Assessing the Meteorological Aspects of High Ozone Over Lake Michigan

Richard T. McNider[1], Arastoo Pour-Biazar[2], Kevin Doty[2], Andrew White[1], Yuling Wu[2], Momei Qin[3], Yongtao Hu[3], Talat Odman[3], Patricia Cleary[4], Eladio Knipping[5], Bright Dornblaser[6], Pius Lee[7], Christopher Hain[8], Stuart McKeen[9]

[1]Department of Atmospheric Science, University of Alabama in Huntsville, Huntsville, Alabama, USA.
[2]Earth System Science Center, University of Alabama in Huntsville, Huntsville, Alabama, USA.
[3]School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA.
[4]Department of Chemistry, University of Wisconsin-Eau Claire, Eau Claire, Wisconsin, USA
[5]Electric Power Research Institute, Washington, DC, USA
[6]Texas Commission on Environmental Quality, Austin, Texas, USA
[7]NOAA Air Resources Laboratory, Silver Springs, Maryland, USA
[8]NASA SPoRT Center, Huntsville, Alabama, USA
[9]NOAA Aeronomy Laboratory, Boulder, Colorado, USA

mcnider@nsstc.uah.edu

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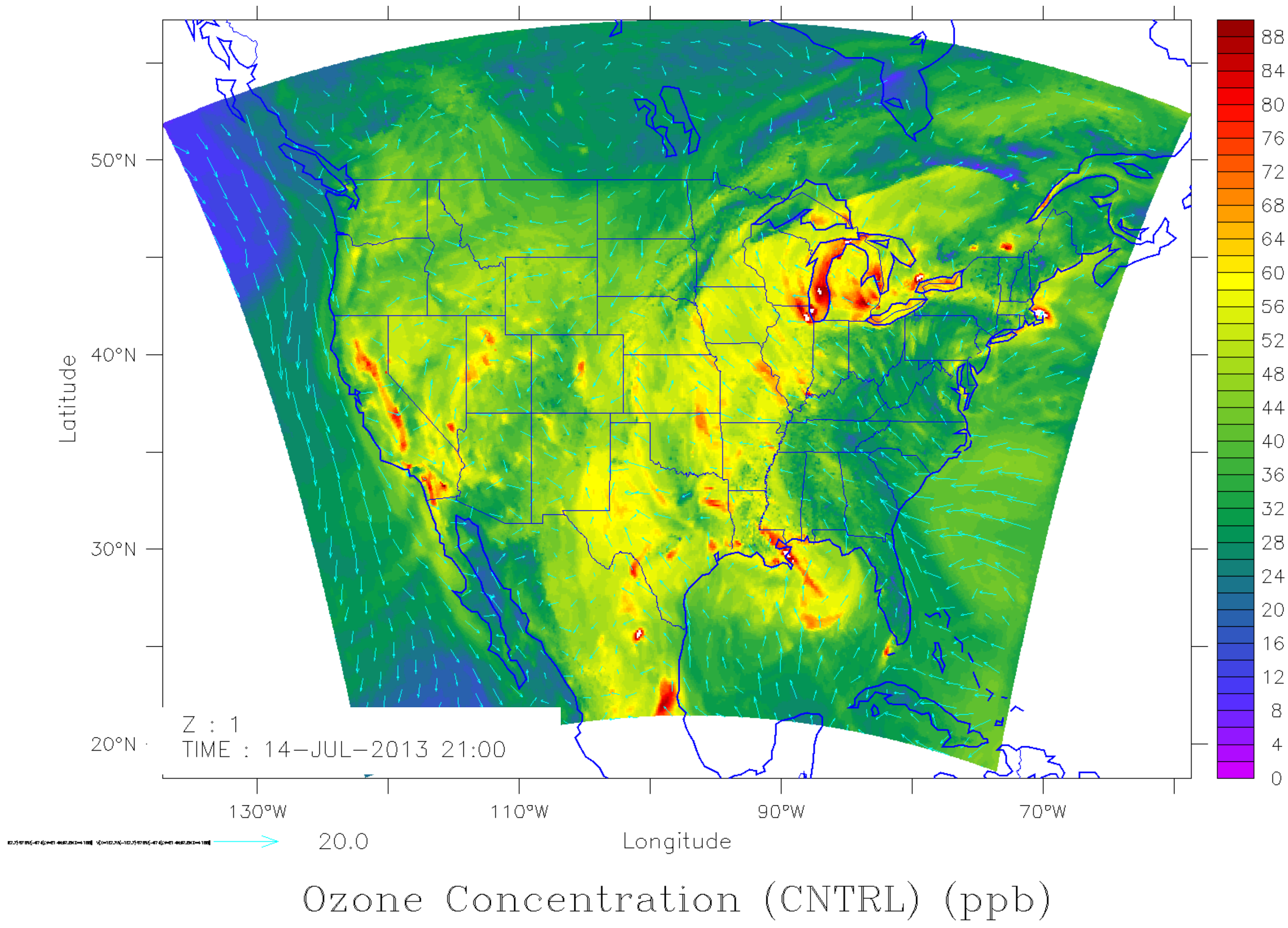
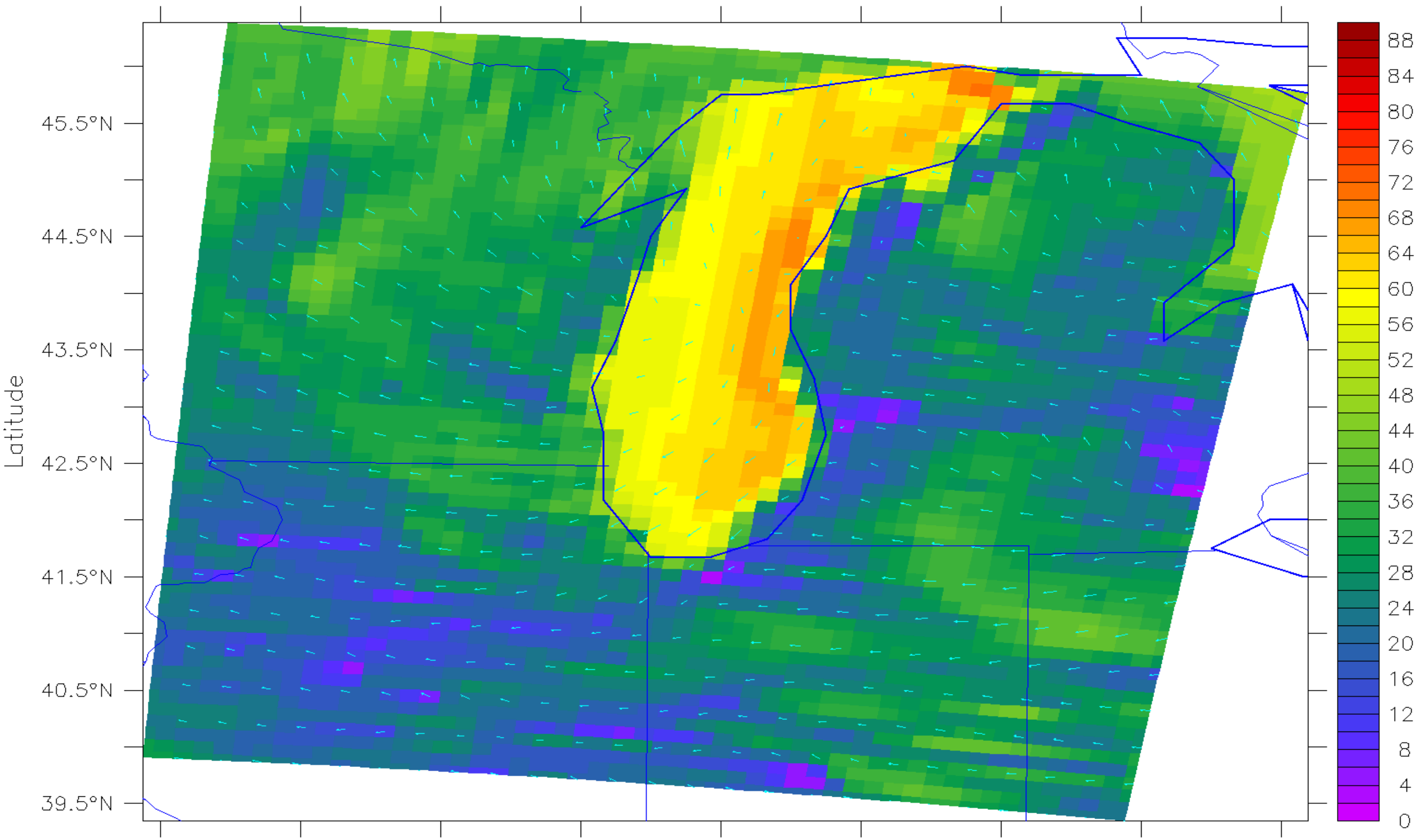
Model images of ozone have long shown high values over the Great Lakes



High ozone appears connected to over water grid boxes. How much of this amplification is real or is it partly a model artifact?



For 2009 ozone season NOAA Operational CMAQ consistently over predicted surface ozone compared to ferry data.

CMAQ Red Ferry Observations Black

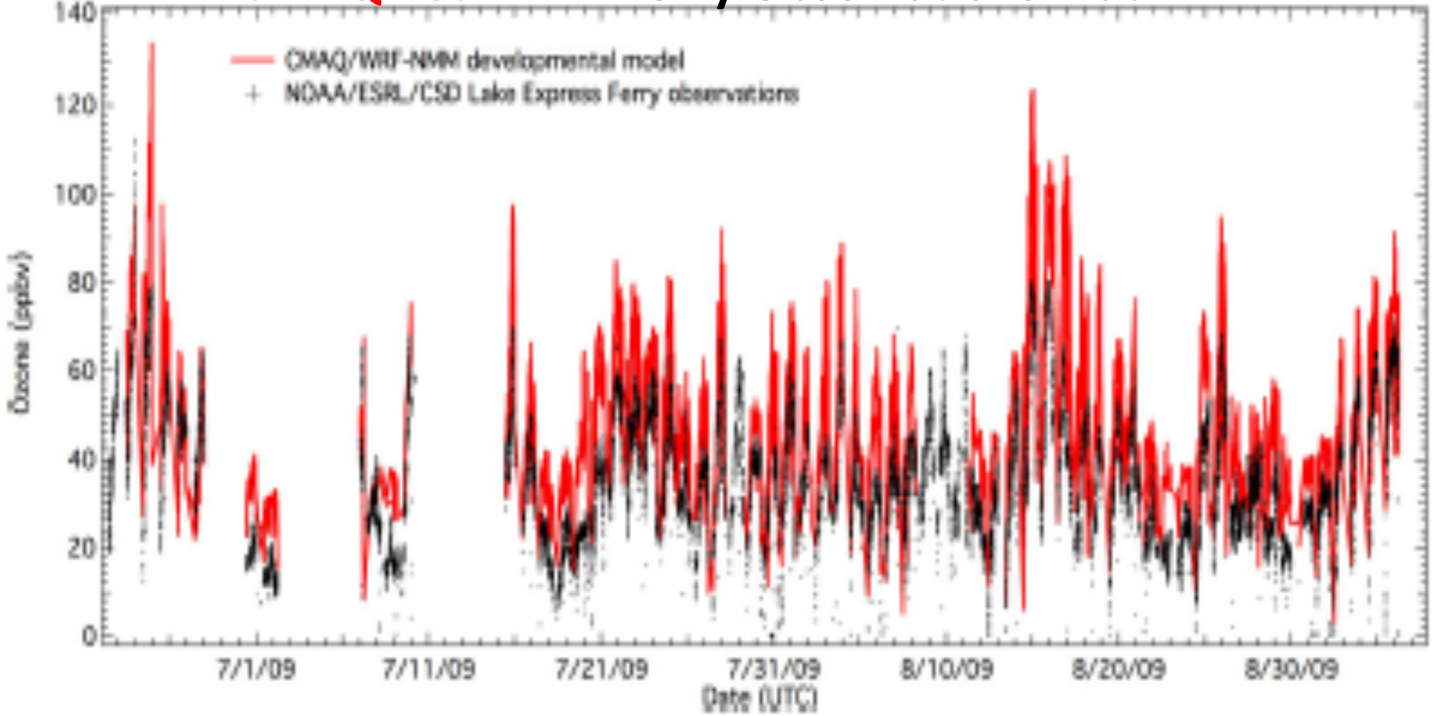


Figure 9. Graph of all CMAQ model forecast ozone mixing ratios in red with *Lake Express* Ferry observations in black from 2009.

From Cleary et al. 2015

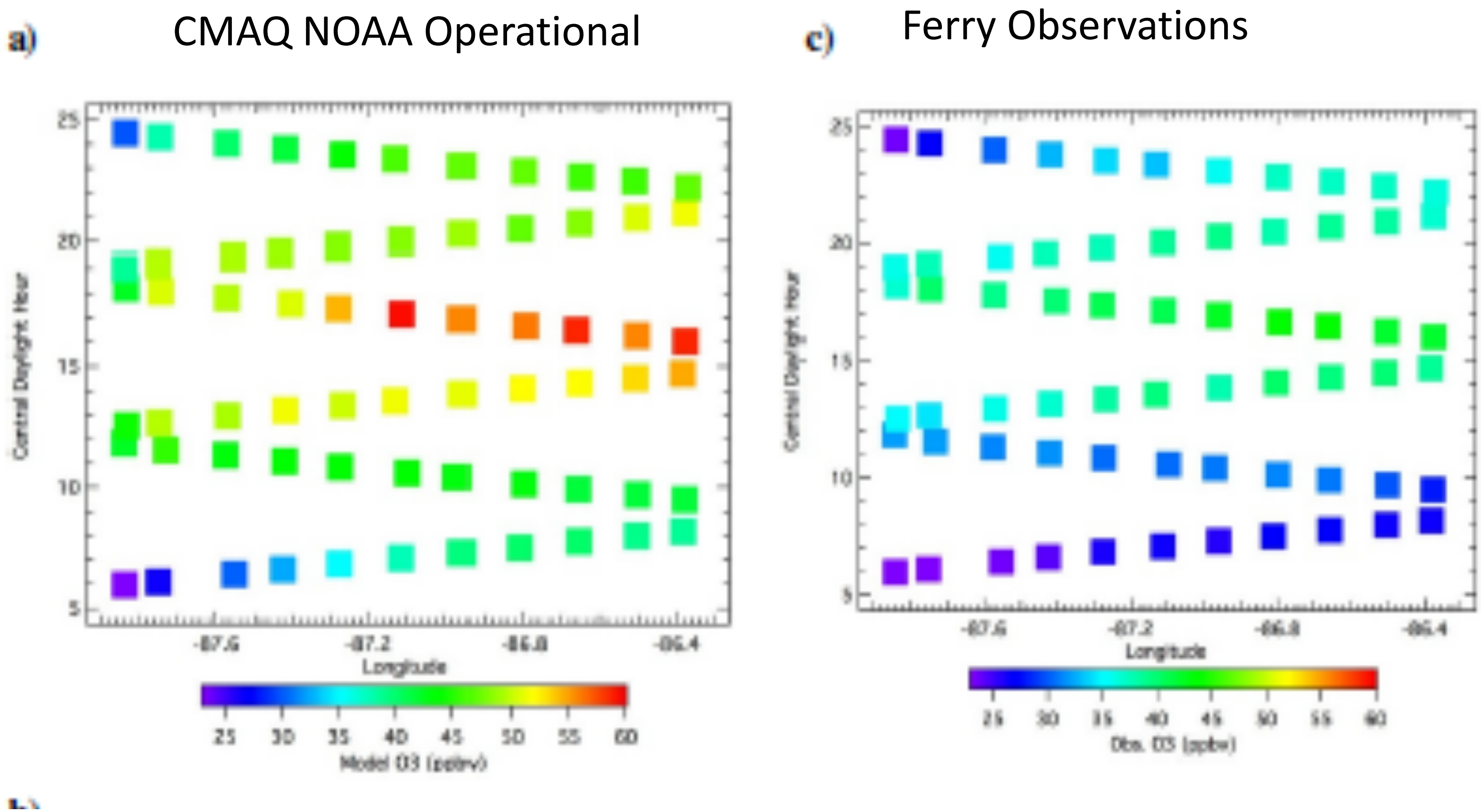


Figure 11. Median O_3 from **(a)** 1 to 24 h CMAQ forecasts, **(b)** 25 to 48 CMAQ forecasts and **(c)** ferry observations.

From Cleary et al. 2015

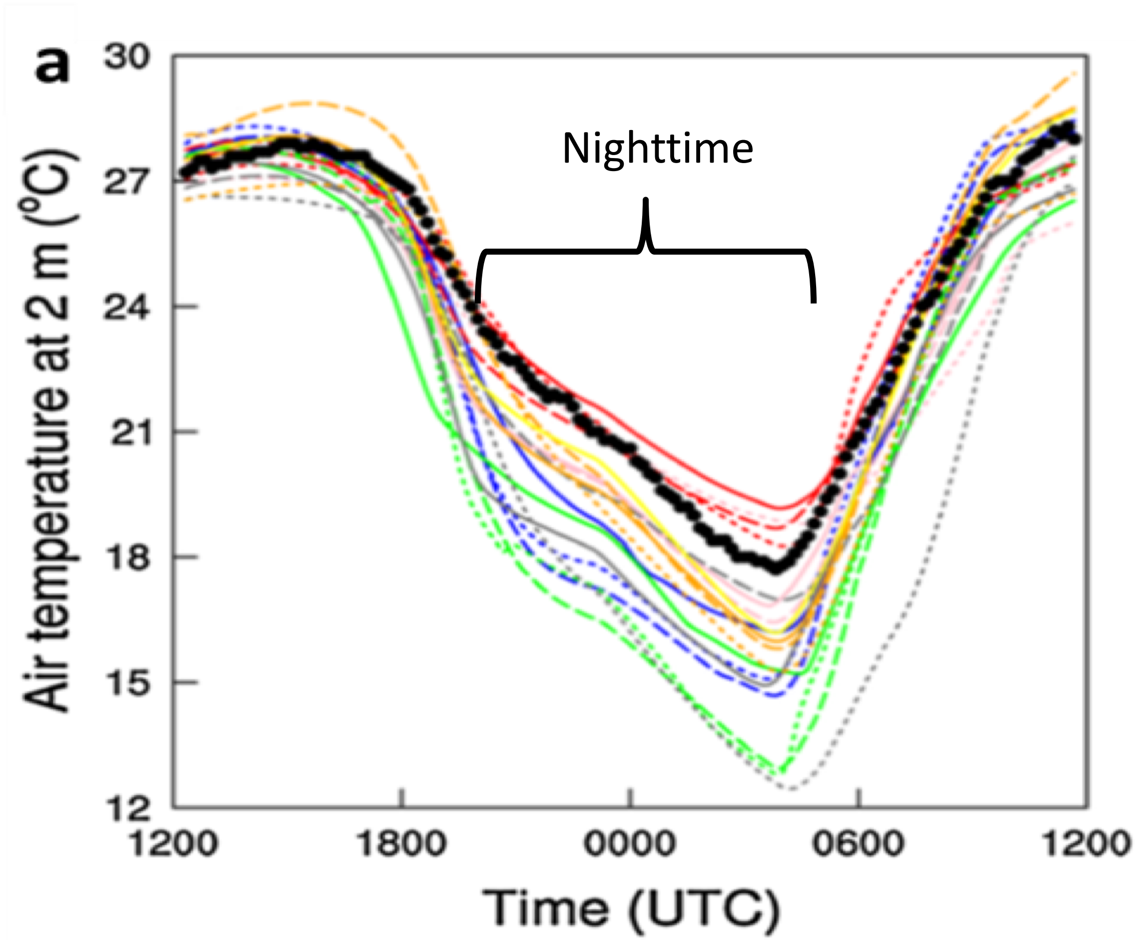
Note that the CMAQ performance discussed above from Cleary et al. 2015 is from the operational CMAQ. The operational CMAQ is forced not by WRF but by NCEP’s 12 km North American Model (NAM).

Excessive Vertical Mixing in Operational Forecast Models

- Operational forecast models (e.g UK Met office and ECMWF -Louis, 1979; Beljaars, 1995; Bechtold et al., 2008)) and climate models have generally had to add mixing to enhance performance evaluations in most settings.
- However, over oceans (Brown et al., 2005) and smooth areas such as the Antarctic interior (King and Connolley, 1997) this added mixing produces problems (Brown et al., 2005). Here reduced mixing formulations such as "short-tailed" forms appear to work better.
- The stable boundary over the Great Lakes may be a place where models have added too much mixing.

For an excellent review – see Savijärvi, H., 2009. Stable boundary layer: Parametrizations for local and larger scales. *Quarterly Journal of the Royal Meteorological Society*, *135*(641), pp.914-921.

Models have uncertain performance in nighttime stable boundary layer



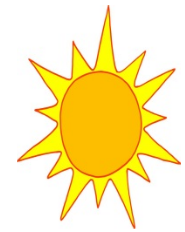
Model Spread in Nighttime Stable Boundary Layer

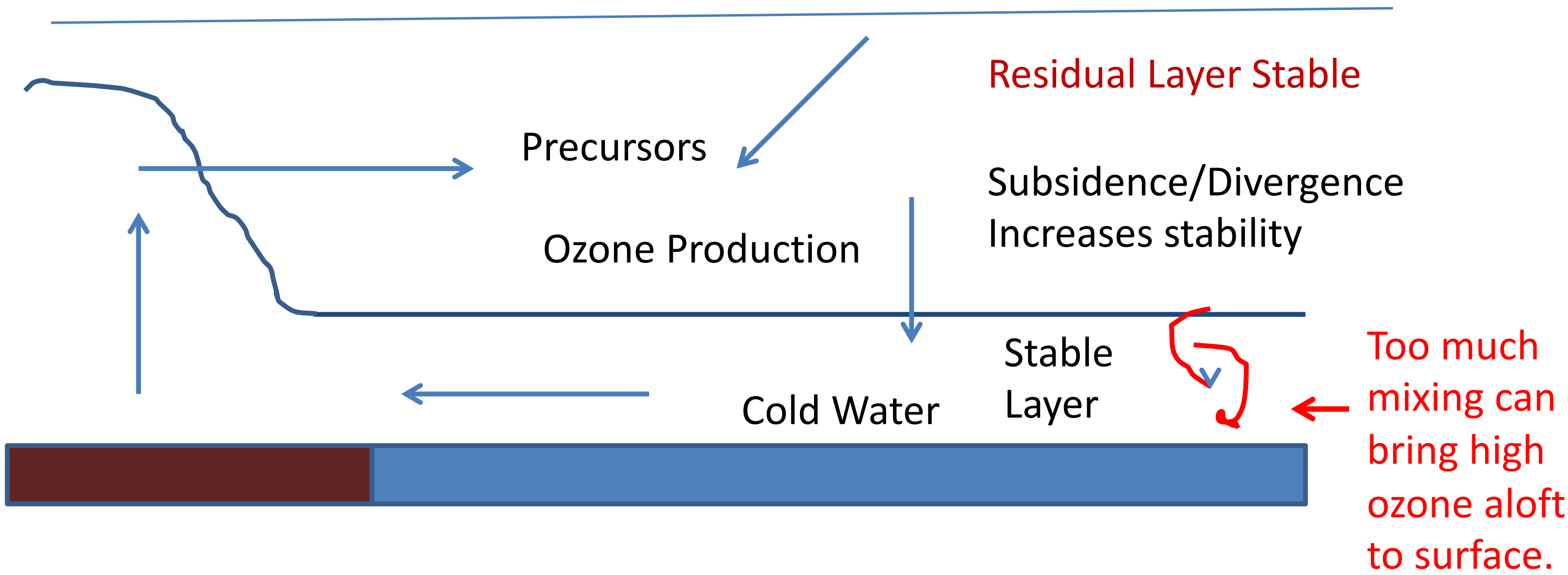
GABLS Model Inter-comparison Study (Bosveld et al. 2014)

CMAQ Over-prediction of Surface Ozone

Hypothesis: There may be due to too much mixing in the stable boundary layer in the operational NAM. This mixing is bringing down ozone from aloft causing surface values to be too high.

Schematic of Ozone Formation in Lake Michigan in the 1990's



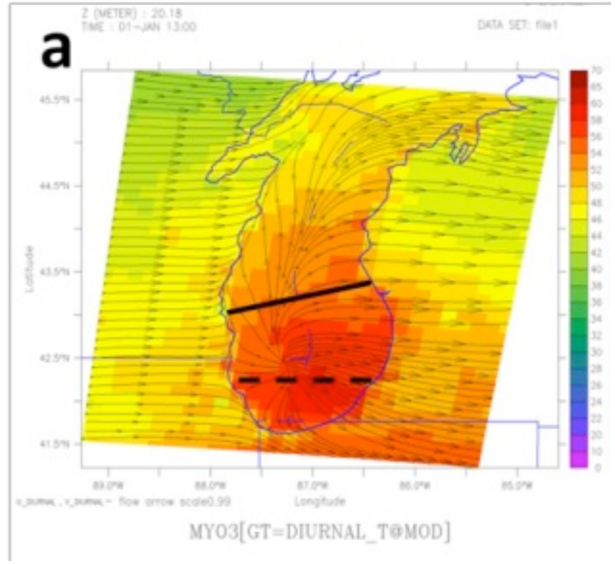


High ozone can be produced in residual layer aloft as a near perfect smog chamber (Dye et al. 1995).

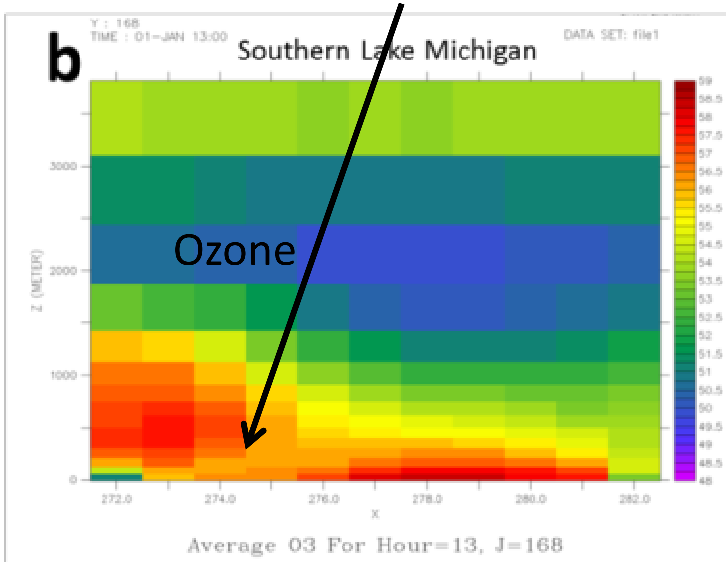
However, if the model has too much mixing then too much ozone from the residual layer may be mixing to surface causing over prediction of surface ozone

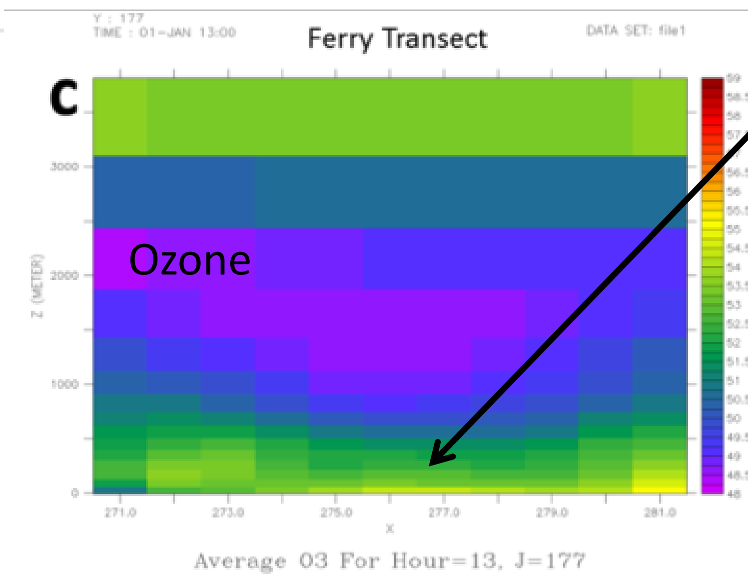
Actual operational CMAQ cross-sections

Over southern Lake Michigan highest ozone was aloft over western shore but not over most of lake



At ferry transact over eastern lake highest ozone was not aloft.





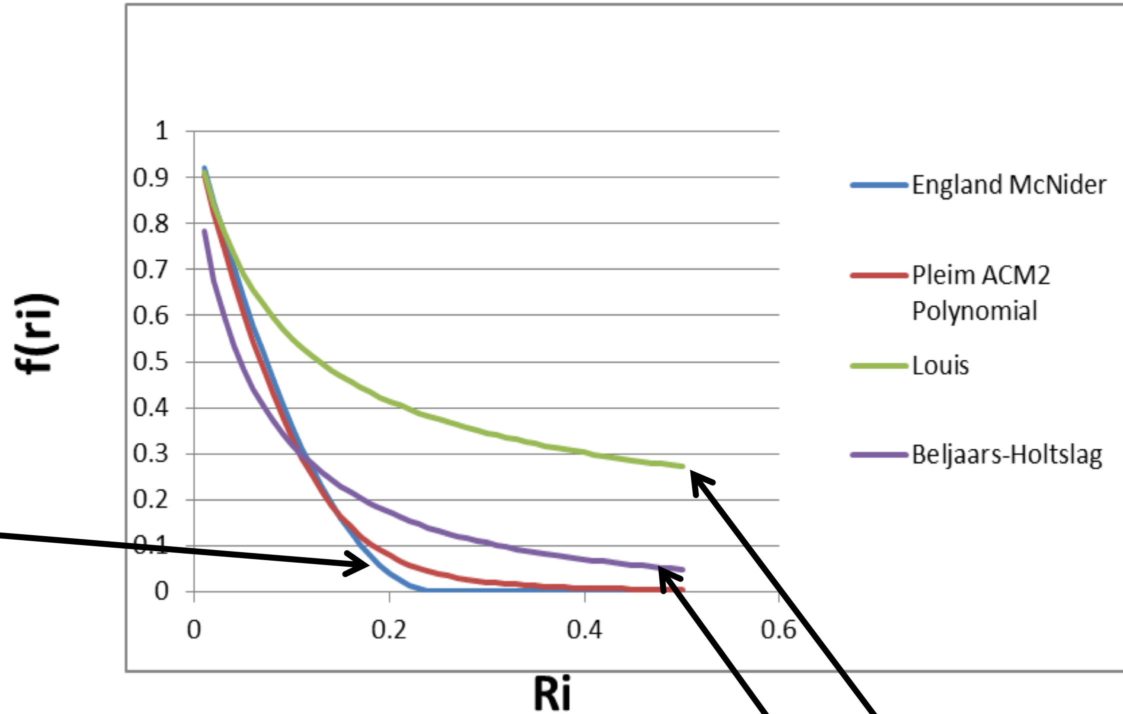
However, in examining VOC/NOx ratios it was found that higher ozone production potential might be aloft over most of lake.

Typical Boundary Layer Stable Parameterization

$$K_z = f(Ri)\ l_m^2 s$$

where l_m is mixing length and s is shear .

$$Ri = \frac{g}{\vartheta}\frac{\partial\theta}{\partial z}/s^2$$

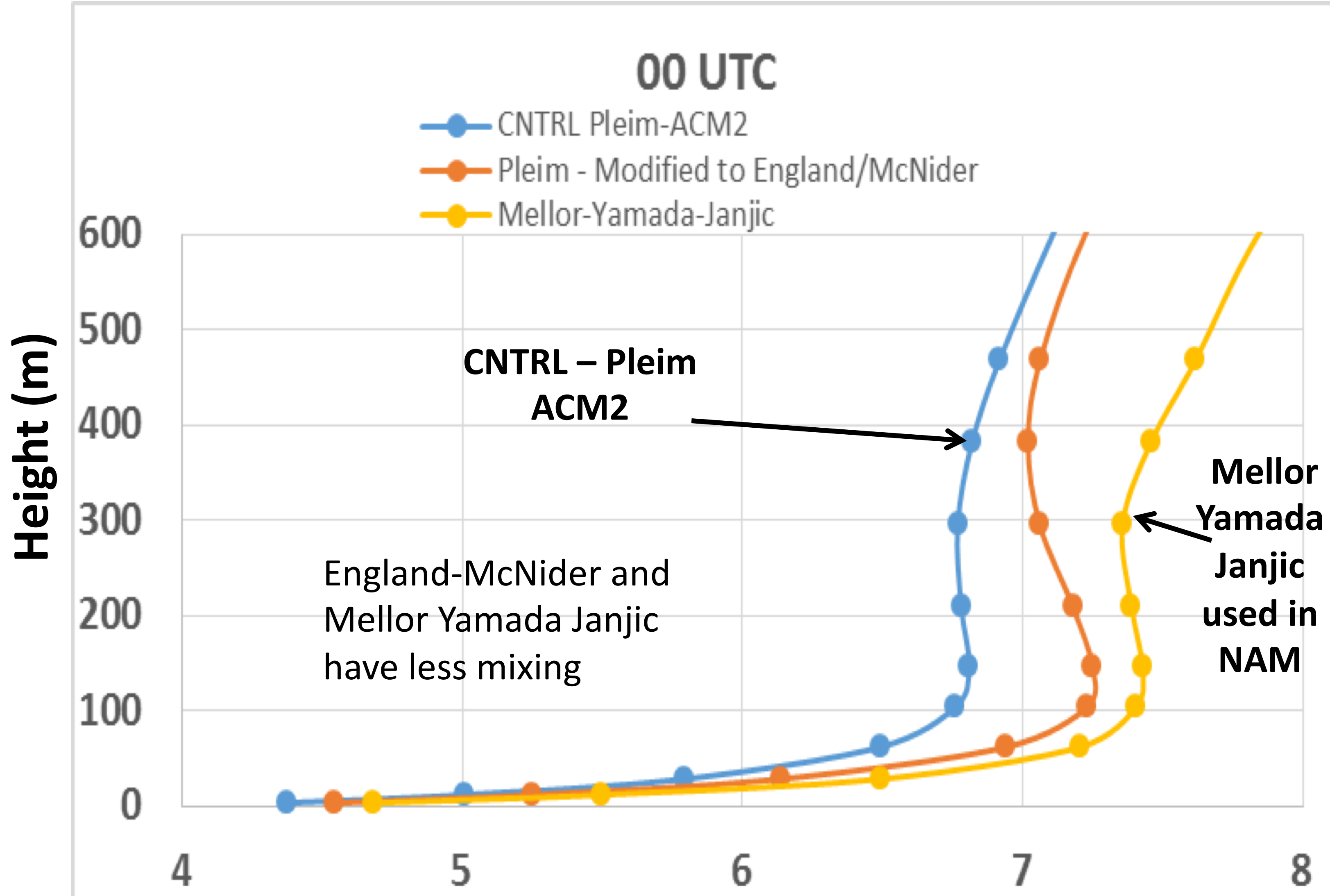


Short-tailed form (England and McNider 1995 *Bound. Layer Meteor) fit to Businger Profiles*

Current Pleim ACM2 scheme has a short-tail form but with slightly more mixing than in McNider et al. 2012 JGR

Long-tailed – Maintains mixing well beyond what fundamental theory prescribes

Wind Speed Profiles



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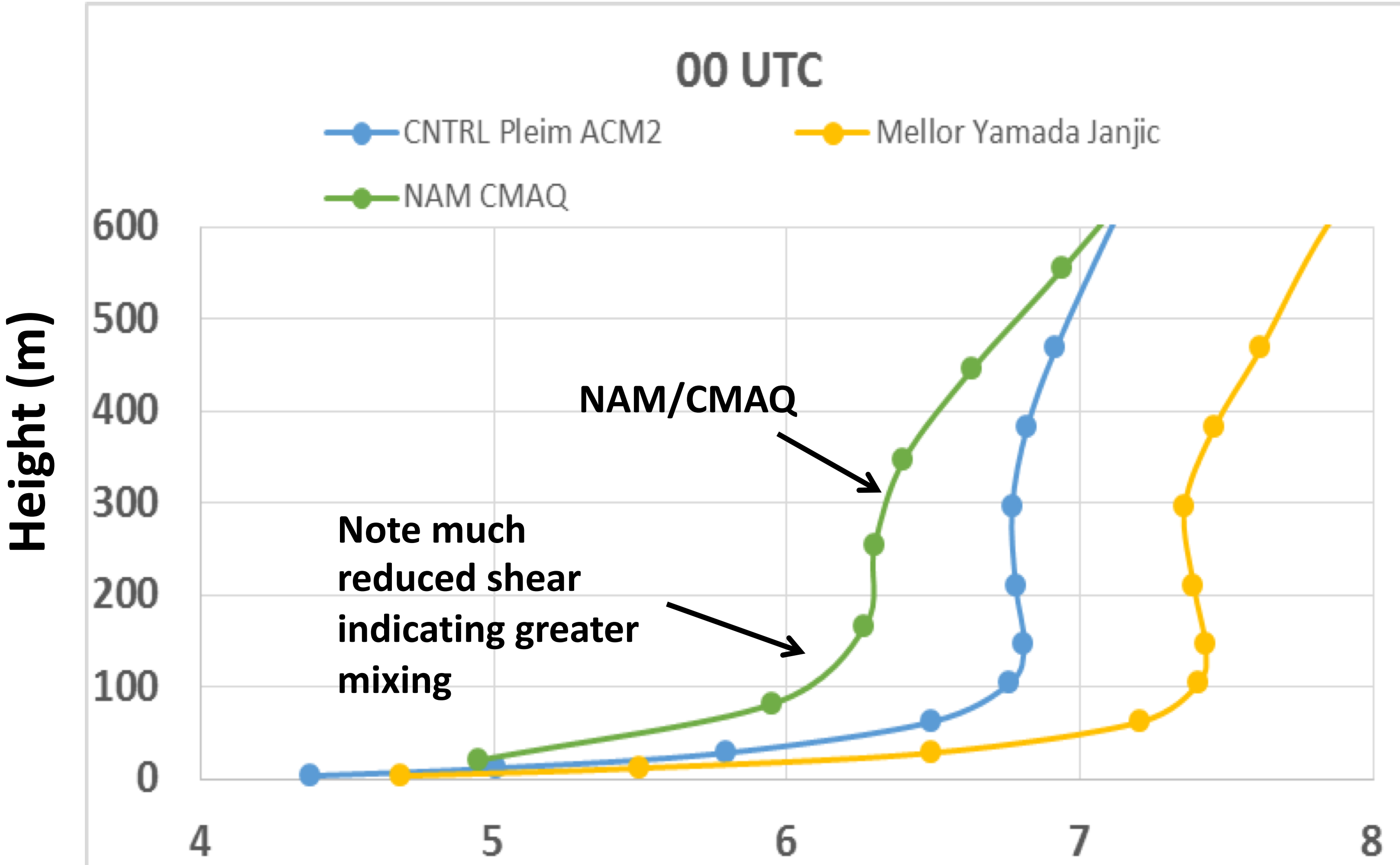
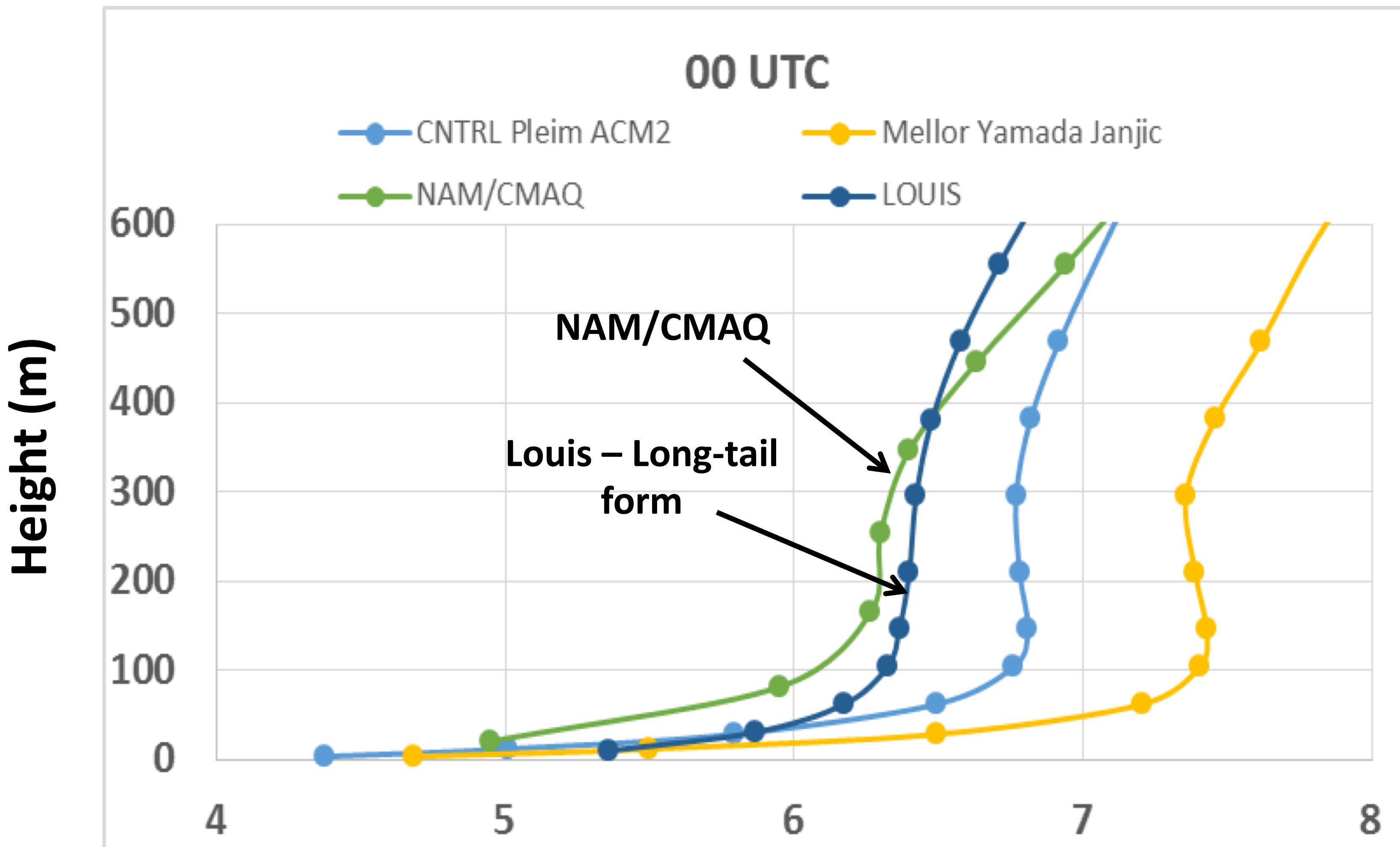


Wind Speed Profiles



CMAQ Chemistry Runs to Examine Impact of Mixing

The mixing sensitivity runs discussed above shows that the operational NAM/CMAQ likely had much larger mixing than the Pleim-ACM2 scheme.

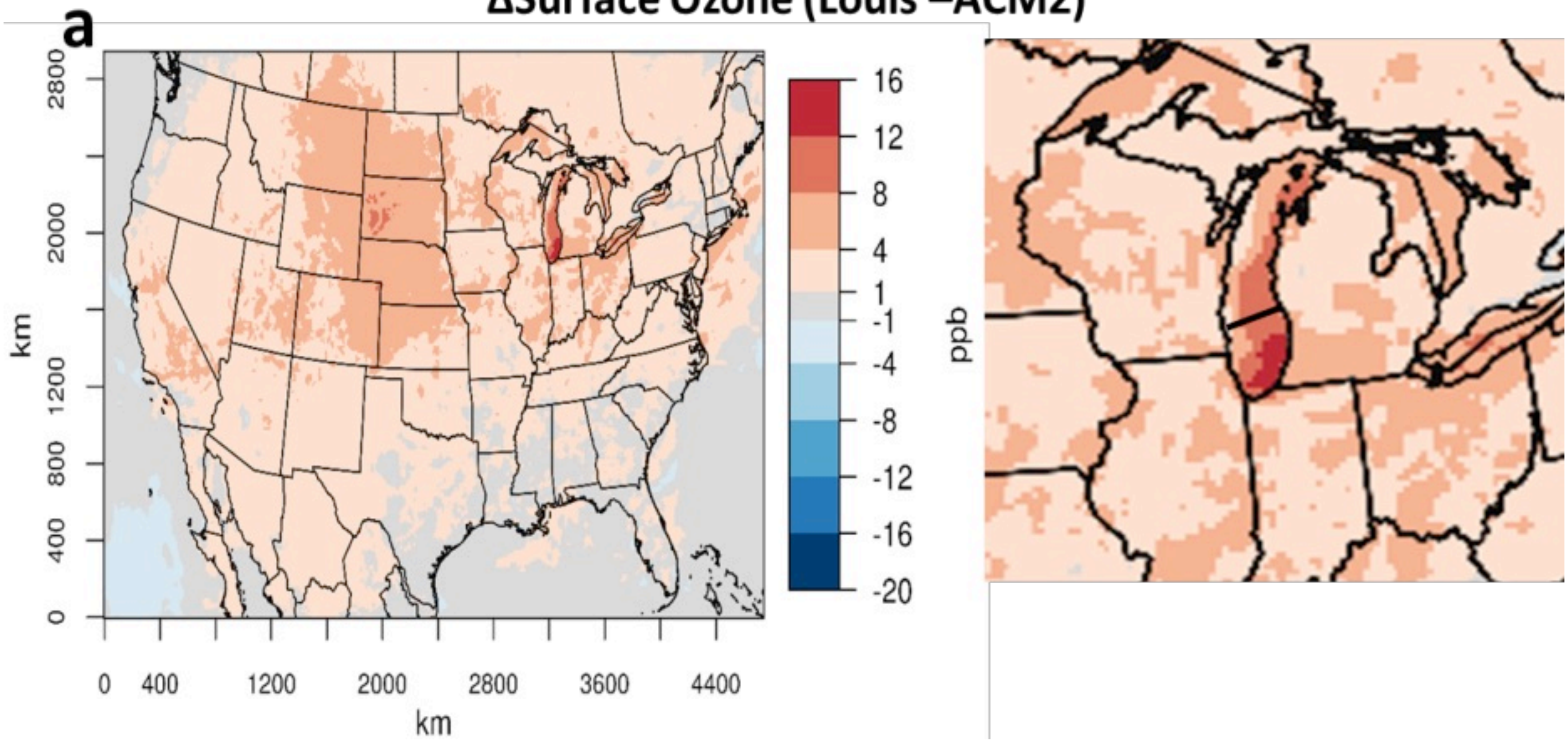
In order to test whether too much mixing may have been responsible for the ozone over-prediction over water two WRF/CMAQ chemistry runs were carried out.

The CMAQ runs were made for August 2011 by Georgia Tech.

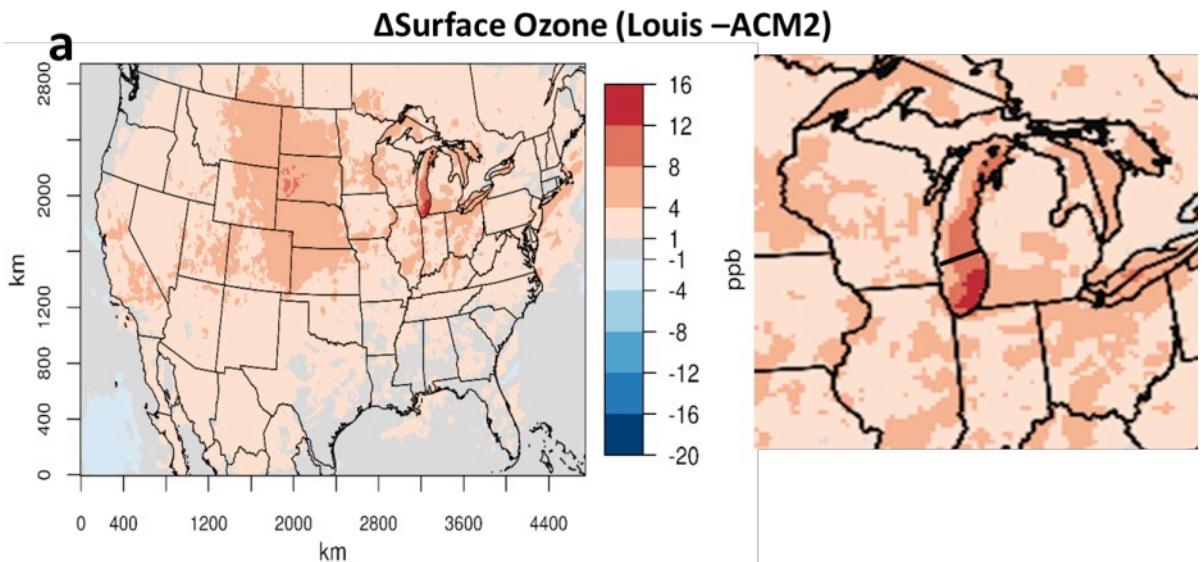
1. **WRF was run with the standard Pleim ACM2. This WRF run was then used to drive CMAQ.**

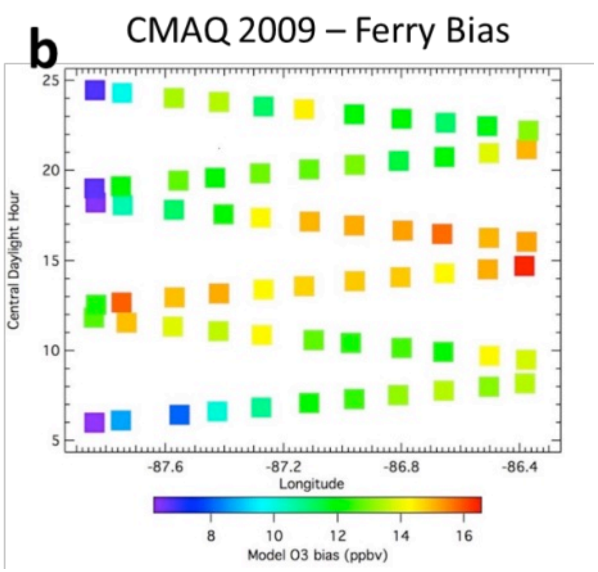
2. **WRF was run with the long-tailed Louis scheme (greater mixing). This WRF was used to drive CMAQ.**

ΔSurface Ozone (Louis –ACM2)



The CMAQ runs showed that indeed the model run driven by the Louis (larger mixing) WRF increased ozone over Lake Michigan





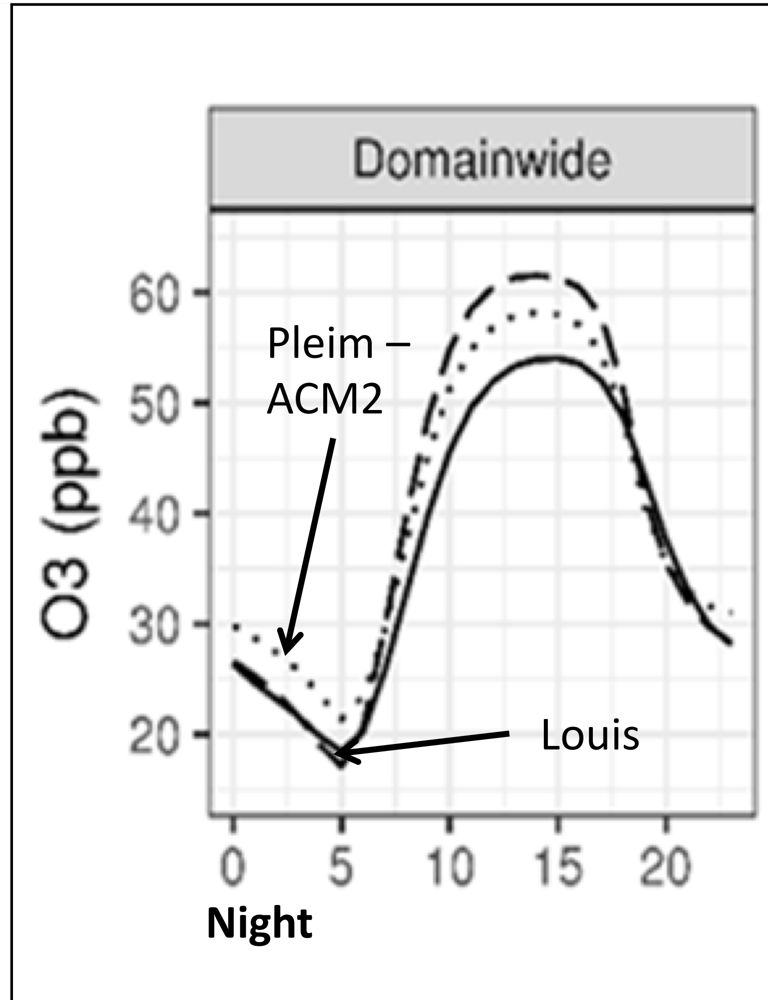
The pattern of increased ozone was consistent with the over-prediction seen in the operational CMAQ runs reported by Cleary et al. 2015.

At this point we might have concluded that our original hypothesis – that too much mixing in the meteorological was responsible for the operational CMAQ over-prediction was valid.

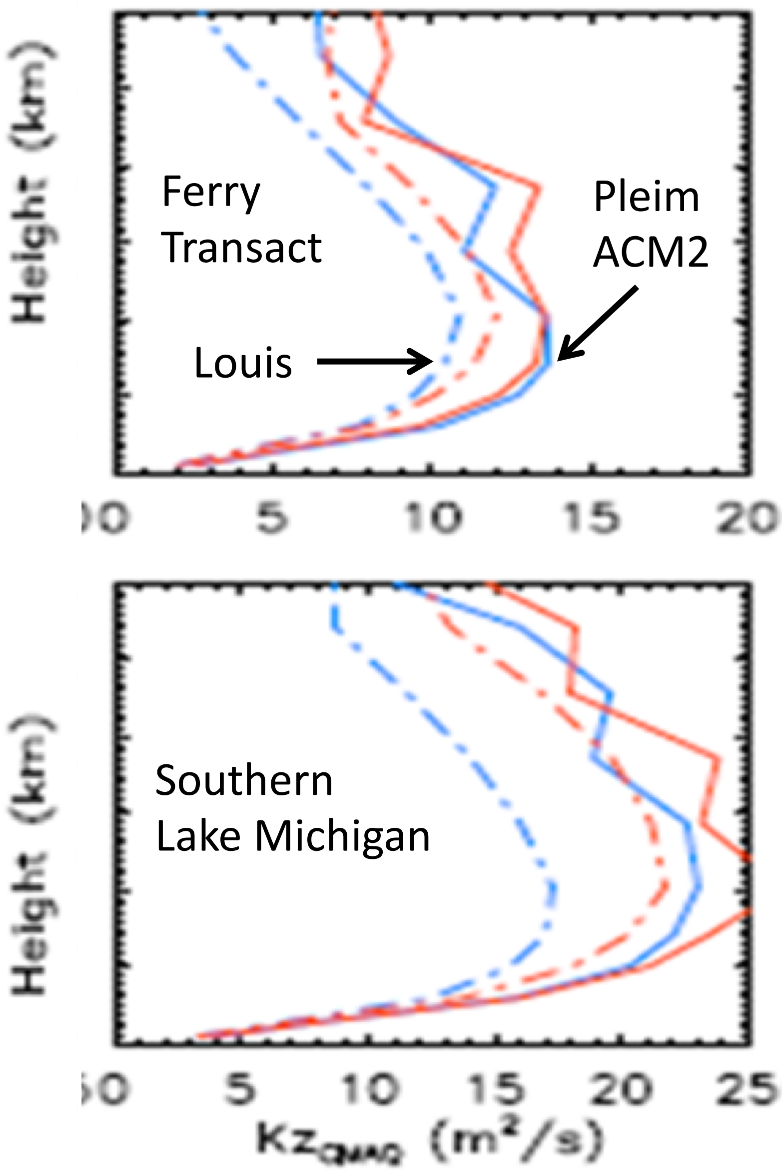
However, an examination of time series plots from the two CMAQ runs gave us pause.

Observed ——— Control (ACM2) ··········· Louis - - - -

The Louis formulation which should have mixed more ozone to the surface at night actually showed lower ozone. This was then a hint that the Louis form was actually producing less mixing in CMAQ than the Pleim-ACM2 formulation.



Vertical Mixing Coefficients



The solid lines are for the Pleim ACM2 case (small mixing) and dashed dotted lines for the Louis case (large mixing).

Blue is for 12 UTC and red for 18 UTC

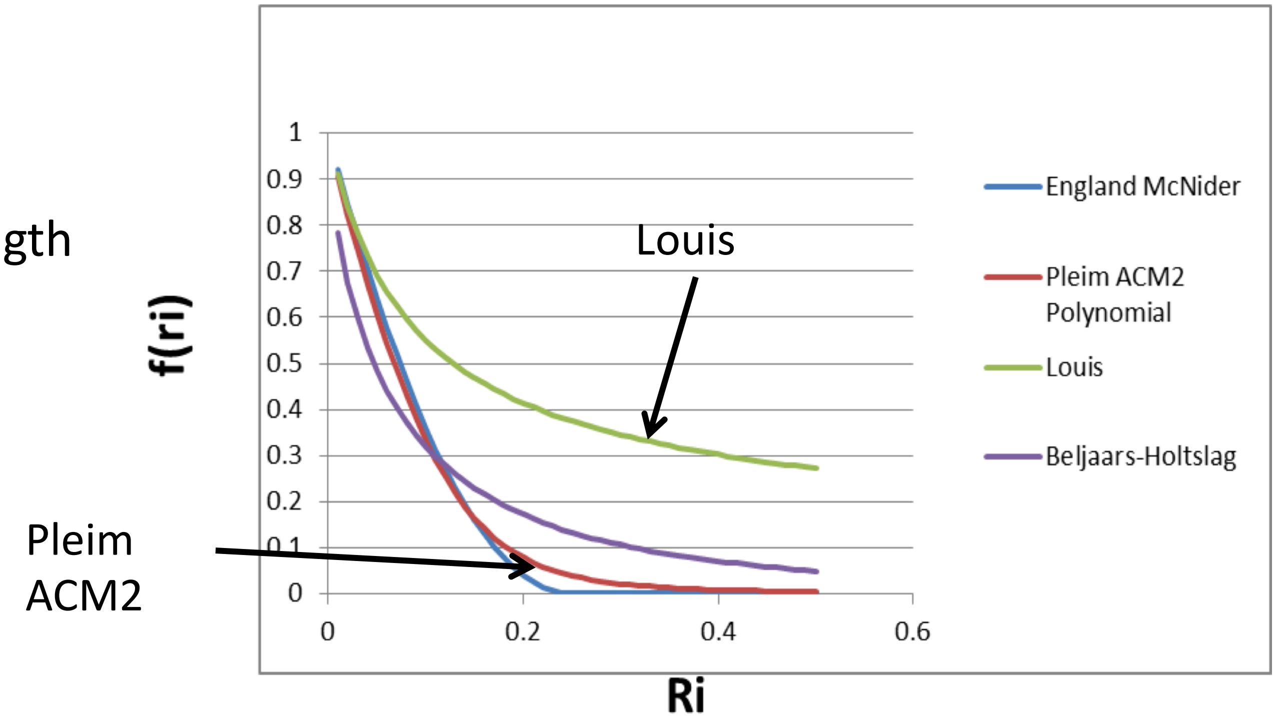
Plots show that the K_z diagnosed in CMAQ are smaller for the Louis form than from the Pleim ACM2.

So why are K's in CMAQ smaller for Louis than Pleim ACM2?

$K_z = f(Ri)\ l_m^2 s$

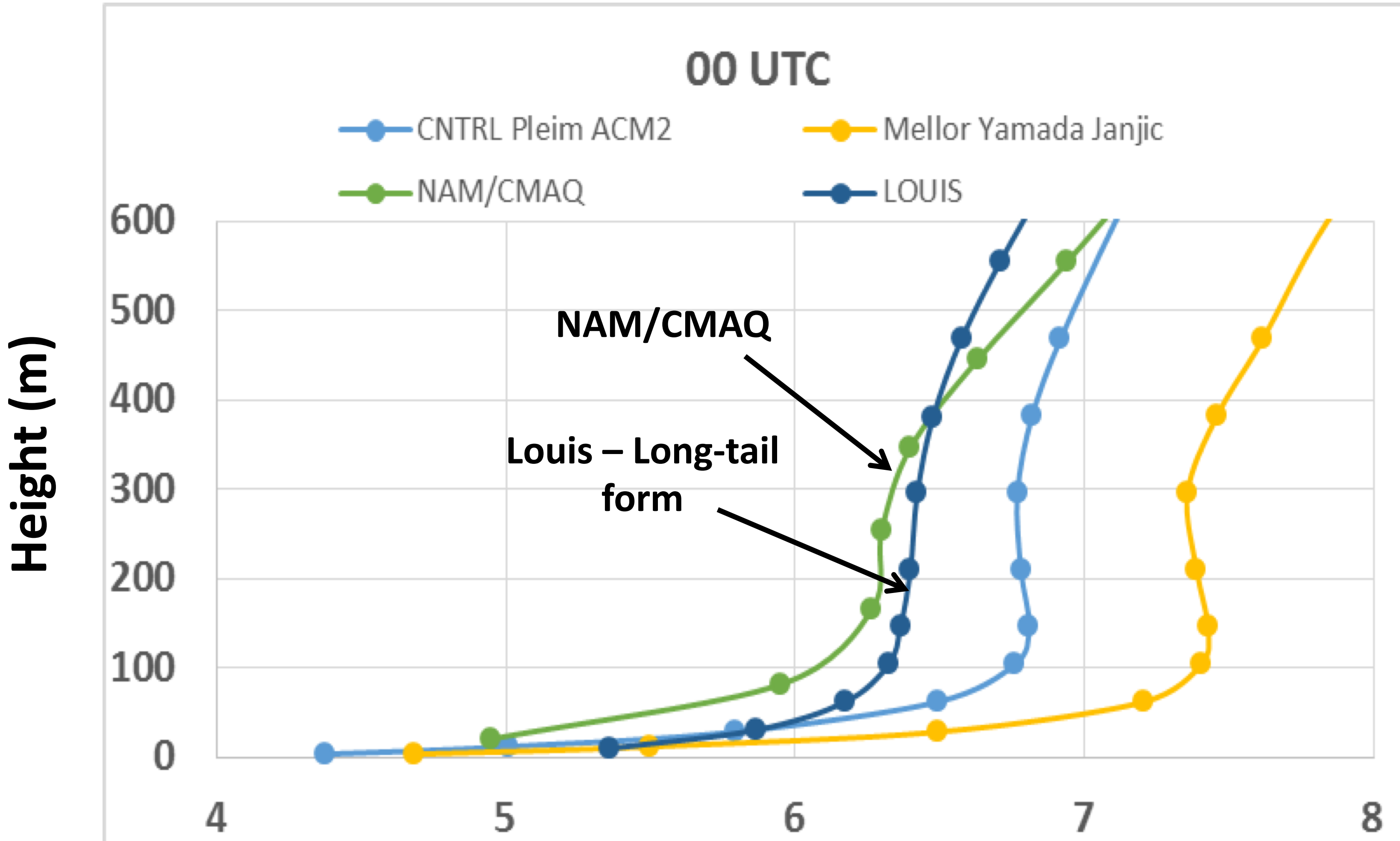
where l_m is mixing length and s is shear .

$$Ri = \frac{g}{\vartheta}\frac{\partial\theta}{\partial z}/s^2$$



The answer is that CMAQ does not use the Ks from WRF or NAM. It rediagnoses Ks from wind and temperature profiles. In WRF the Louis Ks are so large they mix out the shear. When this shear is used in the CMAQ diagnosed Ks it produces a smaller K than in WRF.

The shear that is passed to CMAQ has already been mixed out by the large Ks in WRF (or NAM). Thus, rediagnosed Ks are smaller.



Summary and Conclusions

Based on this analysis it is concluded that excessive mixing in the stable boundary layer in the operational NCEP NAM actually produces less mixing in CMAQ.

The analysis also brings up questions about using CMAQ in an offline form. The wind and temperature profiles passed to WRF represent the result of mixing . Using these to diagnose Ks in CMAQ may lead to error.

Using the same mixing formulation in WRF and in CMAQ may minimize this error.

For example the Pleim –ACM2 should be used in WRF since it is currently the form used in CMAQ . However, the shear in WRF reflects the mixing that has already occurred. Thus, the Ks in CMAQ using Pleim ACM2 may be smaller than Pleim ACM2 Ks in WRF.

The Pleim ACM2 may have more mixing than Mellor-Yamada- Janjic or England-McNider.

Part II: Vertical Nudging Strategies

A common nudging strategy in the air quality community has been to nudge only above the boundary layer.

However, the nocturnal boundary is quite shallow. In the residual layer between the old daytime boundary and the nocturnal boundary layer important physical phenomena such as the low level jet can be manifested.

The impact of nudging in the residual layer was examined.

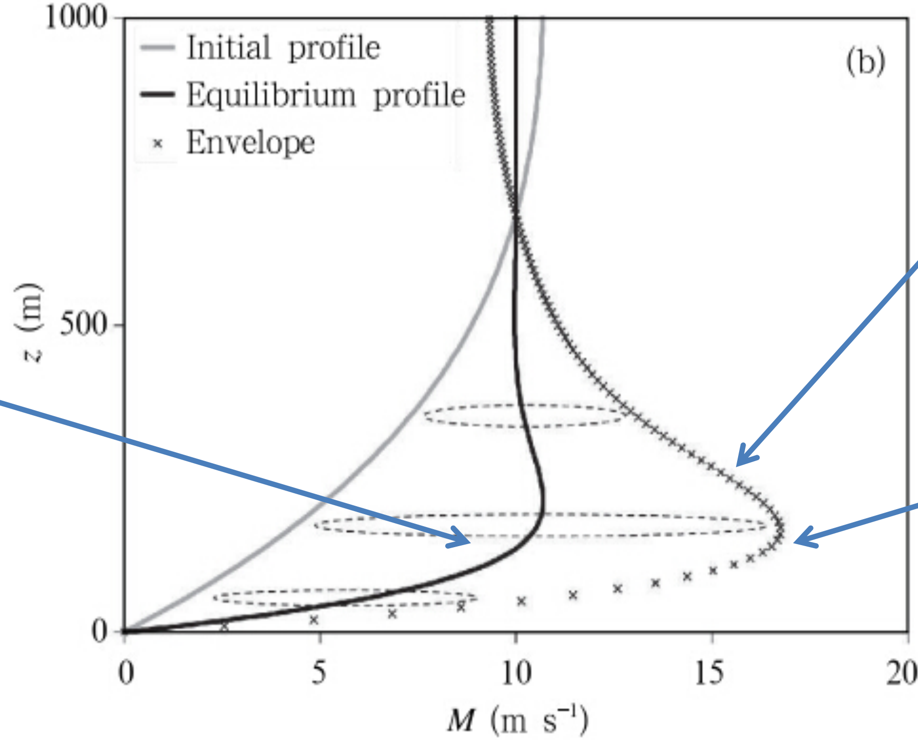
As discussed first by Schafran 2000 in a Great Lakes study, standard rawinsonde data in the Midwestern U.S. at 00UTC (~6PM LST) and 12 UTC (~6AM LST) does not capture the nocturnal low level jet.

Thus, there should be caution in using large scale analyses based on rawinsonde data to nudge the model in FDDA assimilation

Schafran 2000 did not provide any specific examples. Here we provide example impact of nudging on wind profiles and impact on air quality.

Illustration of Blackadar Low Level Jet

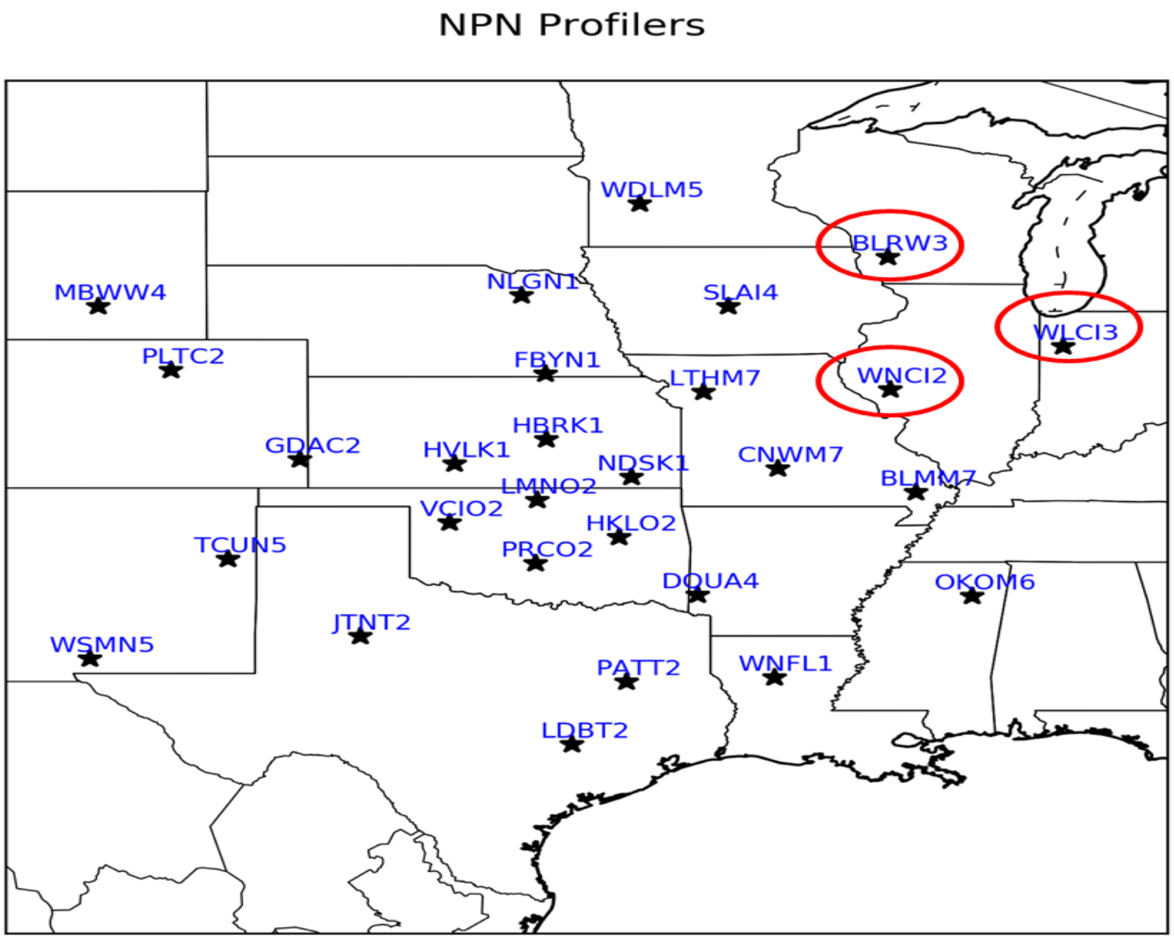
During the day turbulent mixing retards wind speed



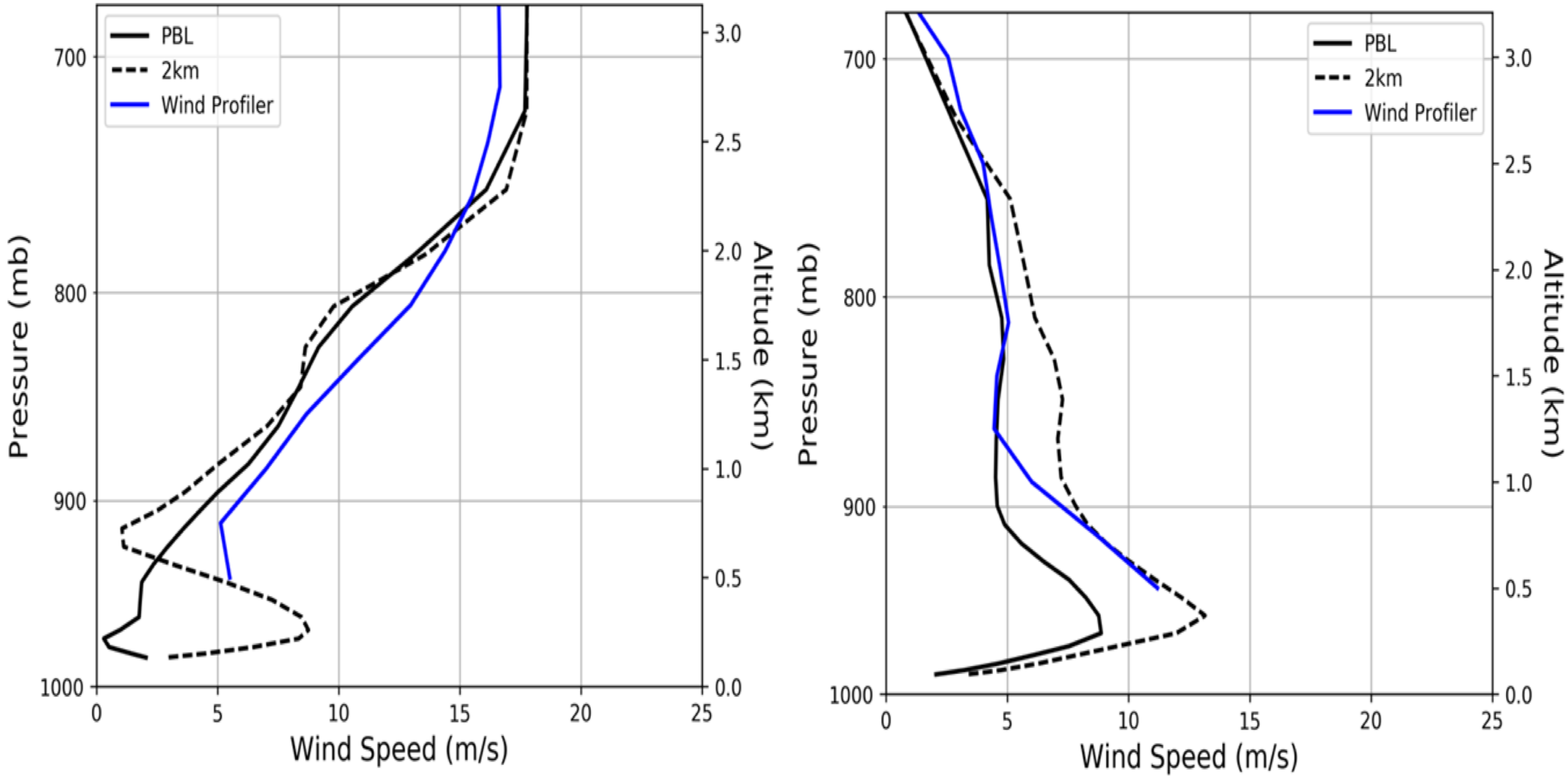
At night the reduced mixing causes the flow to accelerate leading to an inertial oscillation as the flow adjust to a new balance.

This produces a low level jet.

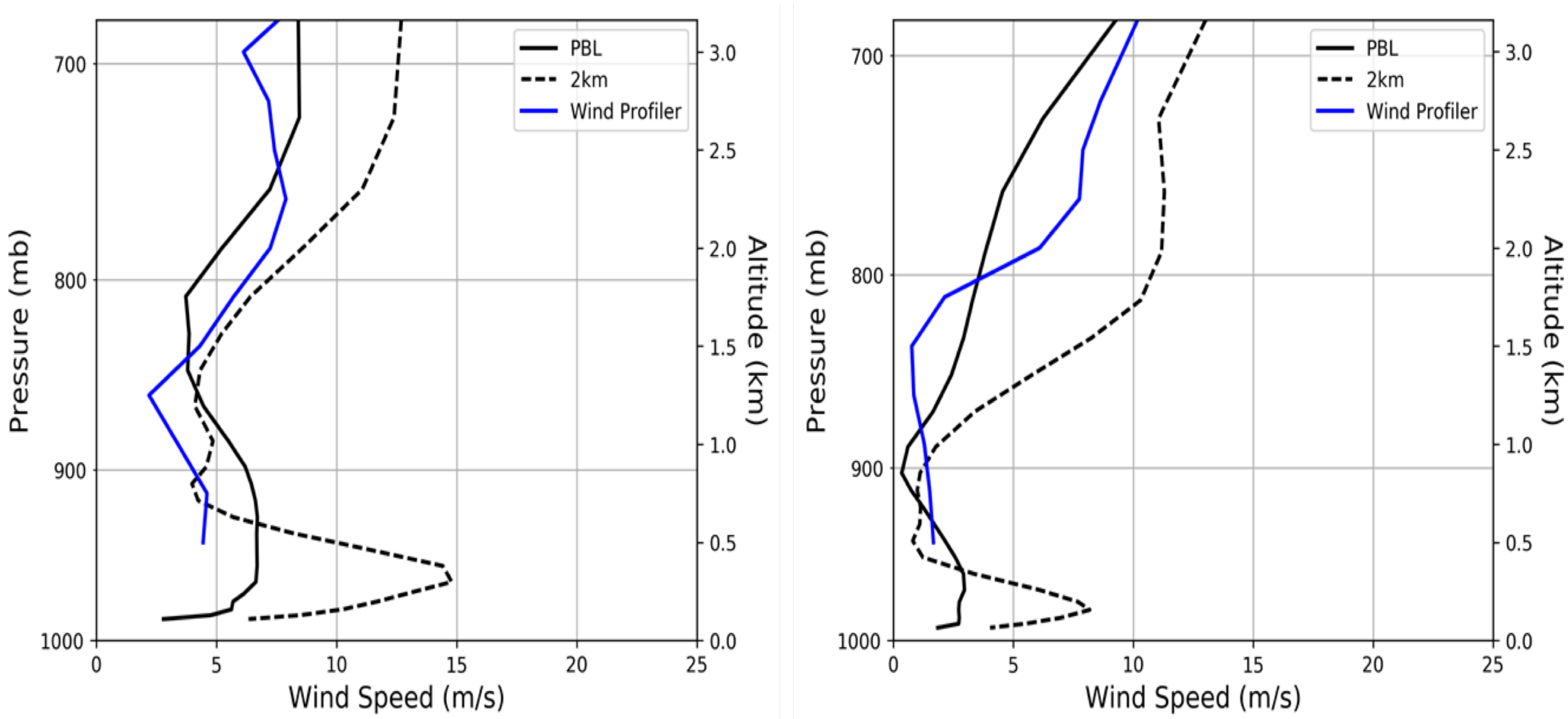
Illustration from LIU Hongbo, HE Mingyang



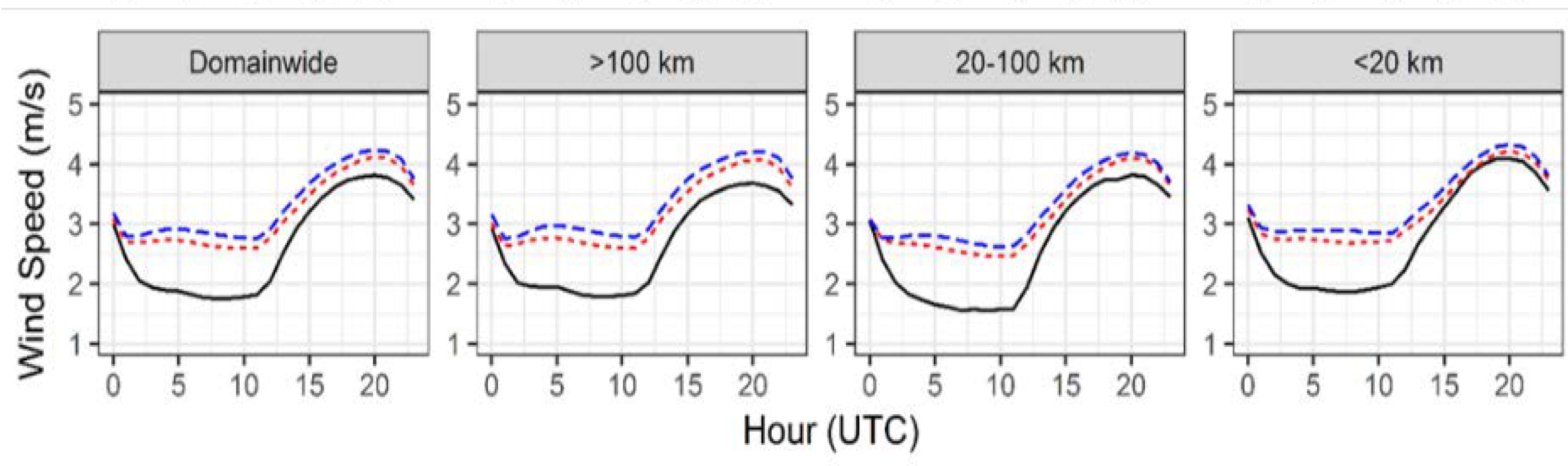
Locations of NOAA National Profiler Network (NPN) profiler sites. Model comparative statistics were based on all sites. Red circled stations show locations where specific low level jets were compared to model nudging strategies.



Model and observed wind profiles at profiler location WLCI3 (Northern Indiana). Left is at 0400 UTC (2200 LST) 17 June 201~~9~~1 and right at 0900 UTC (0300 LST) 24 July 2011. Black solid line is for nudging above PBL. Black dashed line is for nudging only above 2 km. Blue solid line is profiler observation.

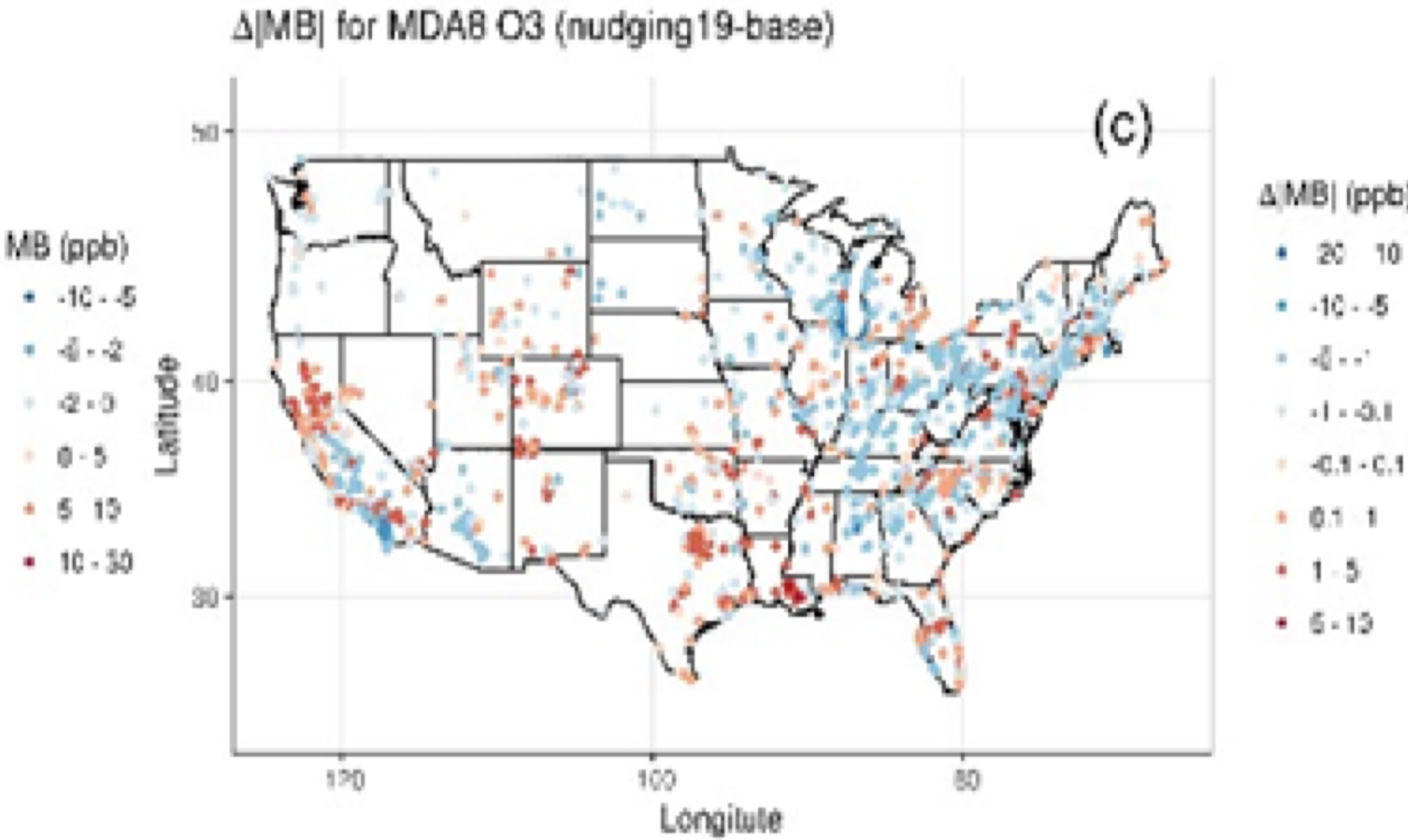


Model and observed wind profiles at profiler location WNCI2 (Western Illinois). Left is at 0300 UTC (2100 LST) 17 June 2011 and right at 0600 UTC (0000 LST) 4 July 2011. Black solid line is for nudging above PBL. Black dashed line is for nudging only above 2 km. Blue solid line is profiler observation.



While nudging only above 2km did allow low level jet to developed it slightly deteriorated surface wind performance

Nudging above 2km did improve ozone bias especially around Lake Michigan



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