Improving the numerical efficiency of storm-scale NWP models

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With special thanks to Kent Knopfmeier & Saulo Freitas

accuracy?

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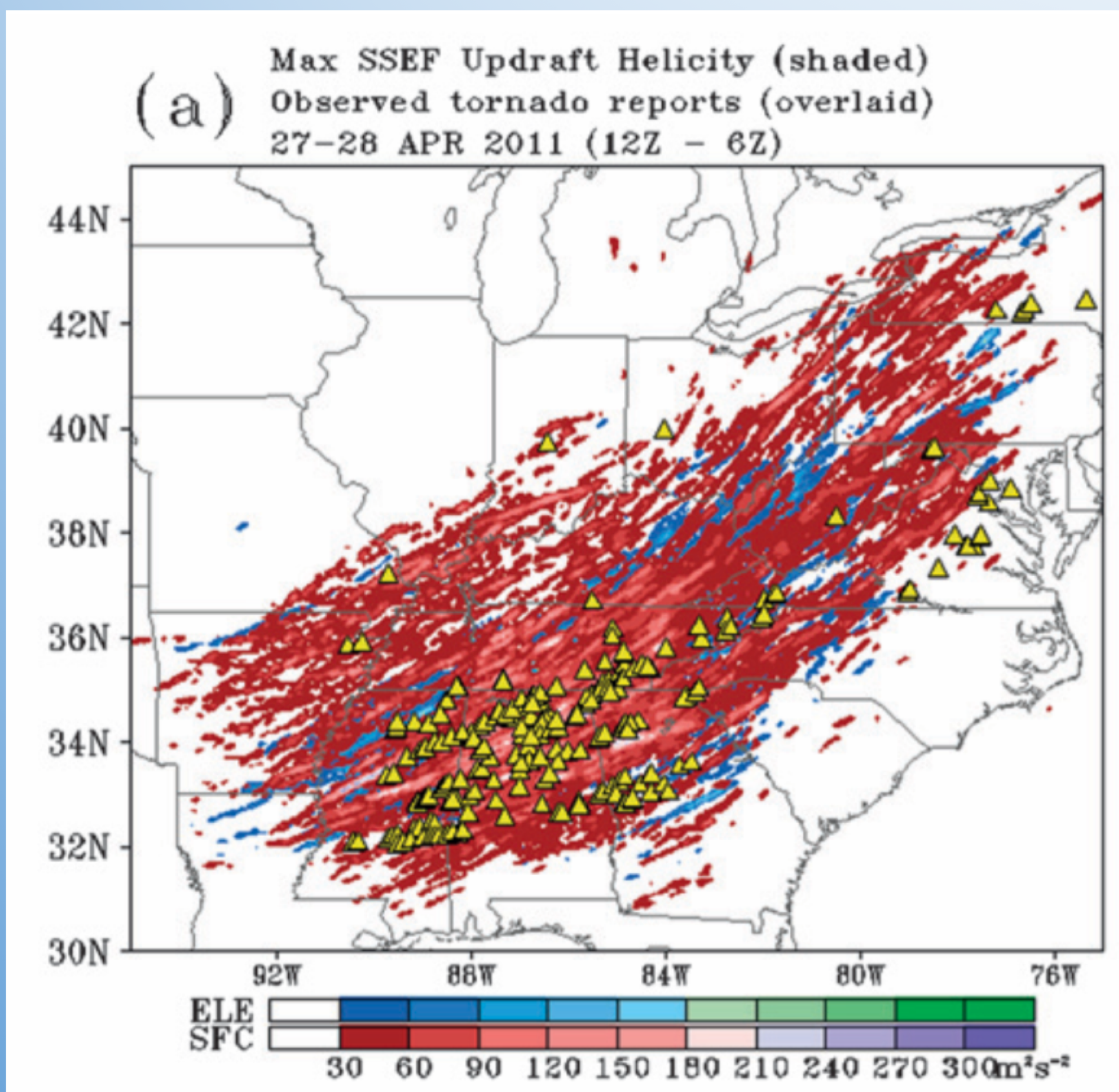
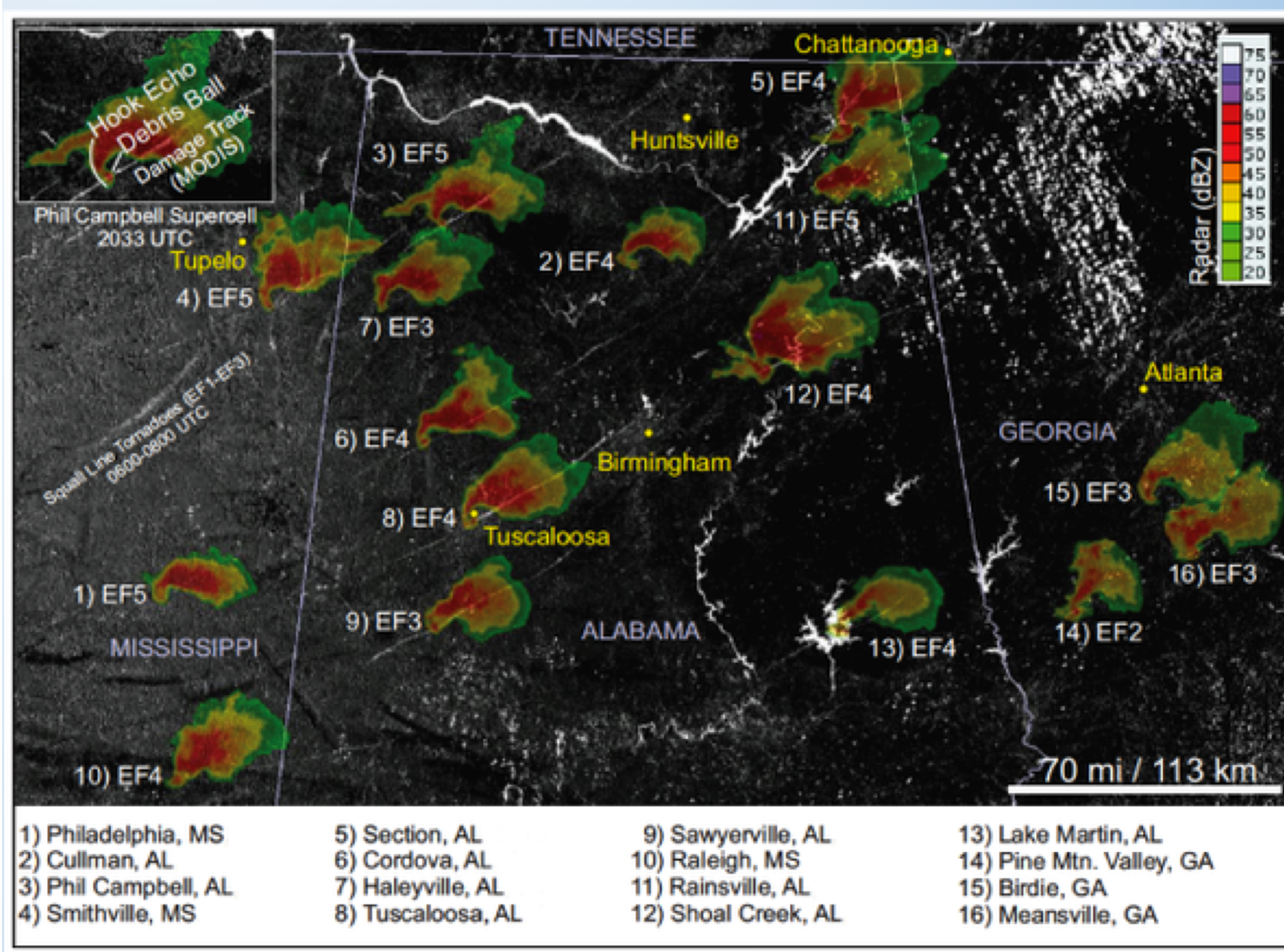
Challenges of CAM Config?

- Convective allowing models have high-aspect ratio grids
  - $\Delta x/\Delta z$ ~O(5-10) → Δx = 3km, Δz = ~ 300-600 m
  - W_{max} ~(20-30 m/s) in updrafts from high cape environments
  - W_{max} ~(5-10 m/s) in lowest kilometer within terrain/downslope events
- Vertical velocity **constrains** maximum stable time step **[Δt ~ 20 sec]**
- To maximize time step, filters are used to reduce **W** in WRF model
  - **w_damp**: directly reduces the vertical velocity using Rayleigh damping
  - **mp_tend_lim**: limits latent heating feedback in pressure equation
- **Ideally**
  - **Would like to increase the stable time step**
  - **Would like to decrease the filtering**

Experiments with 27 April 2011



Ensemble UH Tracks



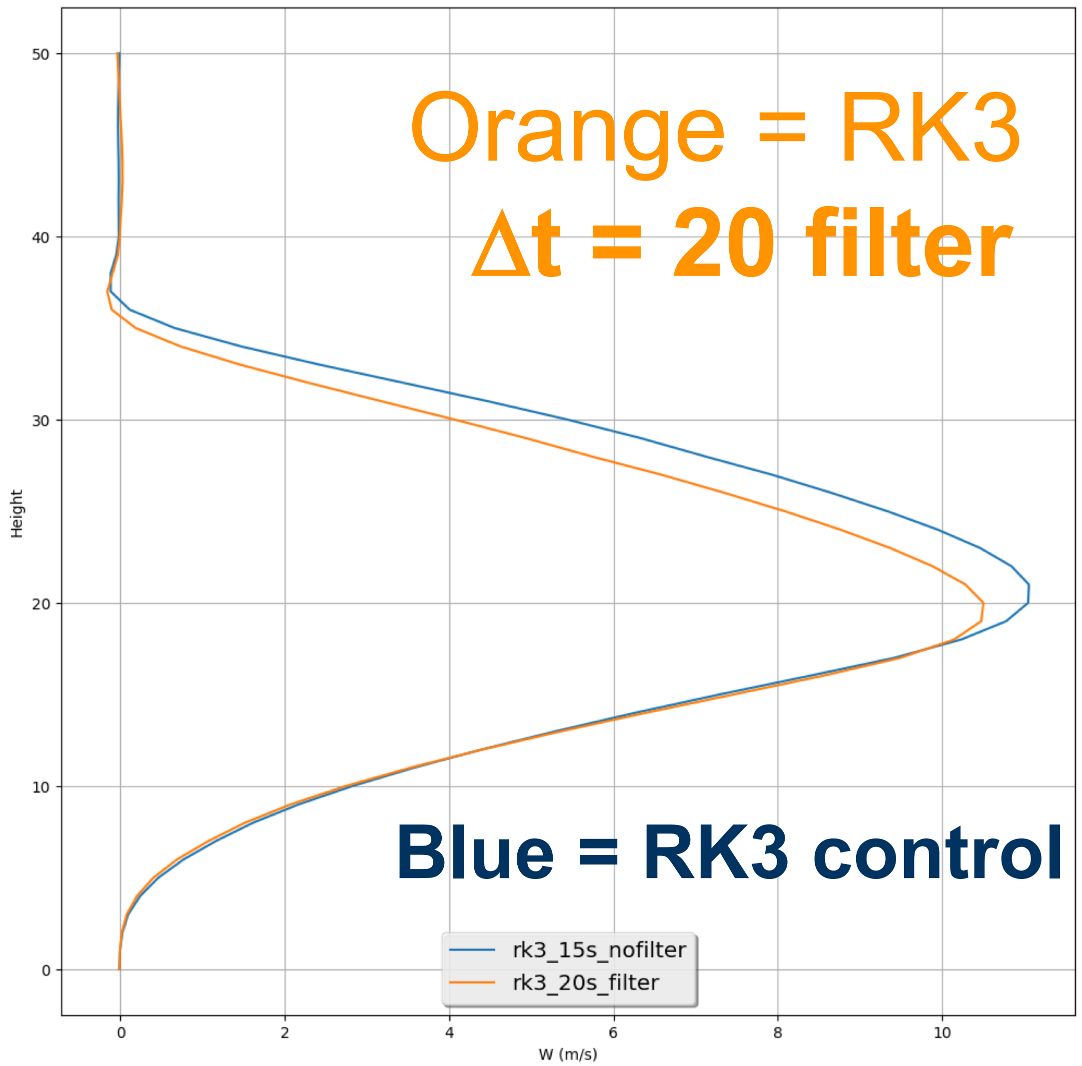
Composite Supercell & Tornadoes

Exp Configuration

- WRF v3.9.1
- HRRR—CONUS configuration (3 km, 51 levels)
- IC's: 00Z NAM 27 April 2011 / BC's every 3 hours.
- FILTER runs have
  - **W_DAMP = 1**
  - **Mp_tend_lim = 0.07**
- NOFILTER
  - **W_DAMP = 0**
  - **Mp_tend_lim = 10.07**
- Thompson microphysics (mp_physics=8)
- Control: Δt = 15 s, no filters, RK3 integrator
- Run Δt = 20 s / Δt = 22.5 s (if possible)

What are impacts from filters?

6 hr Avg Profile of W
where W_{max} column > 10 m/s

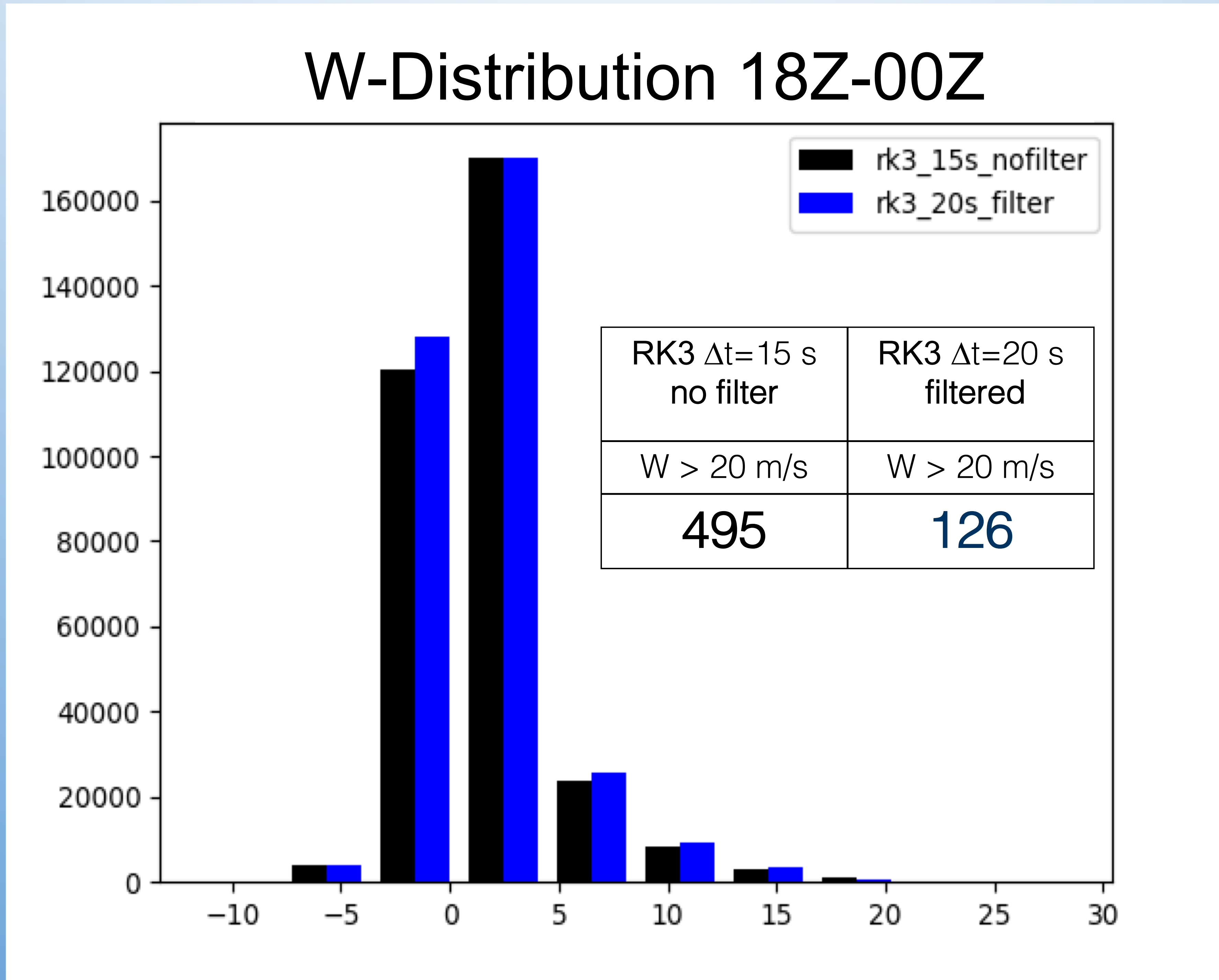


RK3 runs

Δt = 20 sec unstable without filter
Δt = 20 sec stable with filter
Δt = 22.5 sec abs unstable

- W-Profiles computed from each hour
- 6 hour period 18Z-00Z composite
- Each run has about O(1000) profiles

What are impacts from filters?



RK3 Δt=15 s no filter	RK3 Δt=20 s filtered
W > 20 m/s	W > 20 m/s
495	126

Does this matter?

- Maybe not!
- “Next day” CAMS all have unique biases, climates, etc.
- Is reducing the maximum W-intensity a problem?
  - previous work clearly shows big days are detected by CAMs
  - already calibrated using surrogate severe methods, etc….
- CAMs (especially ensembles) are one of our best tools.
  - consistently proven their VALUE in NWS operations!
  - reliability of operational runs extremely important

Does this matter?

- BUT….
- Cycled data assimilation at CAM scales: another story?
- Weaker updrafts for biggest storms could mean:
  - Less water transported into upper troposphere/stratosphere
  - Fewer hydrometeors & smaller hydrometeors?
  - Increases in cloud top radiation errors?
  - Additional bias in reflectivity structure, rainfall, etc.
- Increased bias will definitely impact the efficacy of any cycled DA system at these resolutions..

Where to go from here?

- Can we increase the accuracy AND the efficiency of the models at the same time
  - E.g., is there a win/win here?
- Method
  - Change the time integrator
  - Look whether we can increase Δt
  - Reduce the filtering using increased stability from integrator?
    - Increase fidelity in the updraft distributions/intensities?

Pull ideas from CFD Community

- Other CFD disciplines use higher-order RK schemes to increase efficiency
- These schemes use 4-7 sub-steps
- CFL limits are 2-3x larger than RK3 (e.g., $\omega \sim 3.0$-5.5 vs 1.73)
- Hu et al. (1996, J. Comp. Phys) is one of first "designer" schemes
- Hu96 is 5-step/2nd order scheme: stable to $\omega \sim 3.5$
  - Formulation similar to RK3 ("linear-case" RK-scheme)
  - Easy to implement
    - WRF code modifications mostly in solve_em.F

Hu96 Runge-Kutta Integrator

- Are 2 more RHS evaluations really worth it?
- Depends on dynamics versus physics costs
  - From RK3: dynamics costs 50%, physics costs 50%
  - $\Delta t_{old} / \Delta t_{new} = (5/3 * ½ + ½) = 1.25$
- Same cost as RK3 if you can increase Δt by 25% using Hu96
- Benefits
  - Accuracy: Can you turn down or off the filters?
  - Trickiness: Can you use Hu96 only for the vertical dir?

Compare Runge-Kutta Integrators

RK3

$$u^0 = u^t$$
$$for\ n = 1,3$$
$$\quad u^n = u^0 + c_n \Delta t\, F\left(u^{n-1}\right),\ c_n = [0.3333333, 0.5, 1.0]$$
$$endfor$$
$$u^{t+\Delta t} = u^3$$

Large time steps

Small time steps

$$\Delta t_{small} = \frac{\Delta t}{ns} \rightarrow \text{constant}$$
$$for\ \ m = 1,3$$
$$\quad nsmall = ns/(4-m)$$
$$endfor$$

Hu96

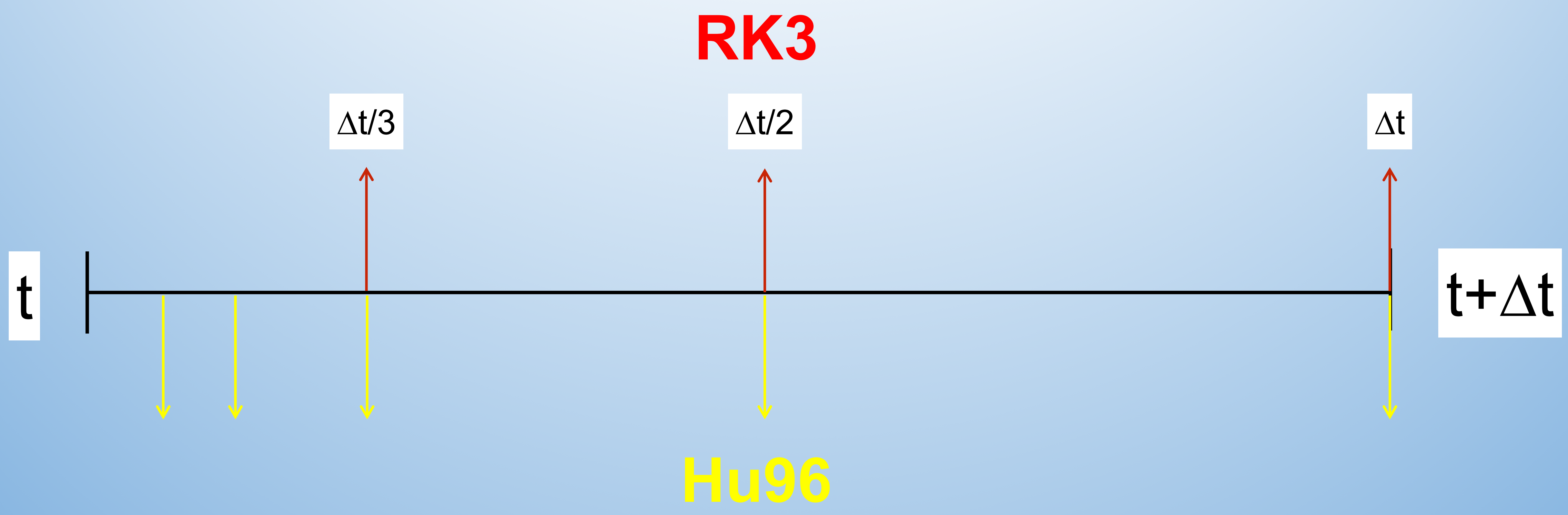
$$u^0 = u^t$$
$$for\ n = 1,5$$
$$\quad u^n = u^0 + c_n \Delta t\, F\left(u^{n-1}\right),\ c_n = [0.197707993, 0.237179241, 0.3333116, 0.5, 1.0]$$
$$endfor$$
$$u^{t+\Delta t} = u^5$$

Large time steps

Small time steps

$$for\ \ m = 1,5$$
$$\quad dt_{rkstep} = \Delta t * c_n$$
$$\quad nsmall_{rkstep} = \max(1, ns * c_n)$$
$$\quad \Delta t_s = \frac{dt_{rkstep}}{nsmall_{rkstep}} \rightarrow \text{non-constant!}$$
$$endfor$$

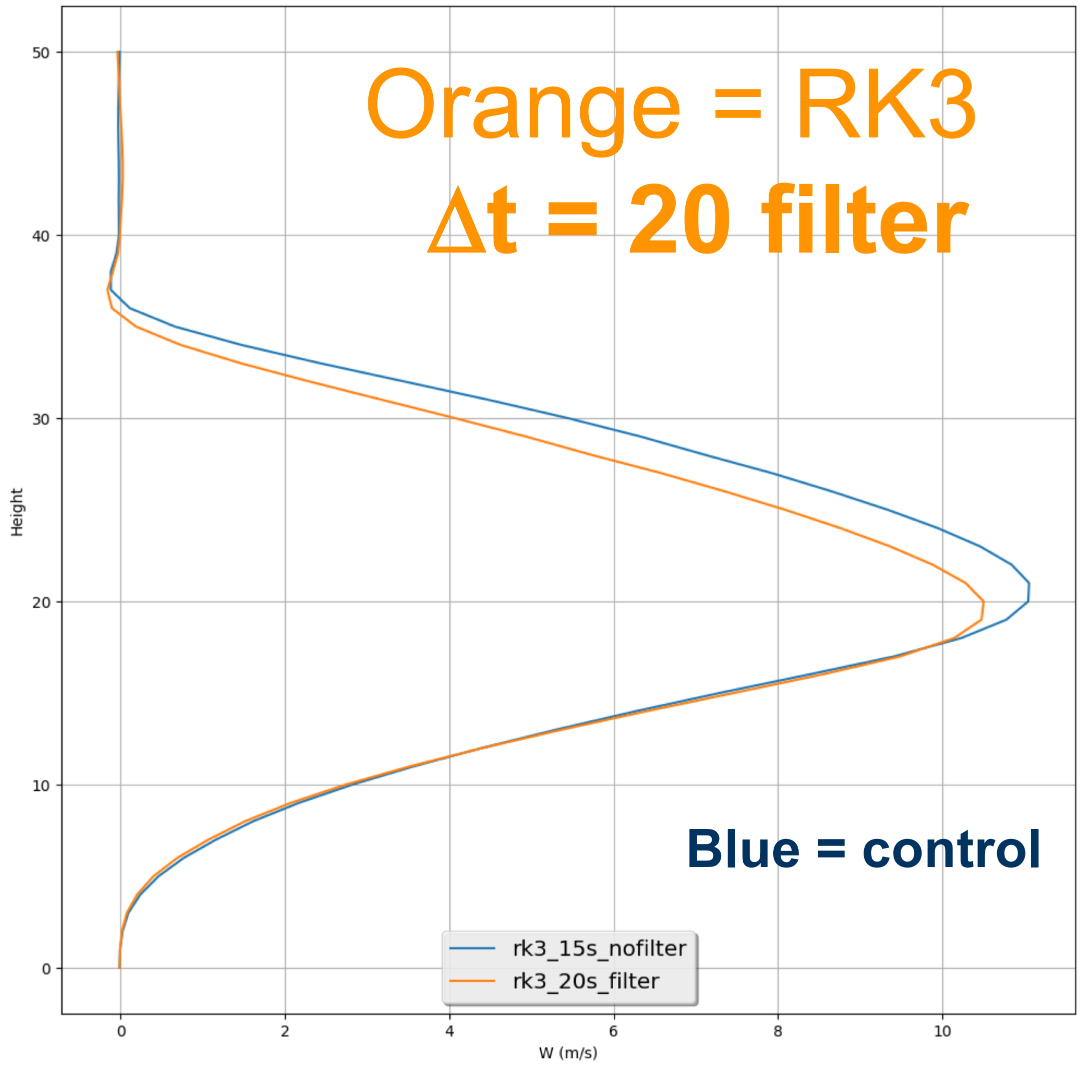
COMBINE RK3 and Hu96?



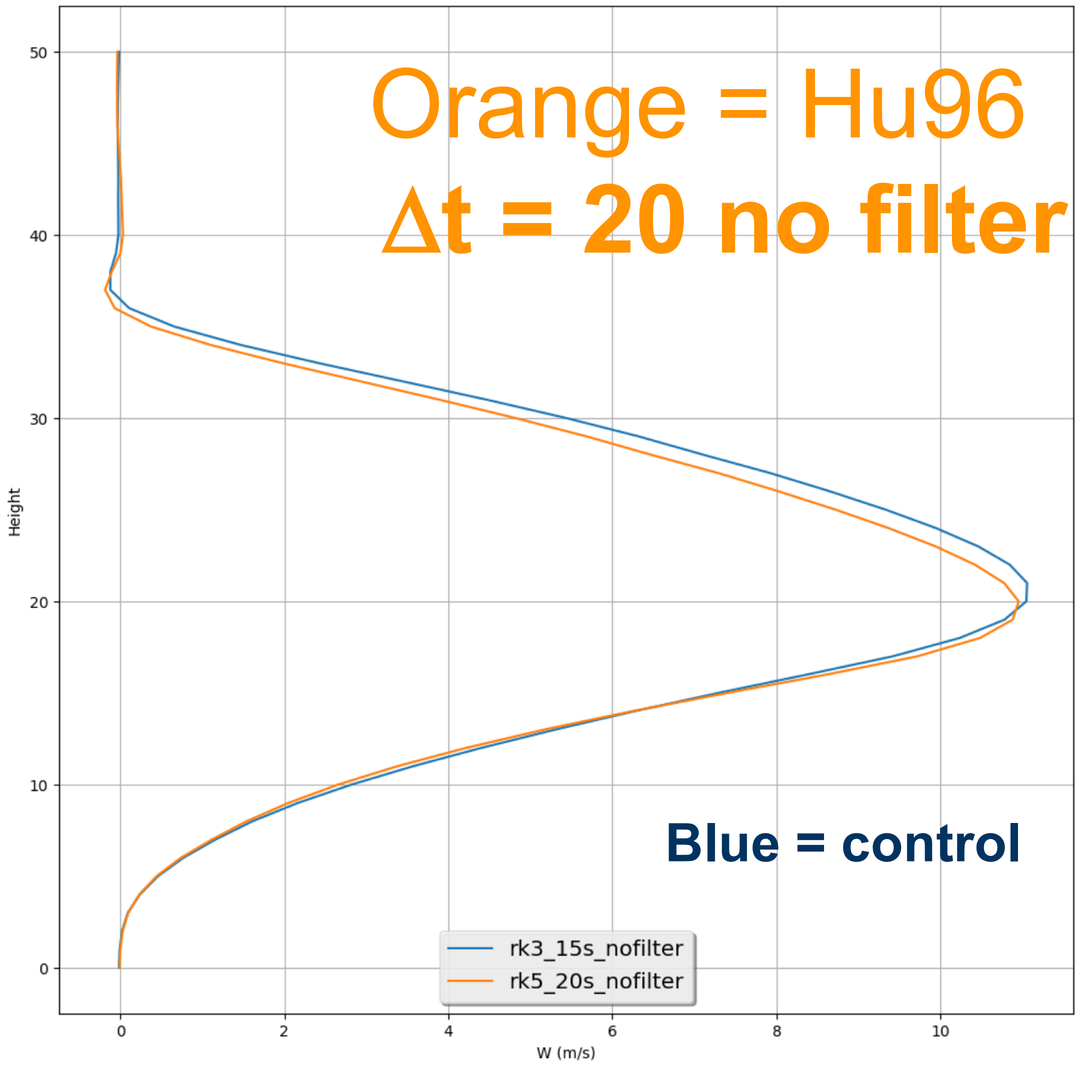
- Hu96 scheme can be ”sync’d” with RK3 on 3rd iteration
- Compute horizontal advection at “t”, hold constant for n=1,2,3
- Compute v-adv using Hu96 – add in h-adv for n=1,2,3
- Compute full 3D advection for last 2 iterations
- Saves the cost of the horizontal advection!
- This is linearly stable for advection AND time splitting!

Impacts of using Hu96?

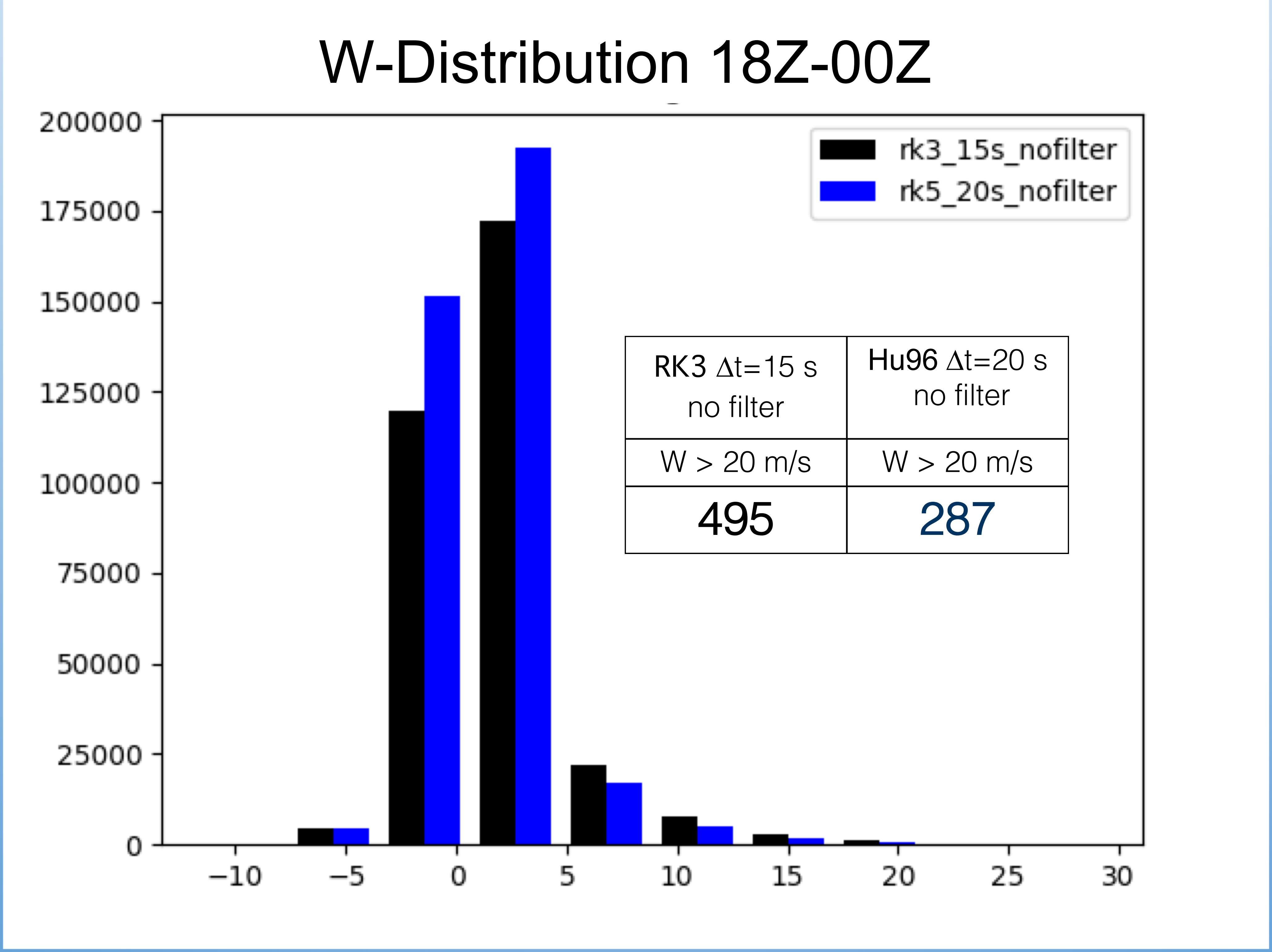
6 hr Avg Profile of W where W_{max} column > 10 m/s



6 hr Avg Profile of W RK3 vs Hu96

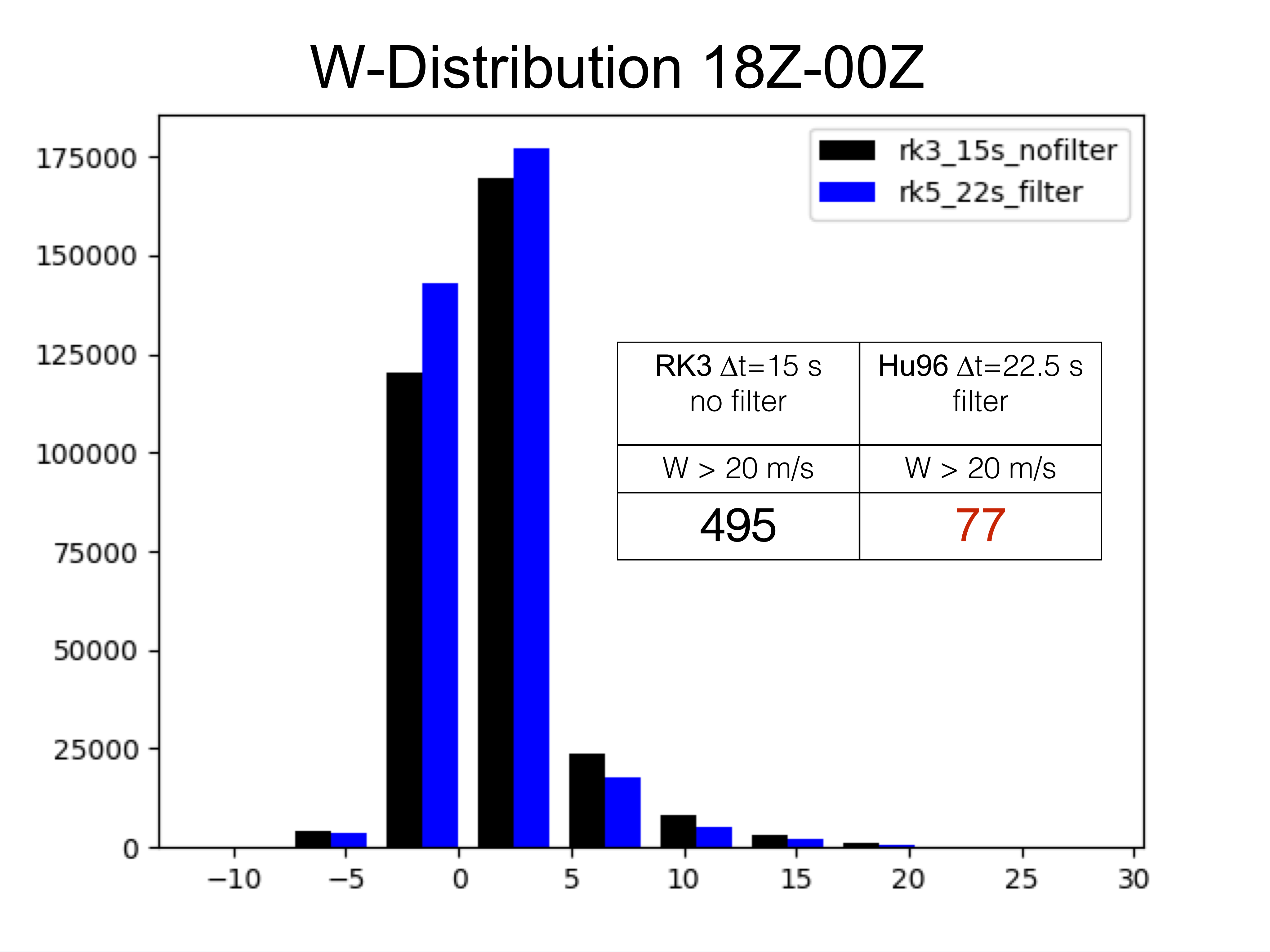


Impacts of using Hu96 with no filter?



RK3 Δt=15 s no filter	Hu96 Δt=20 s no filter
W > 20 m/s	W > 20 m/s
495	287

Hu96 results using larger time step? [with filter, unstable without]



RK3 Δt=15 s no filter	Hu96 Δt=22.5 s filter
W > 20 m/s	W > 20 m/s
495	77

Timings…

- 4 repeated runs for each timing.
- 3 hours of integration starting from 21Z
- Larger time steps also mean more small time steps

	Δt = 15 s	Δt = 20 s	Δt = 22.5 s
RK3	760 s	584 s	unstable
Hu96	x	711 s (584 s + 20%)	630 s (584 s + 8%)
Hu96V-RK3H	x	715 s [???]	x

- *Hu96 would run faster than RK3 at Δt = 25 s*
- *More hydrometeors, more physics → more efficiency*
- *Split advection should be even faster…*

Summary

- More to this story…
  - Scheme(s) were first tested in dry 2D models
    - NH/H Gravity wave tests, translating bubble all yielded results consistent with linear theory.
  - Full physics WRF results are much less promising than runs using WRF in idealized cloud model mode.
  - Appear to be some differences in results from v3.8.1
- Implementation of split HV-advection scheme?
  - Cost of storage and storing tends may not be worth it
- Other possibilities are available
  - Strong stability preserving RK methods? [trick is time-splitting them]
  - New optimizations tuned by wedding spatial and time discretizations
  - Lots of work being done on diagonal implicit RK schemes…

Thanks!
Questions?

Bluto expresses my feelings after working on this project last few years….