Vertical mixing in the atmospheric boundary layer and its implications for air quality

Xiaoming Hu
@ Peking University

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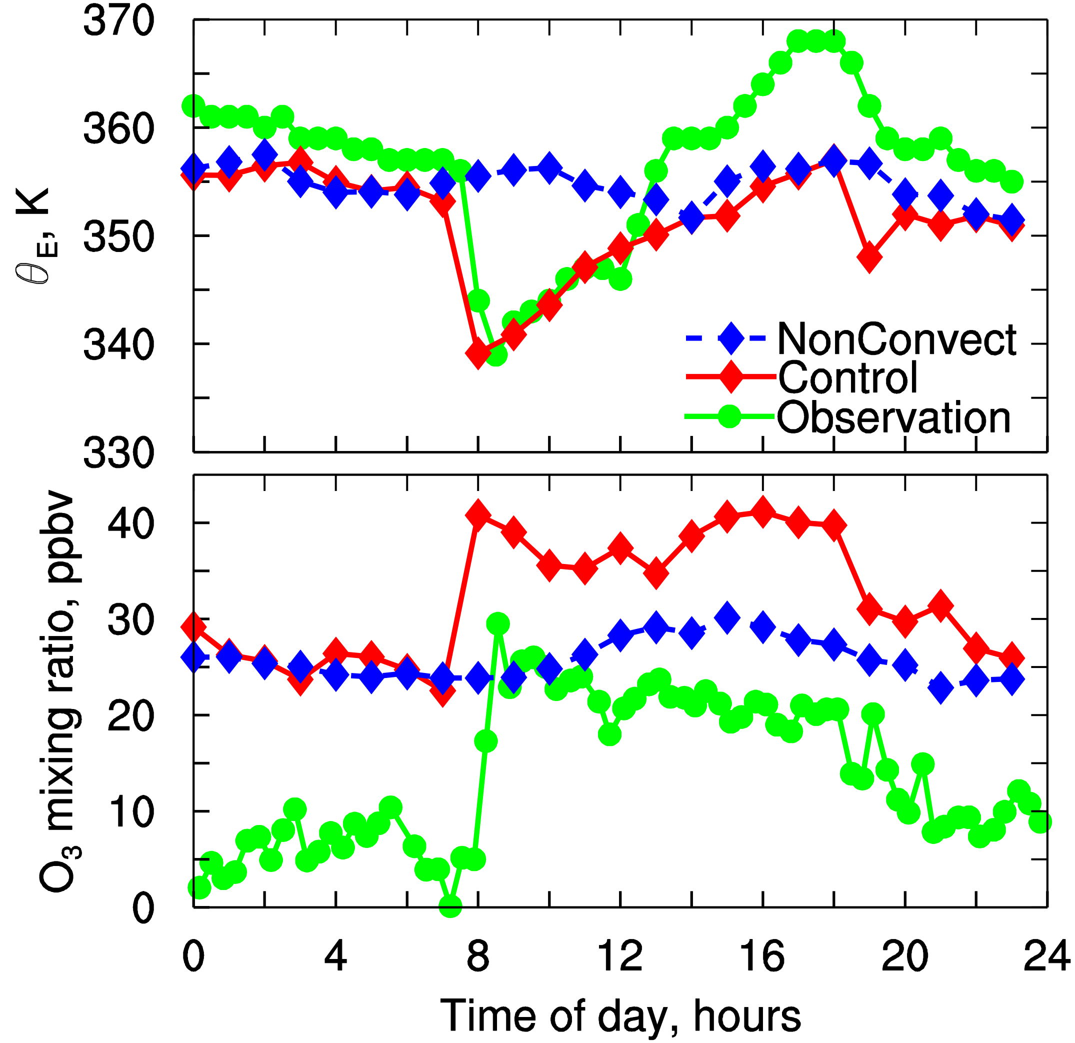
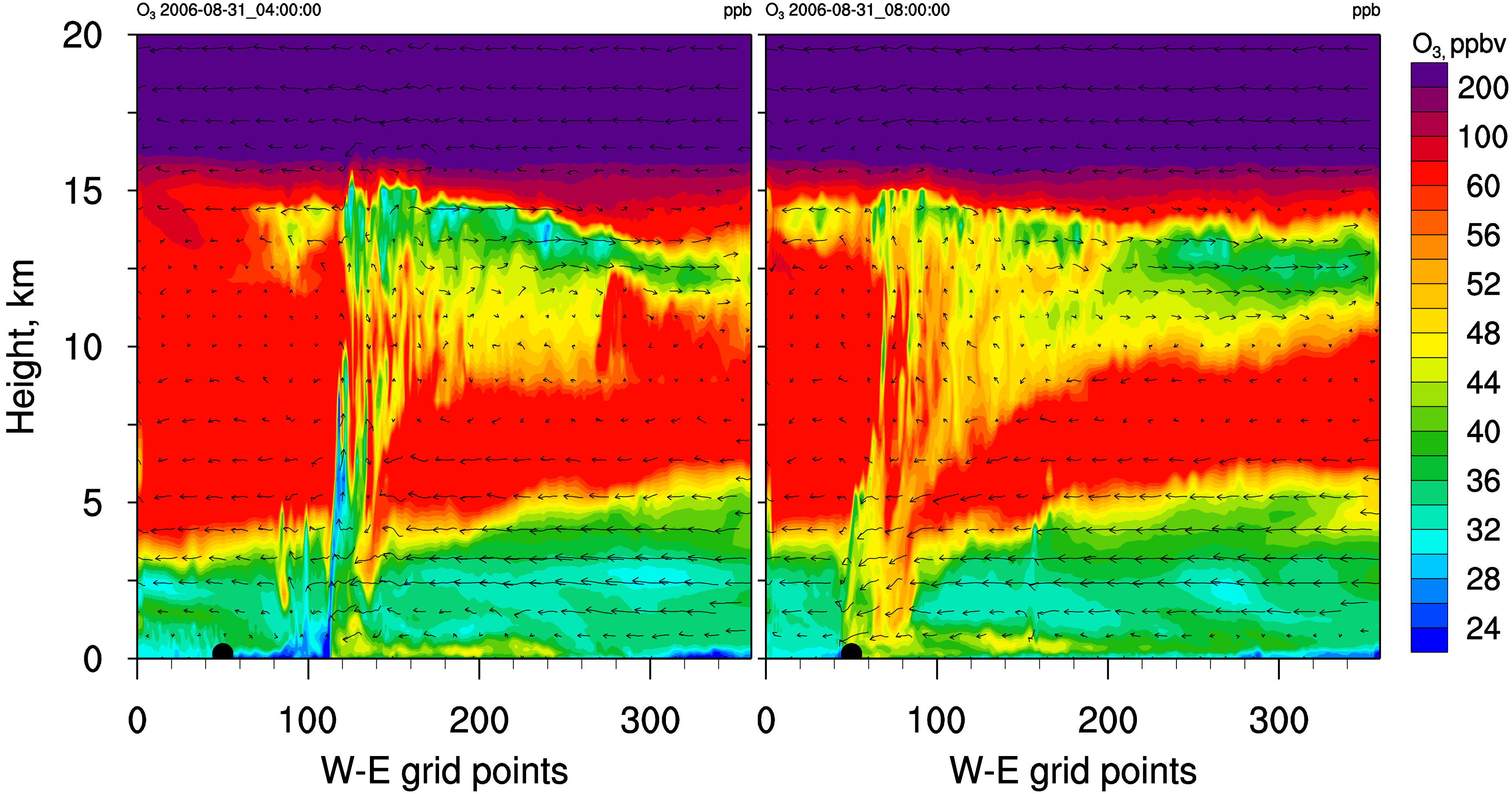
- Different forms of vertical mixing and their impact on O_3 variability
  - Moist deep convection in the tropic
  - Mixed-phase clouds in the Arctic
  - Low-Level Jets (LLJs) in the eastern US
  - Nocturnal warming events in Oklahoma

Impact of moist deep convection, a case in Senegal on Aug. 31, 2006



Ozone increased when deep convection passed (Hu et al., 2010a)

Impact of moist deep convection, WRF/Chem 3D simulation



Ozone is transported down in the downdrafts

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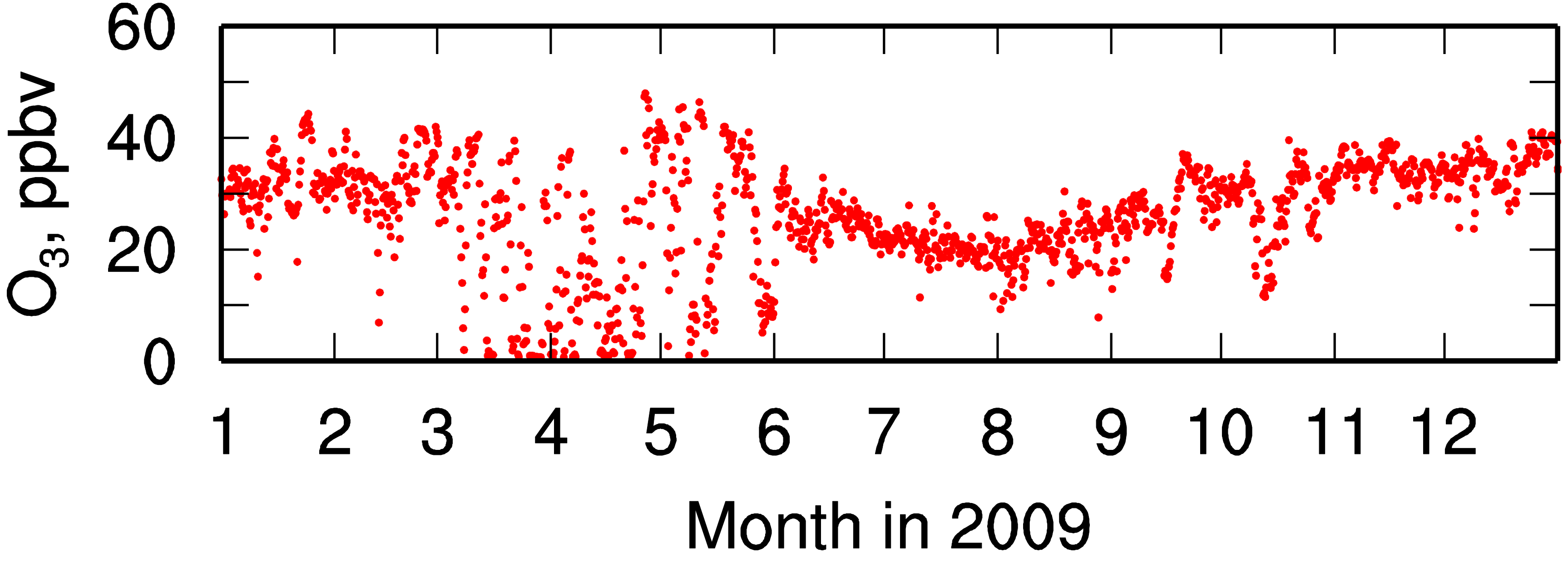
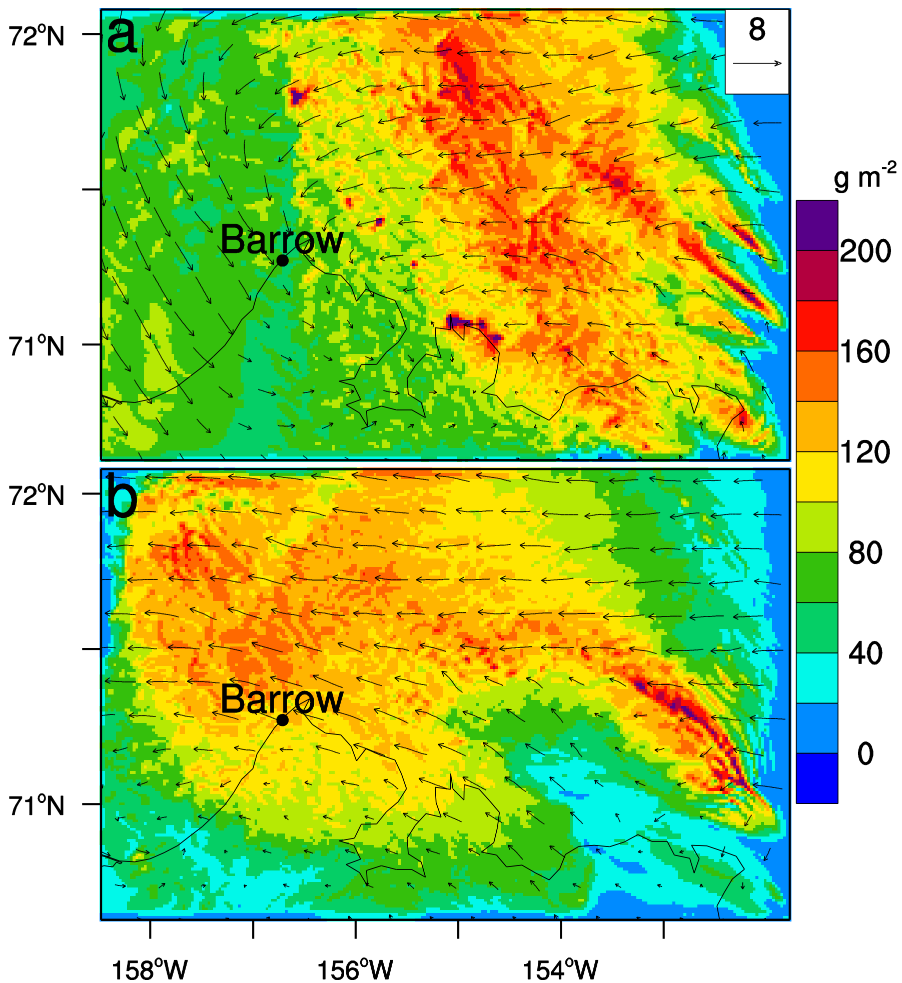
Impact of mixed-phase clouds, O_3 depletion events (ODEs) in the Arctic

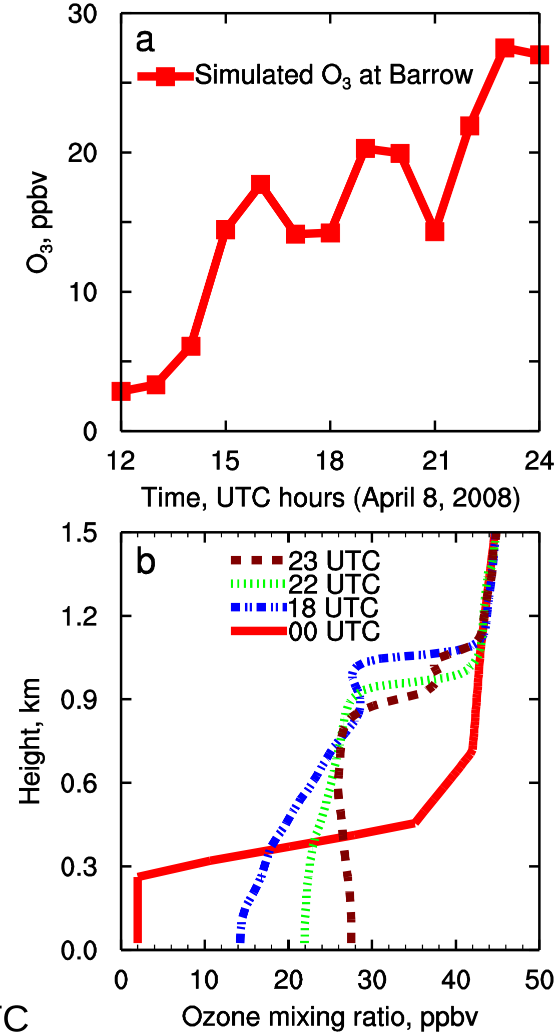


While the reactions responsible for the occurrence of ODEs are understood, their termination mechanisms remain debatable.

Impact of mixed-phase clouds, WRF/Chem simulation

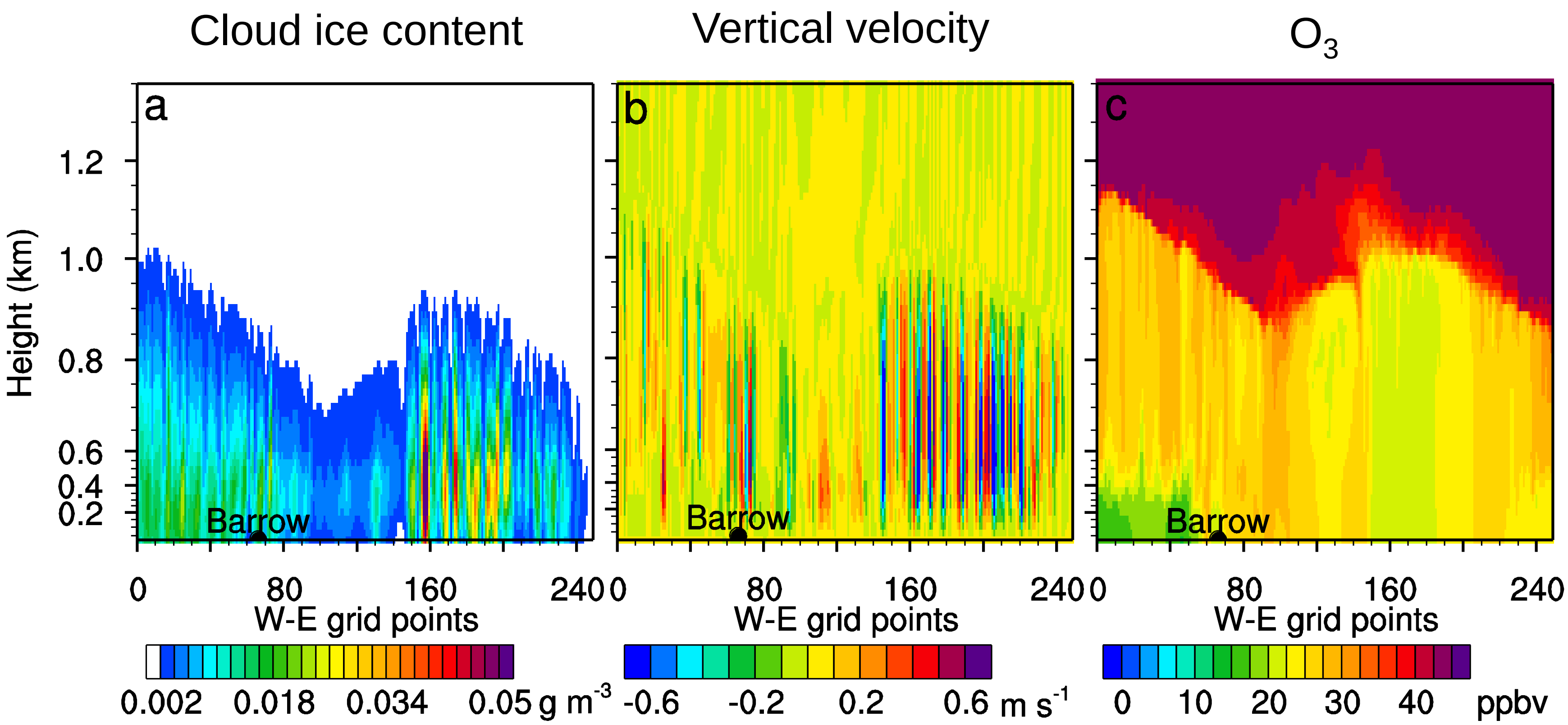


Column integrated condensed water at 12 and 18 UTC



Surface O_3 increased when the clouds passed by (Hu et al., 2011)

Vertical mixing induced by cloud top radiative cooling



Cloud-top radiative cooling induced strong downdrafts and updrafts, which mixed O_3-richer air downward, thus terminated the ozone depletion event.

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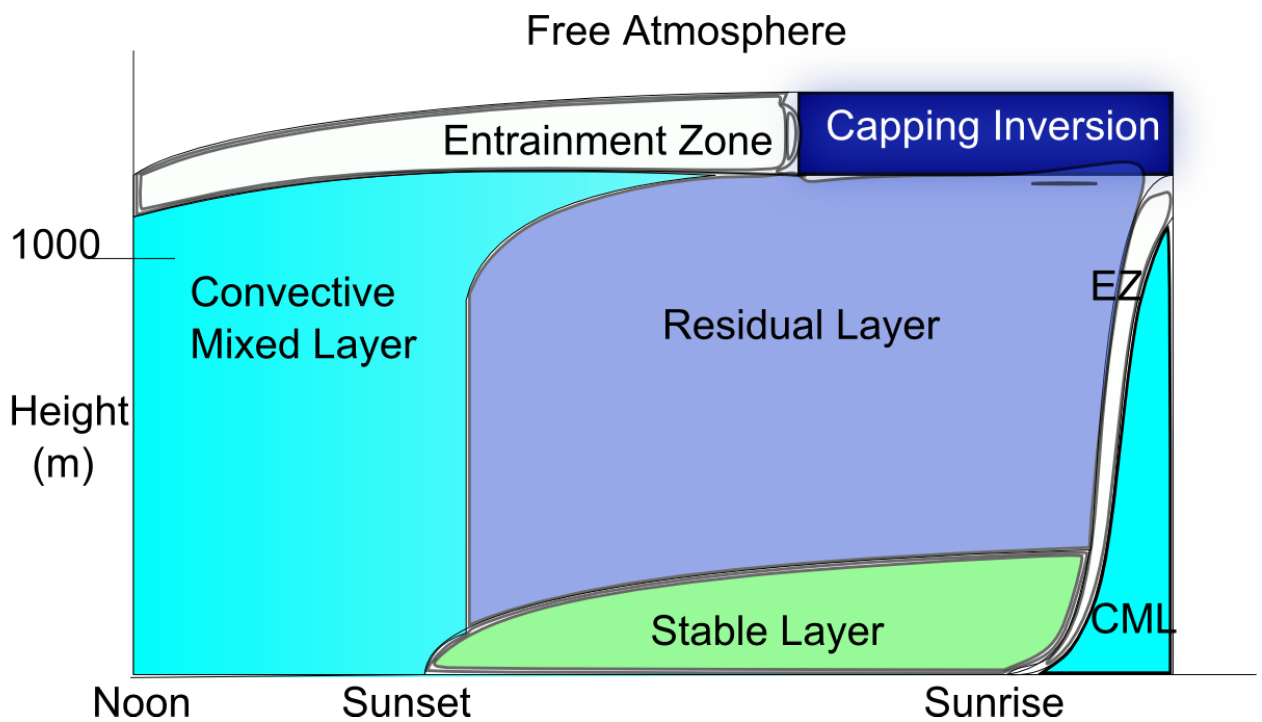
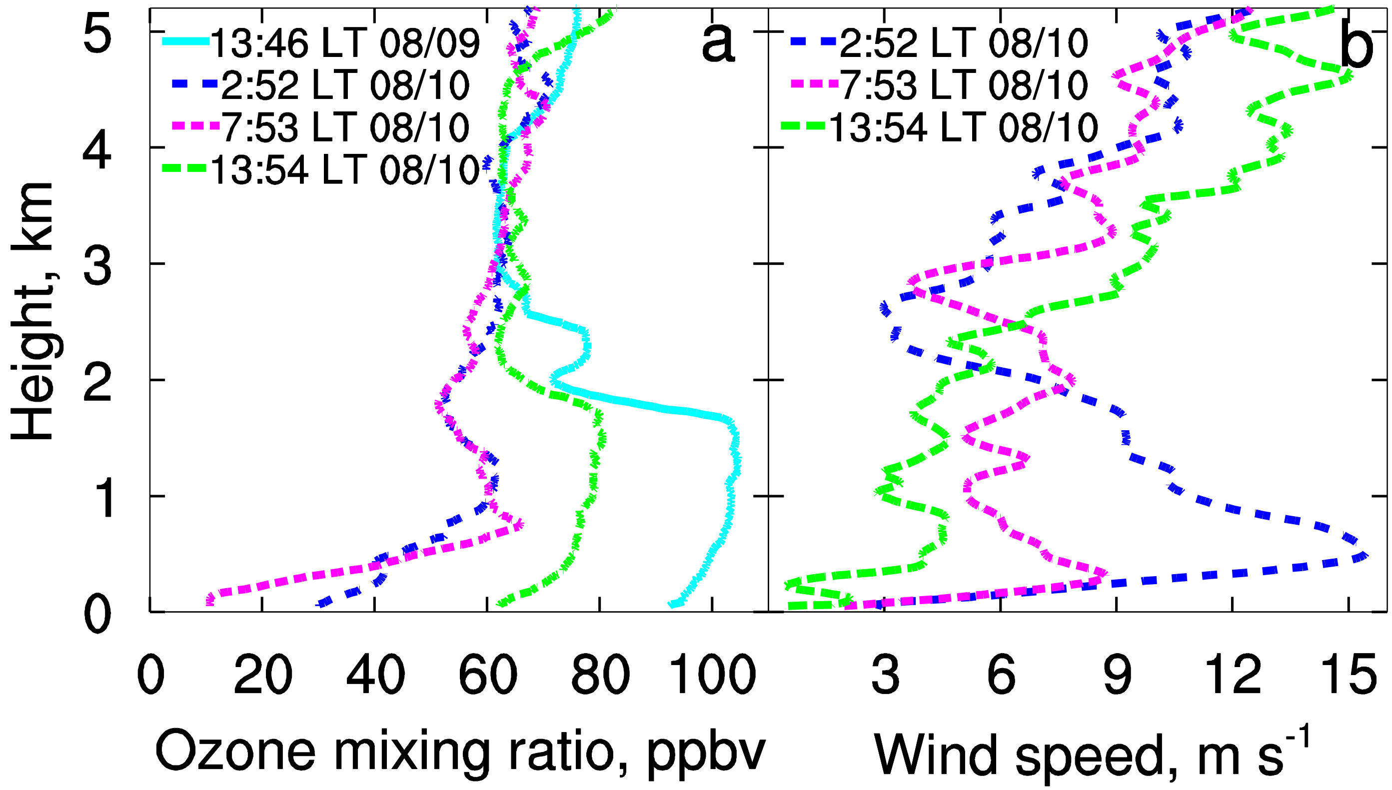
Impact of LLJs on BL O_3, Classical view of the residual layer



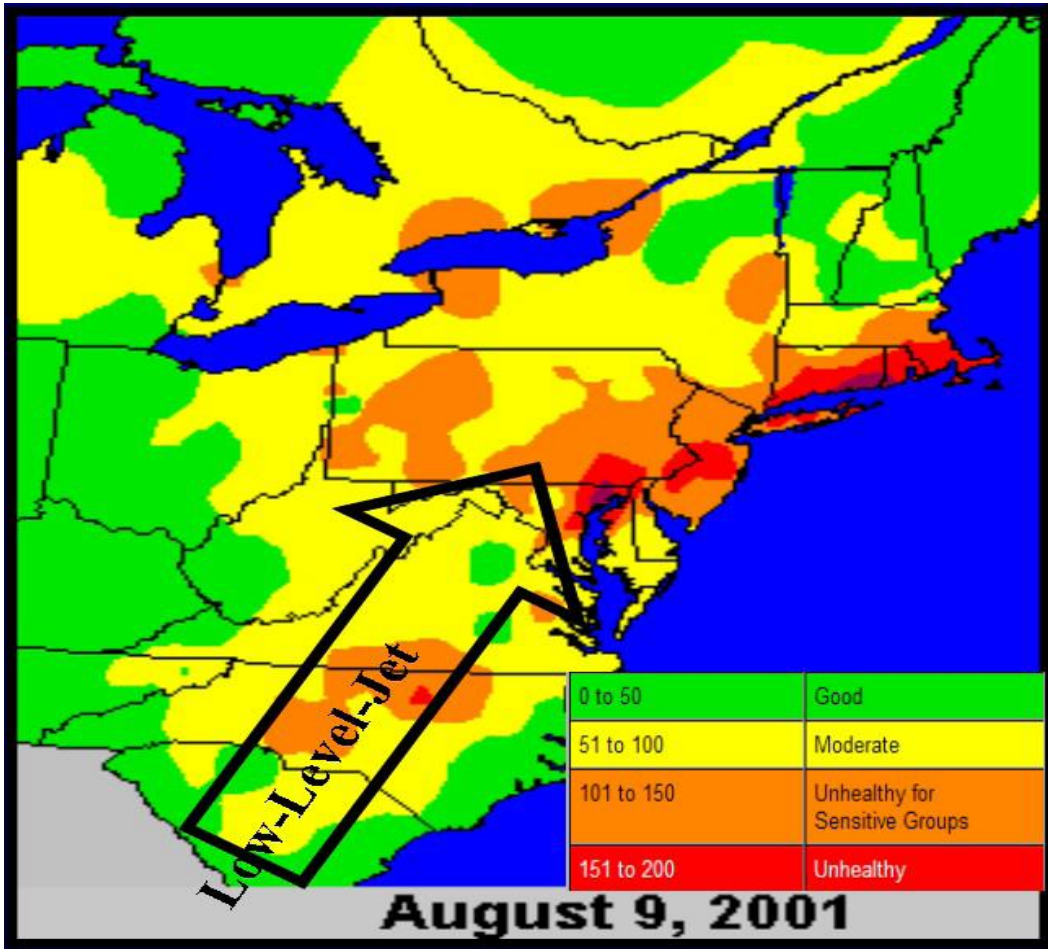
The residual layer is often thought to be a reservoir of pollutants

Observation challenges the classical view of the residual layer



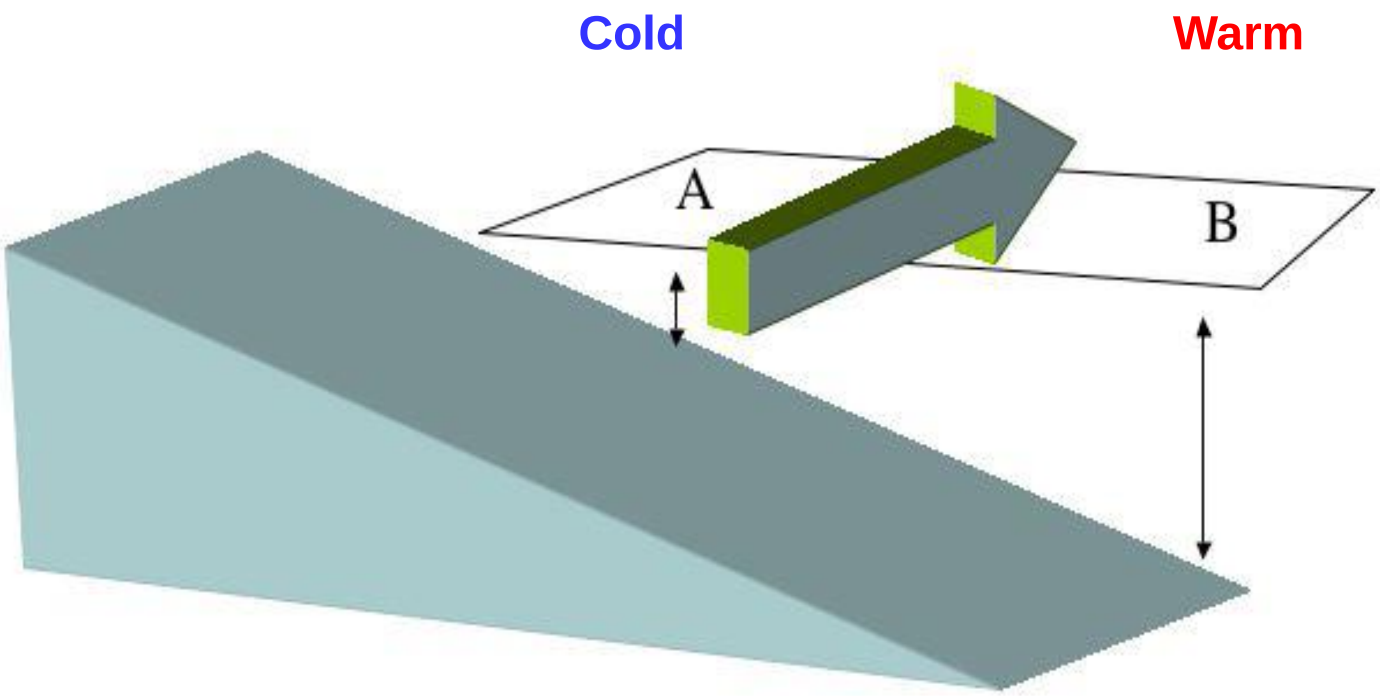
The residual layer in Beltsville is rarely a reservoir of O_3 (Hu et al., 2012b)

Mid-Atlantic costal LLJs



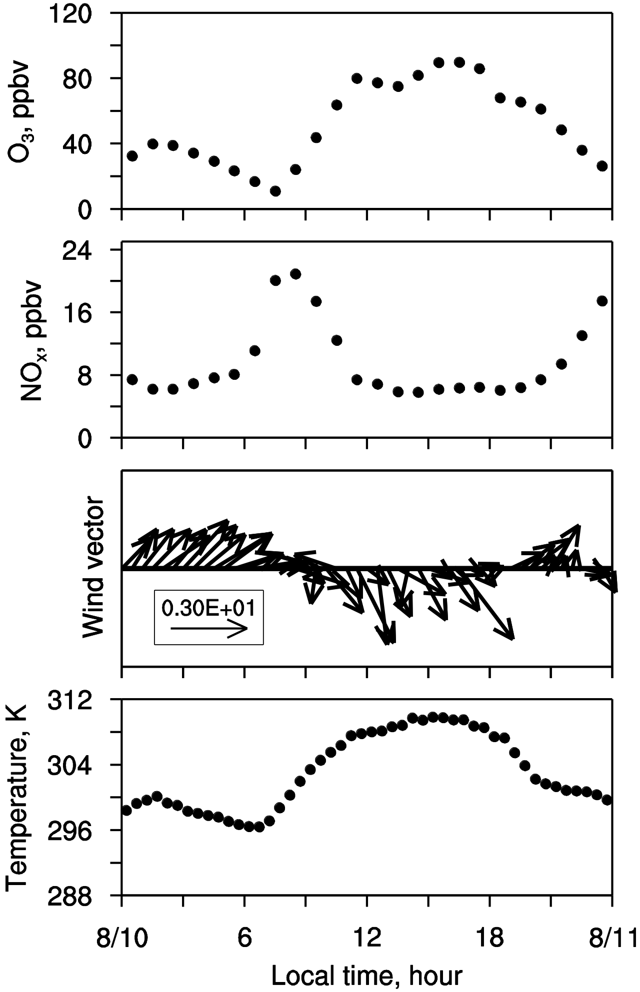
LLJs occur frequently in the eastern costal area. (Figure: Air quality index during an ozone episode, Ryan and Piety, 2001)

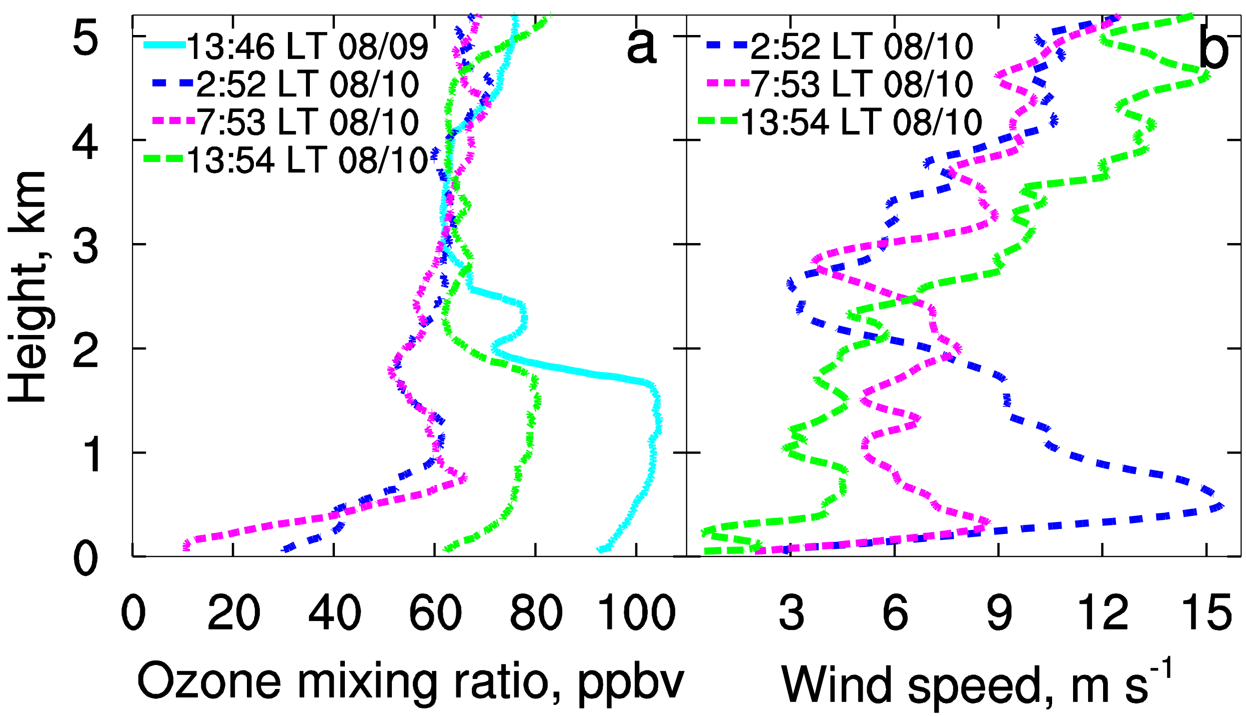
LLJs formation in Beltsville



Thermal wind contributed to the formation of the Mid-Atlantic costal LLJs

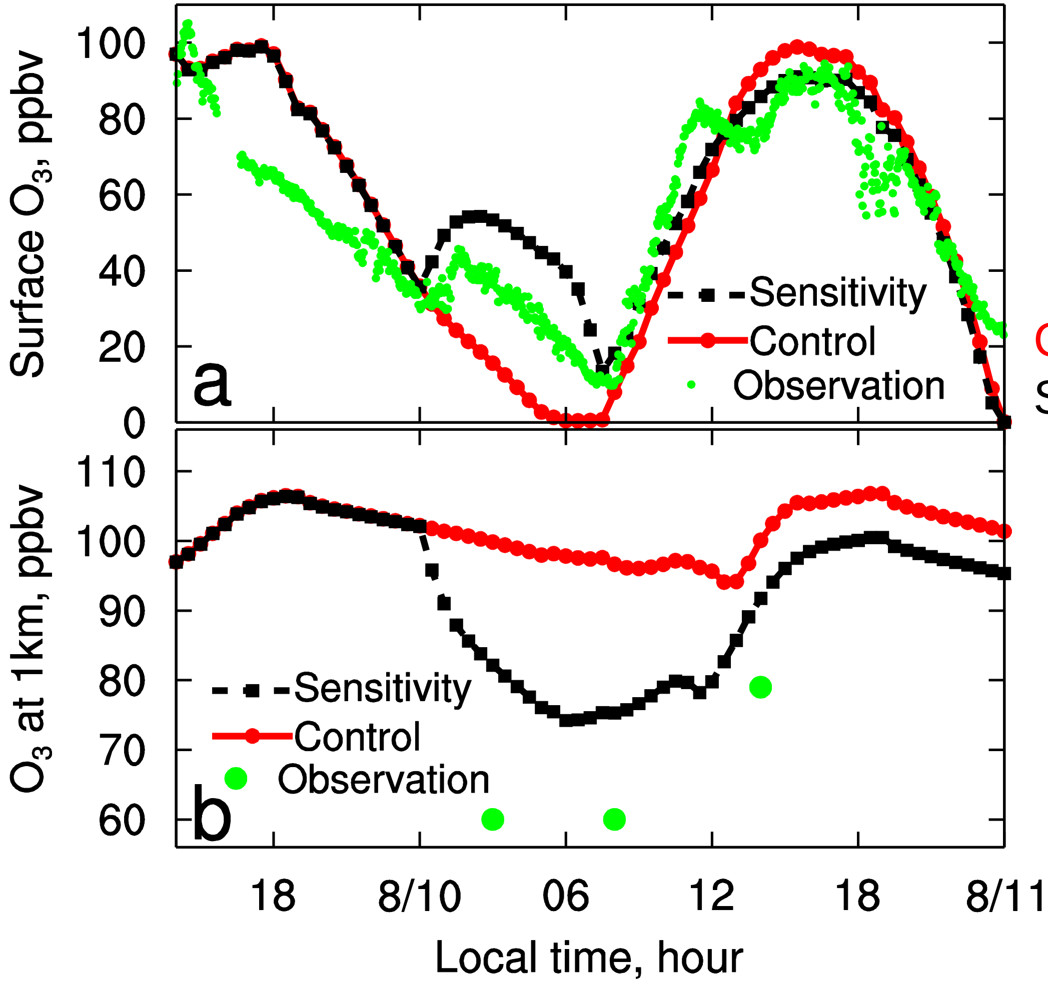
Case study of August 10, 2010, Observation





It appears a LLJ played an important role in vertical O_3 redistribution (Hu et al., 2012b)

Case study of August 10, 2010, 1D simulations

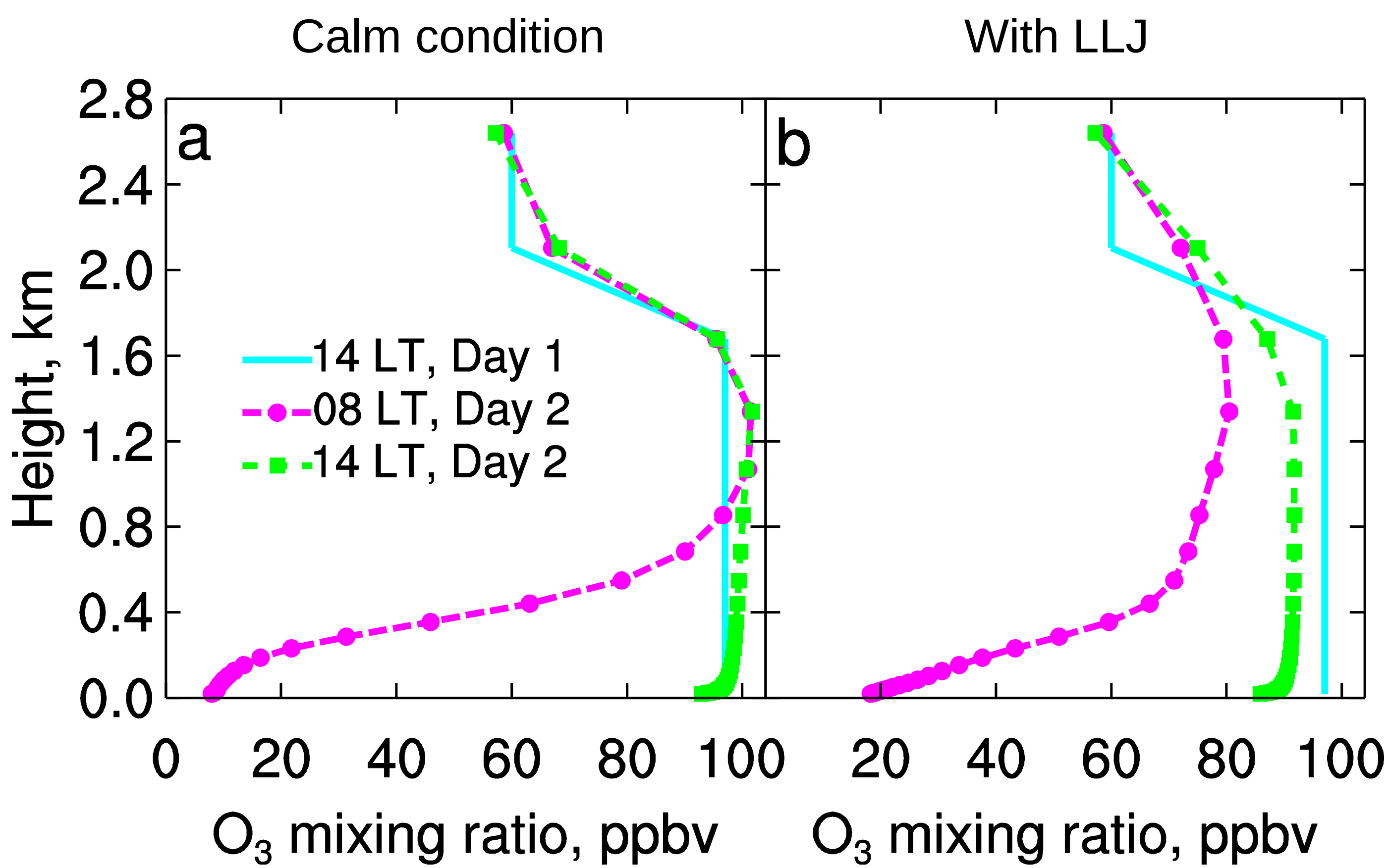


Control : Calm condition, no LLJ

Sensitivity: with LLJ

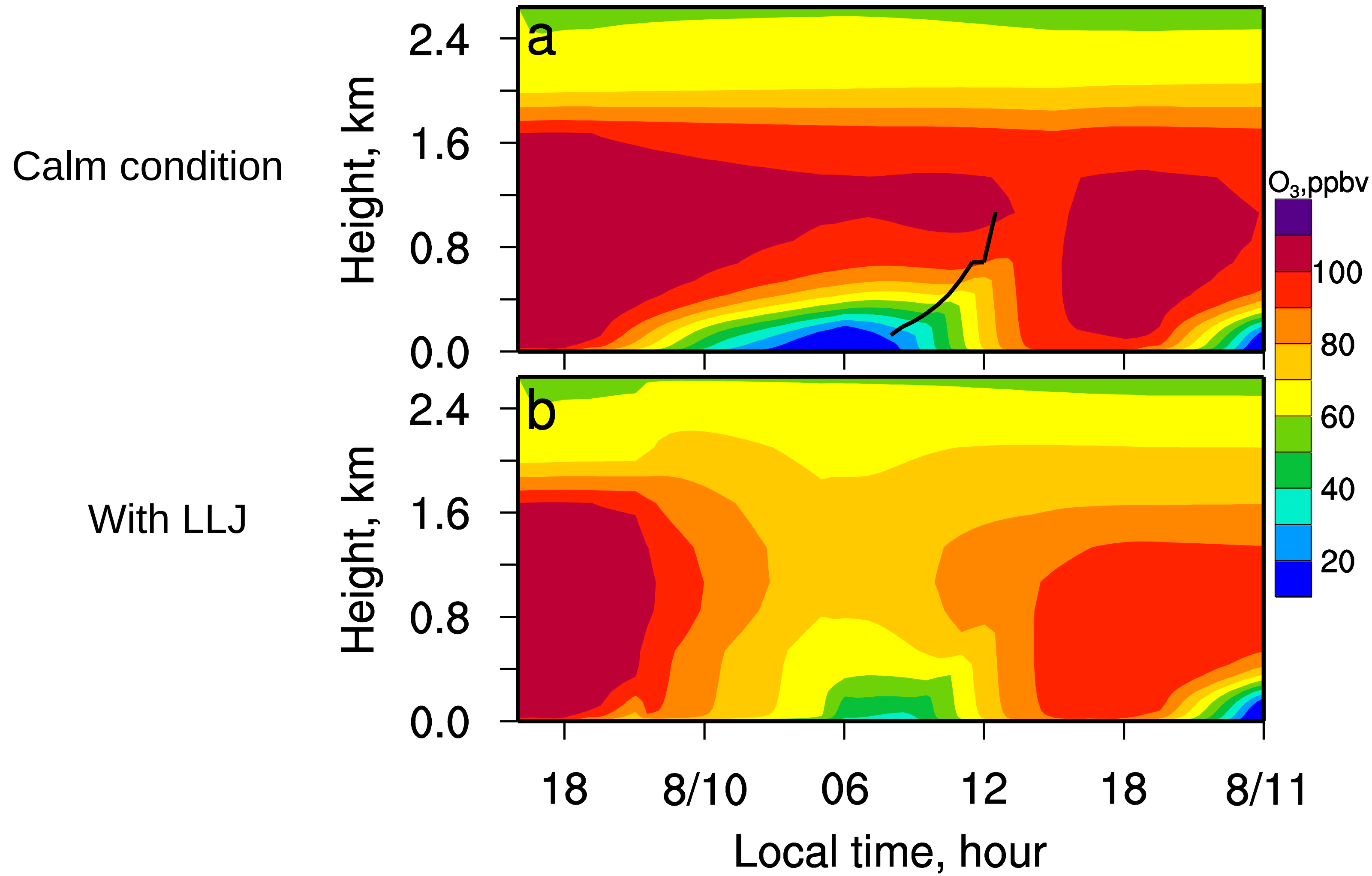
Simulation could capture the main features associated with the LLJ.

Simulated profiles of O_3 w/o & with LLJ



The presence of the LLJ reduces the RL O_3 substantially. Downward transported O_3 is removed near the surface by dry deposition and chemistry reactions. As a result the BL O_3 on the following day is reduced.

Time-height diagrams of simulated O_3



The RL is not a reservoir of O_3 in the presence of a strong LLJ

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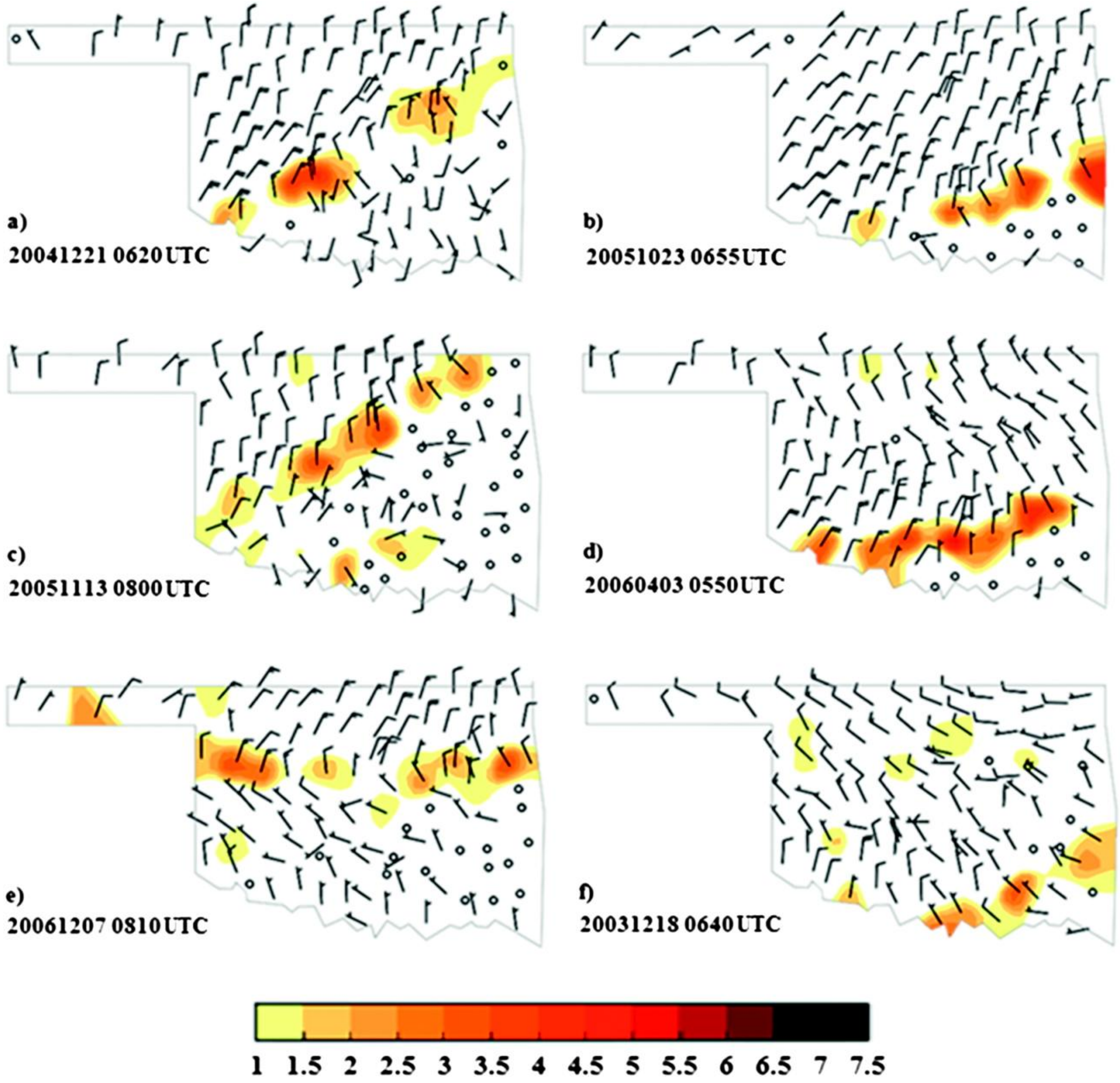
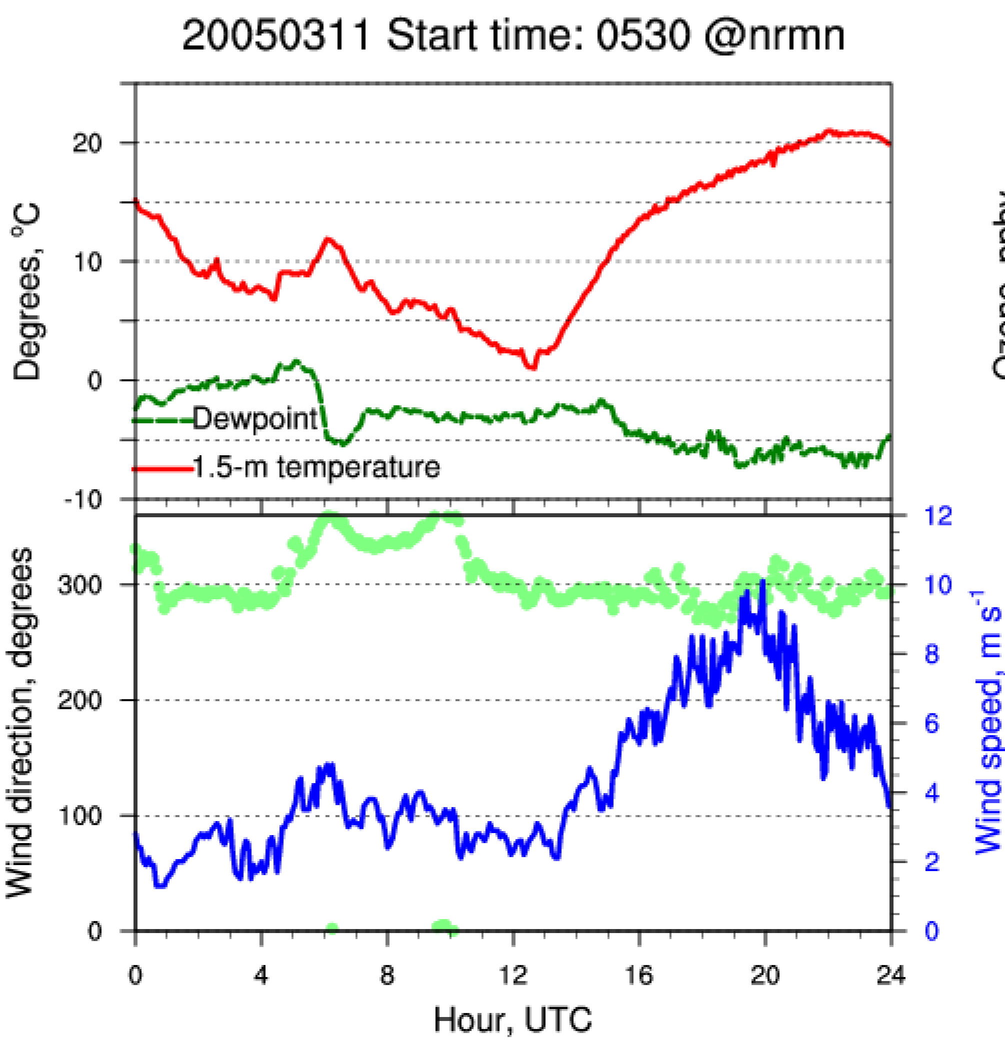
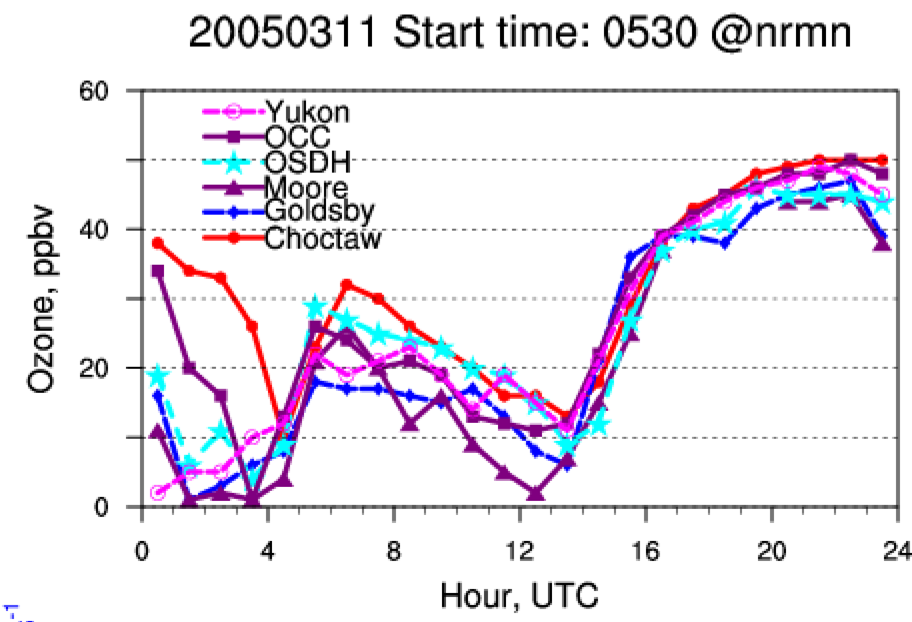
Impact of nocturnal warming events



Temperature increases associated with cold-frontal passages (Nallapareddy et al., 2011)

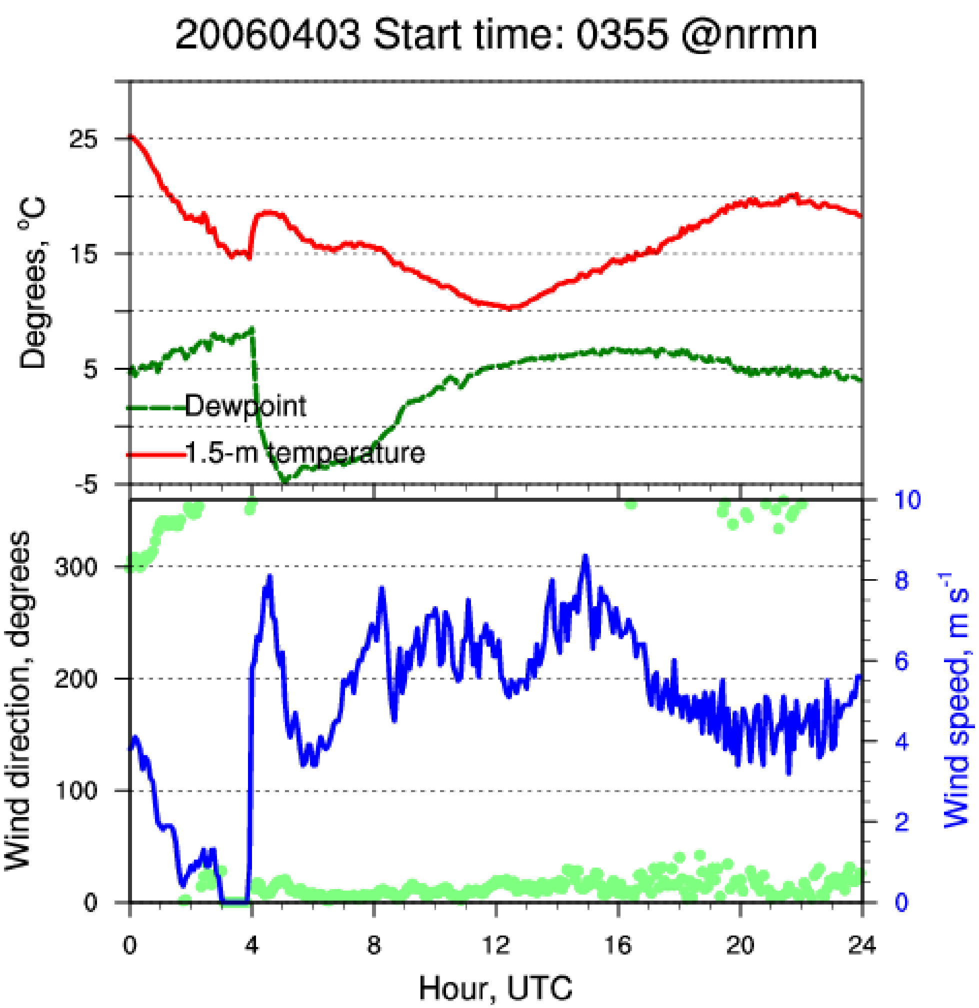
Nocturnal warming events on Mar. 11, 2005

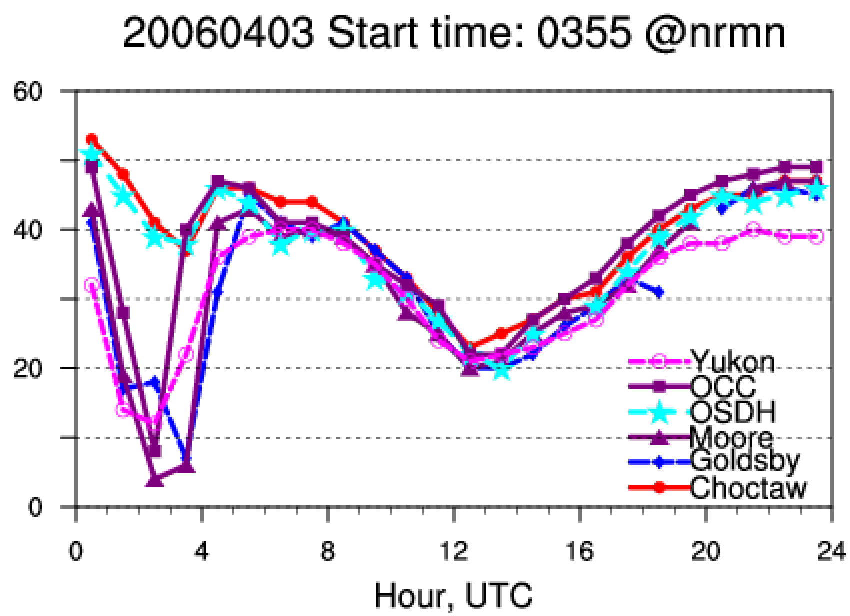




Ozone increased associated with the nocturnal warming events

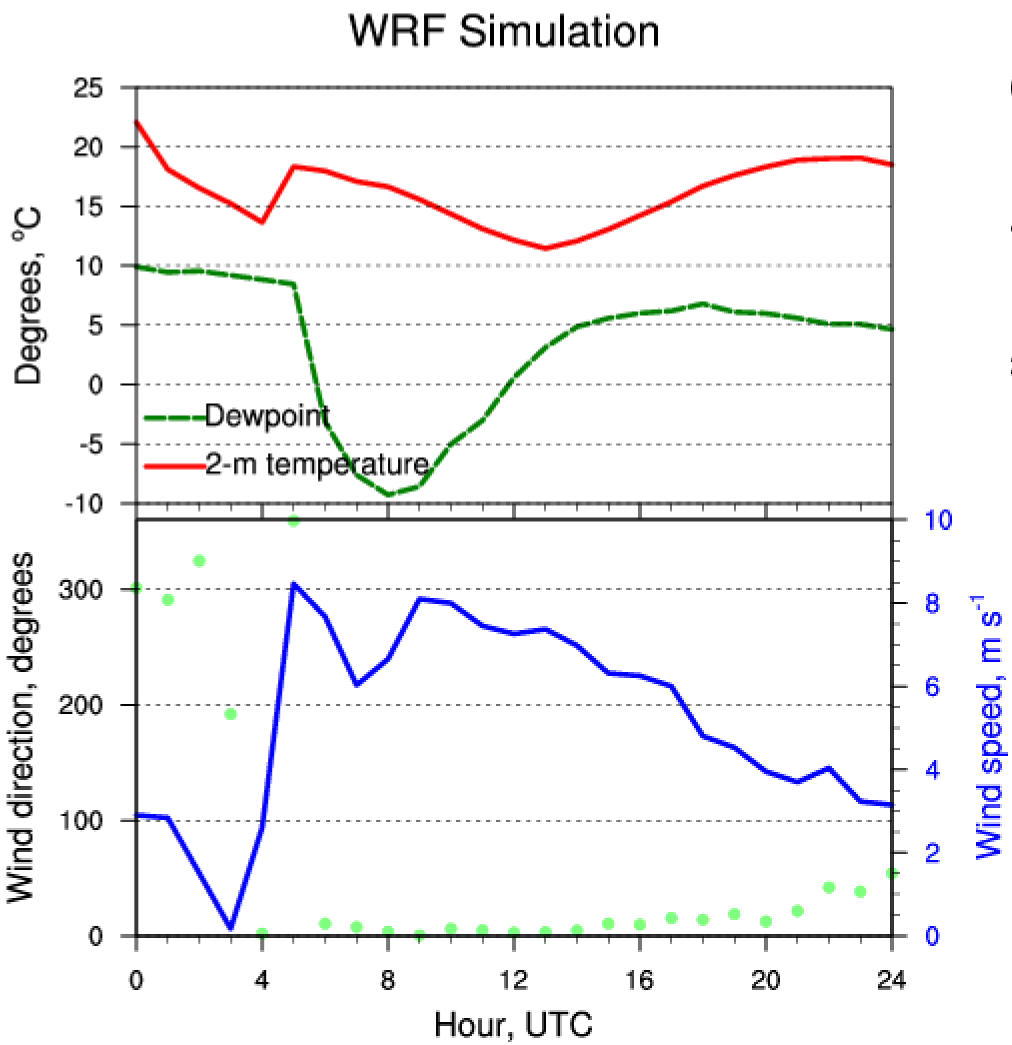
Nocturnal warming events on April 3, 2006

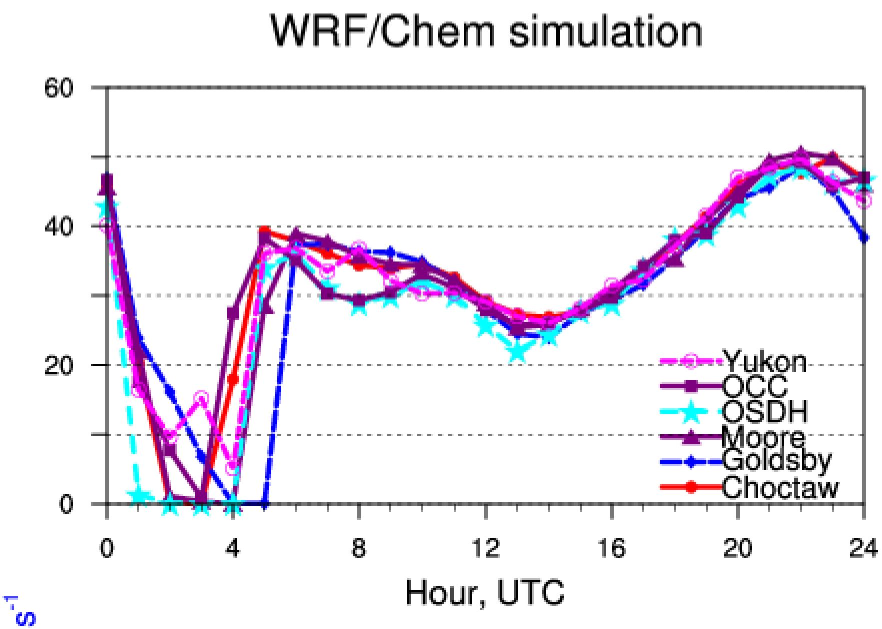




Ozone increased by 40 ppbv when the nocturnal warming event occurred

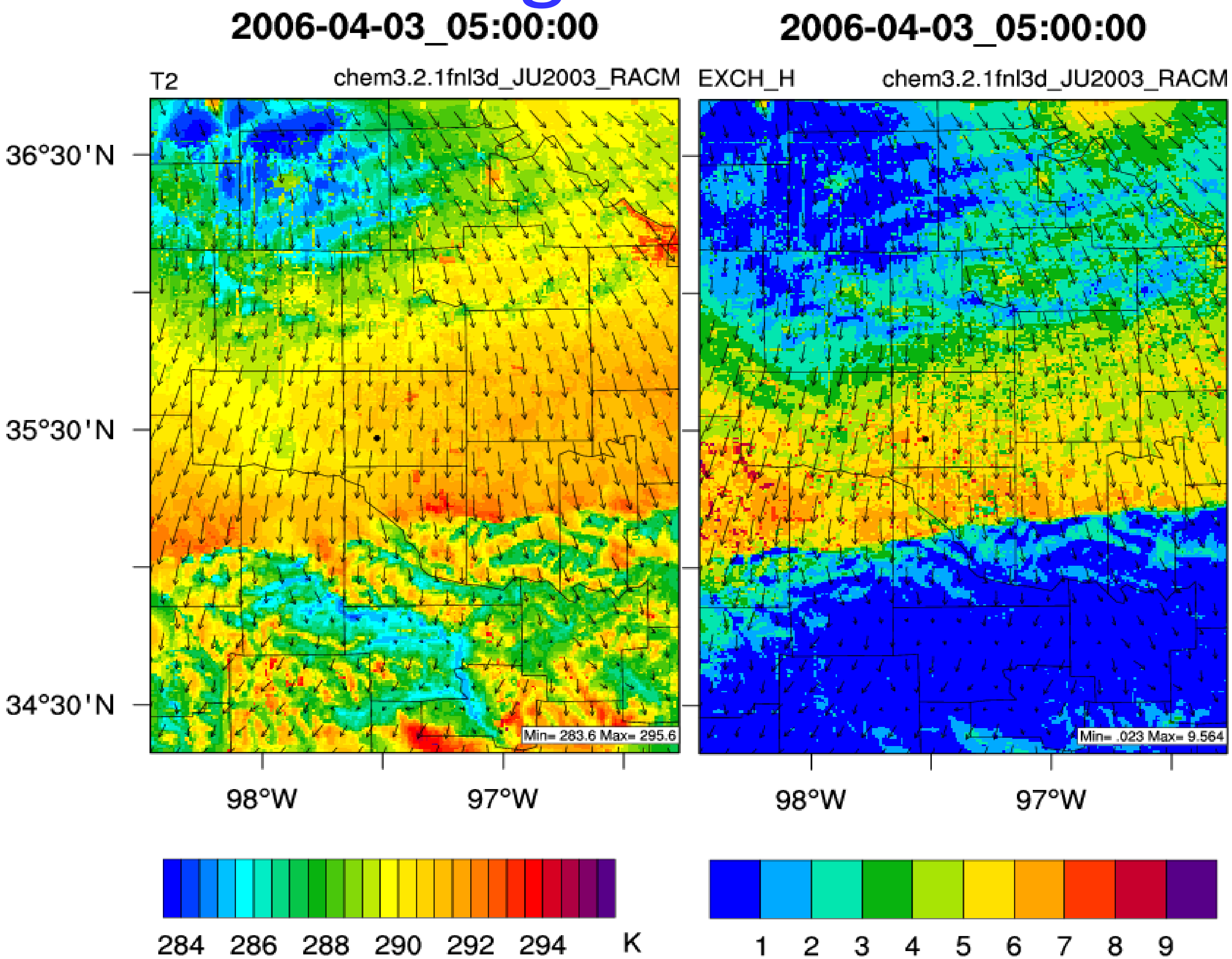
Case study of April 3, 2006 WRF/Chem simulation



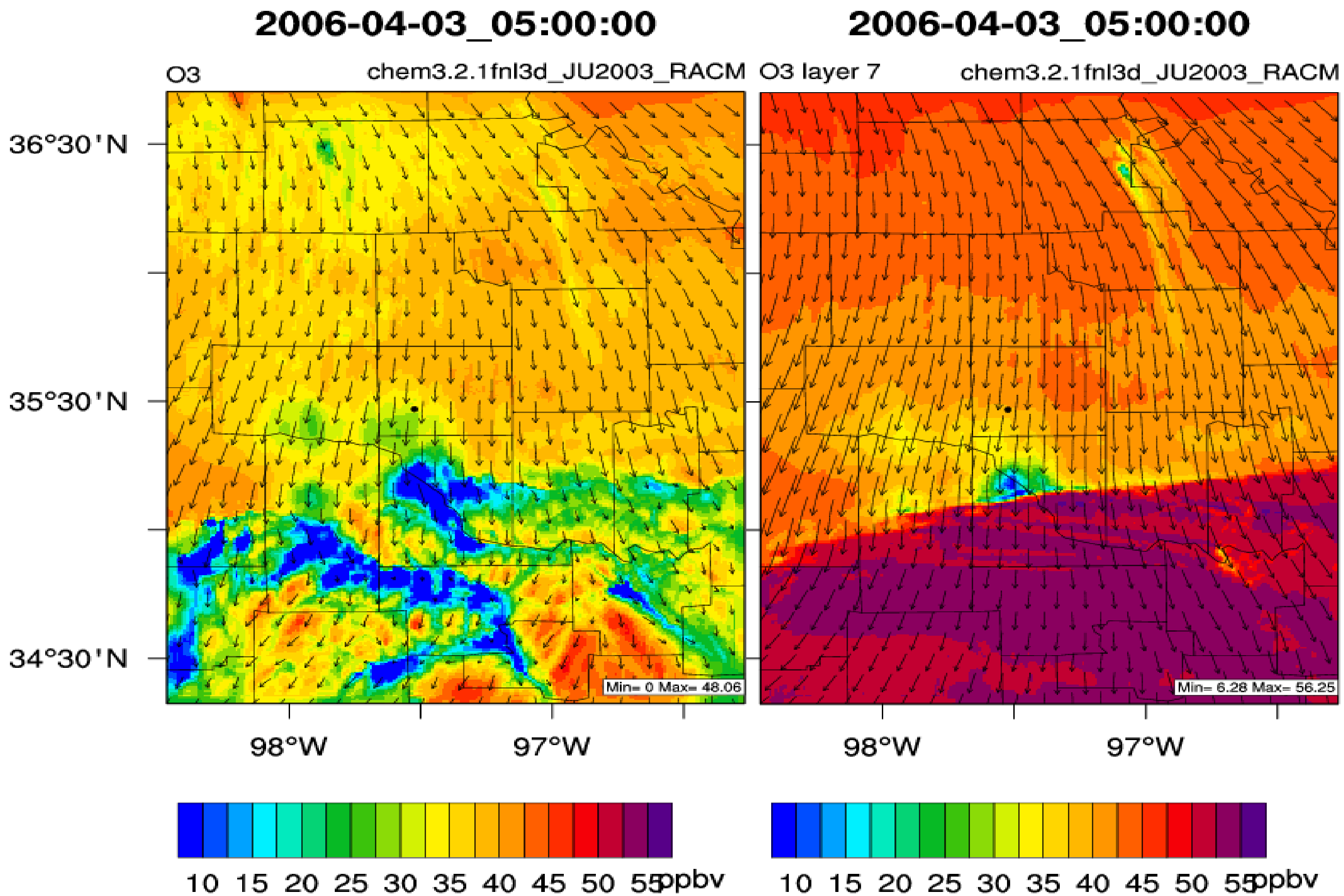


WRF/Chem could reproduce important characteristics of the nocturnal warming events

Spatial distribution of T2 and vertical mixing coefficient



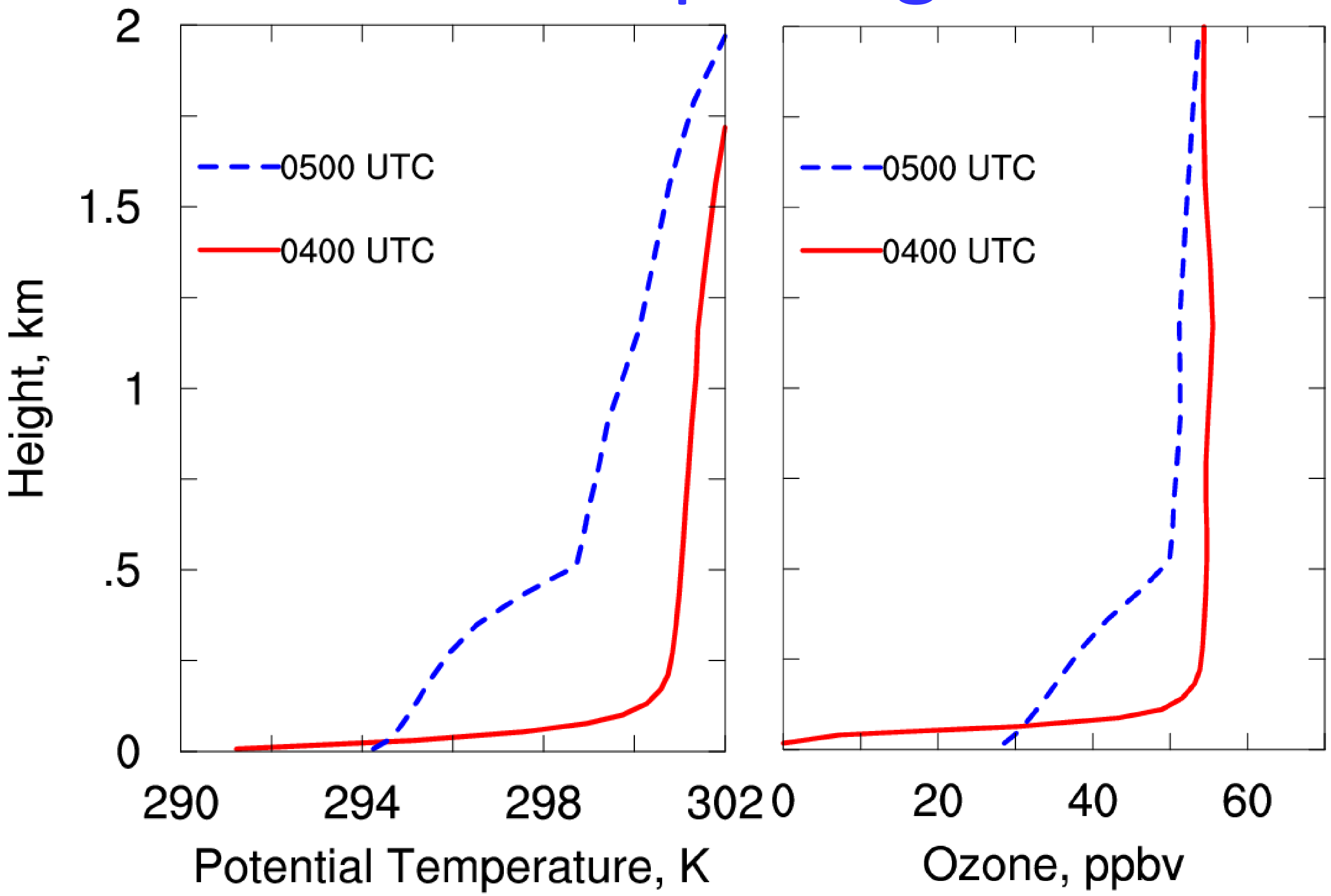
Spatial distribution of O_3 at surface and ~200 m AGL



Surface

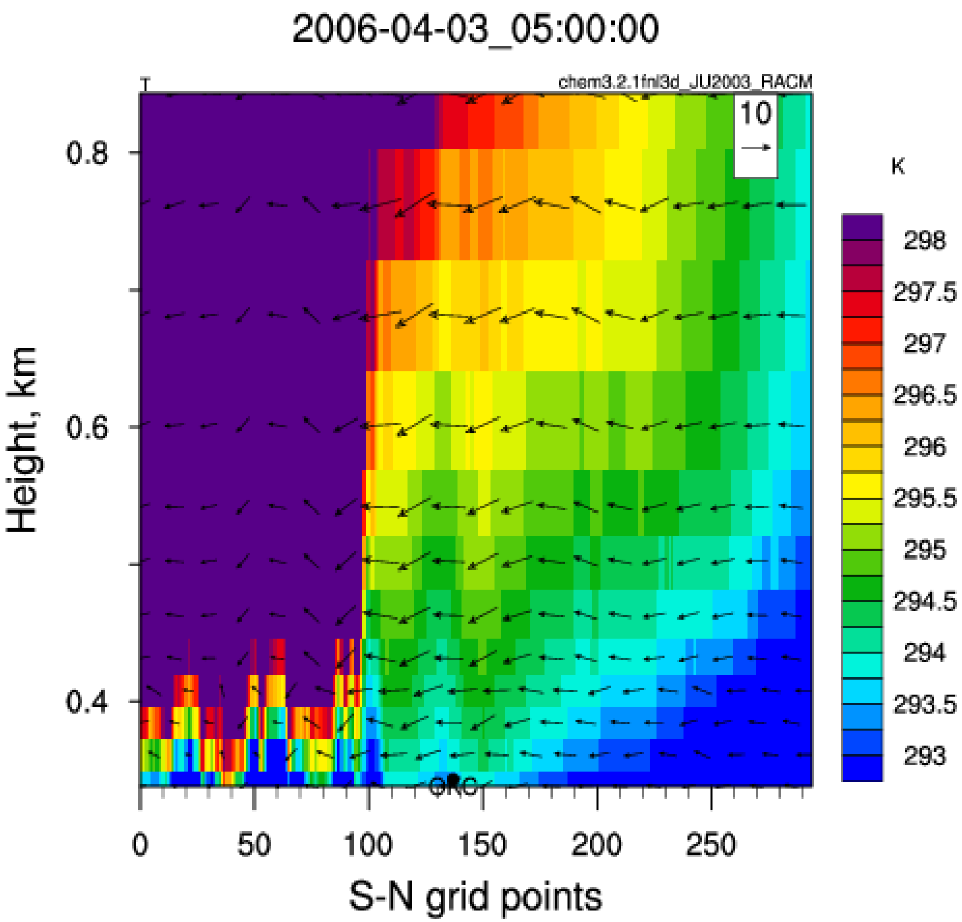
~200 m AGL

Profiles before and after the cold-frontal passage

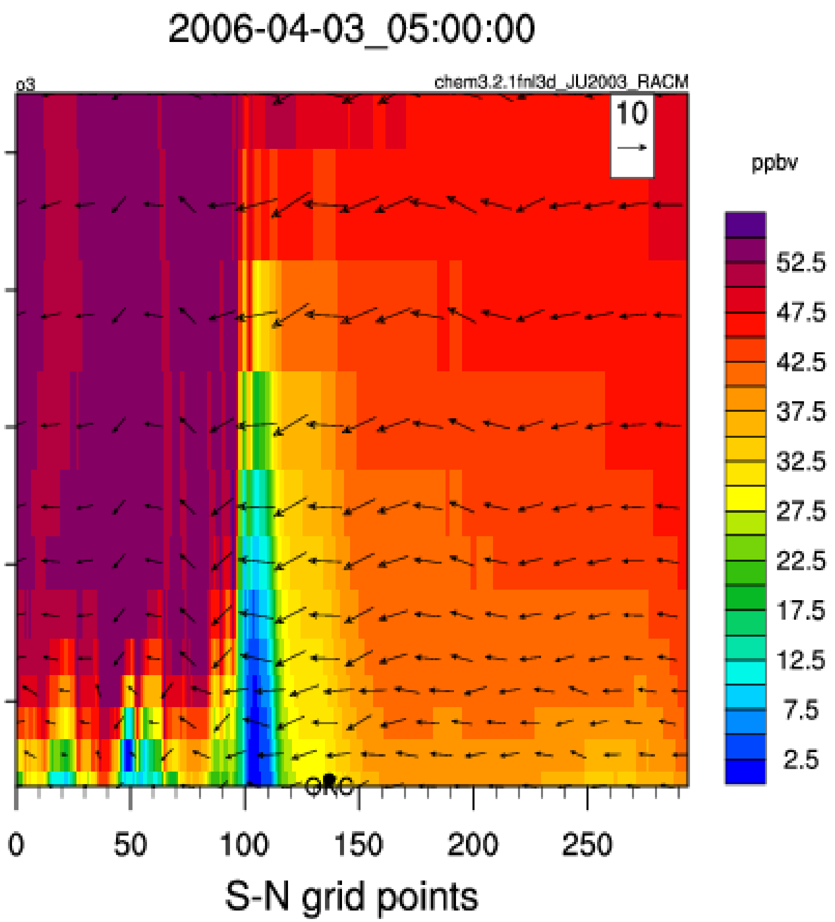


Vertical mixing associated with the cold front increased surface temperature and O_3

Contrast of T and O_3 around the front



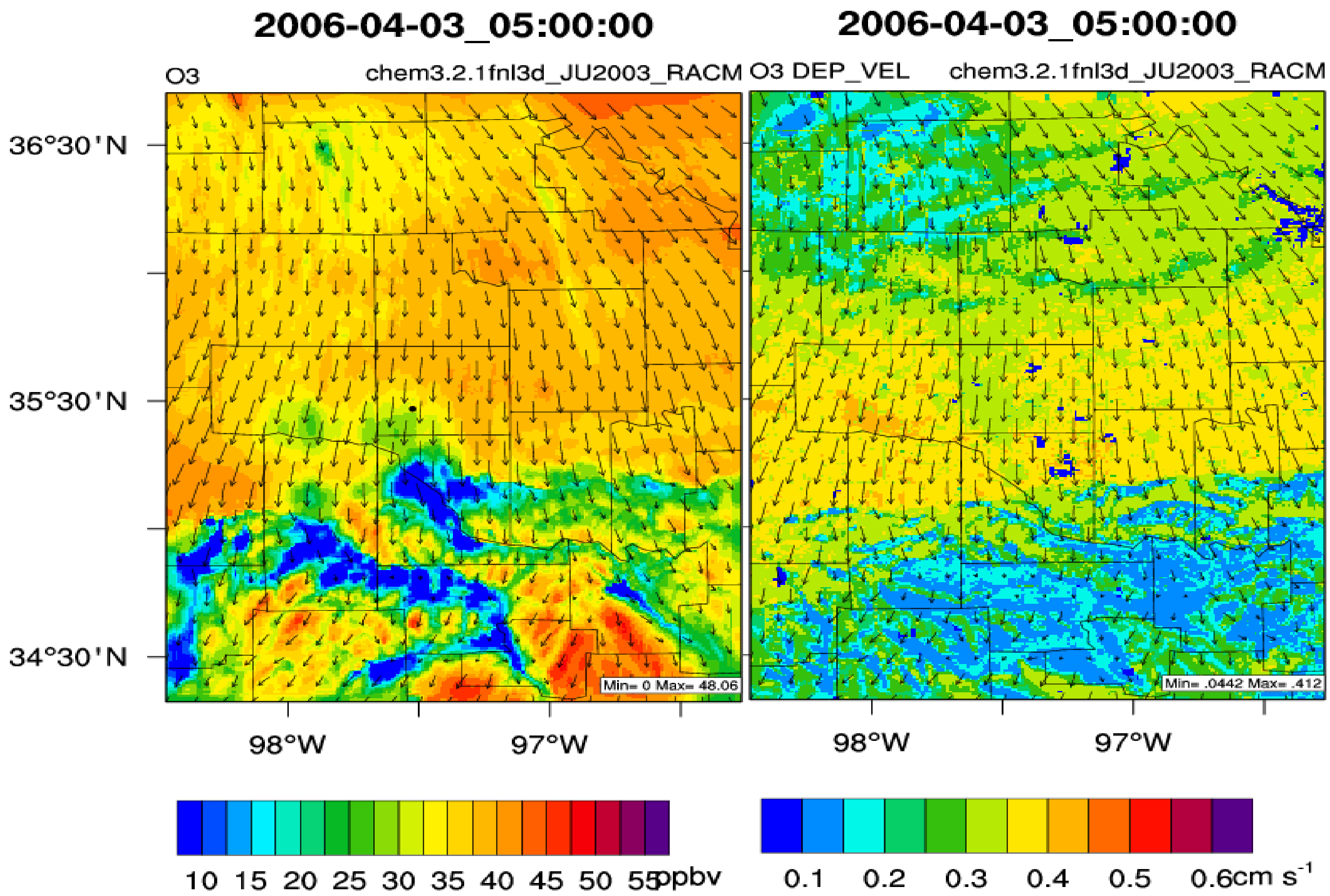
Potential temperature



Ozone

Temperature and O_3 are vertically well mixed behind the cold front

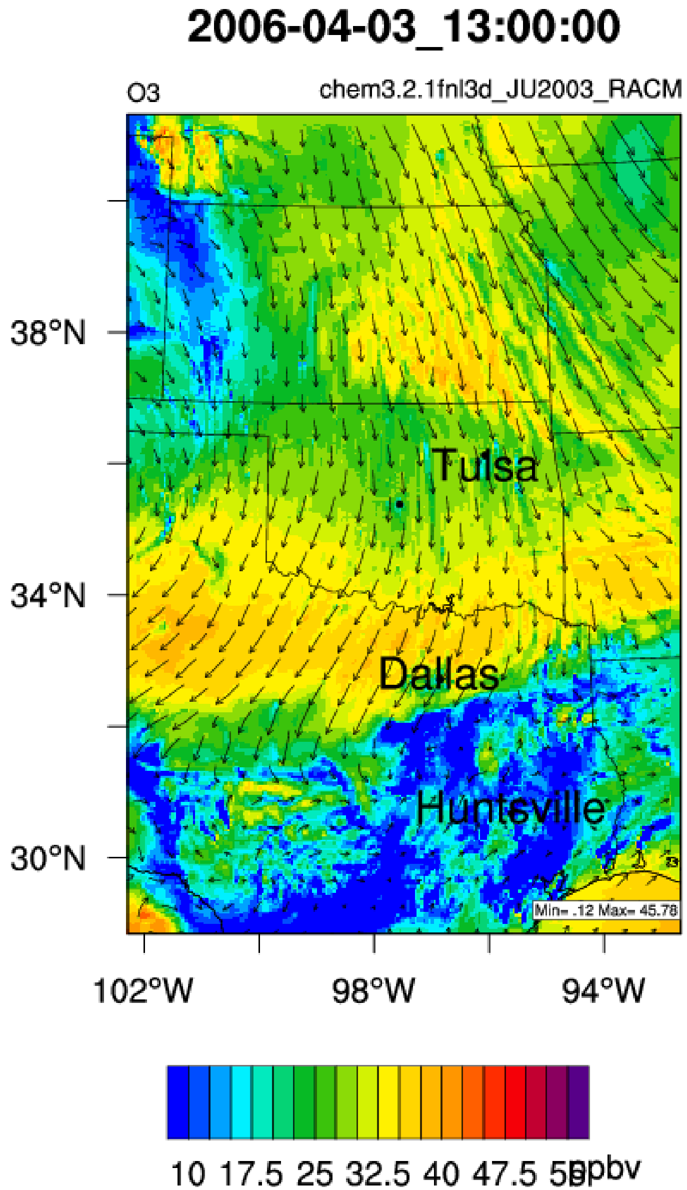
Impact on O_3 budget



Surface O_3 O_3 dry deposition velocity

Ozone is more efficiently removed at the surface, thus reducing O_3 budget

Impact on the downwind area



Ozone-richer surface air mass will reach Dallas in the next morning

Conclusions and implications

1. Meteorological phenomena such as deep convection, mixed-phase boundary layer clouds, LLJs play very important roles in vertical redistribution of O_3.
2. The residual layer may not be a reservoir of pollutants in some cases (e.g., strong LLJs).
3. The nocturnal warming events play an important role for the distribution of boundary layer O_3.
4. Apart from LLJs and cold fronts, mesoscale motions such as gravity waves, density currents can also cause nocturnal vertical mixing events.

References

1. **Hu, X.-M.,** J. D. Fuentes, and F. Zhang (2010a), Downward transport and modification of tropospheric ozone through moist convection, *J. of Atmos. Chem.*, 65, 13–35.
2. **Hu, X.-M.**, J. M. Sigler, and J. D. Fuentes (2010b), Variability of ozone in the marine boundary layer of the equatorial Pacific Ocean , *J. of Atmos. Chem.,* 66, 117–136.
3. **Hu, X.-M.**,F. Zhang, G. Yu, J.D. Fuentes, and L. Wu (2011), Contribution of mixed-phase boundary layer clouds to the termination of ozone depletion events in the Arctic. *Geophys. Res. Lett.*, 38, L21801, doi:10.1029/2011GL049229.
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5. **Hu, X.-M.**, P. M. Klein, M. Xue, F. Zhang, D. C. Doughty, and J. D. Fuentes (2012b), Impacts of low-level-jets induced vertical mixing on boundary layer ozone. *Atmos. Environ.*, Conditionally accepted

Observation from wind profiler on April 3, 2006