WRF/Chem forecasting of boundary layer meteorology and O_3

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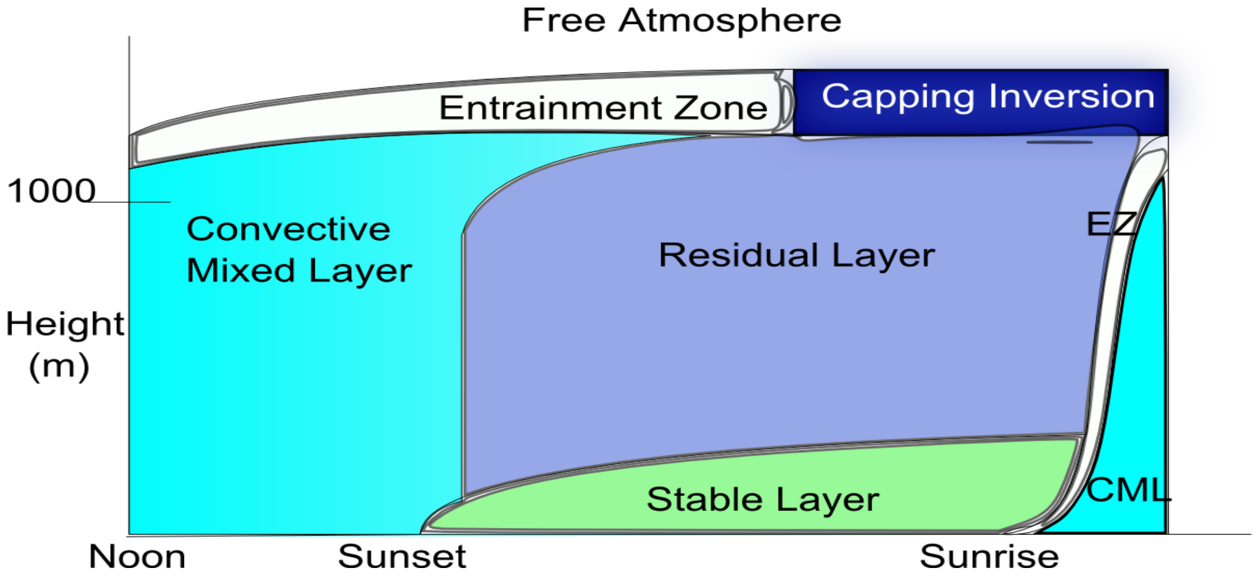
Importance of O_3, Aerosols

- **Have adverse effects on human health and environments**
- **Reduce visibility**
- **Play an important role in climate changes**
  - Direct effect
  - Indirect effects

Boundary layer diurnal variation



Boundary layer meteorology simulation is most important for air quality forecasting
PBL schemes are most critical for boundary layer meteorological simulation.

Outline

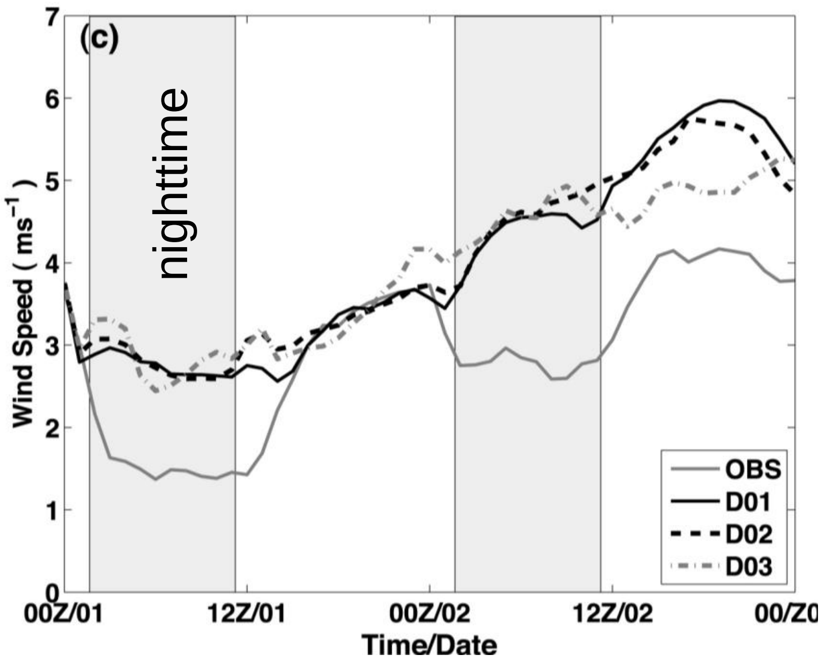
- Current status of performance of PBL schemes in terms of wind and O_3
- Results of WRF model with chemistry (WRF/Chem) for an episode from the Joint Urban 2003 field campaign
- Future plan regarding improving vertical mixing in WRF/Chem

Current status of performance of PBL schemes

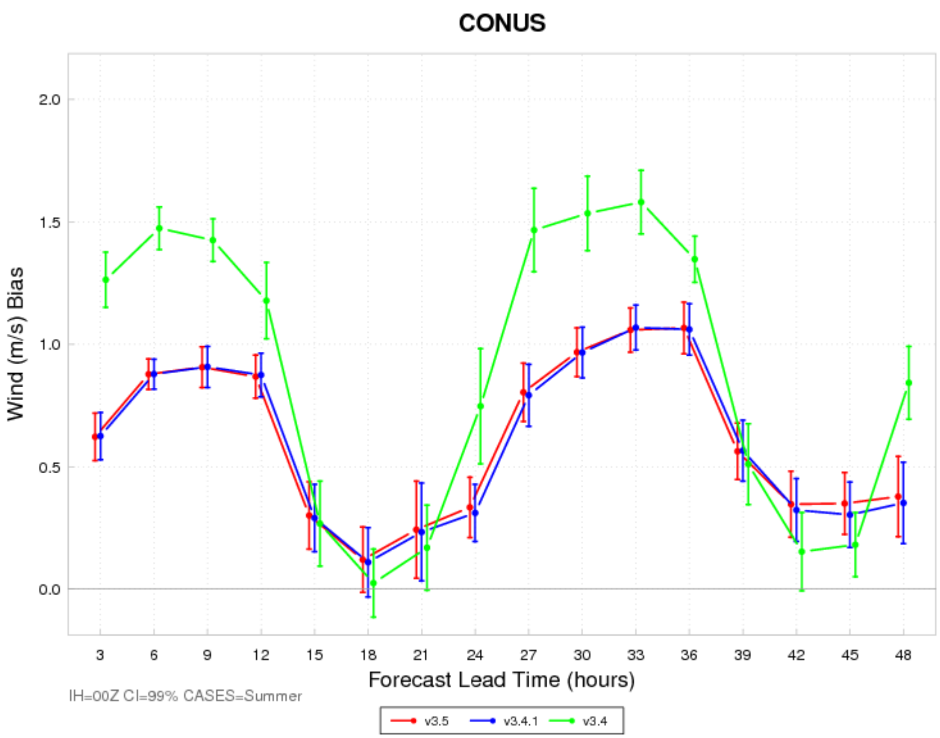
- Errors and uncertainties associated with PBL schemes still remain one of the primary sources of inaccuracies of model simulations
- While much progress has been made in simulating daytime convective boundary layer (CBL), progress with the modeling of nighttime boundary layer has been slower

PBL schemes play critical roles for simulation of wind, turbulence, and air quality in the boundary layer

Systematic over-estimations of near-surface winds during stable conditions with several models

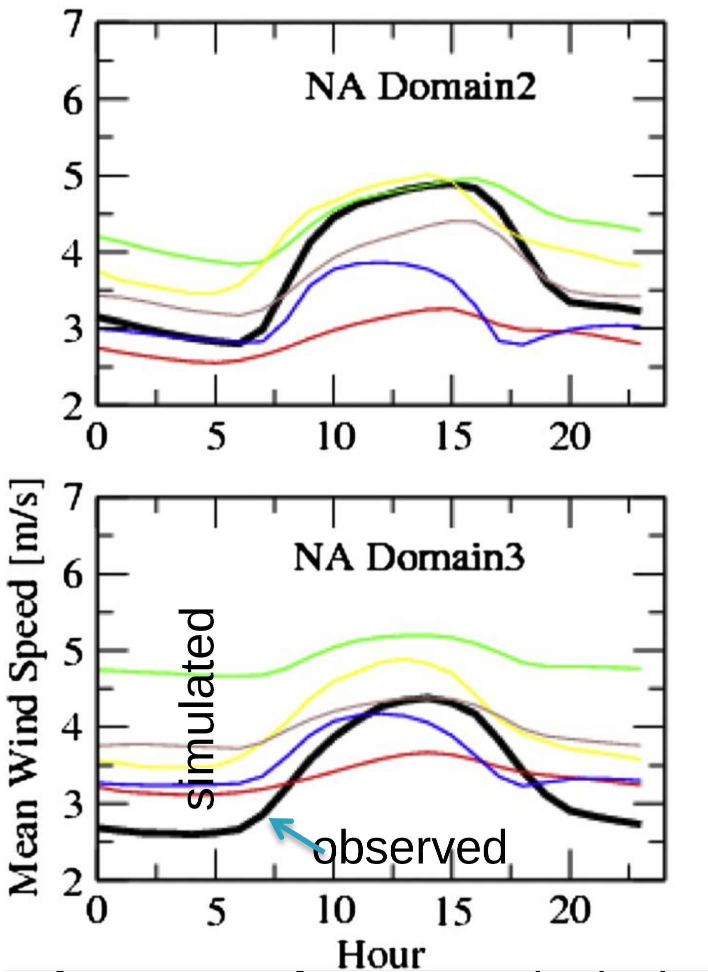


WRFV3.3 with YSU (Zhang et al., 2013)



WRF (Wolff and Harrold, 2013)

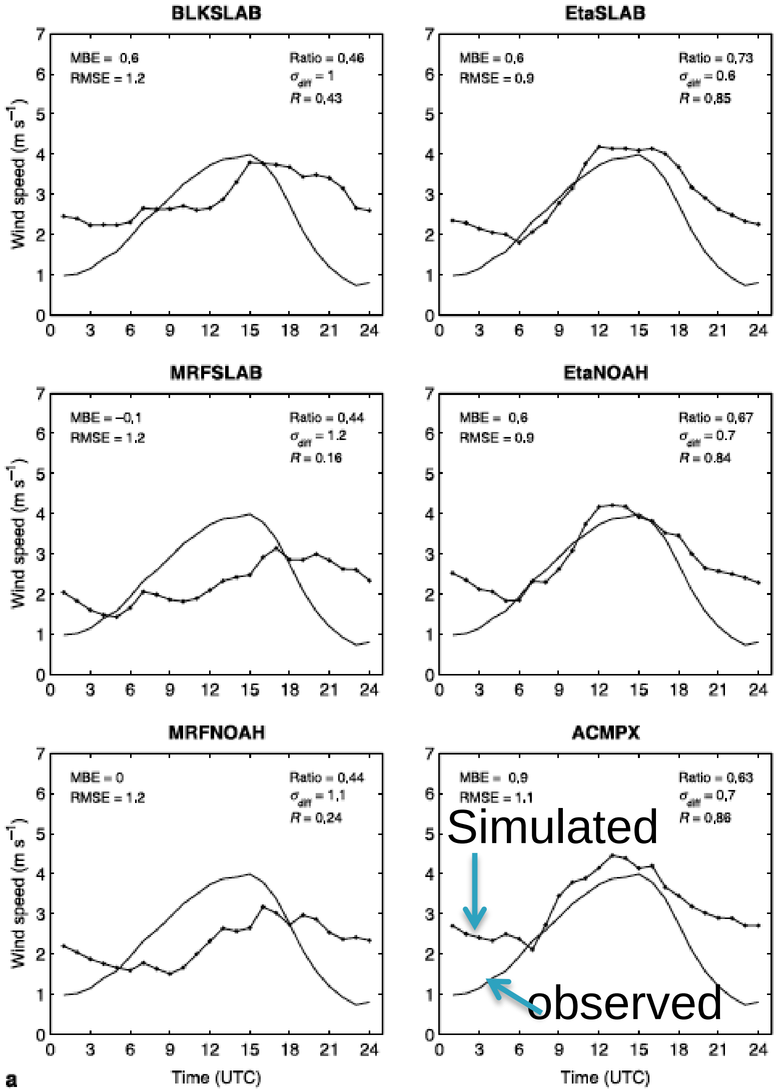
Over-estimation of near-surface winds during stable conditions (2)



Performance of 5 meteorological models
(Vautard et al., 2012)

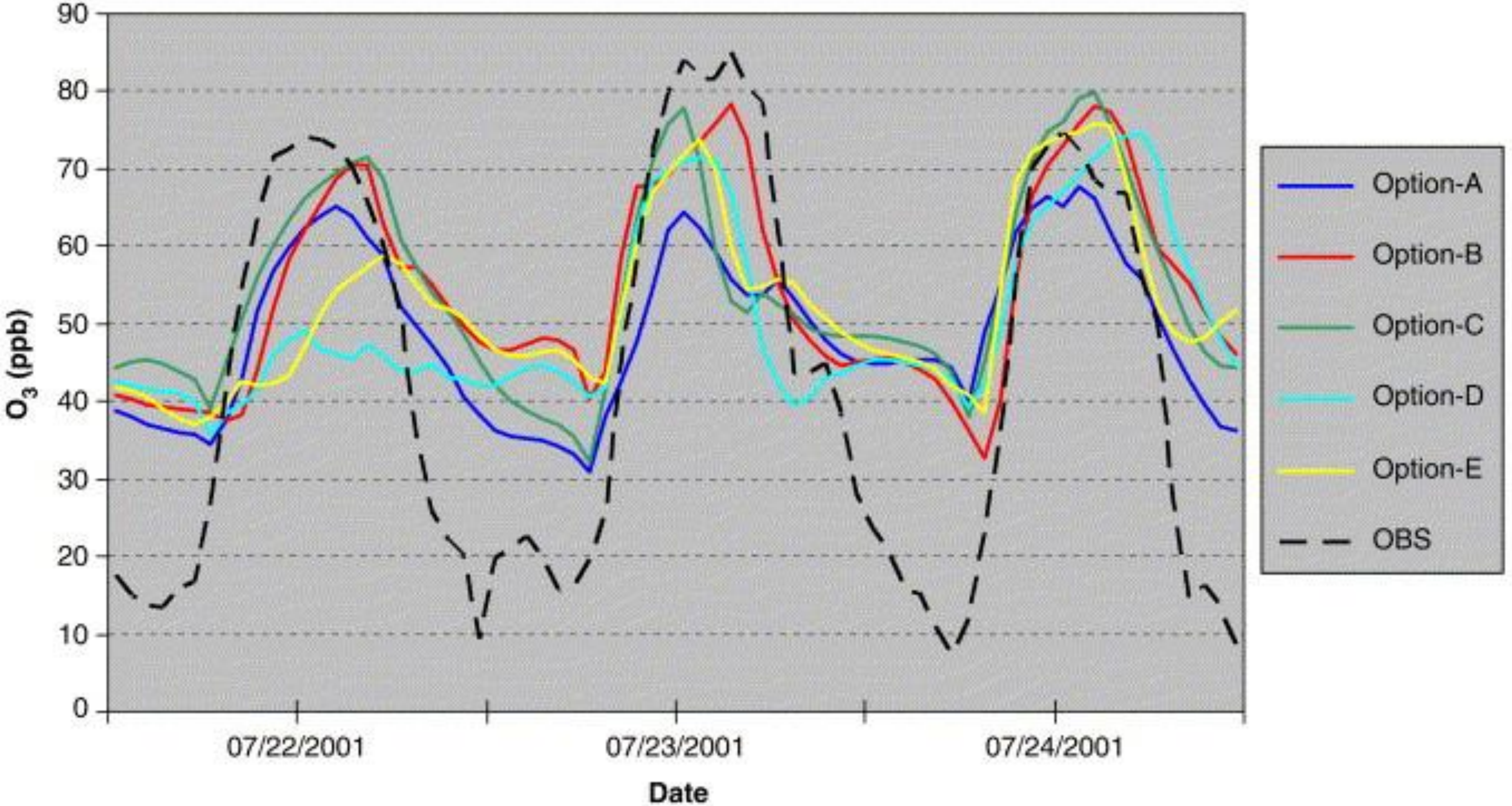
Systematic positive model biases for surface wind speed during nighttime.

Over-estimations of near-surface winds during stable conditions (3)



Performance of MM5 applied in Sweden (Miao et al., 2008)

Overestimation of nighttime surface O_3

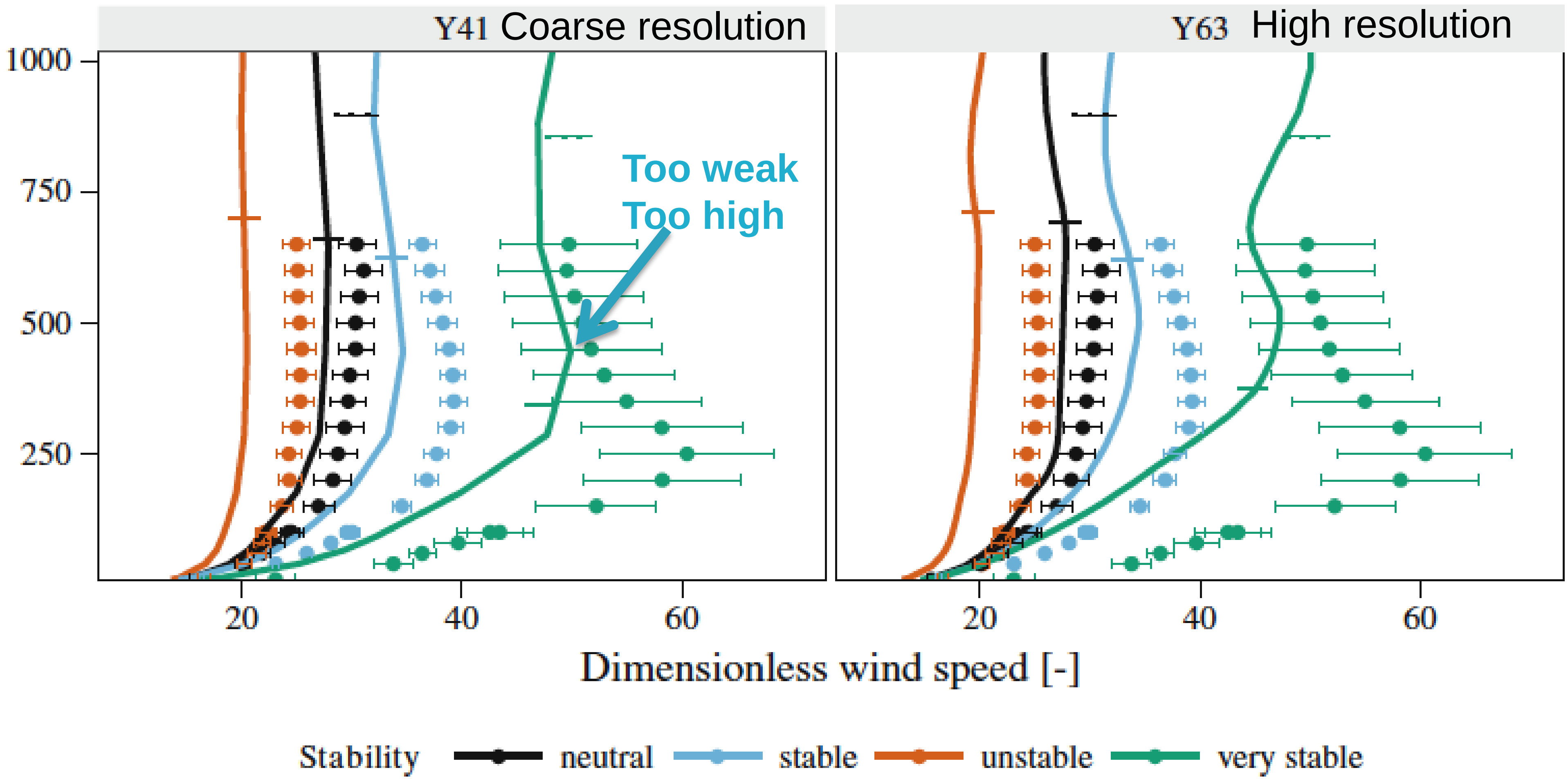


MM5-CMAQ (Mao et al., 2006)

Summary of current status

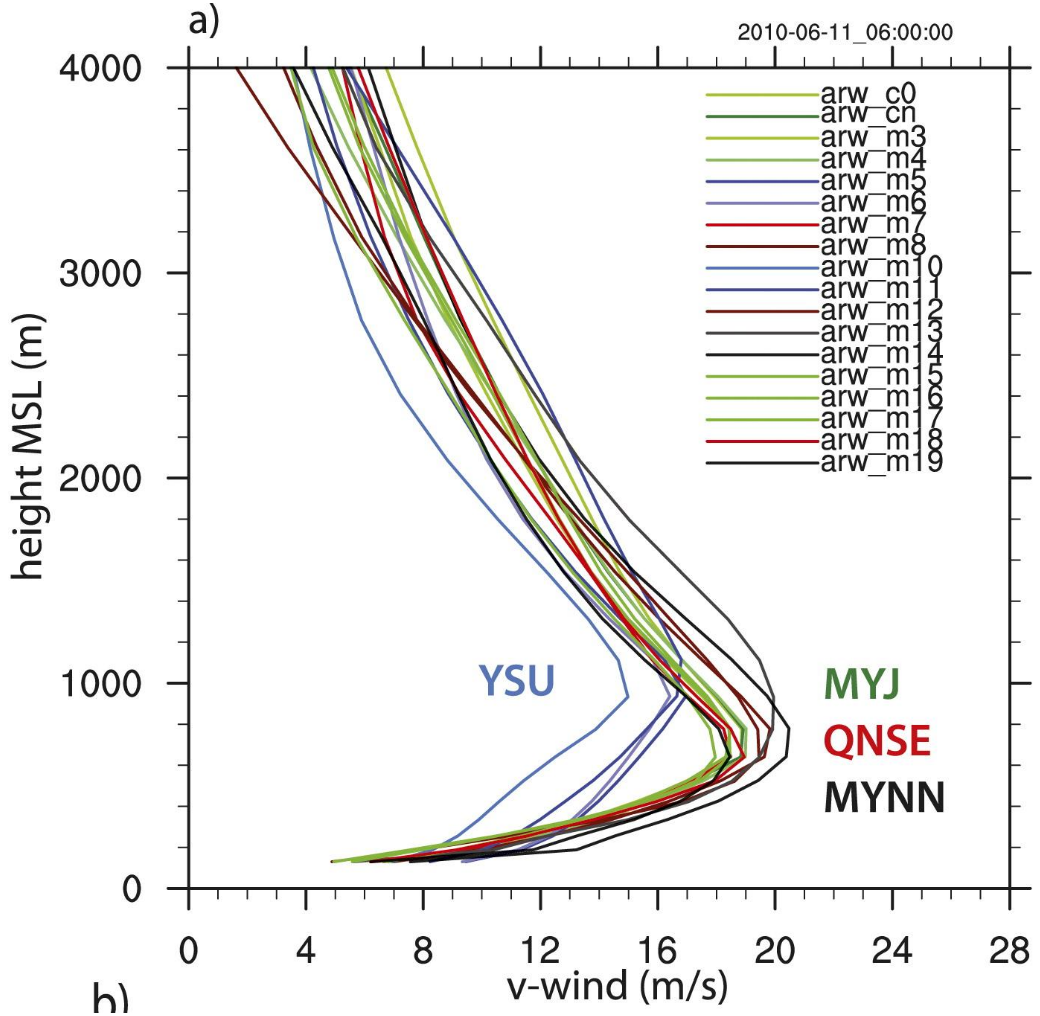
- A few models face the problem of overestimation of near-surface wind and O_3 during nighttime.
- Previous studies did not identify the exact cause and solution.
- PBL schemes play critical roles for simulation of wind, and air quality in the boundary layer. Would PBL schemes be fully responsible for the problems?

Past evaluation of the YSU PBL scheme
One of the mostly widely used schemes



Longstanding problem with YSU in WRF:
simulating weaker and higher LLJs (Floors et al., 2013)

Past evaluation of YSU (2)



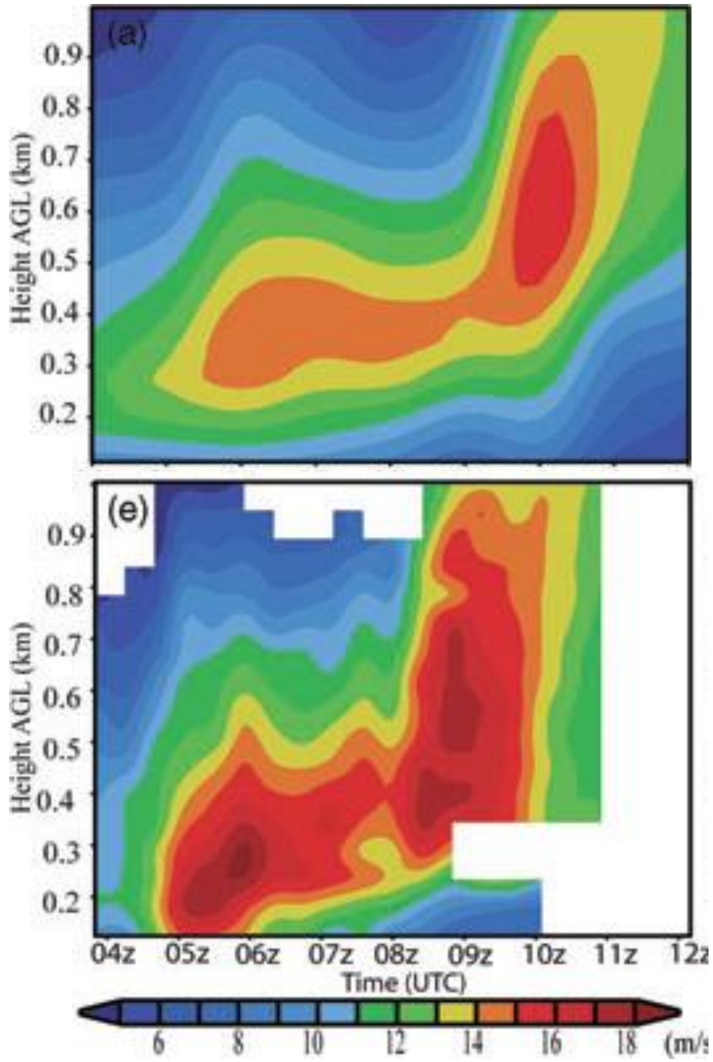
(Schumacher et al., 2013)

Simulations from CAPS 2010 Spring Experiment

Past evaluation of YSU (3)

YSU

Observation



Time-height diagram of wind speed (Storm et al., 2009)

Updates of YSU from V3.4 to V3.4.1

Eddy diffusivity $$K_m = kw_s z(1 - \frac{z}{h})^2$$

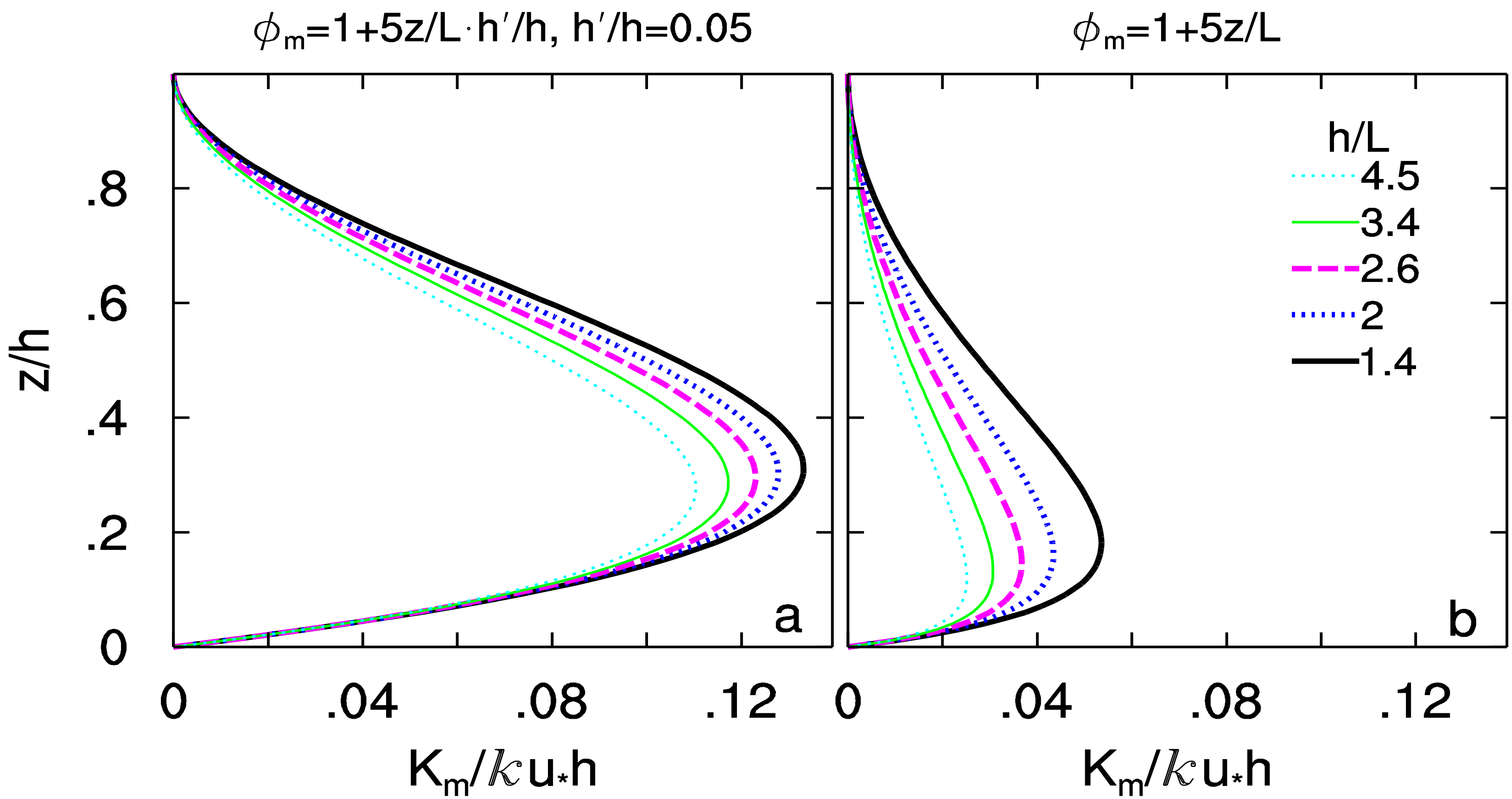
Velocity scale $$w_s = u_*/\Phi_m$$

Version 3.4 and earlier $$\phi_m = 1 + 5\frac{z}{L} \cdot \frac{h'}{h}$$

Version 3.4.1 $$\phi_m = 1 + 5\frac{z}{L}$$

h' is diagnosed using a critical Richardson # of 0 while h is diagnosed using Ri # of 0.25

Vertical profiles of K_m under different stabilities



Old YSU in earlier WRF (i.e., 3.4 and earlier) Updated YSU in WRF 3.4.1

Vertical mixing simulated by the updated YSU in WRF is reduced

Objectives of this study

- –**Document the impact of YSU updates on the boundary layer prediction.**
- –**Evaluate PBL schemes for wind resource and air quality assessments.**
- –**Diagnose possible reasons for the often reported overestimation problem for near-surface wind and O_3**

Numerical experiments with WRF/Chem

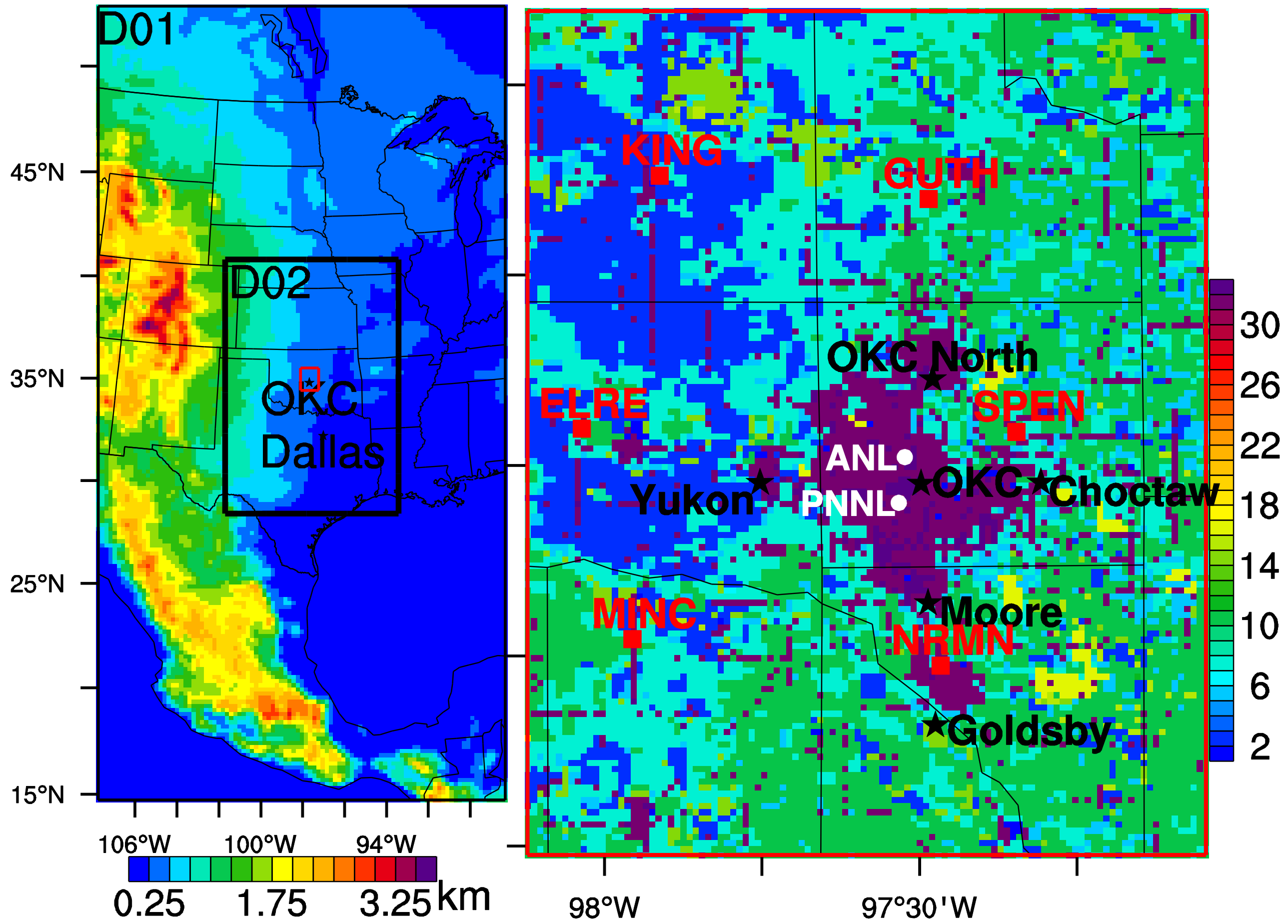
Abbreviation	WRF version	PBL scheme	Surface layer scheme* (option number in WRF)
YSU3.4	**3.4**	**old YSU**	MM5 similarity (1)
YSU3.4+	**3.4**	**updated YSU**	MM5 similarity (1)
YSU3.4.1	**3.4.1**	**updated YSU**	MM5 similarity (1)
MYJ	3.4.1	MYJ	Eta similarity (2)
MYNN2	3.4.1	MYNN2	Eta similarity (2)
BouLac	3.4.1	BouLac	Eta similarity (2)
QNSE	3.4.1	QNSE	QNSE (4)
UW	3.4.1	UW	Eta similarity (2)

⍰

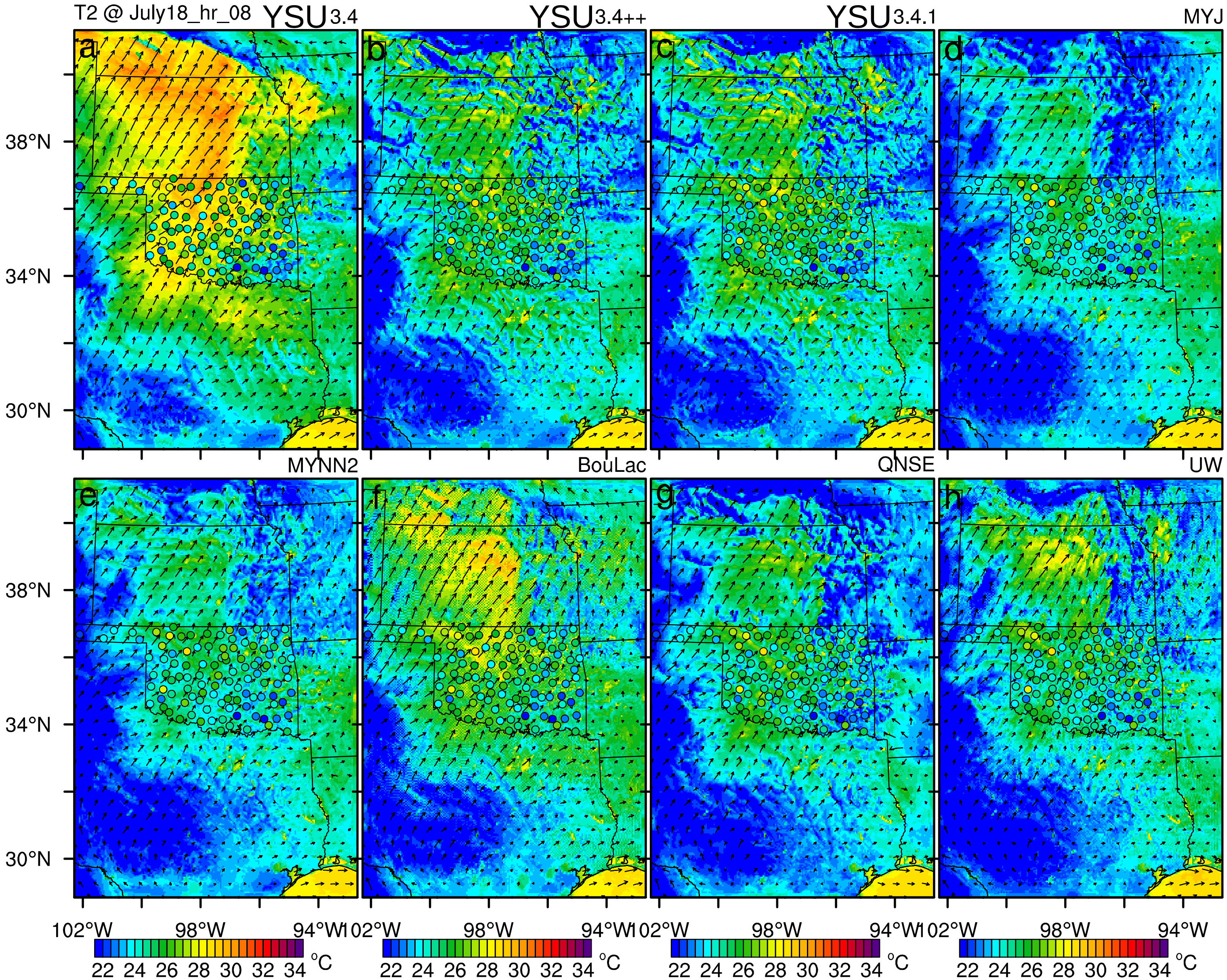
To isolate the impact of YSU update, the updated YSU from WRF3.4.1 is implemented into WRF3.4. The experiment with this version is referred to as YSU3.4+

Domain configuration and observation sites around OKC

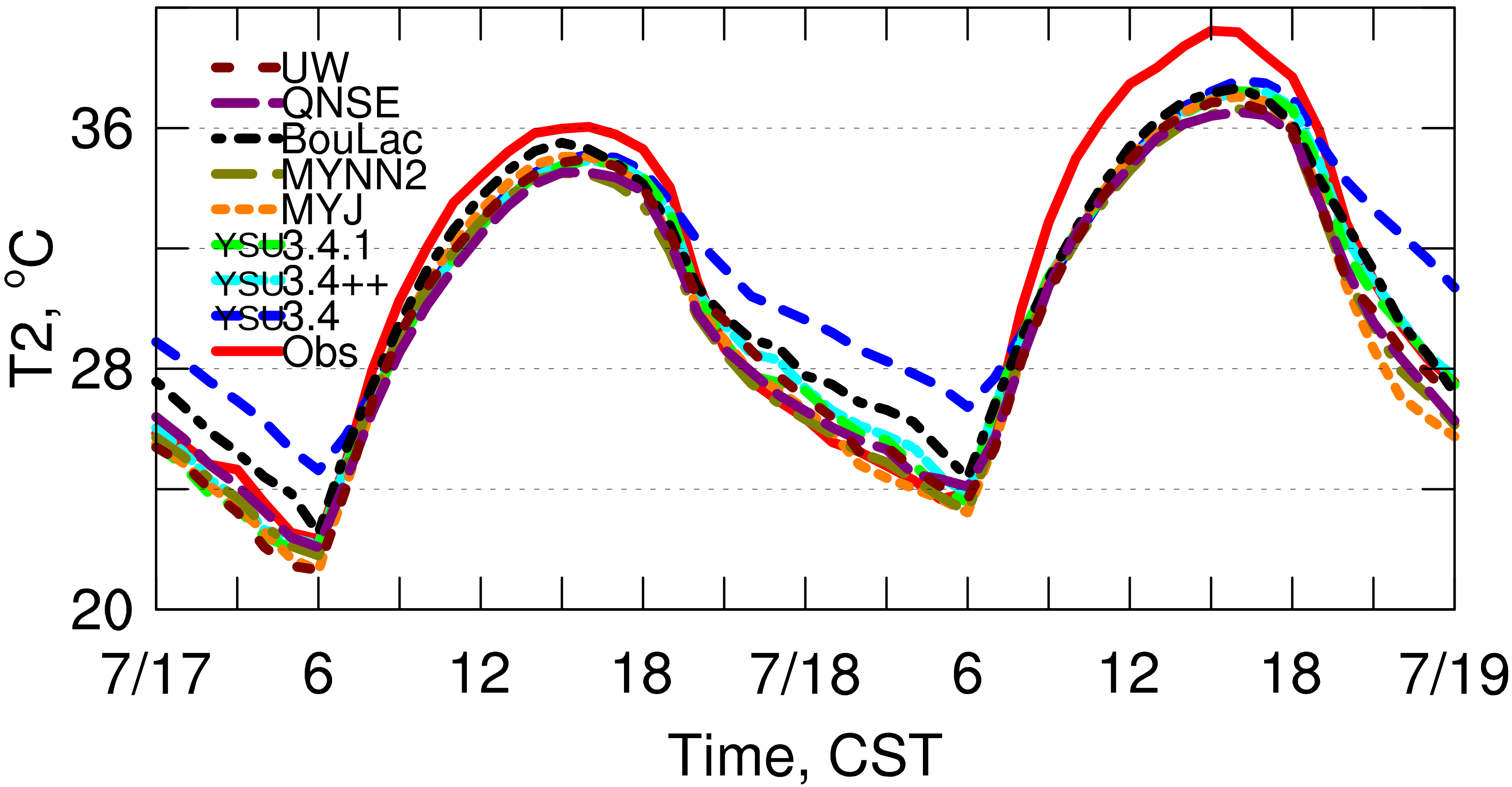
Resolution: 22.5->4.5km
Episode: July 17-19, 2003
Initial conditions
meteo: FNL
chemical: MOZART
Emission: NEI2005



YSU3.4 overestimates nighttime T2

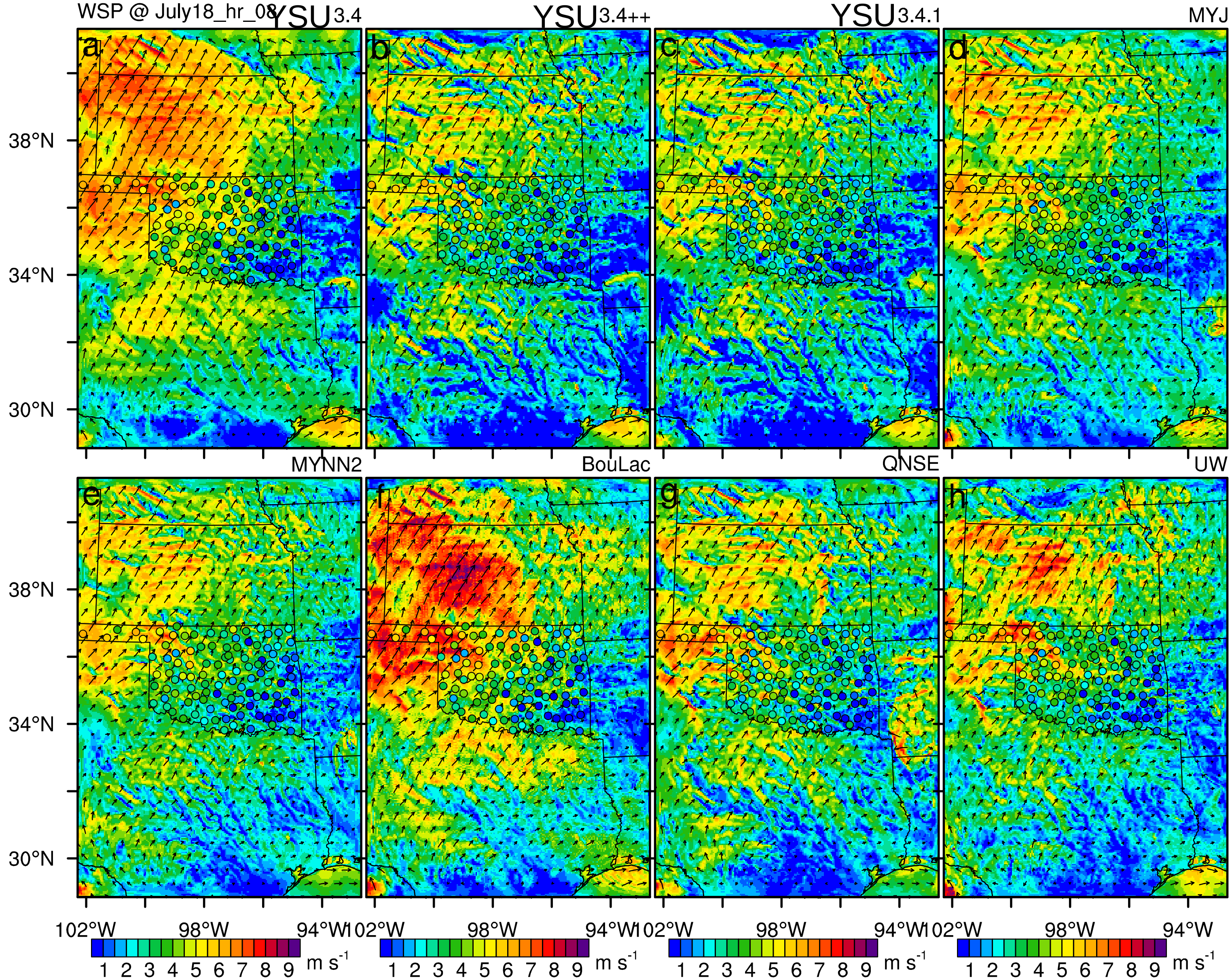


Temporal variation of T2

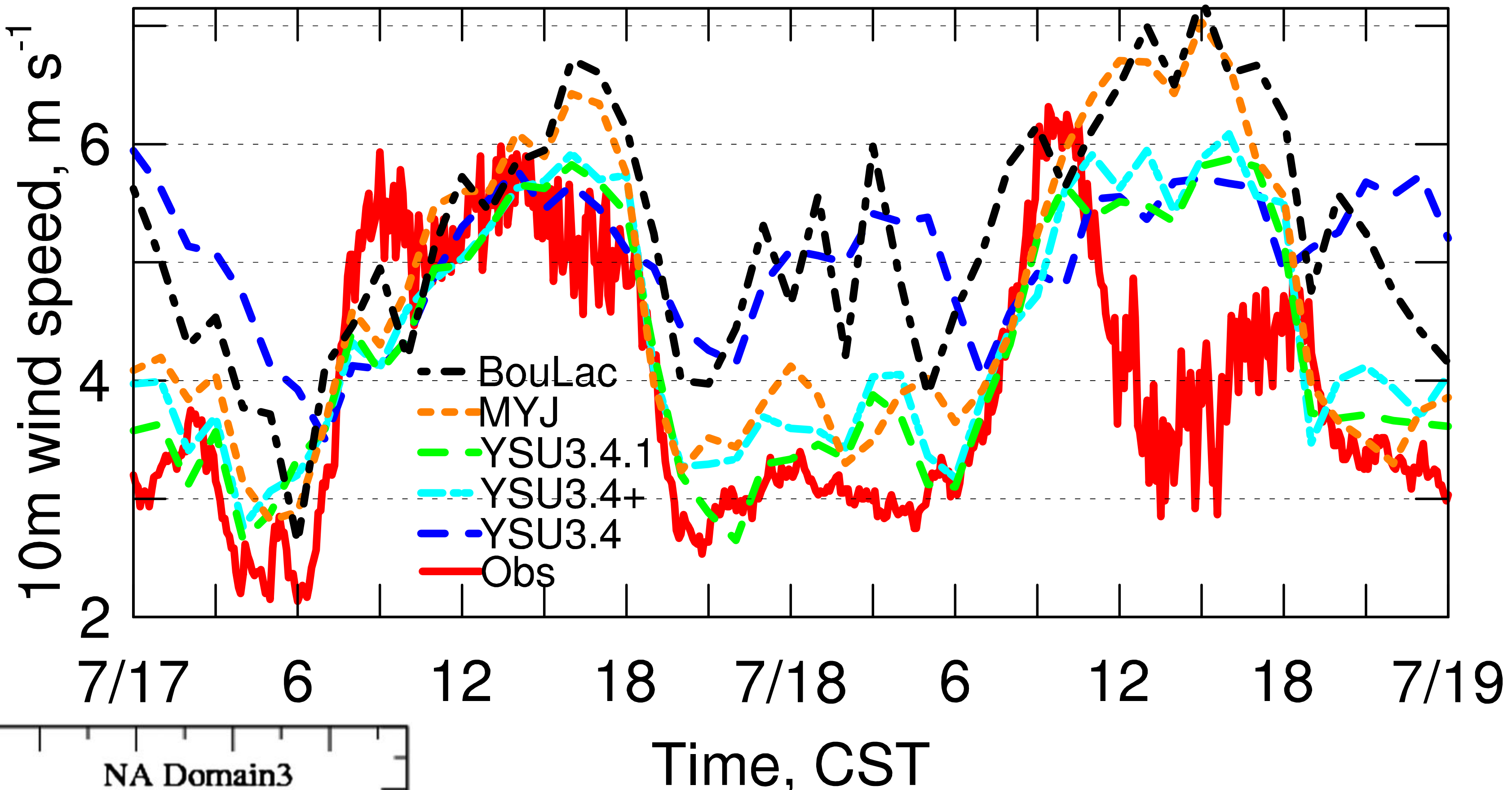


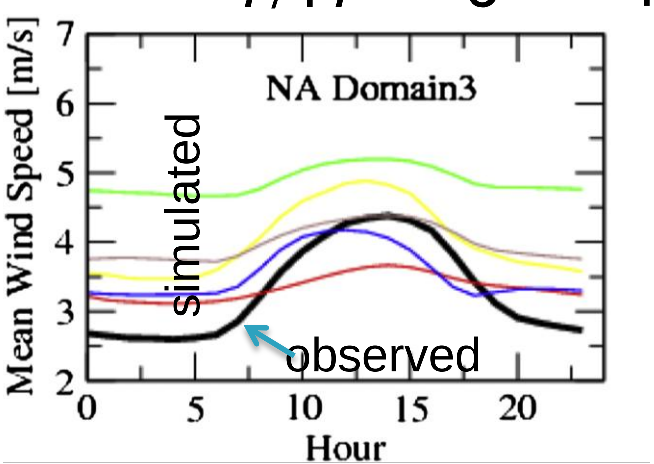
YSU3.4 stands out during nighttime, BouLac has a similar but less severe problem
The nighttime performance is improved with the updated YSU.

YSU3.4 and BouLac overestimates nighttime wind speed at 10 m AGL



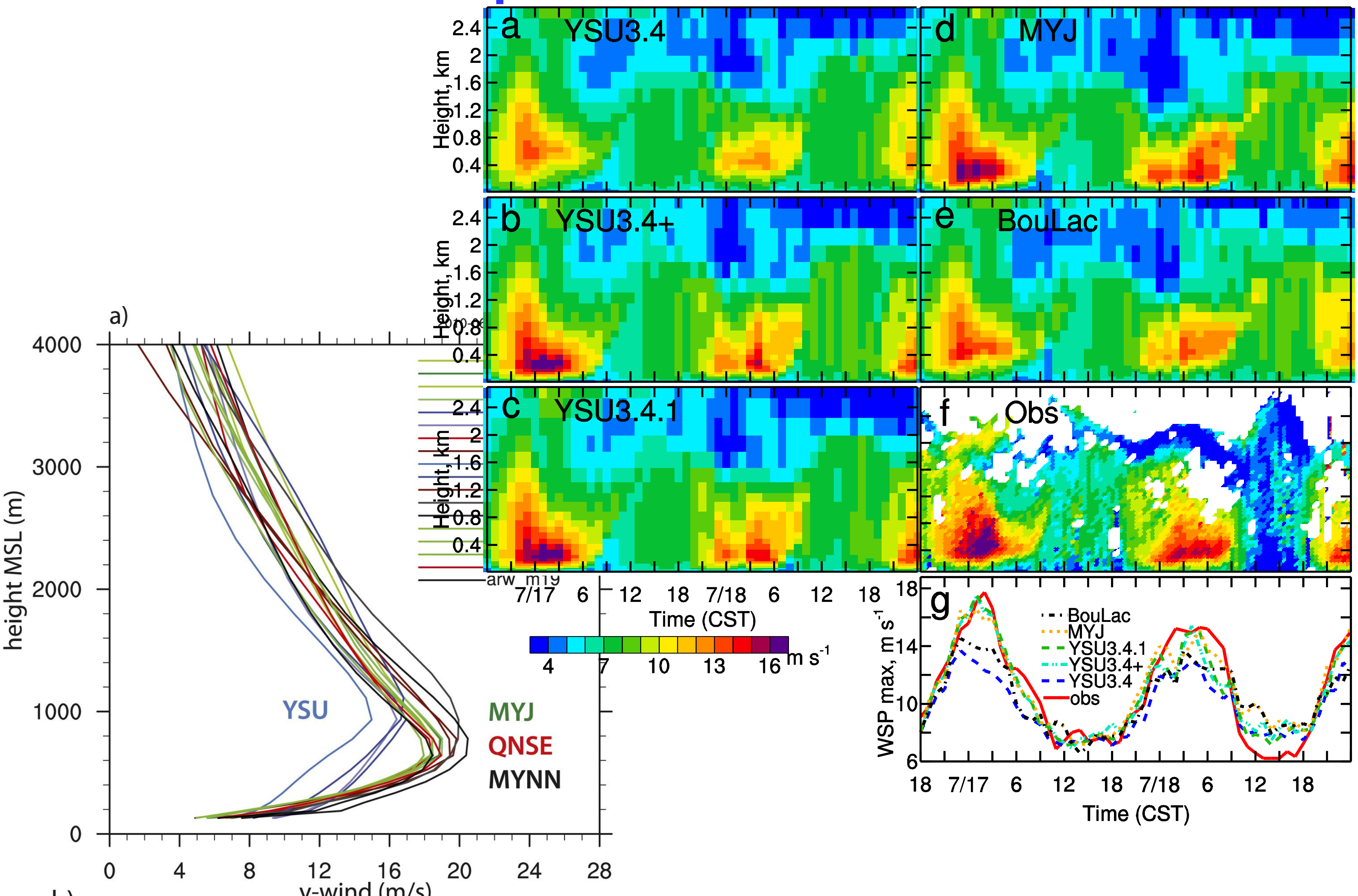
Improvement for nighttime wind



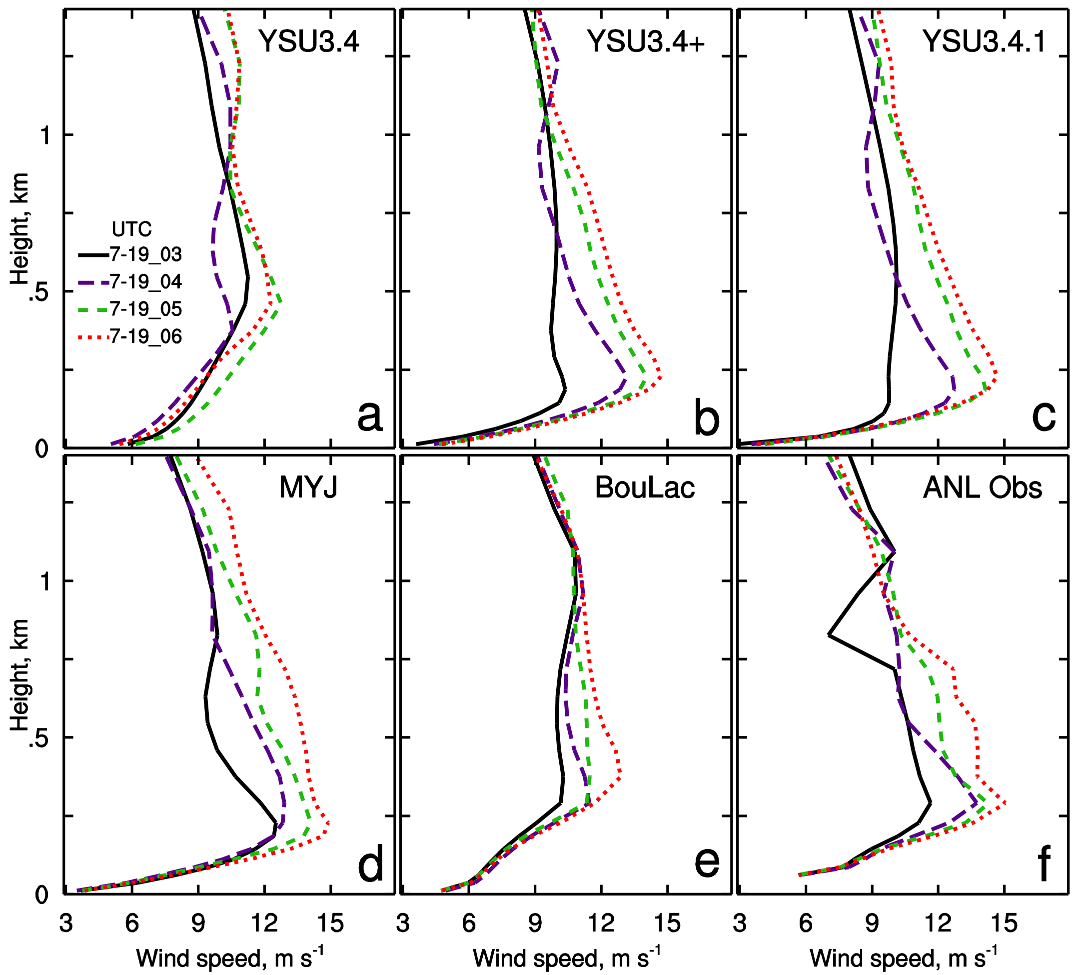


The update of YSU did not affect daytime simulation but improved performance during nighttime

The updated YSU better reproduces LLJs

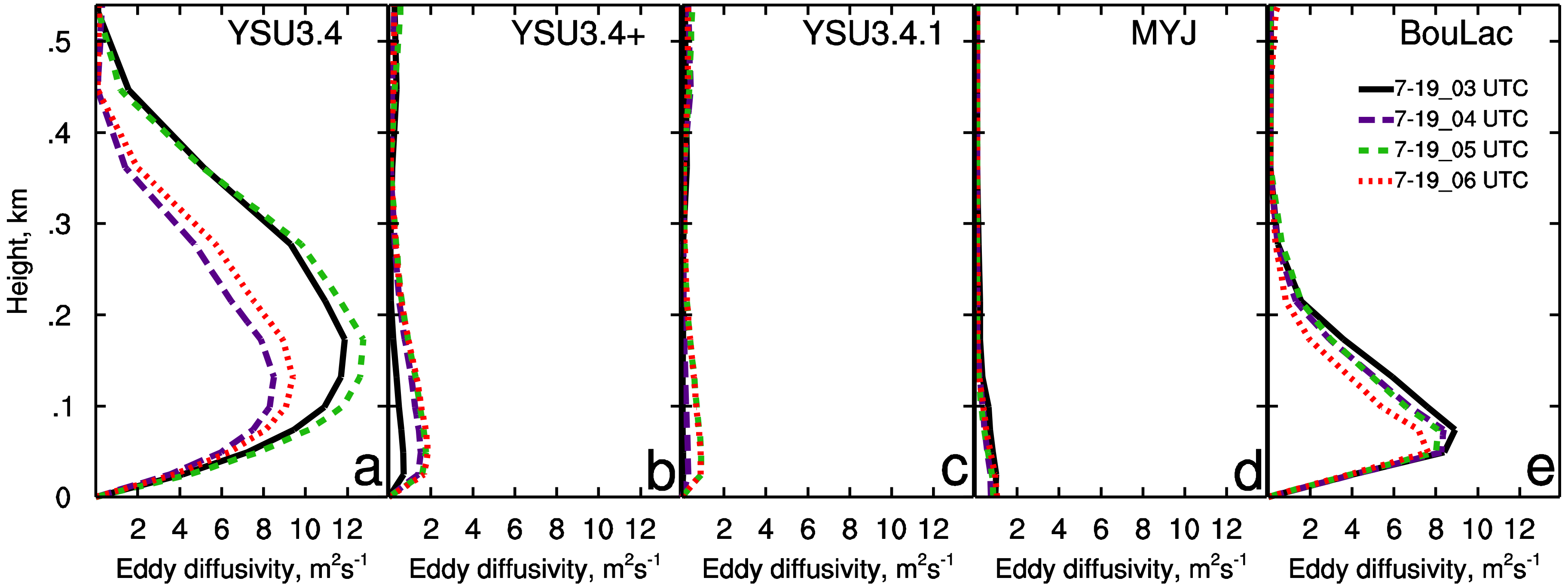


YSU3.4 simulated too weak and elevated LLJs



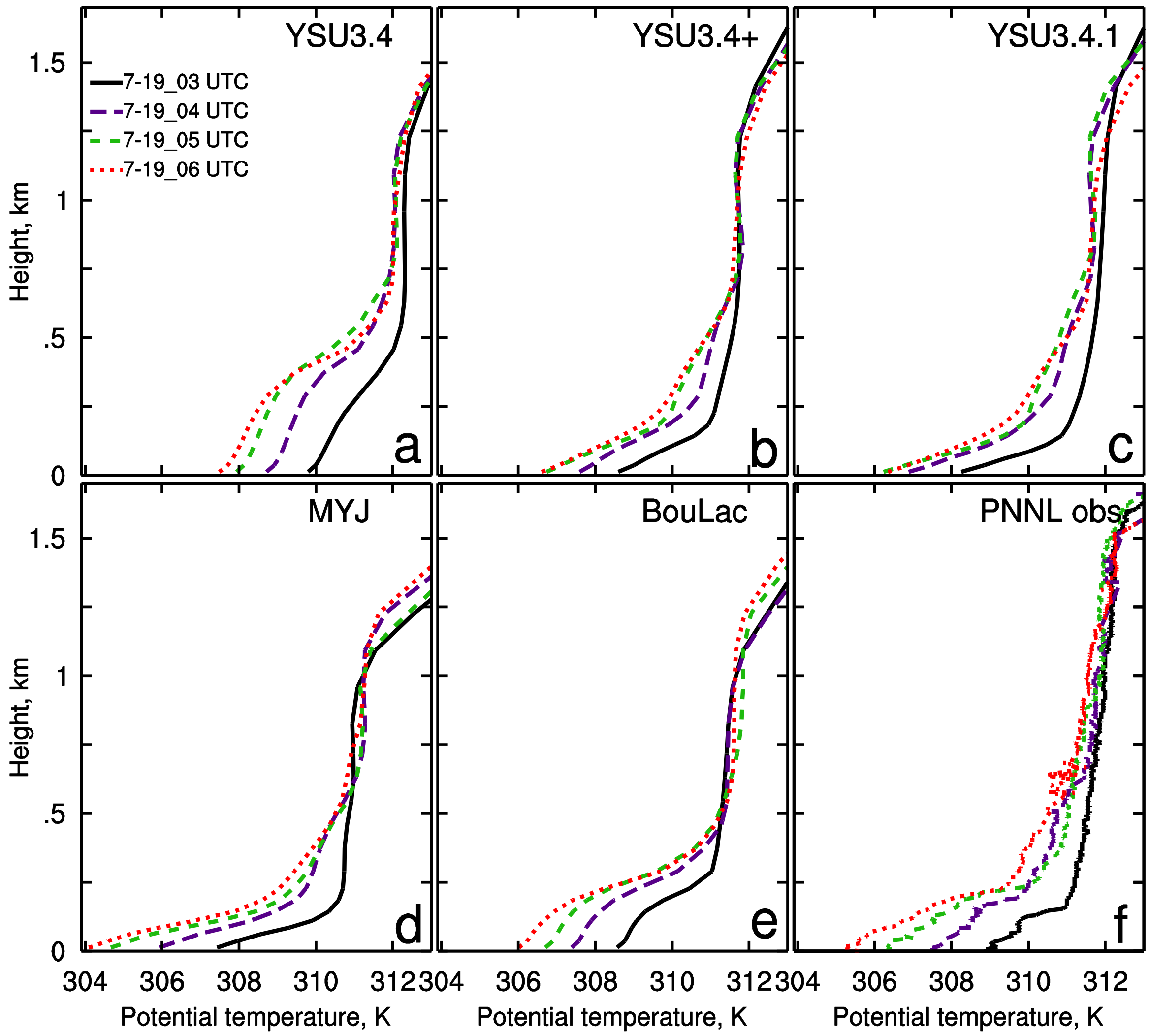
The updated YSU simulates lower and stronger LLJs, showing a better agreement with observation

Root cause of the improvement



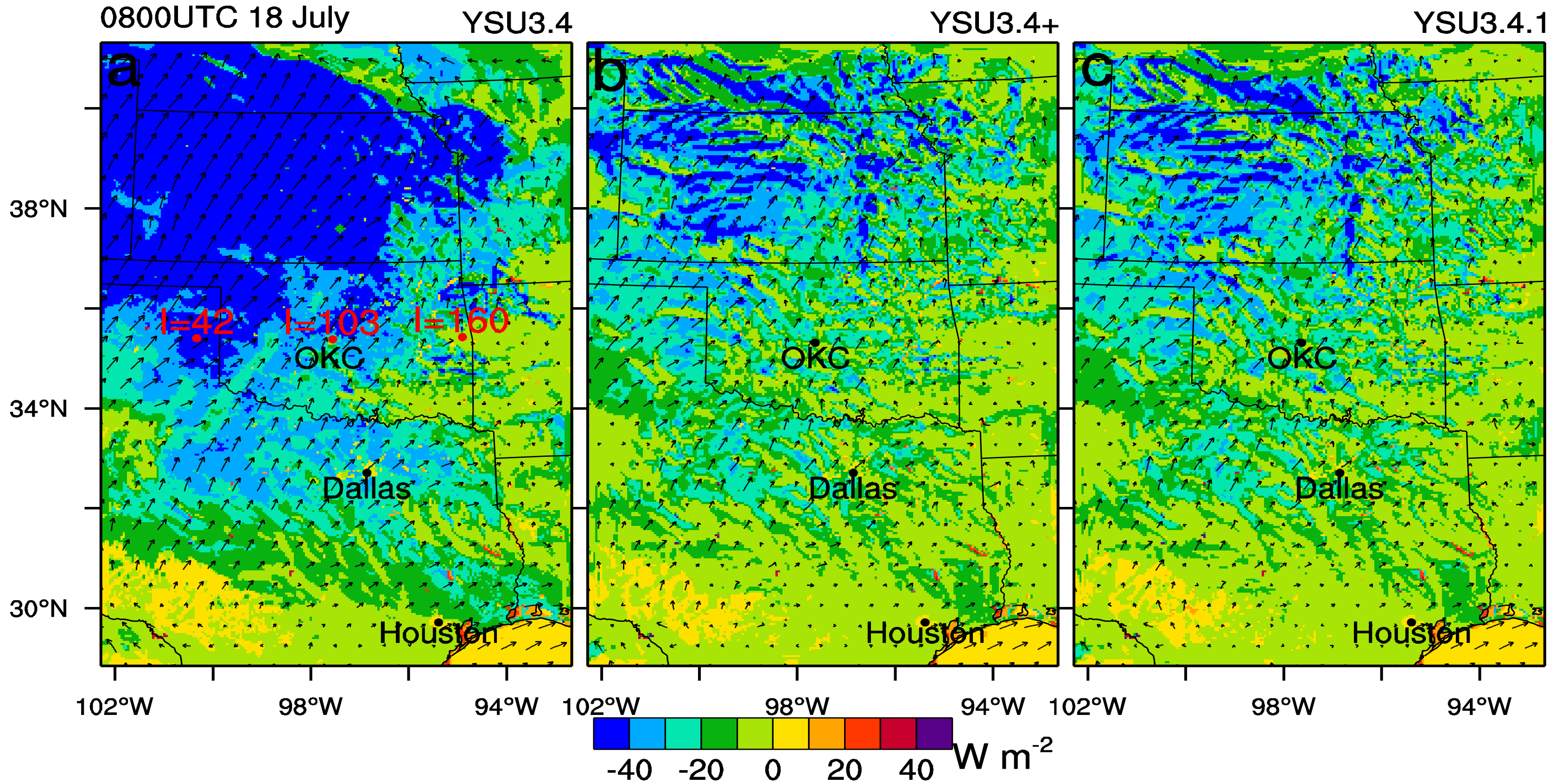
The updated YSU reduces nighttime vertical mixing
The BouLac has a similar problem as the old YSU

Improvement in vertical thermal structure



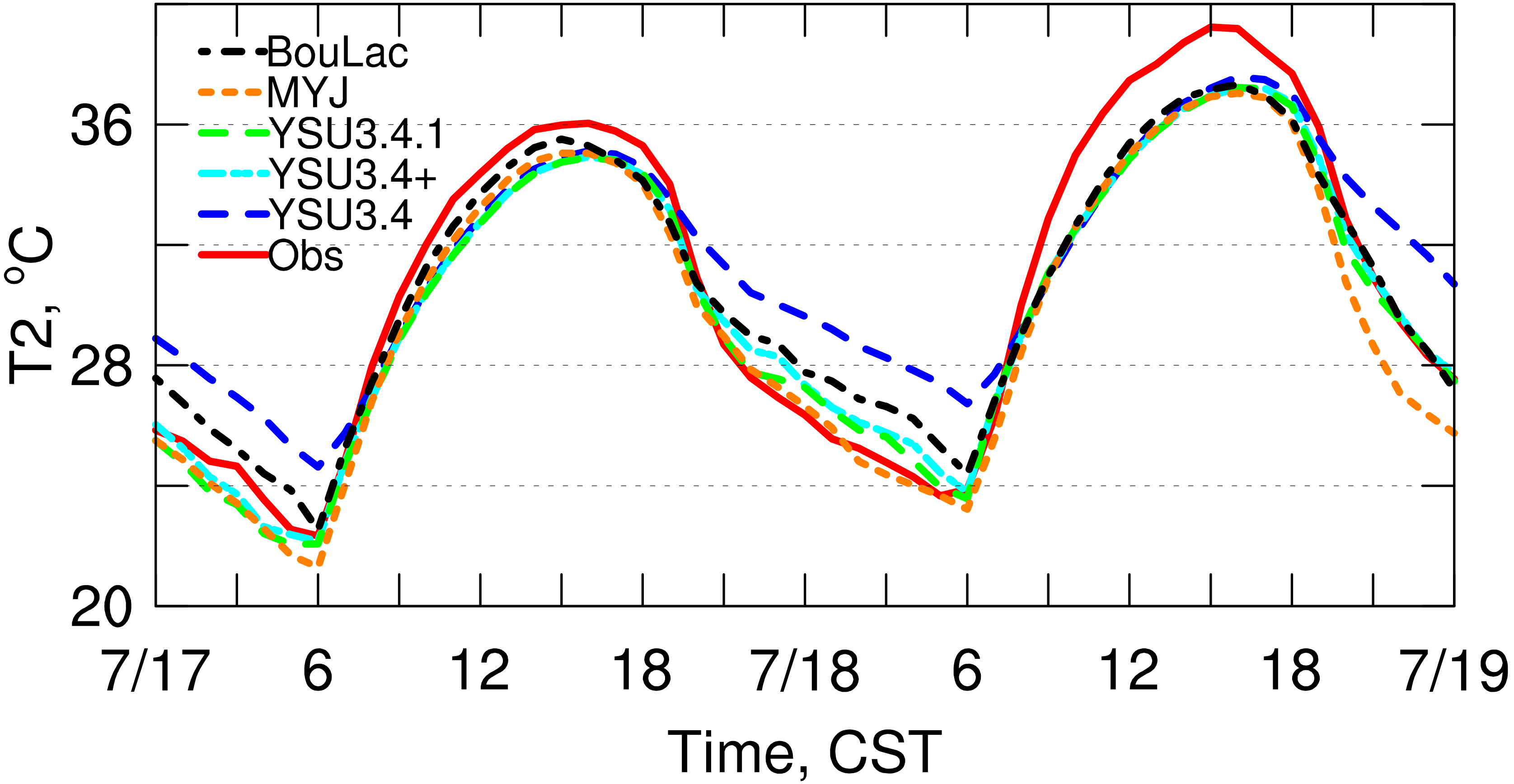
The old YSU simulates too neutral boundary layer, while the updated YSU simulates a more stable boundary layer.

Reduced heat flux leads to improved T2

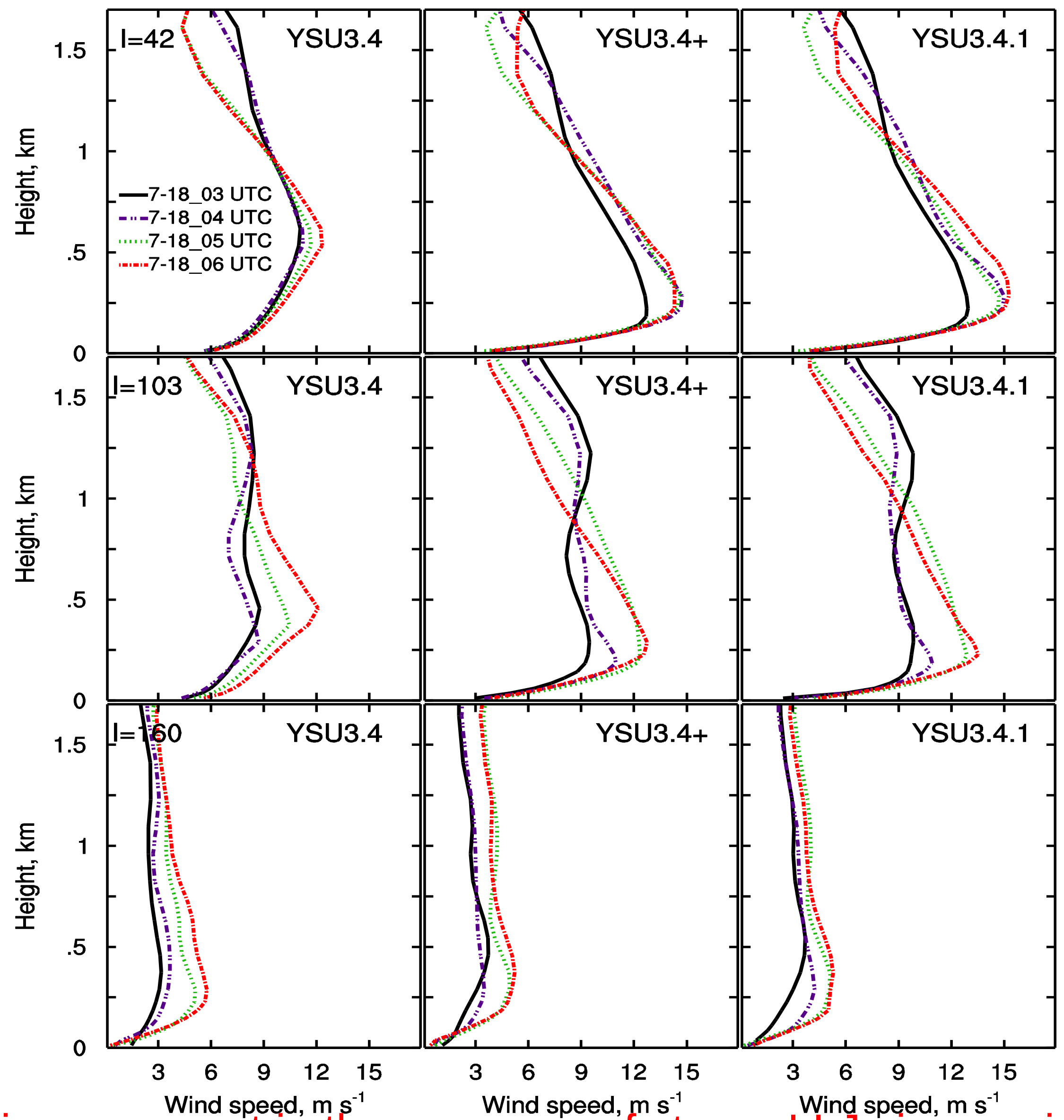


Reduced downward heat flux during nighttime leads to lower T2.

Temporal variation of T2



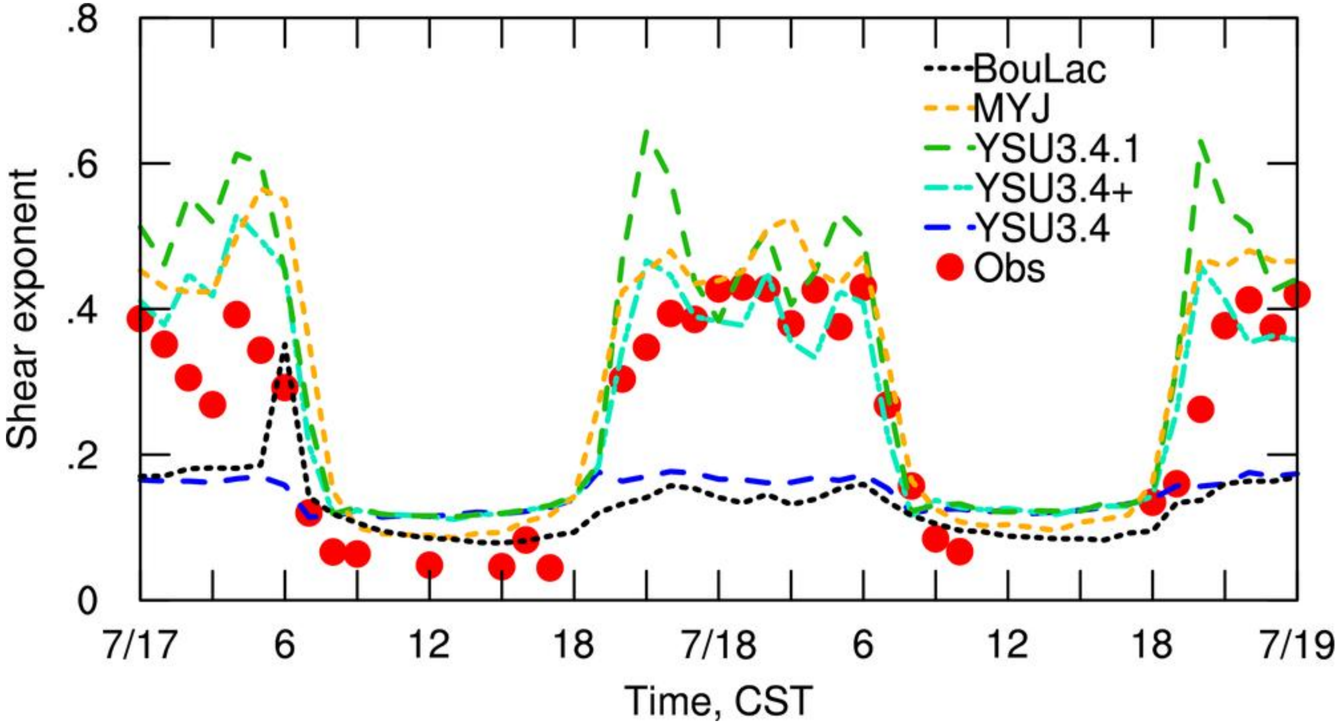
The nighttime performance is improved with the updated YSU.



The improvement in the presence of strong LLJs is prominent while it is less prominent for weak wind regimes (e.g., in the absence of LLJ).

Improvement of wind shear exponent

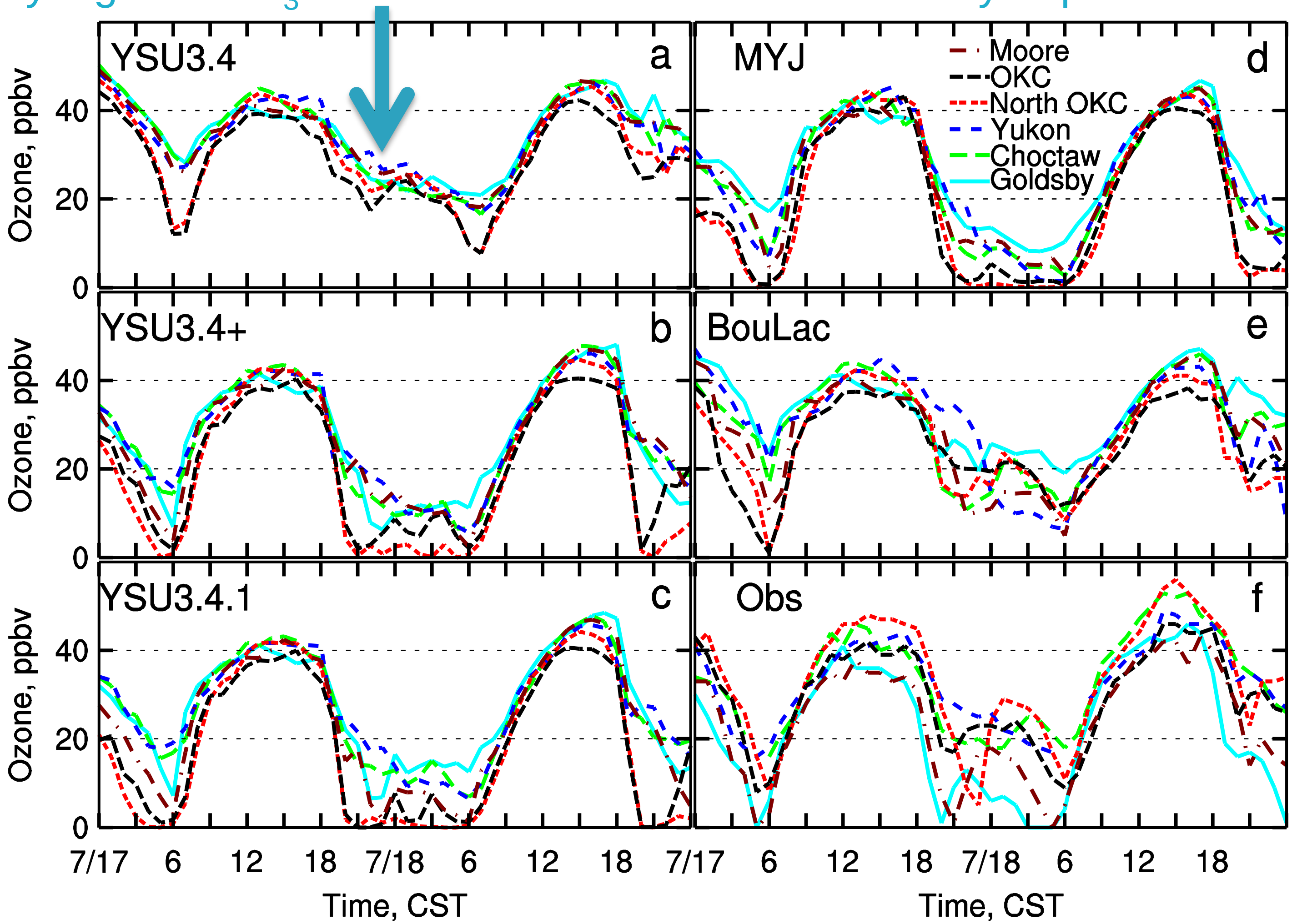
Wind extraporlation eq $U(z) = U_r(\frac{z}{z_r})^\alpha$



The old YSU and BouLac significantly underestimate the shear exponent during nighttime

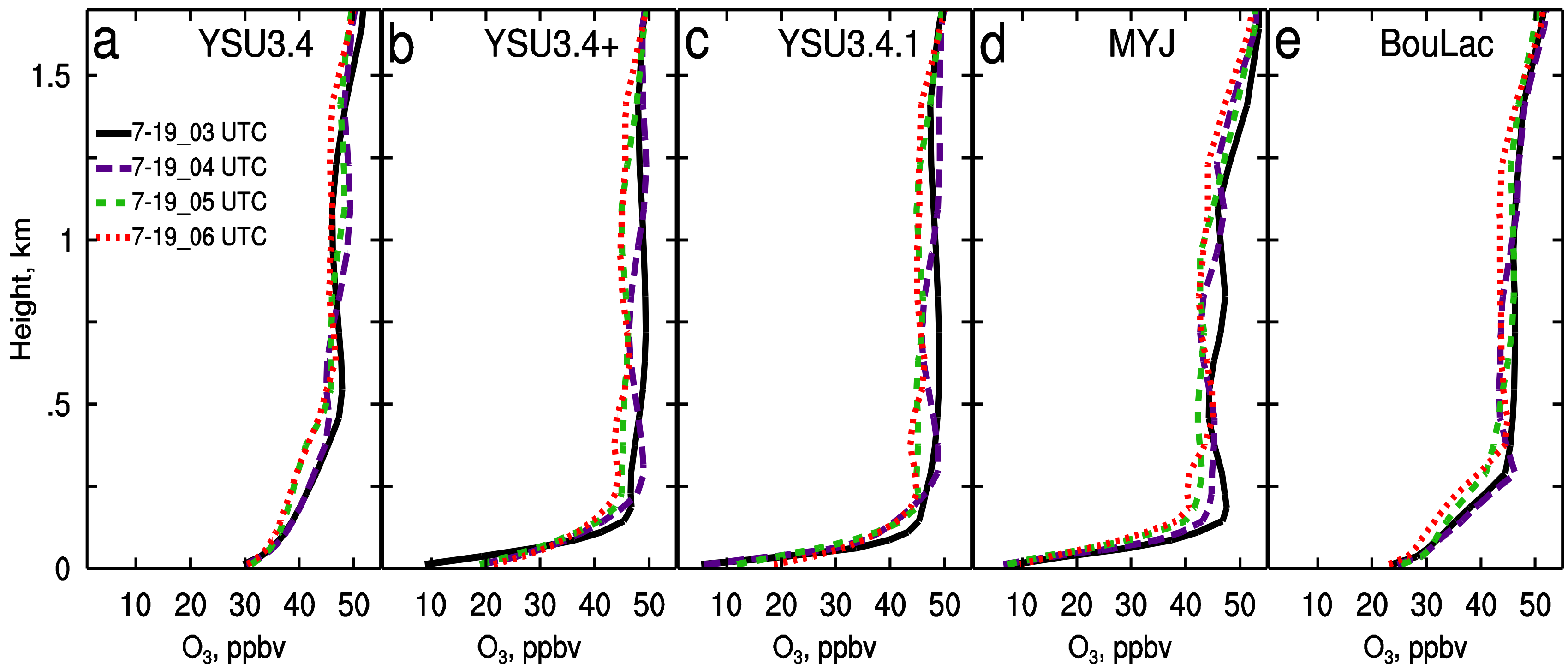
Improvement of nighttime O_3

Previously nighttime O_3 overestimation was attributed to dry deposition and emissions



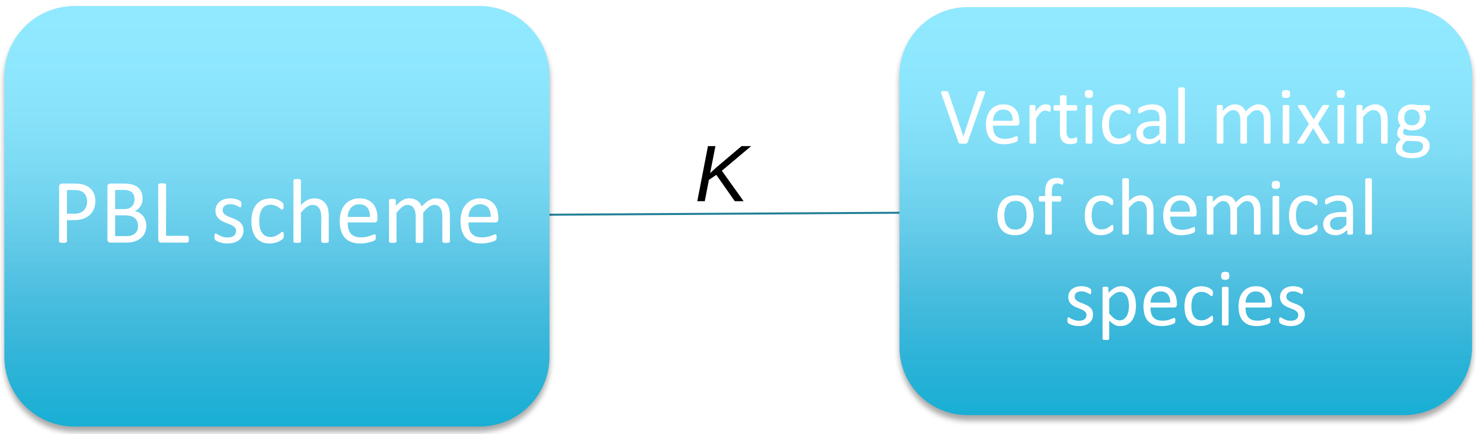
The updated YSU improved predictions of the early evening decline of O_3

Impact on vertical distribution of O_3



The updated YSU reduces the downward transport of O_3 during nighttime

Limitation of vertical mixing of chemical species in current WRF/Chem



$$\overline{w'c'} = -K_c \frac{\partial c}{\partial z}$$

Vertical mixing of chemical species is treated with a simple 1st order closure scheme using the *K* diagnosed by PBL schemes

Conclusions (1)

1. The update of the YSU scheme in WRF3.4.1 improved predictions of the nighttime boundary layer and can thus provide better wind resource assessments
2. The BouLac scheme gives the strongest vertical mixing in the nighttime boundary layer. It consequently overestimates near-surface wind and temperature and underestimates the wind shear exponent at night.

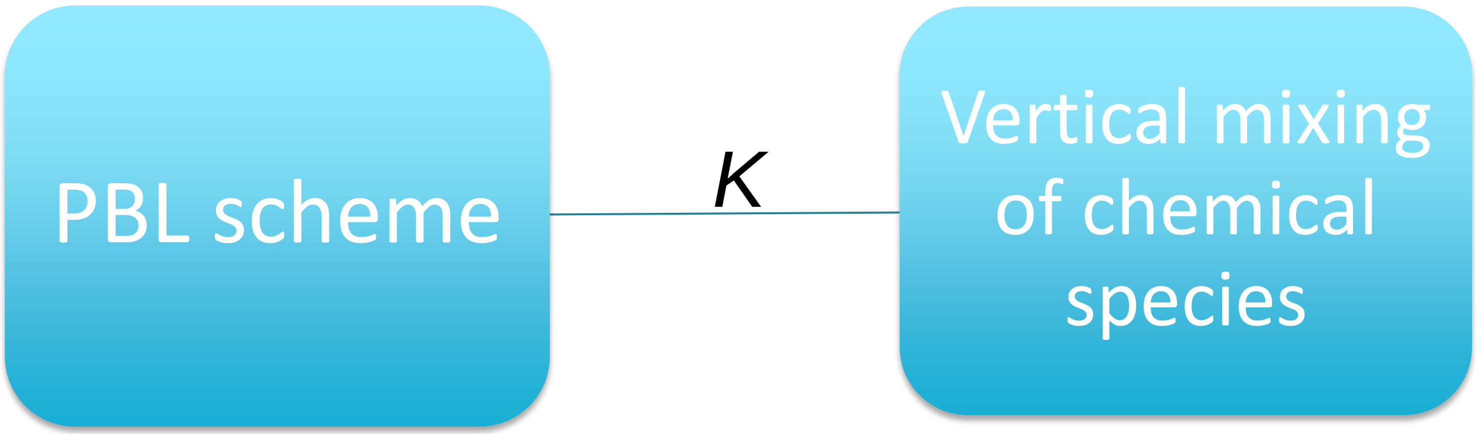
Conclusions (2)

3. Overestimation of nighttime O_3 is related to overestimation of surface winds, both of which can be partially attributed to excessive vertical mixing
   - This has wide implications for the previously often reported overestimation of surface winds and O_3 from many models. Vertical mixing might be the cause and should be carefully considered.

Outline

- **Current status of performance of PBL schemes**
- **Results of WRF model with chemistry (WRF/Chem) for an episode from the Joint Urban 2003 field campaign**
- **Future plan regarding improving vertical mixing in WRF/Chem**

Improvement of vertical mixing of chemical species



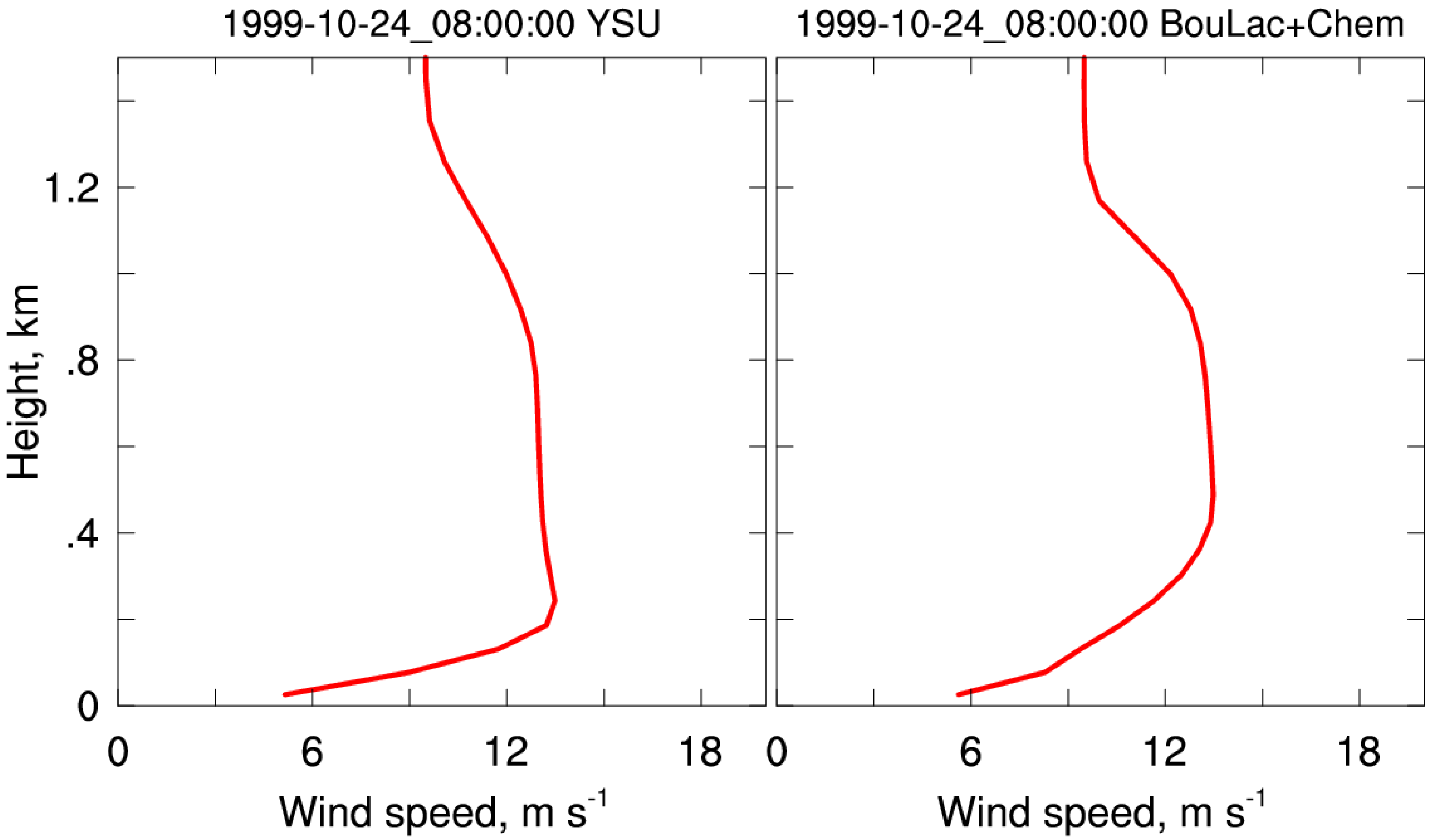
Current treatment: $\overline{w'c'} = -K_c \frac{\partial c}{\partial z}$

Proposed: $\overline{w'c'} = -K_c \left(\frac{\partial c}{\partial z} - \gamma_c\right) + \overline{(w'c')_h}(\frac{z}{h})^3$

$$\overline{(w'c')_h} = -A{w_m}^3/h$$

$${w_m}^3 = {w_*}^3 + B{u_*}^3$$

Test of SCM WRF



References

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