \frac{w\Delta t}{\Delta z} >> 1$$

time step now controlled by vertical CFL from convective updrafts

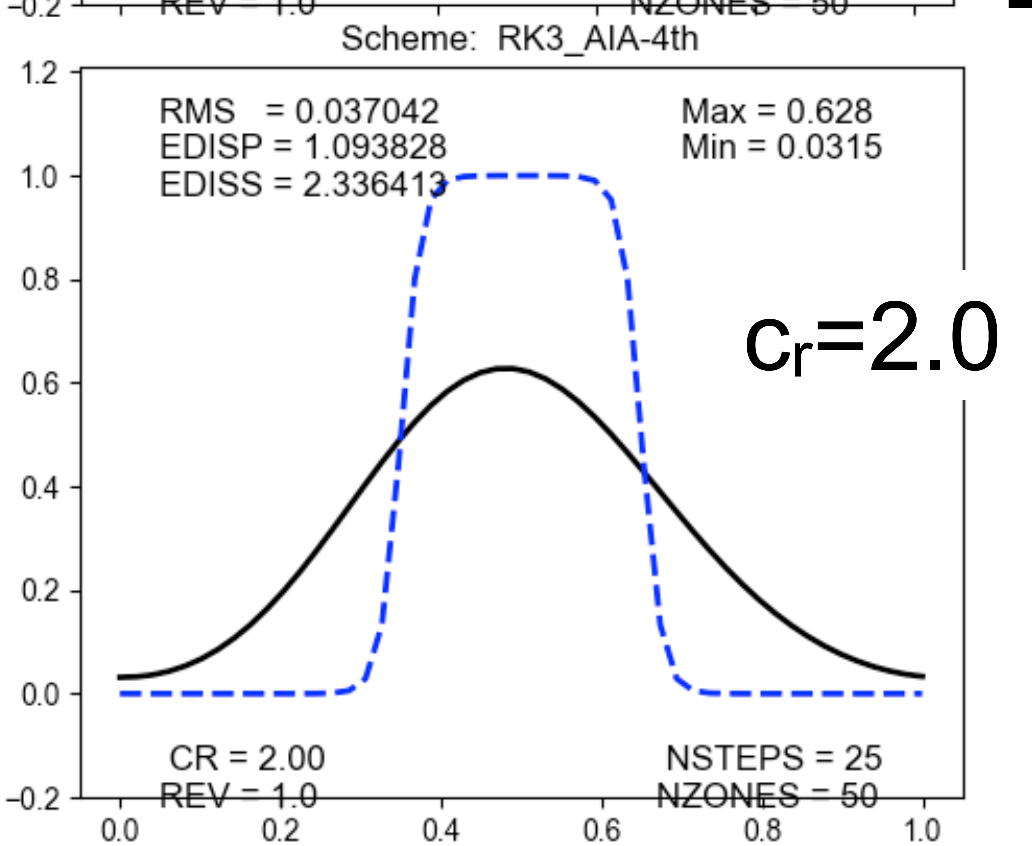


1D Advection

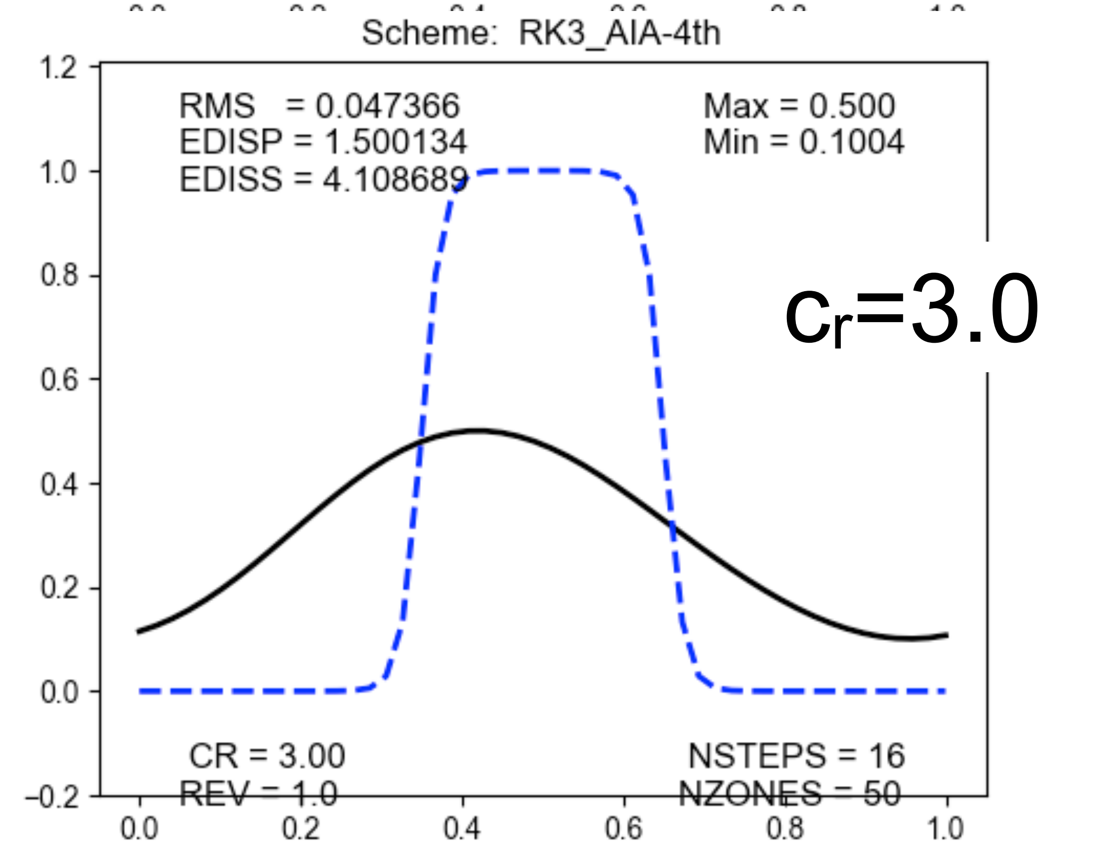




RK3
4th order



Uses the blending algorithm (0.8, 1.1)



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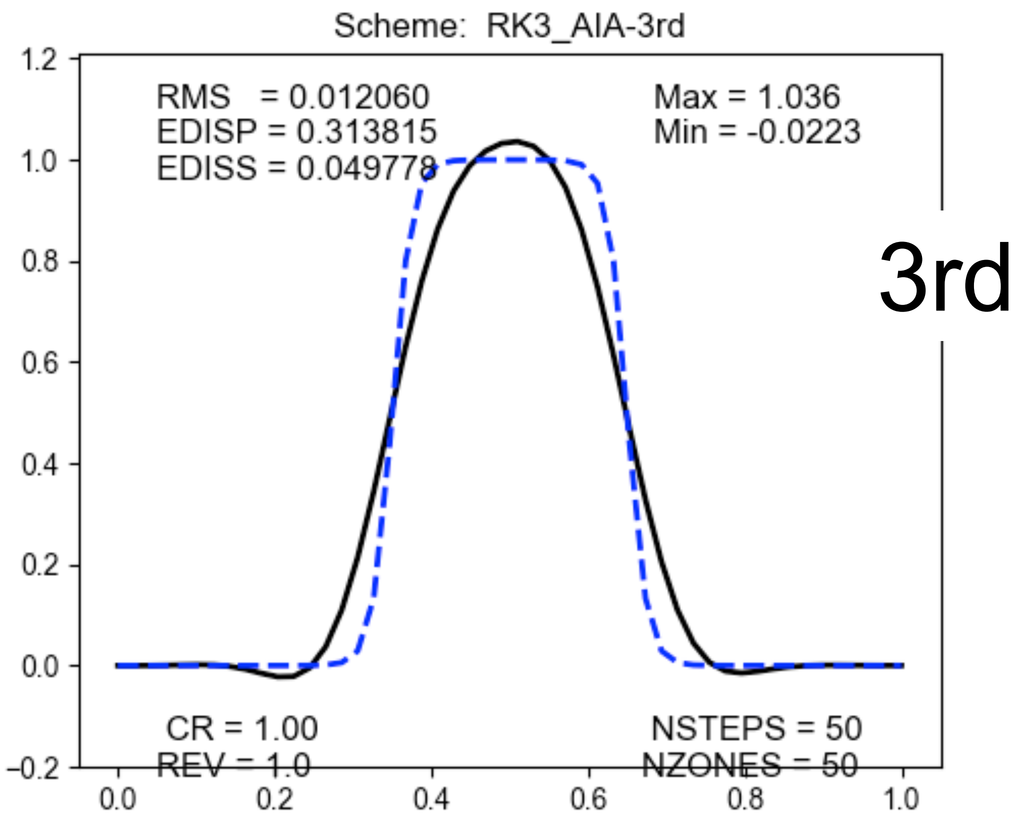
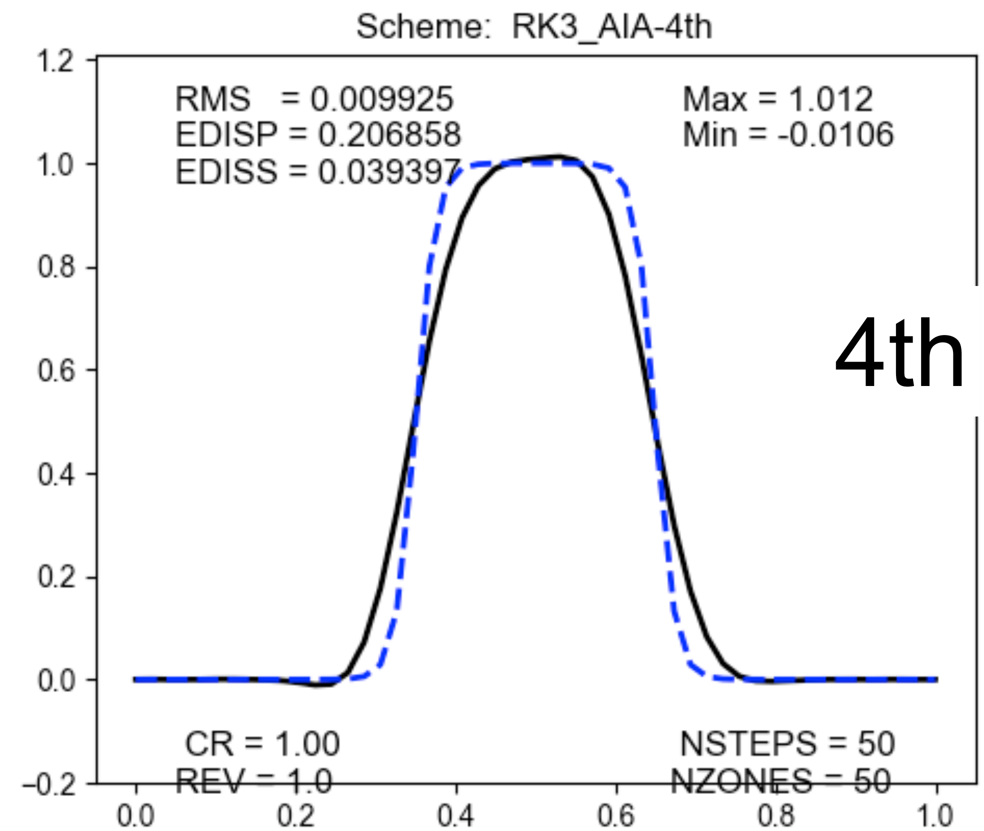
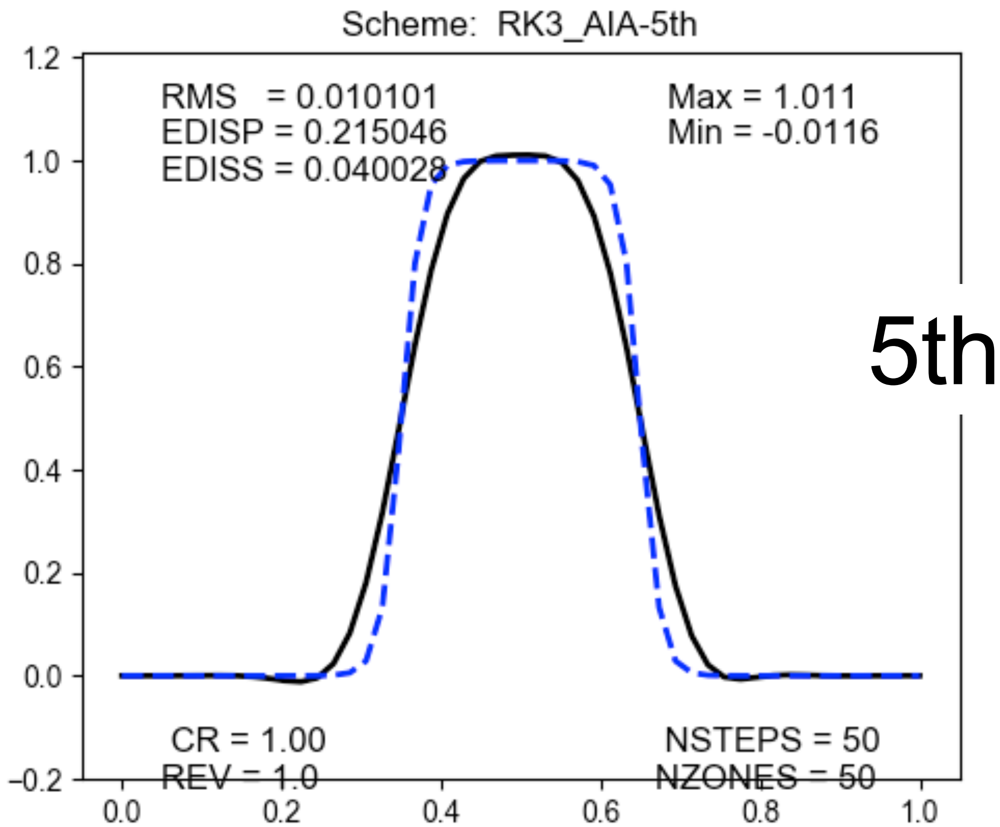
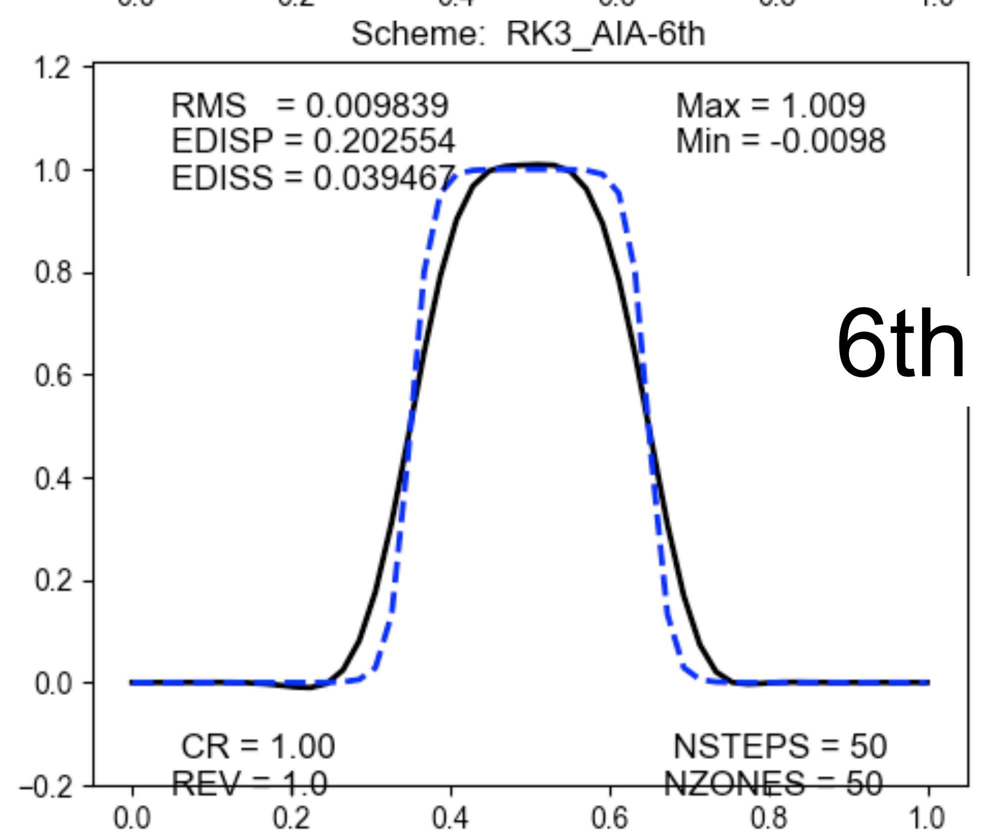




RK3

c_r=1.0



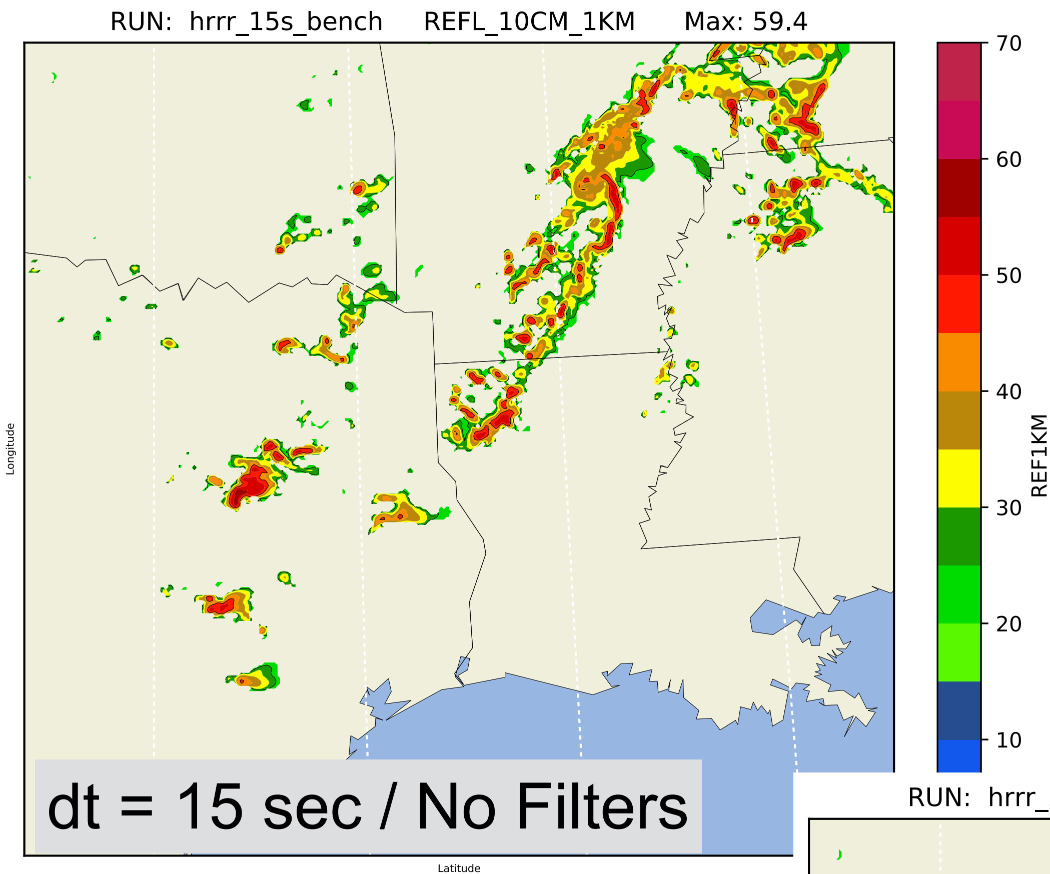


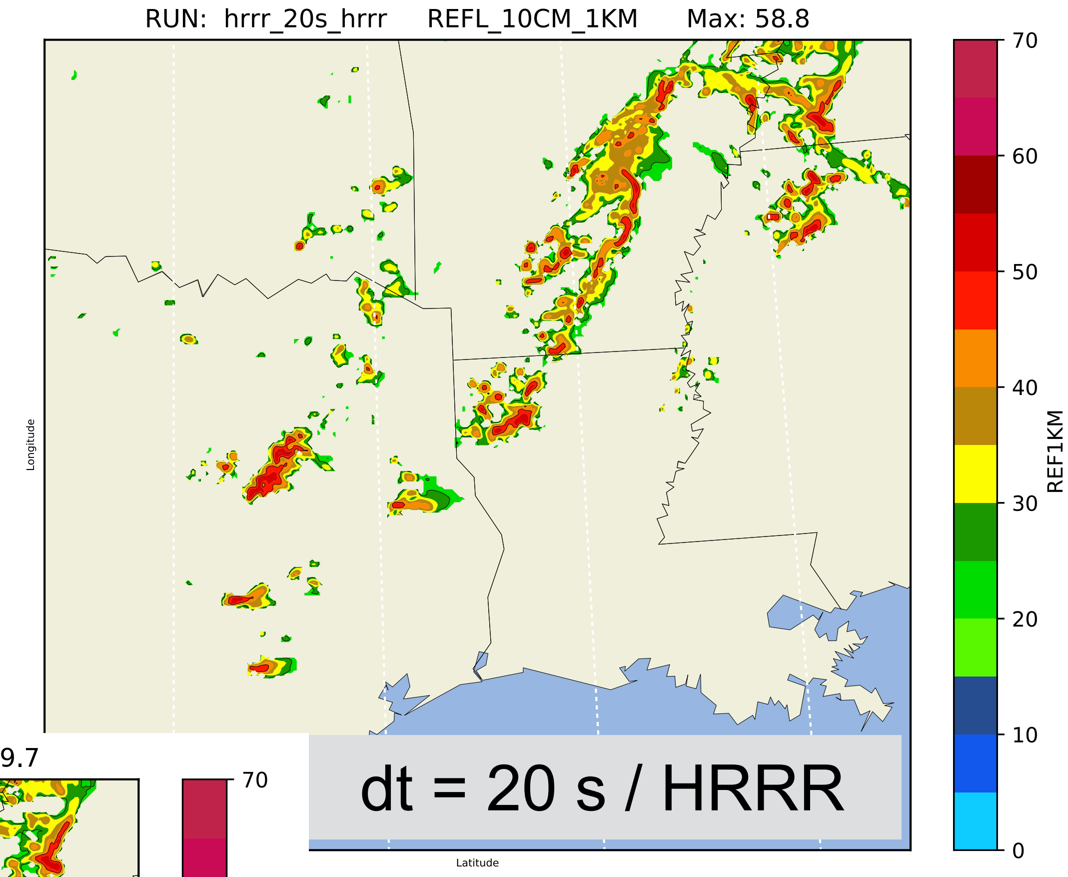
Uses the blending algorithm (0.8, 1.1)

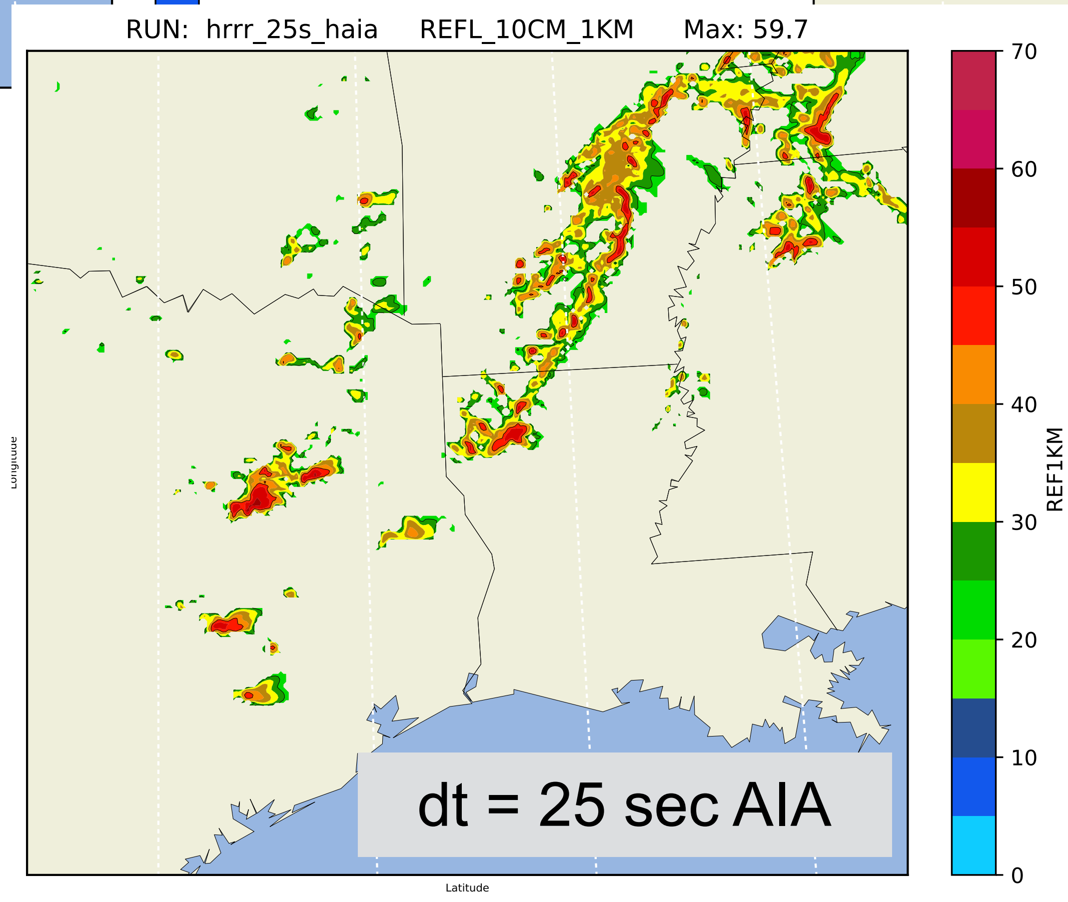
Summary (so far)

- Adapted the Shchepetkin (2015) split implicit-explicit vertical advection scheme into Runge-Kutta framework.
- Shown that it is stable for fast-slow time splitting methods (Wicker and Skamarock 2002)
- Coded it up for several test problems and a simply dry 2D model
- Implemented it in WRF - works as expected for an idealized supercell simulation
- Time step can be increased by 20-50% while…preserving the statistics of vertical velocity better than other approaches.
- Time to move onto full physics NWP run (been hopeful before!)

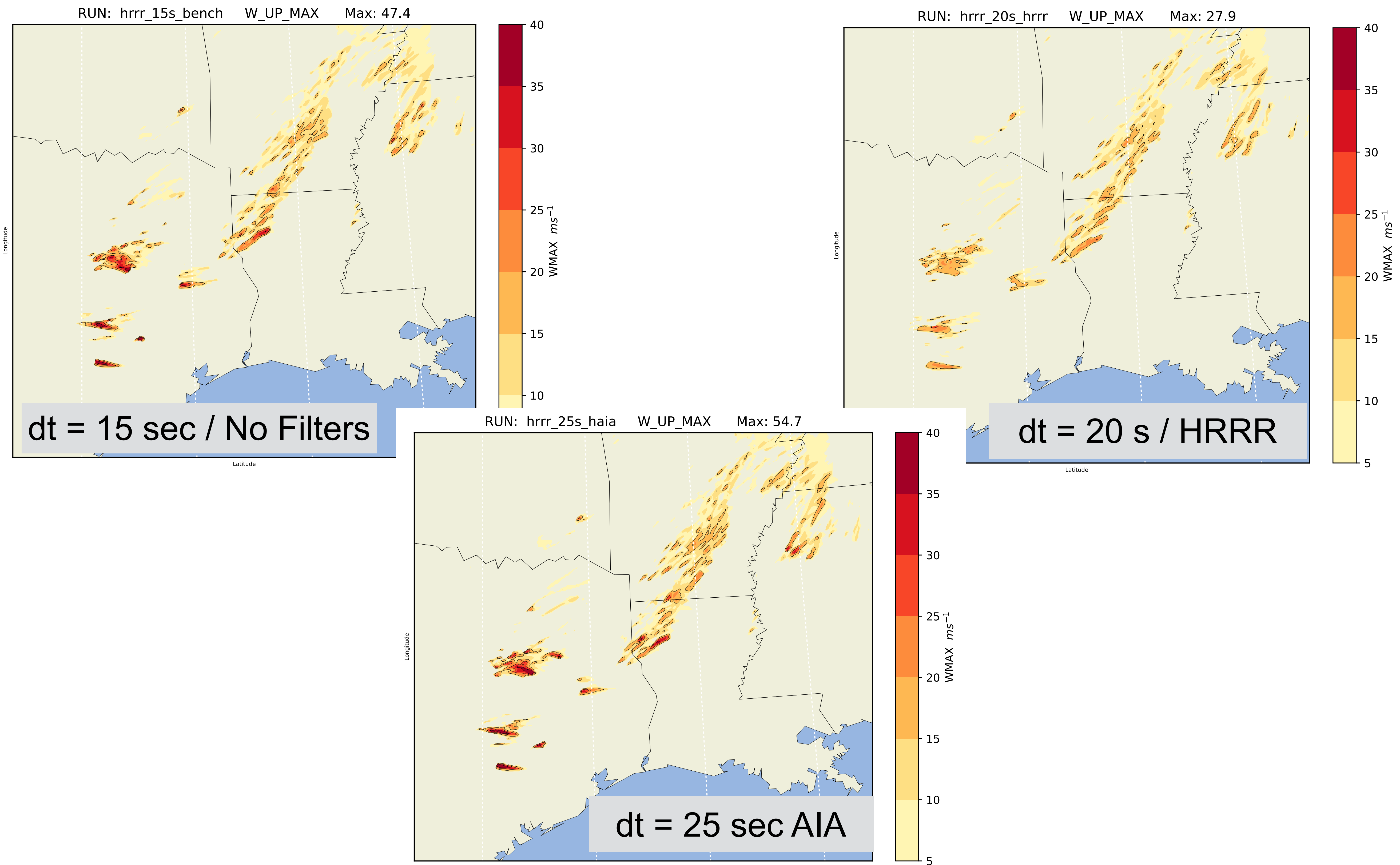
27 April 03Z 1 KM REF







27 April 03Z 1 hour Max Updraft



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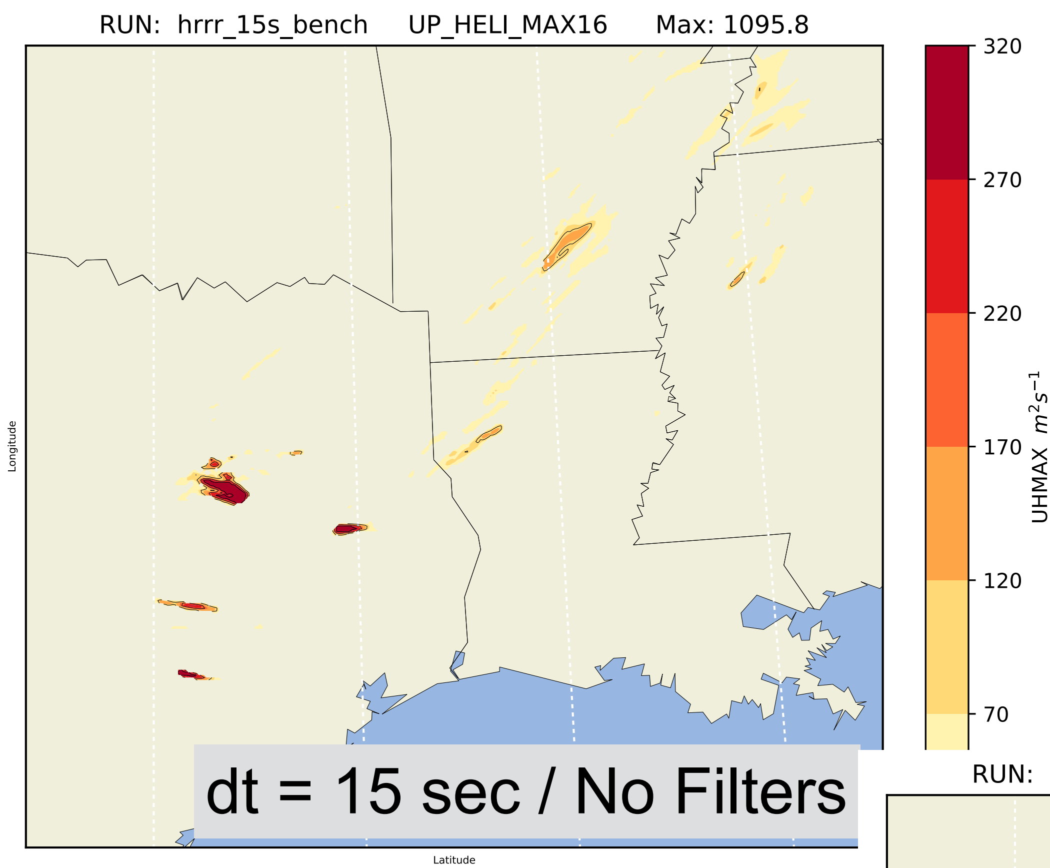

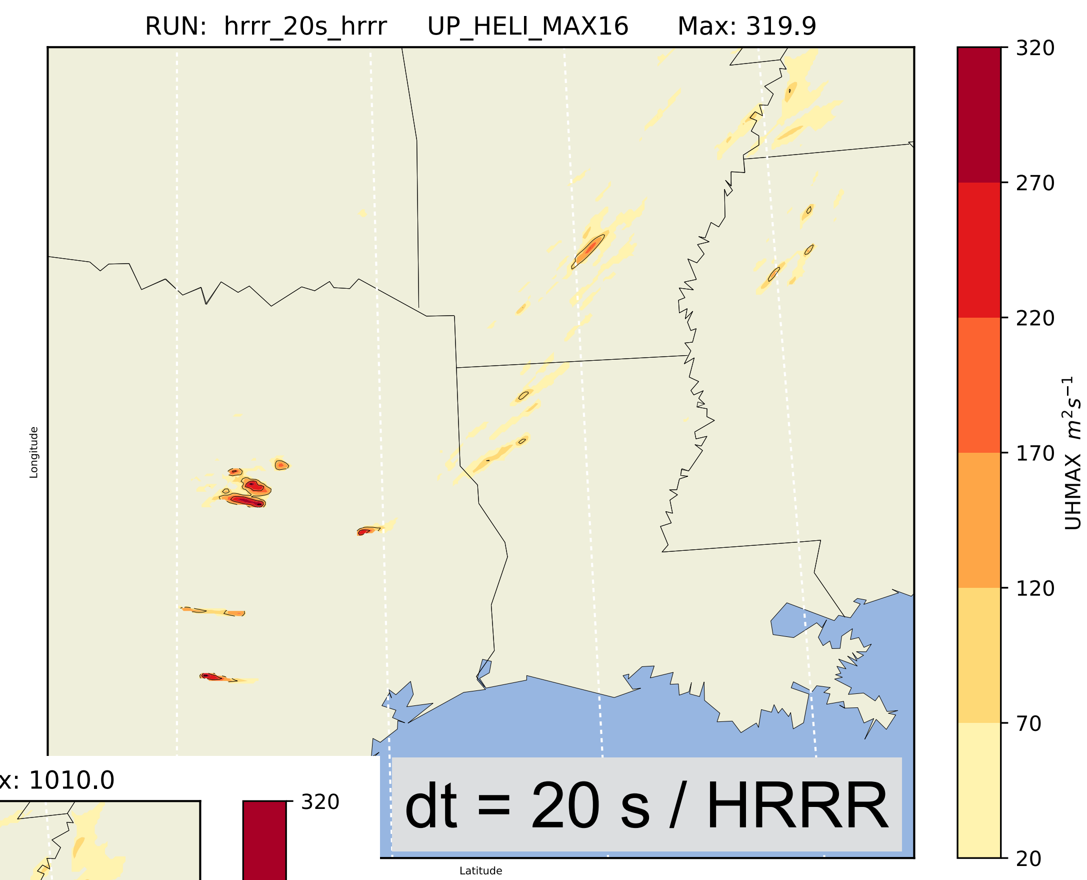

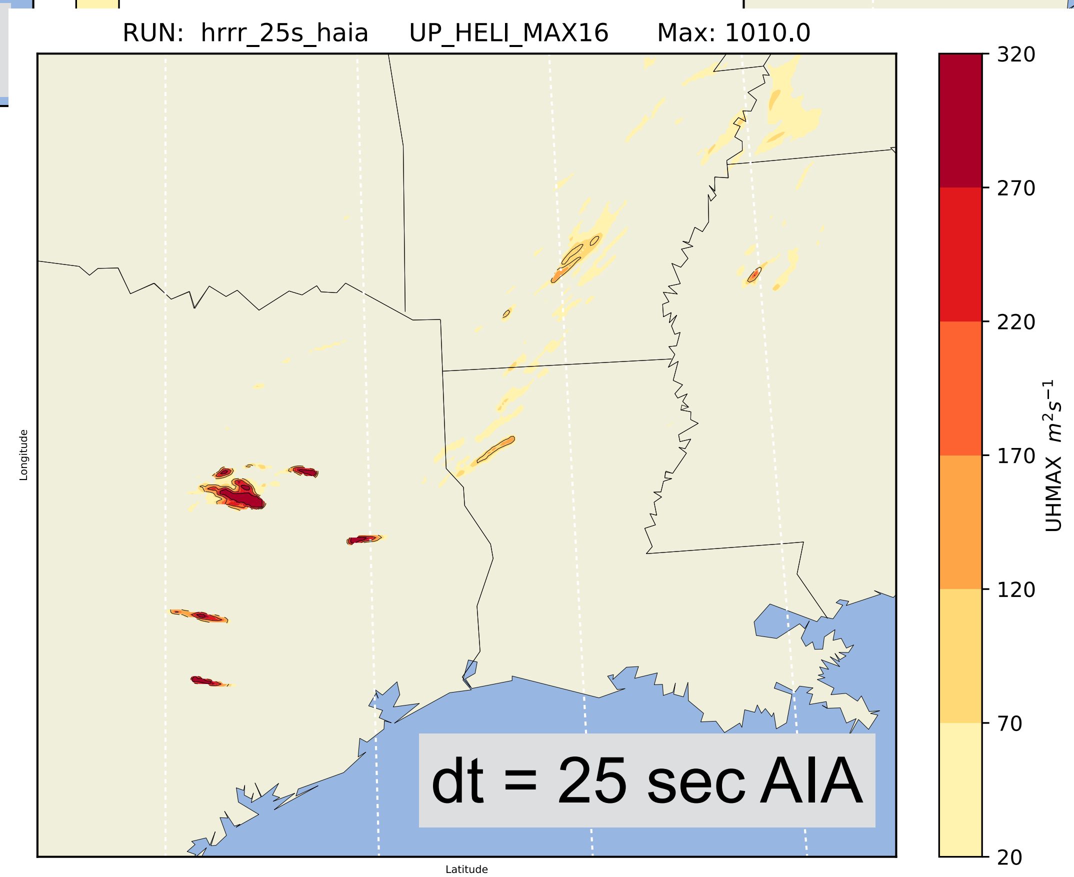

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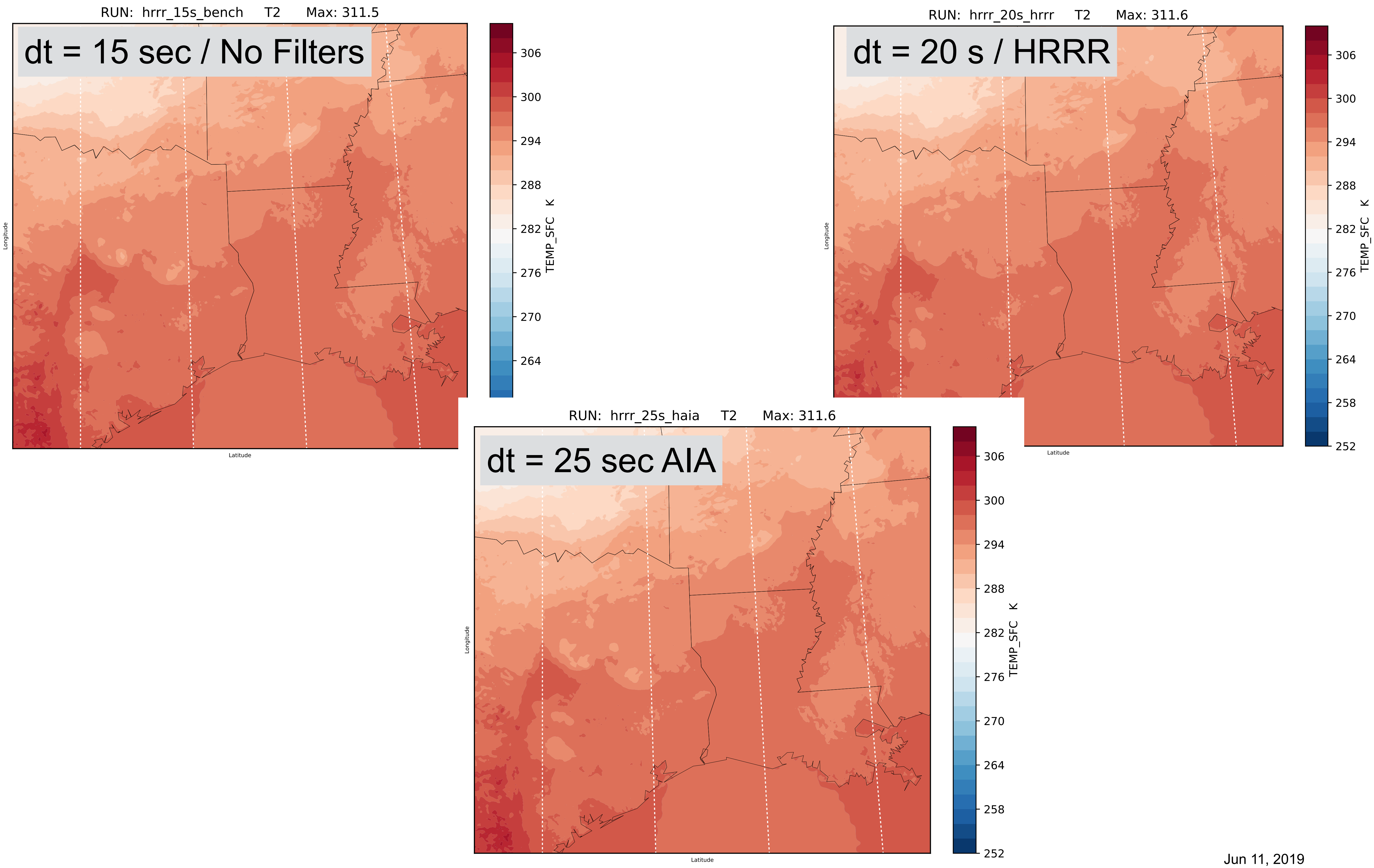
27 April 03Z Temp-2m



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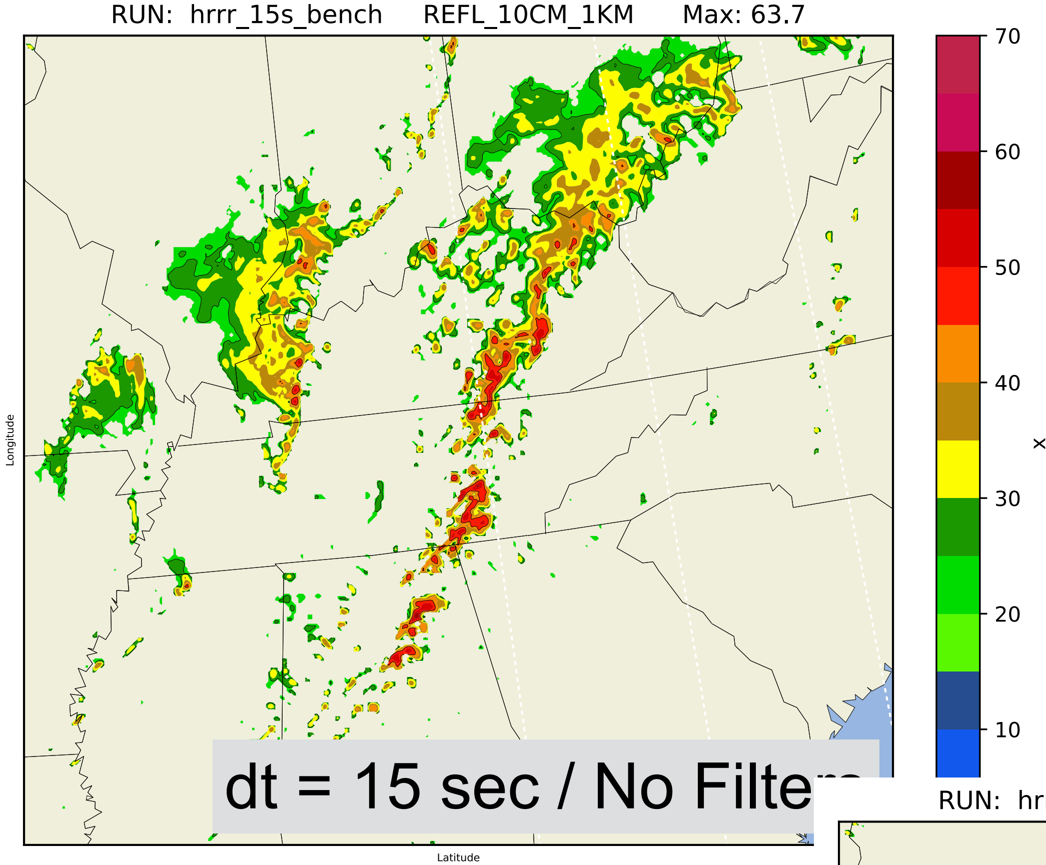
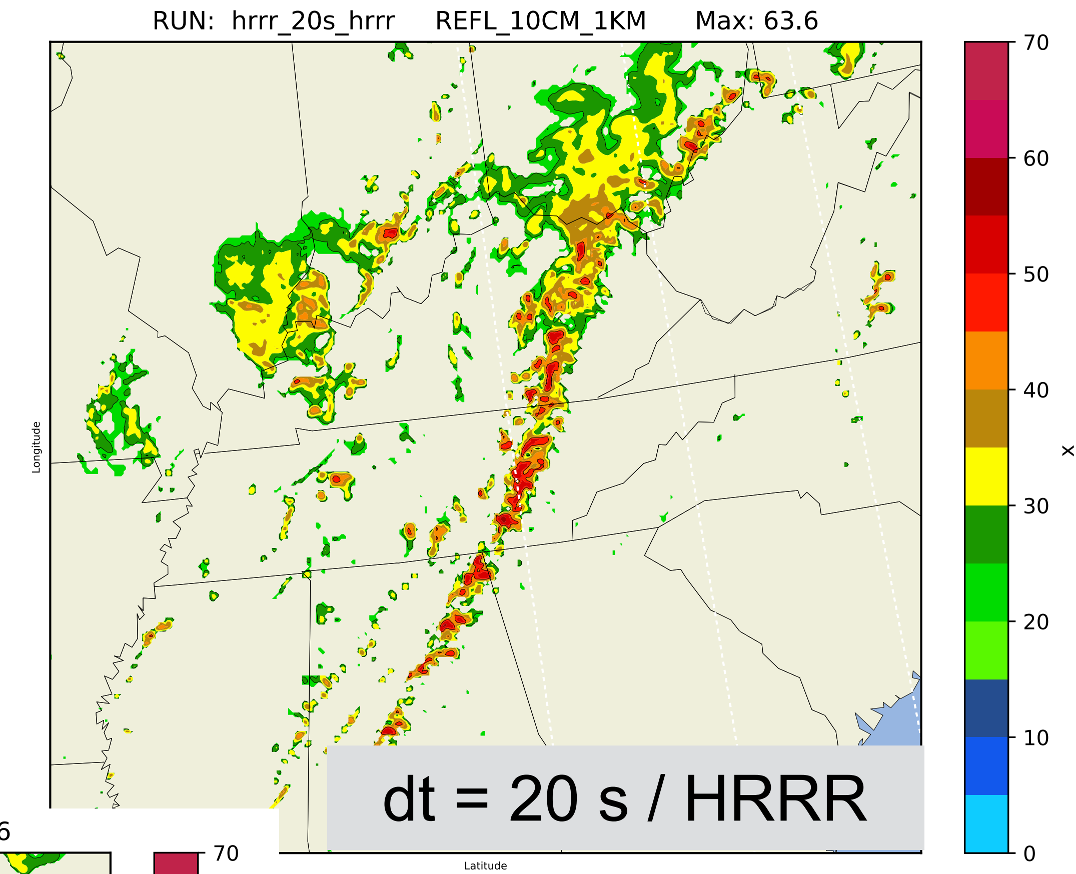
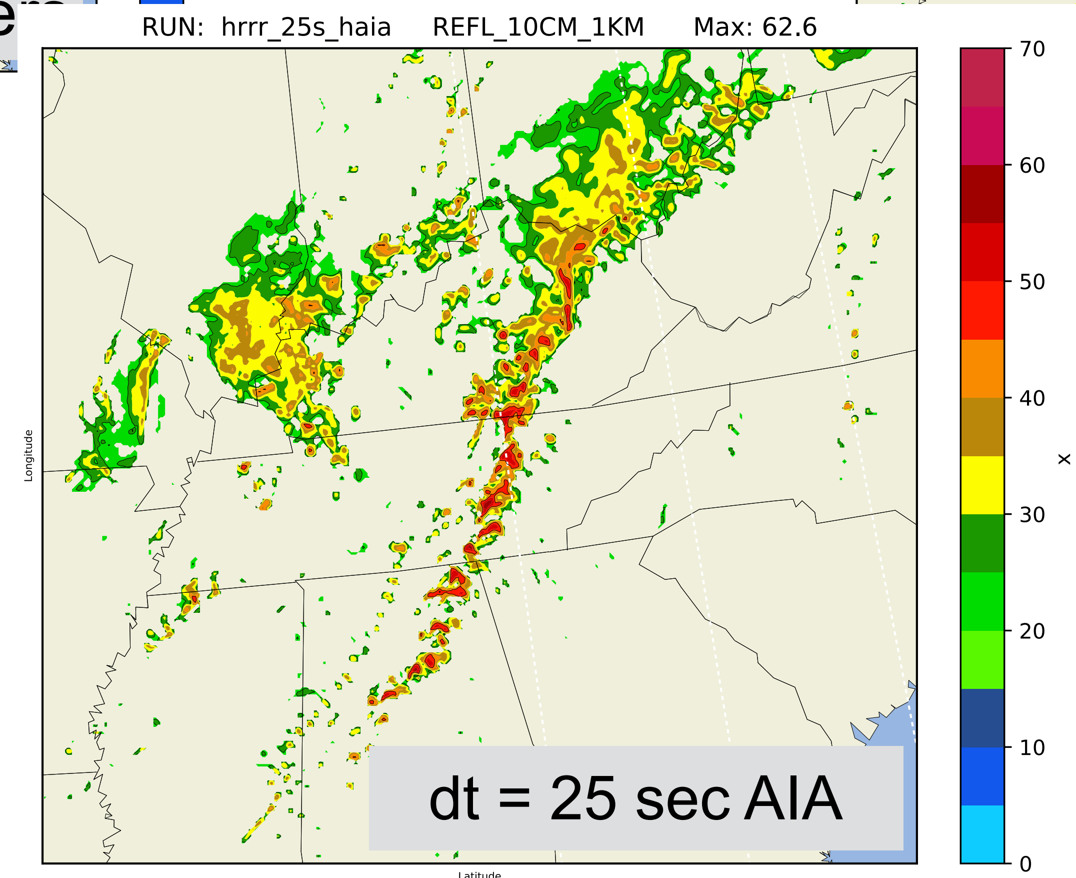
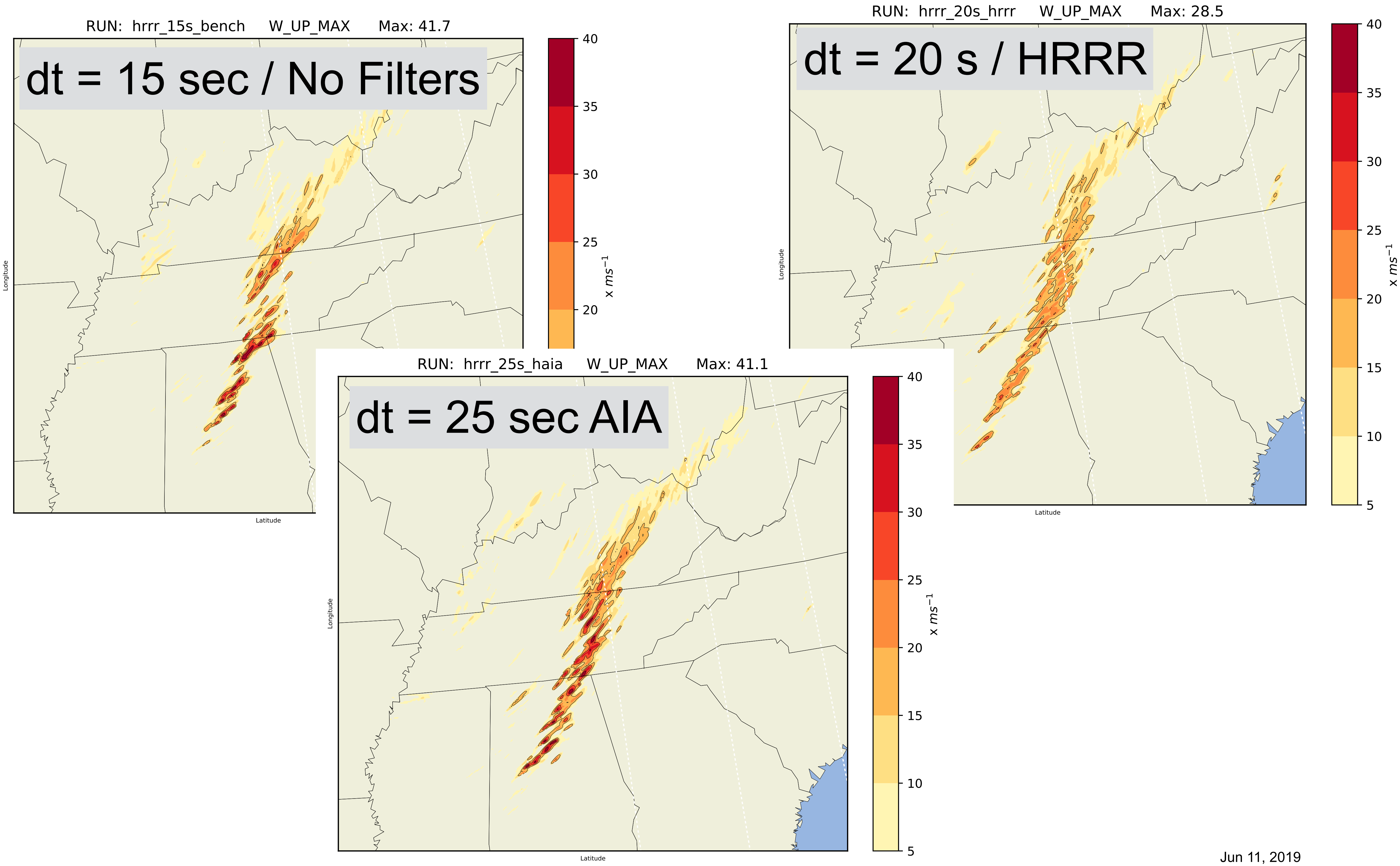
28 April 00Z 1 KM REF







28 April 00Z 1 hour Max Updraft



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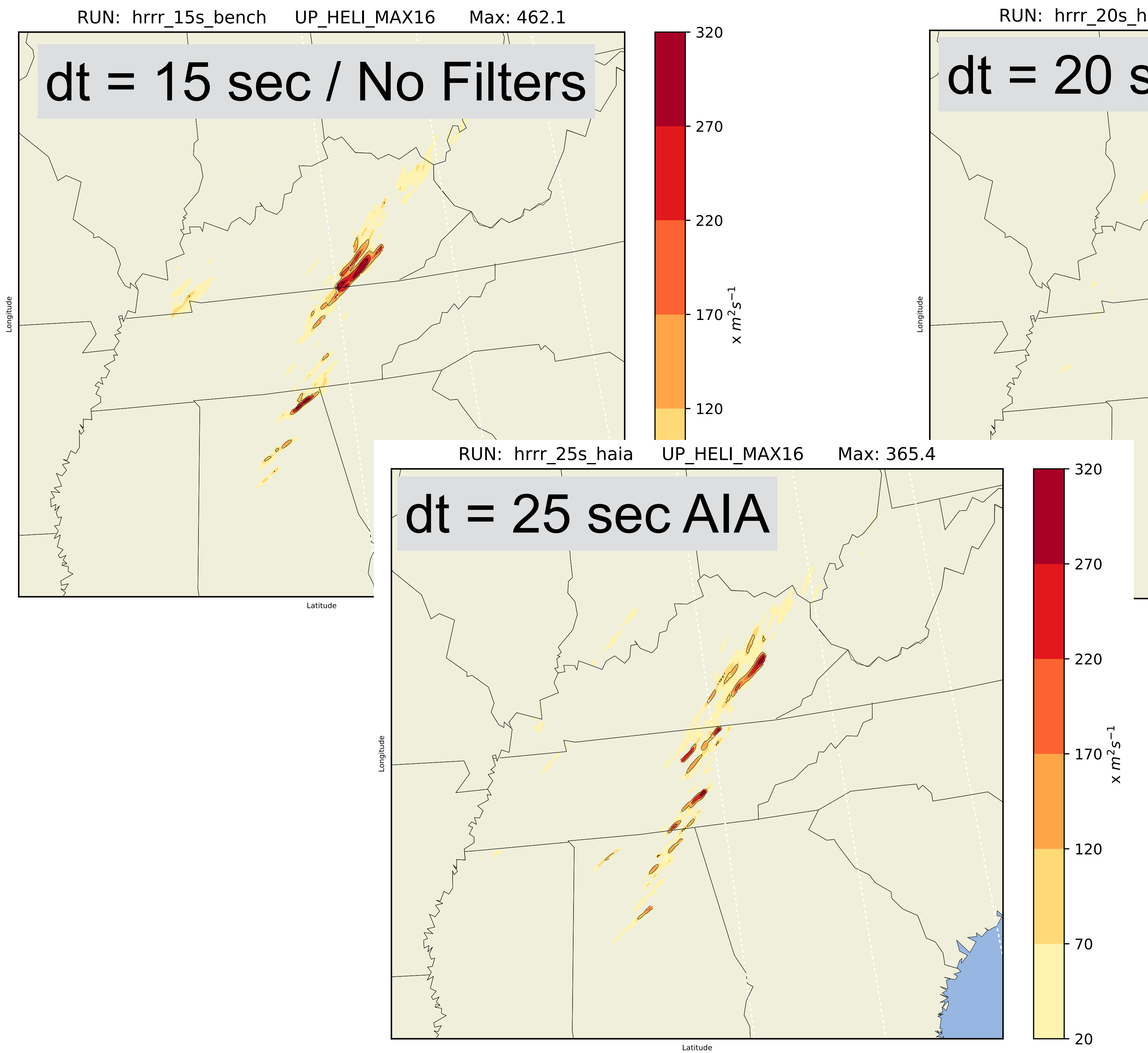

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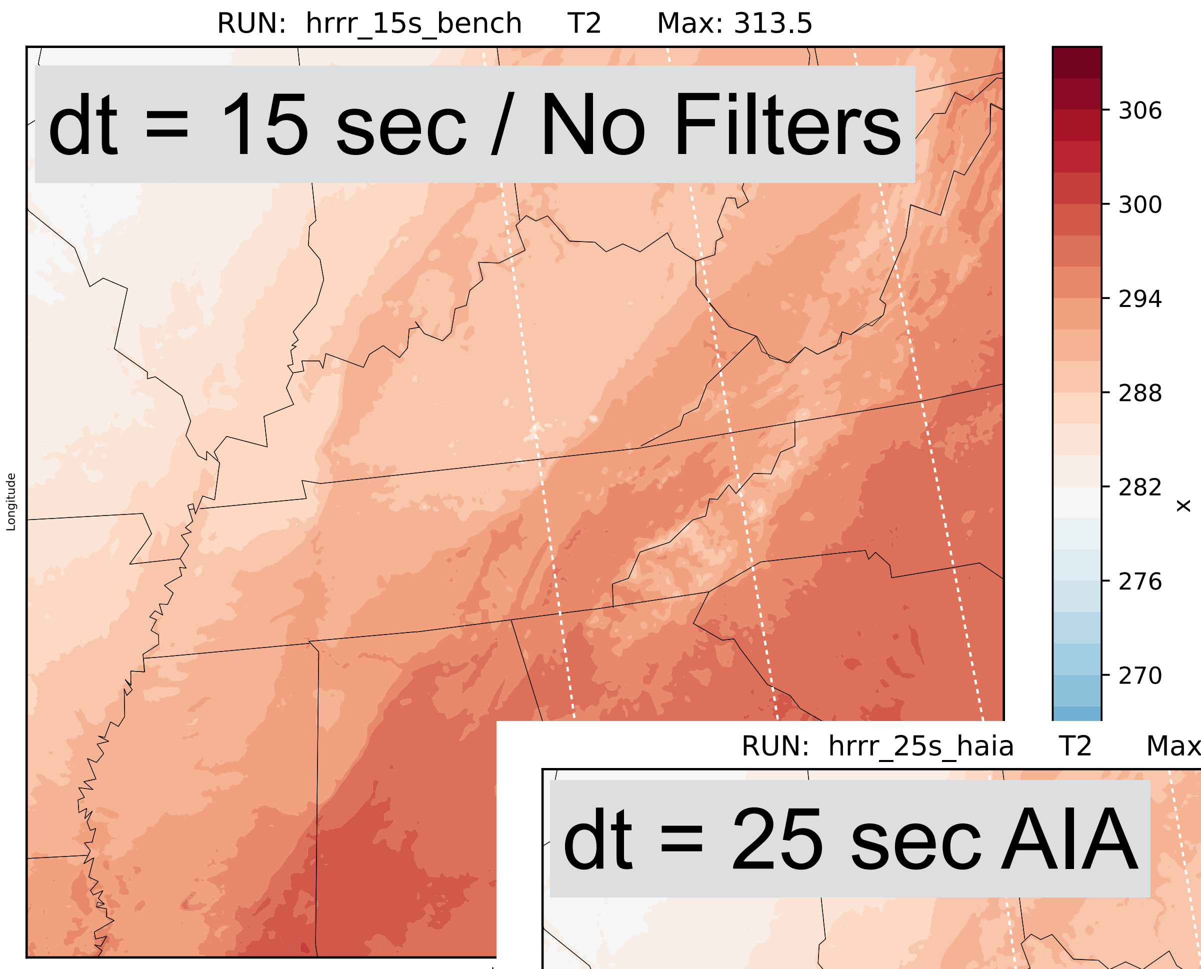
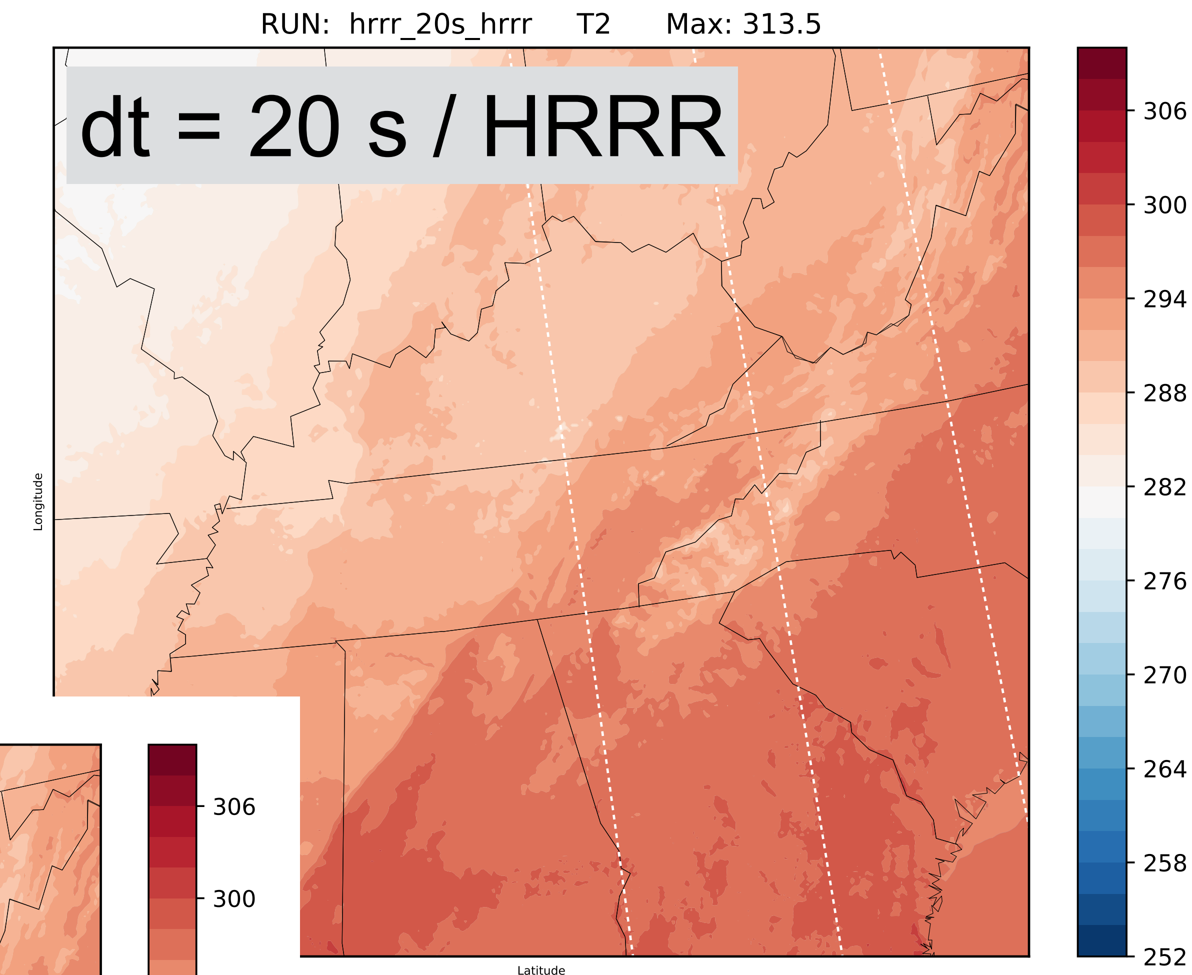
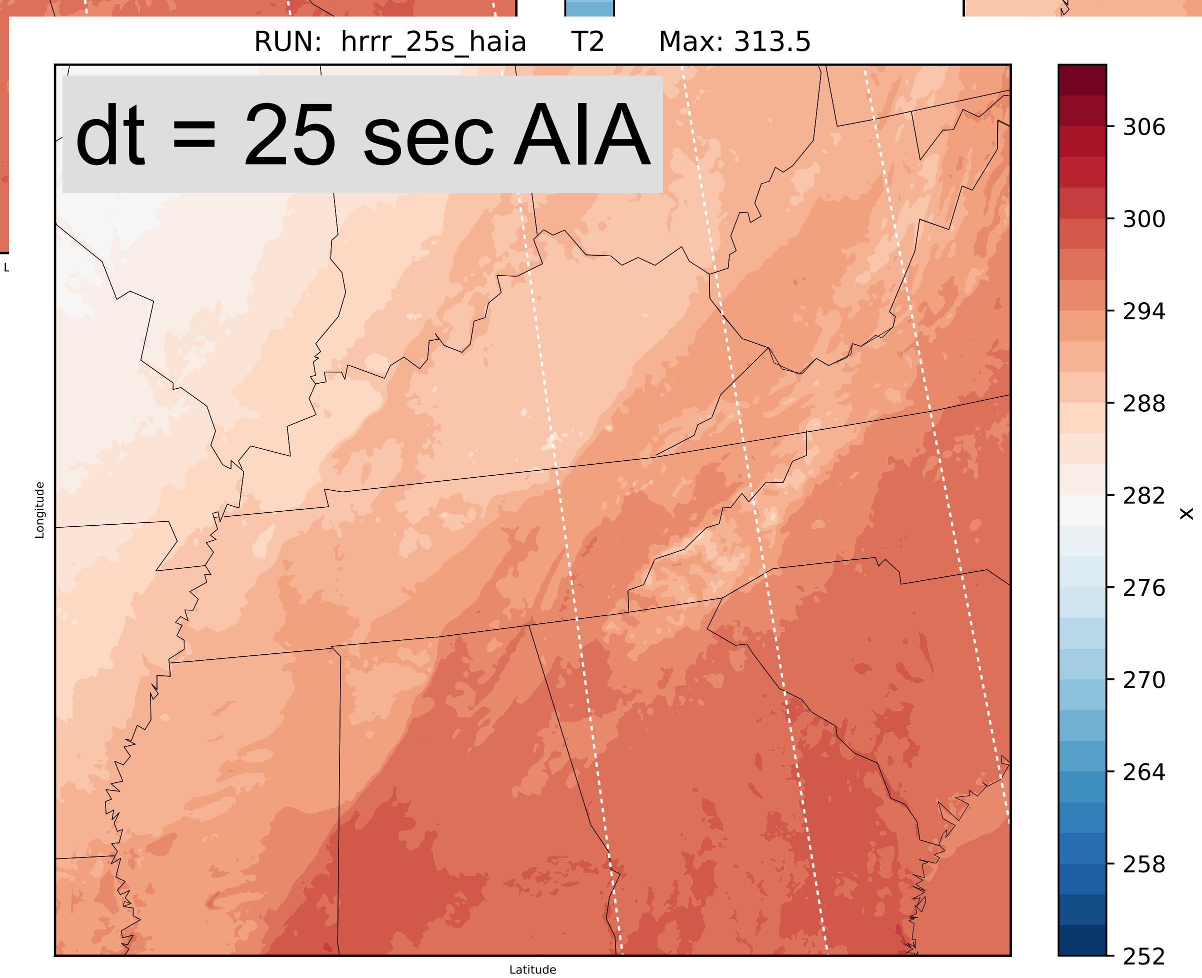
28 April 00Z Temp-2m







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Spring Exp (2017) CAM Updraft Statistics

700 mb W for hours 18-26 (21 days)

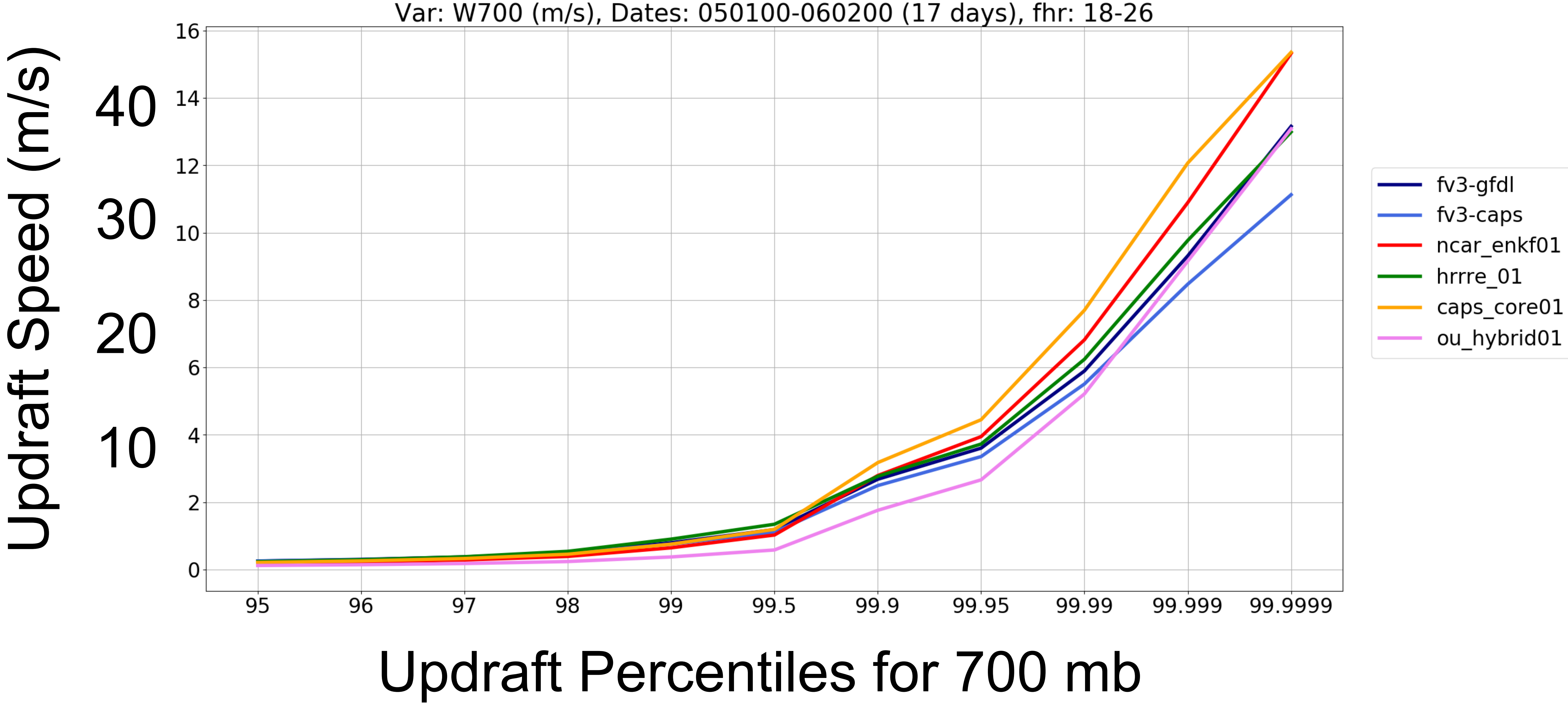


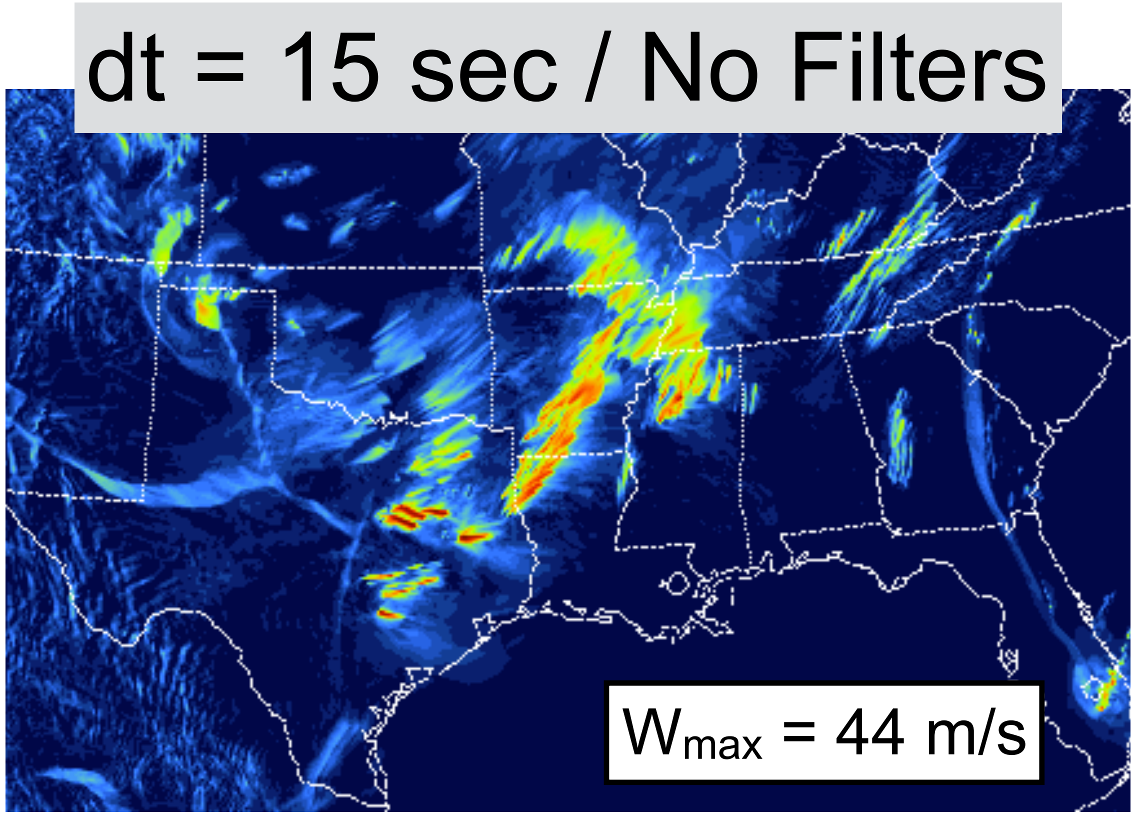
Figure courtesy of C. Potvin

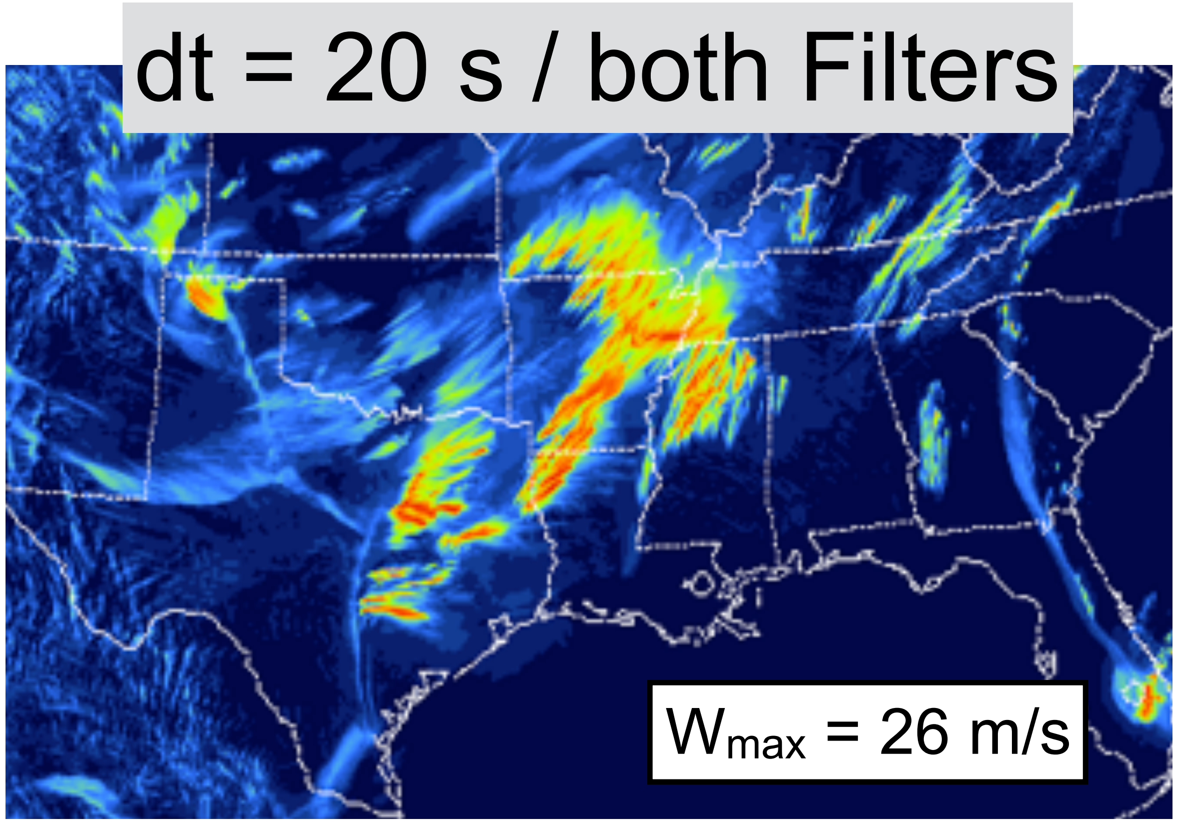
WRFv3.8 Timings

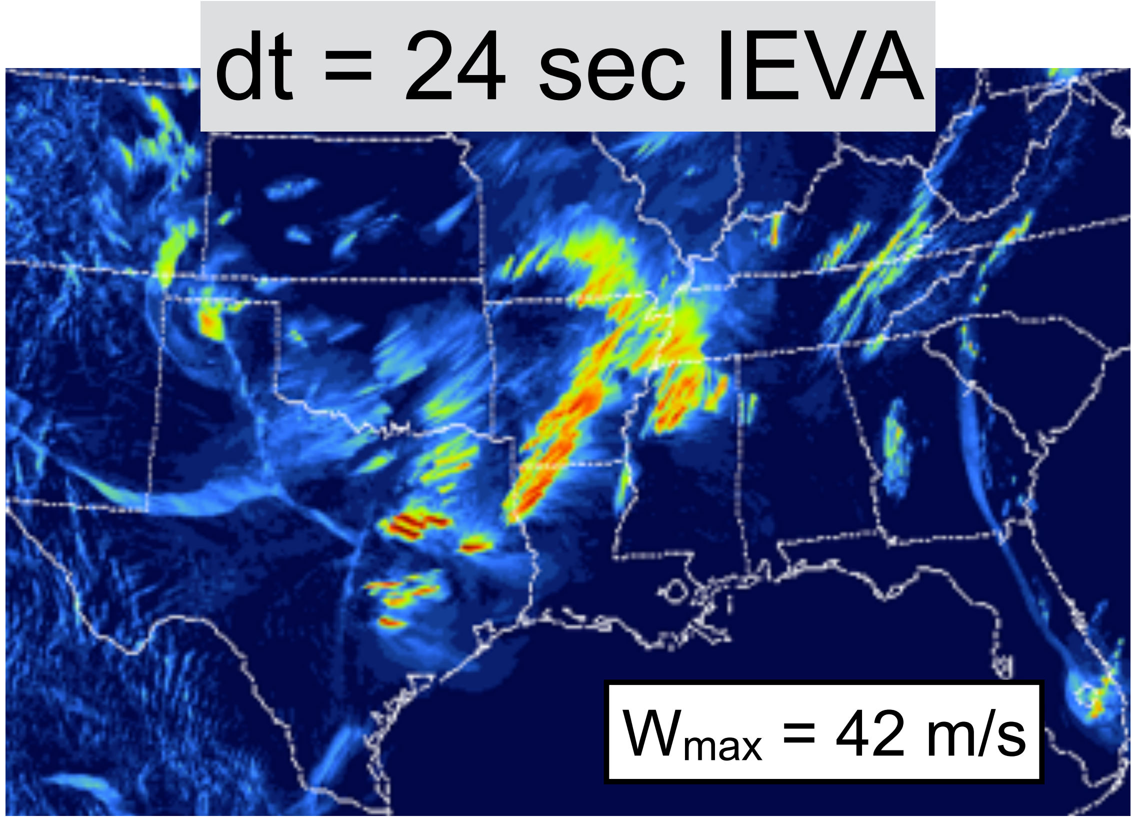
- Timings from 3 hour run 00Z-03Z 27 April
  - I/O omitted
  - 960 cores
  - 3 runs for each configuration

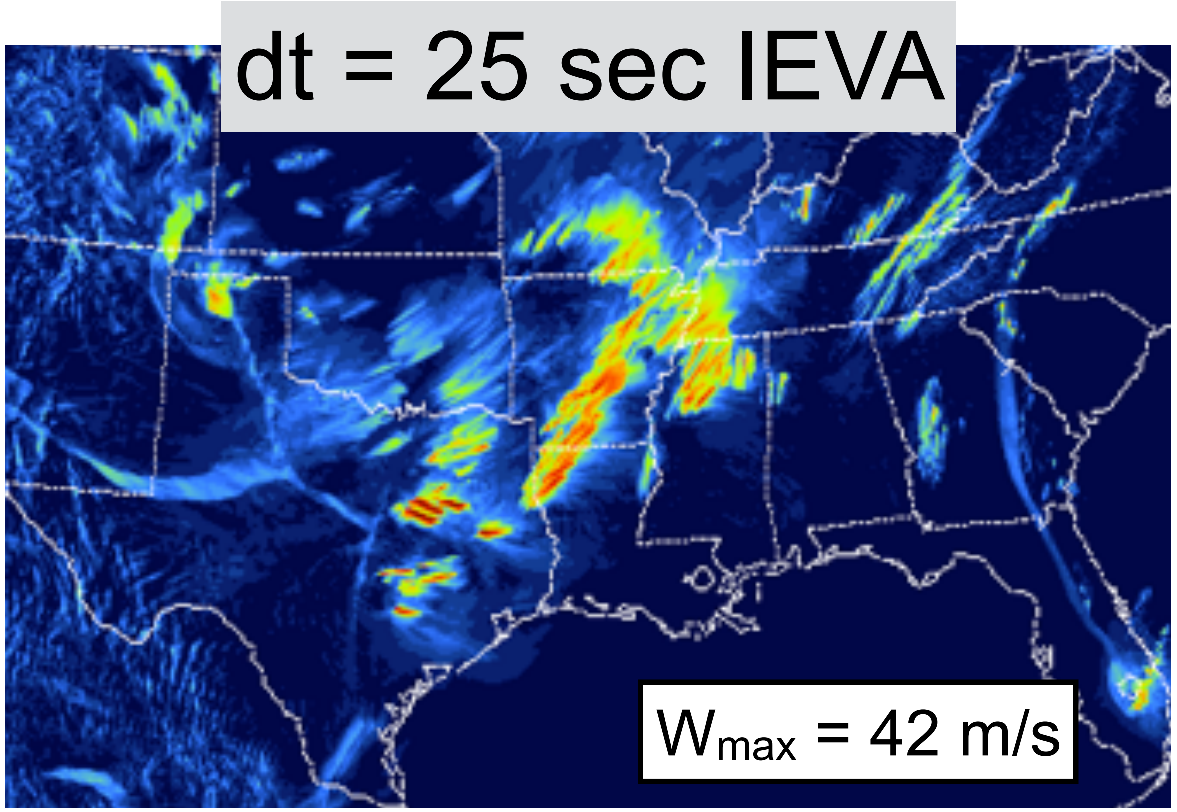
dt:	HRRR 20 s	IEVA-3 24 s	IEVA-1 24 s
Run1	443.1		383.4
Run2	443.0		383.5
Run3	442.1		386.9
Avg	442.7		384.6
Speed Up from HRRR config			14%

27 April 03Z 1 hour Max Updraft

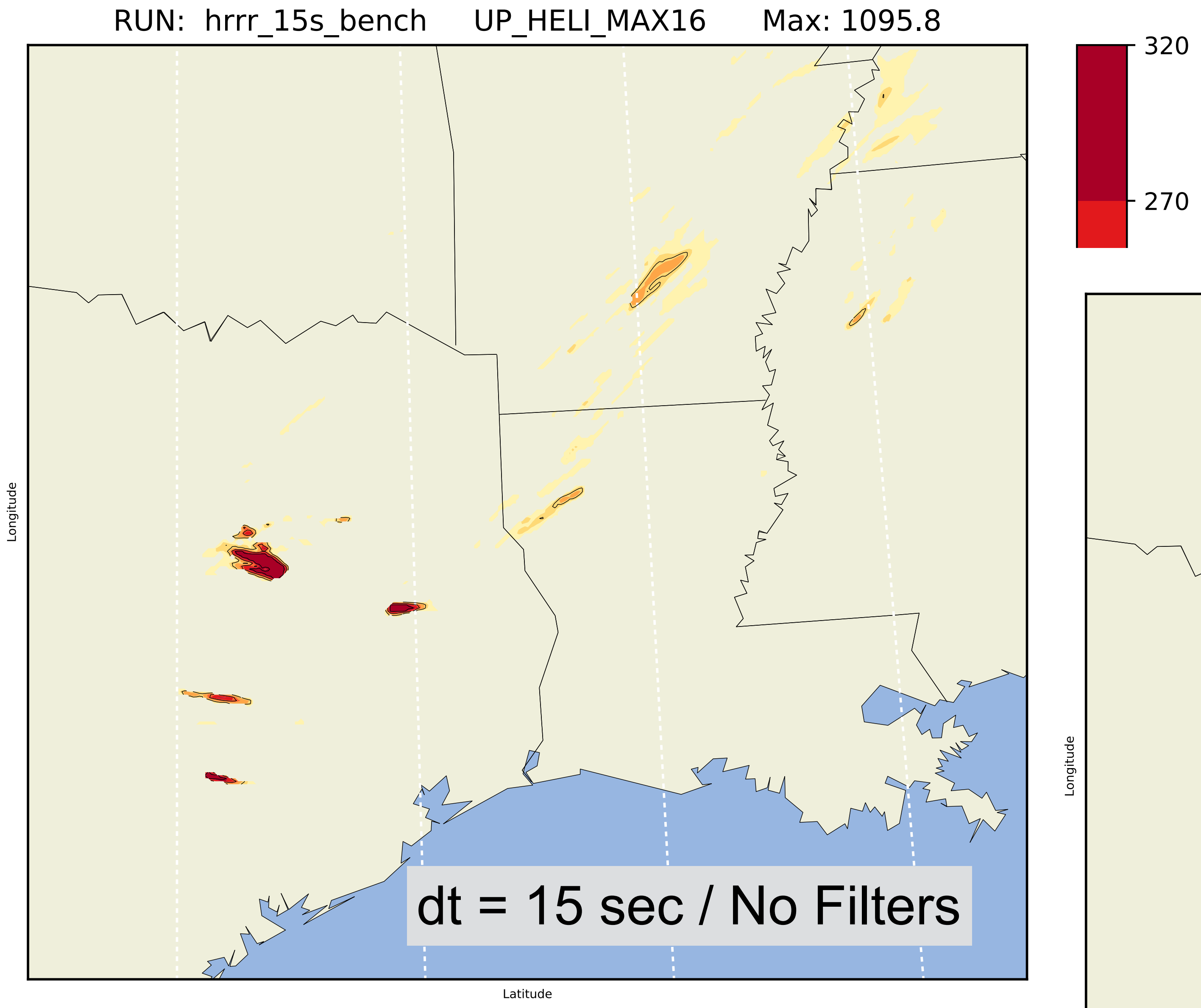


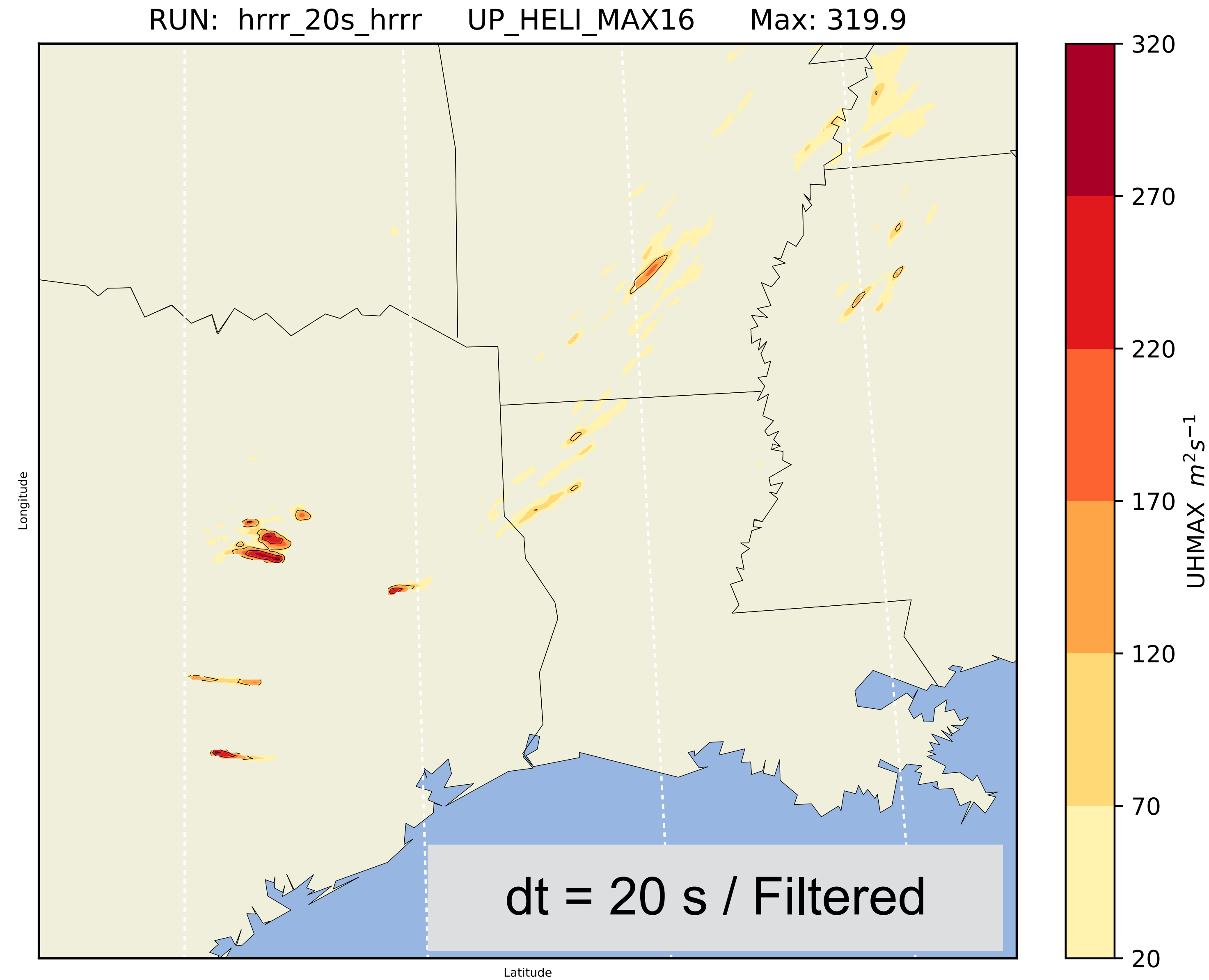




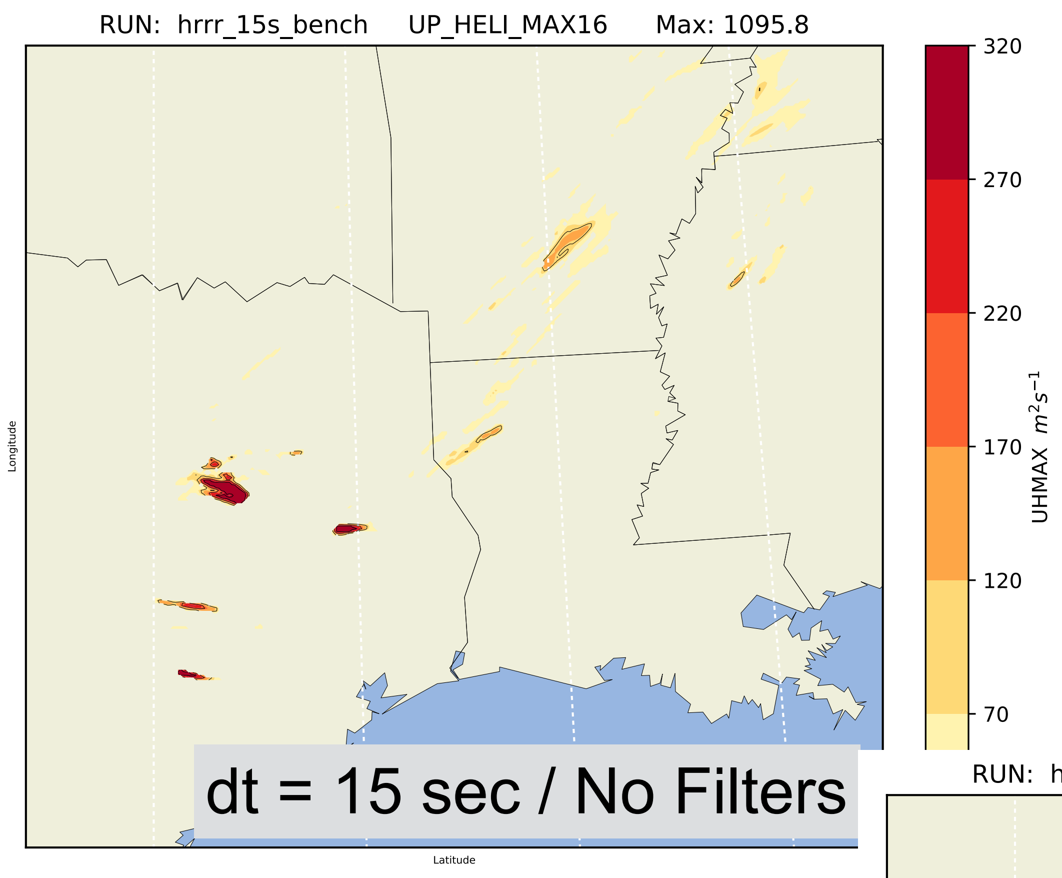


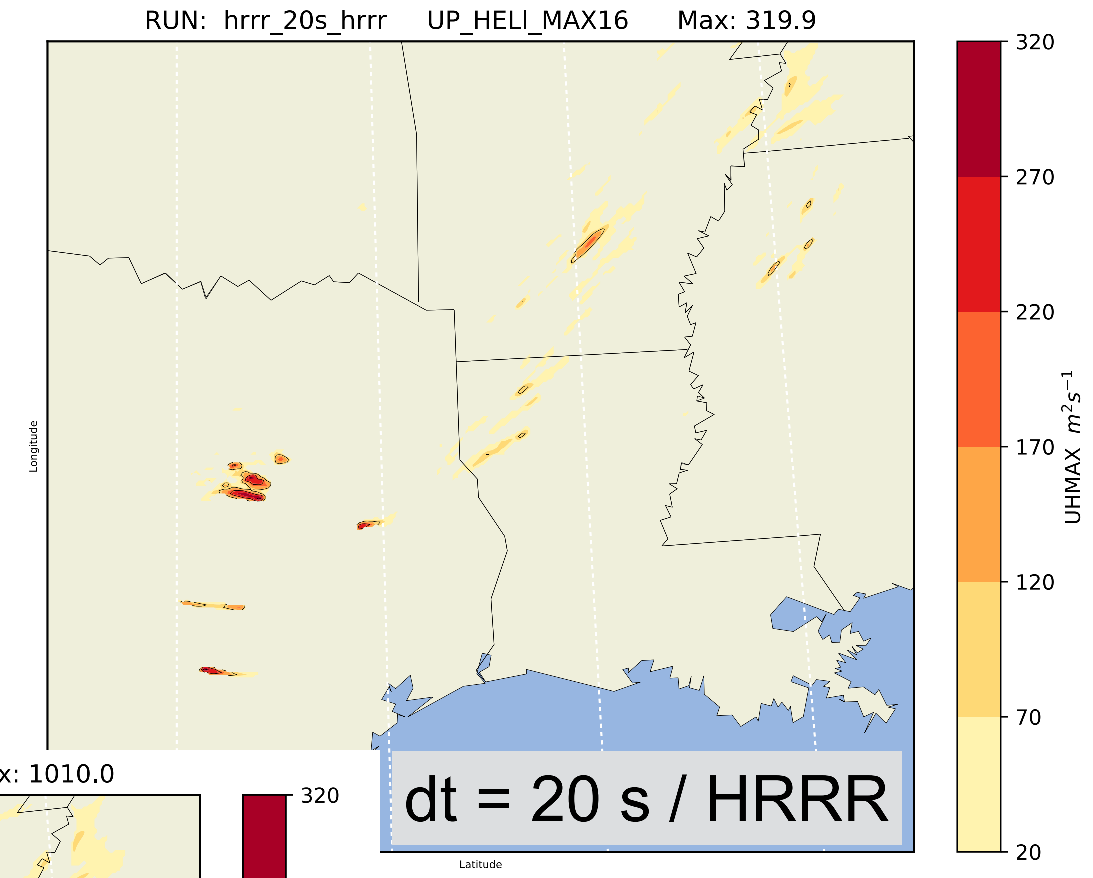
27 April 03Z 1 hour Max UH

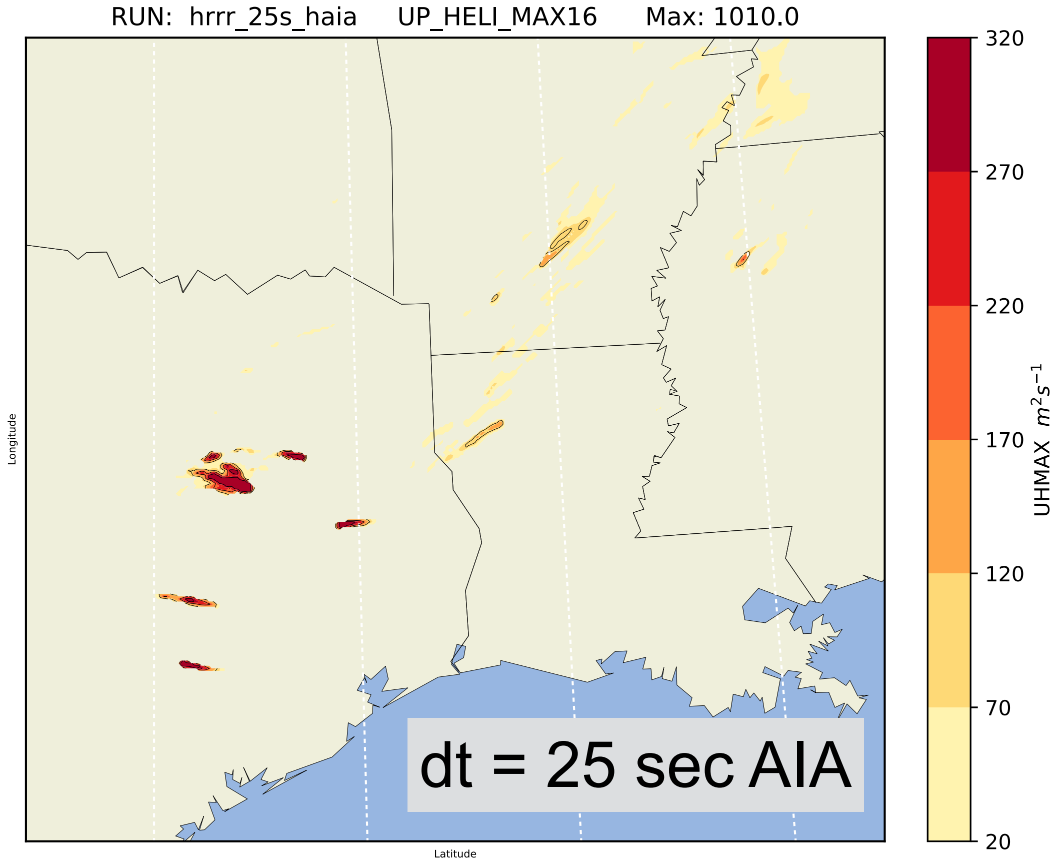




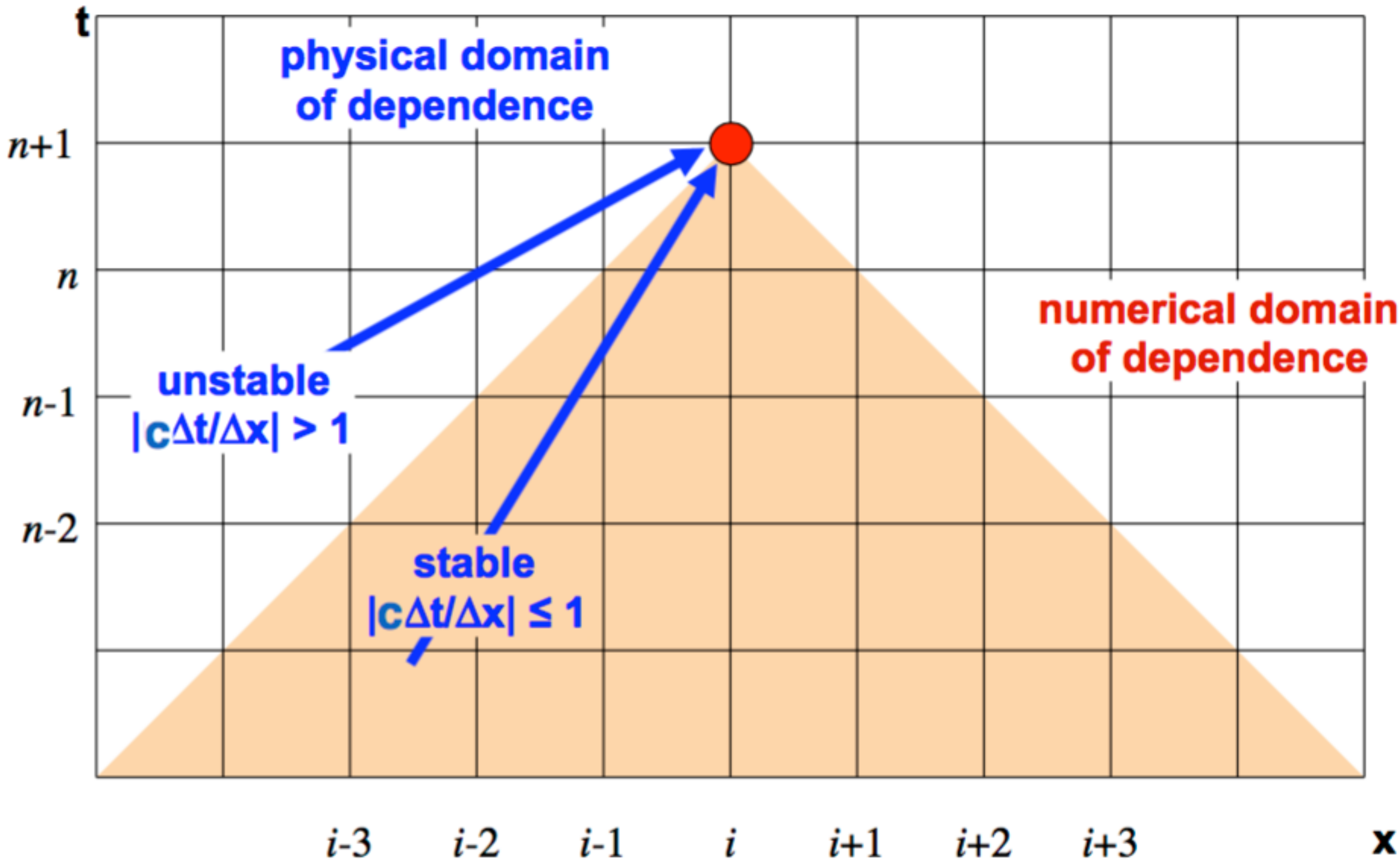
27 April 03Z 1 hour Max UH





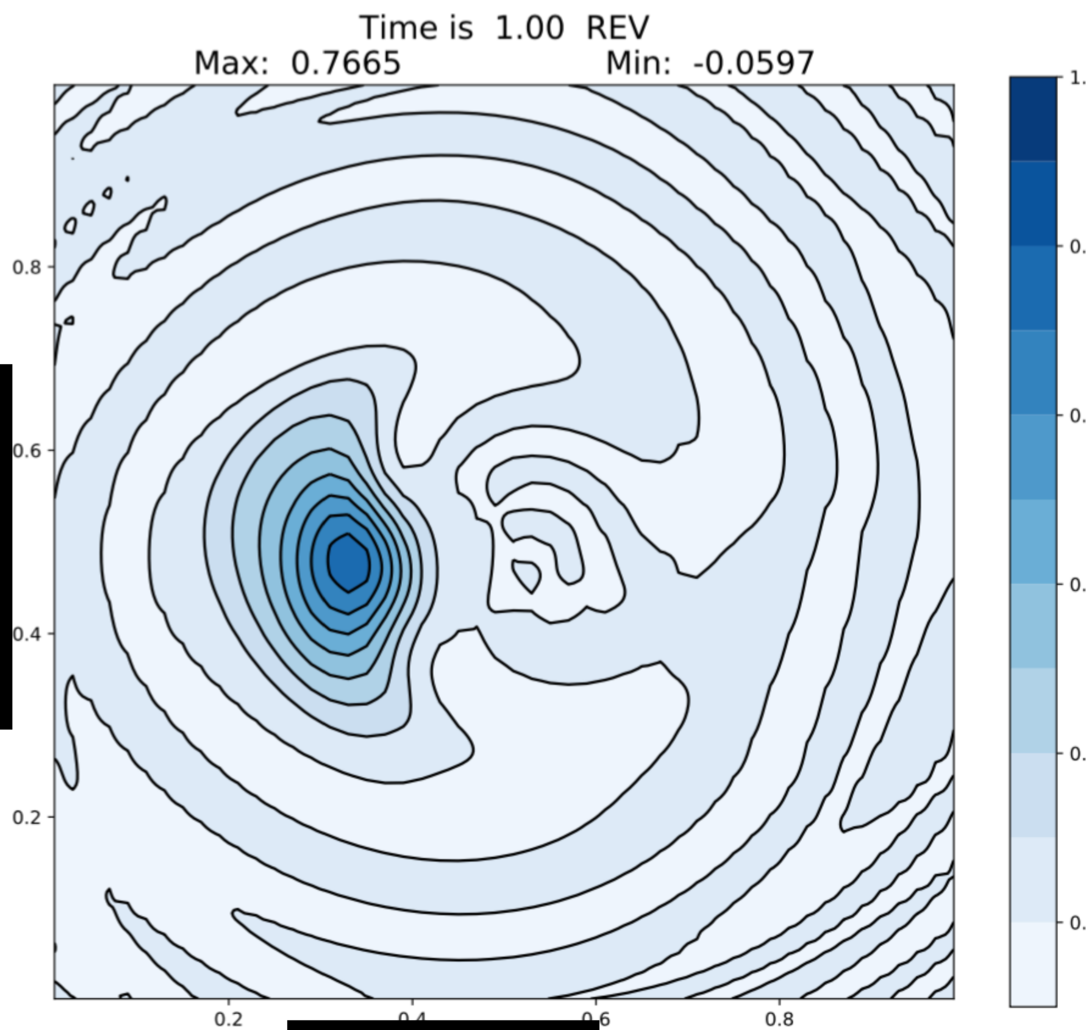


Jun 11, 2019


t
physical domain
of dependence
$n+1$
n
numerical domain
of dependence
$n-1$
unstable
$|c\Delta t/\Delta x| > 1$
$n-2$
stable
$|c\Delta t/\Delta x| \leq 1$
$i-3$
$i-2$
$i-1$
i
$i+1$
$i+2$
$i+3$
x

2D Advection Tests

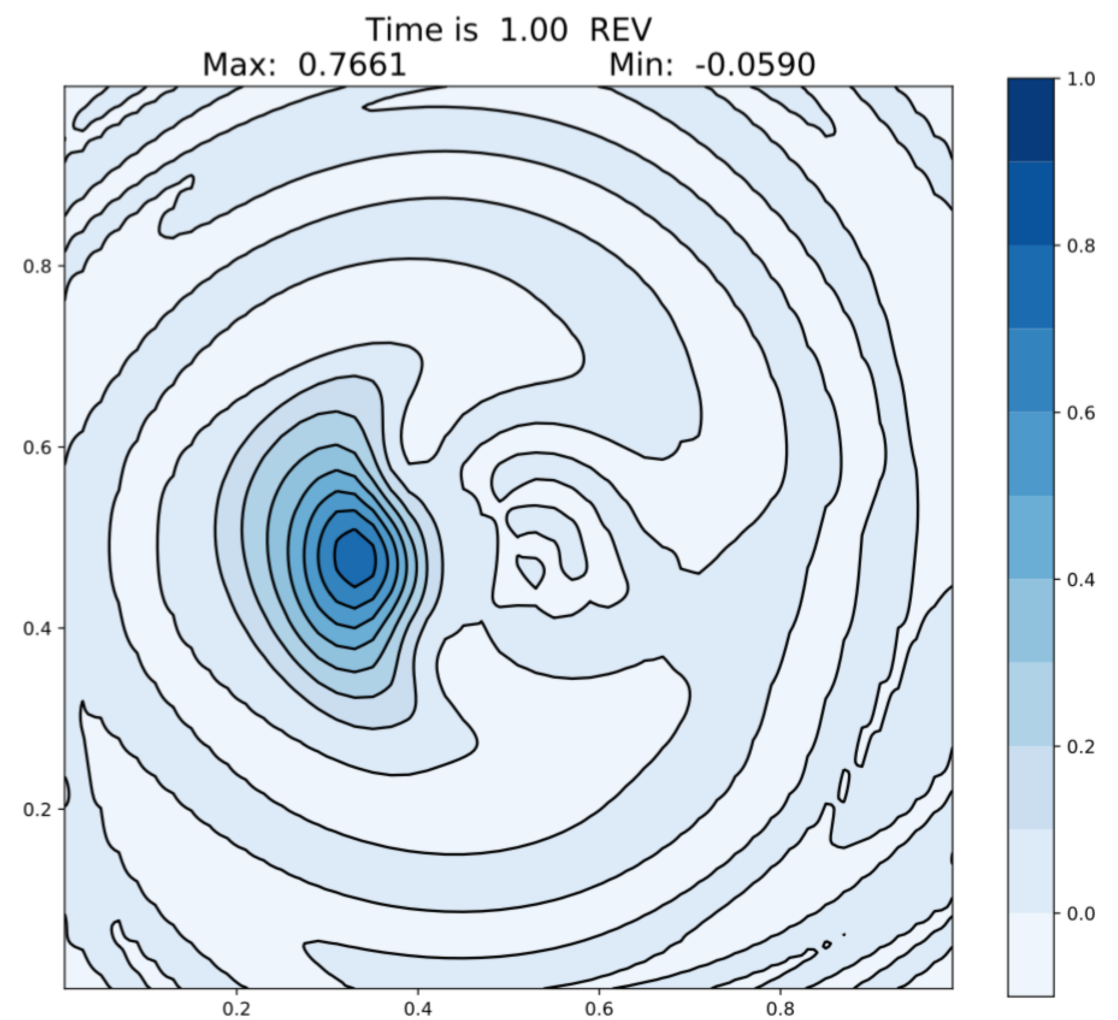
Durran-Blossy Test



300 pts

50 pts

Small dt
Max c_r in y-direction ~0.5



300 pts

50 pts

Large dt
Max c_r in y-direction ~2.0

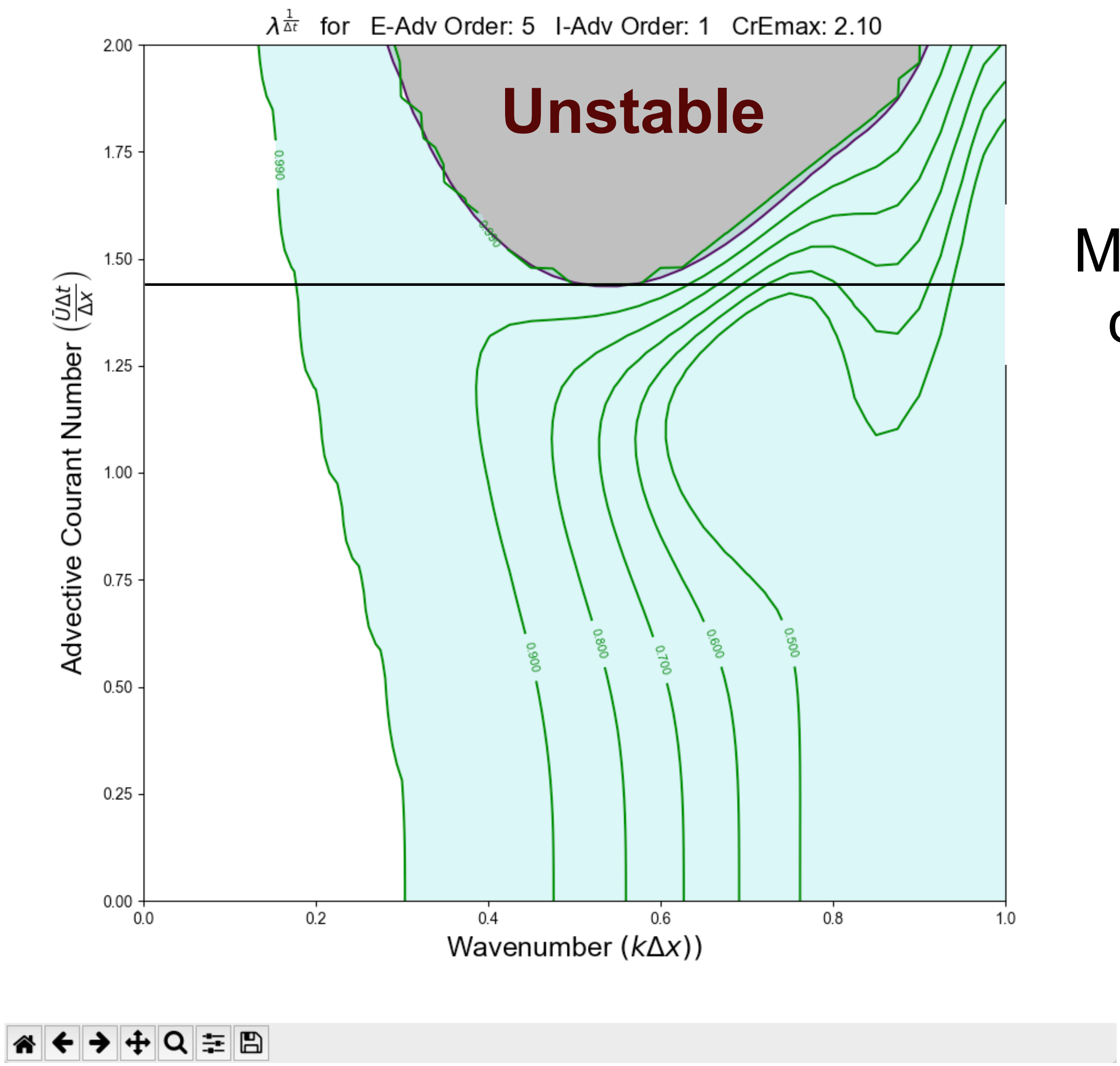
Previous Work

- Other approaches?
  - FV3: partially decouple vertical advection from horizontal via “lagrangian" vertical discretization
  - Baldauf (2010) RK4 with 4th order advection? (potentially 45% increase in time step vs RK3)
  - Semi-lagrangian vertical advection (Wicker, 2015) - unstable with time splitting (but worked!)
  - Increase time step through more RK iterations (Hu 1996, Wicker RK5 WRF scheme)
- If we can increase the large time step and gain an efficiency increase:
  - by 10%? Valuable for operational systems!! (10% is probably 7-10 minutes for HRRR run)
  - by 20%?
    - higher horizontal and vertical resolution (but increased vertical costs current has 2x cost).
    - more complex physics (2-moment microphysics?)
    - more ensemble members?

Stability Analysis

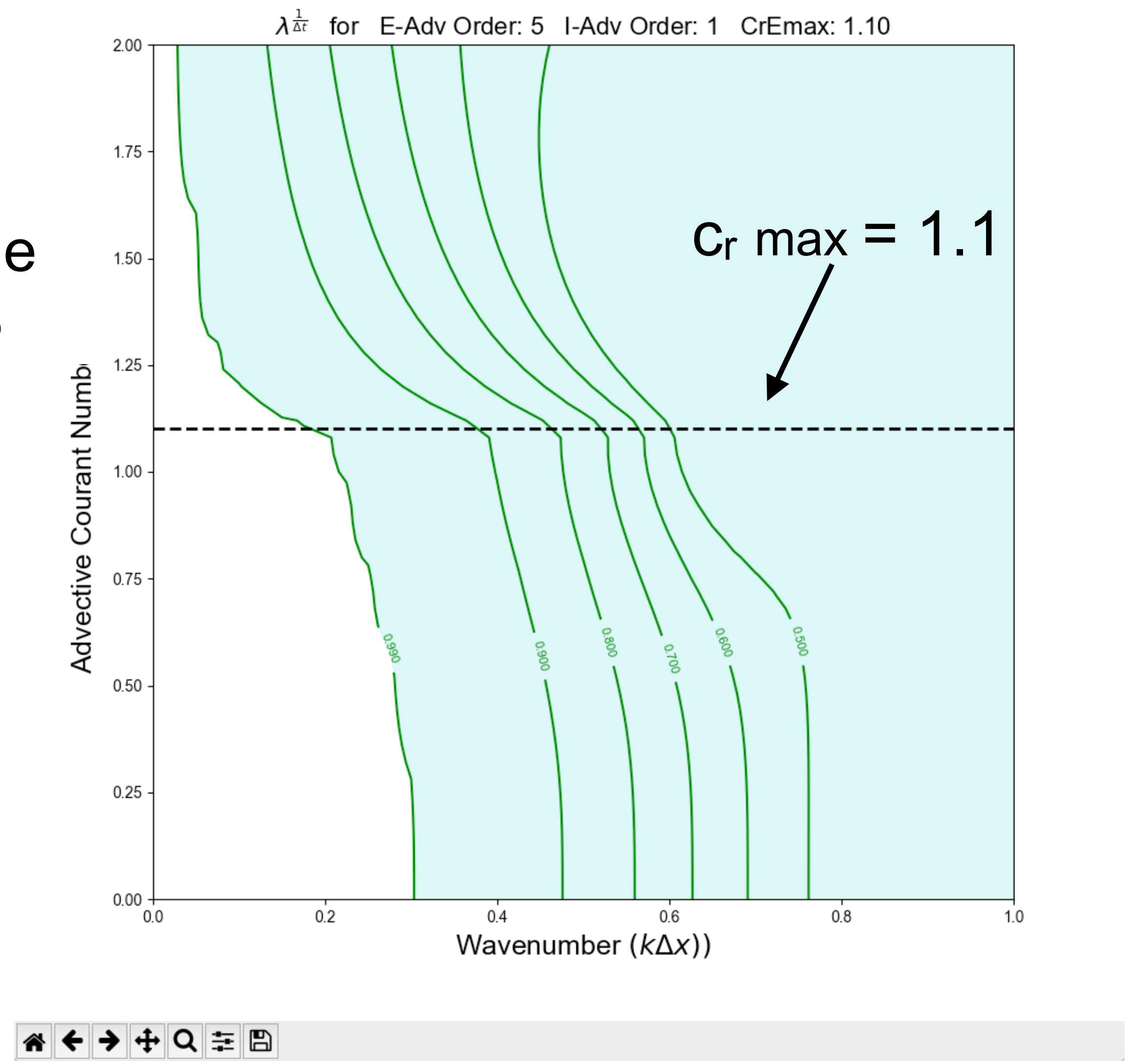
RK3 Advection Only
5th order spatial

Pure RK3



Max stable
c_r = 1.43

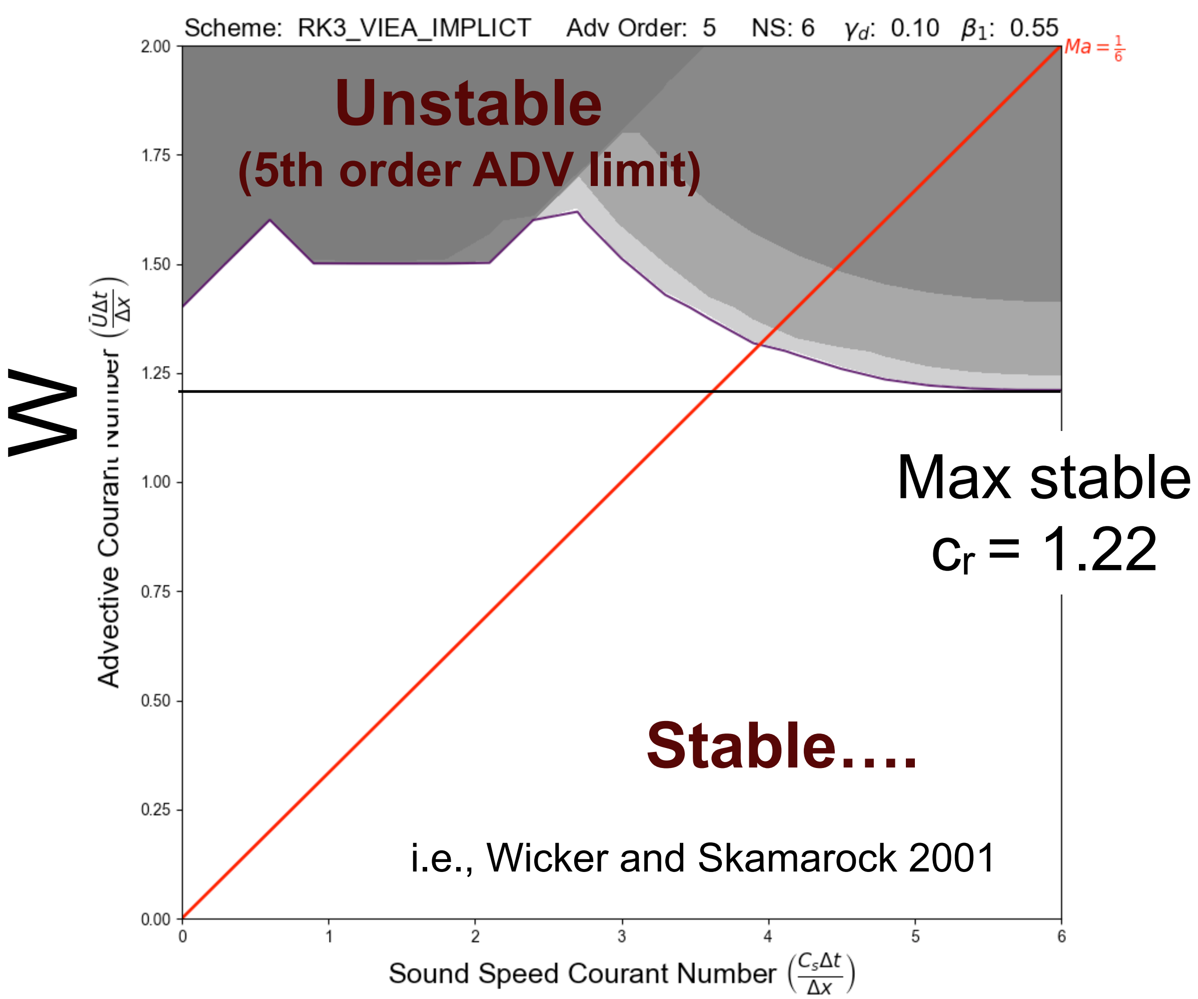
RK3-IEA



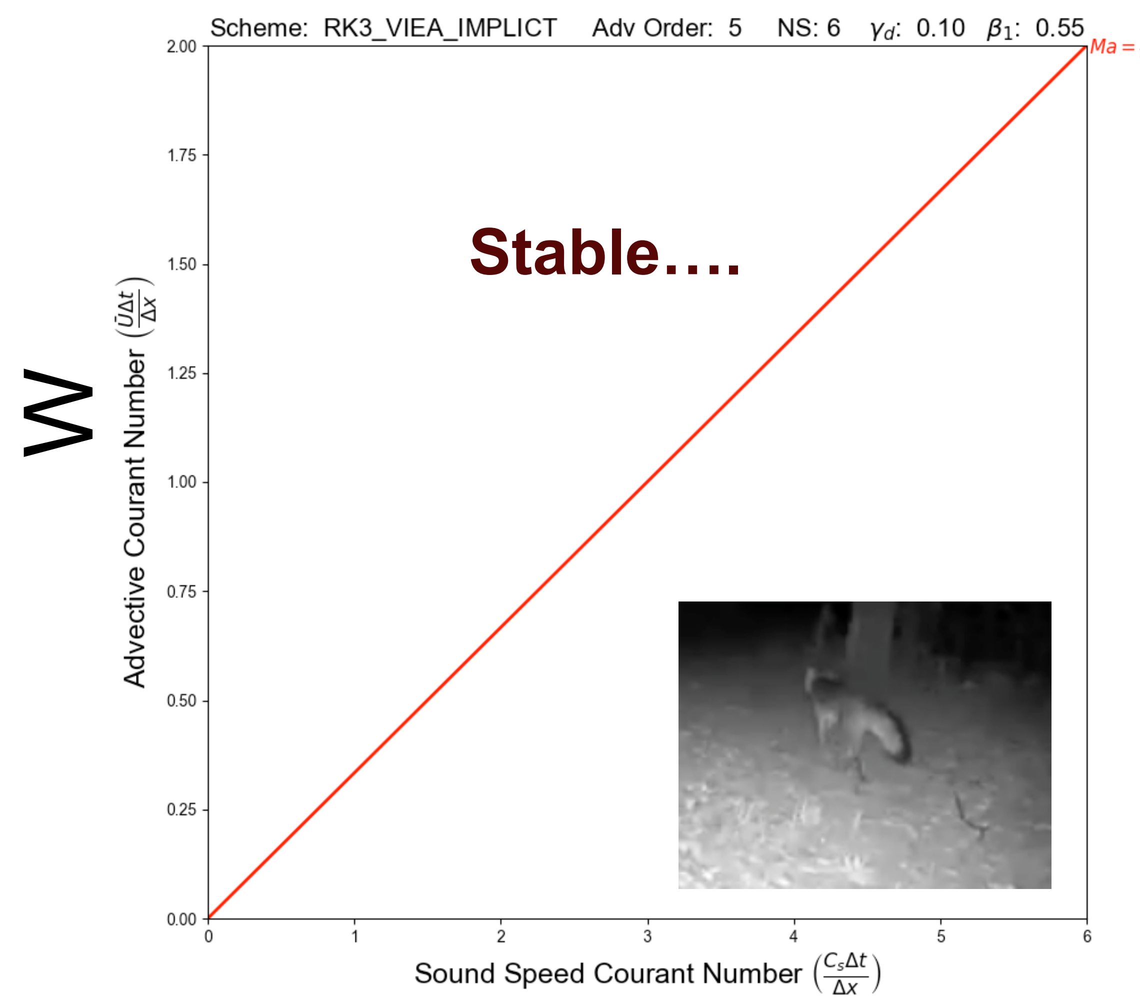
Stability Analysis

Time-Split RK3
5th-order Adv & Vert. Implicit (beta_offset=0.55)

RK3-WS01



RK3-IEVA



Some details

- Prototype WRF eq for "S"
- Solving only for Ex/Im advection piece…
  - could add other pieces (pos-def tends, etc)
  - ROMS adds in vertical diffusion solving that implicitly as well.
- Tridiagonal solution written in incremental form
  - extra terms on RHS accounts for increments from time "n".
  - solved on each sub-RK step

$$
\begin{aligned}
s_{ijk}^{l+1} &= s_{ijk}^{l} + \Delta t^{\,l}\; F_{adv}^{ex}\left(s^{l}\right) \\
&\quad - \frac{\Delta t^{\,l}}{\Delta z_{ijk}}\left[\max(w_{k+1/2}^{im},0)\, s_{k}^{l+1} + \min(w_{k+1/2}^{im},0)\, s_{k+1}^{l+1}\right]_{jk} \\
&\quad + \frac{\Delta t^{\,l}}{\Delta z_{ijk}}\left[\max(w_{k-1/2}^{im},0)\, s_{k-1}^{l+1} + \min(w_{k-1/2}^{im},0)\, s_{k}^{l+1}\right]_{jk}
\end{aligned}
$$

$$
\begin{aligned}
A_k \delta s_{k-1}^{l+1} + \left(1 + B_k\right)\delta s_{k}^{l+1} + C_k \delta s_{k+1}^{l+1} &= \Delta t^{l}\; F_{adv}^{ex}\left(s^{l}\right) \\
&\quad - A_k s_{k-1}^{n} - B_k s_{k}^{n} - C_k s_{k+1}^{n}
\end{aligned}
$$

$$
\begin{aligned}
F_{adv}^{ex} &= F_{adv}^{ex} + \frac{\delta s}{\Delta t} \\
A_k &= -\Delta t \max(w_{k-1/2}^{im},0) \\
C_k &= \Delta t \min(w_{k+1/2}^{im},0) \\
B_k &= \Delta t\left[\max(w_{k+1/2}^{im},0) - \min(w_{k-1/2}^{im},0)\right]
\end{aligned}
$$

$$
\begin{aligned}
&rk3-loop \\
&l = 1,2,3 \\
&\Delta t^{l} = \left[\Delta t/3, \Delta t/2, \Delta t\right]
\end{aligned}
$$

Algorithm Details…

DO LOOP = 1, RK-ORDER

Dynamical variable advection

Partition omega into ww^e and ww^i using S2015 algorithm using splitting subroutine

↓

Using the ww^e (explicit partition of the vertical motion) compute explicit advection tend

↓

After the explicit tend is computed, call the implicit advection routine passing ww^i and explicit tend

↓

Now have complete advection tend
Run small time step

→

Scalar Advection

Partition time-averaged omega into ww^e and ww^i using S2015 algorithm (call subroutine again with time-averaged omega)

↓

Using the ww^e (explicit partition of the vertical motion) compute explicit advection tend

↓

After the explicit tend is computed, call the implicit advection routine passing ww^i and explicit tend

↓

Now have total advection tend
update Scalars

ENDDO RK LOOP

Feeling Dazed and Confused?

Translating Downburst Test

- 2D dry compressible model
- 36 x 6 km Box: X(periodic) / Z(rigid)
- Adiabatic profile
- T_{Init} = -16K bubble
- U_{init} = 20 m/s (no shear)
- T=900 s:

  Solution should be anti-symmetric
- U_{max} ~ 55 m/s
- W_{max} ~ -30 m/s

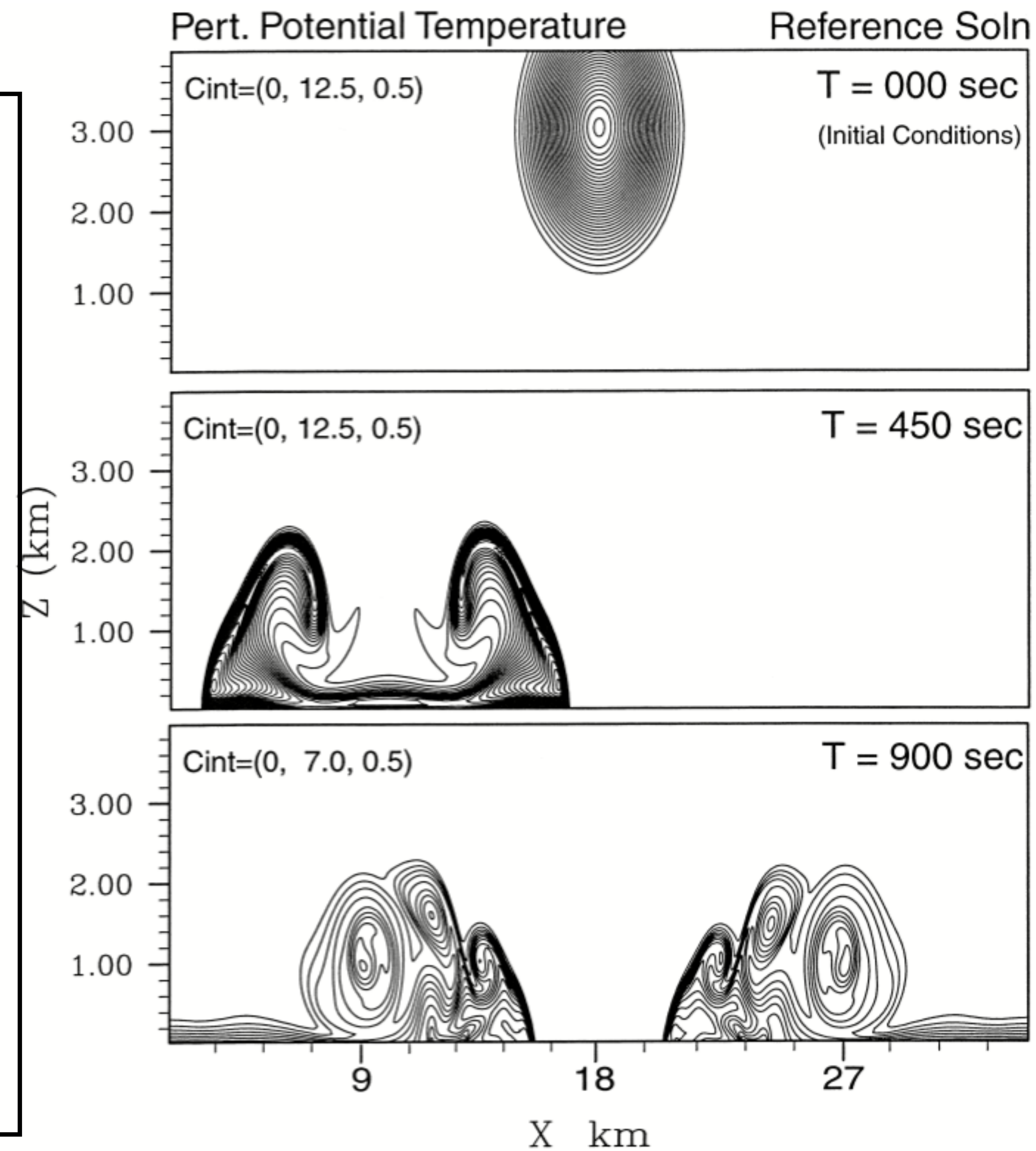
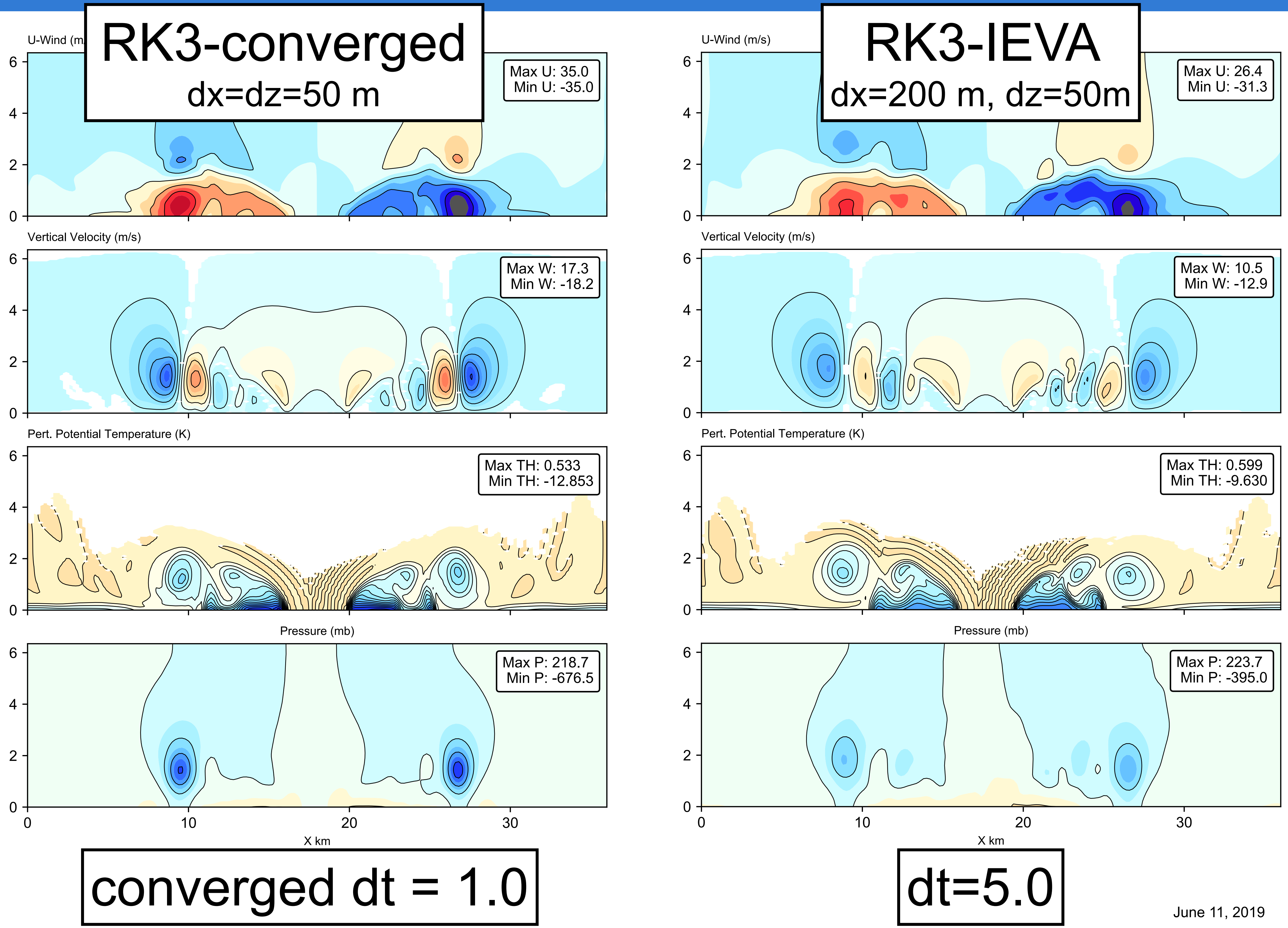


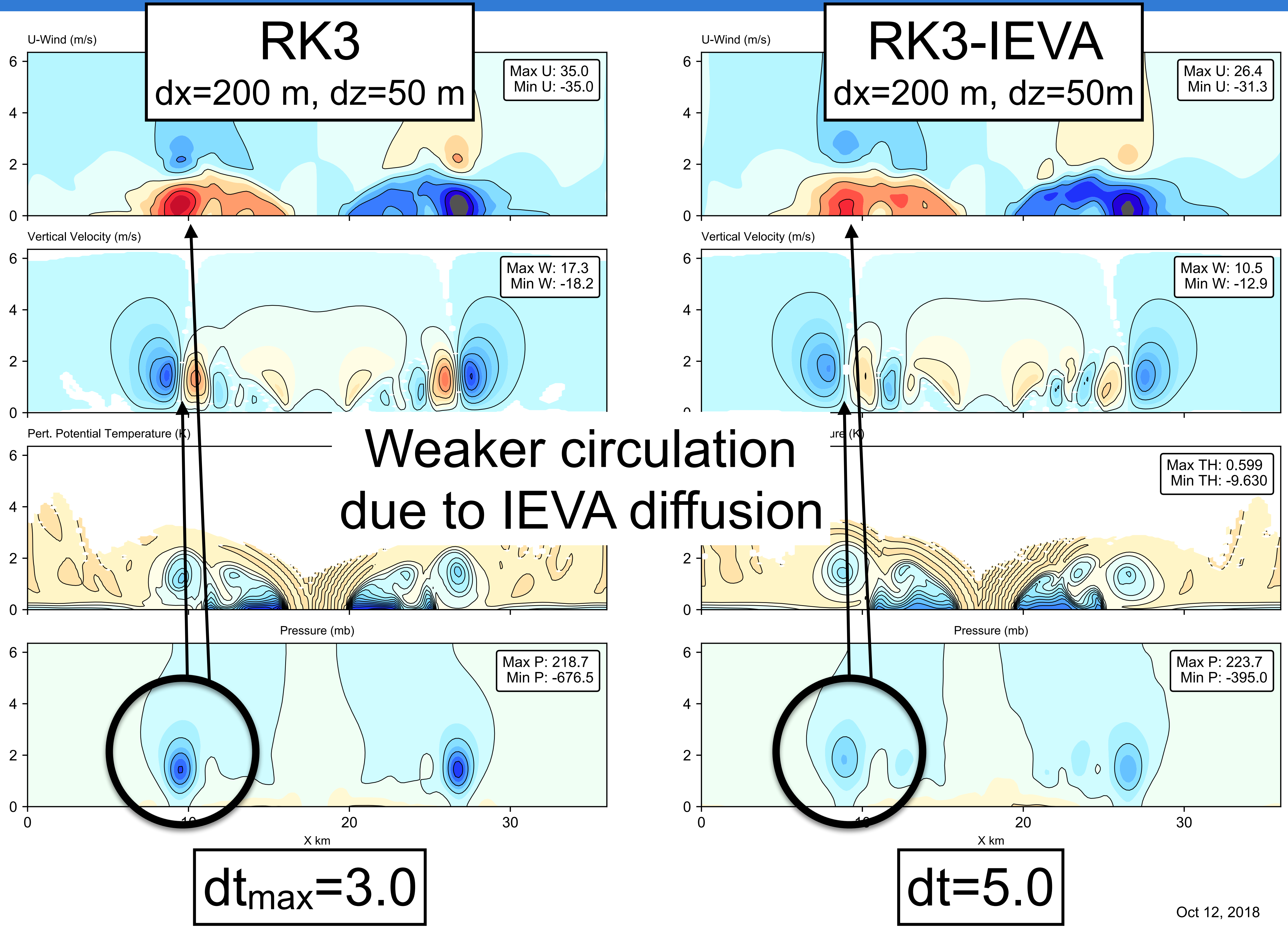
FIG. 2. Perturbation potential temperature reference solution for the translating downburst problem using a 4th-order leapfrog integration method with a grid resolution of 50 m. The max, min, and contour interval are displayed in the upper left.

Translating Downburst / $\frac{\Delta x}{\Delta z} = 4$



June 11, 2019

Translating Downburst / $\frac{\Delta x}{\Delta z} = 4$



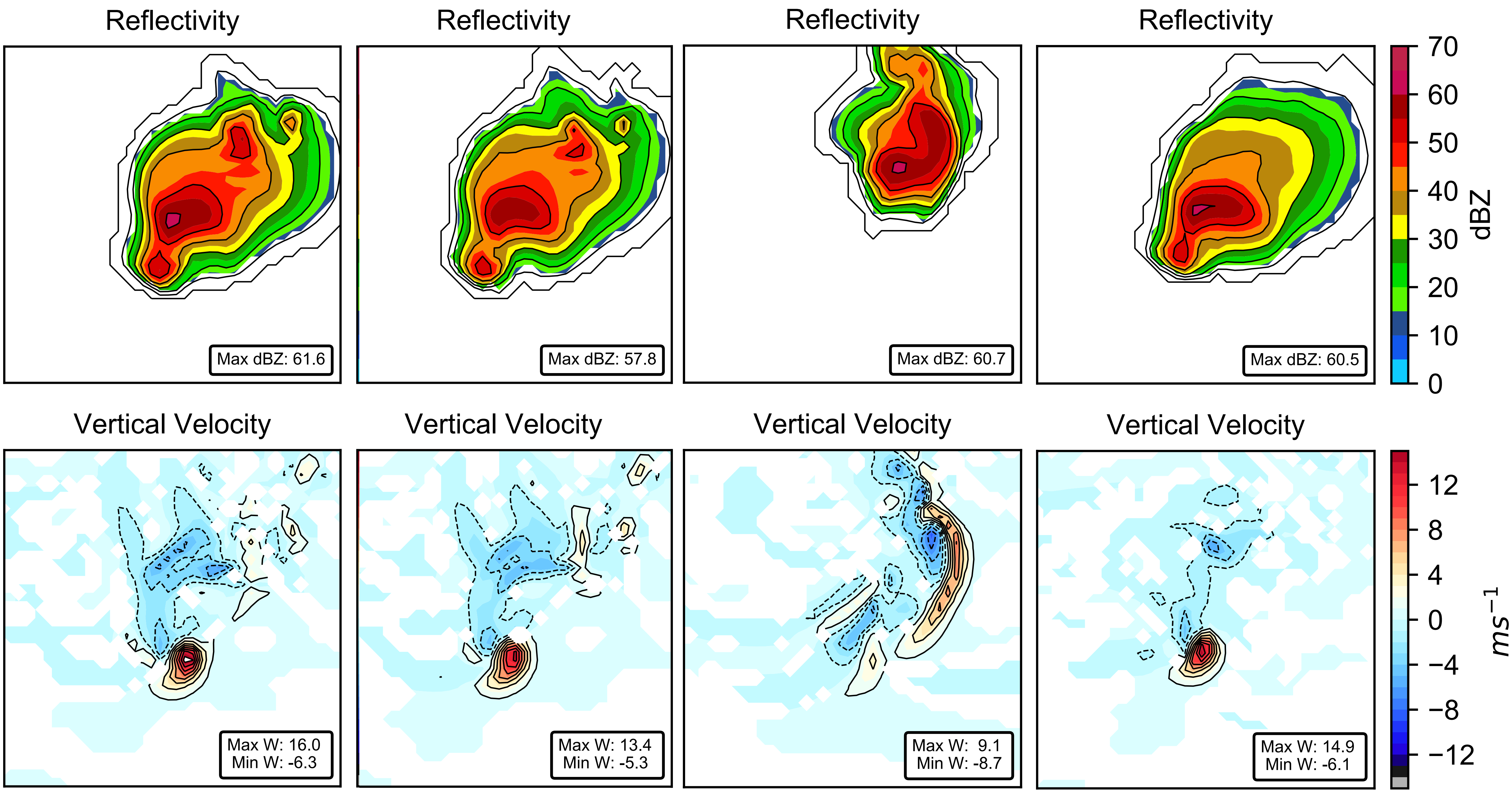
Oct 12, 2018

Idealized Supercell

- El Reno 24 May 2011 Sounding (i.e., the Orf supercell)
- Domain: 240 x 240 x 20 km (2 km x 2 km x 61L)
- WRF-ARW 3.9.1
- NSSL 2-mom microphysics scheme
- 2.5 hour simulation
- 4 runs shown
    - benchmark (no filtering) max dt = 7.5 sec
    - w-damp ON, max dt = 10 sec
    - w-damp ON, mp_tend = 0.07, max dt = 12 sec
    - IEVA, (no filtering), dt = 18 sec

El Reno T = 2 hrs

Bench	W-damp	MP-tend	IEVA
(dt=7.5)	(dt=10)	(dt=12)	(dt=18)



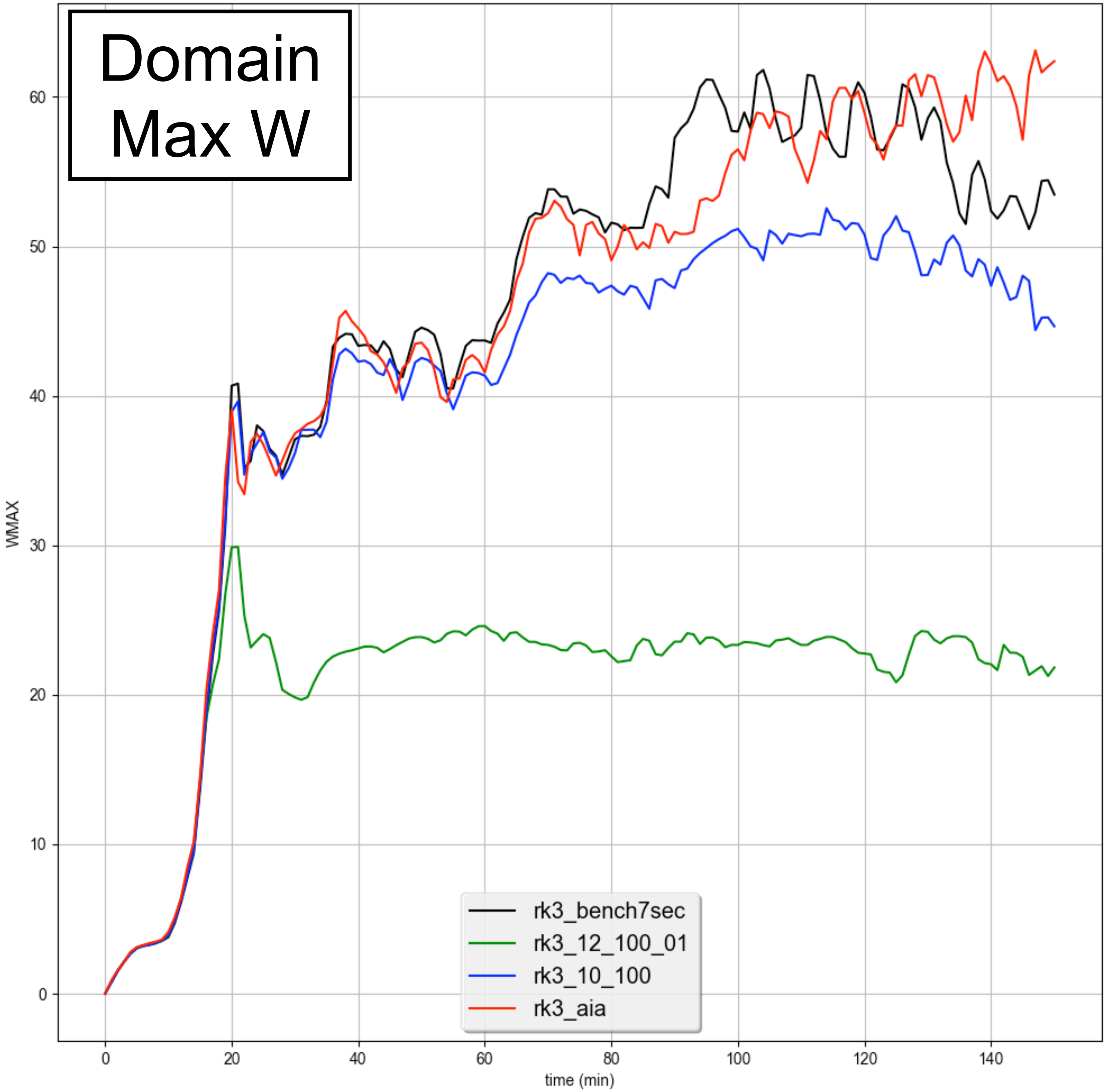
El Reno Supercell

RK3
Bench (dt=7.5 sec)
no filters

Red (dt=18 sec)
IEVA
no filters

Blue (dt=10 sec)
w_damp on

Green (dt=12 sec)
mp_tend = 0.07
w_damp on



El Reno Updrafts

RK3
Bench (dt=7.5 sec)
no filters

Red (dt=18 sec)
IEVA
no filters

Blue (dt=10 sec)
w_damp on

Green (dt=12 sec)
mp_tend = 0.07
w_damp on