Boundary layer structure and processes, interactions with pollutants/urban

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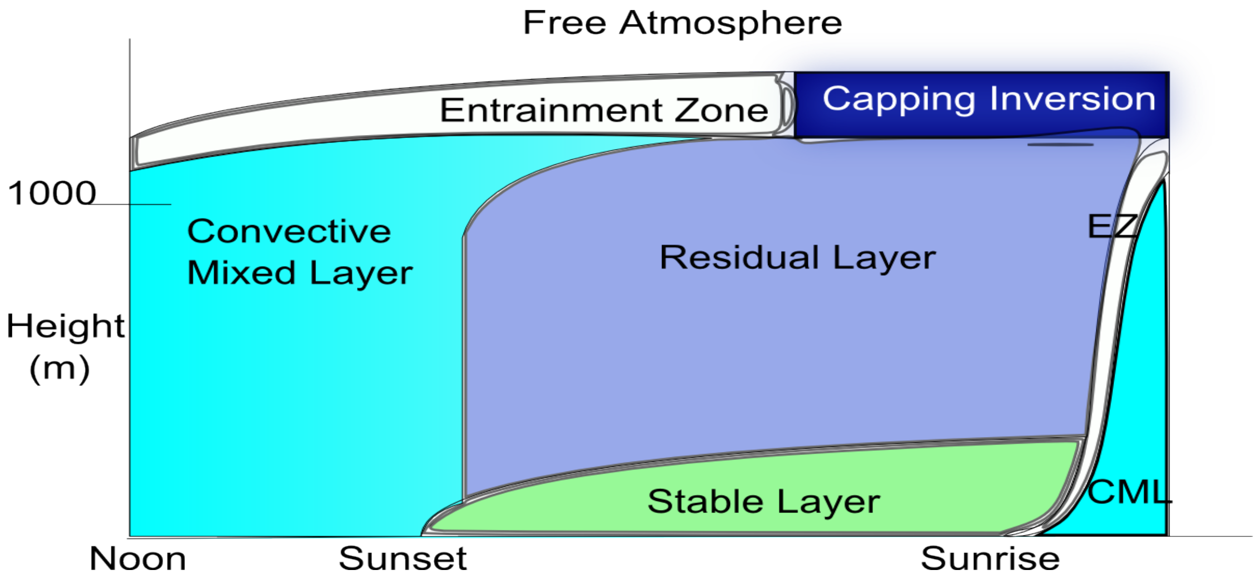
PBL training @ XinJiang

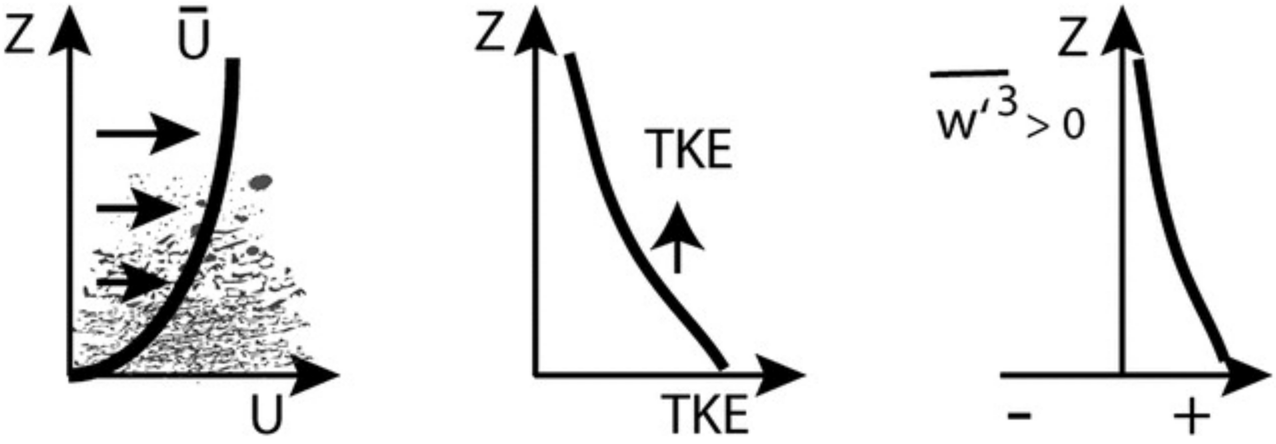
July 1st, 2019

- Part 1: Daytime
  - a) **Structure, static stability, T vs. θ_v**
  - b) PBL top retrieval
  - c) Interaction with pollutants
- Part 2: Nighttime
  - a) LLJs formation mechanism
  - b) Upside-down boundary layer
  - c) Implications for air quality and urban environment

The “traditional” boundary layer

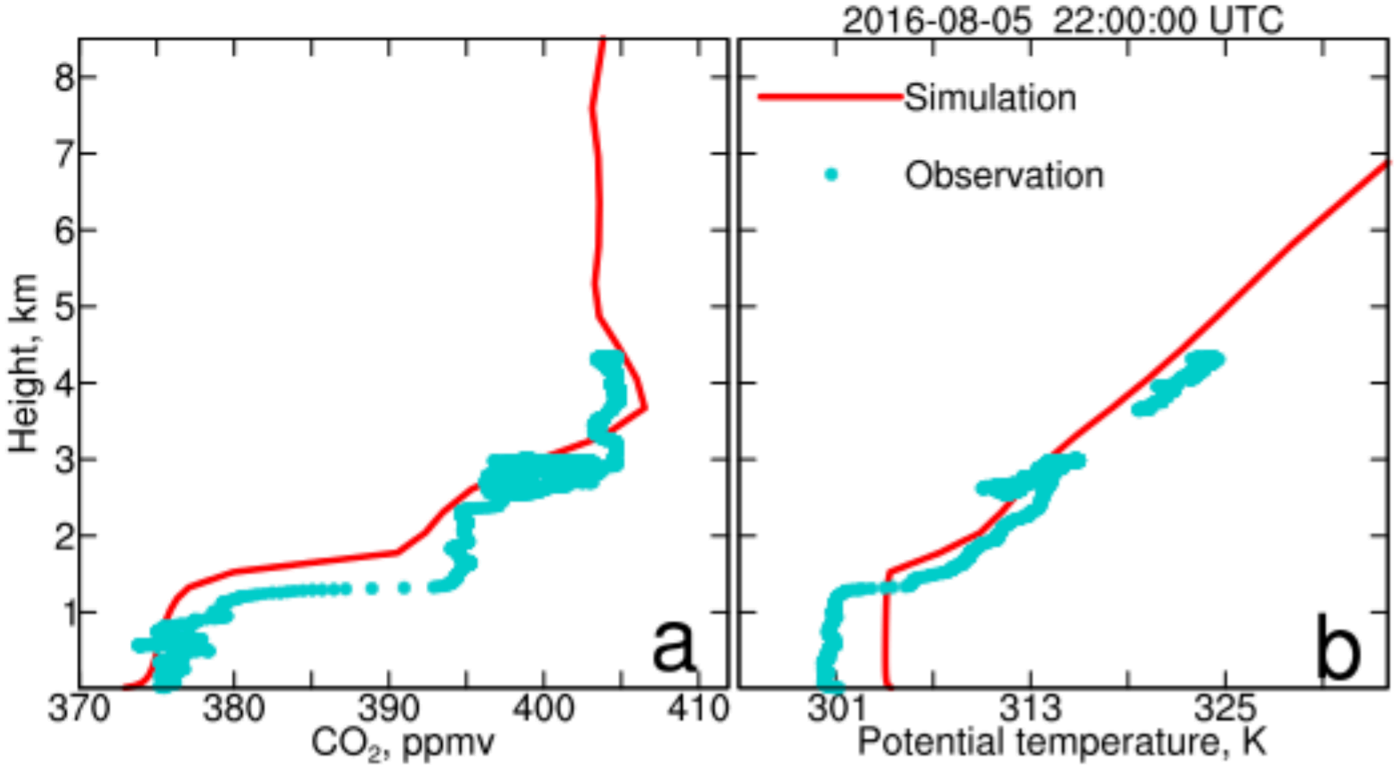


“TRADITIONAL” Boundary Layer



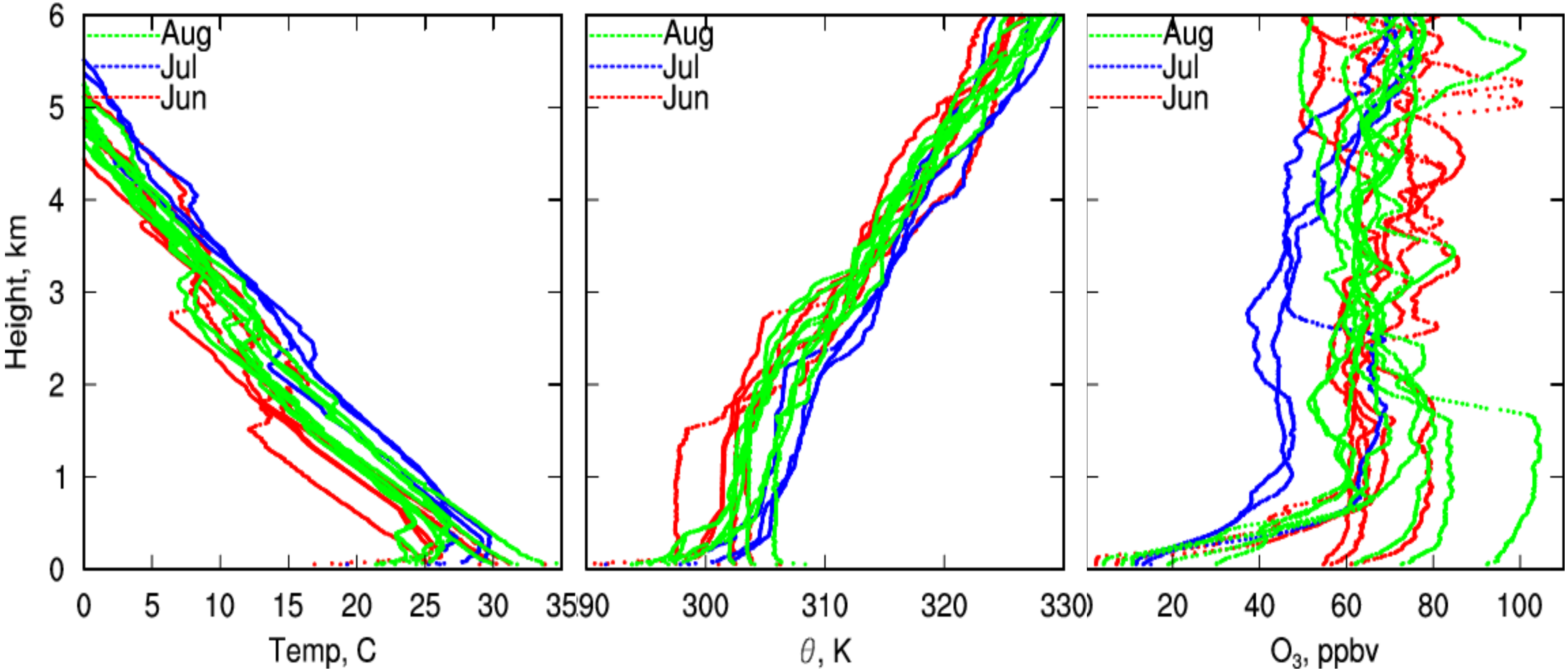
In the traditional BL, turbulence is generated at the surface and transported upward.

Daytime boundary layer structure



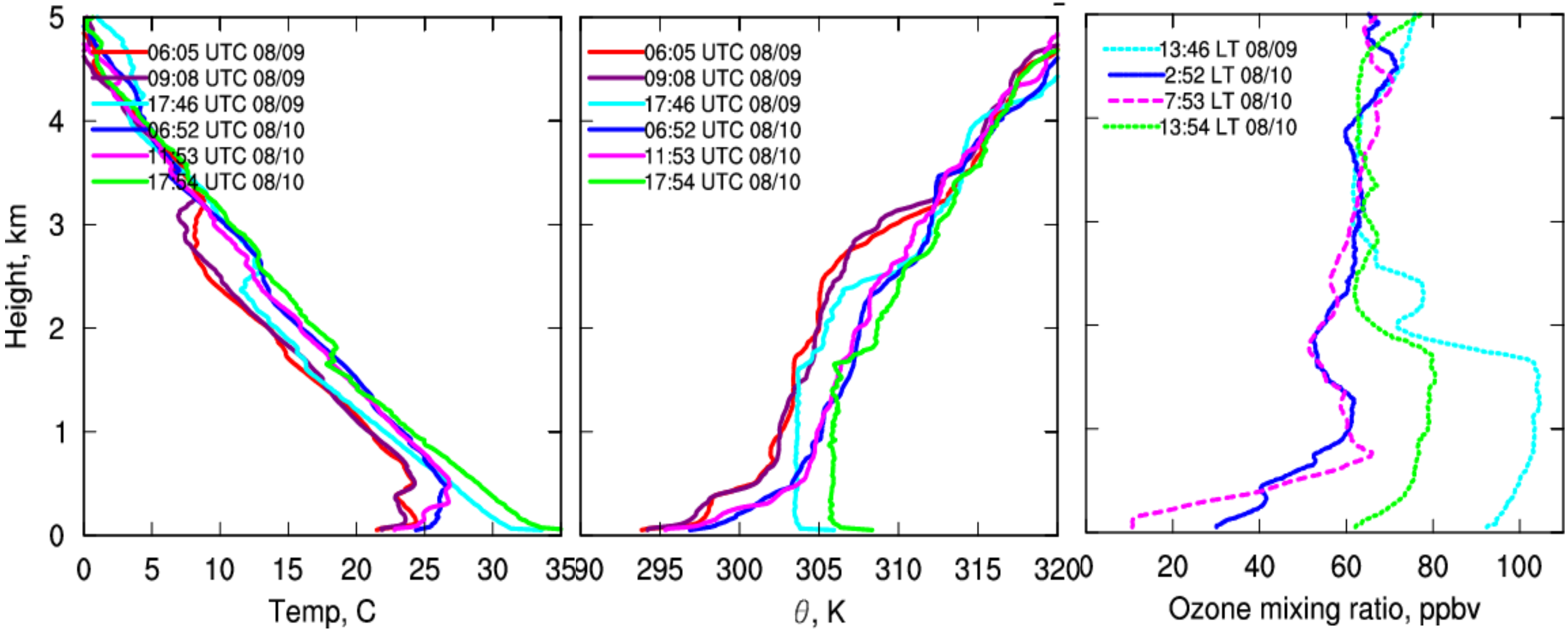
Aircraft sounding over Lincoln (Hu et al., 2019, in revision)

Daytime boundary layer structure



Profiles over Beltsville (Hu et al., 2012, AE)

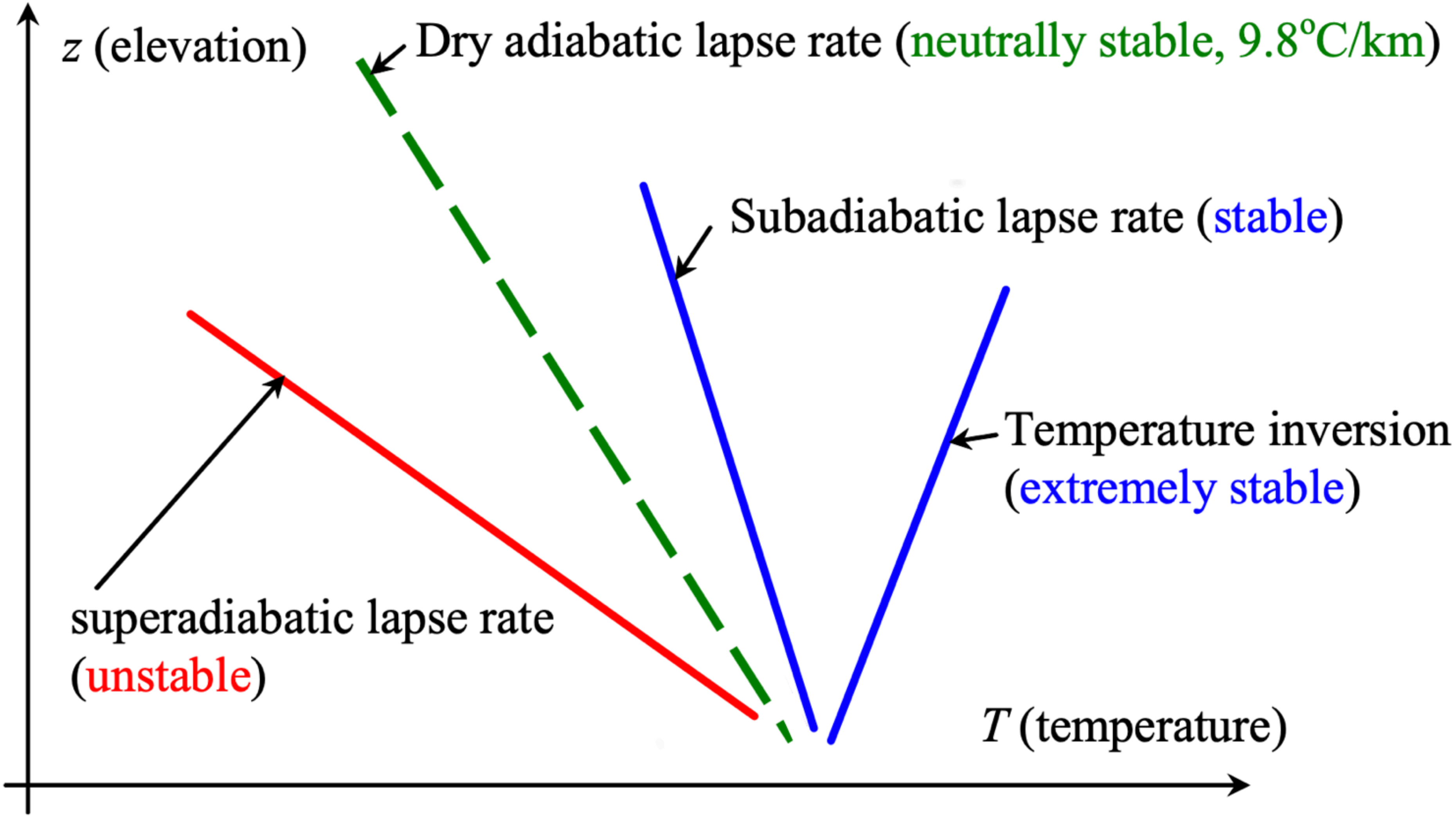
Daytime boundary layer structure



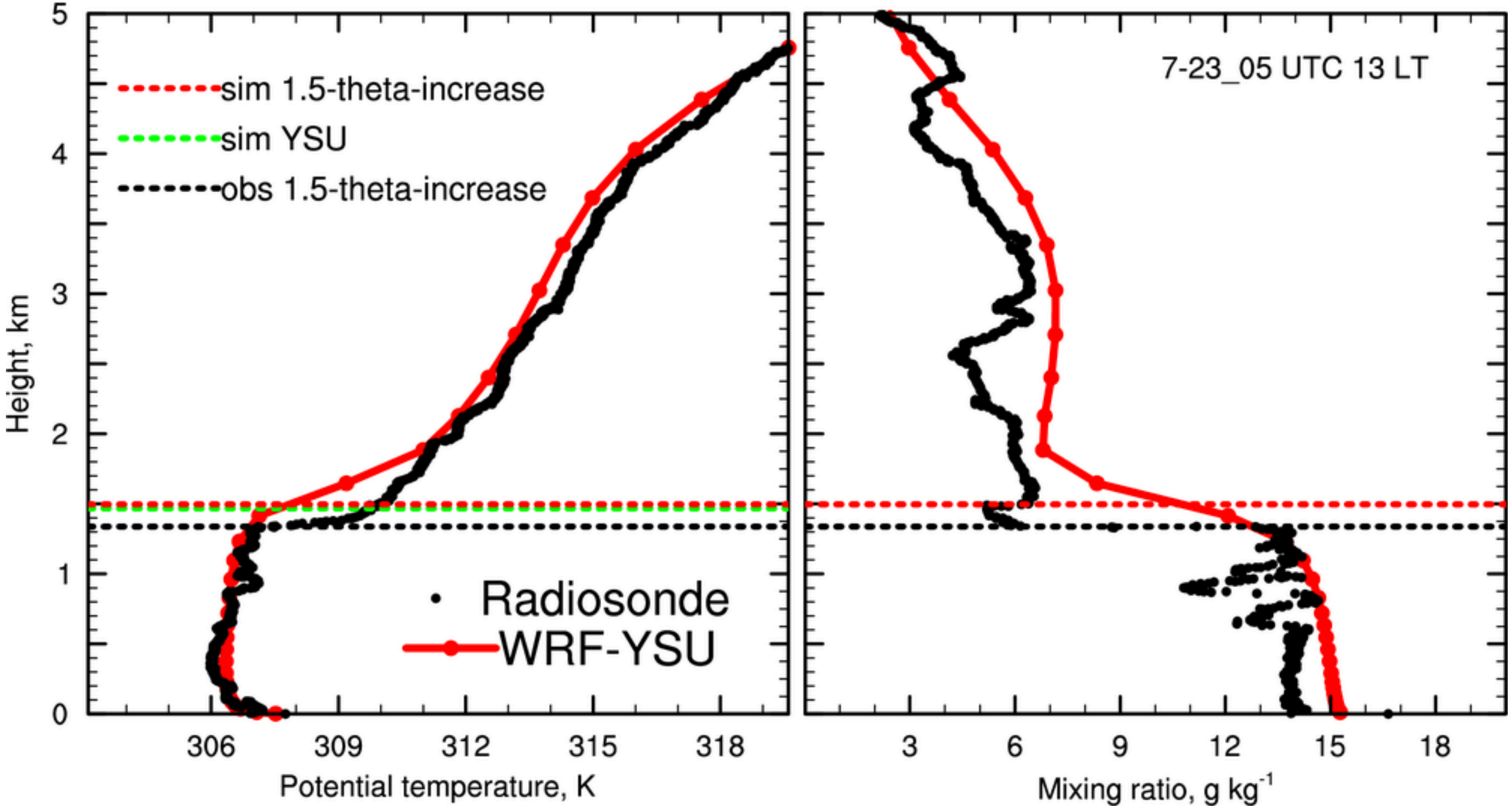
Hu et al., 2012, *Atmospheric Environment*

PBLH is most critical for pollutant dispersion
Temperature inversion is not really important

Local static stability in terms of T



Local static stability in terms of θ



Discussing stability in θ is much simpler!

Discussion of T and θ

Application of neutral stability?

Nonlocal stability?

Temperature inversion: most inappropriate concept, most abused!

Why do we need T? Models use θ

How do we diagnose PBL top?

Measurements for ABLH determination

Method	Advantages	Shortcomings	Examples of References
Radiosoundings			
Radiosonde	● widely distributed all over the word ● long observation history, suited for ABLH climatology study ● providing the most accurate information of the troposphere and low stratosphere	● infrequently, only 2-4 times per day ● in-situ observation, sparse spatial coverage	Norton and Hoidale, 1976 Cooper et al., 1994 Seidel et al., 2010 Guo et al., 2016
Tethered balloons	● turbulence measurements possible ● the ascent velocity can be controlled according to the desired resolution	● high cost ● limited to field campaigns with manned operation ● limited measurement range ● inapplicable in case of high wind speed or strong convection	Moores et al., 1979 Vernekar et al., 1991 Holden et al., 2000
Aricraft	● simultaneous measurements of mean and turbulent quantities ● high sample rate	● high cost ● limited to field campaigns ● the lowest observation height (or flight level) is restricted (security)	Galmarini and Attié, 2000 Dai et al., 2011 Dai et al., 2014
Remote sensing			
Sodar	● a simple and less expensive remote sensing system ● continuously operated in an unattended mode ● high temporal and vertical resolutions ● obtaining the height of any elevated temperature inversion layer	● limited vertical observation range, a few hundred meters to 1 km ● reduced data availability in special weather situations (near-perfectly adiabatically stratified CBL in the afternoon) ● interpretation of the remotely-sensed structures sometimes ambiguous	Beyrich and Weill, 1993 Beyrich, 1997 Lokoshchenko, 2002 Emeis et al., 2004 Helmis et al., 2012
Microwave radiometer	● providing good estimates of temperature and humidity in the lower troposphere with high temporal resolution	● the vertical resolution decreases with altitude ● poor data quality in cloudy and rainy conditions	Crewell et al., 2007 Cimini et al., 2013 Saeed et al., 2015 Liu et al., 2015
Doppler Rardar wind profiler	● continuous operation ● high temporal and vertical resolutions ● providing horizontal and vertical wind profiles with high precision	● expensive ● invalid data at the lowest range, unable to resolve shallow ABL ● limited vertical resolution ● the SNR easily influenced by several factors such as birds and insects. ● inapplicable when signal is dominated by rain or snow	White et al., 1991 Angevine, 2000 Bianco et al., 2002
Lidar	● operated continuously in an almost automated status ● observing vertical distribution of the aerosols with high temporal resolution and wide vertical spatial coverage ● a great number of aerosol lidars deployed and established networks all over the world	● limited data quality near surface because of the blind zone ● the ABLH determination easily interfered by multiple aerosol layers (advected or elevated) or cloud layers	Steyn et al., 1999 Davis et al., 2000 Sawyer and Li, 2013 Pal et al., 2013 Toledo et al., 2017

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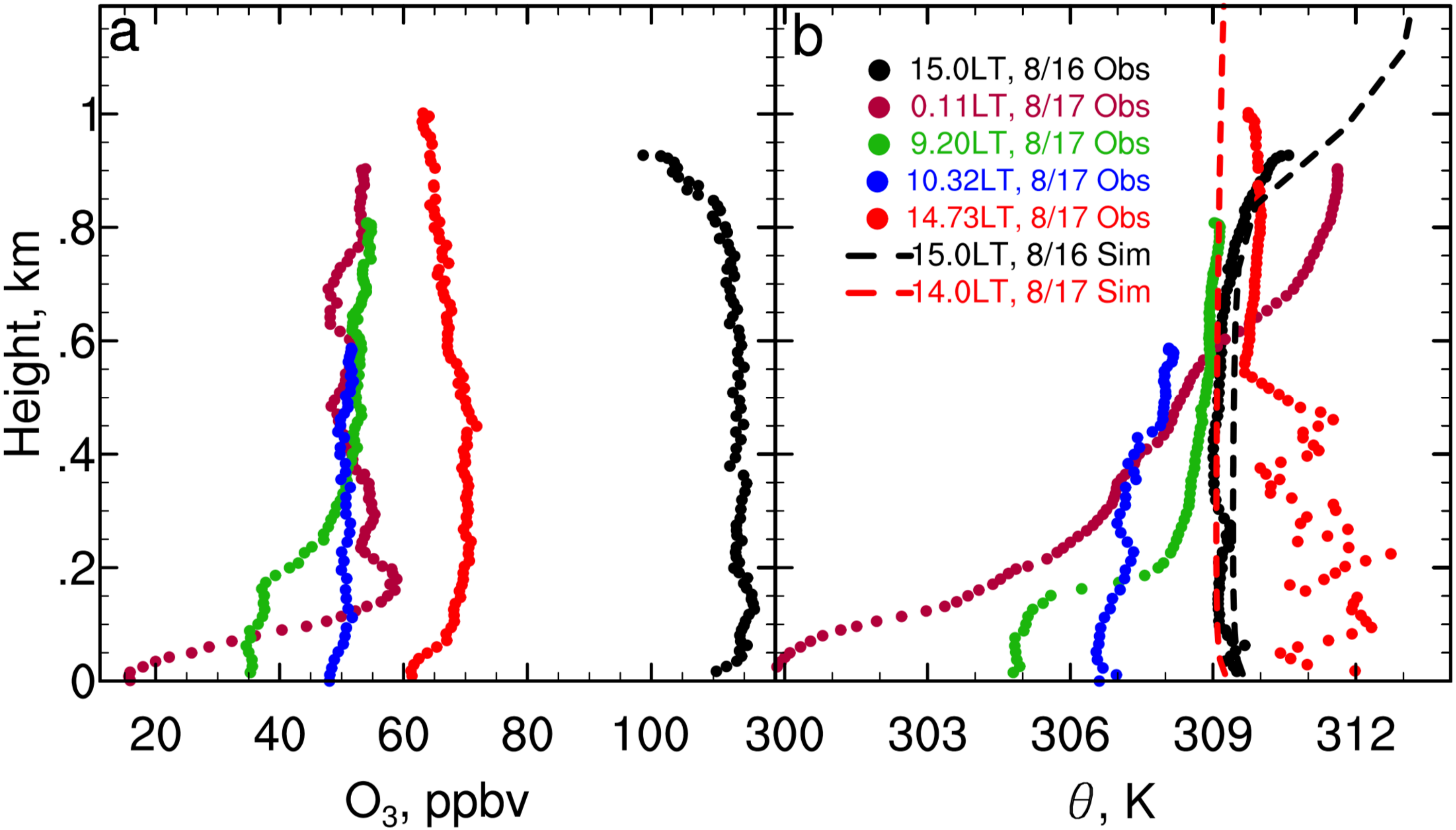
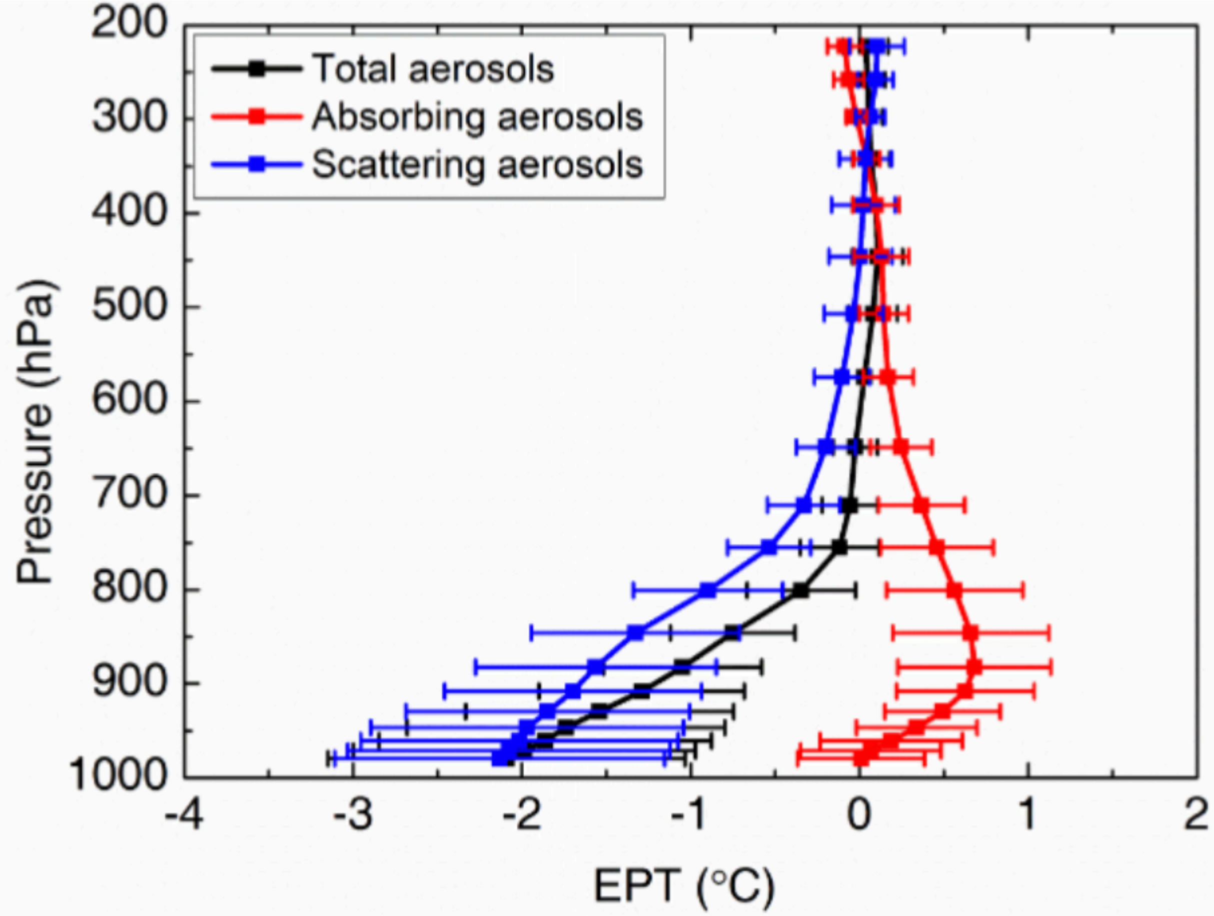
Impact of PBL height on pollutants



Low PBLH led to high O_3 on 8/16 (Hu et al., 2014)

Impact of pollutants on CBLs

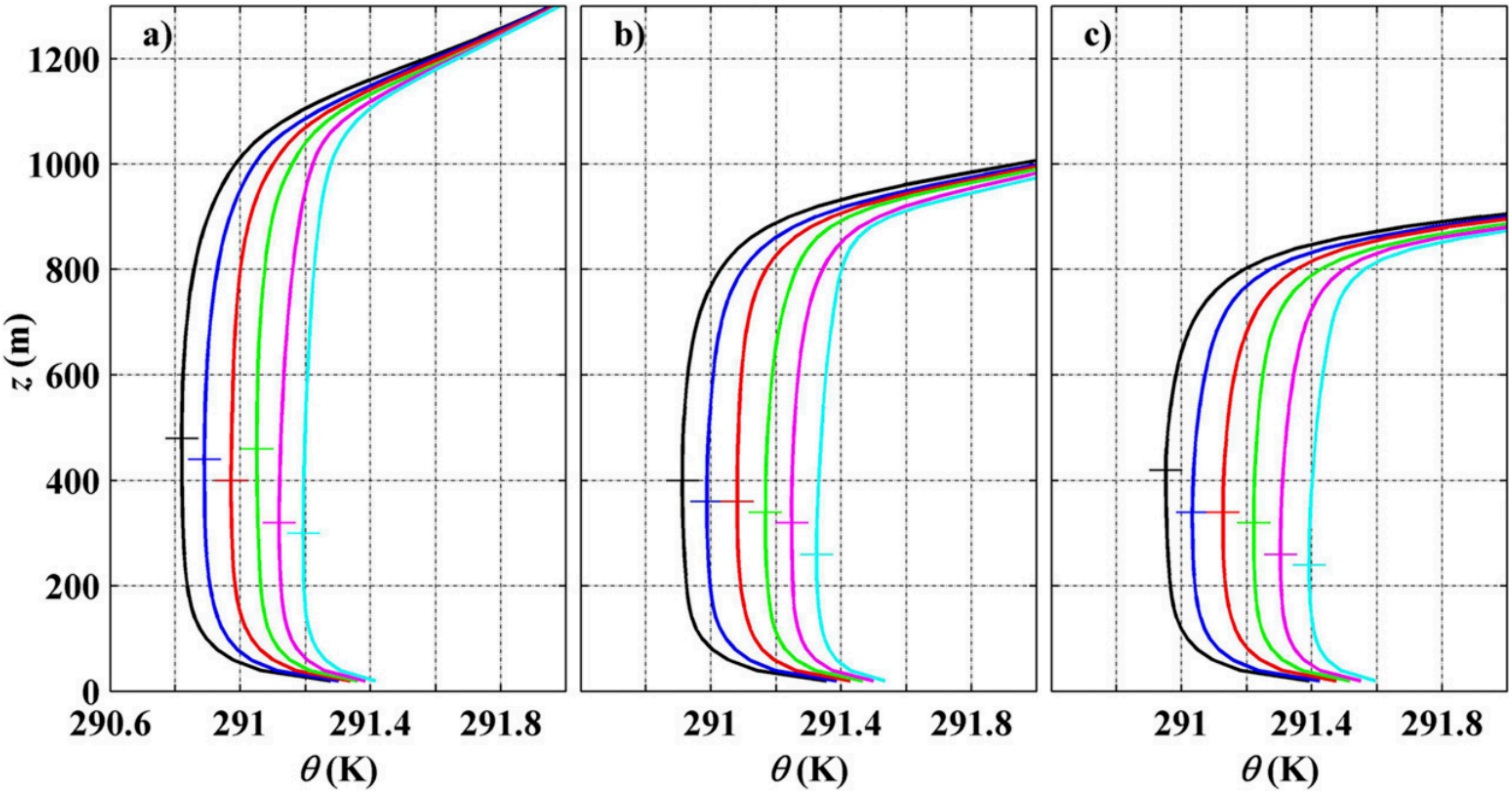
Aerosol effects make CBLs more stable? Show me θ profile for one case!



http://onlinelibrary.wiley.com/doi/10.1002/2016JD026309/epdf, which uses WRF/Chem simulations to show that aerosols make lower troposphere more stable

Impact of pollutants on CBLs

Aerosol effects make CBLs more stable?



Liu, Fedorovich, Huang, Hu et al. (2019, JAS)

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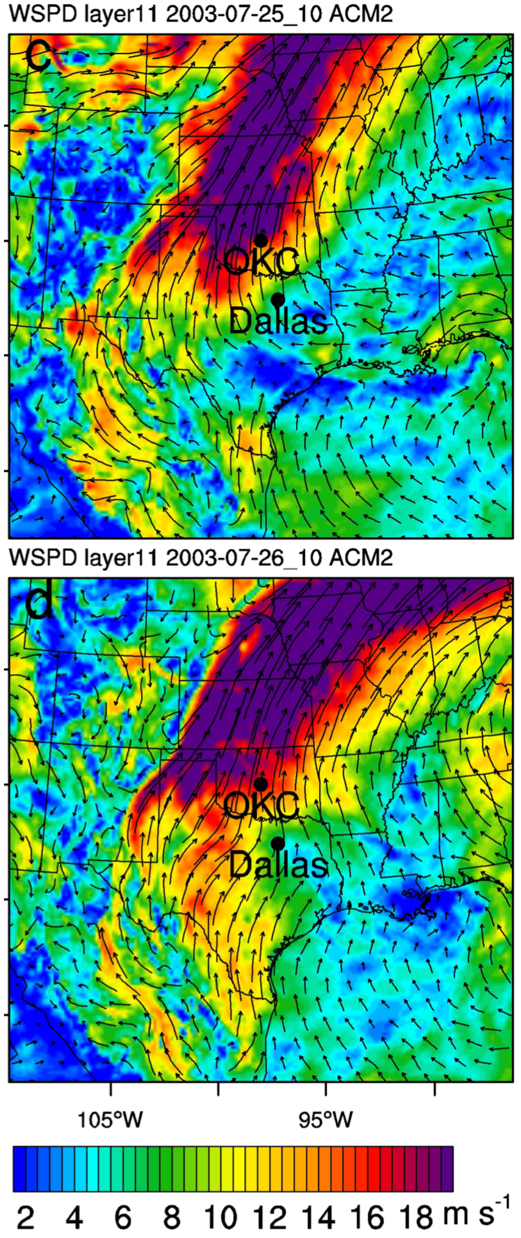
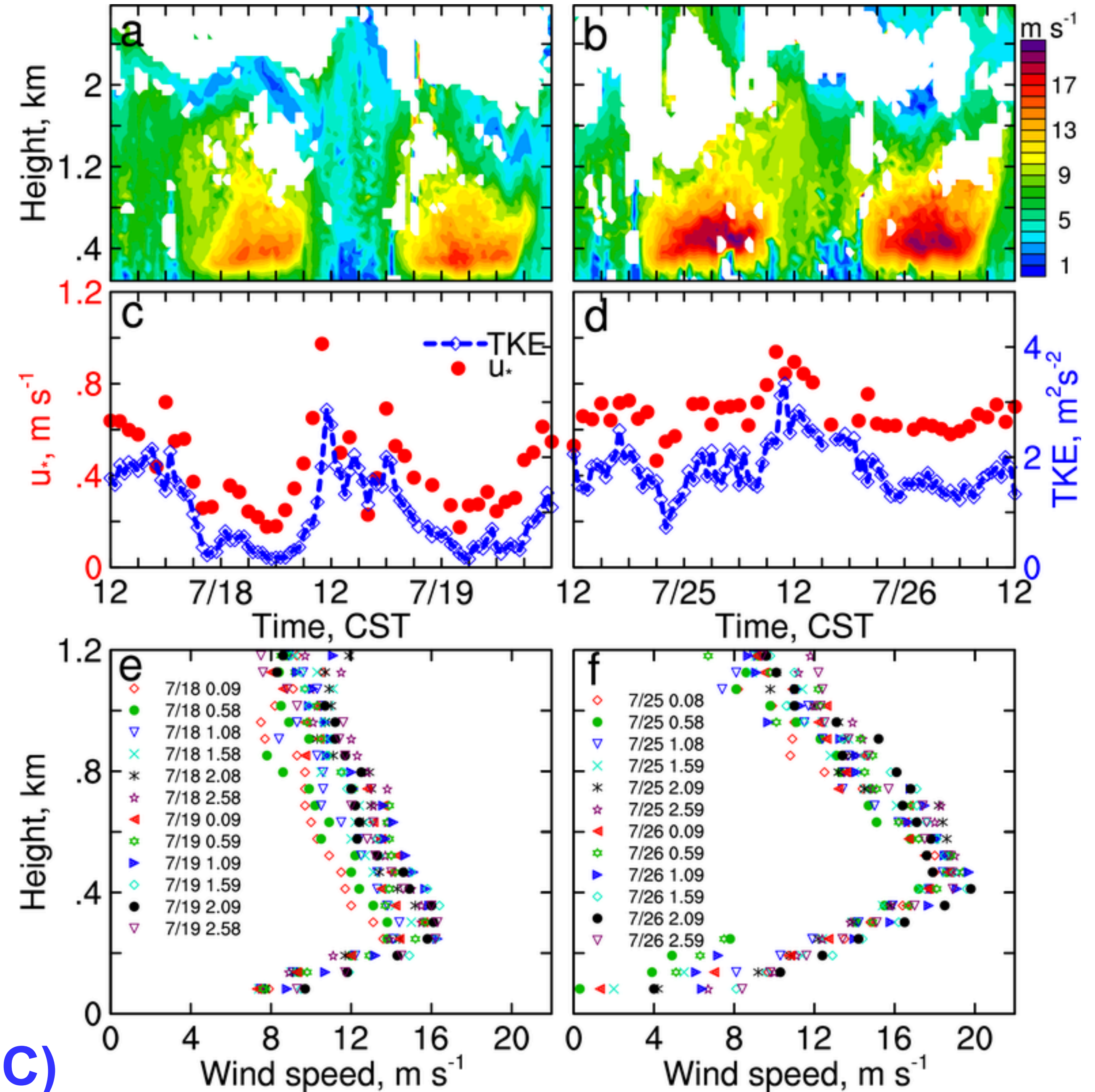
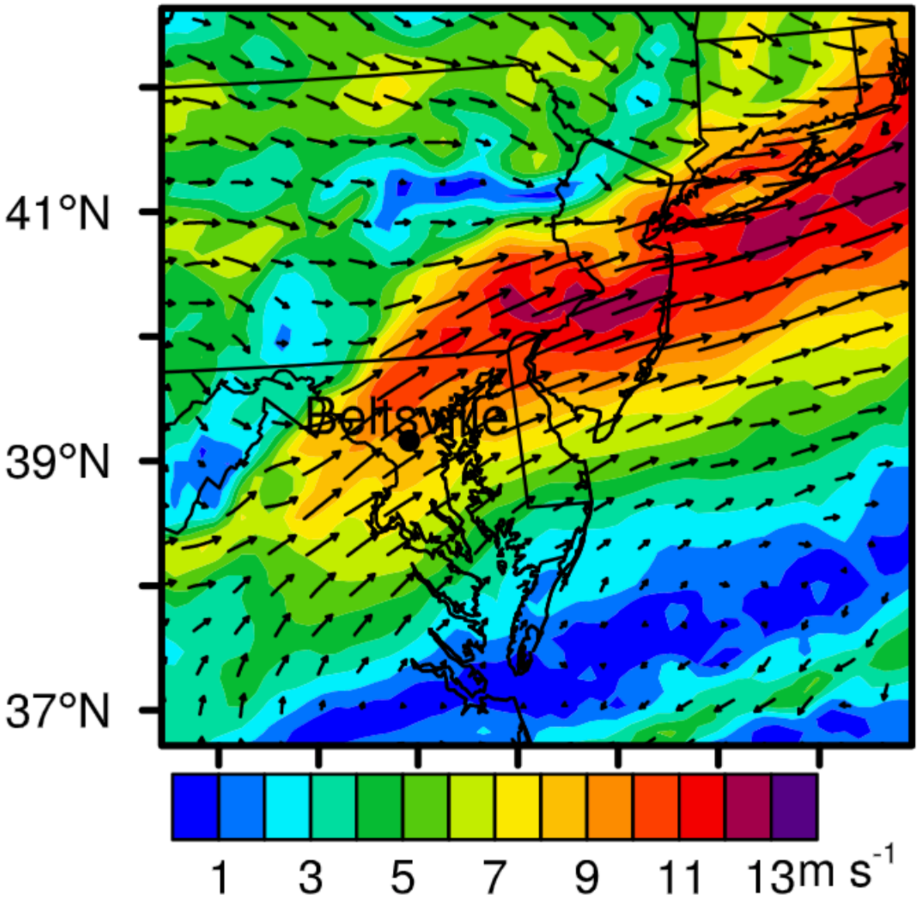
LLJs over the Great Plains

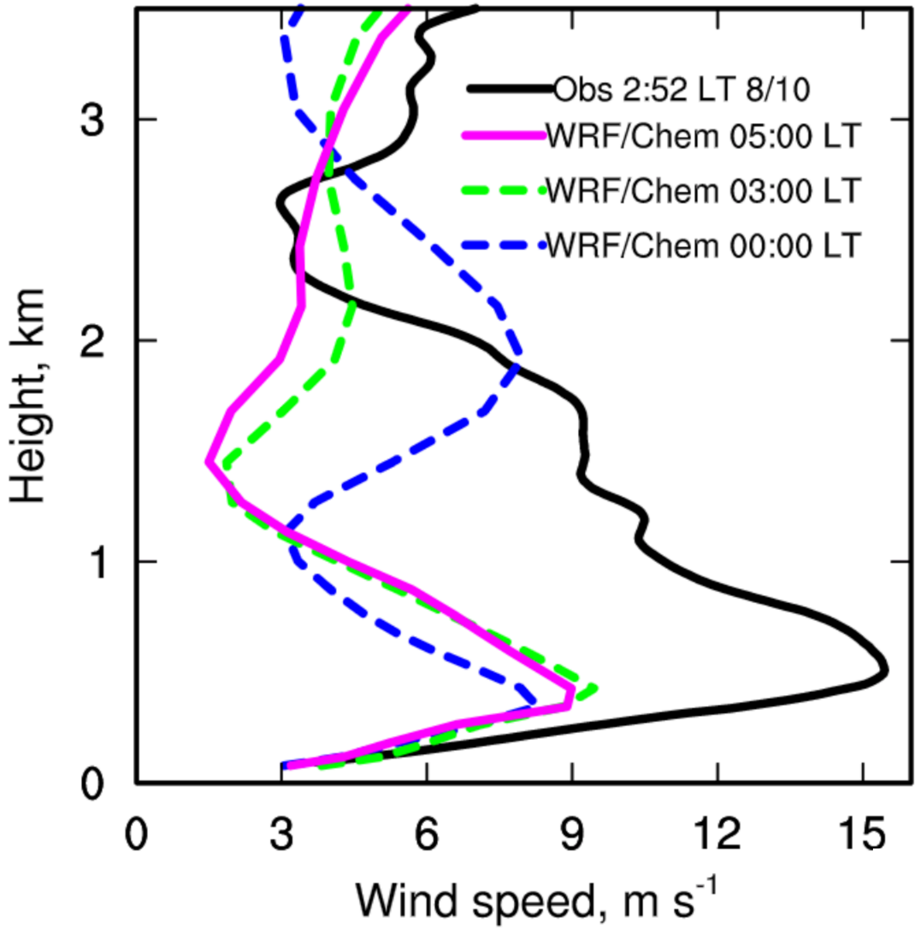




Hu et al. (2013,JAMC)

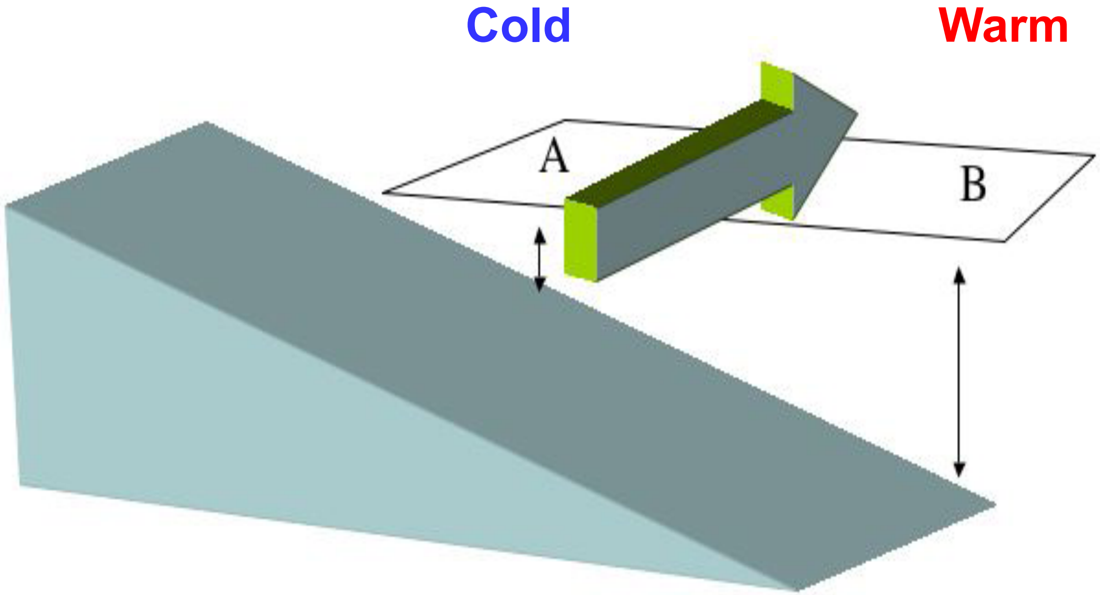
LLJs over the US eastern coast

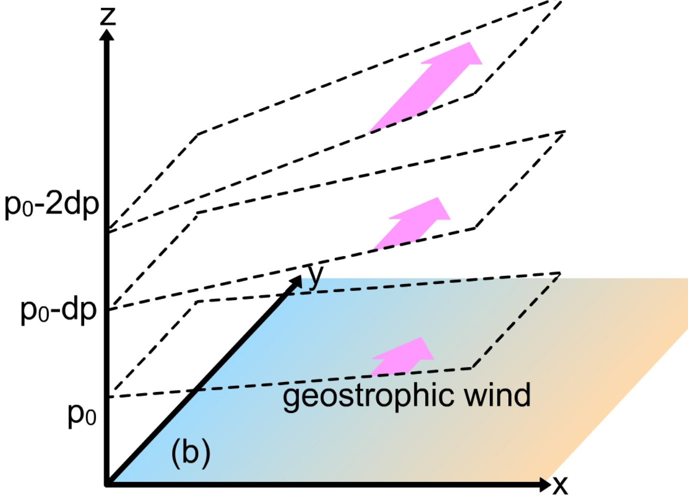




Hu et al. (2013, AE)

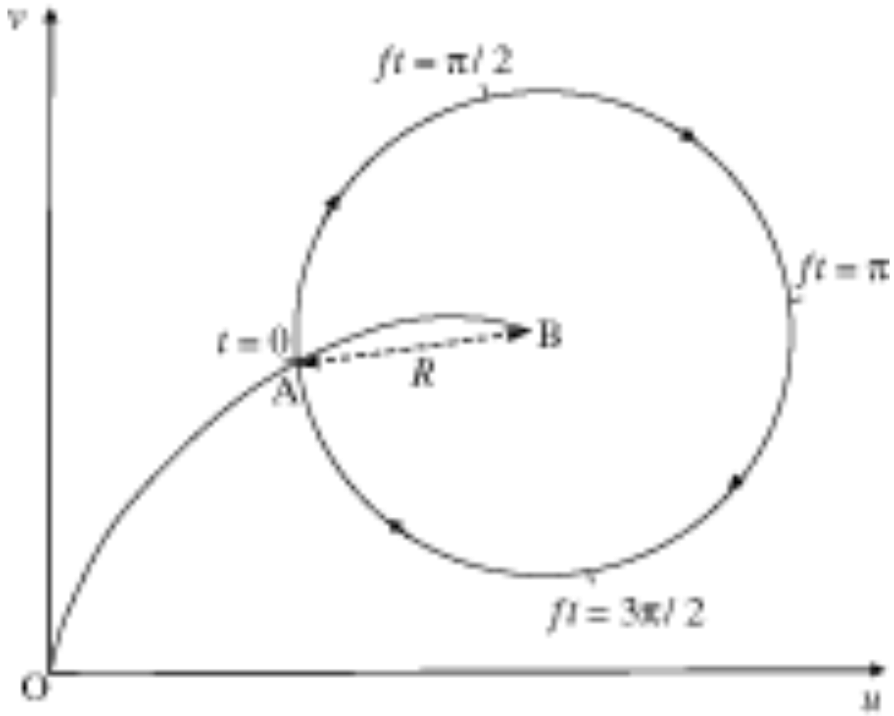
LLJs formation mechanism(1): thermal wind





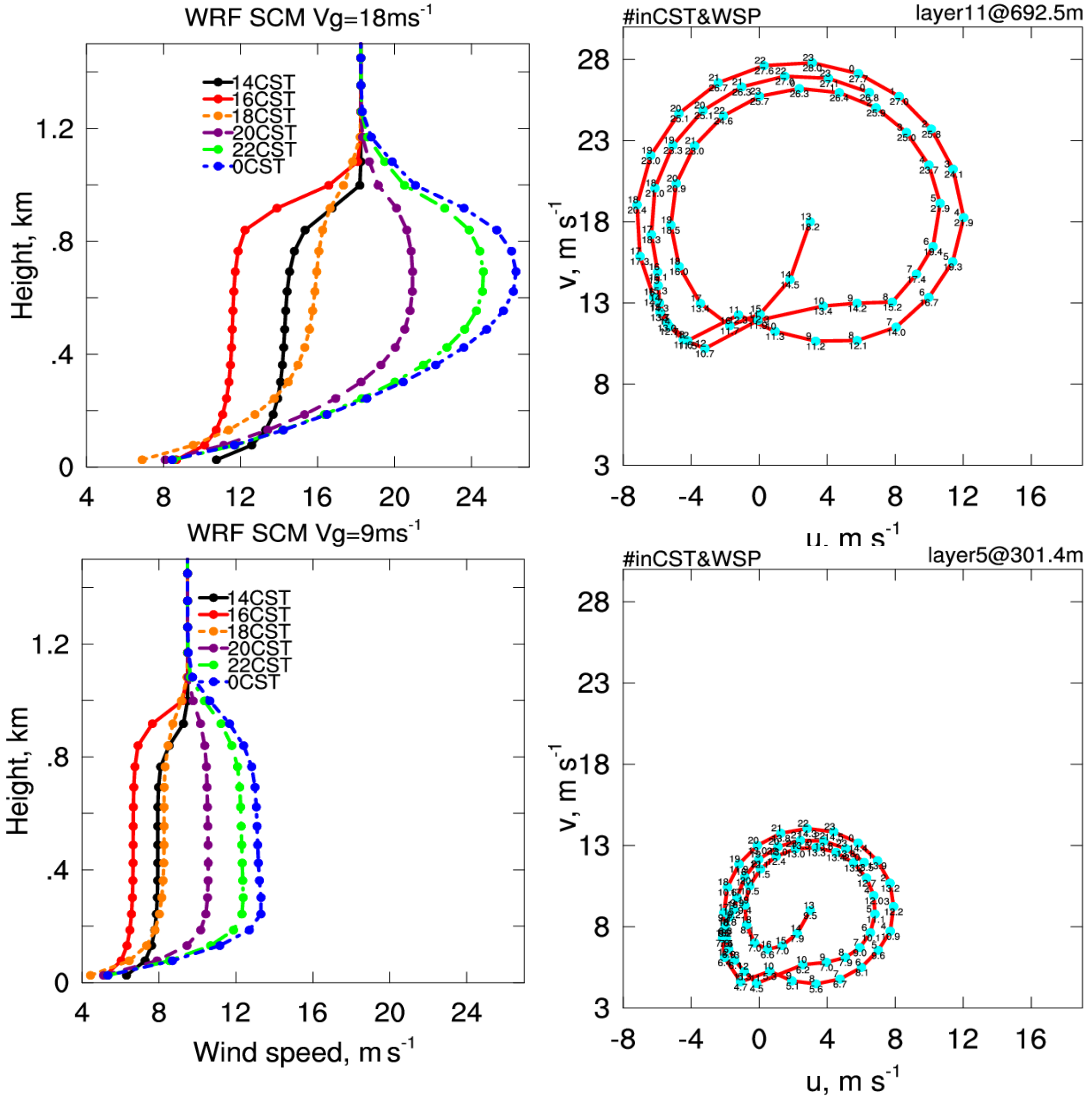
Thermal wind is actually vertical shear of horizontal wind speed

LLJs formation mechanism(2): inertial oscillation



The premise of inertial oscillation is significant decrease of turbulence during the early evening transition. So weaker turbulence, strong decoupling favor LLJs development in this theory. Inertial oscillation also cannot explain LLJ location preference.

Inertial oscillation:1D WRF results



(Hu, unpublished)

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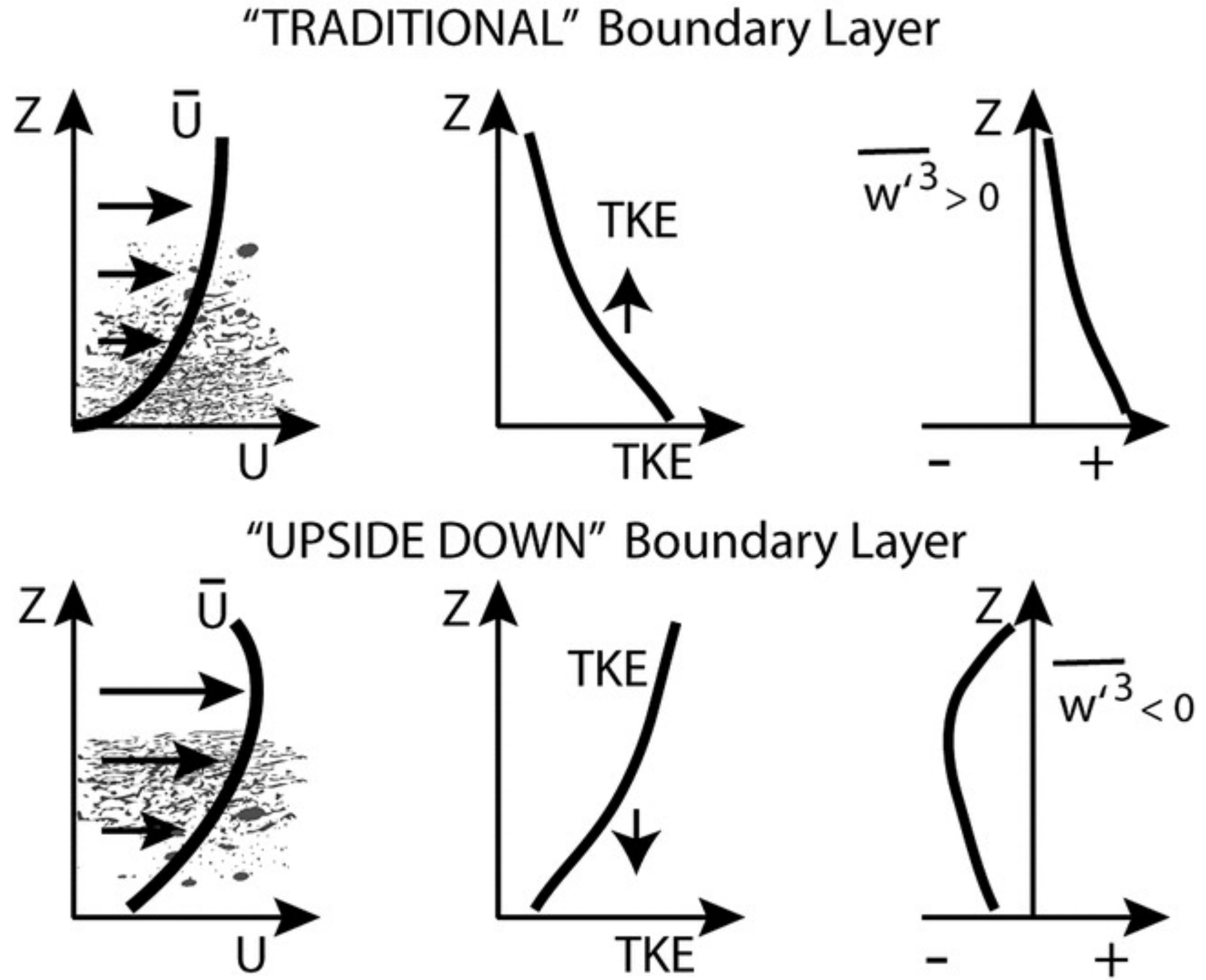
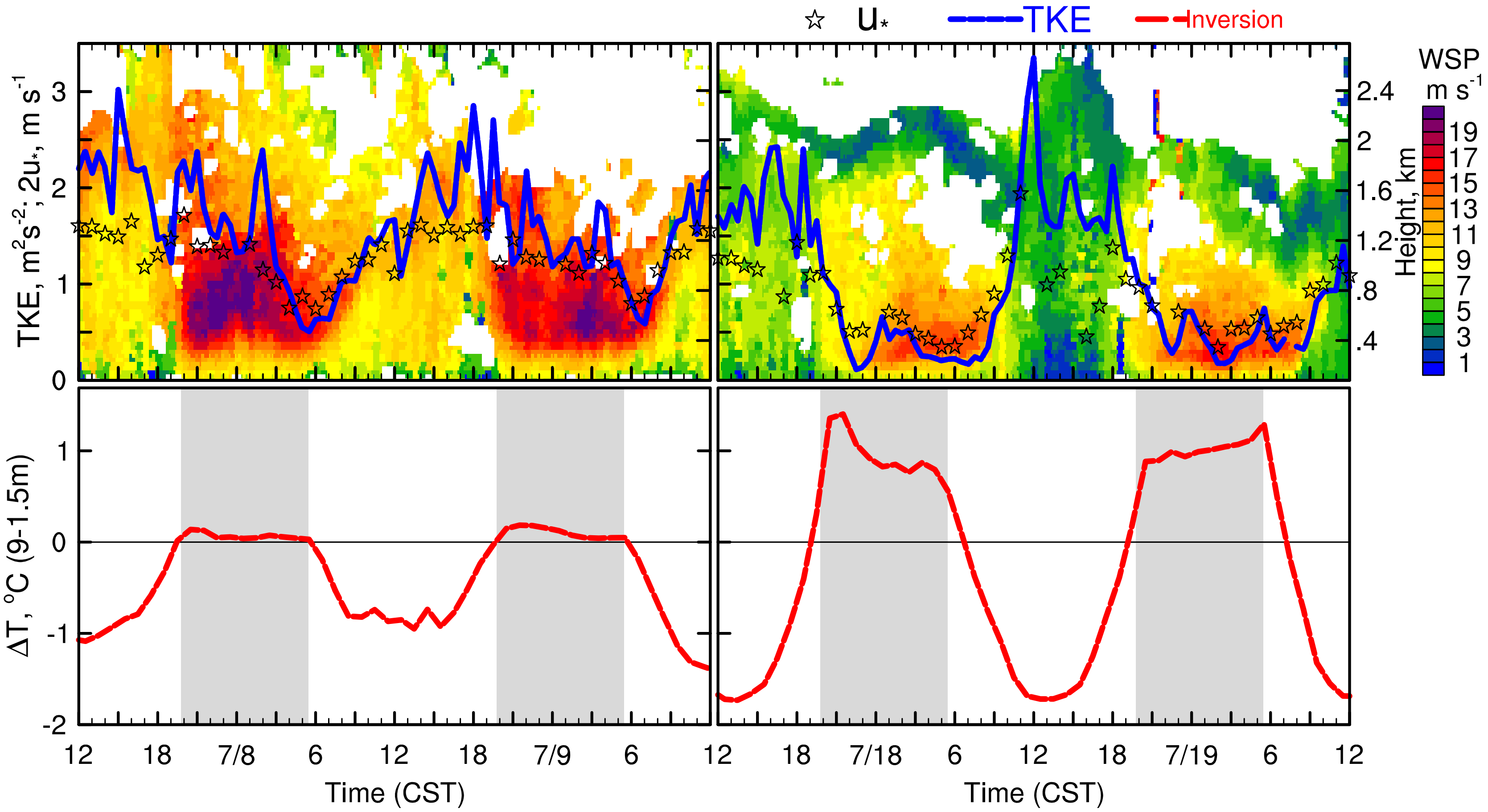
The “upside-down” boundary layer



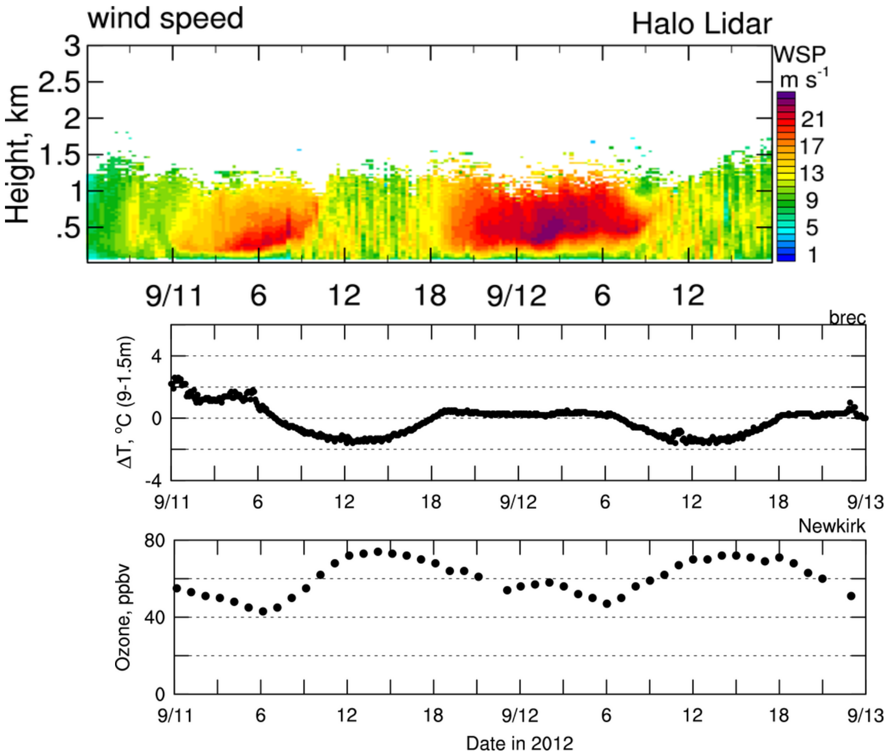
In the upside-down BL, turbulence is generated aloft and transported downward (Banta et al., 2006).

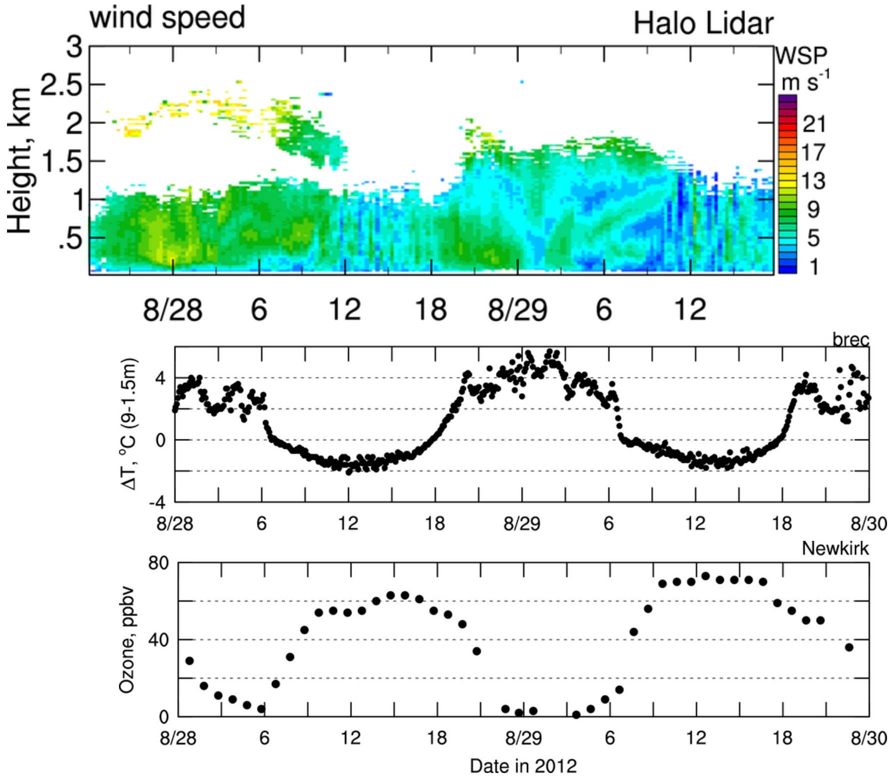
Upside-down boundary layer, case



Lidar data from the 2003 Joint Urban campaign (Klein, Hu, 2016, BLM)

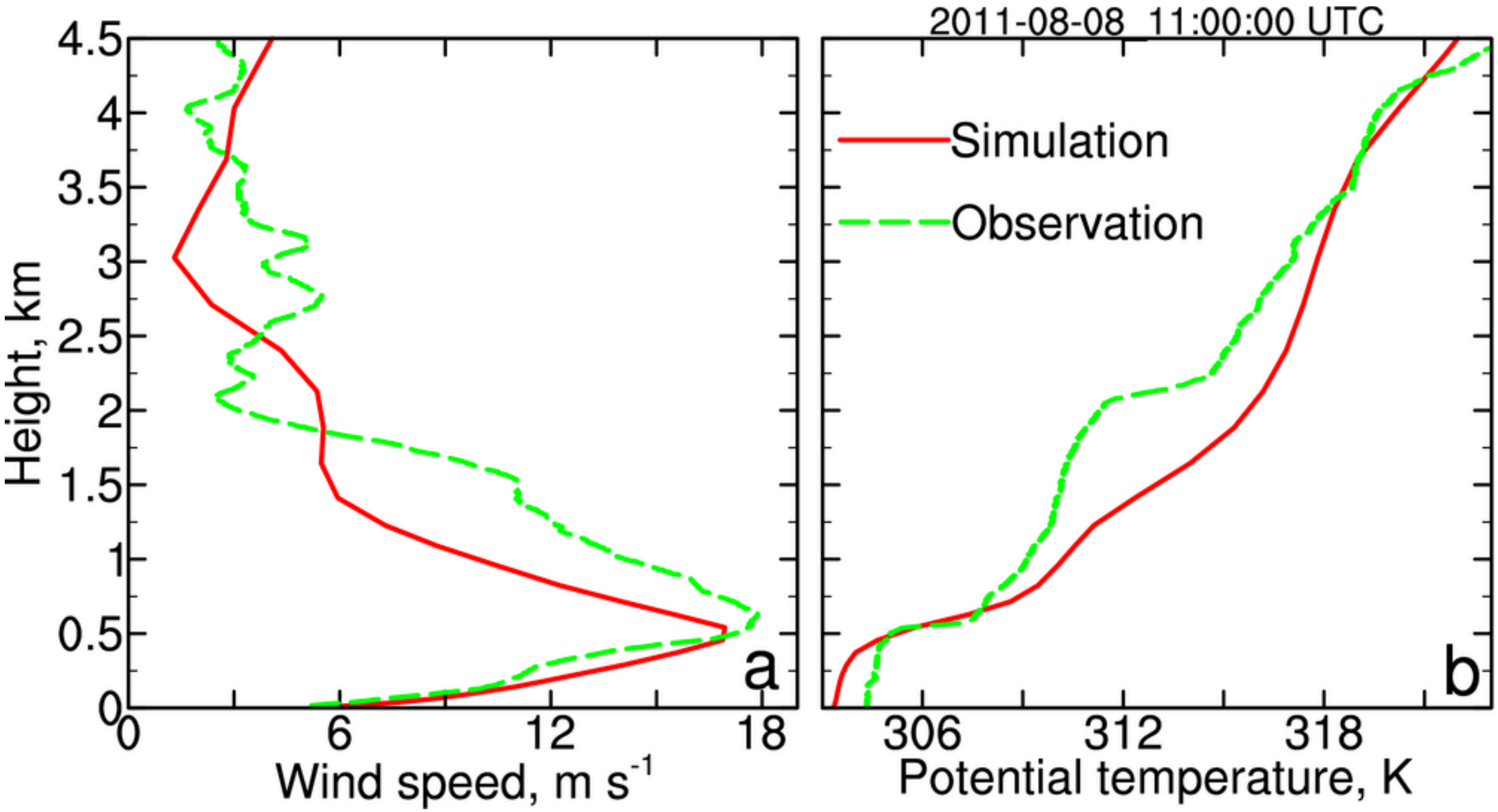
More LLJ/upside-down cases





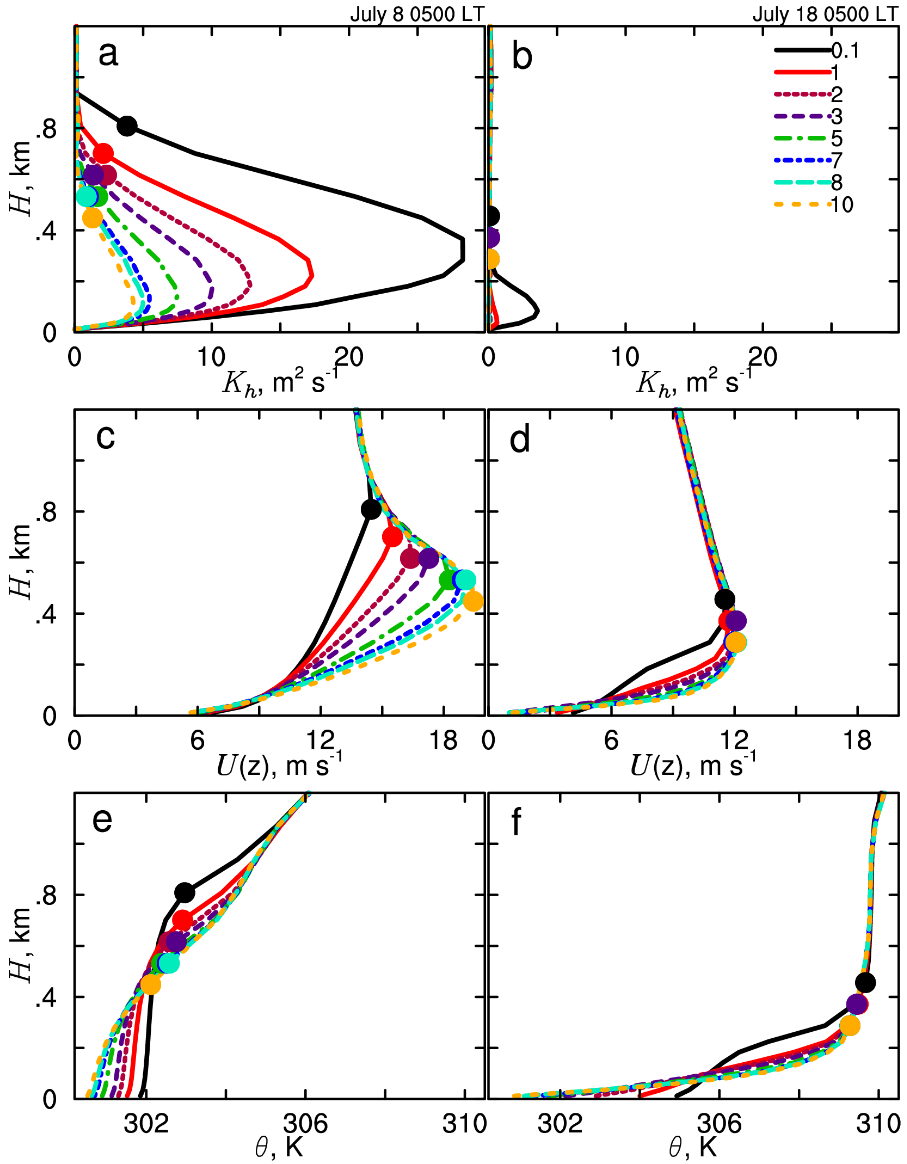
Strong/weak LLJs lead to coupling/decoupling (Hu, unpublished)

Nighttime boundary layer structure: case 1



Hu and Xue (2016, MWR)

Nighttime boundary layer structure: case 2



How to diagnose nighttime PBL height?

Klein, Hu (2016, BLM)

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The upside-down BL forms under certain circumstances, e.g., in the presence of LLJs and clouds (Hu et al., 2011, 2012, 2013a,b)

- **Impact of LLJs on O_3 in the eastern coast** (Hu et al., 2013a)
- **Impact of LLJs on UHI in the Great Plains** (Hu et al., 2013b)

Impact of LLJs on O_3 in the eastern coast (Hu et al., 2012, 2013a)

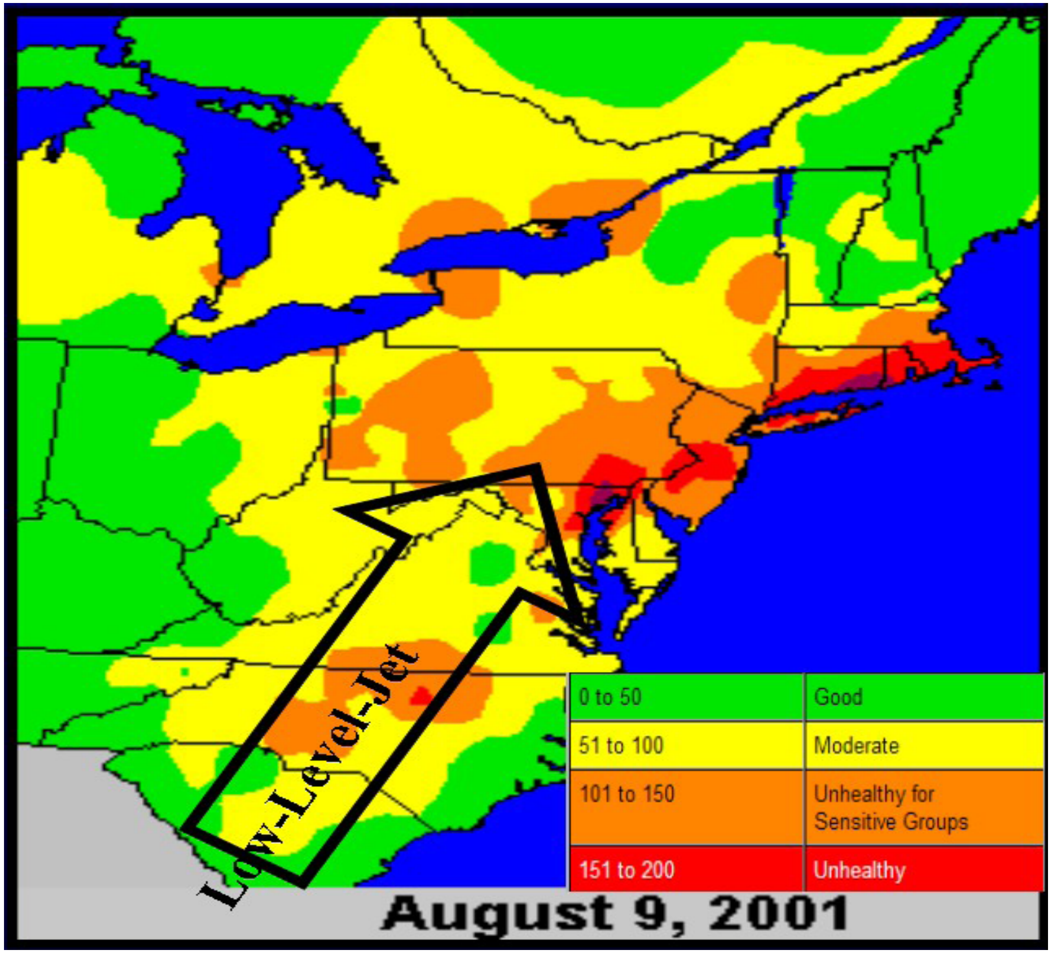
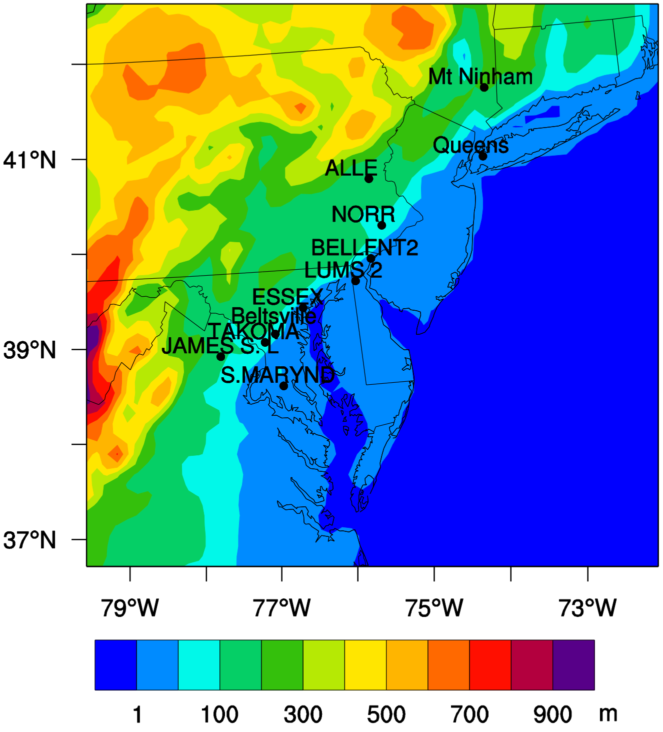
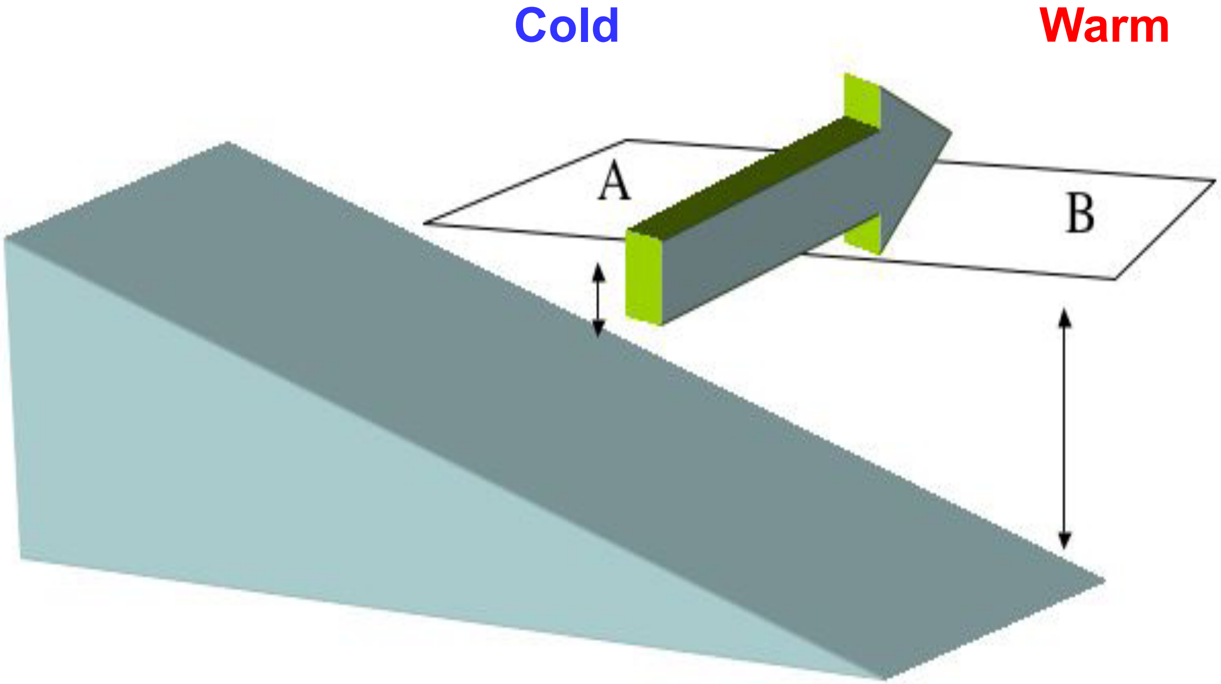


Figure: Air quality index during an ozone episode, Ryan and Piety, (2001)

High O_3 episodes and LLJs occur frequently in the eastern costal area.

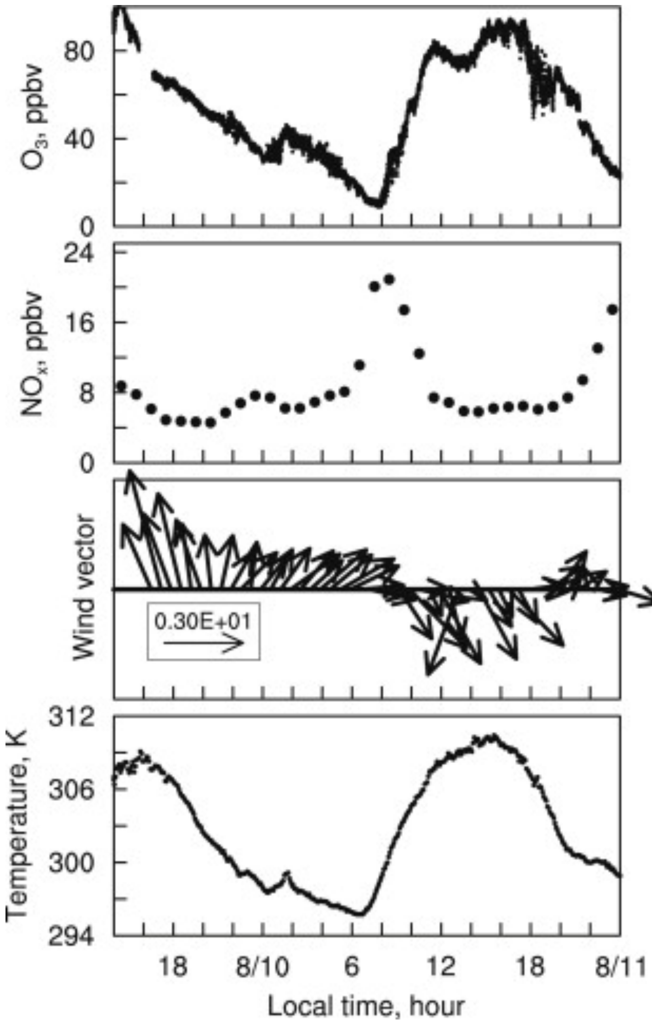
LLJs formation in the eastern coast

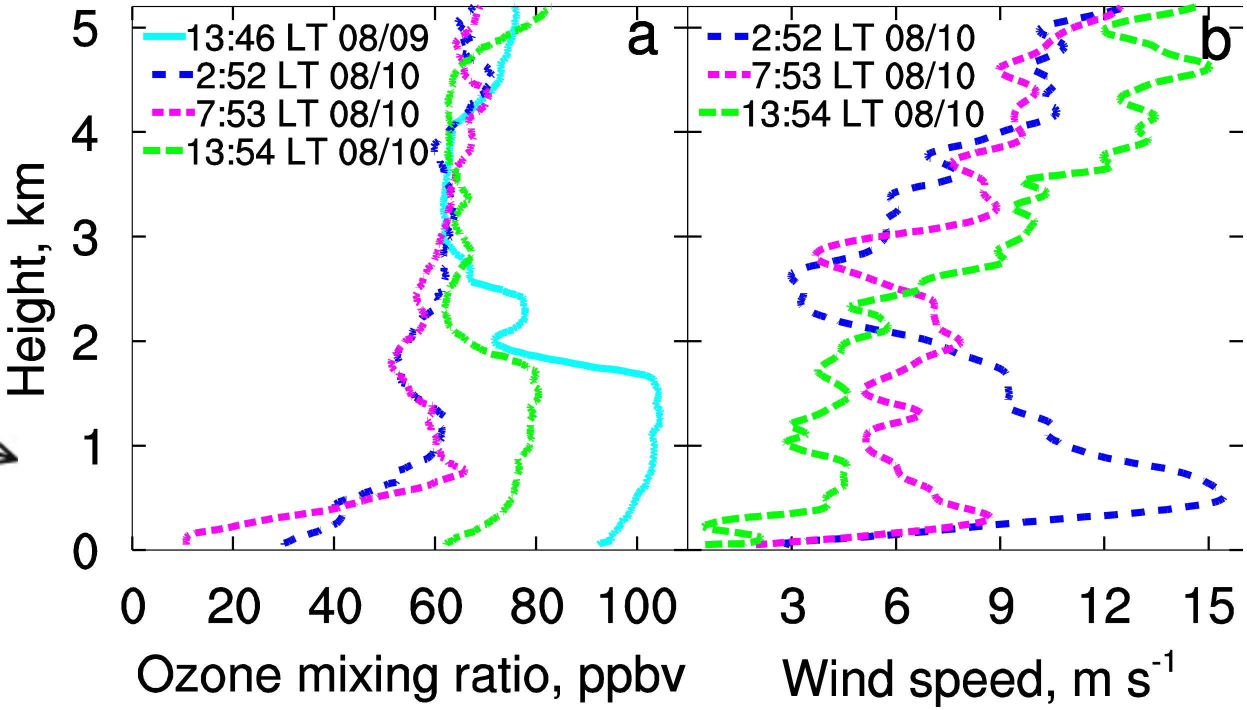




Thermal wind contributed to the formation of the Mid-Atlantic costal LLJs
The meridional variation of the Coriolis parameter may also accelerate LLJs

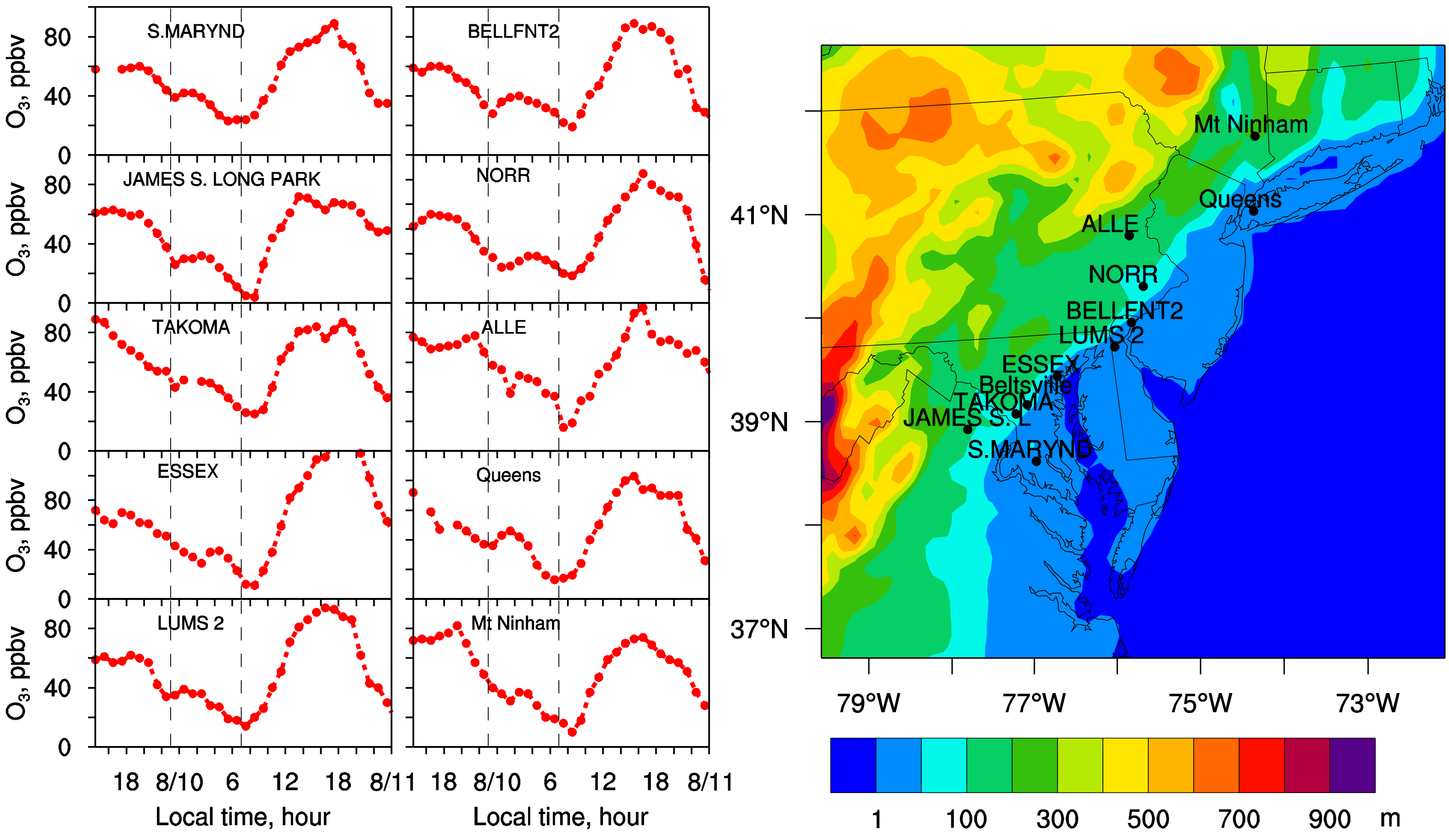
Case study of August 10, 2010, Observation





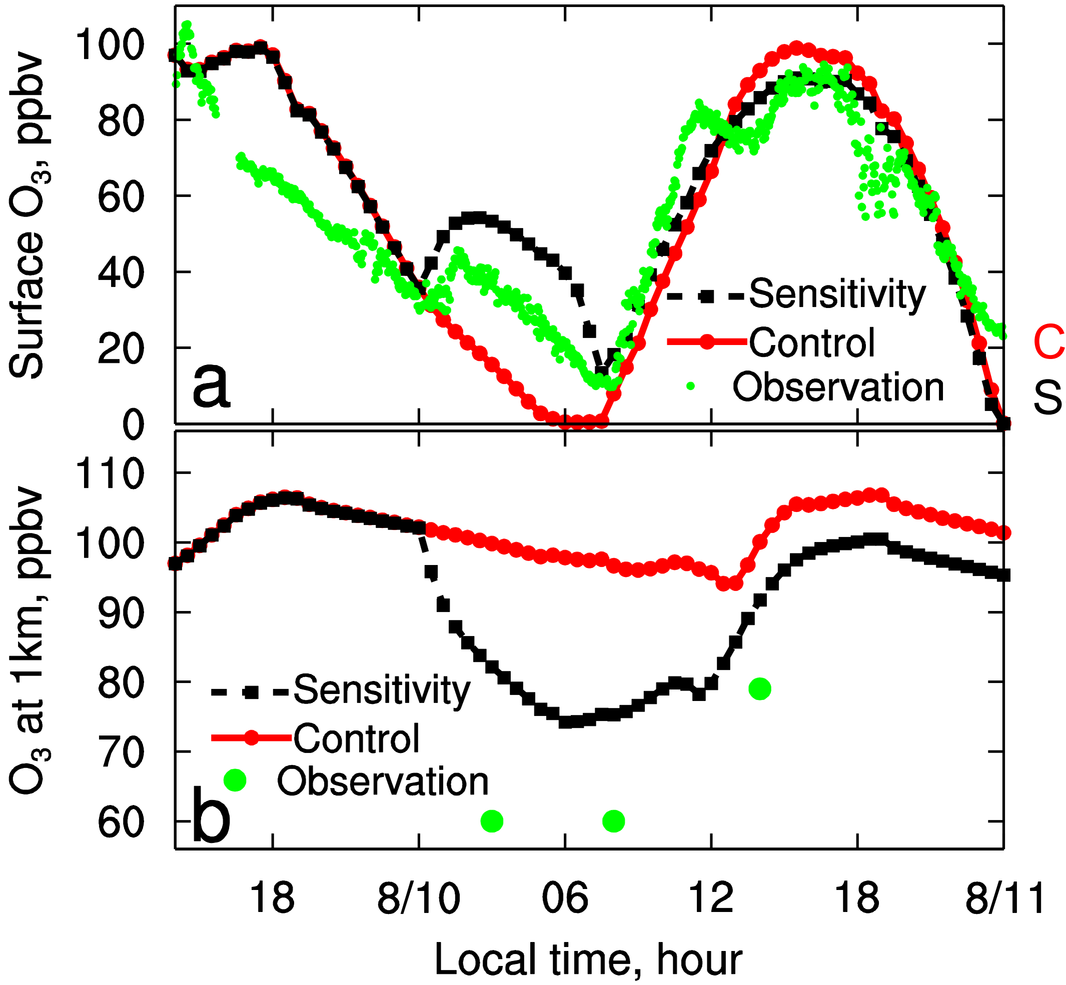
The LLJ played an important role in vertical O$_3$ redistribution (Hu et al., 2013a)

Case study of August 10, 2010



Nocturnal O_3 maxima occurred concurrently at multiple sites along the corridor and advection can not explain (Hu et al., 2013a)

Case study of August 10, 2010, 1D simulations

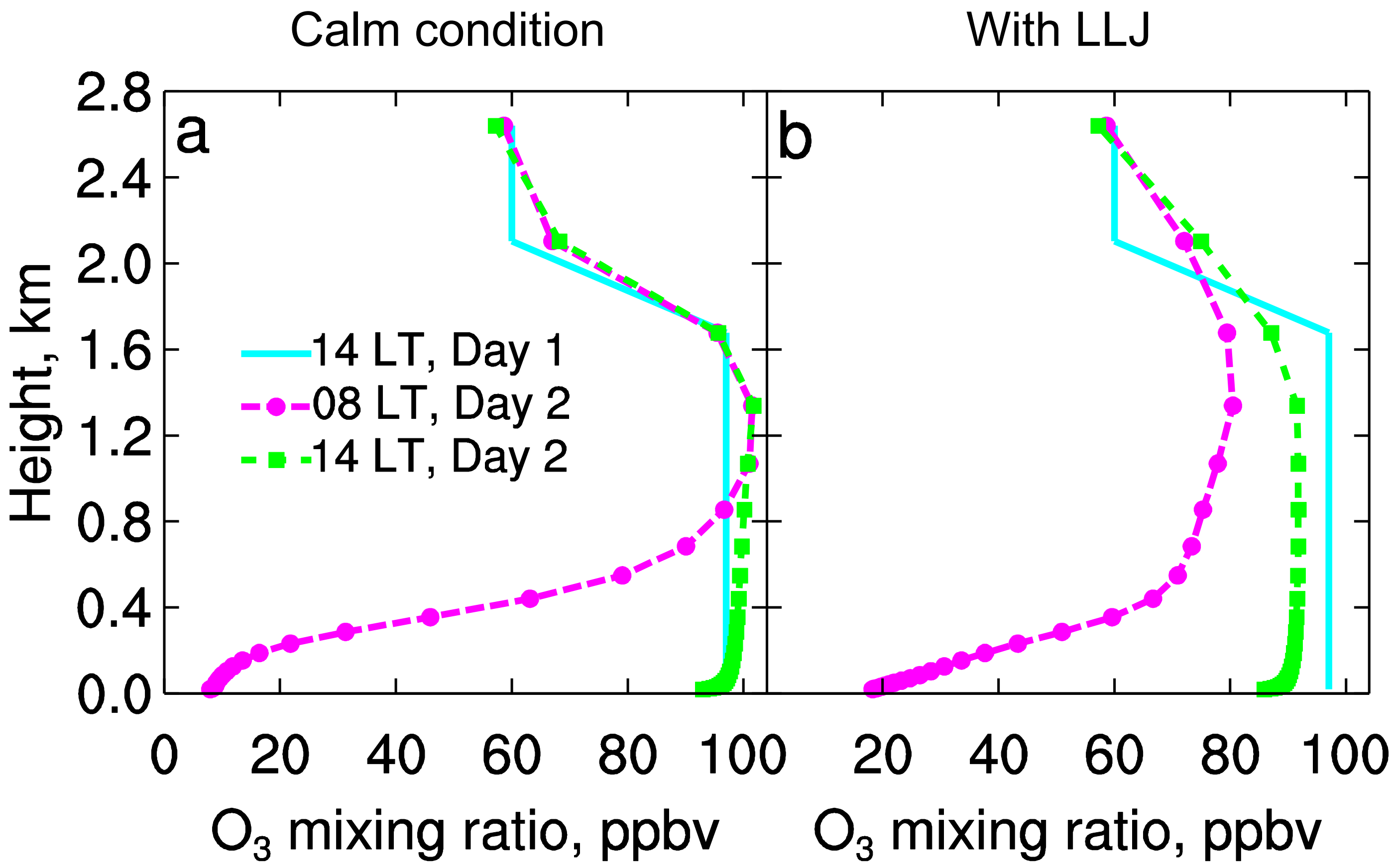


Control : Calm condition, no LLJ

Sensitivity: with LLJ

The 1D simulations capture the main features associated with the LLJ.

Simulated profiles of O_3 w/o & with LLJ

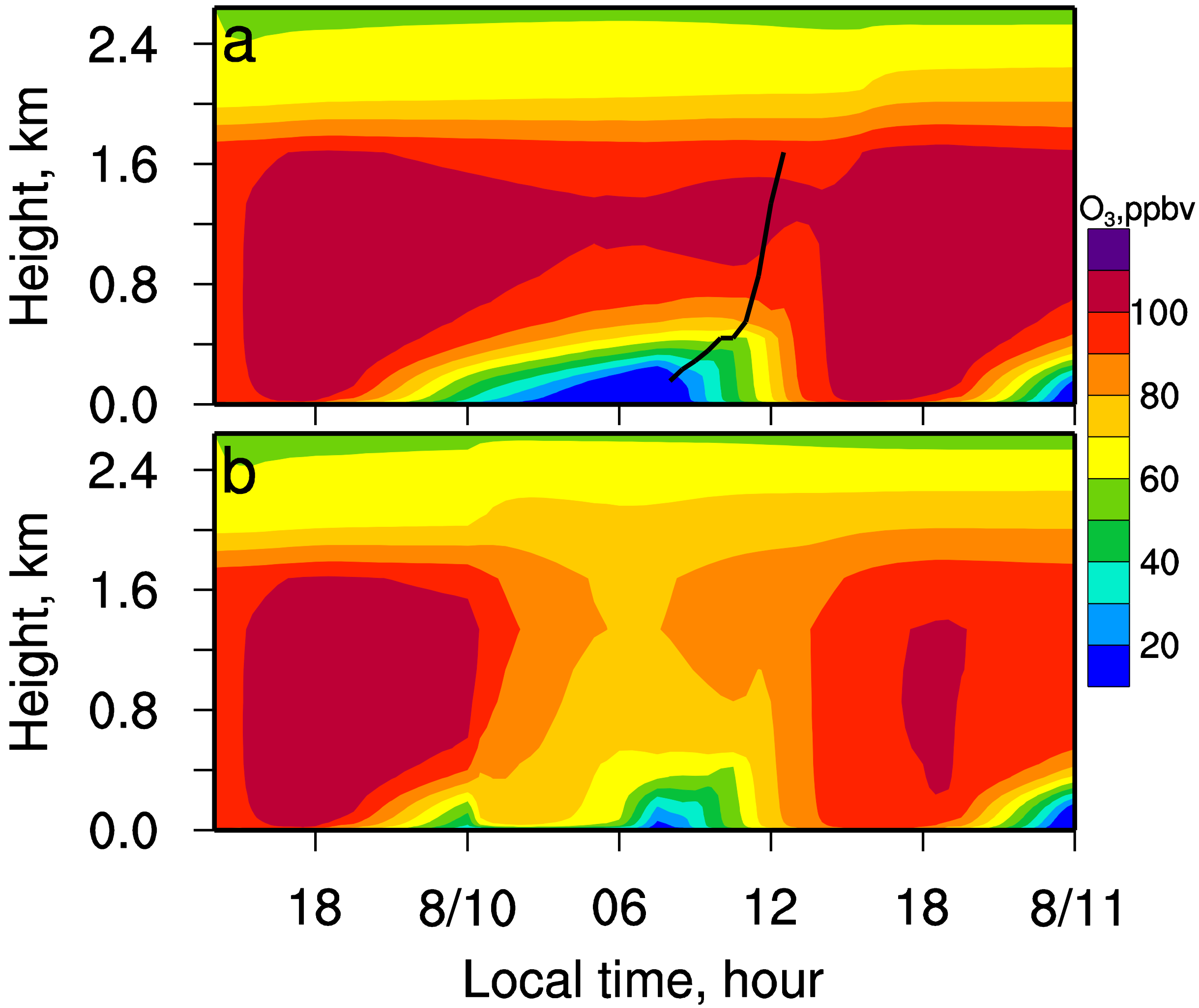


LLJ reduces the RL O_3 substantially. Downward transported O_3 is removed near the surface by dry deposition and chemistry reactions. Consequently the BL O_3 on the following day is reduced.

Time-height diagrams of simulated O_3

Calm condition

With LLJ

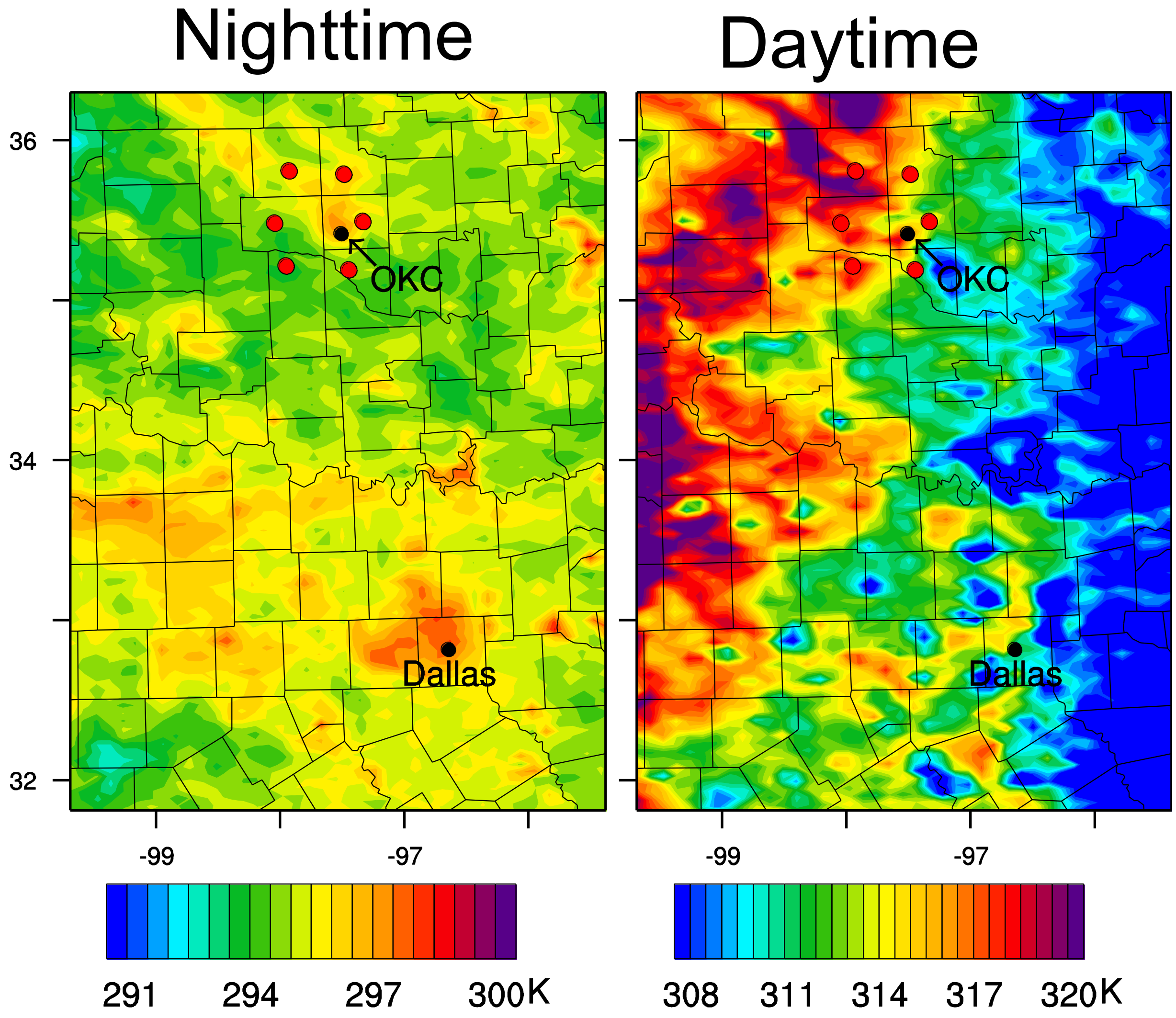


The RL is not a reservoir of O_3 in the presence of a strong LLJ (Hu et al., 2013a)

The upside-down BL forms under certain circumstances, e.g., in the presence of LLJs and clouds (Hu et al., 2011, 2012, 2013a,b)

- **Impact of LLJs on O_3 in the eastern coast** (Hu et al., 2013a)
- **Impact of LLJs on UHI in the Great Plains** (Hu et al., 2013b)

UHI is prominent during the nighttime



LLJs occur frequently in this region, must play some roles.

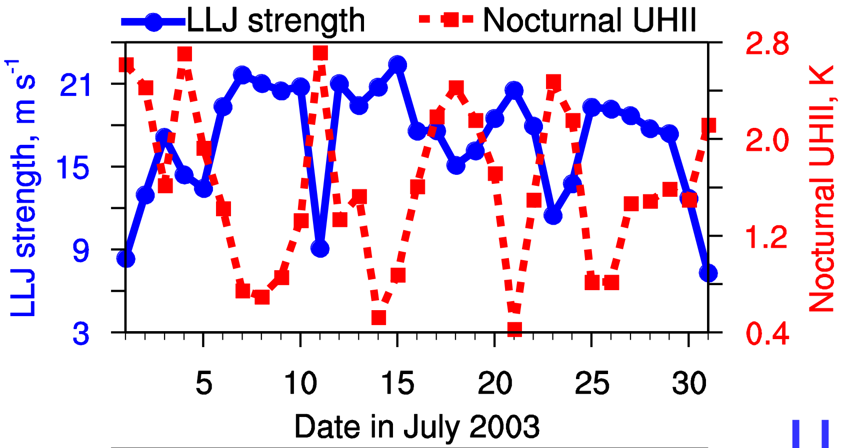
Red dots around OKC:
Six rural sites

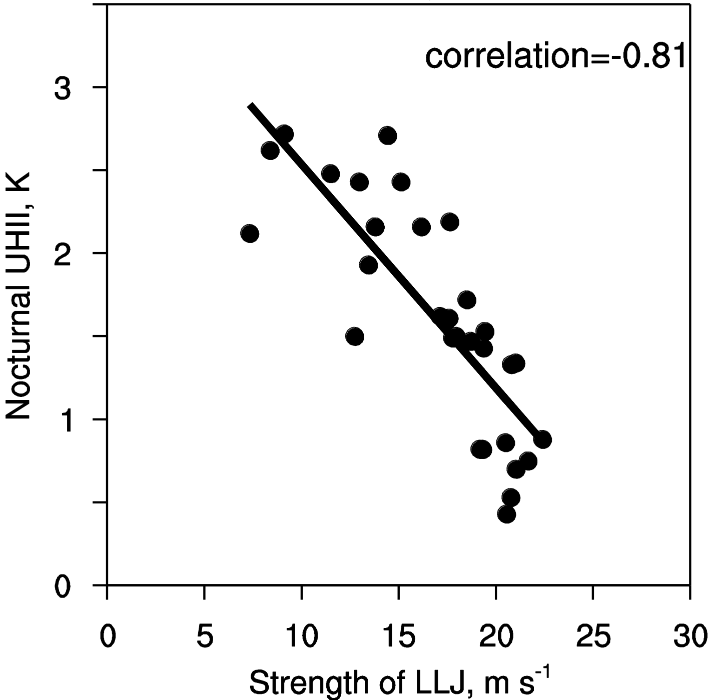
Factors affecting UHI intensity

- Intrinsic characteristics of a city
  - E.g., canyon geometry, thermal properties of the fabric, anthropogenic heat
- External meteorological factors
  - E.g, cloud, wind, radiation

Our study will demonstrate the dominant effect of LLJs on UHI intensity in the Oklahoma City (OKC) metro area

Relationship between LLJs and nocturnal UHI intensity



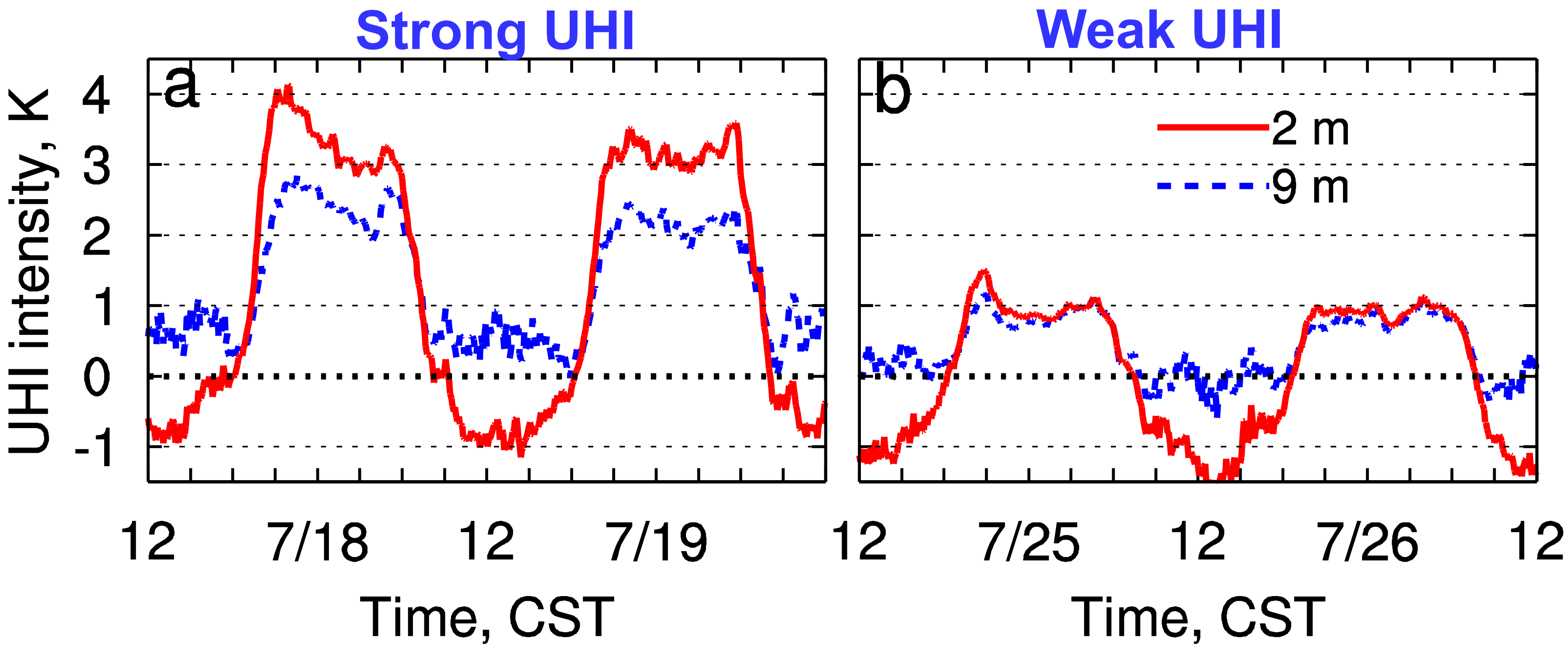


LLJ strength: maximum wind speed of a LLJ

Nocturnal UHII: mean T difference between urban and rural area during nighttime

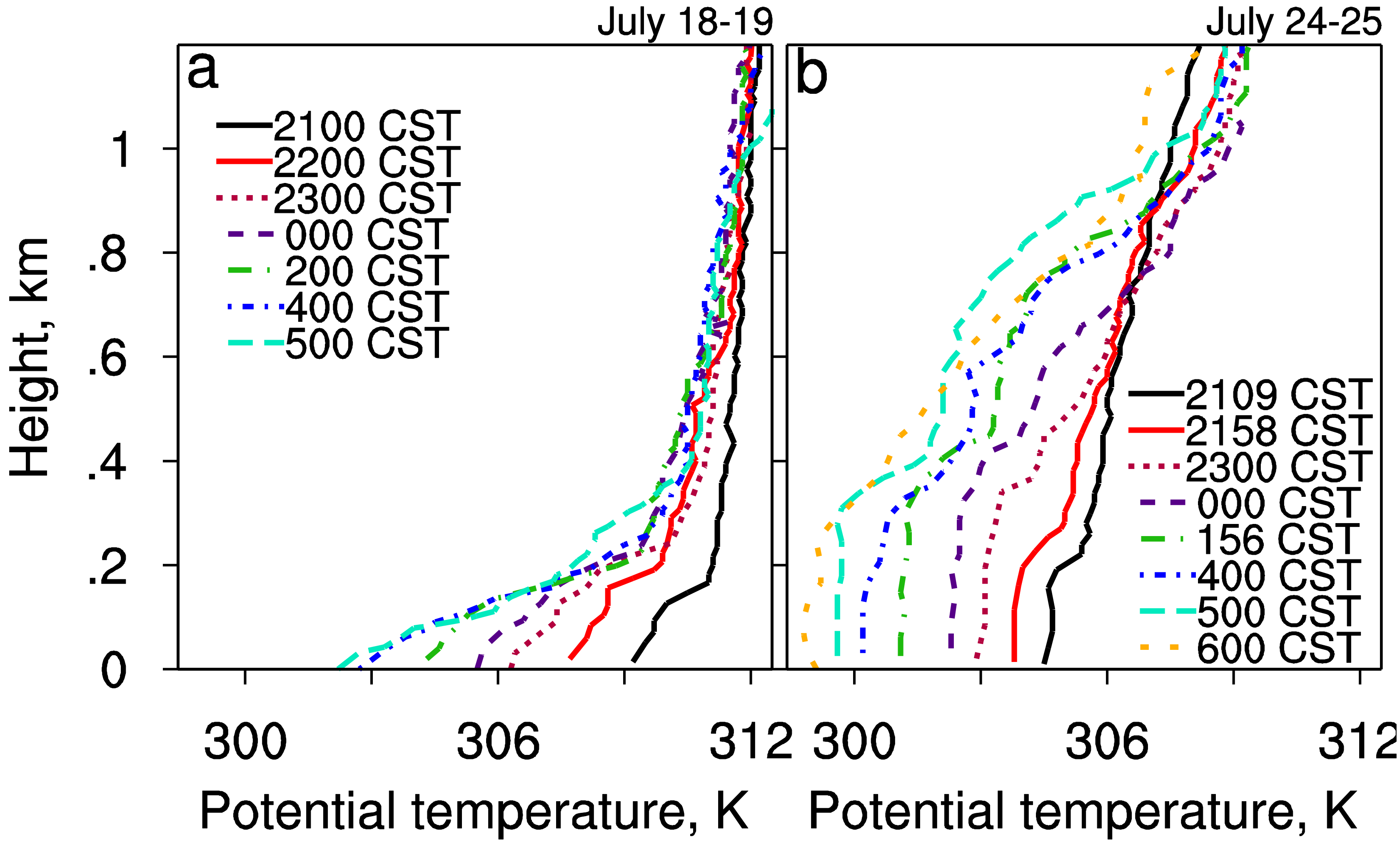
LLJs modulate nocturnal UHI intensity

Two different episodes



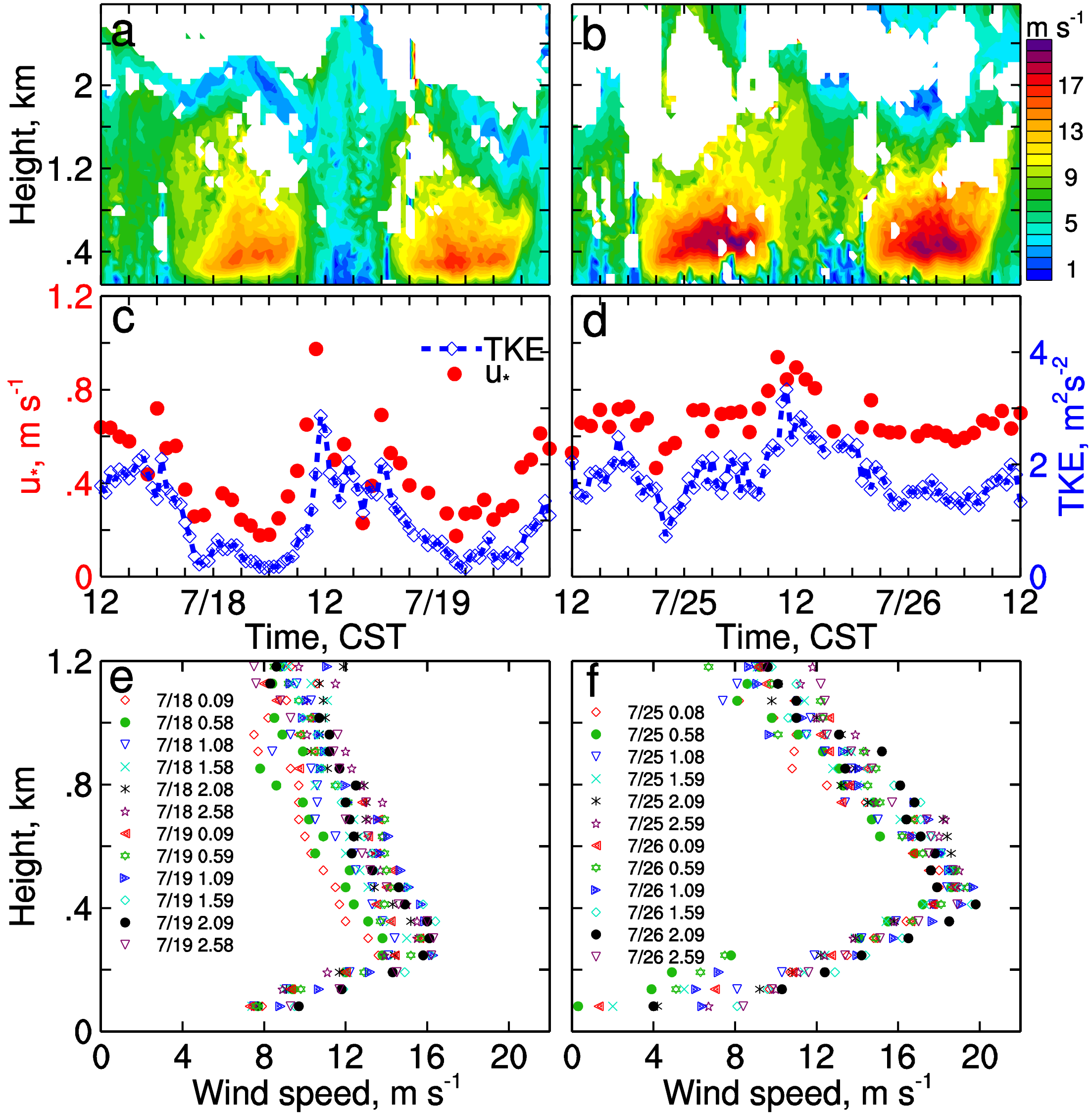
UHI is primarily a nocturnal problem and its day-to-day variation is significant

Two different episodes: temperature profiles



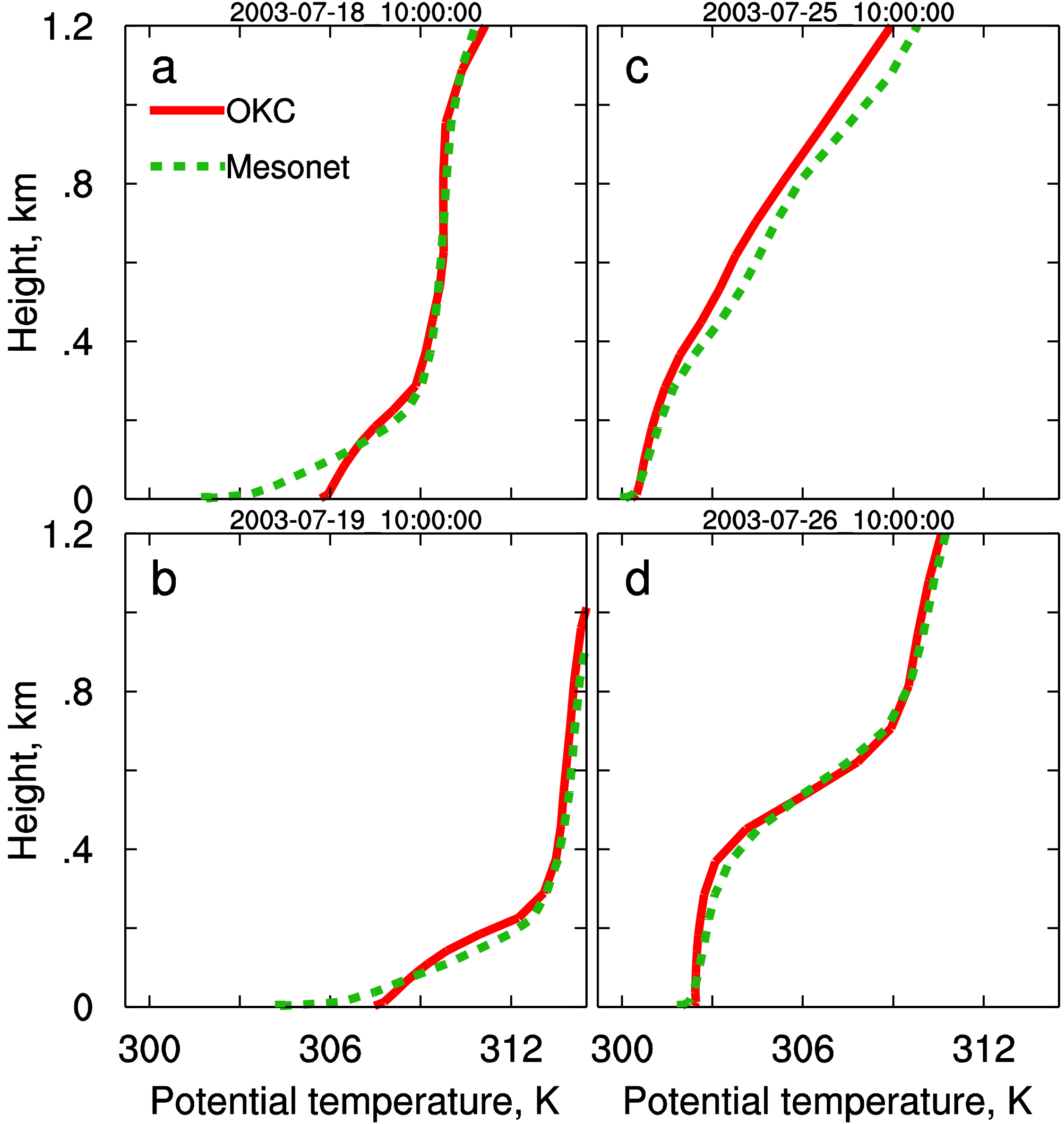
Near surface thermal structure is different, will investigate the reason and effect

Stronger LLJs leads to stronger mixing



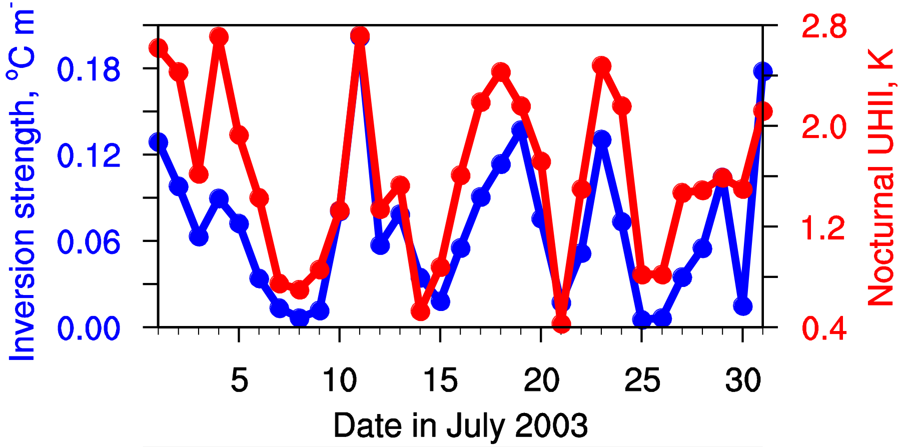
Stronger LLJs=>stronger mixing in a deeper BL=>nearly neutral BL

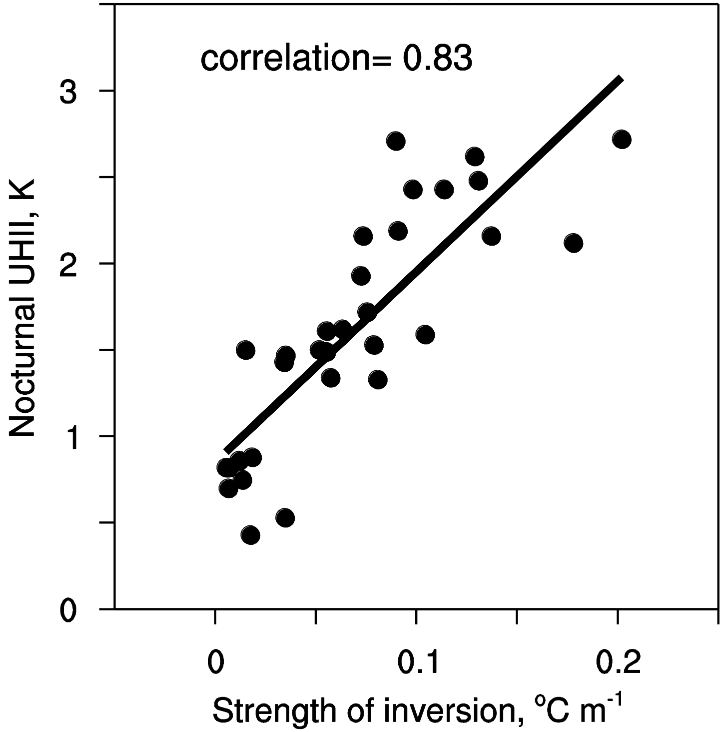
WRF simulation: Different vertical T gradients dictate UHI intensity



Stronger vertical T gradients lead to larger UHI intensity

Relationship between inversion strength and UHI intensity





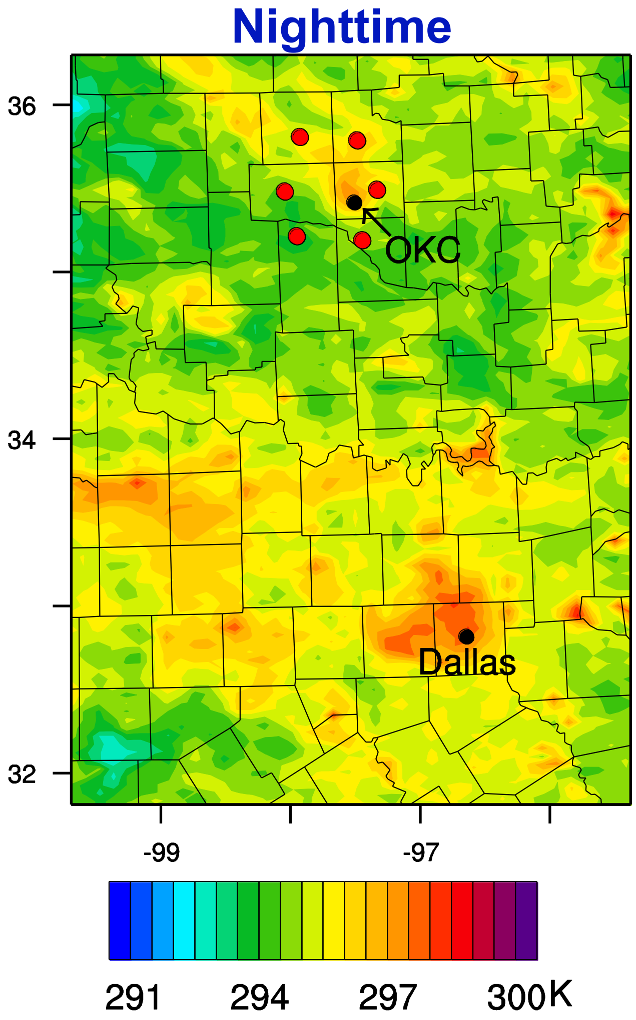
Inversion strength is a good indicator of UHI intensity

Conclusions

1. The residual layer may not be a reservoir of pollutants in some cases (e.g., strong LLJs).
2. LLJs play important roles in modulating UHI.

Question: urban effects on LLJs? Idea for proposal!!

MODIS-derived land surface temperature

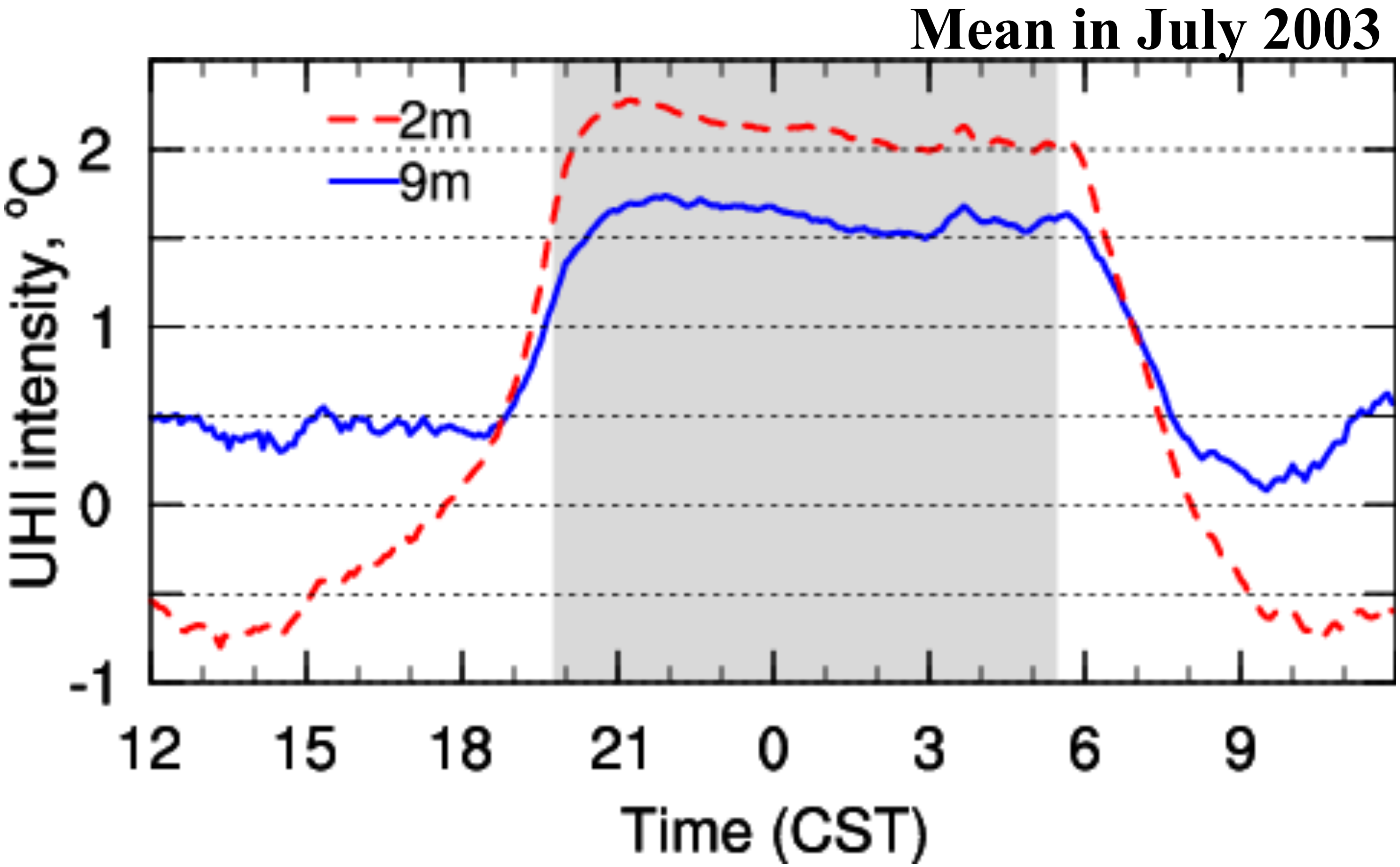


Hu et al. (2013, JAMC)

UHI is prominent during nighttime

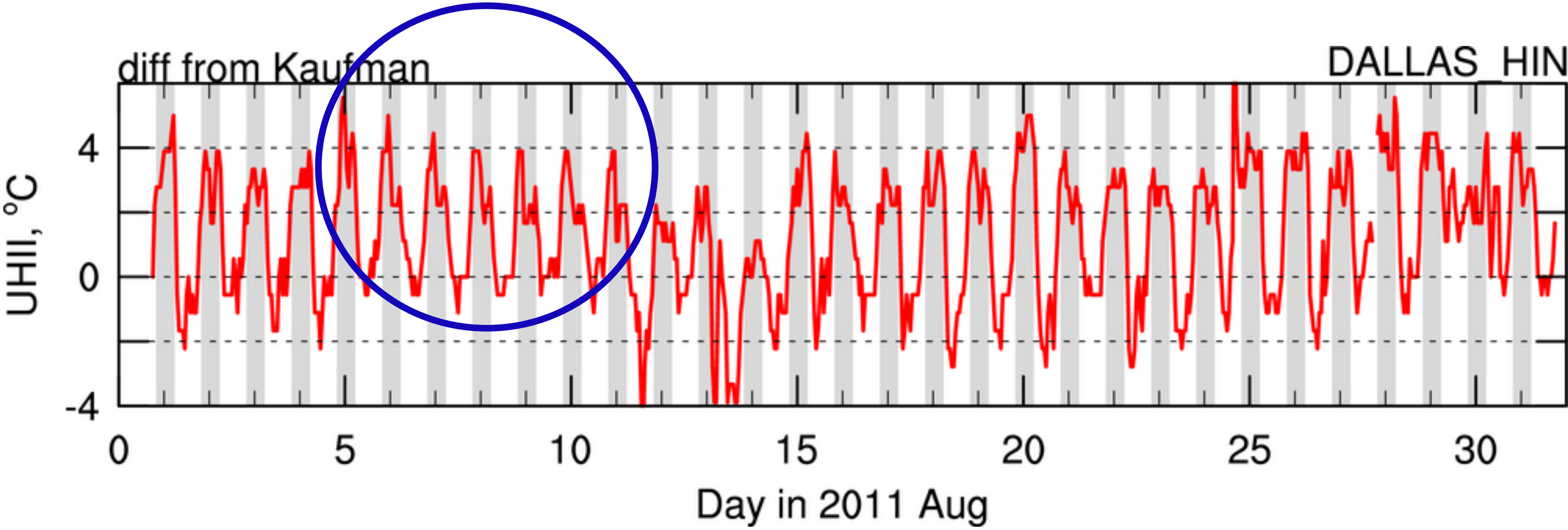
UHI intensity = T at urban location – T at rural sites

Diurnal variation of UHI intensity in OKC



UHI intensity normally increases around sunset quickly and then stays at a roughly constant level throughout the night.

Unique variation of nocturnal UHI in Dallas



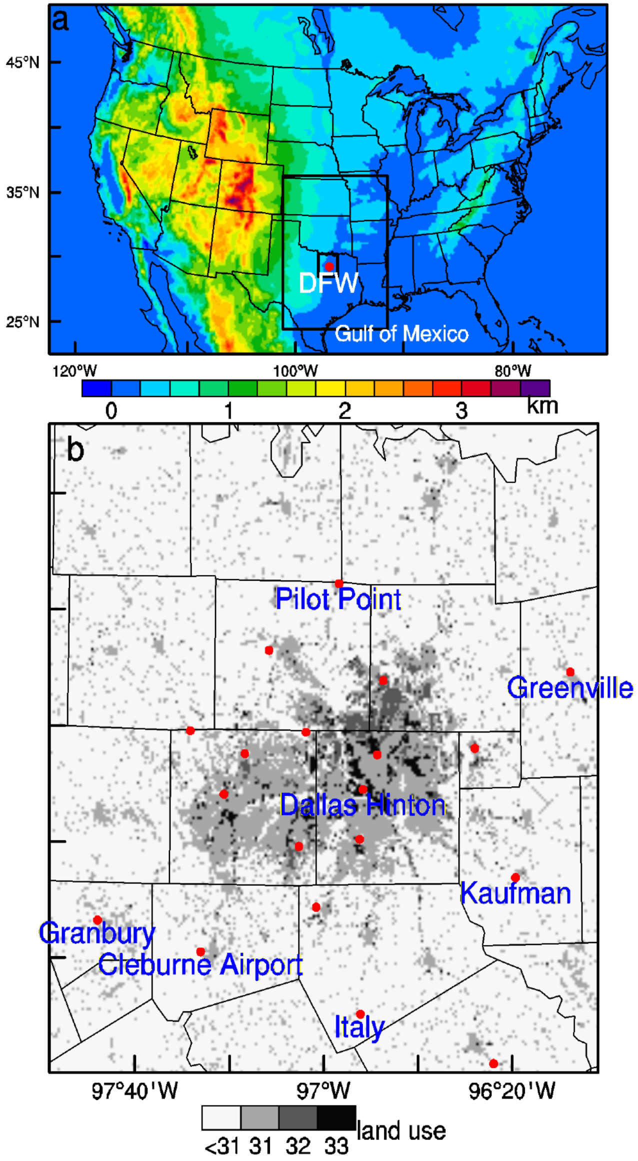
Sharp decrease ("collapse") of the nocturnal UHI intensity

Objectives of this study

- Understand such a unique temporal variation of the nocturnal UHI intensity in Dallas

- Investigate WRF model capability to reproduce UHI

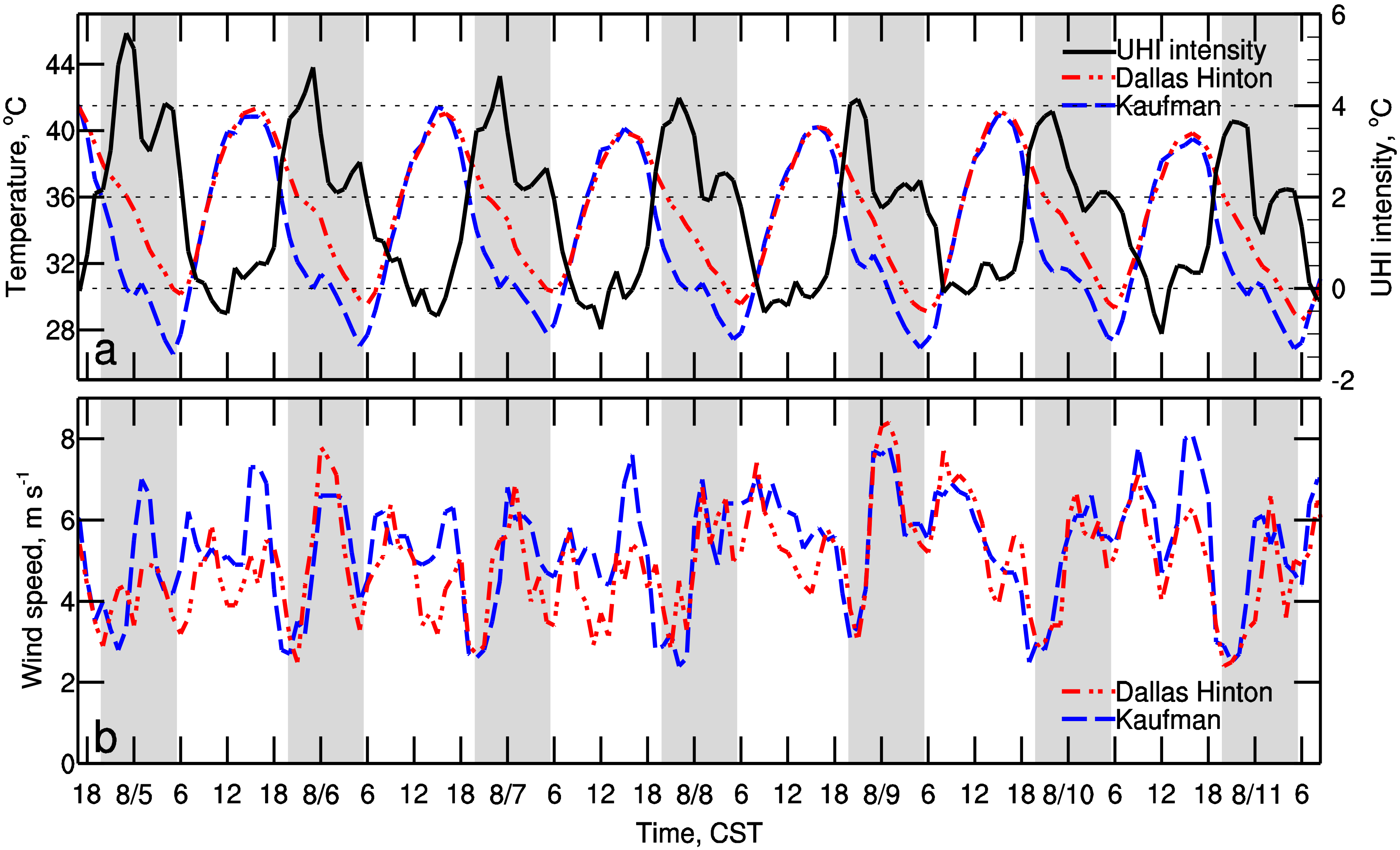
Model domains and configurations



- WRF3.6.1
- 12->4->0.8km
- NOAH+Urban canopy model
- Boundary layer scheme: YSU
- Simulation period: August 7-8 2011

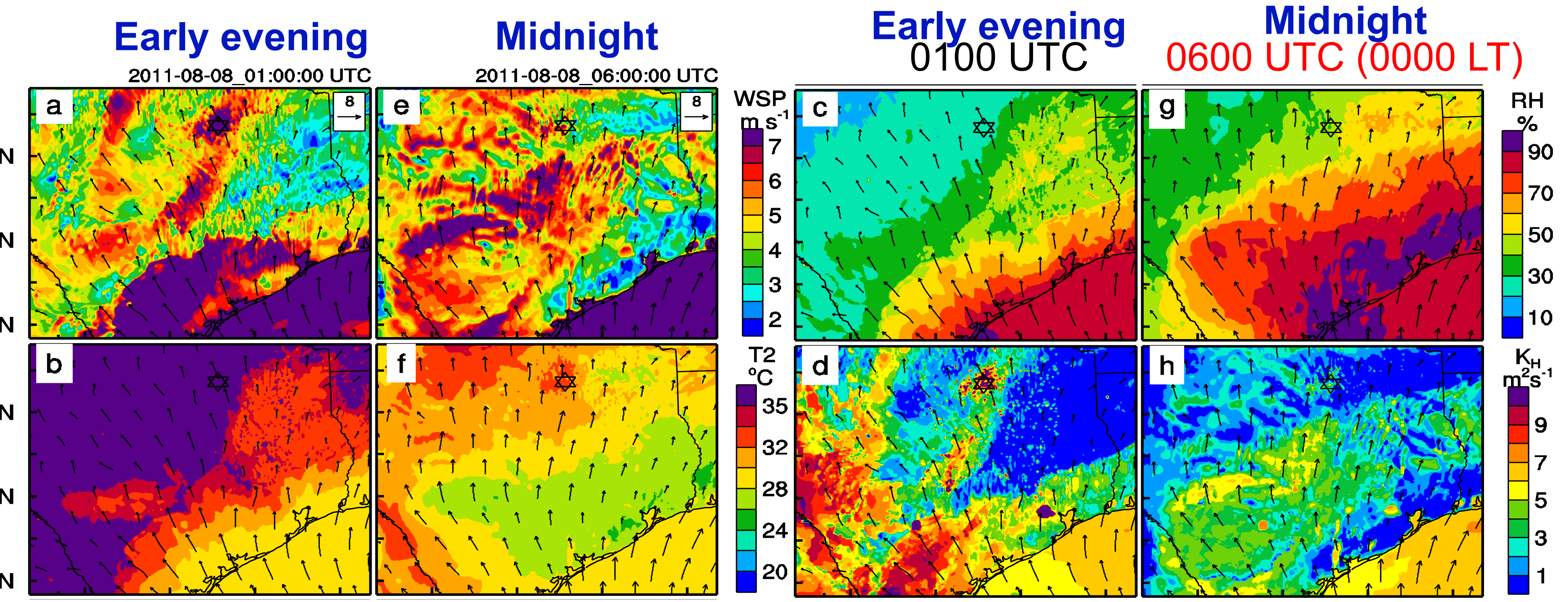
UHI intensity = T at Dallas Hinton – T at Kaufman
to be consistent with Winguth (2013, JAMC)

Observed variation of UHI, T, wind speed



Collapses of UHI coincided with wind maximum and rural nocturnal warming events

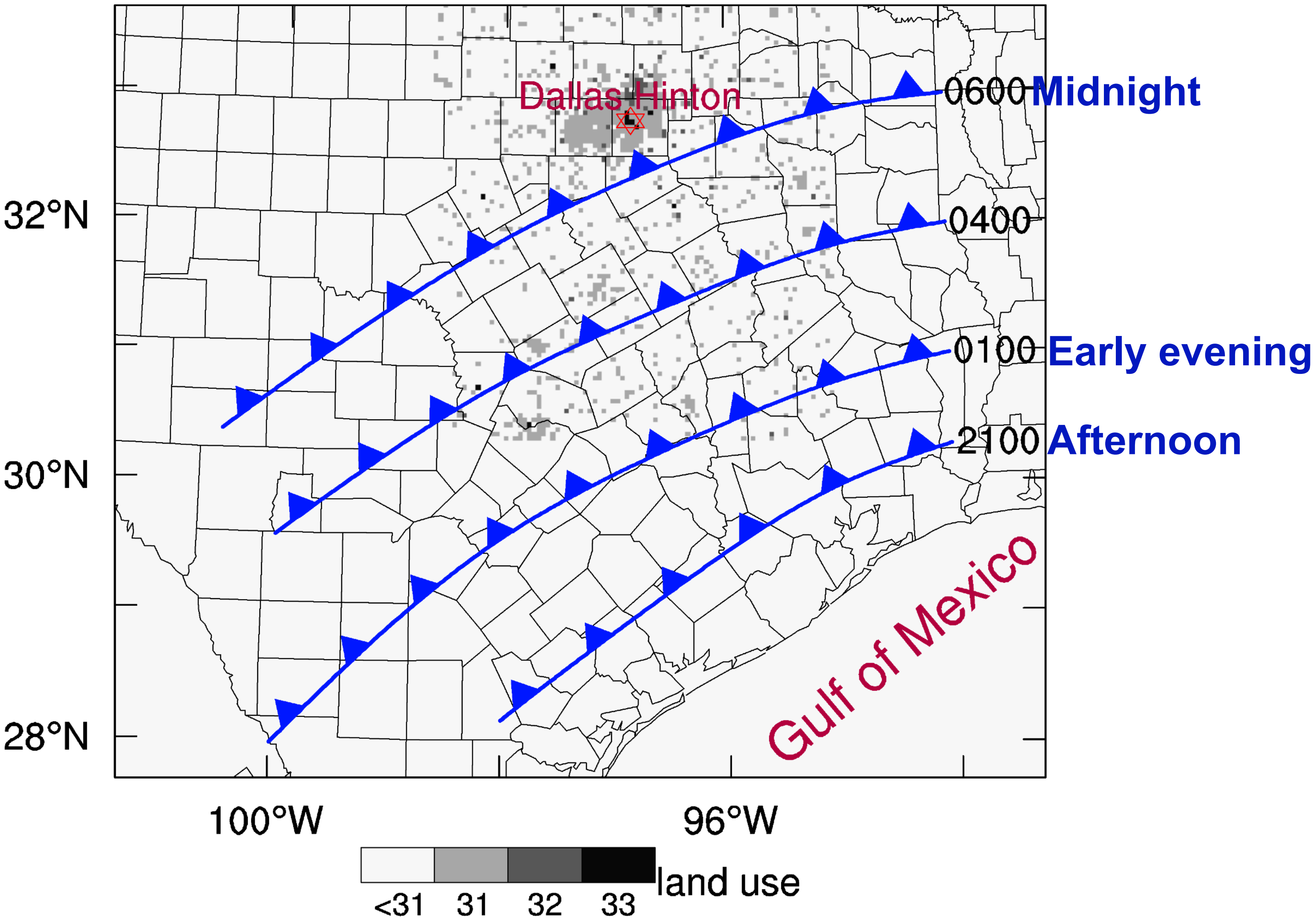
Map of wind, T2, RH, K_h at 00 and 06 UTC



Indications of a sea breeze front:

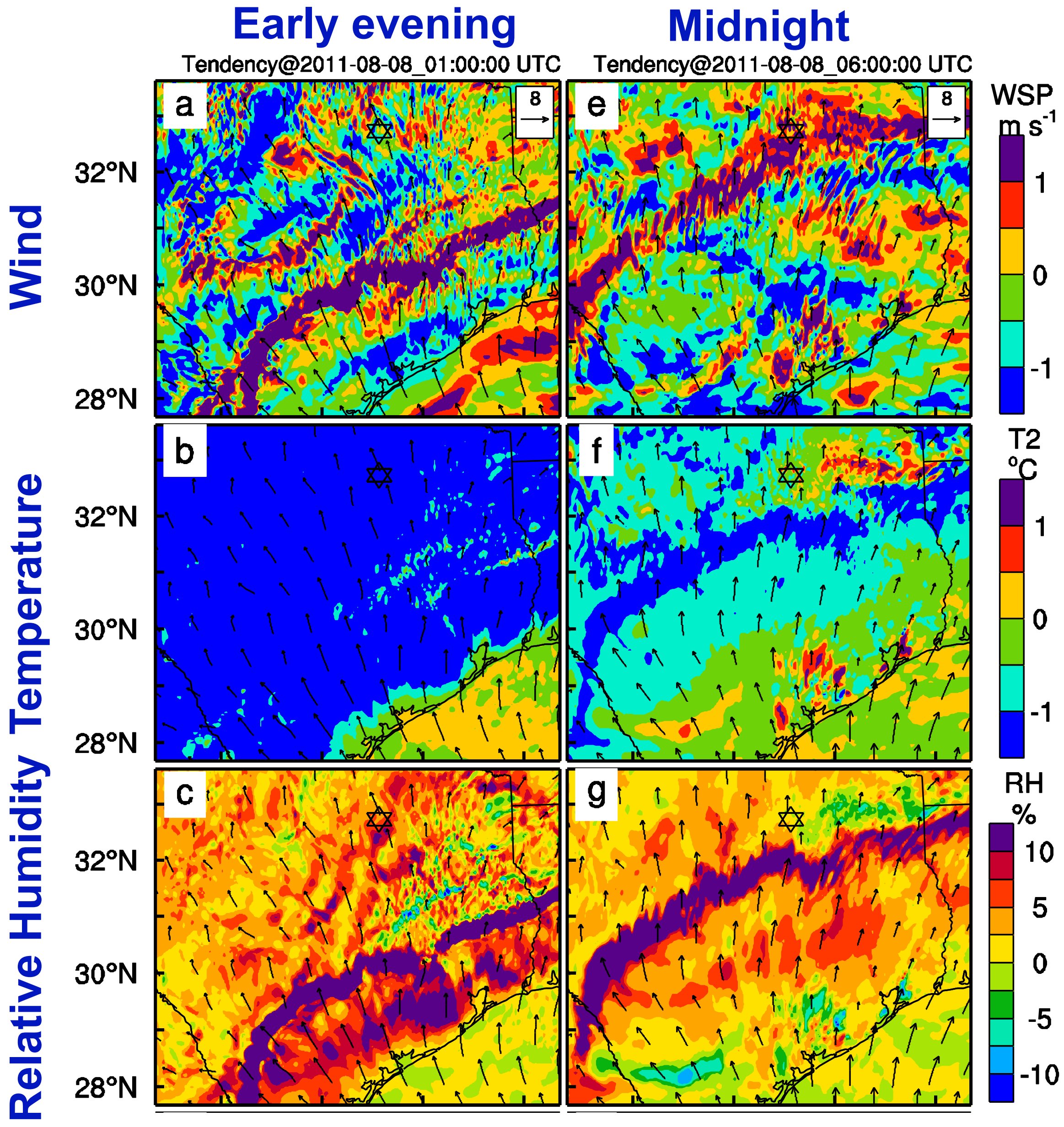
Cooler and moister air behind the front with stronger momentum and vertical mixing

Inland penetration of the sea breeze front



The sea breeze front approached Dallas around midnight (0600 UTC)

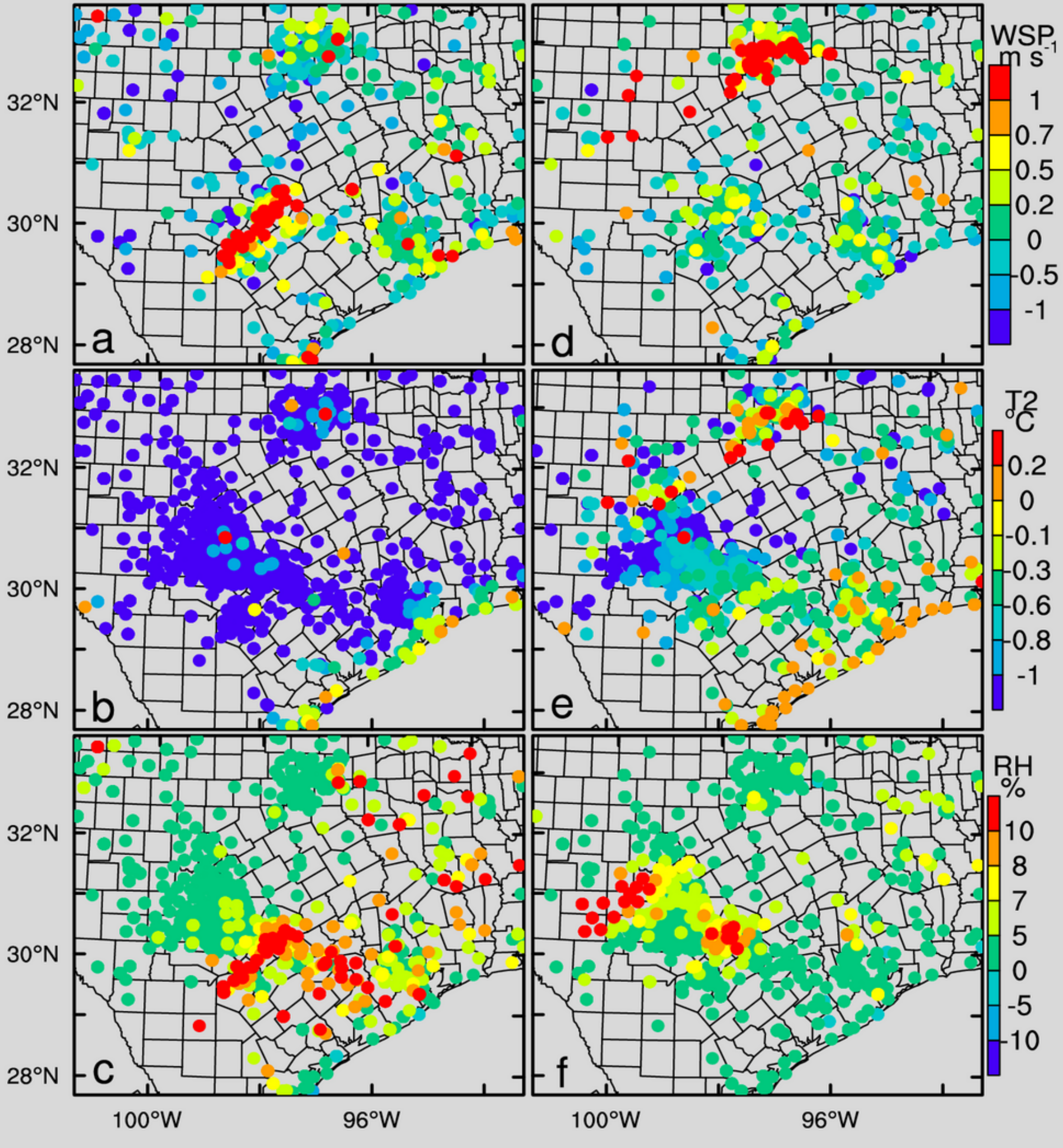
Tendency: difference between current and next hours



The inland penetration of sea breeze front can be clearly illustrated in the tendency of WSP, T2, RH.

Observed tendency in MADIS data

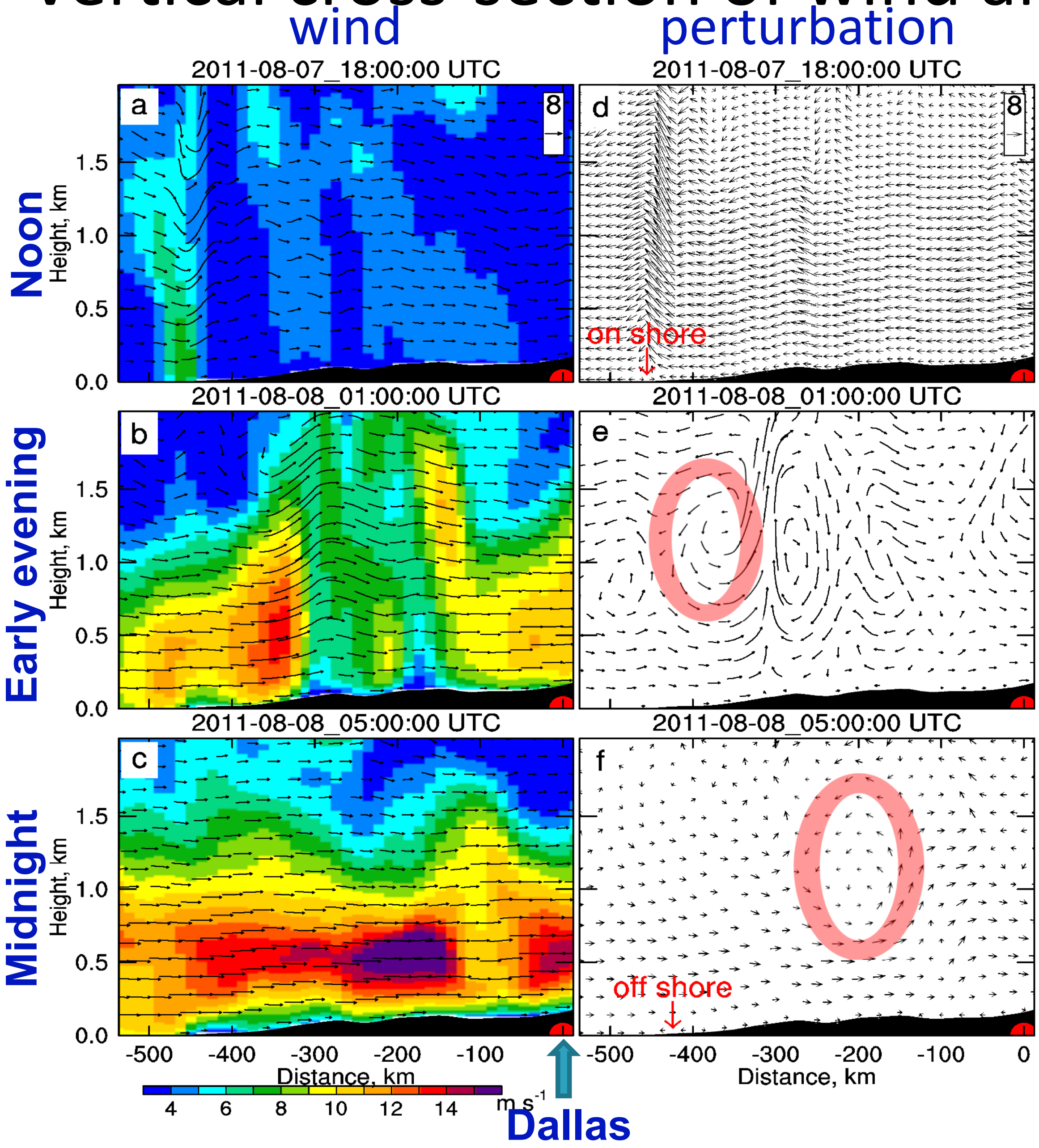
Early evening **Midnight**



MADIS integrated data from many providers

In the spatial distribution of tendency, the small scale local heterogeneity in instantaneous values is removed and only the spatial information of temporal variation is remaining.

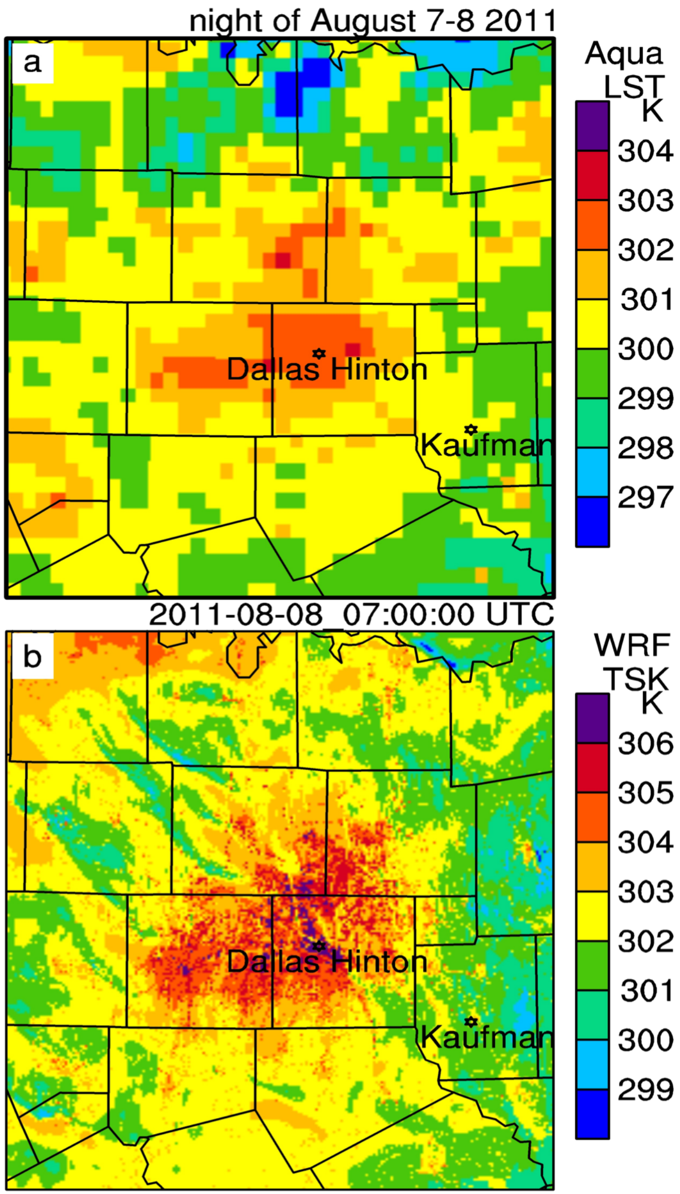
Vertical cross-section of wind and its perturbation

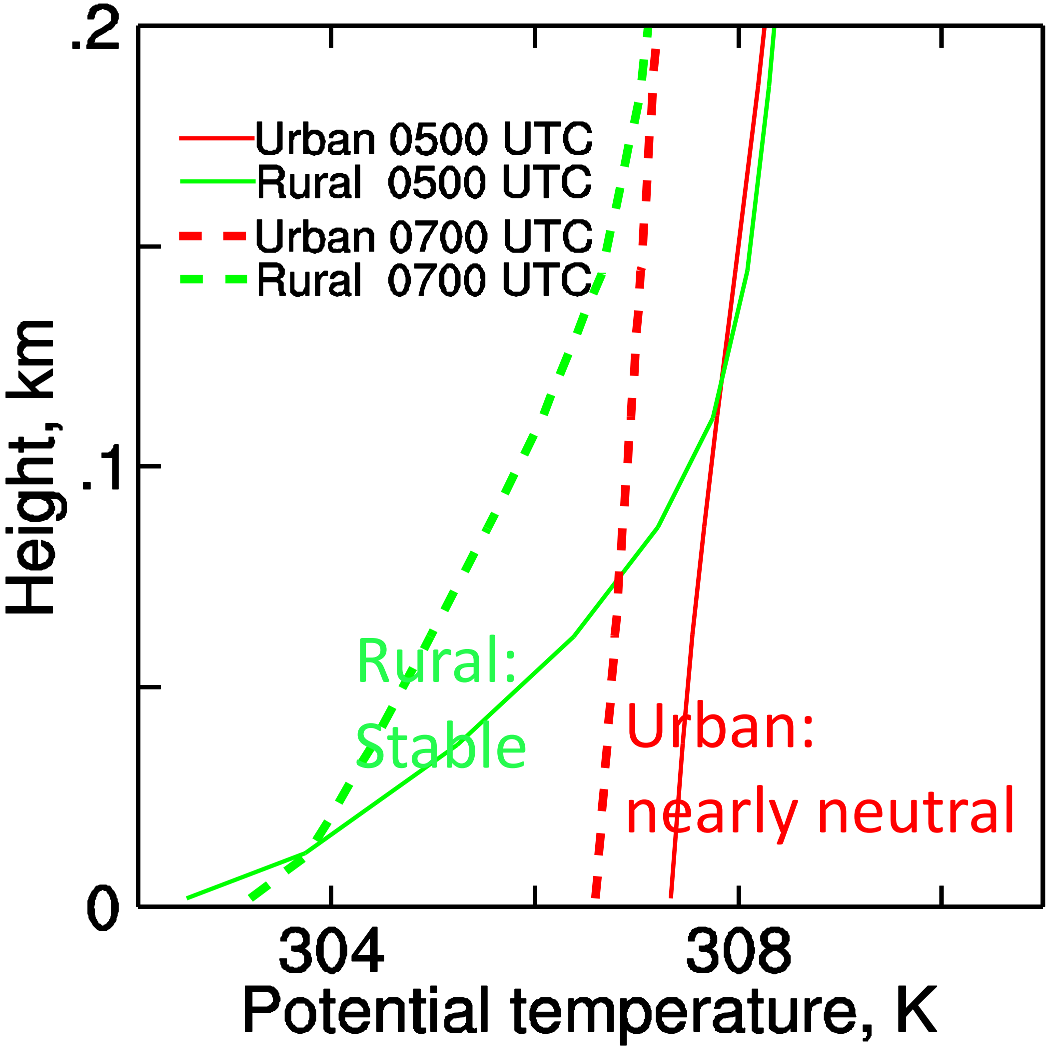


Sea breeze develops in the morning and is advected by Low-Level Jet at night

Synoptic sea breeze

Different response to the front in rural and urban

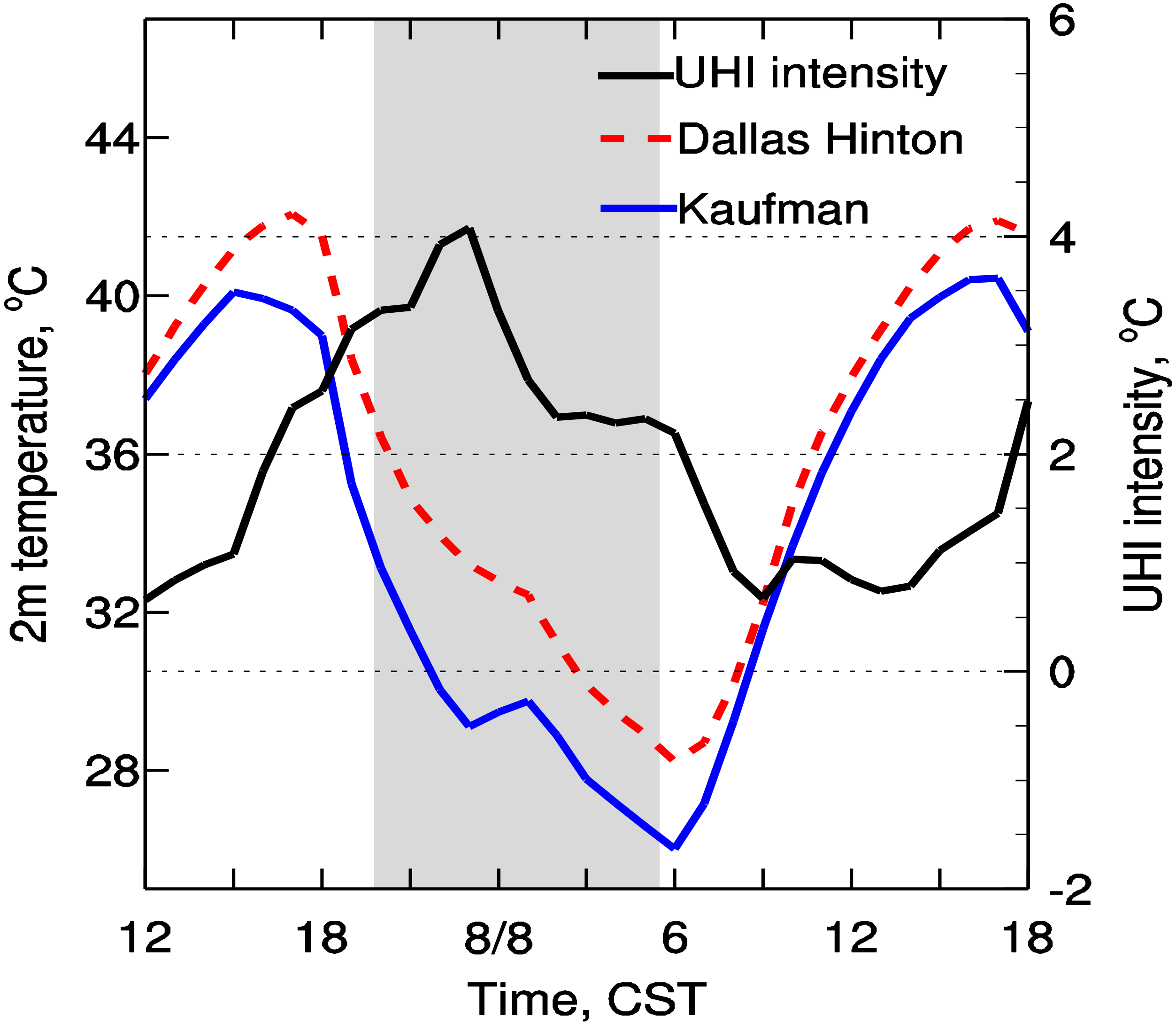




Rural: Stable

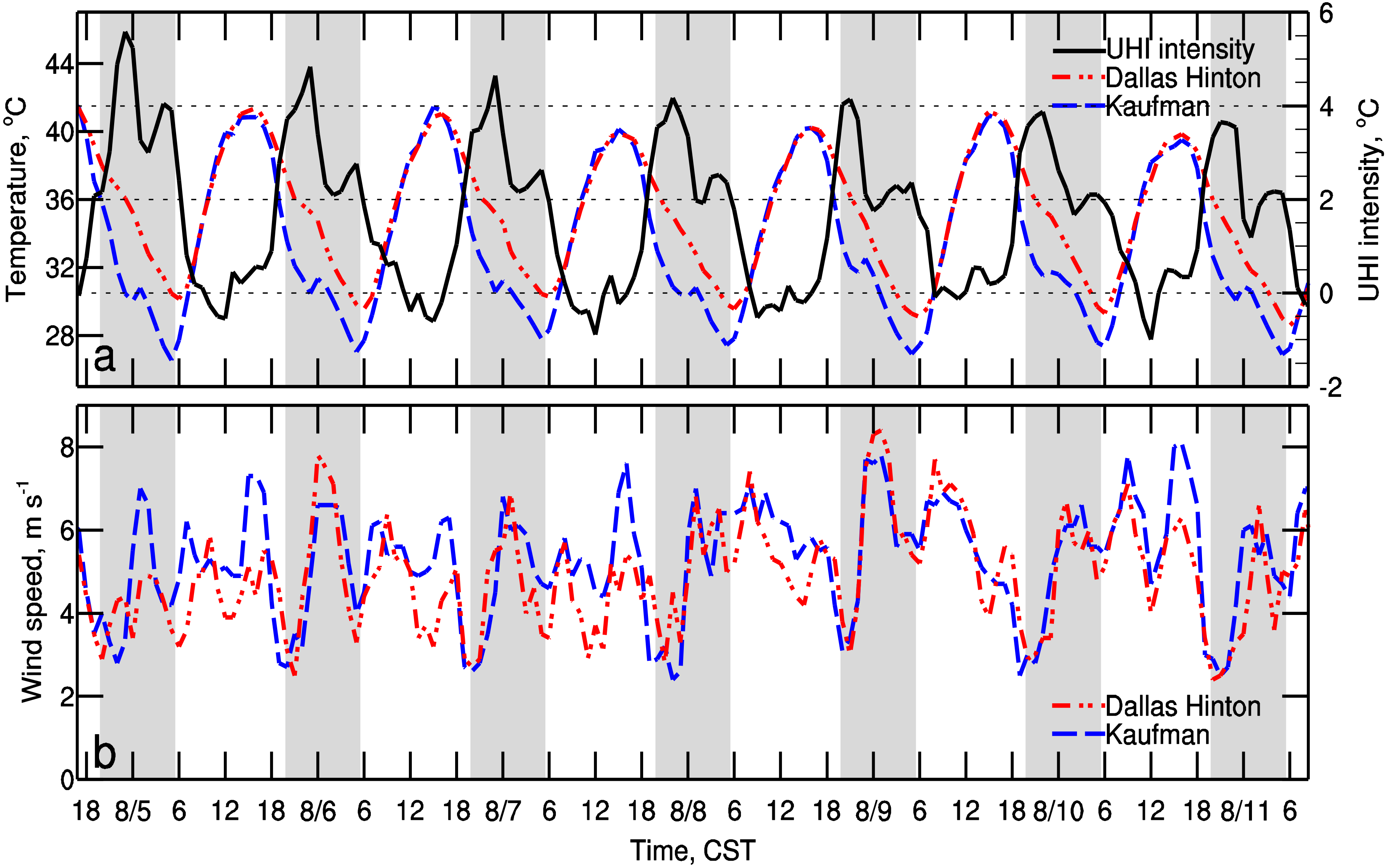
Urban: nearly neutral

Simulated variation of T, and UHI intensity



Nocturnal warming in rural and non-warming in urban lead to collapse of UHI

Observed variation of UHI intensity in Dallas



Conclusions

1.“collapse” of nocturnal UHI intensities occurred frequently around mid-night in August 2011 in Dallas.

2. Sea breeze circulation cells can be advected to Dallas and influence its UHI

3. Sea breeze frontal passage induced nocturnal warming events in rural area, while it did not alter urban boundary layer much.

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