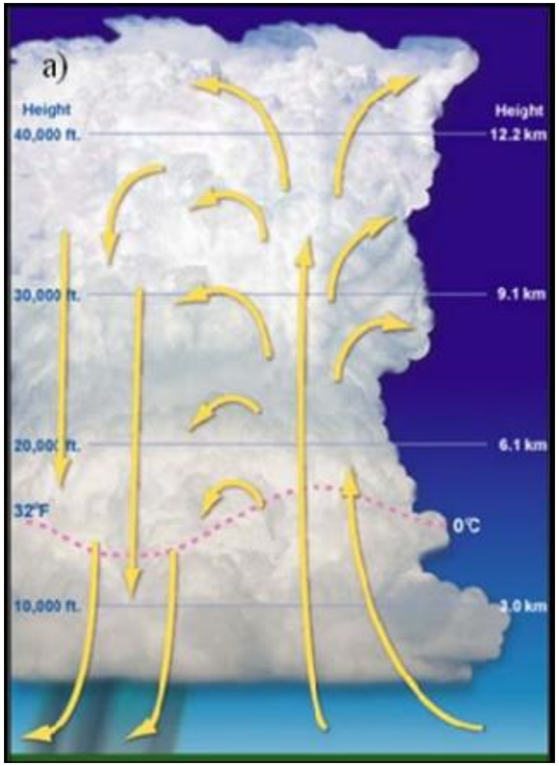
WRF-Chem Simulation of Deep Convective Transport in Different Scale Storms using Lightning Data Assimilation

Yunyao Li (*University of Maryland*)

Kenneth Pickering, Mary Barth, Megan Bela, Kristin Cummings, Dale Allen, Larry Carey, Retha Mecikalski, and Alexandre Fierro

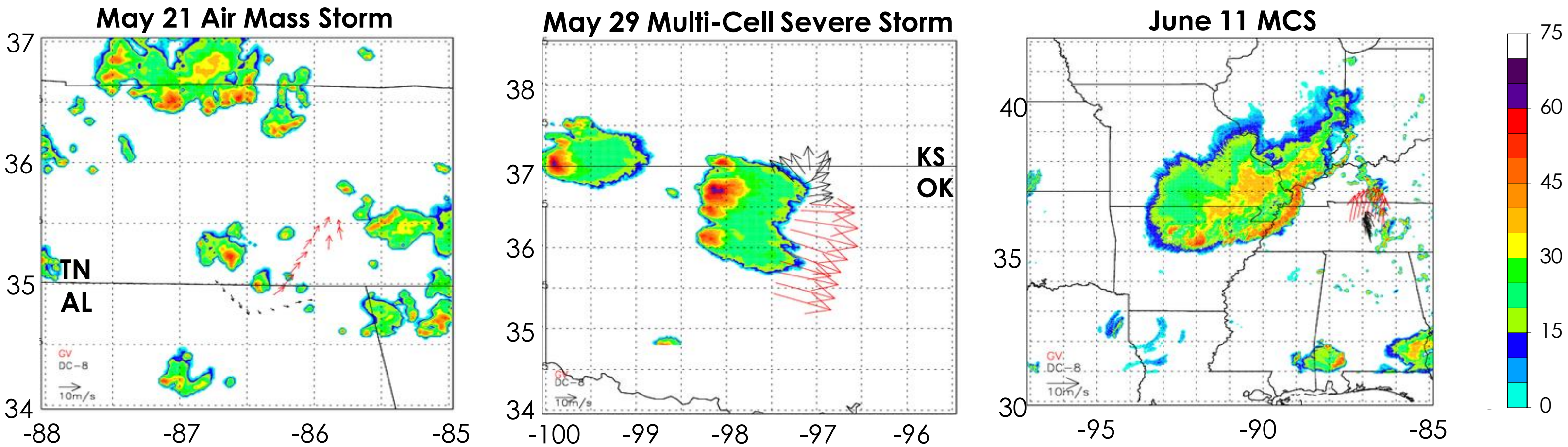
Background

- **Deep convection** can transport **surface moisture and pollution** from PBL to the upper troposphere and lower stratosphere (UTLS) within **a few minutes to a few hours**.
  - **Vertical transport of local air pollutants**
    - Transform the local air pollution problems into regional or global atmospheric chemistry problems.
  - **Vertical transport of O_3 and O_3 precursors**
    - increase the production rate of ozone in the cloud outflow
  - **Vertical transport of surface moisture**
    - Affects the Earth's radiation budget and climate.
  - **Vertical transport of aerosol**
    - Influence aerosol vertical distribution, which is an important component of aerosol radiative forcing.
- Deep convective transport of trace gases also provide us a useful tool to study storm dynamics.



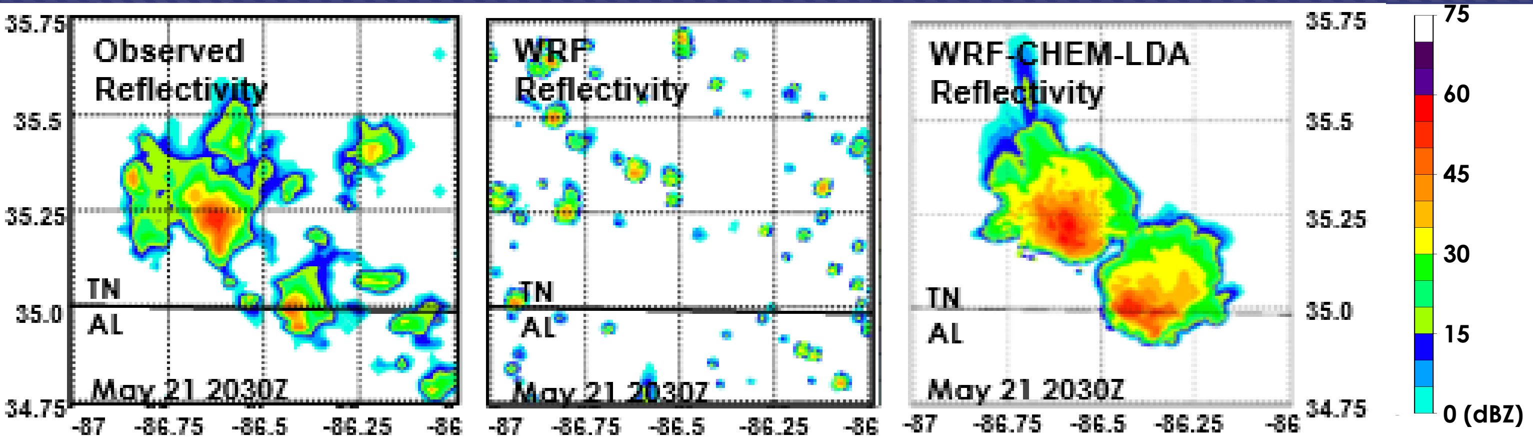
Case Studies Storms

- Previous studies report that **storm types** have a significant impact on the depth and magnitude of deep convective transport (Bigelbach et al., 2014).
- Use WRF-Chem to simulate three different scale storms observed during Deep Convective Clouds and Chemistry (DC3) field campaign.
  - May 21st Alabama air mass case
  - May 29th Oklahoma multi-cell case
  - June 11th central U.S. MCS case
- Analyze differences in deep convective transport characteristics among these three cases.



NEXRAD Composite Reflectivity with Aircraft Wind Arrow

WRF-Chem with Lightning Data Assimilation (LDA)



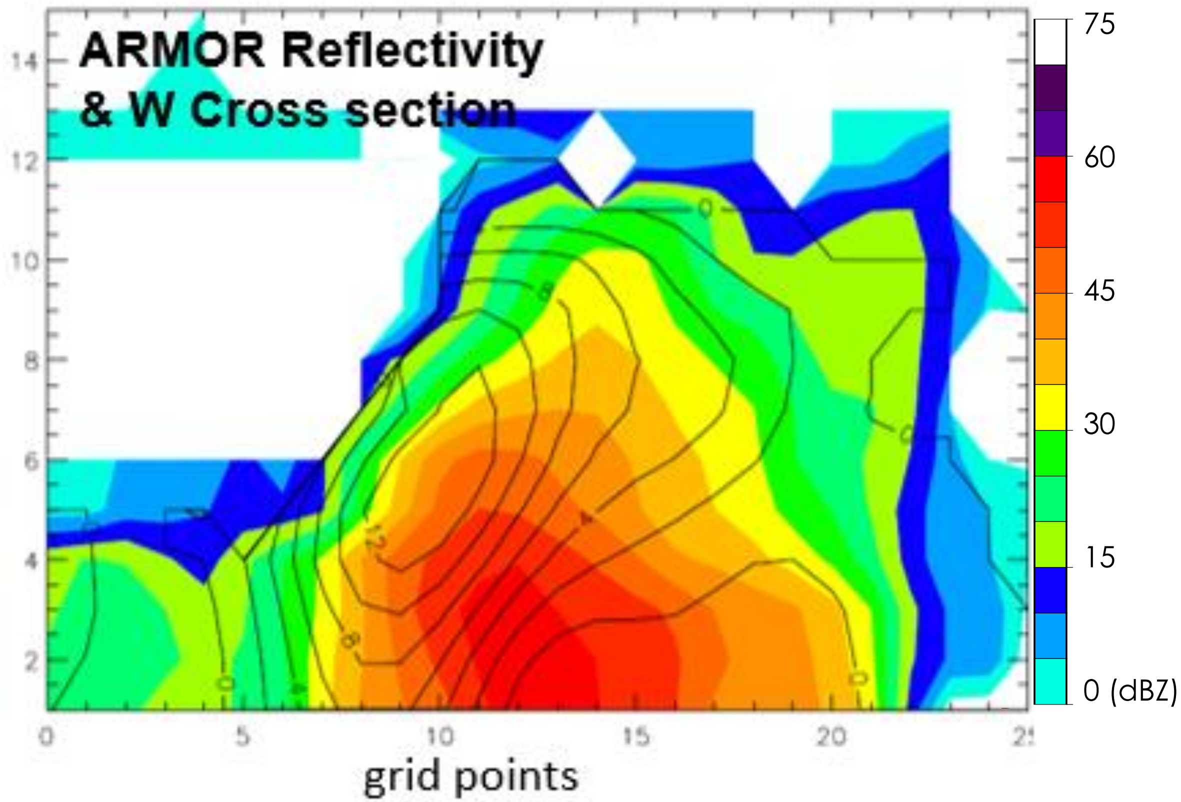
- We tried different PBL, MP schemes, IC/BC condition (Morrison, Thompson, WSM6, NSSL, YSU, MYJ, ACM2, QNSE, ERA, GFS, FNL, NARR, NAM), analysis & observational nudging , but cannot get the storm in the right place.
- Fierro (2012) lightning data assimilation scheme: fast, can be applied to high resolution (600 m) WRF-Chem.
- Increase water vapor at constant temperature layer (273k-253k) in grid cells containing lightning. (*Fierro et al. 2012*)

$$Q_v = AQ_{sat} + BQ_{sat}\tanh(CX)\left[1 - \tanh\left(DQ_g^{\alpha}\right)\right]$$

  - Qv: Water vapor mixing ratio
  - Qsat: Water vapor saturation mixing ratio
  - X: 10-minute interval ENTLN recorded total flashes
  - Qg: Graupel mixing ratio

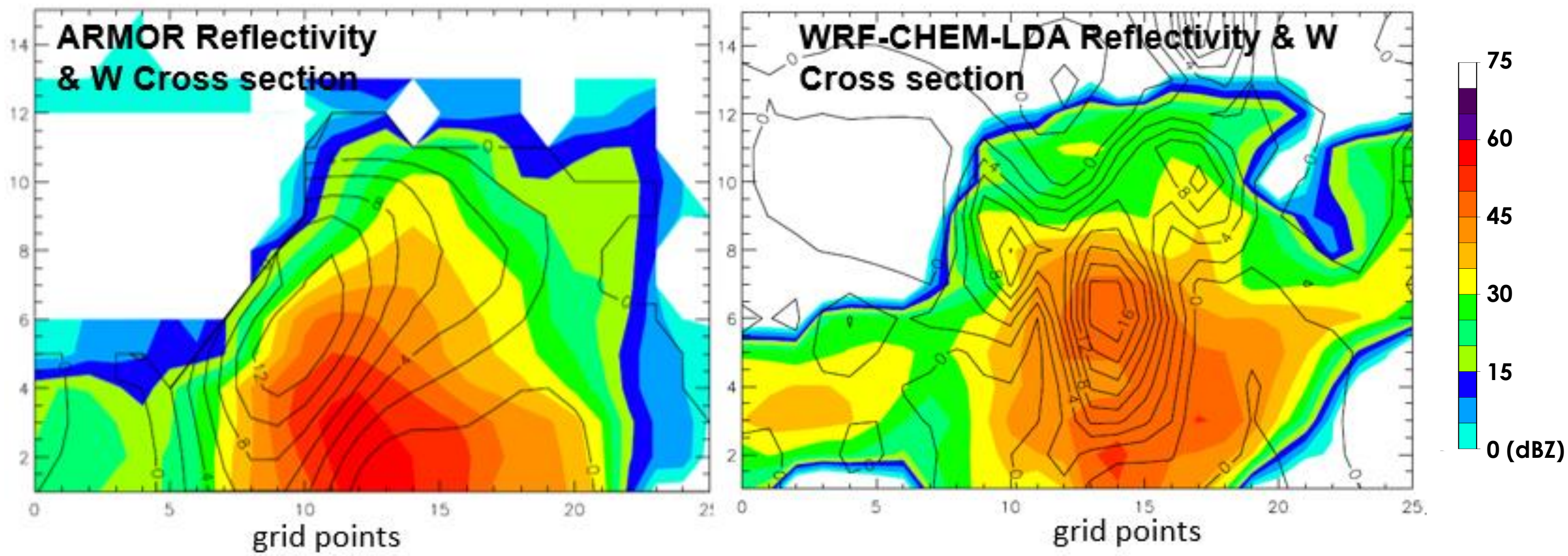
WRF-Chem with Lightning Data Assimilation (LDA)

- We care about the simulation of storm vertical structure
- Very hard to reproduce the vertical structure of May 21 air mass storm.
  - Maximum vertical velocity: ~12 m/s
  - Level of maximum vertical velocity: ~6km
  - Storm extended to 12 km.
- Fierro (2012) focused on reproducing the storm horizontal structure.
- Modified Fierro (2012) scheme.
  - Adding water vapor at a lower altitude (LCL to level of maximum vertical velocity)



Contour filled image represents the reflectivity in dBZ, the solid black lines represent the vertical motion.

WRF-Chem with Lightning Data Assimilation (LDA)



Contour filled image represents the reflectivity in dBZ,
the solid black lines represent the vertical motion.

- Applied LDA to several microphysics schemes: Morrison, NSSL, WSM6.
- Improved simulation of storm vertical structure

WRF-Chem Setup

- We tried different combinations of different IC/BC condition, WRF starting time, Planetary Boundary layer scheme, Microphysics scheme. Below are the best options:

	May 21 Air Mass	May 29 * Multi-cell	June 11 MCS
Initialization	GFS	NAM (12km)	NAM (12km)
Resolution	15km, 3km, 0.6km	1km	3km
Microphysics	WSM6	Morrison	WSM6
Cumulus Parameterization	Grell 3D (in 15km domain only)	No	No
Chemical IC/BC	Using aircraft measurements to generate Chemical IC/BC		MOZART
Chemistry Option	MOZART Chemistry and GOCART aerosols (MOZCART)		
LNOx Option	Separate IC, CG vertical distributions following DeCaria et al. (2000).		

- *May 29 Case was run by Megan Bela (CU Boulder)

with Lightning Data Assimilation (LDA)

- WRF-Chem-LDA well simulates the chemistry field.
- Lower tropospheric CO mixing ratio

	May 21 Air Mass	**June 11 MCS**
Aircraft measurements	146.01 (±4.89)	113.36 (±2.12)
WRF-Chem simulation	149.86 (±1.81)	115.2756 (±6.19)

- Upper tropospheric CO mixing ratio

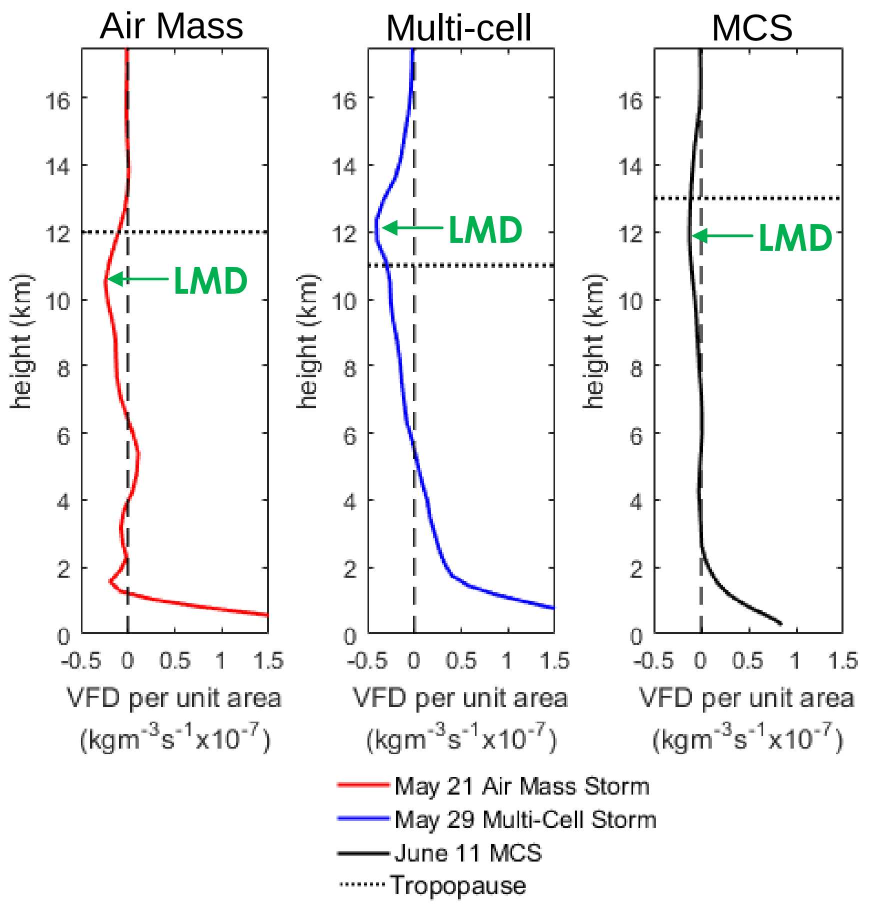
	May 21 Air Mass		**June 11 MCS**	
	Affected by storm outflow	Unaffected by storm outflow	Affected by storm outflow	Unaffected by storm outflow
Aircraft measurements	100.17 (±4.51)	89.57 (±9.67)	110.00 (±5.32)	92.84 (±2.47)
WRF-Chem simulation	98.82 (±4.77)	89.53 (±1.01)	109.83 (±3.02)	92.05 (±11.22)

Vertical Transport Calculation
Vertical Flux Divergence

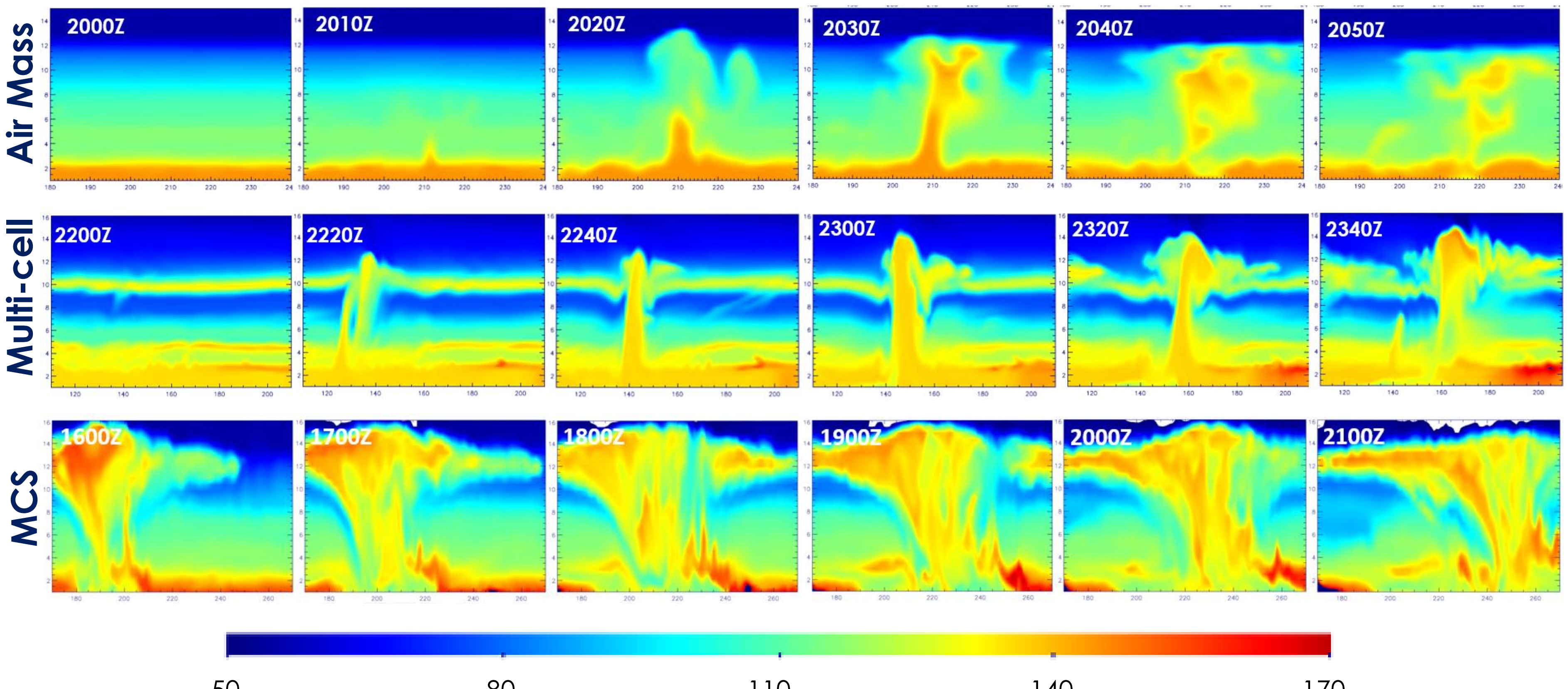
- Vertical Flux Divergence (VFD) per unit area

$$VFD = \sum \frac{\partial \rho w C_{gas}}{\partial z} \quad (Unit: \frac{\frac{g}{m^3} \cdot \frac{m}{s}}{m} = gm^{-2}$$

  - If VFD>0: Vertical Divergence. Vertical transport tends to decrease trace gas concentration at that model layer.
  - If VFD<0: Vertical convergence. Vertical transport tends to increase trace gas concentration at that model layer.
- Vertical Transport Strength: Amplitude of VFD
- Vertical Transport Depth: Level of Maximum Detrainment (LMD), which is the point at which the vertical divergence is most negative.
- We use CO as an example tracer.

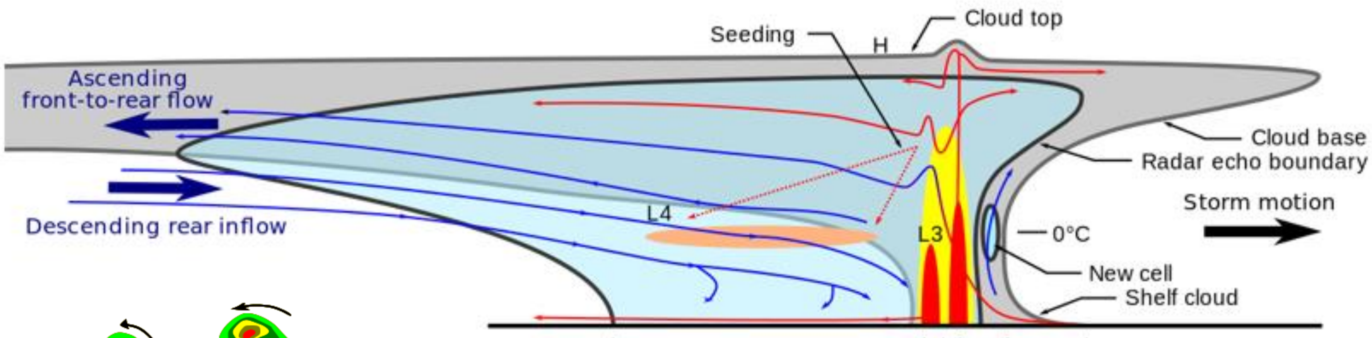


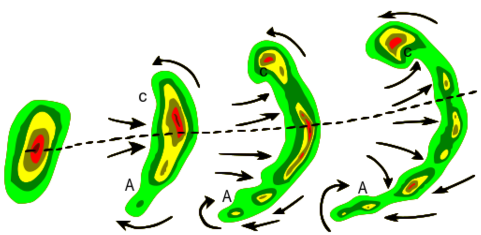
Vertical Transport Calculation Trace Gases Cross Section



WRF-Chem-LDA simulated CO mixing ratio cross section

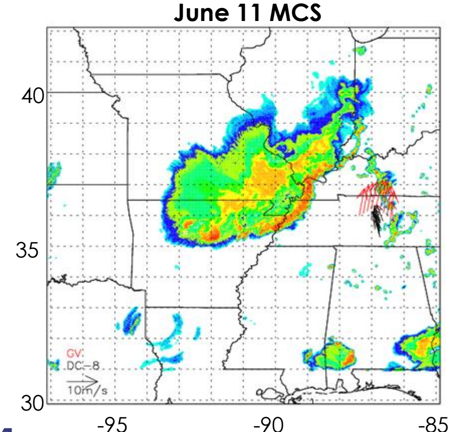
Vertical Transport Calculation Rear-Inflow Influence





$$VFD = \frac{\partial \rho w C_{gas}}{\partial z} = \rho w \boxed{\frac{\partial C_{gas}}{\partial z}} + \boxed{C_{gas}} \frac{\partial \rho w}{\partial z}$$

June 11 MCS



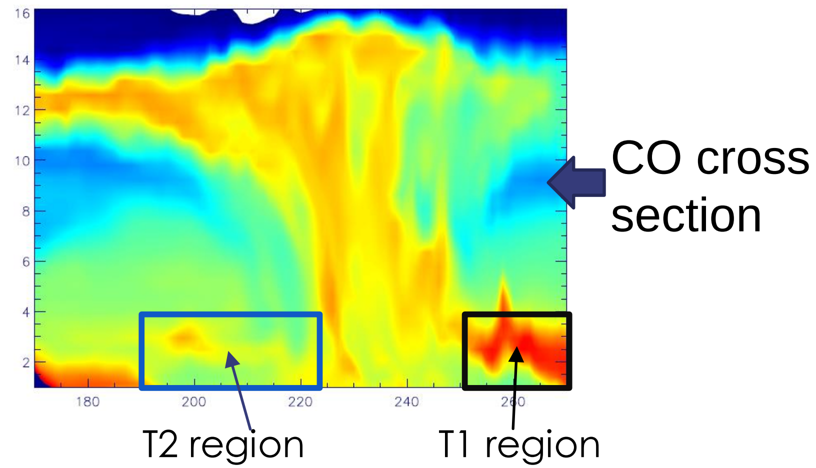
- Rear inflow jet brought relatively clean mid-level air into the storm, which then descended in downdrafts.
- If this relatively clean air enter the updraft region, it will reduce CO mixing ratio as well as CO vertical mixing ratio gradient, and thus reduce the VFD for June 11 case.

Vertical Transport Calculation Rear-Inflow Influence

Tracer experiment:

- To determine the source of the air entering the updraft region.
-

	storm downdraft	Out off storm
Tracer 1 (0-4km)	0	1 ppmv
Tracer 2 (0-4km)	1 ppmv	0



- After 30 minutes:

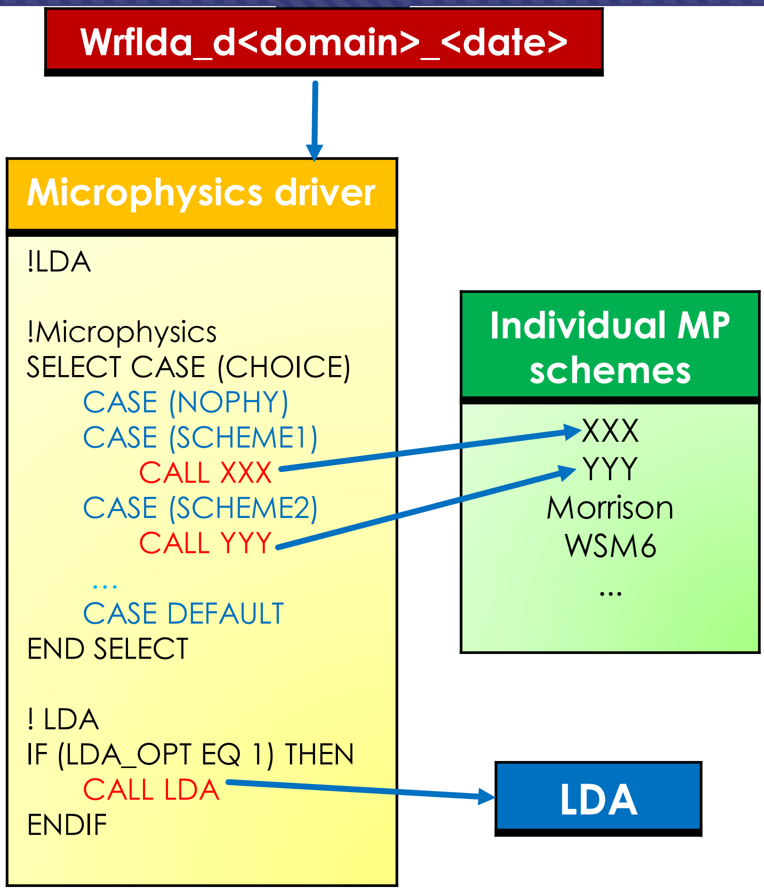
$$rear\ inflow\ effect = \frac{LMD\ Tracer\ 2\ concentration}{LMD\ Tracer\ 1\ concentration}$$

- June 11 MCS: (T2/T1)=7.4
- May 21 Air mass: (T2/T1)=1.26
- **The cleaner downdraft air dominates what is going into the updrafts for the June 11 case.**

Other Vertical Transport Results

- During storm development, the level of maximum detrainment becomes higher in altitude, and the depth of the detrainment envelop increases.
- The vertical flux divergence profiles of different trace gases look similar, which means that the dominant component of vertical transport is vertical motion rather than mixing ratio vertical distribution.
- Comparing upward transport and downward transport, we found that upward transport dominates the vertical transport.
- Below the cloud top, downward transporting of high mixing ratio stratospheric ozone to this region causes the tropospheric ozone enhancement.
- Vertical transport is deeper and stronger in higher composite reflectivity region.

WRF-Chem-LDA Module



Namelist.input: time_control

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Namelist.input: physics

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Conclusion

- Lightning Data Assimilation (LDA)
  - Improved WRF-Chem simulation of **storm location** and **vertical structure**.
  - LDA is fast, cheap. It's suitable for using WRF-Chem to study chemistry and thunderstorm interaction problems (i.e. lightning NO_x production, lightning transport and photochemical production of ozone, deep convection injection of water vapor, aerosol indirect effects, using trace gases as tracer to study cloud dynamics)
- The MCS has the weakest vertical transport ability per unit area. Rear-inflow jet reduced its vertical transport of trace gases.
- Some mesoscale mechanism determine the strength of deep convective transport. In the future, we will take a look at cloud parameterized scale, to evaluate cloud parameterized WRF-Chem simulation of deep convective transport.

Contact

- Yunyao Li (liyunyao@umd.edu)