Advection of cloud and precipitation in models (improving efficiency while retaining accuracy)

Hugh Morrison (NCAR*)

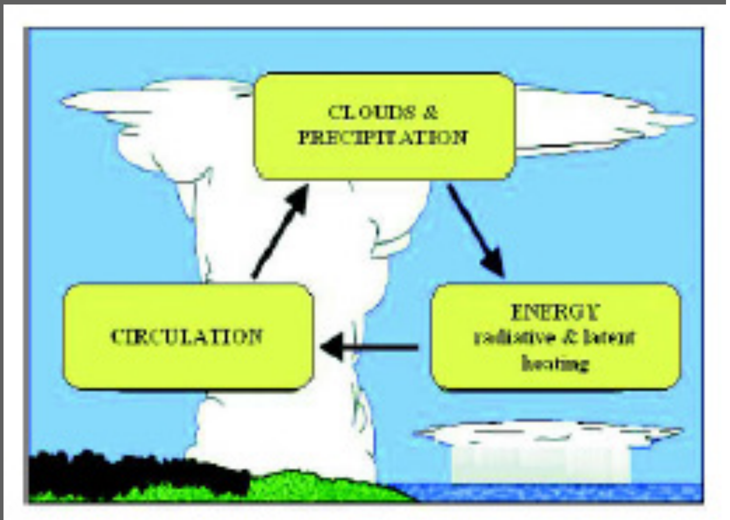
Thanks to: Jerry Harrington, Anders Jensen, Jason Milbrandt

*NCAR is sponsored by the
National Science Foundation

CMMAP summer meeting August 4, 2015

Cloud microphysics plays a key role in cloud, climate and weather models

Stephens (2005)



-Latent heating/cooling

(condensation, evaporation, deposition, sublimation, freezing, melting)

-Condensate loading

(mass of the condensate carried by the flow)

-Precipitation

(fallout of larger particles)

-Coupling with surface processes

(moist downdrafts leading to surface-wind gustiness, cloud shading)

-Radiative transfer

(mostly mass for absorption/emission of LW, particle size also important for SW)

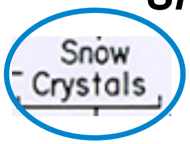
-Cloud-aerosol-precipitation interactions

(aerosol affect clouds: indirect aerosol effects, but clouds process aerosols as well)

Microphysics Parameterization Schemes

The <u>particle size distributions</u> are modeled

e.g. ***SNOW***

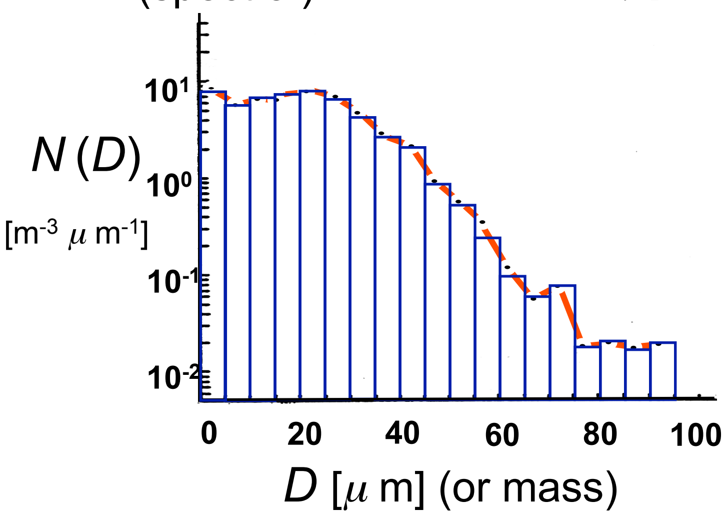


For each category, schemes predict the evolution of the *<u>particle size (or mass) distribution, $N(D)$</u>*

MAIN TYPES of SCHEMES:

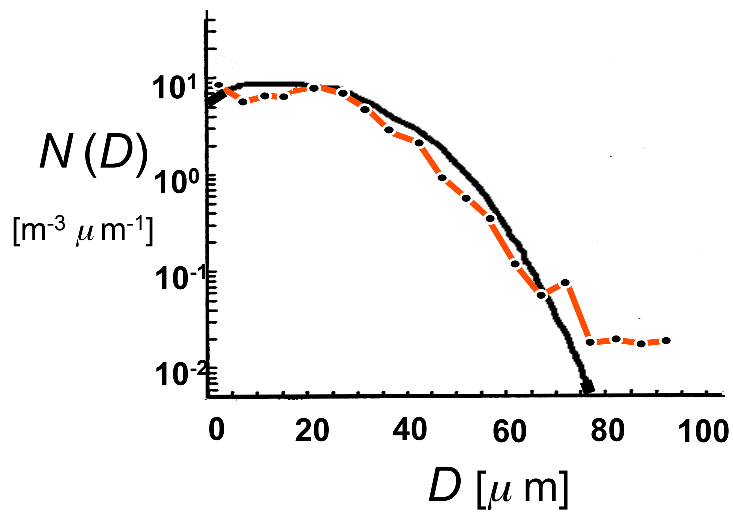
<u>Bin-resolving:</u> (spectral)

$$N(D) = \sum_{i=1}^{I} N_i$$



<u>Bulk:</u>

$$N(D) = N_0 D^{\alpha} e^{-\lambda D}$$



Bin schemes:

- Have several 10’s to 100’s of prognostic variables

Bulk schemes:

- 1-moment → Prognostic bulk mass for each category
- 2-moment → Prognostic bulk mass + number
- 3-moment → Prognostic bulk mass + number + reflectivity

…

Microphysics is costly, to a varying degree..

- Accounts for ~ 1/5 to 1/3 of total model run time for a typical 2-moment scheme, a bit less for 1-moment, WAY more for bin

- Significant factor in cost is advection of microphysics prognostic variables (~3% total run time per tracer in WRF)

Timing Tests for 3D WRF Simulations

Scheme	Squall line case (Δx = 1 km)	Orographic case (Δx = 3 km)	# prognostic variables
P3	0.436 (**1.043**)	0.686 (**1.013**)	**7**
MY2	0.621 (1.485)	1.012 (1.495)	12
MOR-H	0.503 (1.203)	0.813 (1.200)	9
THO	0.477 (1.141)	0.795 (1.174)	7
WSM6	0.418 (**1.000**)	0.677 (**1.000**)	**5**
WDM6	0.489 (1.170)	0.777 (1.148)	8

- Average wall clock time per model time step (units of seconds.)
- Times relative to those of WSM6 are indicated parenthetically.

What we want in advection schemes (for clouds/precip):

- Positive definite for mass (needed for water conservation), or even better monotonic, but not as critical for *non-mass* microphysical variables
- Preserves initial linear relationships between advected quantities
- Accurate
- Efficient

There are trade-offs!

Issues with advection and microphysics…

- The traditional approach is to advect each cloud/ precipitation prognostic variable <u>independently</u>.

- Problems:

 - Slow

 - Derived quantities (e.g., ratios) may not be monotonic even if each scalar is advected using a monotonic scheme

Similar problems arise in aerosol modeling

“Non-traditional” methods to address this:

- Vector transport (VT) → very fast and preserves monotonicity of derived relationships, but large loss of accuracy (Wright 2007)
- Least squares-based method → better accuracy, but very slow (McGraw 2007)

Is there an alternative?

Yes, using a little bit of jiu jitsu…

Instead of attacking the problem head-on with brute force, we take advantage of the inherent coupling between related microphysical scalars.

New method: *Scaled Flux Vector Transport*

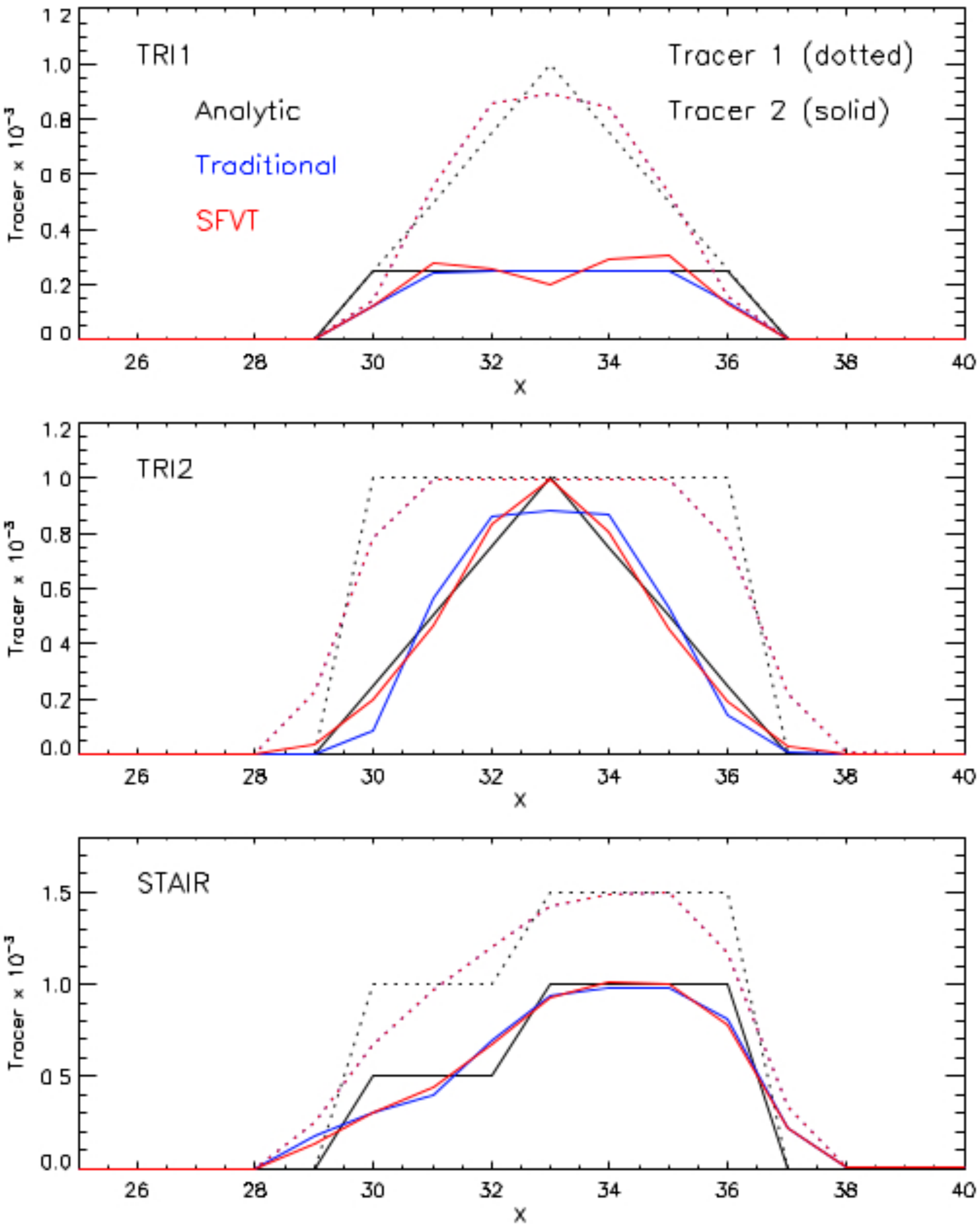
Similar to VT, but scales mass fluxes instead of derived quantities directly

1) Mass (Q) quantities advected are using the unmodified scheme

2) Other scalars (N, Z, V, etc.) then advected by scaling of Q fluxes into and out of grid cells using higher-order <u>linear</u> weighting

Retains features of applying unmodified scheme to ALL scalars, but at a fraction of the cost..

→ Accurate, fast, and preserves initial linear relationships



1D analytic test cases

Illustrated tests use 5th order advection w/ monotonic limiter from WRF

- CFL # = 0.1
- Solutions shown are advanced 50 time steps

Statistics for 1D analytic test cases

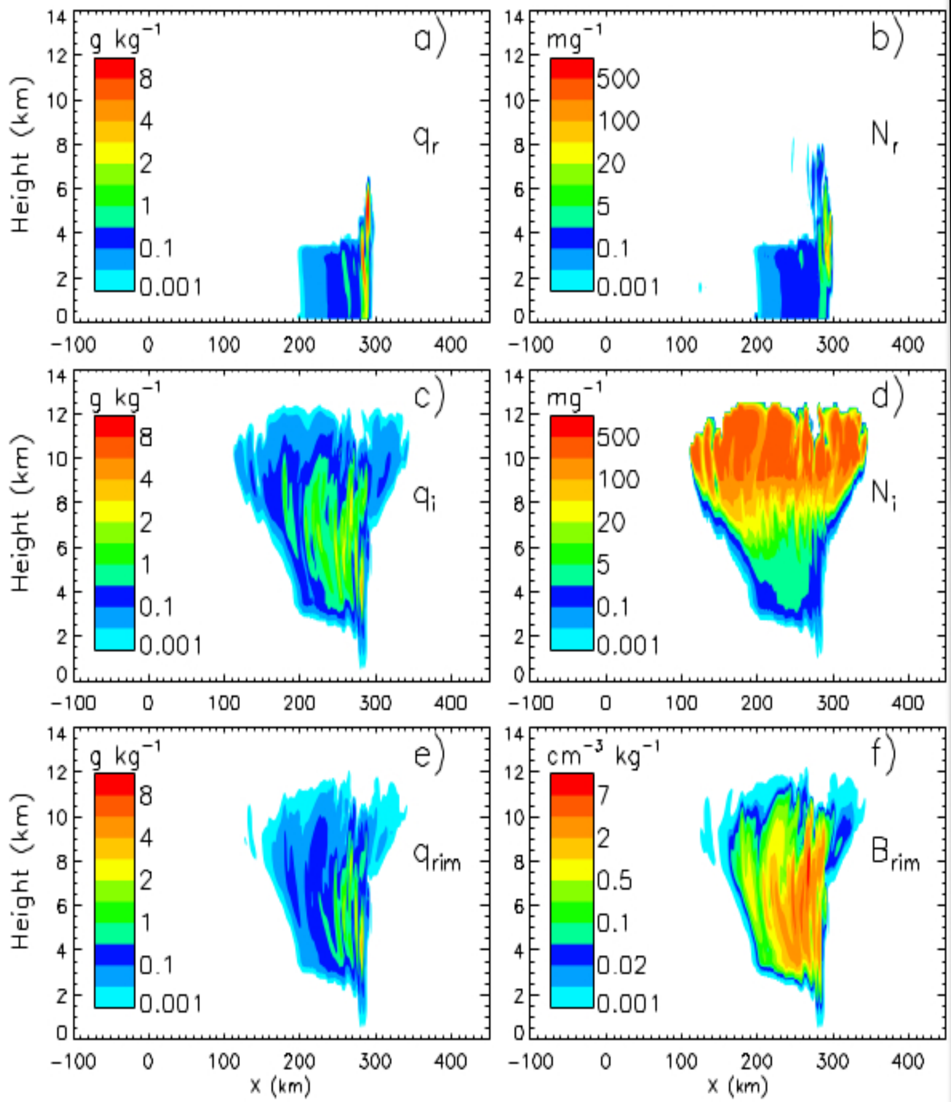
$\text{ERROR} = \Sigma|TR - TR_{ana}|/N \times 10^5$

	WRF-MONO	MONO-SFVT	WENO	WENO-SFVT
TRI1	0.81	1.42	1.19	1.23
TRI2	2.32	1.28	1.55	1.58
STAIR	3.86	3.75	4.31	4.55
	WRF-PD	**PD-SFVT**	**Non-PD**	**MONO scalar1**
TRI1	1.94	1.21	1.72	1.89
TRI2	1.97	1.38	2.18	1.62
STAIR	6.82	4.74	7.18	6.48

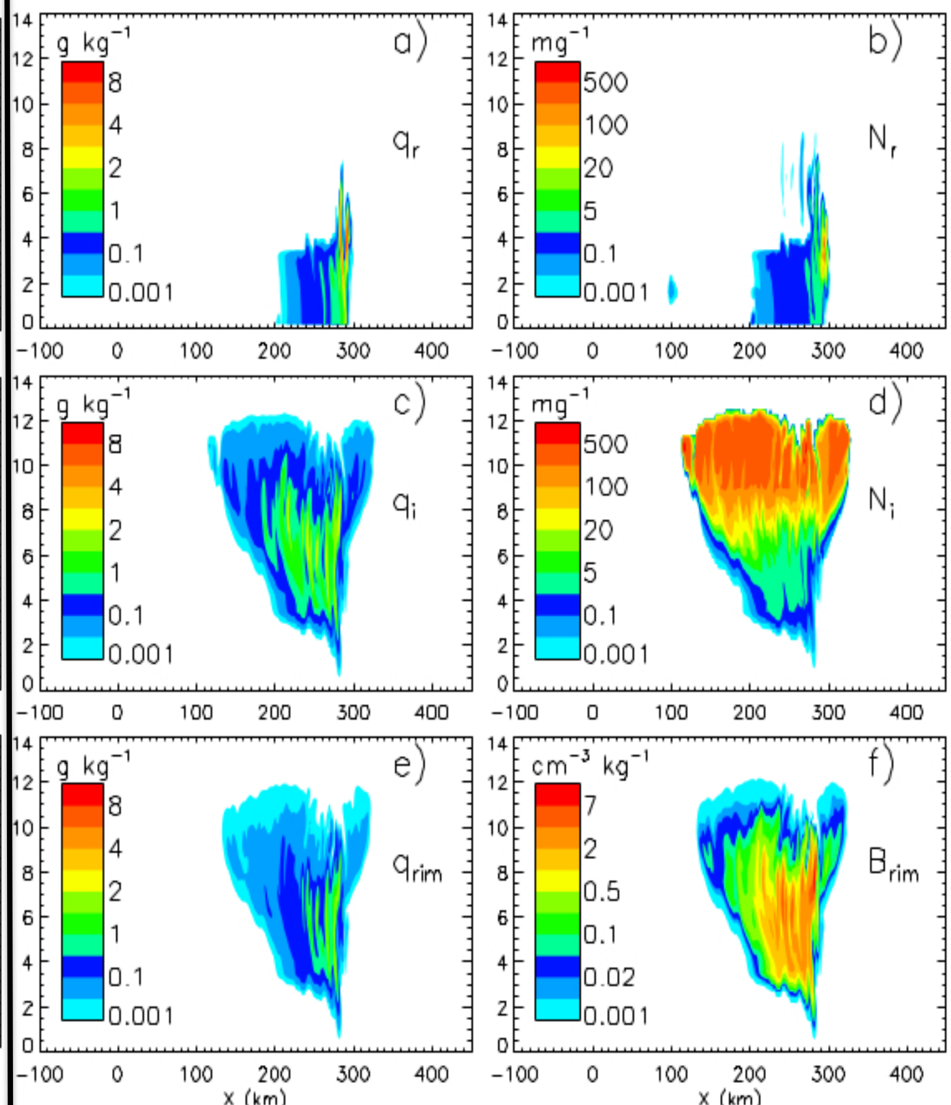
2D dynamical WRF tests
(using P3 bulk microphysics)

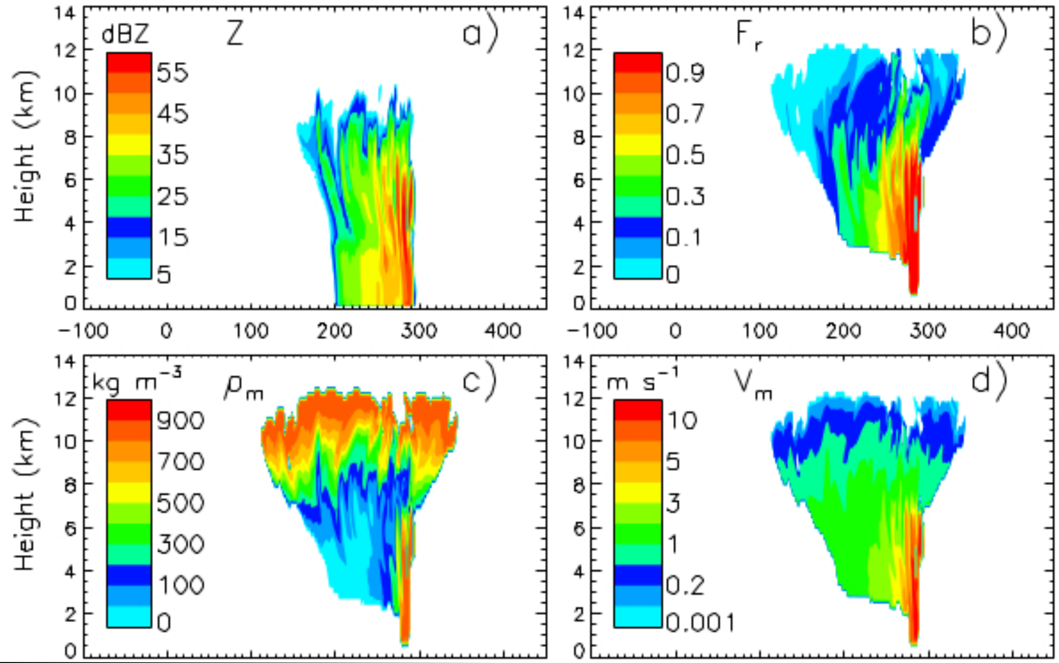
$t = 4$ h

WRF- 5th order PD

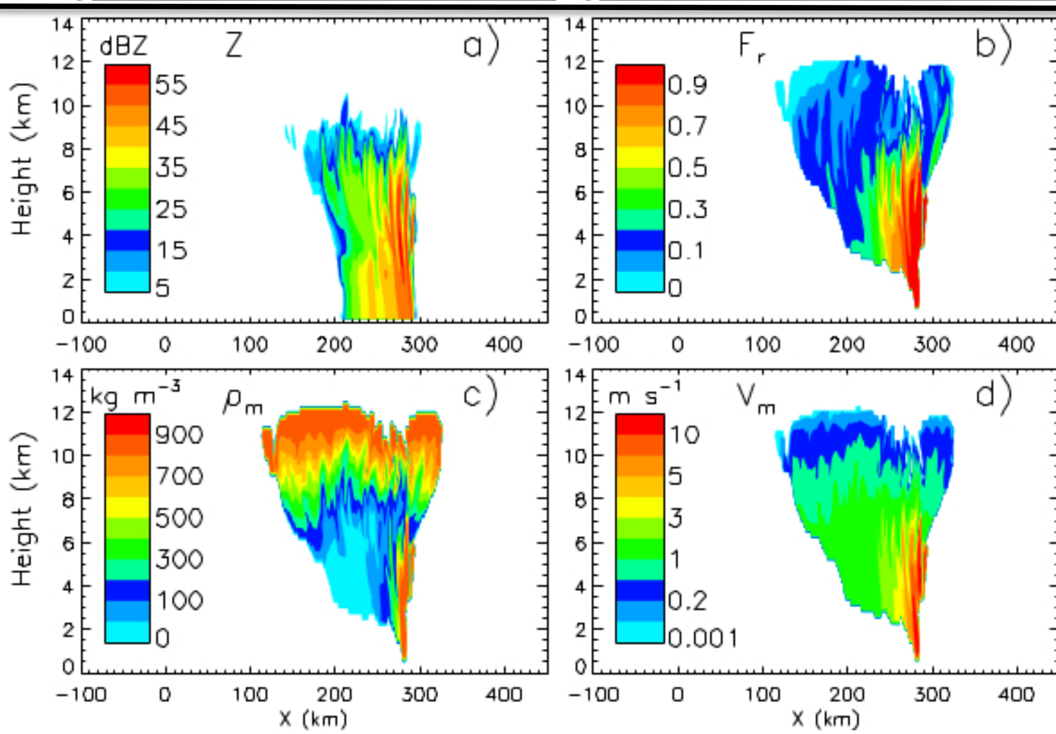


w/ SFVT

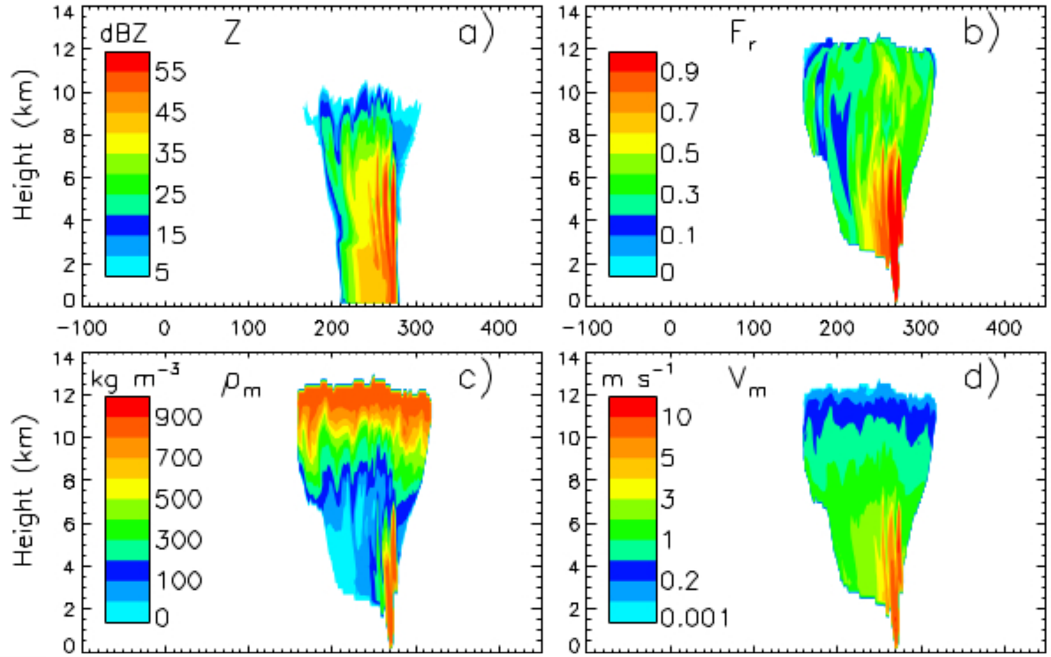




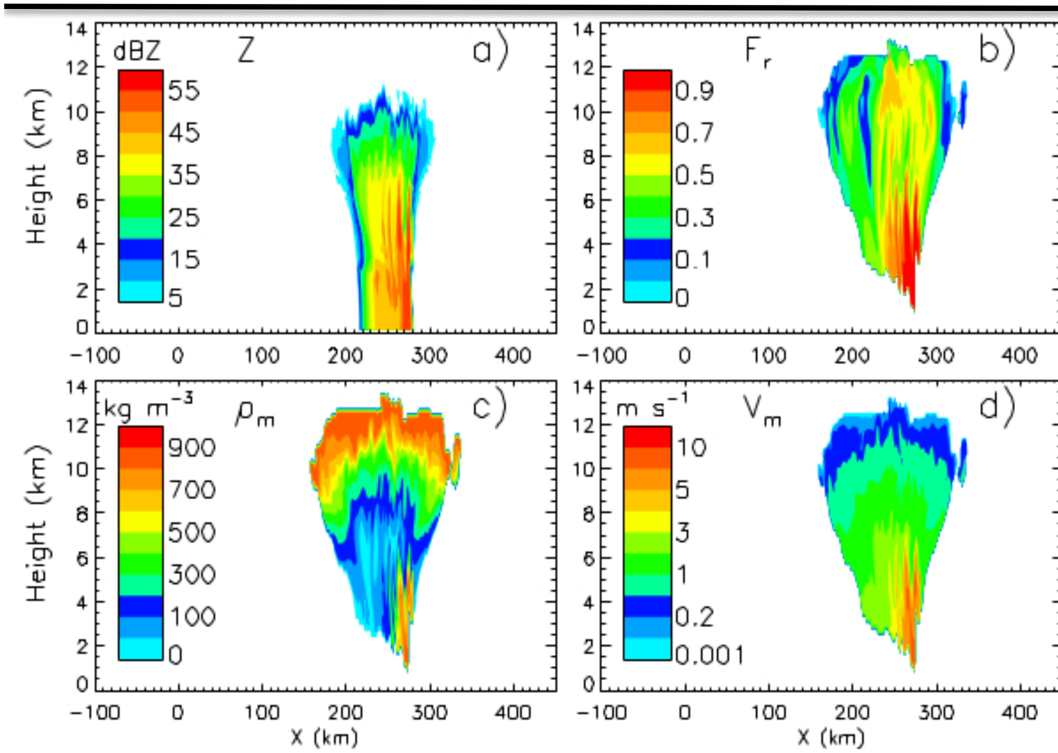
WRF- 5[th] order PD



w/ SFVT



5th order WENO



w/ SFVT

Timing (<u>total</u> model run time)

Name	Mean wall clock time (sec)	Percent change using SFVT compared to the corresponding unmodified scheme
WRF-S08	0.176	-15.4%*
WRF-PD	0.208	-
WRF-PD-5-SFVT	0.186	-10.7%
WRF-PD-3-SFVT	0.185	-11.2%
WRF-PD-5M-SFVT	0.188	-9.7%
WENO	0.222	-
WENO-5-SFVT	0.196	-11.7%
WENO-3-SFVT	0.190	-14.4%
WSM6	0.228	+22.6%**
THOMPSON	0.230	+23.7%**

*Calculated relative to WRF-PD

**Calculated relative to WRF-PD-5-SFVT

SFVT can also be applied to bin schemes!

One additional step is needed:

1) Sum up bins to get bulk mass Q, advect Q using the model's unmodified advection scheme

2) Advect each bin variable by scaling the Q fluxes into and out of grid cells using higher-order linear weighting

3) After advection, scale variables each bin by Q for consistency

This kills two birds…

→ fast and accurate as for bulk schemes, but also ensures local consistency between advection of scalars and sums of scalars, which most advection schemes do not guarantee (Ovchinnikov et al. 2009)

Summary and Conclusions

- A new method has been developed that improves advection of coupled microphysical quantities → the approach is general and can be applied to any flux-based scheme
- *Accuracy:* similar or slightly better overall relative to analytic test cases, exactly preserves initial linear relationships, very similar overall solutions for dynamical test cases compared to traditional approach of separately advecting each tracer
- *Cost:* Reduction in total model run time by ~ 10-15% (for P3)
- Can be applied to any multi-moment bulk scheme → brings cost much closer to 1-moment schemes
- Can also be applied to bin schemes: Preliminary results show reduction of total run time by ~20% while giving nearly the same solutions (using fast SBM in WRF)

Thanks!