Boundary layer processes and their impacts on Urban Heat Island & Air Quality

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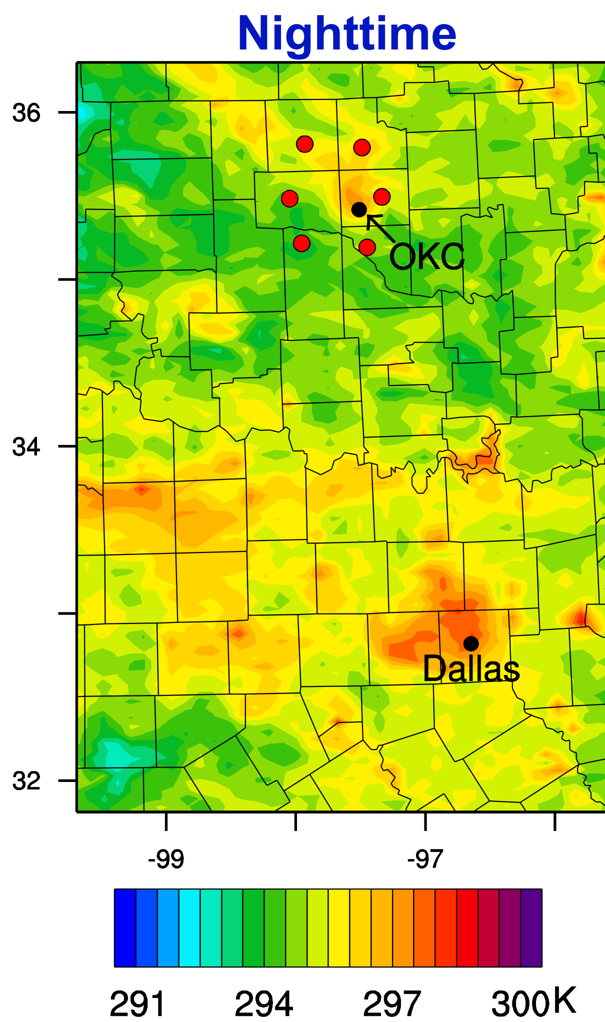
at TianJin

1. **Boundary layer processes in Texas**
2. **Boundary layer processes in NCP**

MODIS-derived land surface temperature

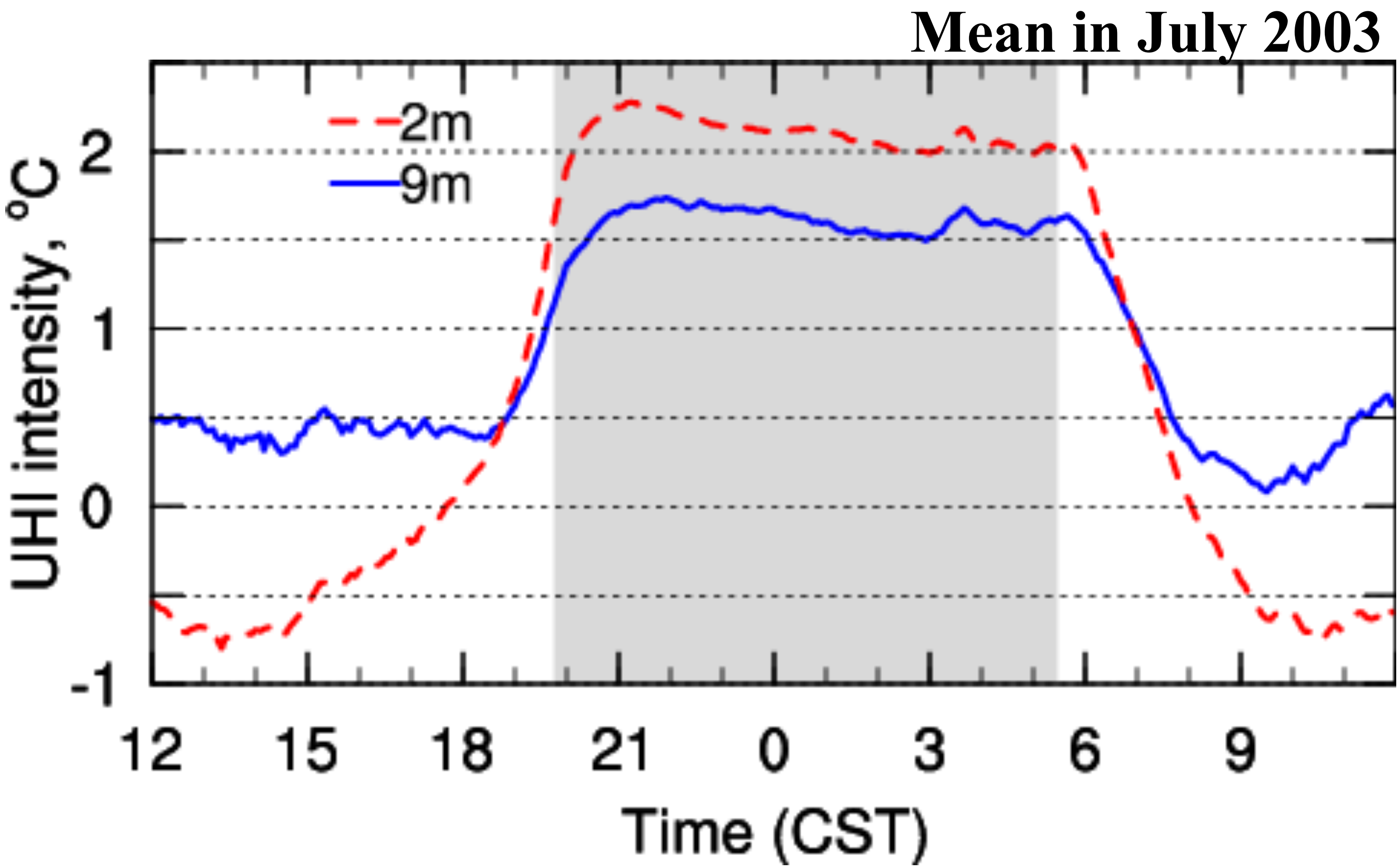


Hu et al. (2013, JAMC)

UHI is prominent during nighttime

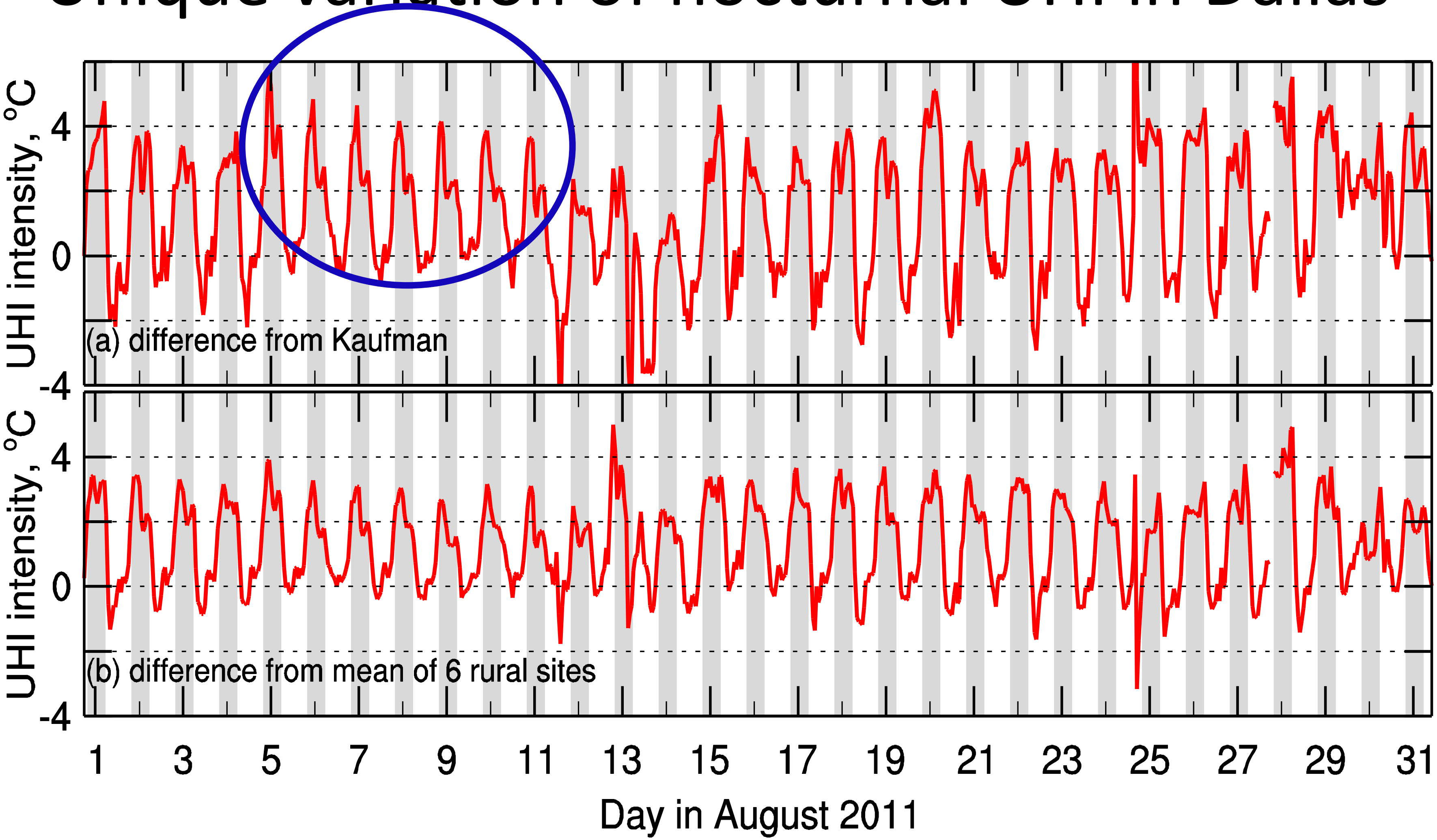
UHI intensity = T at urban location – T at rural sites

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



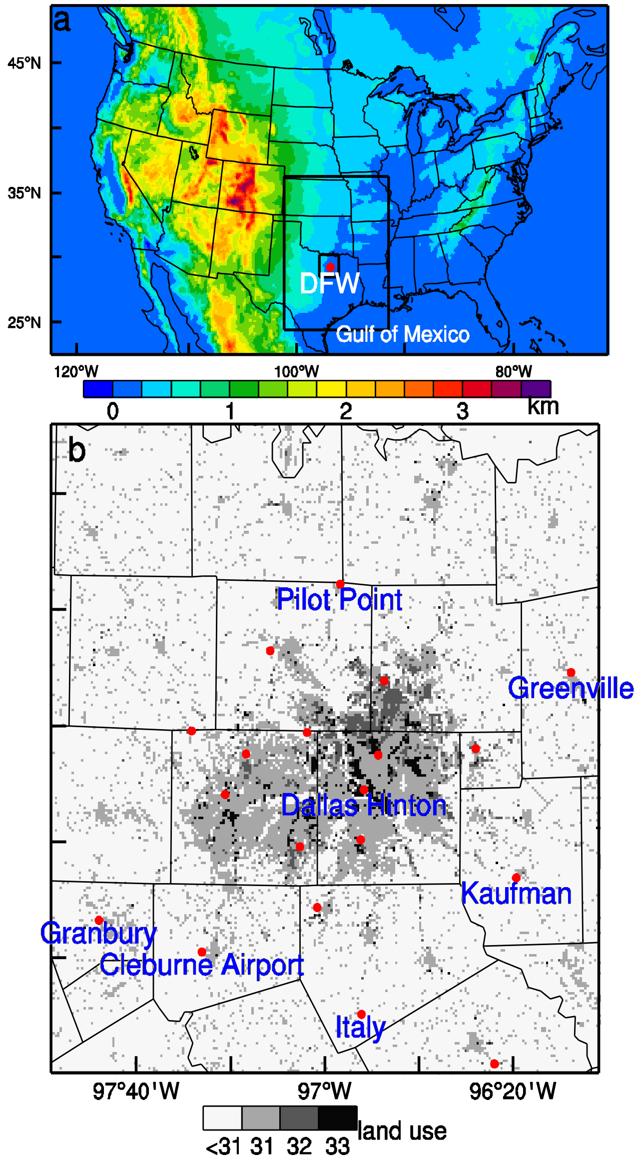
Sharp decrease ("collapse") of the nocturnal UHI intensity

Motivations/objectives of this study

Hu and Xue (2016, MWR)

- Understand such a unique temporal variation of the nocturnal UHI intensity in Dallas
  - Mountain-Plain solenoid
  - Sea breeze
  - Nocturnal warming events
- Investigate WRF model capability to reproduce UHI
- Impact on air quality

Model domains and configurations

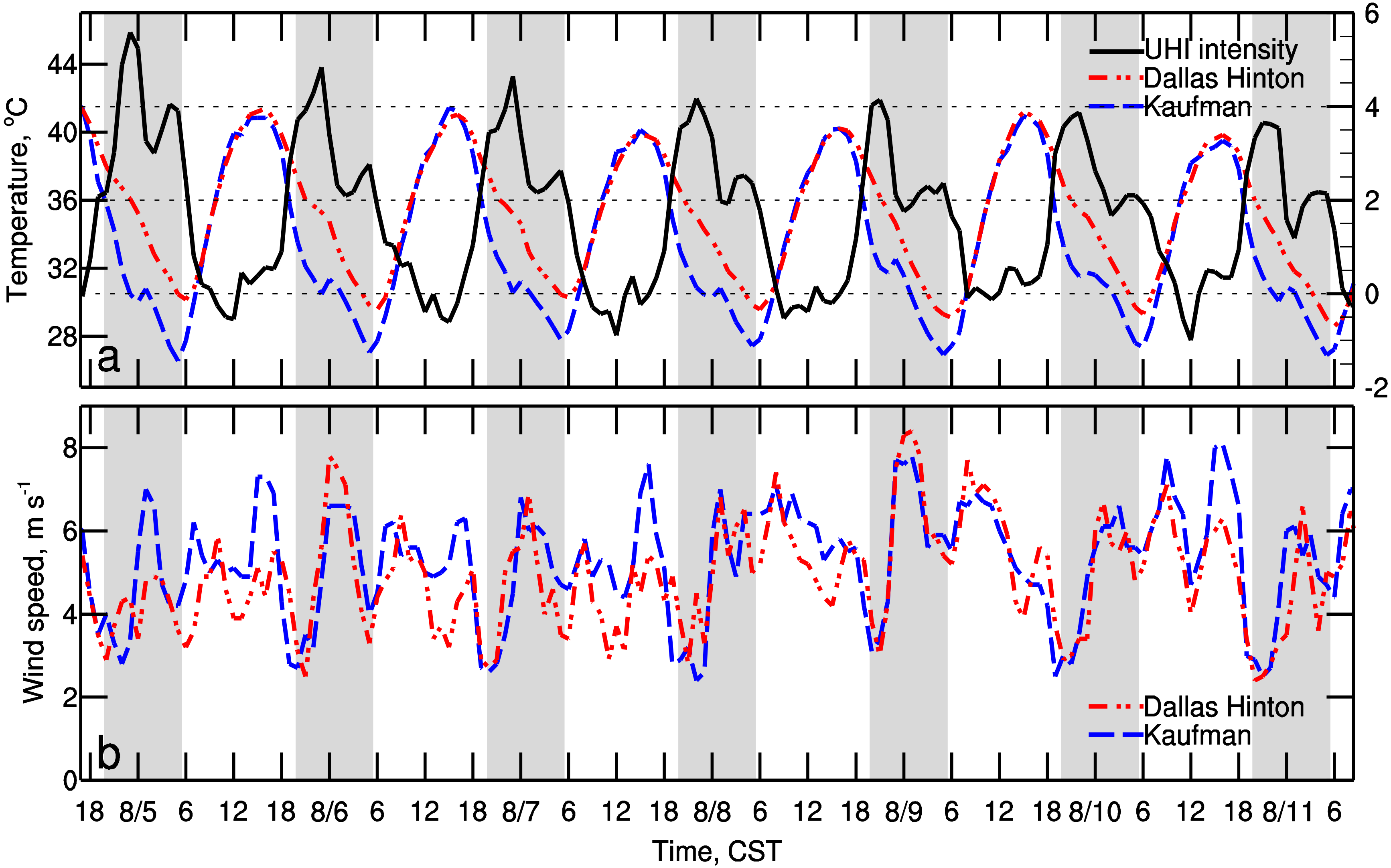


- WRF3.6.1
- 12->4->0.8km
- NOAH+Urban canopy model
- Boundary layer scheme: YSU
- Simulation period: August 7-8 2011

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

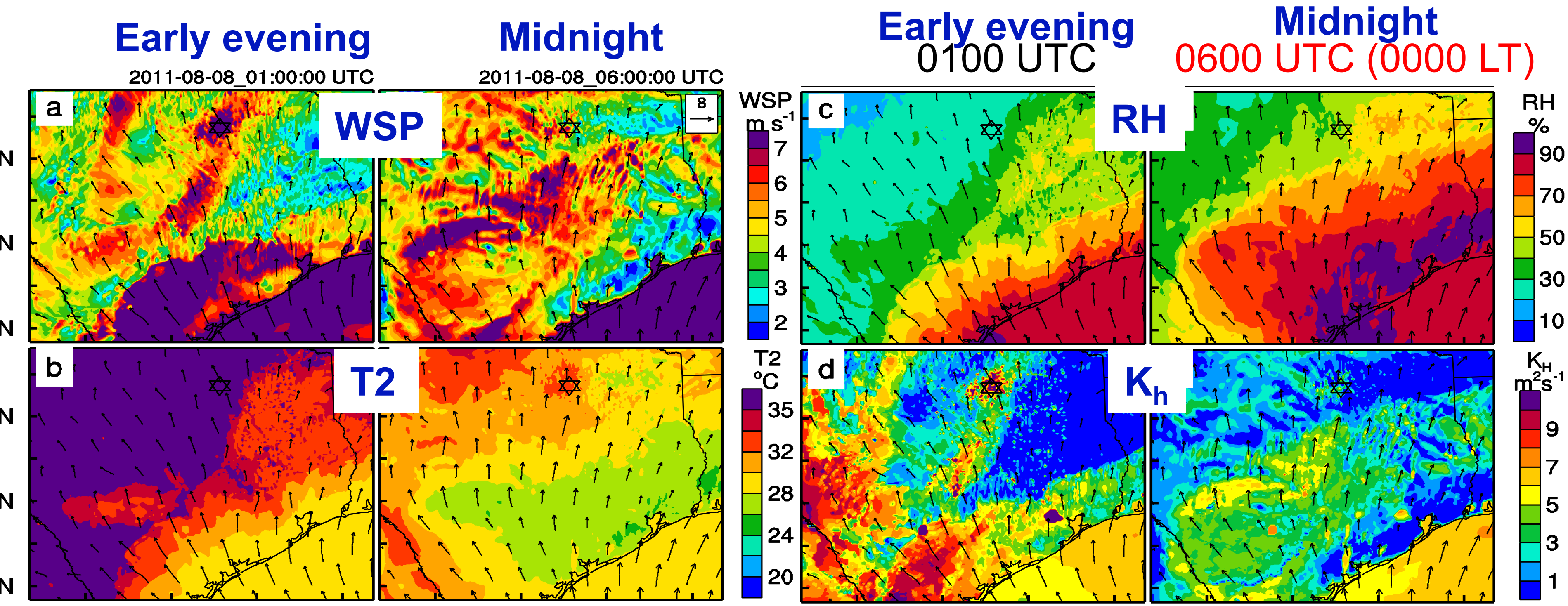
WRF/Chem for air quality impact

Observed variation of UHI, T, wind speed



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

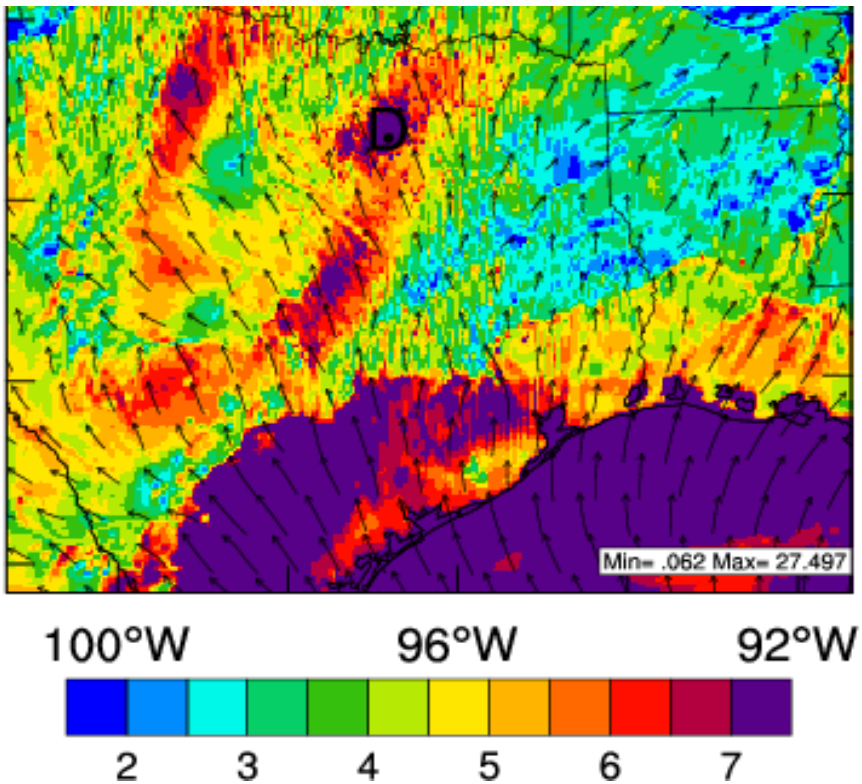
Map of wind, T2, RH, K_h at 00 and 06 UTC

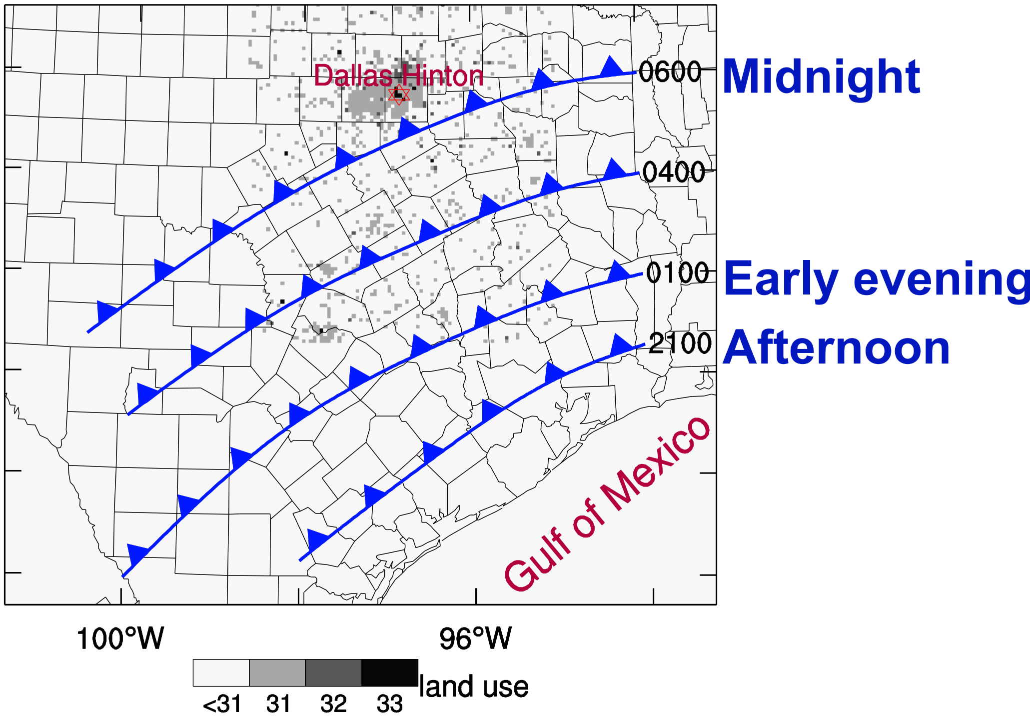


Indications of a sea breeze front:

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

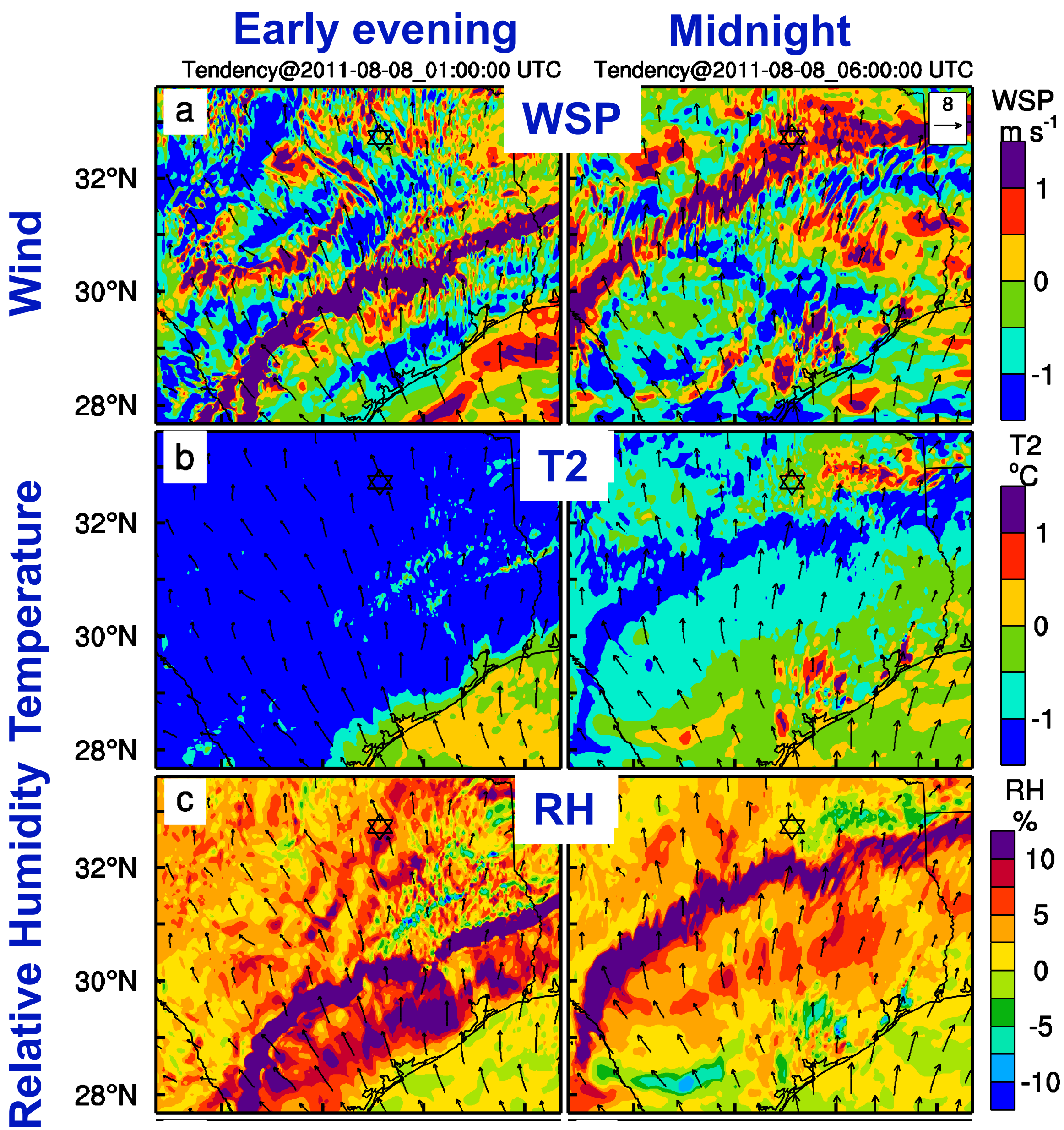
Inland penetration of the sea breeze front





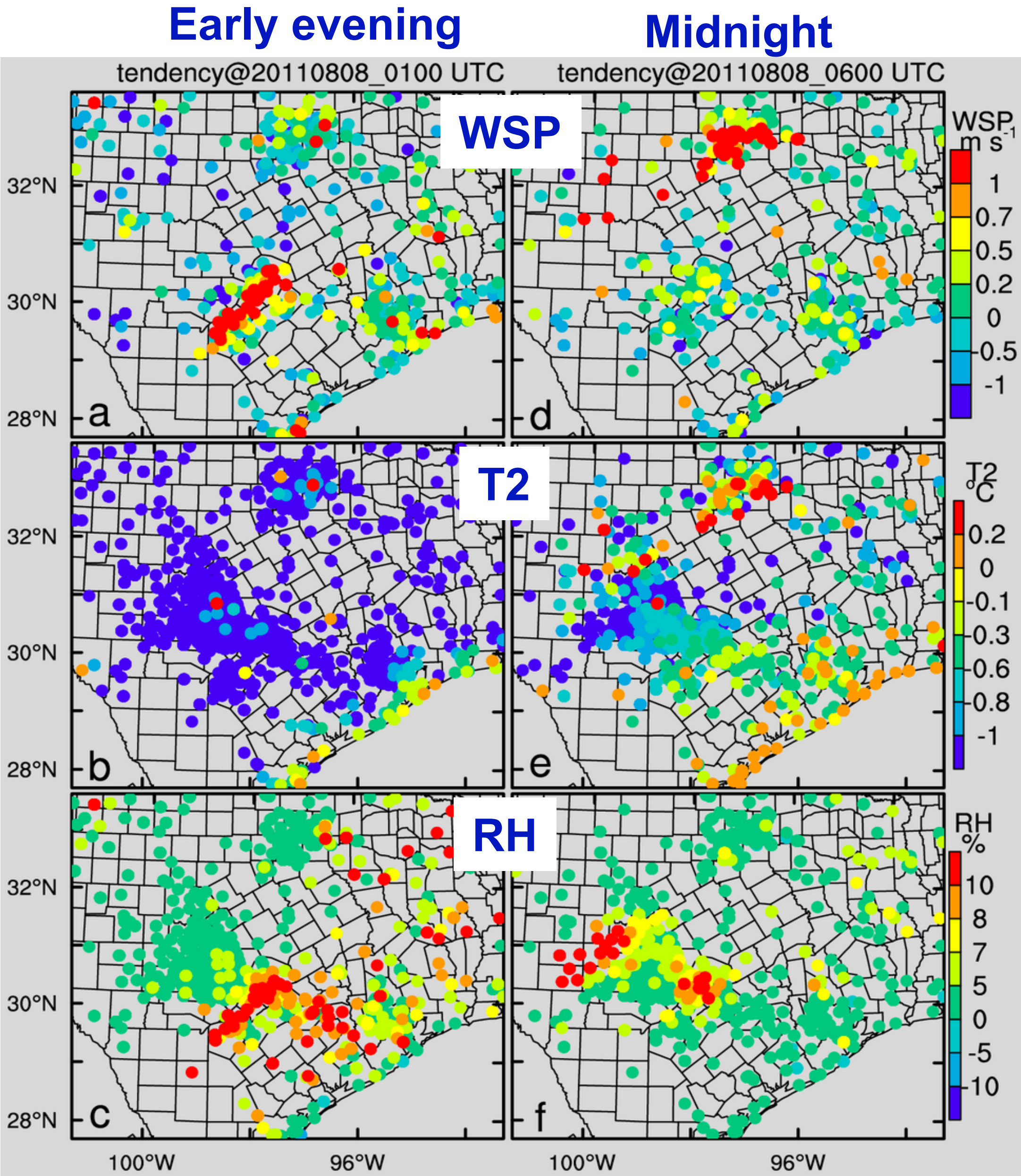
The sea breeze front approached Dallas around midnight (0600 UTC)

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.

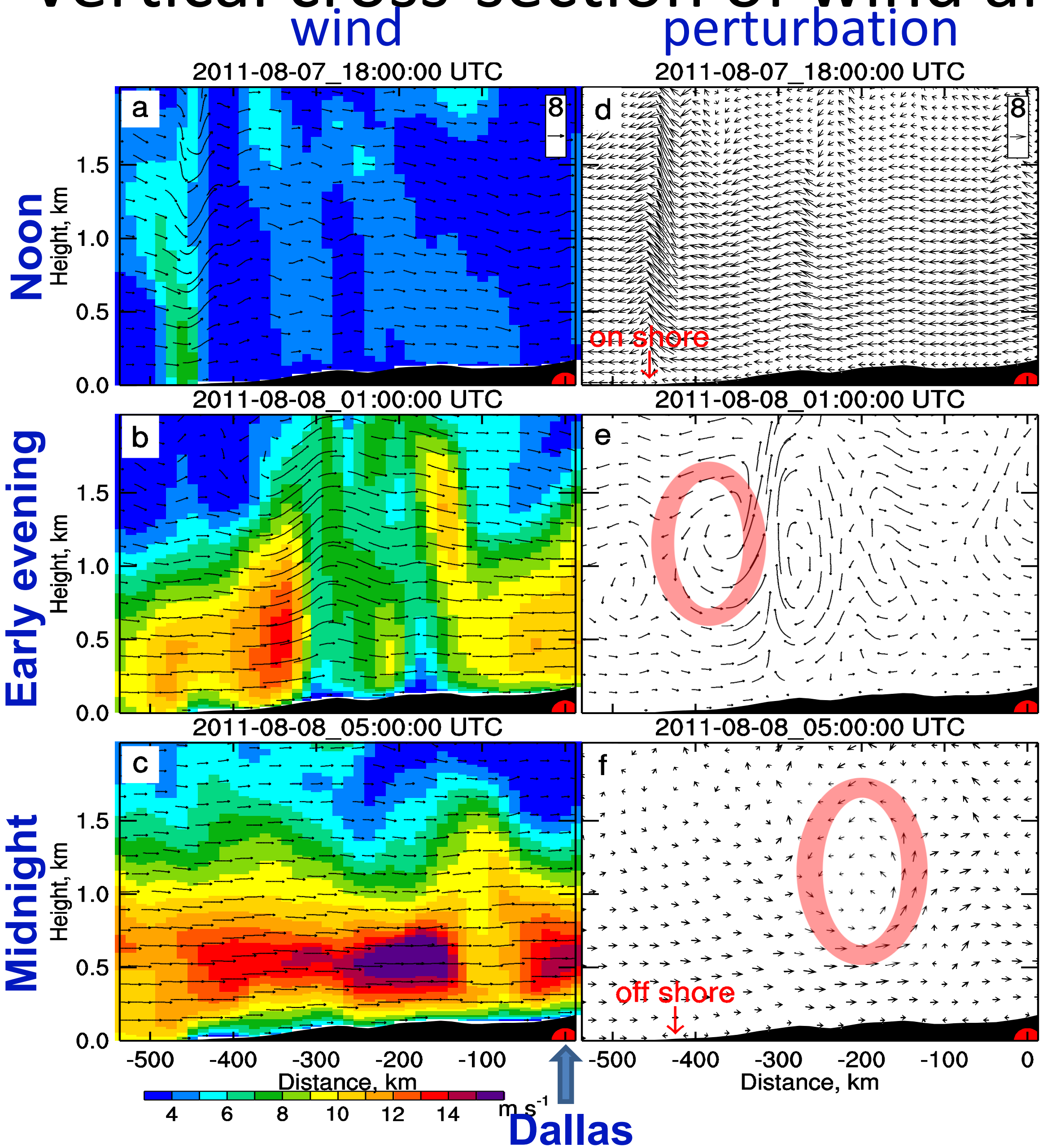
Observed tendency in MADIS data



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.

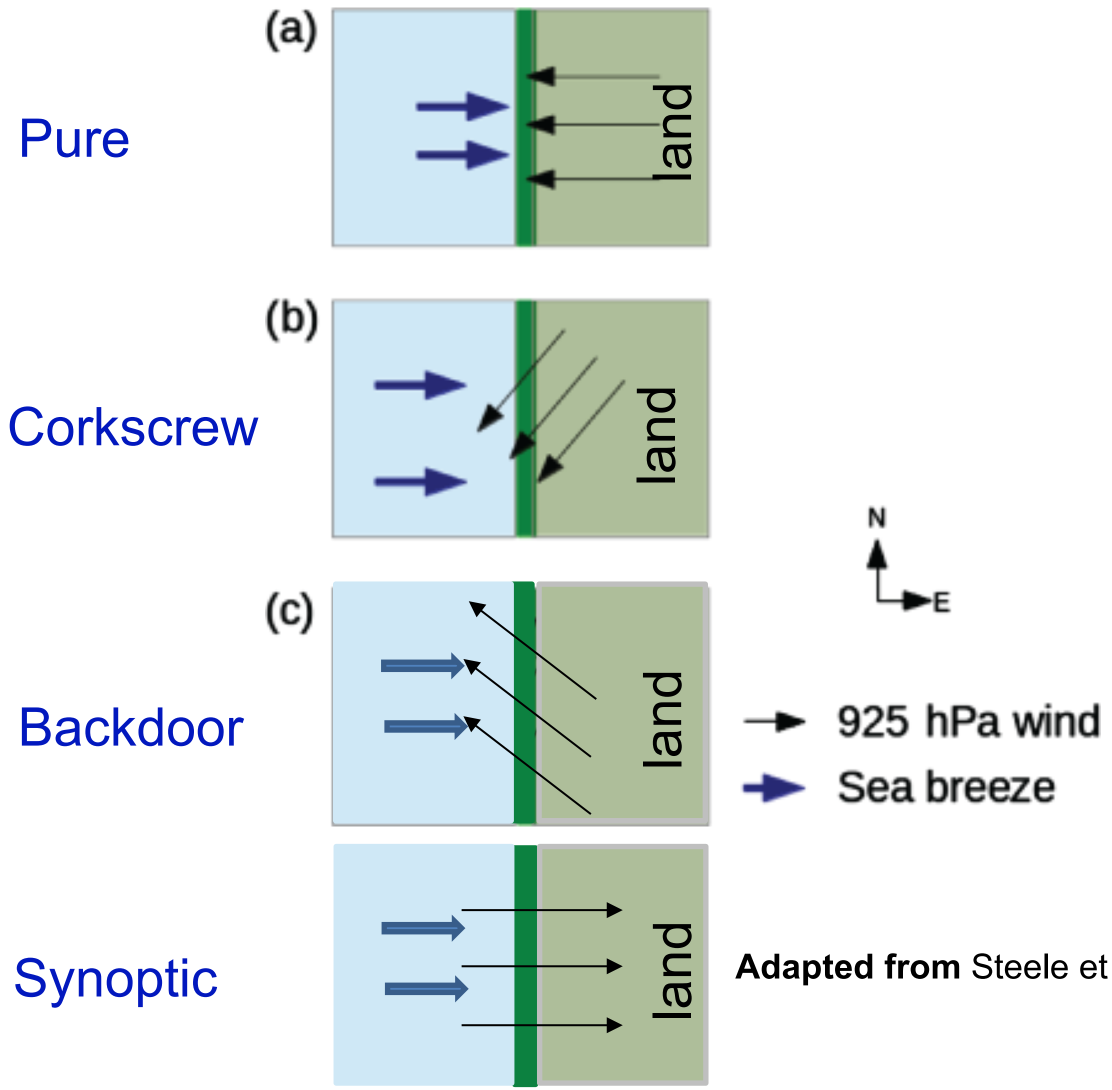
Vertical cross-section of wind and its perturbation



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

Synoptic sea breeze

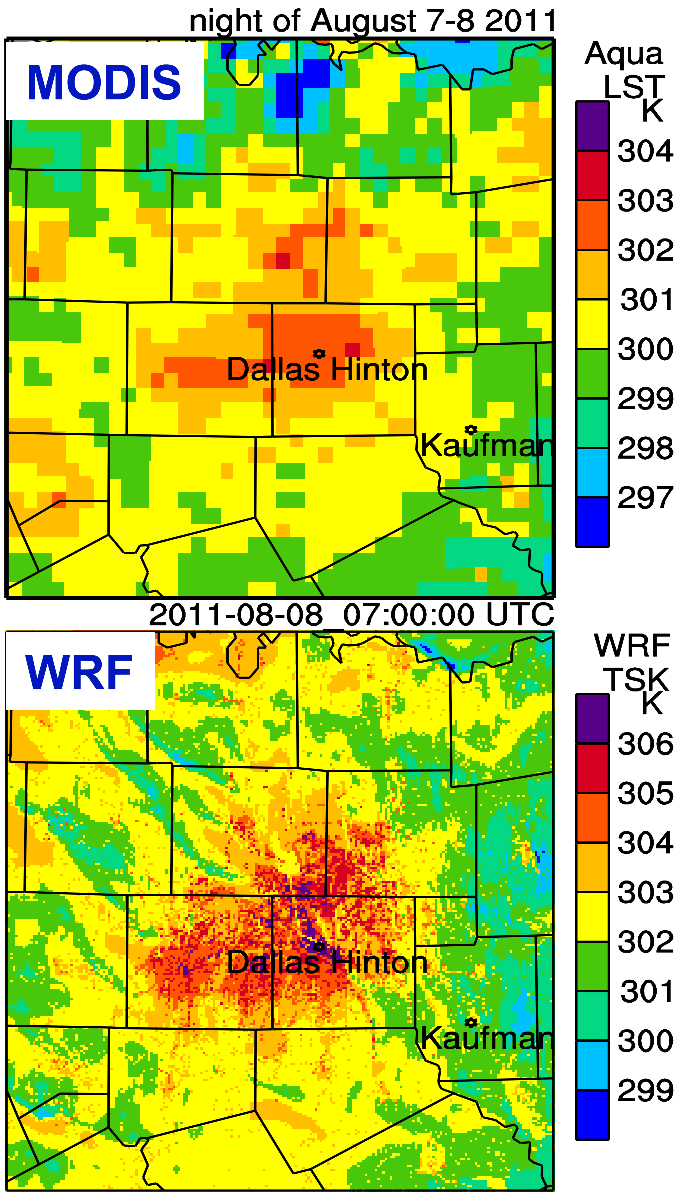
Categories of Sea Breeze

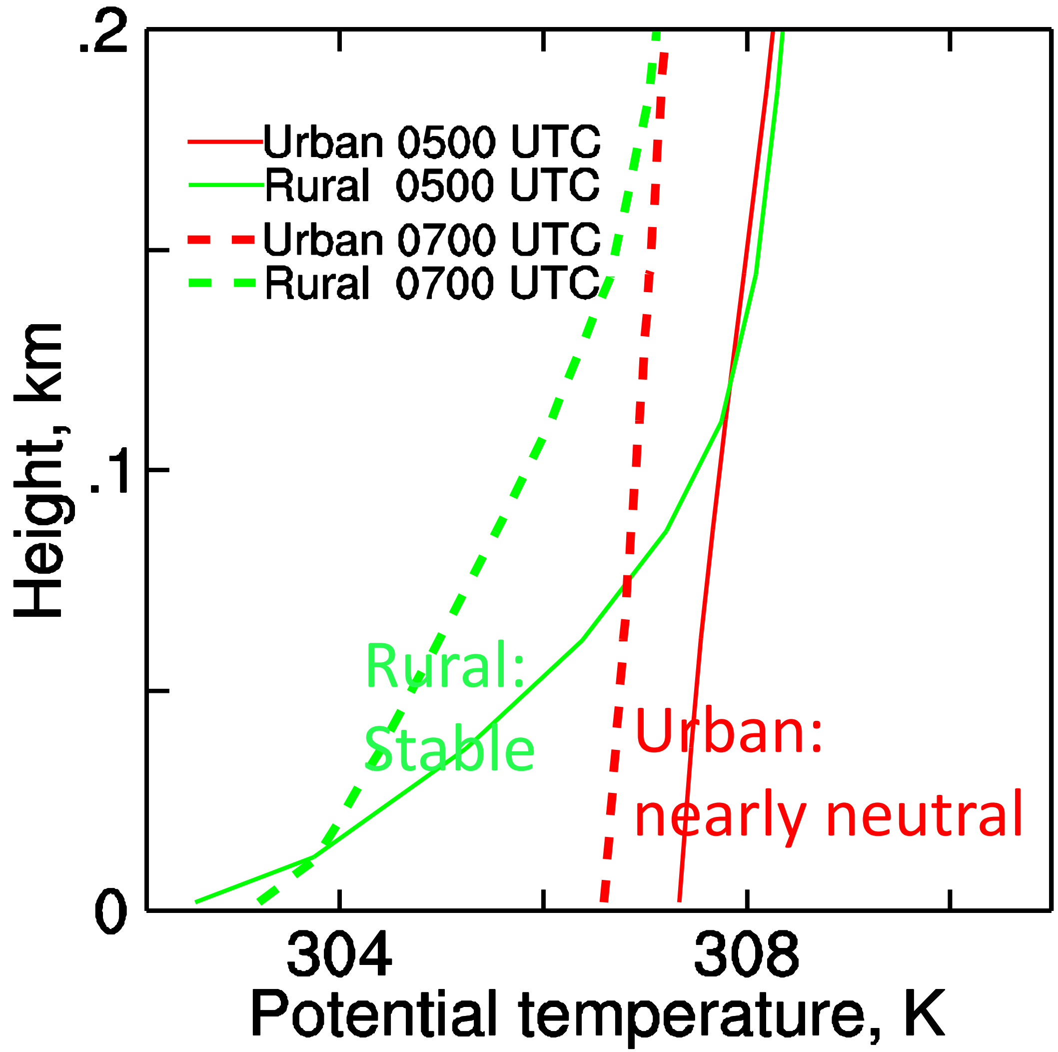


Adapted from Steele et al. (2014, QJ)

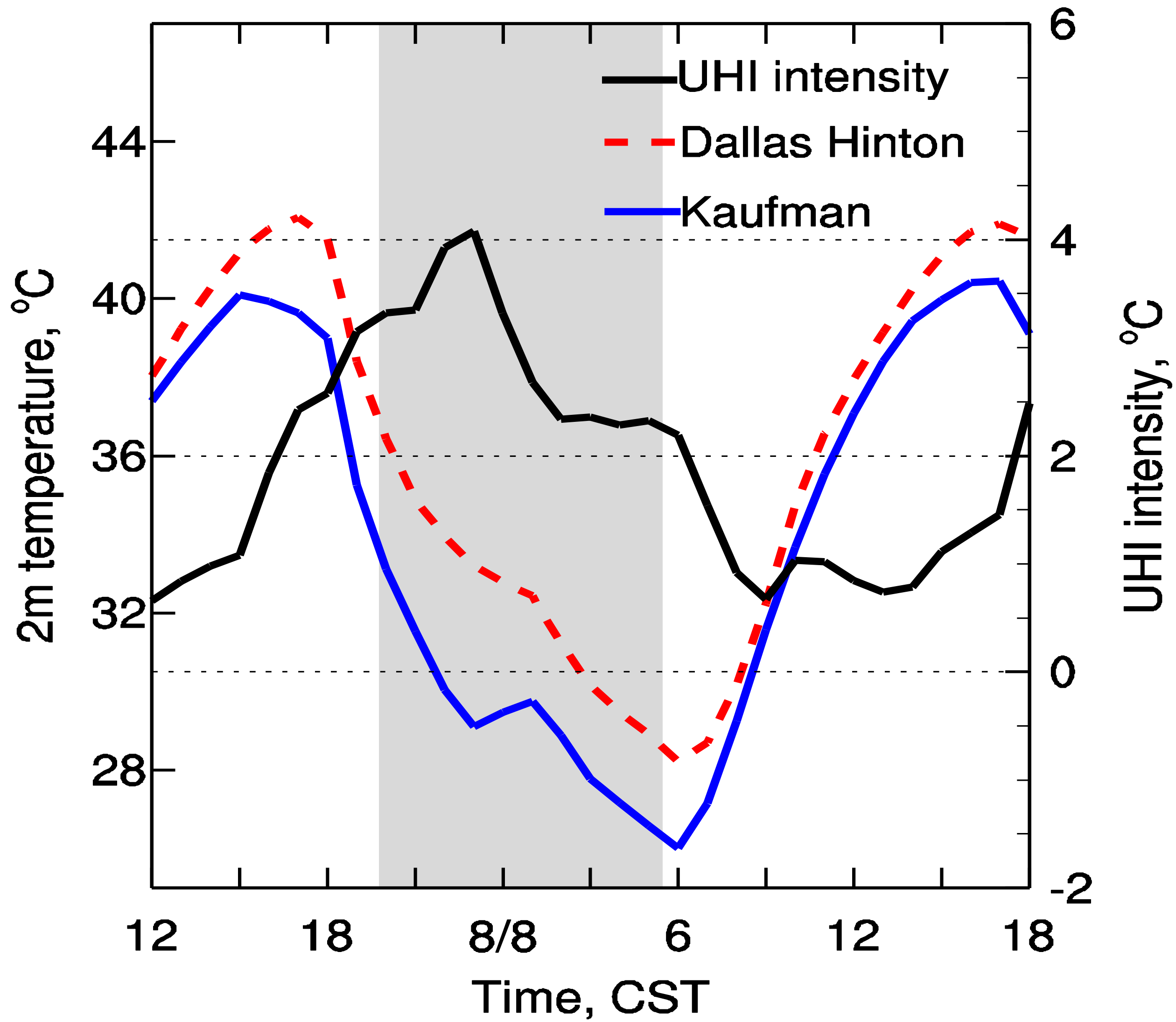
Synoptic sea breezes were less studied previously

Different response to the front in rural and urban



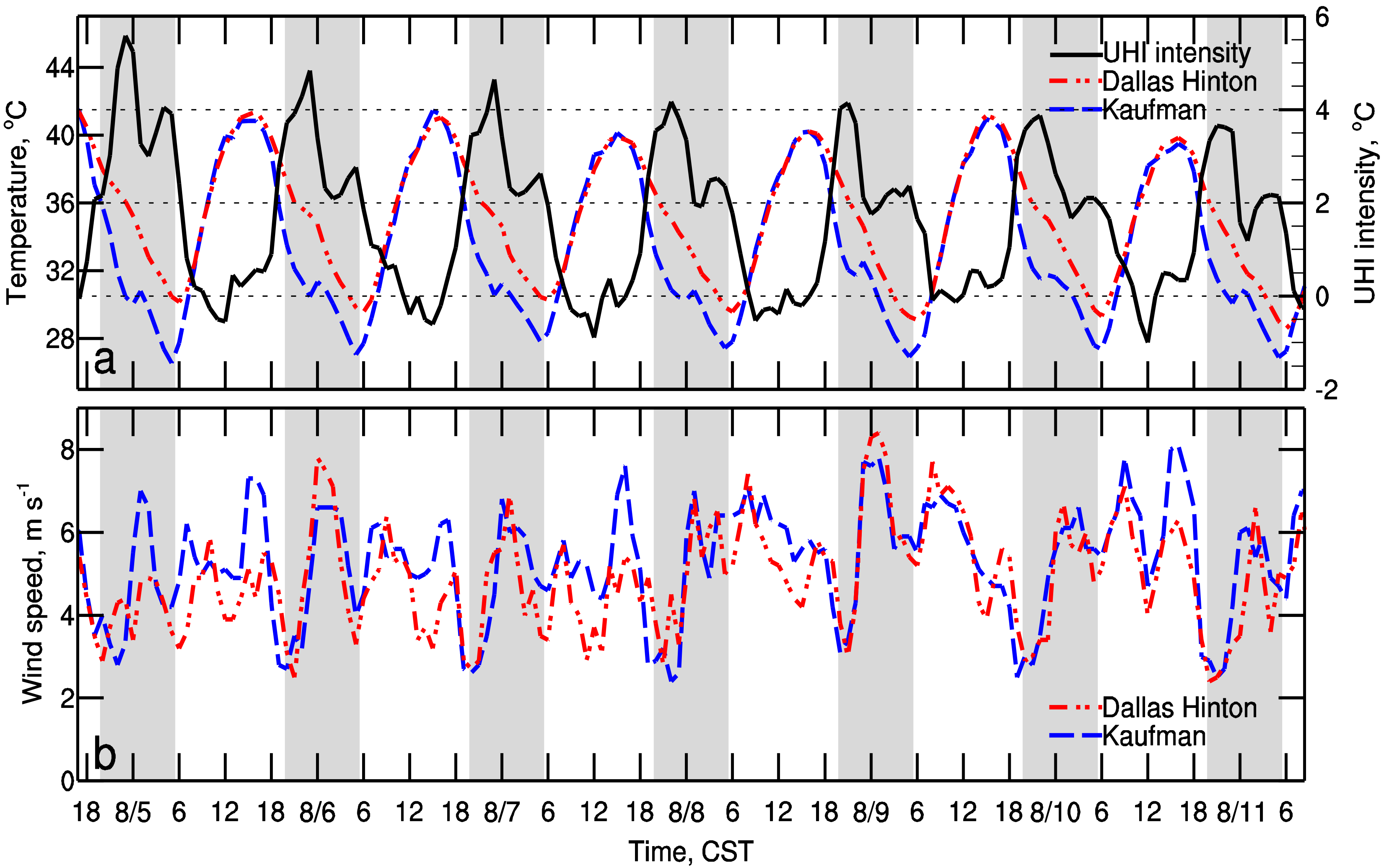


Simulated variation of T, and UHI intensity

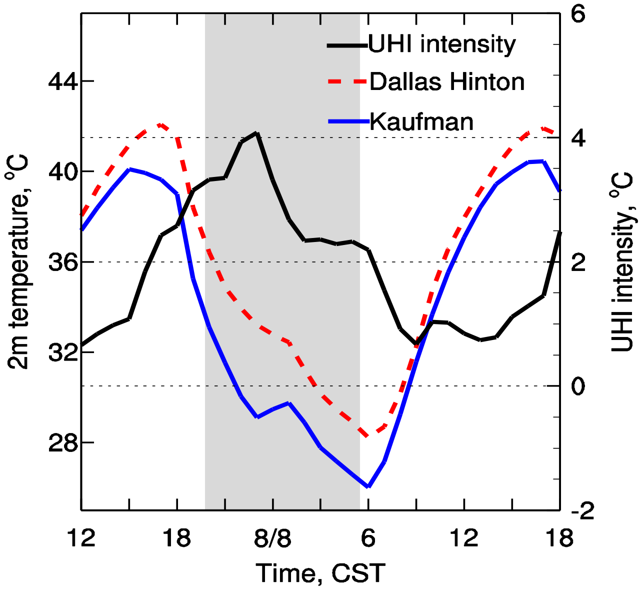


Nocturnal warming in rural and non-warming in urban led to collapse of UHI

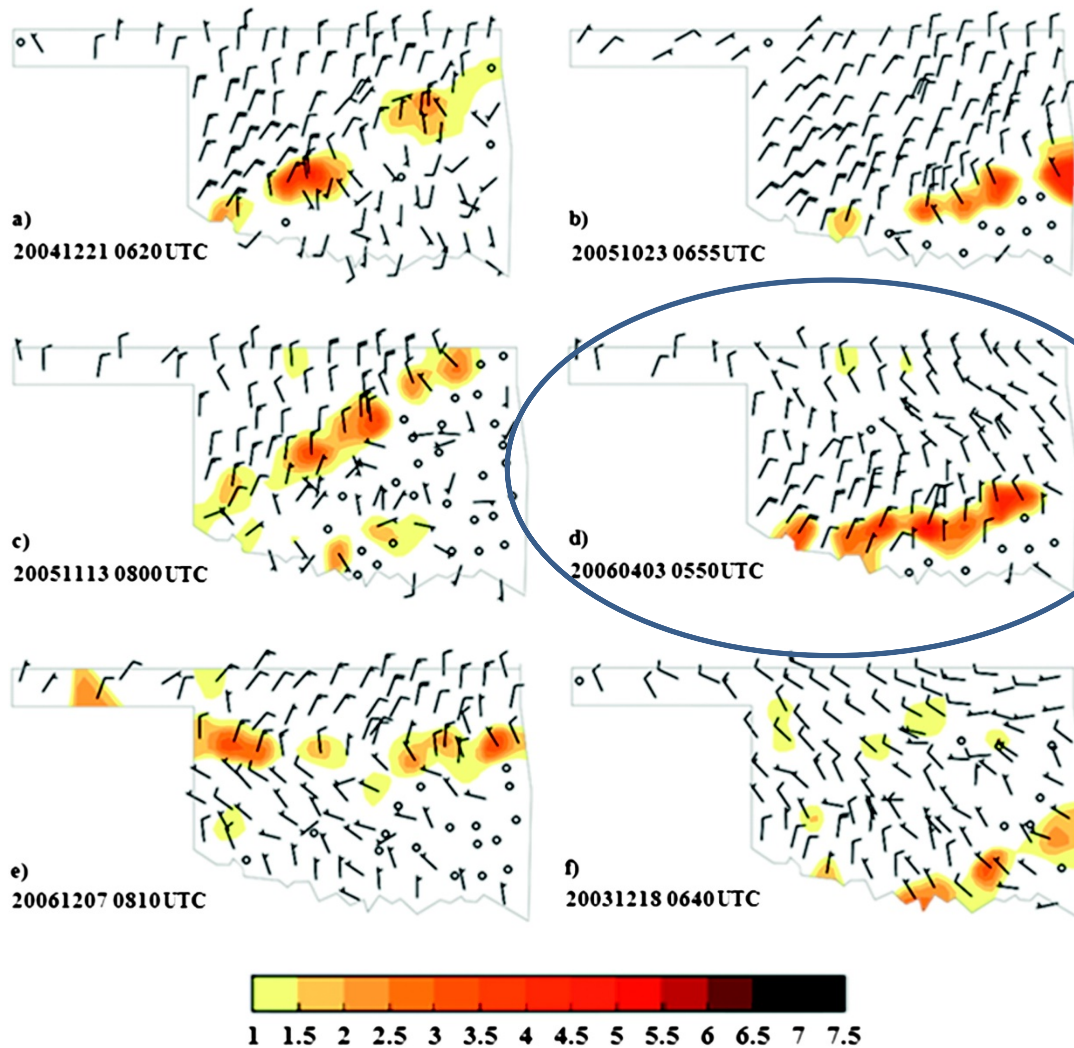
Observed variation of UHI intensity in Dallas



Nocturnal warming events reported previously

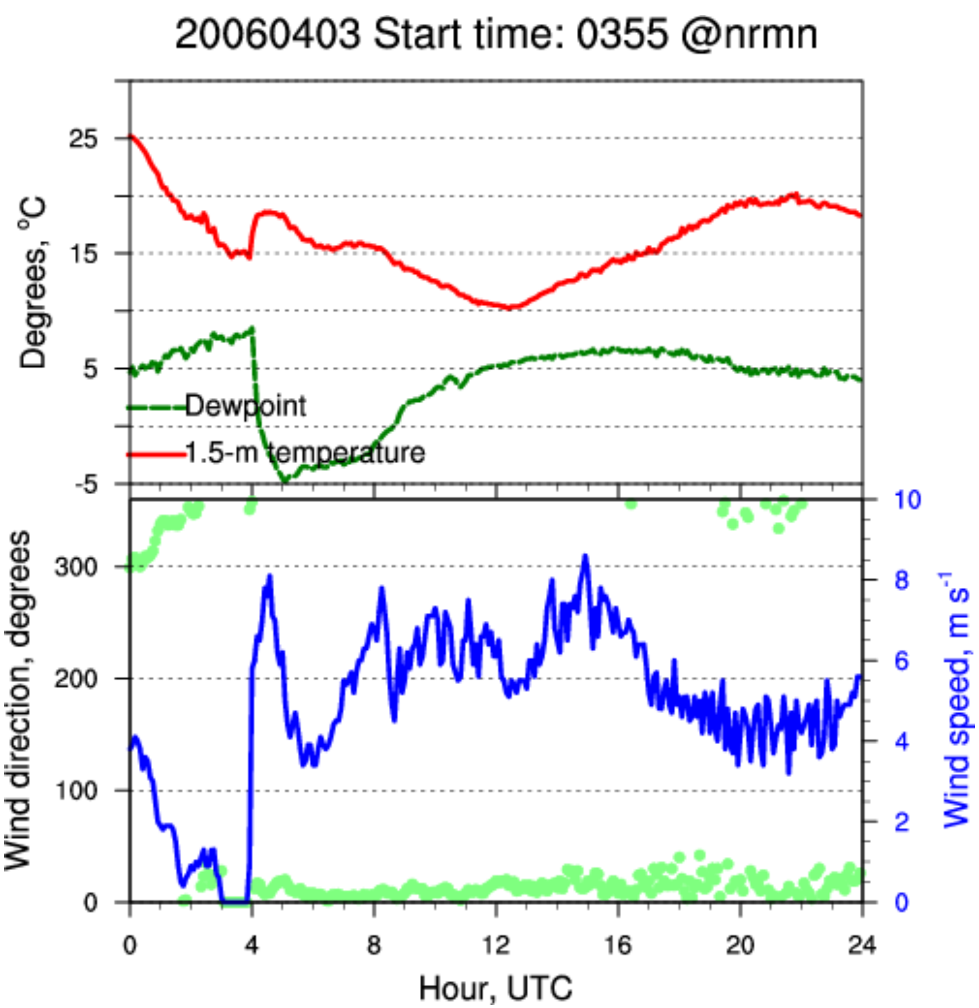


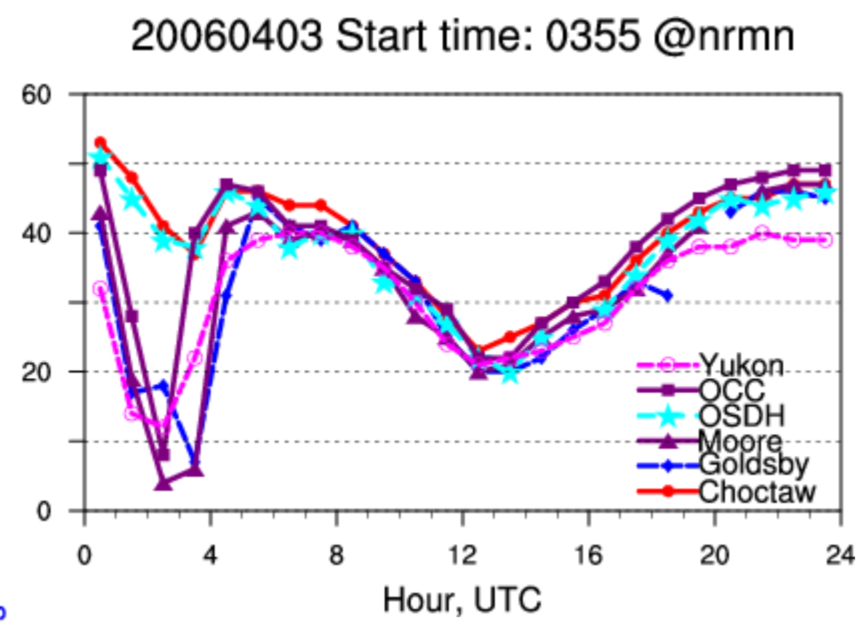
Induced by sea breeze



Induced by **synoptic cold fronts** (Nallapareddy et al., 2011)

Nocturnal warming events and O_3 maximum induced by a cold front





O_3 increased by 40 ppb when the nocturnal warming event occurred (Hu, 2013, JGR)

Conclusions

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

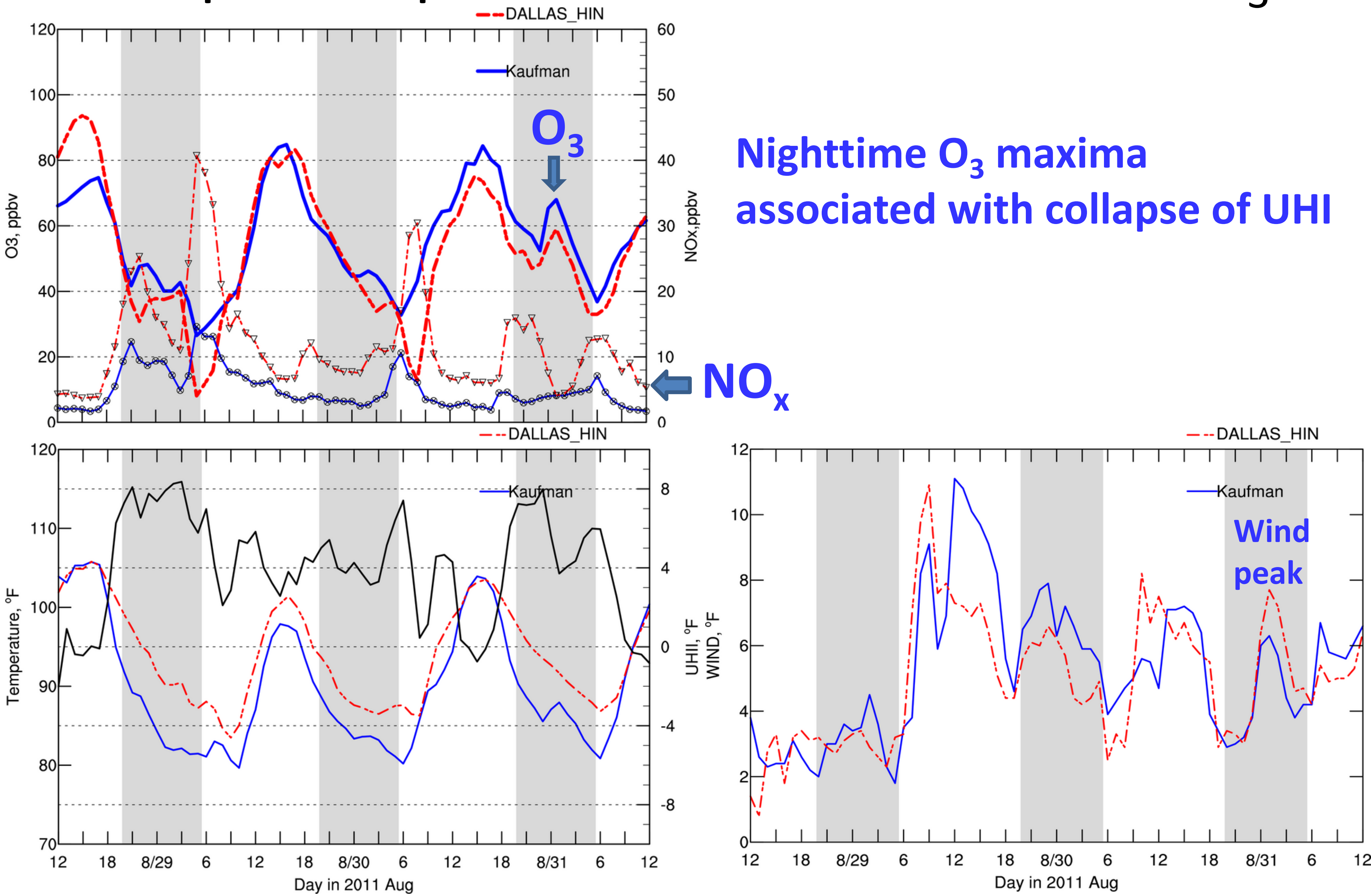
2. Synoptic sea breeze circulation cells can be advected to Dallas and influence its UHI, such a sea breeze category is rarely studied in the past.

Conclusions

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

Nocturnal warming events were reported before, but as a result of synoptic cold fronts. In both cases the mechanism is similar, i.e., enhanced vertical mixing associated with momentum fronts plays a dominant role.

Unique temporal variation of nocturnal O_3



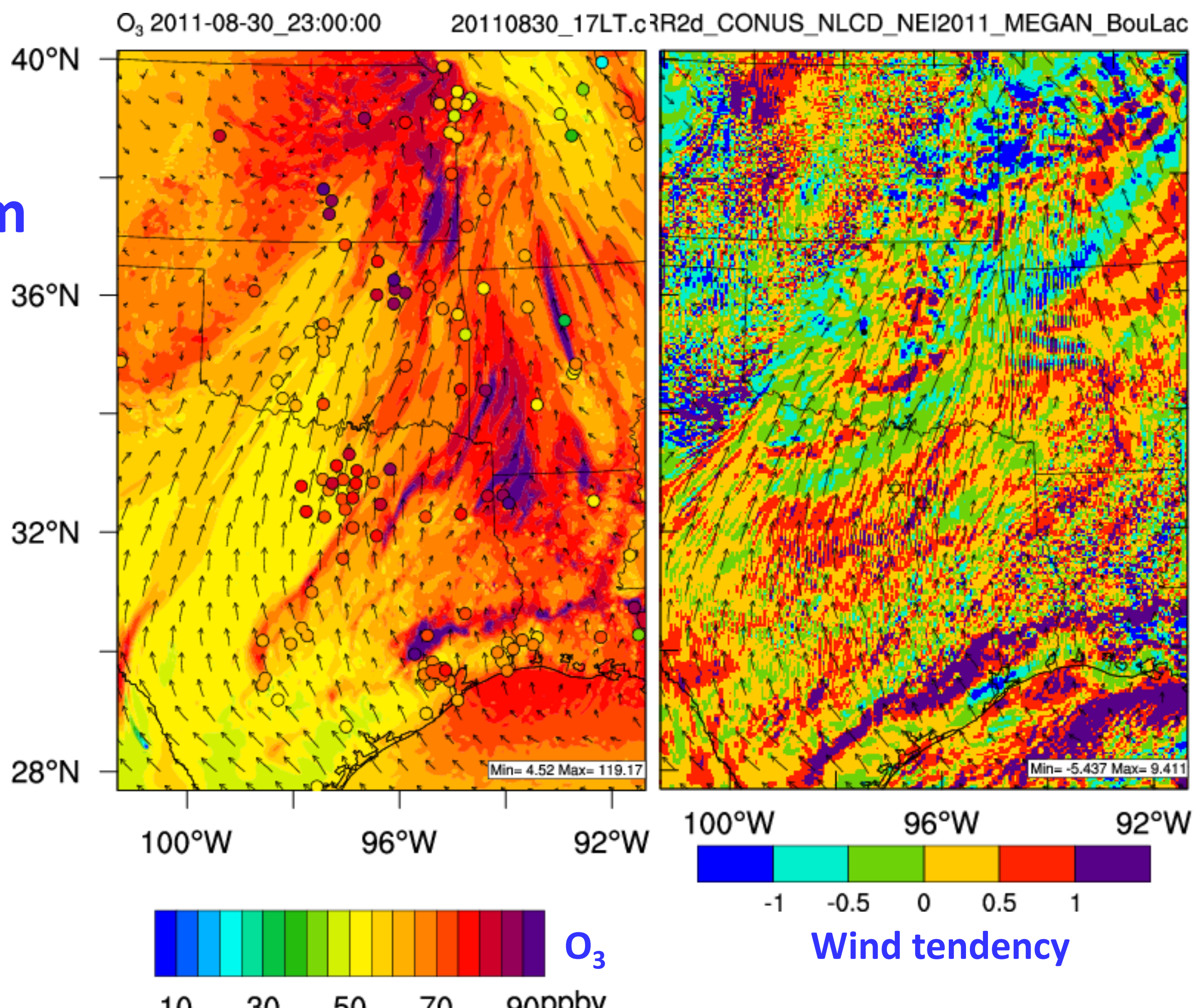
Nighttime O_3 maxima associated with collapse of UHI

Impact of sea breeze fronts on O_3 in the afternoon

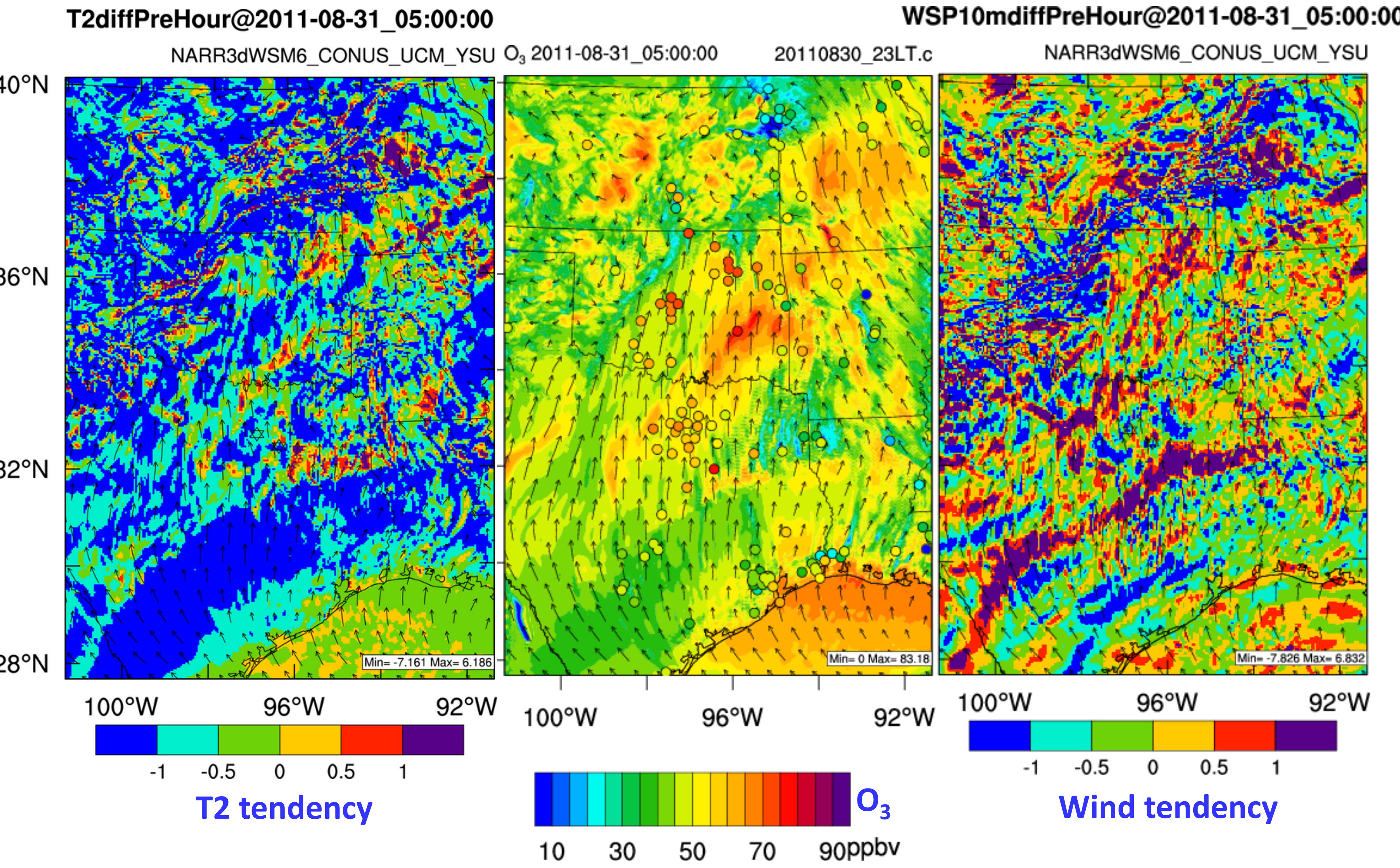
WRF/Chem 3.7

Emission:
NEI2011
MEGAN

IC/BC:
NARR



Impact of sea breeze front on O_3 at night

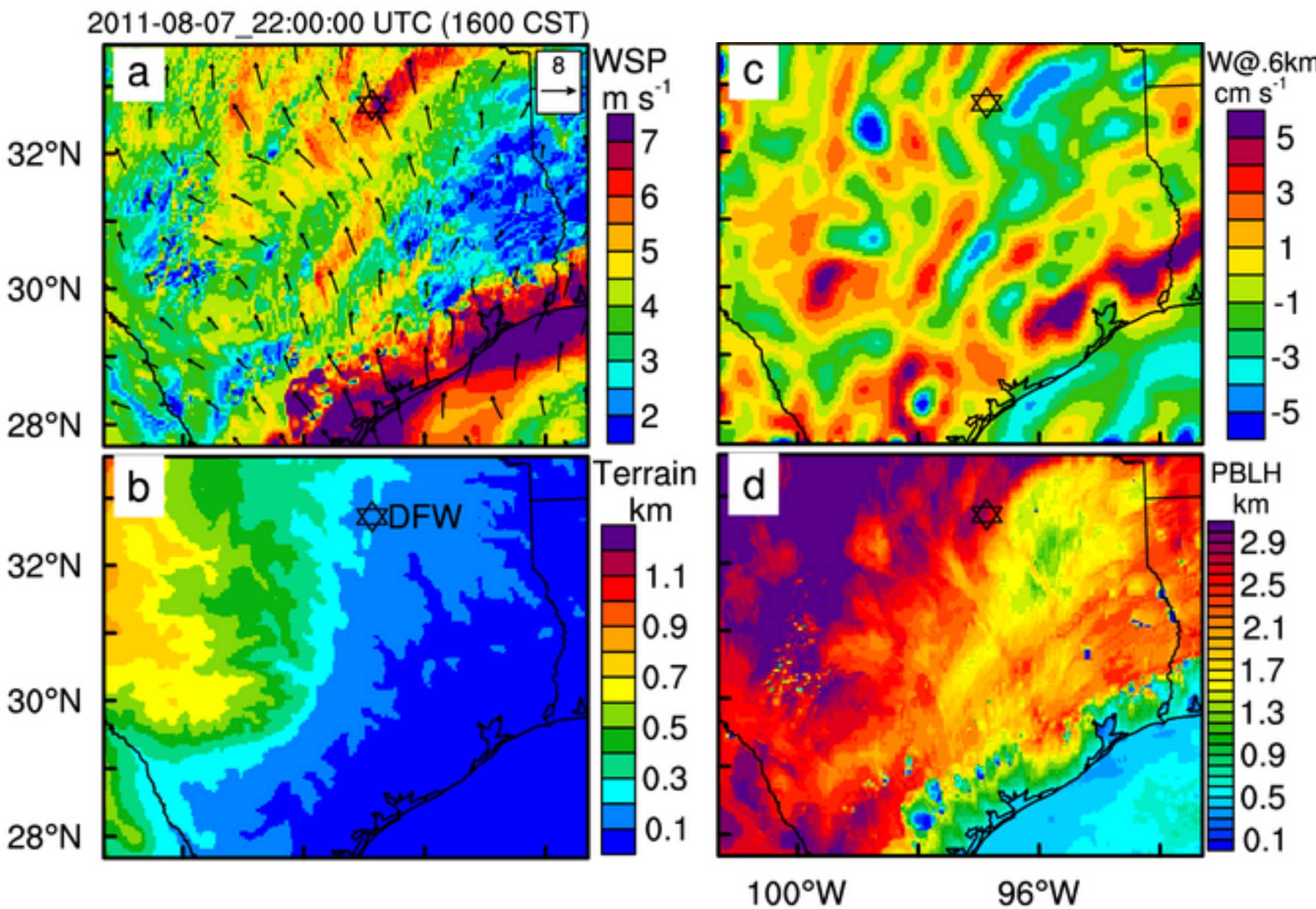


1. **Boundary layer processes in Texas**
2. **Boundary layer processes in NCP induced by Terrains**
    - Thermal (active*) effect
    - Dynamic (passive) effect

Mountain-Plain Solenoid induced wind maximum band?

Wind speed

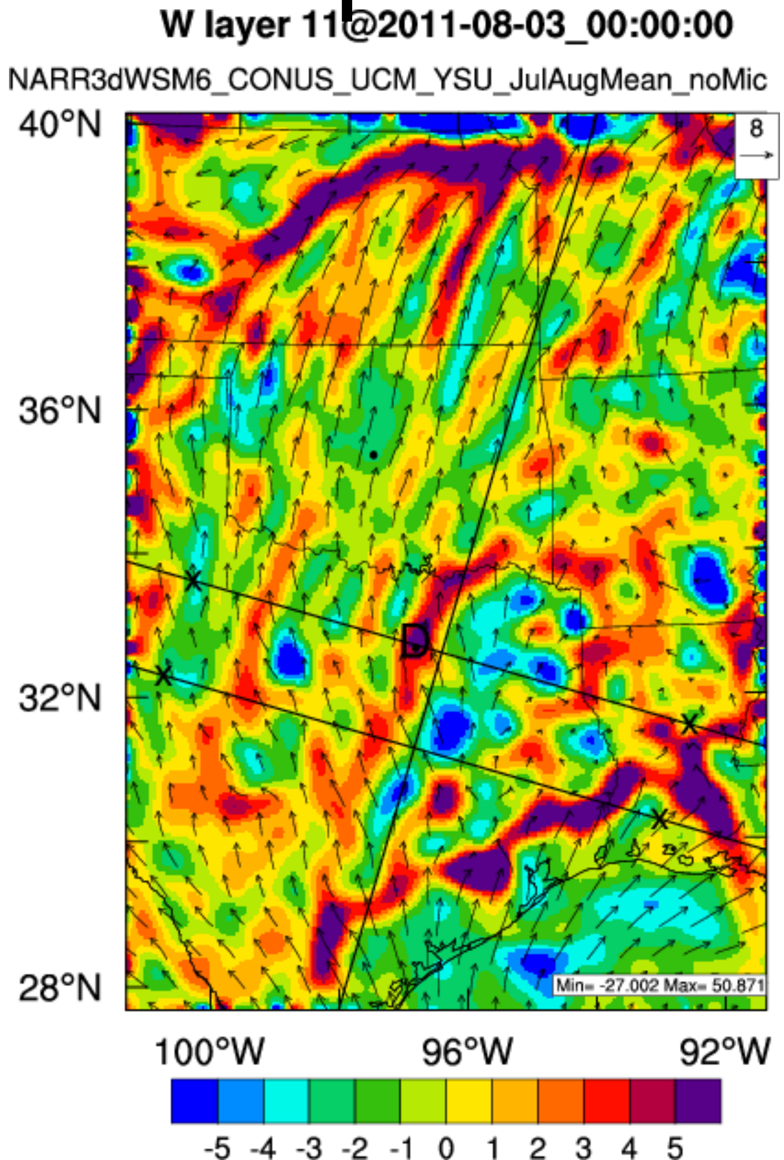
Terrain height

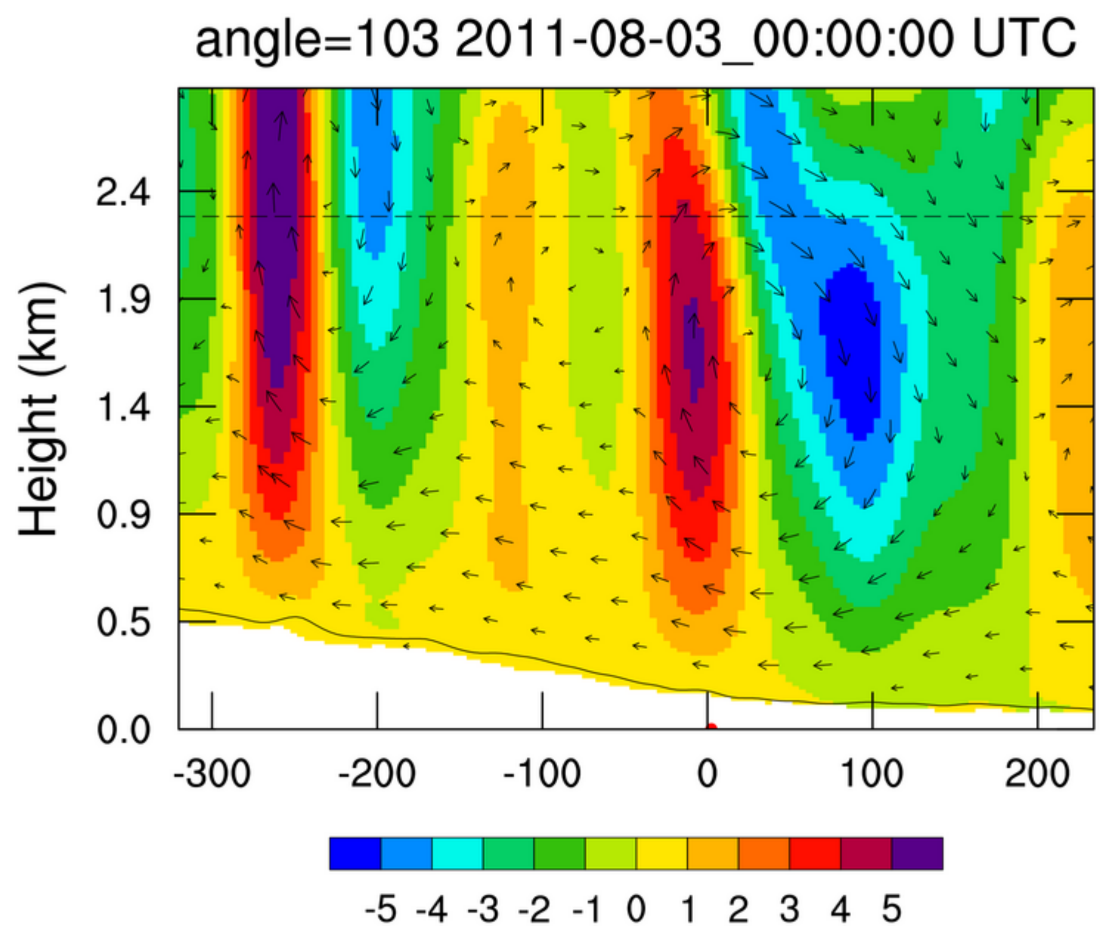


Vertical velocity

PBLH

Mountain-Plain Solenoid was prominent in Aug. 2011



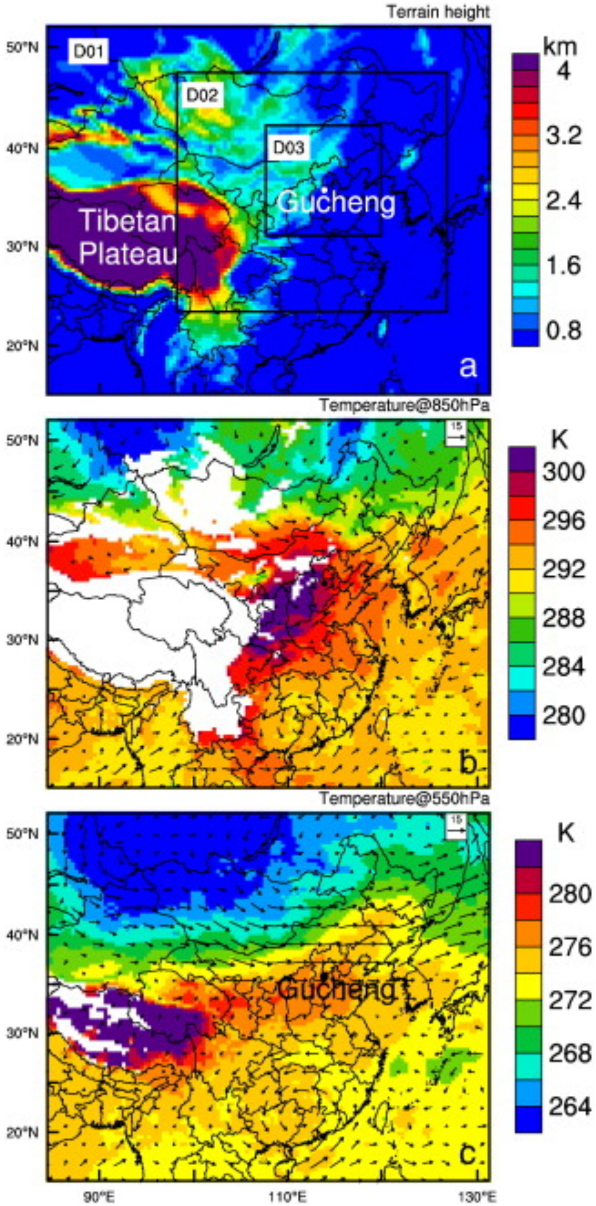


Similar as North China Plain?

Terrain height

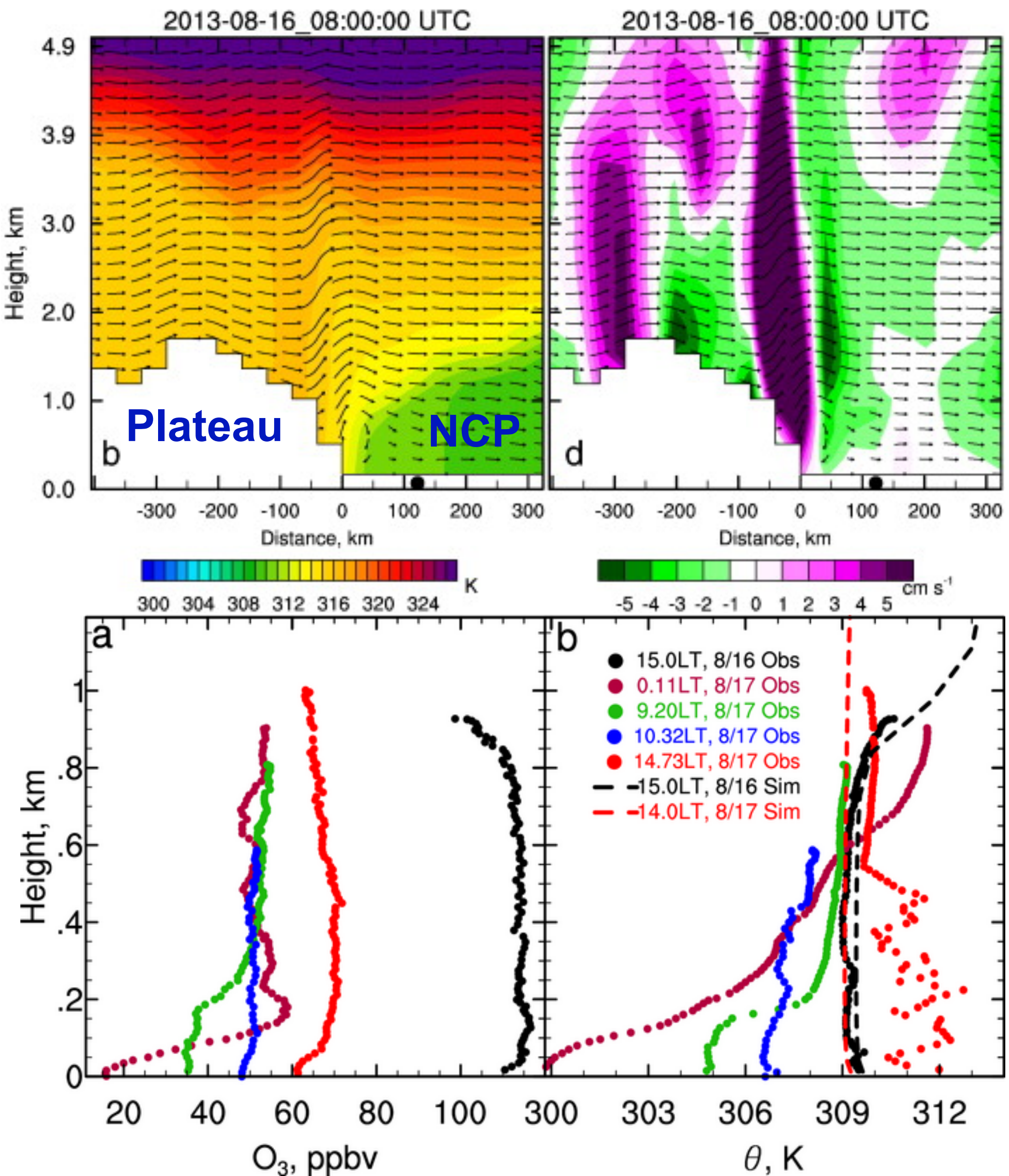
T@850hPa

T@550hPa



The Plateau acts as a heated source in Summer (Hu et al., 2014, STE)

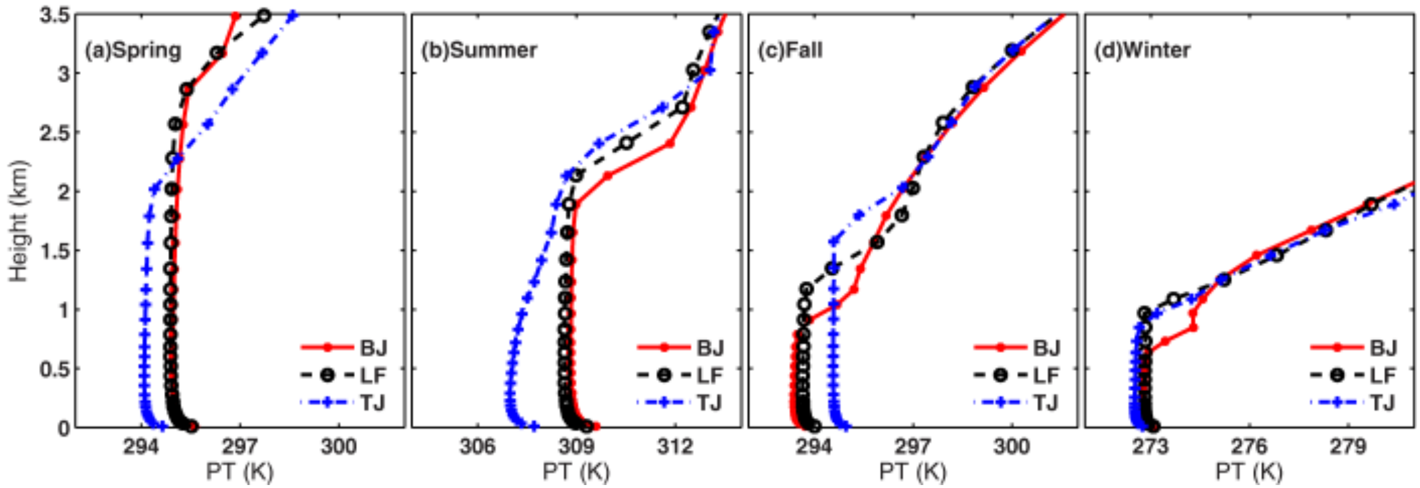
Impact of Mountain-Plain solenoid on boundary layer

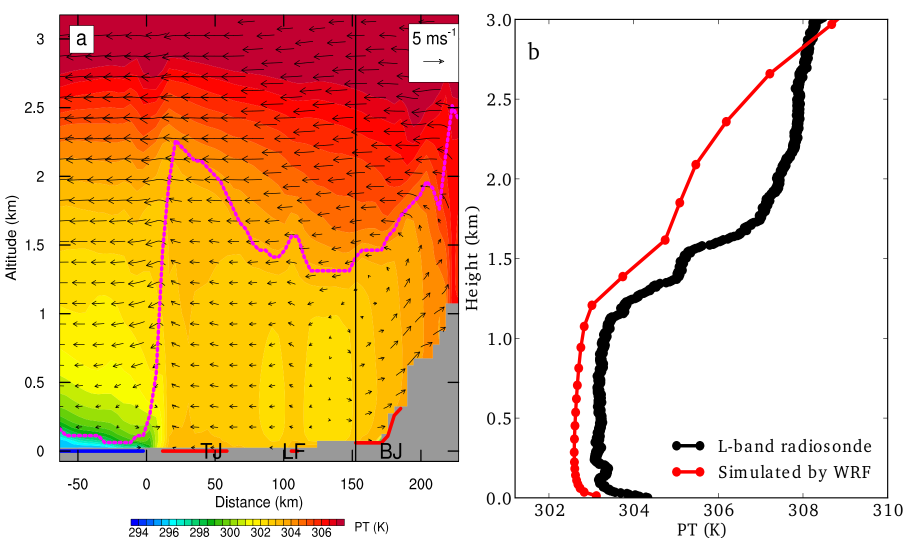


Mountain-Plain solenoid suppress boundary layer development and enhance air pollution (Hu et al., 2014, STE)

Impact of thermal effects on boundary layer

Seasonal study for the Beijing-Tianjin-Hebei region





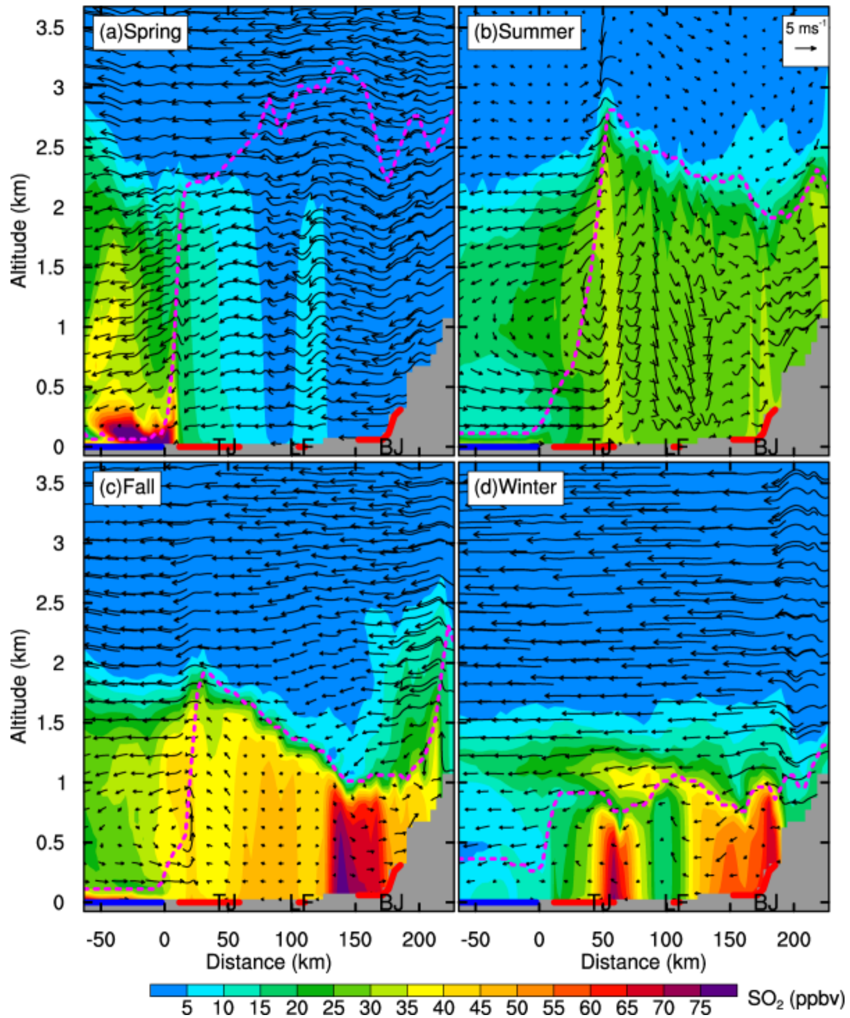
Thermal effects of Plateau partially lead to PBL height spring > summer > fall > winter

Miao and Hu et al. (2015, *JAMES*)

12 September 2010 simulated by WRF and observed by the L-band radiosonde.

Impact of thermal effects

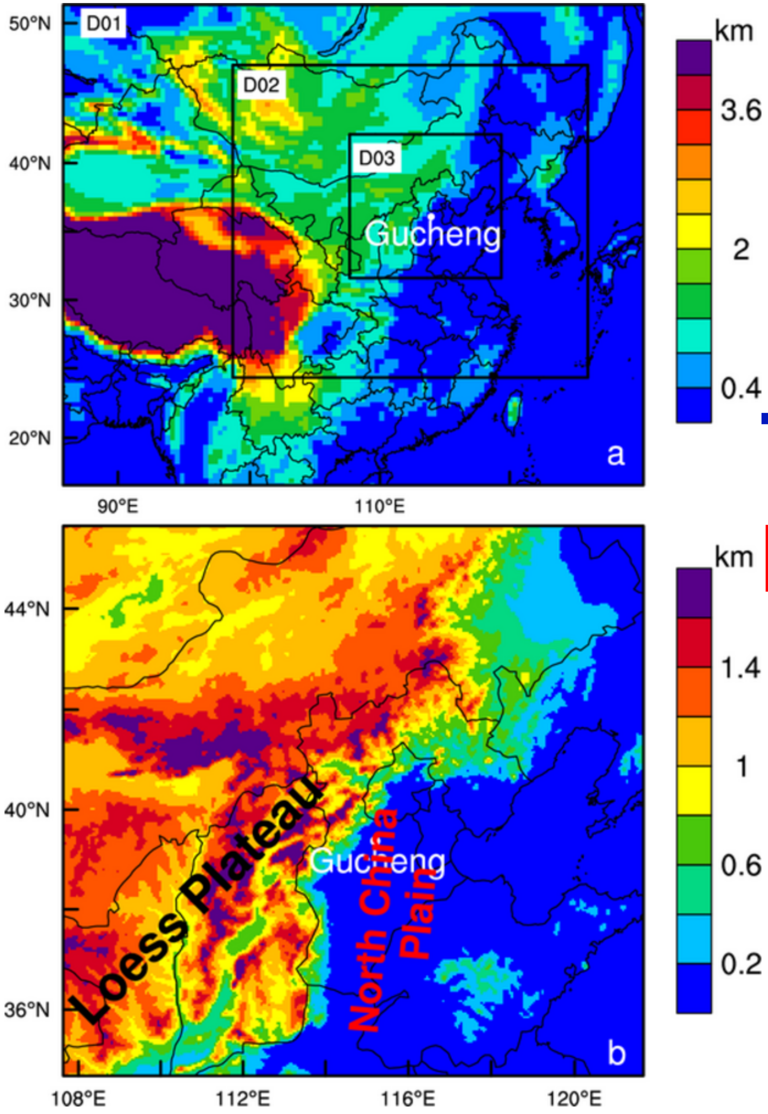
Seasonal variation of pollutants in the boundary layer



Thermal effects of Plateau partially lead to frequent haze events in Fall and Winter

Miao and Hu et al. (2015, *JAMES*)

Effects of Loess Plateau: part 2



Thermal (active*) effect

Dynamic (passive) effect

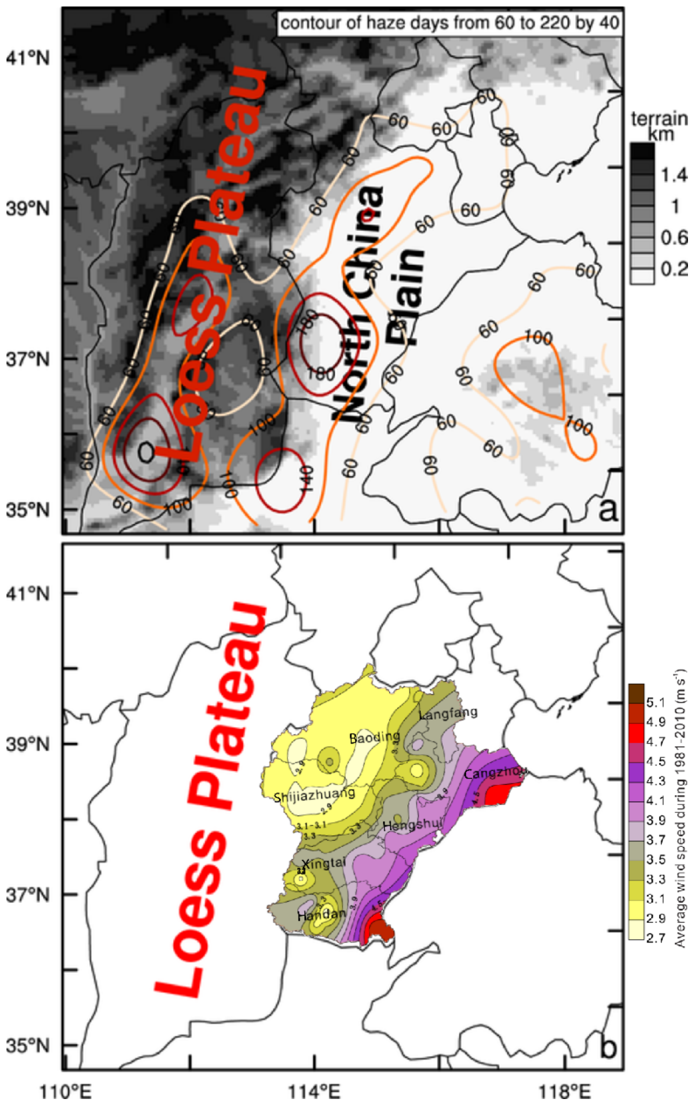
Dynamic effect of Loess Plateau

Hu, Li and Xue (2016a, BLM)*

- –**Identify the dynamic effects of Loess Plateau**
- –**Investigate the impact of such effects on air quality in the North China Plain (NCP)**

*Hu, X.-M., et al. (2016a), The Formation of Barrier Winds East of the Loess Plateau and their Effects on Dispersion Conditions in the North China Plains, *Bound.-layer meteor.*, DOI:10.1007/s10546-016-0159-4 .

Spatial distribution of haze days & wind speed



Weak winds in the west of NCP (Fu et al. 2014) **lead to** more frequent haze events in this region (Wu et al. 2014)

Fu GQ et al. (2014) The distribution and trends of fog and haze in the North China Plain over the past 30 years. Atmos Chem Phys 14:11949–11958.

Hu, X.-M., et al. (2016), The Formation of Barrier Winds East of the Loess Plateau and their Effects on Dispersion Conditions in the North China Plains, *Bound.-layer meteor.*, DOI:10.1007/s10546-016-0159-4 .

Wu D et al. (2014) The long-term trend of haze and fog days and the surface layer transport conditions under haze weather in North China. Acta Sci Circumst 34:1–11

Develop a slab model to simulate winds in NCP

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} + fv - g\frac{\partial h}{\partial x} - \phi_x \,, \qquad (1)$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - fu - g\frac{\partial h}{\partial y} - \phi_y \,, \qquad (2)$$

$$h = -\tau H\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right), \qquad (3)$$

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} - v\frac{\partial C}{\partial y}\,, \qquad (4)$$

C is the concentration of a passive pollutant

$H \approx 1$ km

h is the perturbation height of the layer top,

representing the pressure perturbation caused by mountain blocking and subsequent flow rising

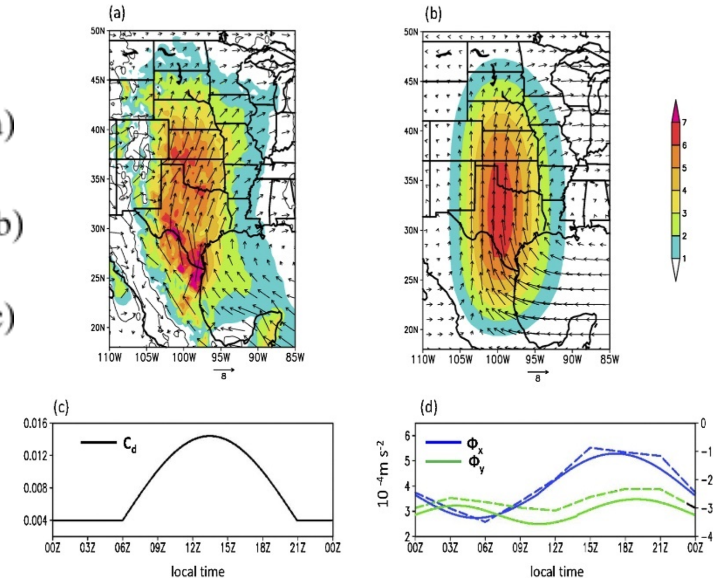
A slab model based on Pu and Dickinson (2014)

Pu and Dickinson (2014, JAS)

$$\frac{\partial u}{\partial t} = fv - g\frac{\partial h'}{\partial x} - \varepsilon u - \phi_x, \quad (1a)$$

$$\frac{\partial v}{\partial t} = -fu - g\frac{\partial h'}{\partial y} - \varepsilon v - \phi_y, \quad (1b)$$

$$h' = -\tau H\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right), \quad (1c)$$



Hu (2016, BLM)

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} + fv - g\frac{\partial h}{\partial x} - \phi_x, \quad (1)$$

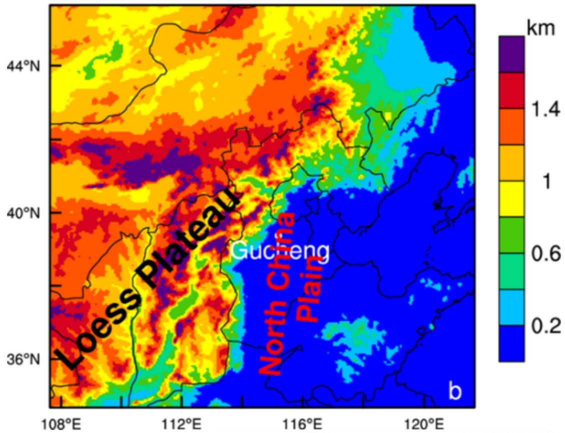
$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - fu - g\frac{\partial h}{\partial y} - \phi_y, \quad (2)$$

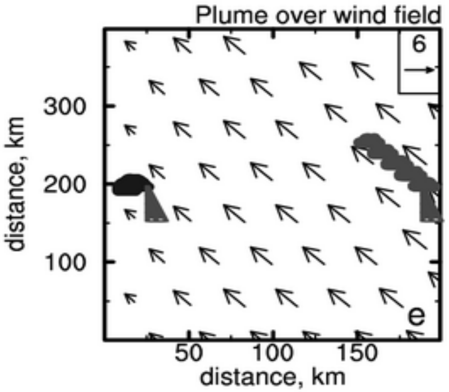
$$h = -\tau H\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right), \quad (3)$$

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} - v\frac{\partial C}{\partial y}, \quad (4)$$

1. Removed friction
2. Added advection
3. Added pollutants

Model configuration of the slab model





$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} + fv - g\frac{\partial h}{\partial x} - \phi_x\,, \qquad (1)$$

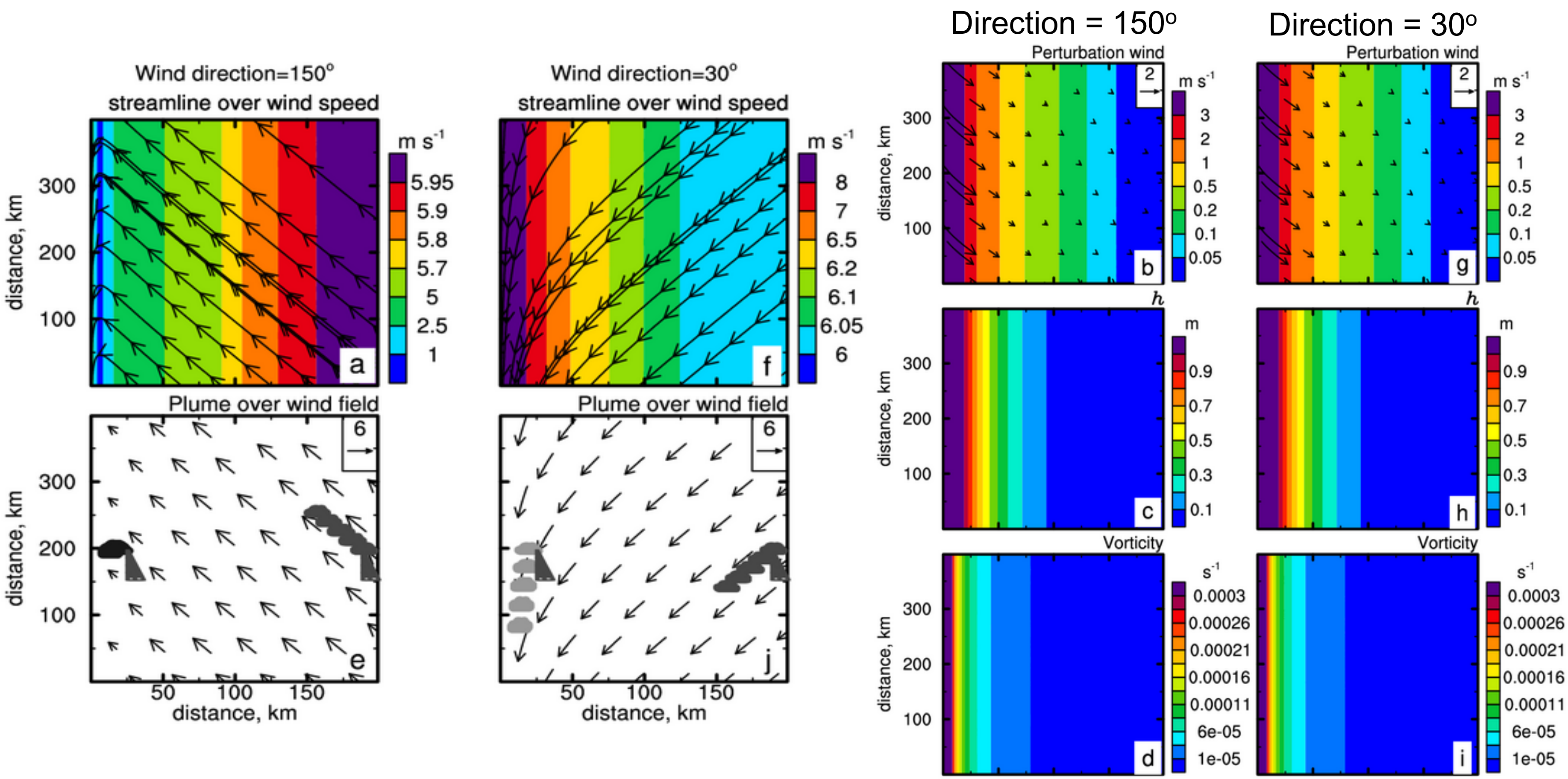
$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - fu - g\frac{\partial h}{\partial y} - \phi_y\,, \qquad (2)$$

$$h = -\tau H\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right), \qquad (3)$$

$$\frac{\partial C}{\partial t} = -u\frac{\partial C}{\partial x} - v\frac{\partial C}{\partial y}\,, \qquad (4)$$

Domain: 400kmx400km
Boundary condition: slip-wall in west boundary
open condition in east
Ambient wind: 150^{o}C (southeasterly)
30^{o}C (northeasterly)
Geopotential gradient: constant

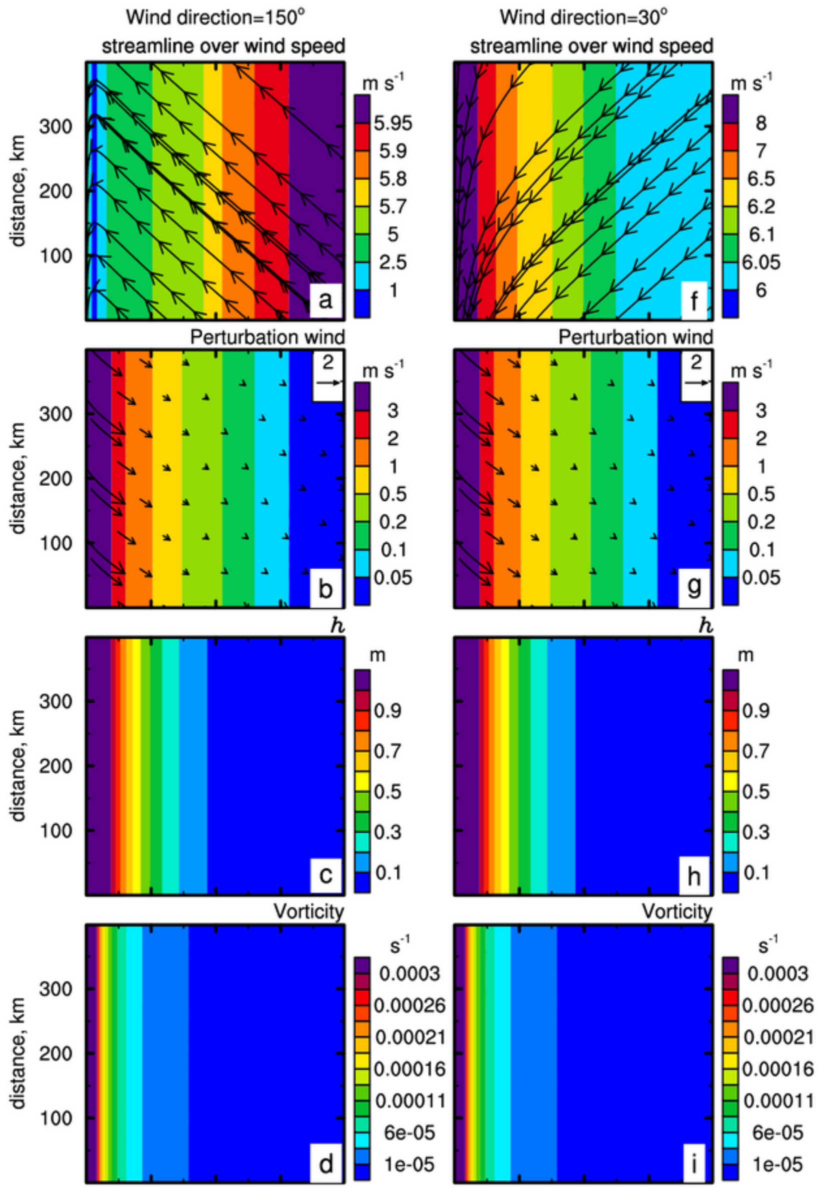
Simulated winds in NCP under 2 conditions



Same perturbation winds lead to different spatial distribution of wind speed.

- **Weak wind region for 150°C, leading to poor dispersion!**
- Barrier jet for 30°C, good dispersion!

Use vorticity budget to explain cyclonic turning of wind



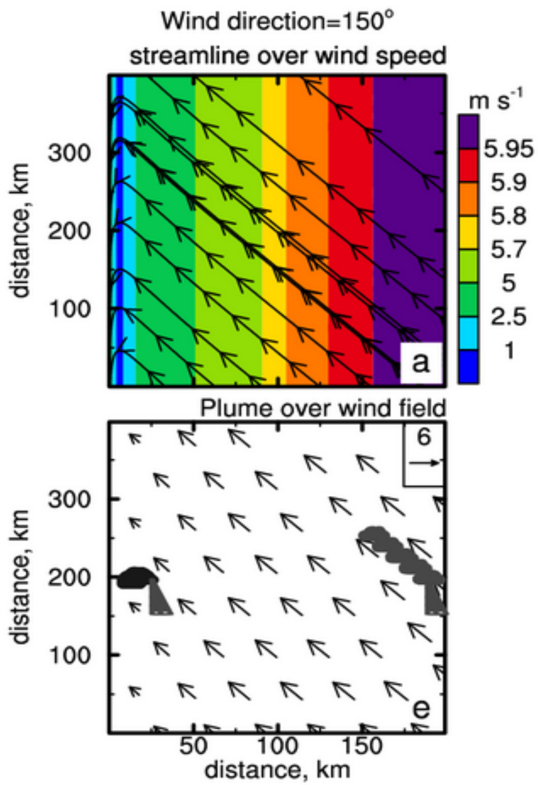
$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} + fv - g\frac{\partial h}{\partial x} - \phi_x\,, \quad (1)$$

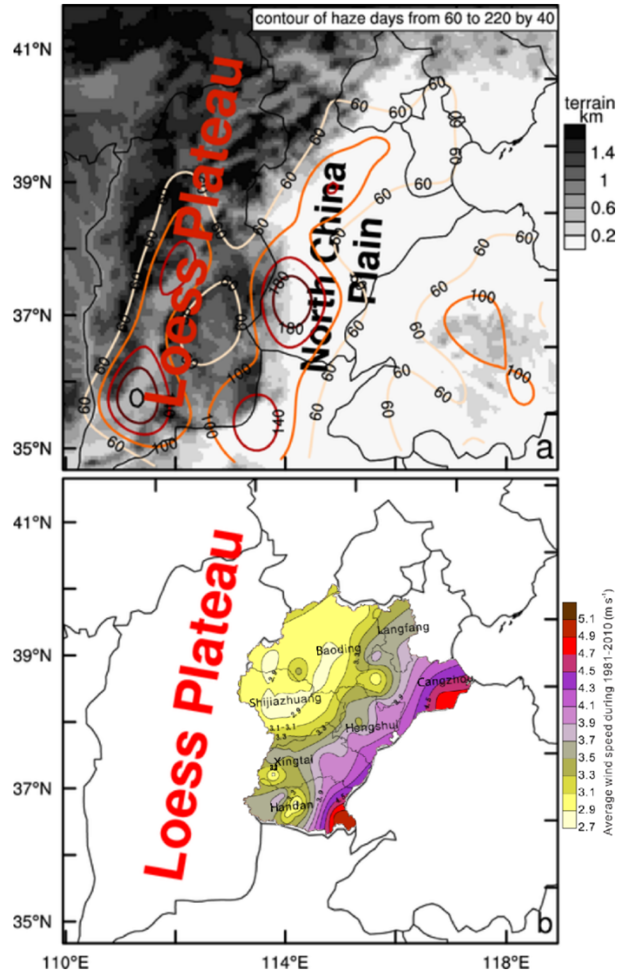
$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - fu - g\frac{\partial h}{\partial y} - \phi_y\,, \quad (2)$$

Taking $\partial/\partial x$ of Eq. 2 and subtracting $\partial/\partial y$ of Eq. 1 gives the rate of relative vorticity

$$\frac{\partial \zeta}{\partial t} = -u\frac{\partial \zeta}{\partial x} - v\frac{\partial \zeta}{\partial y} - (\zeta + f)\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$$

Impact on air quality in NCP





Weak wind region for southeasterly winds, leading to poor dispersion!

Conclusions for NCP

1.The Mountain-Plains Solenoid (MPS) circulation suppresses the mixed layer, exacerbating air pollution over the NCP

2.Thermal effects lead to seasonal variation of boundary layer and pollutants (more haze in fall and winter)

3.A one-layer slab model is developed to investigate the wind field in the North China Plain (NCP)

4. Dynamic modification by the Loess Plateau leads to barrier wind formation in the NCP

5. Barrier wind formation reduces the wind speed in the western part of NCP, leading to poor dispersion condition and exacerbating air pollution.

References

1. **Hu, X.-M.**, X. Li, M. Xue, D. Wu et al. (2016a), The Formation of Barrier Winds East of the Loess Plateau and their Effects on Dispersion Conditions in the North China Plains, Bound.-layer meteor., DOI:10.1007/s10546-016-0159-4
2. **Hu, X.-M.**, and M. Xue (2016b), Influence of synoptic sea breeze fronts on the urban heat island intensity in Dallas-Fort Worth, Texas, *Mon. Wea. Rev.*, doi:10.1175/MWR-D-15-0201.1.
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6. **Hu, X.-M.**, et al. (2013), Impact of Low-Level Jets on the Nocturnal Urban Heat Island Intensity in Oklahoma City. *J. Appl. Meteor. Climatol.*, 52, 1779–1802.
7. **Hu, X.-M.**, et al. (2013), Enhanced vertical mixing associated with a nocturnal cold front passage and its impact on near-surface temperature and ozone concentration, *J. Geophys. Res.*, 118, 2714– 2728.