A New Combined Local and Non-Local Boundary Layer Model: ACM2

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Outline

- Model development
- 1-D testing and evalution
  - Large Eddy Simulation (LES)
  - GABLS Experiment (CASES99)
- MM5 testing and evaluation
- Preliminary CMAQ testing
- WRF implementation

Purpose

- Develop a simple PBL model that:
  - Produces realistic profiles in CBL
  - Accurate PBL heights
  - Appropriate for all stability conditions w/ minimal discontinuities
  - For both meteorology and chemistry models
  - Computationally efficient

Background

- Local flux-gradient proportionality (i.e. Eddy diffusion) is not appropriate for Convective Boundary Layers
  - Upward heat flux penetrates to ~80% of *h* while potential temperature gradients are very small through most of the PBL
  - Eddies in CBL are larger that vertical grid spacing (local closure is not appropriate)
- Two common alternative approaches:

1. Gradient adjustment term:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K_h \left(\frac{\partial \theta}{\partial z} - \gamma_h \right) \right)$$

Deardorff 1966,Troen and Mahrt 1986, Holstlag and Boville 1993, Noh et al. 2003

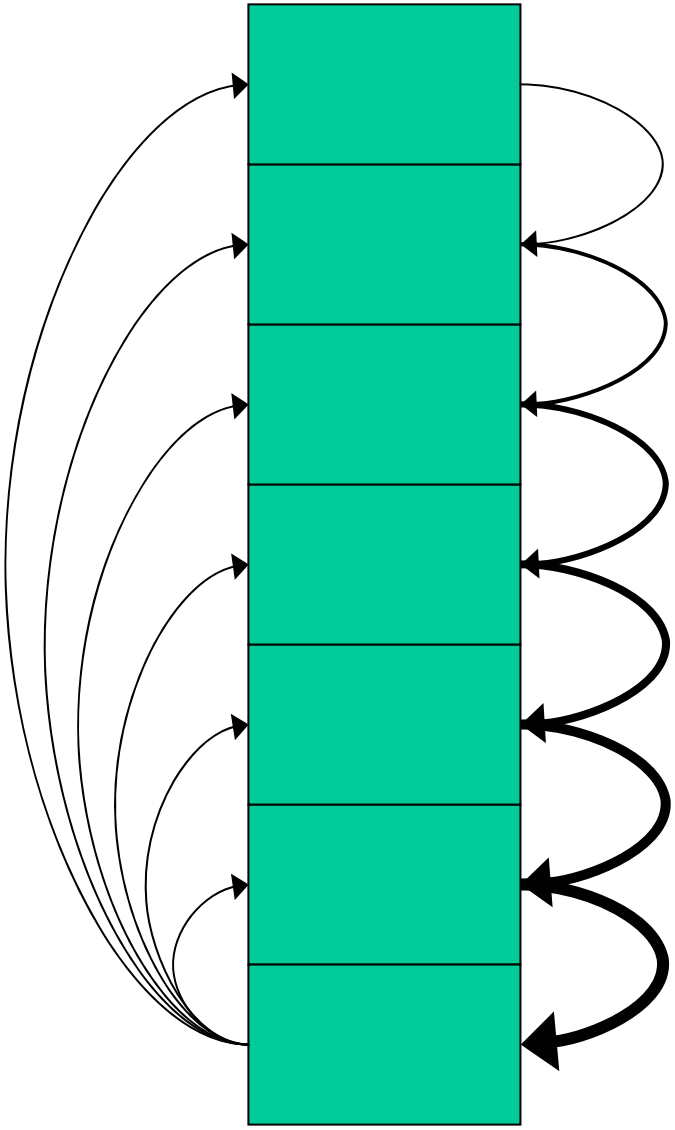
2. Transilent or non-local closure:

$$\frac{\partial \theta_i}{\partial t} = M_{ij}\theta_j$$

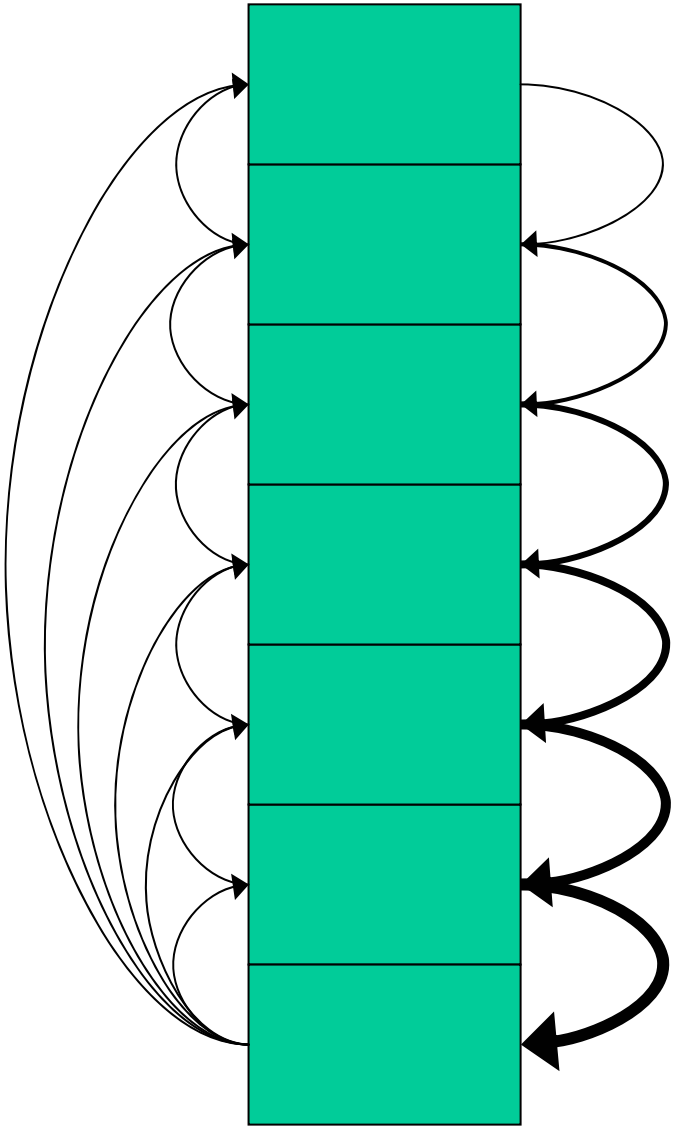
Stull 1984, Blackadar 1976, Pleim and Chang 1992

Asymmetric Convective Model (ACM)

- Original ACM
  - Simple Transilient model
  - Rapid upward transport by convectively buoyant plumes
  - Gradual downward transport by compensatory subsidence
  - Part of the PX-LSM in MM5
- ACM2
  - Added eddy diffusion to ACM
  - Allows local mixing at all levels
  - More realistic (continuous) profiles in lower layers
  - Smooth transition from stable to unstable



ACM



ACM2

Model equations

$$\frac{\partial C_i}{\partial t} = Mu\, C_1 - Md_i C_i + Md_{i+1} C_{i+1} \frac{\Delta z_{i+1}}{\Delta z_i}$$

$$+ \frac{1}{\Delta z_i}\left(\frac{K_{i+1/2}(C_{i+1} - C_i)}{\Delta z_{i+1/2}} + \frac{K_{i-1/2}(C_i - C_{i-1})}{\Delta z_{i-1/2}} \right)$$

Where C_i is mass mixing ratio at center of Layer i
$K_{i+1/2}$ is eddy diffusivity at top of layer i [$m^2 s^{-1}$]
Mu is upward convective mixing rate [s^{-1}]
Md_i is downward mixing rate from layer i to layer i-1 [s^{-1}]

$$Md_i = Mu\left(h - z_{i-1/2}\right) / \Delta z_i$$

h is top of PBL

Non-local Mixing rates

Convective mixing rate derived by conservation of buoyancy flux:

$$\overline{M} = B_{1+\frac{1}{2}} / \left[\left(h - z_{1+\frac{1}{2}} \right) \left(\theta_{v1} - \theta_{v2} \right) \right]$$

Buoyancy flux at top of first layer defined by eddy diffusion:

$$B_{1+\frac{1}{2}} = K_z(z_{1+\frac{1}{2}}) \frac{\left(\theta_{v2} - \theta_{v1} \right)}{\Delta z_{1+\frac{1}{2}}}$$

Where:

$$K_z = k \frac{u_*}{\phi(\frac{z_s}{L})} z(1 - z/h)^2 ; z_s = \min(z, 0.1h)$$

Thus, Convective mixing rate is a function of K_z but not a function of potential temperature gradient:

$$\overline{M} = \frac{K_z(z_{1+\frac{1}{2}})}{\Delta z_1 \left(h - z_{1+\frac{1}{2}} \right)}$$

Partitioning local and non-local

Mixing rate, defined by K_z, is partitioned into local and non-local components

$$Mu = \frac{f_{conv} K_z(z_{1+1/2})}{\Delta z_1 \left(h - z_{1+1/2}\right)} = f_{conv} \overline{M}$$

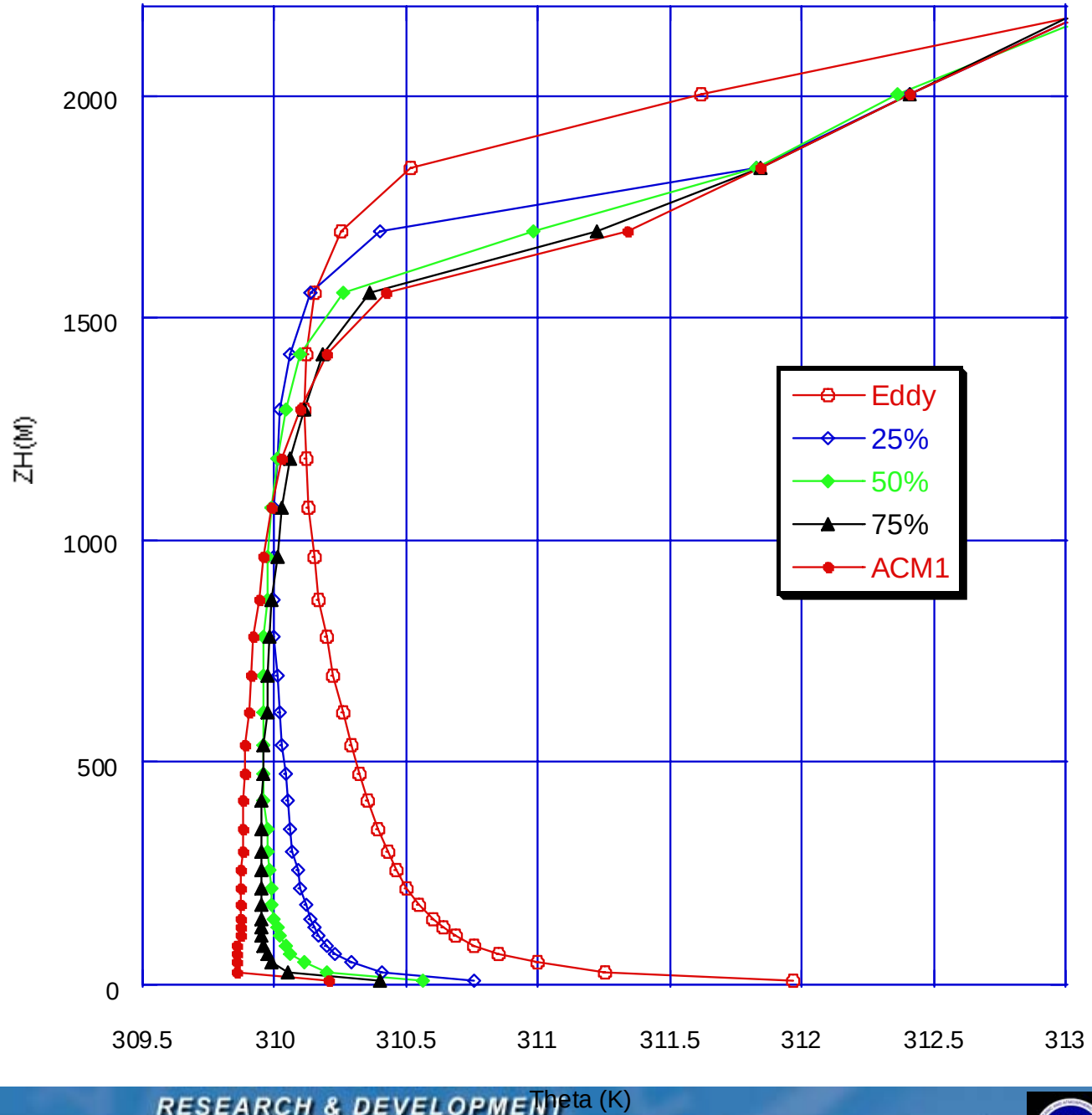
$$K_i = K_z(z)\left(1 - f_{conv}\right)$$

The Question is: How to define f_{conv}?
Clearly it should increase with increasing instability,
but what is its upper limit for free convection?
and what should be its stability function?

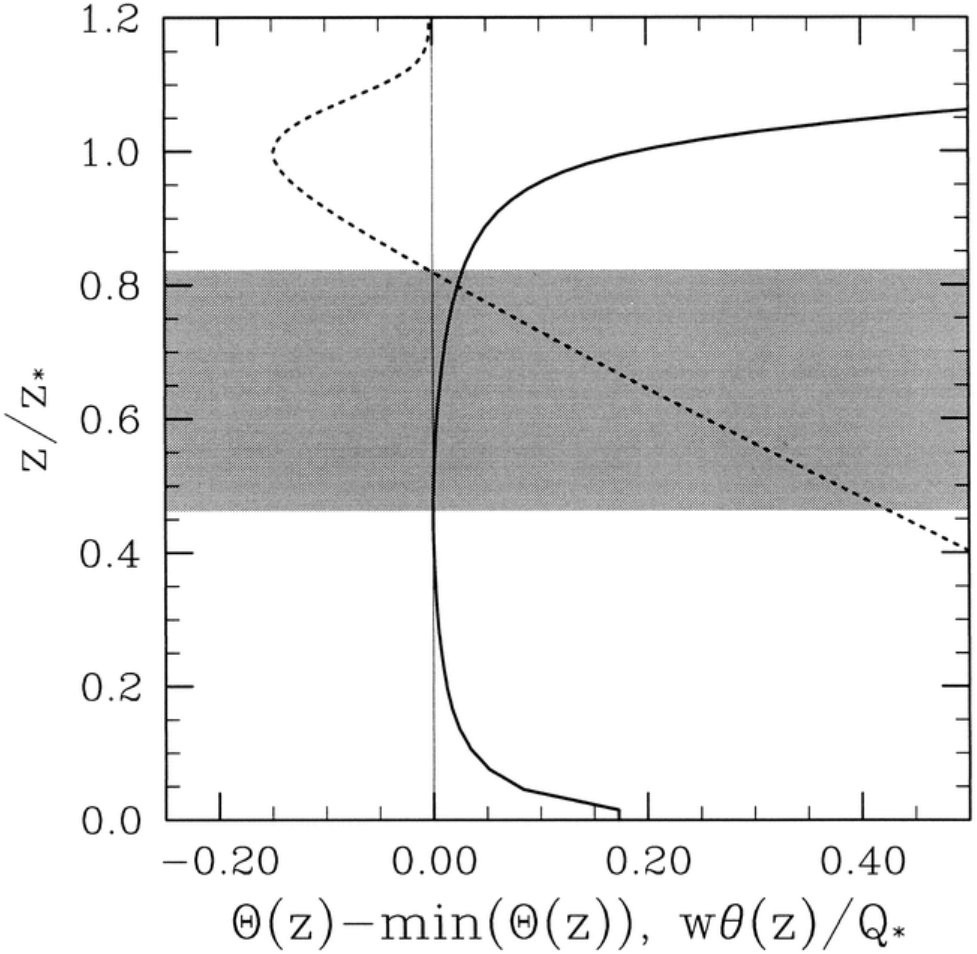
First a sensitivity study for convective conditions

1-D experiments –

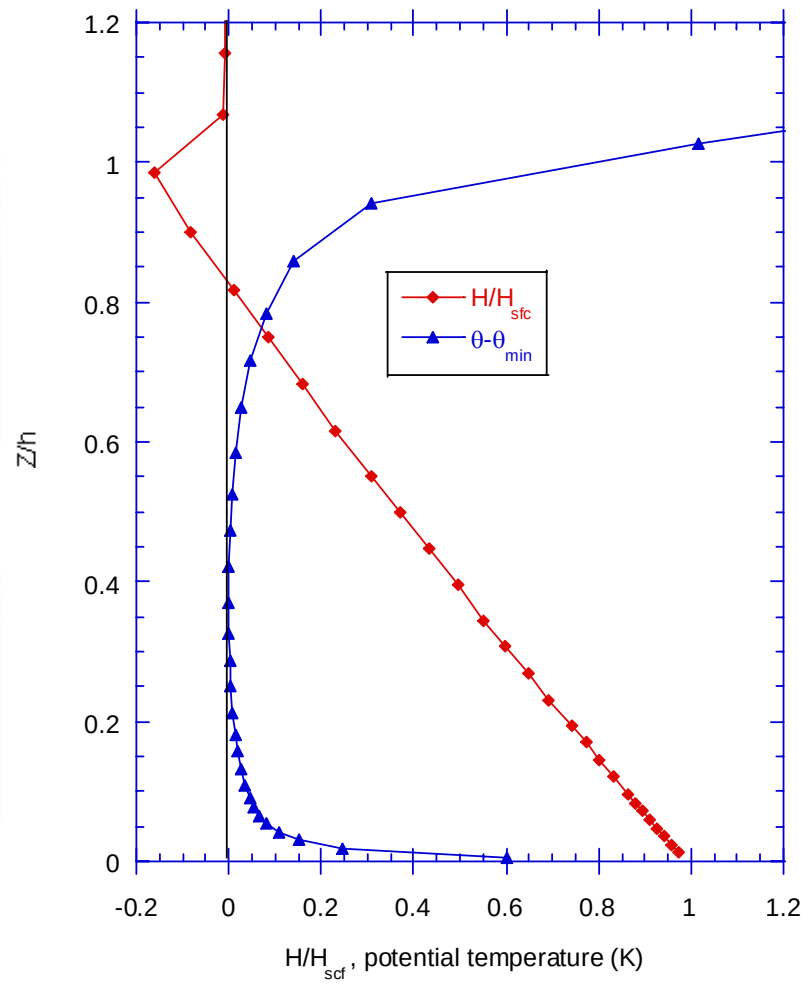
Variations in partitioning of local and non-local transport



Normalized heat flux and potential temperature profiles



LES (Stevens 2000)



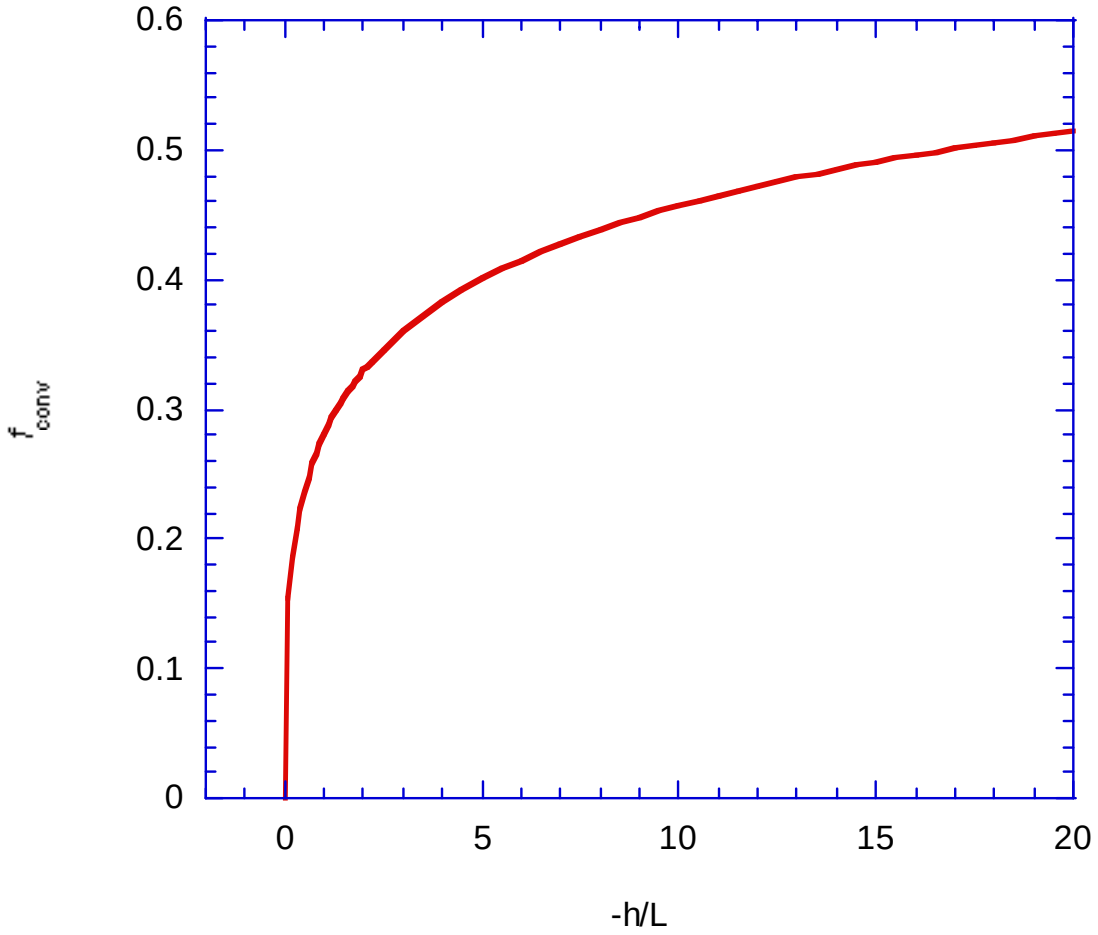
ACM2

Non-local partitioning

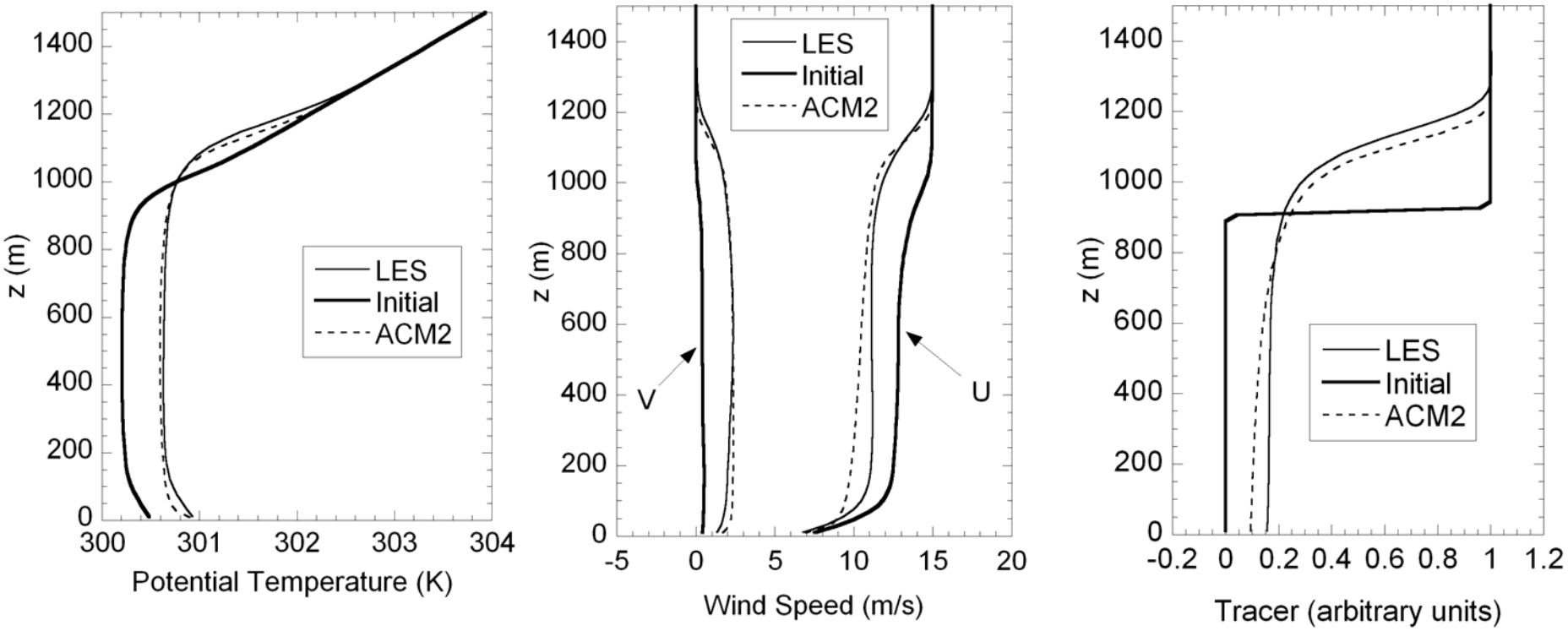
- These tests suggest that the upper limit of f_{conv} should be about 50%
- An expression for f_{conv} can be derived from gradient adjustment models (e.g. Holstlag and Boville 1993) at top of surface layer:

$$f_{conv} = \left(1 + \frac{k^{-2/3}}{0.1a}\left(-\frac{h}{L}\right)^{-1/3}\right)^{-1}$$

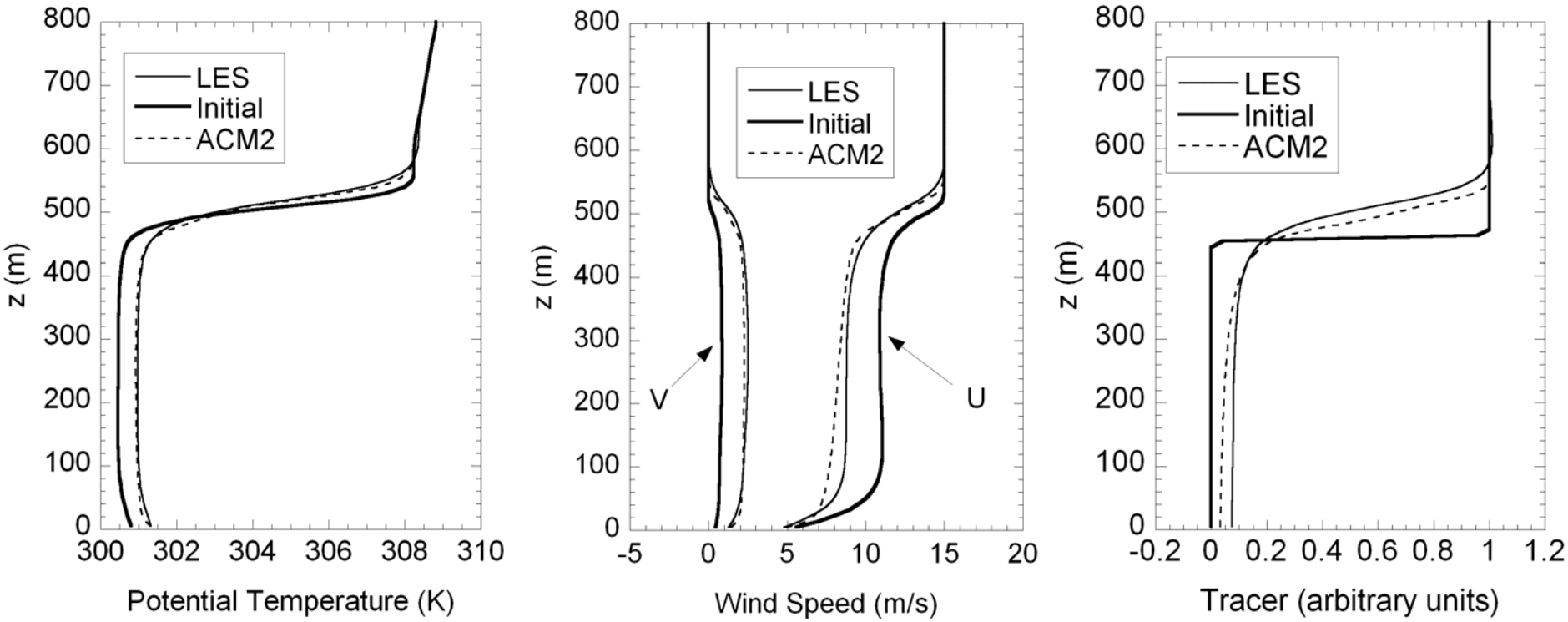
Non-local fraction (f_{conv}) as function of stability



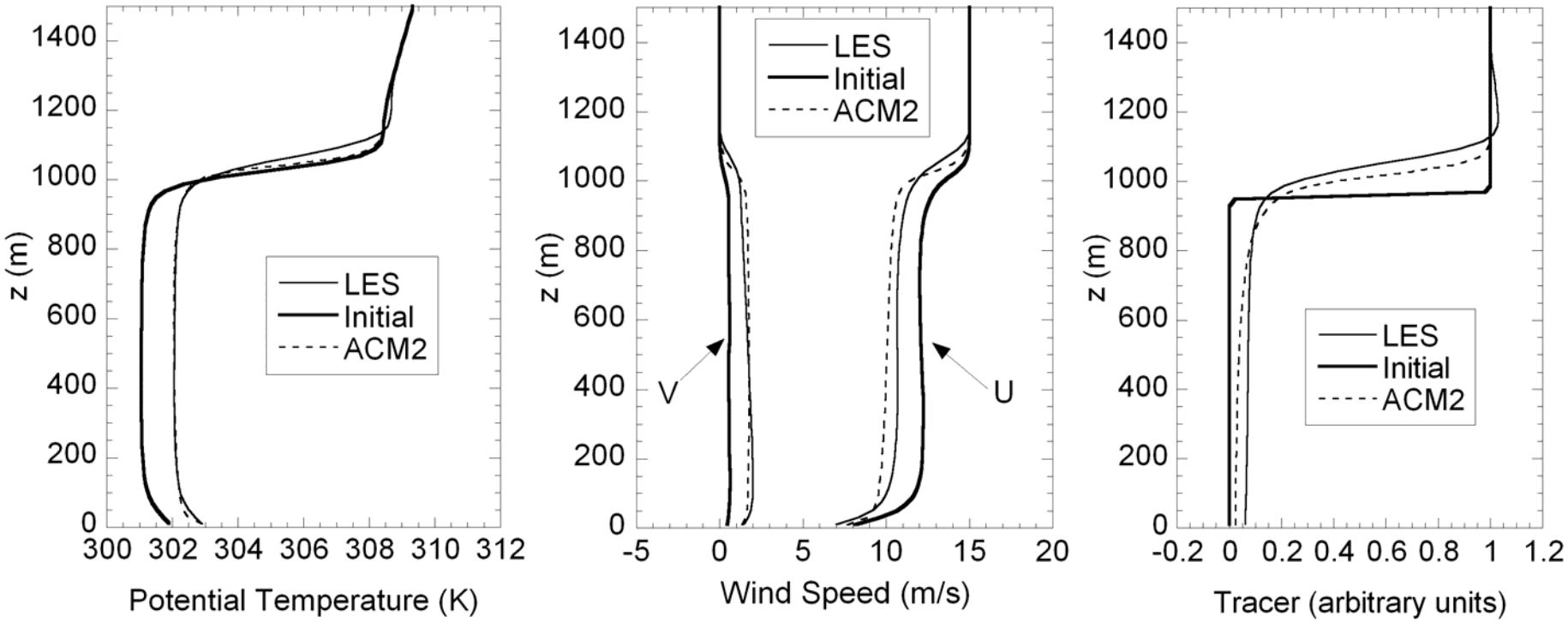
LES experiment low heat flux (Q* = 0.05 K m s-1), weak cap



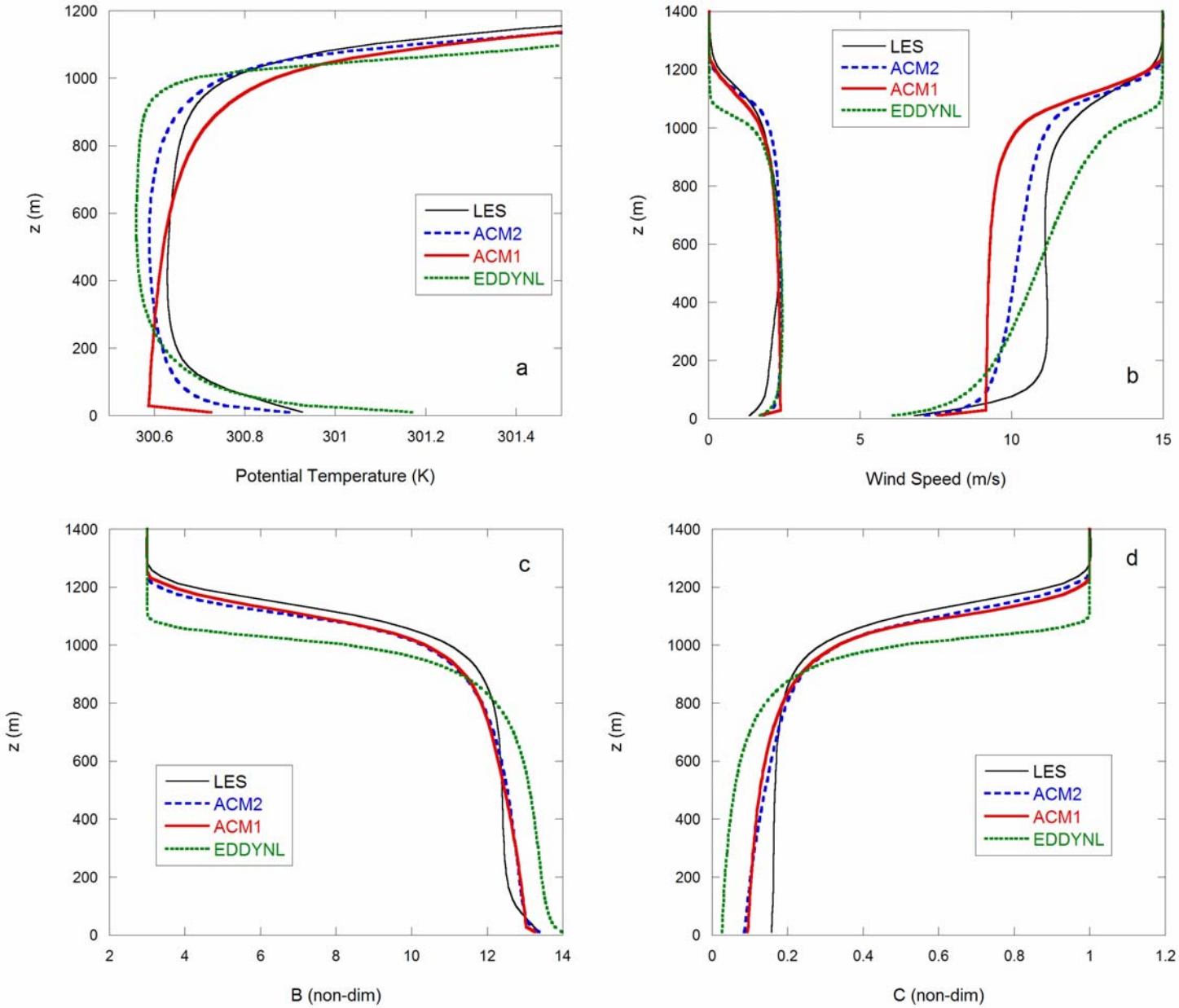
LES experiment low heat flux (Q* = 0.05 K m s-1), strong cap



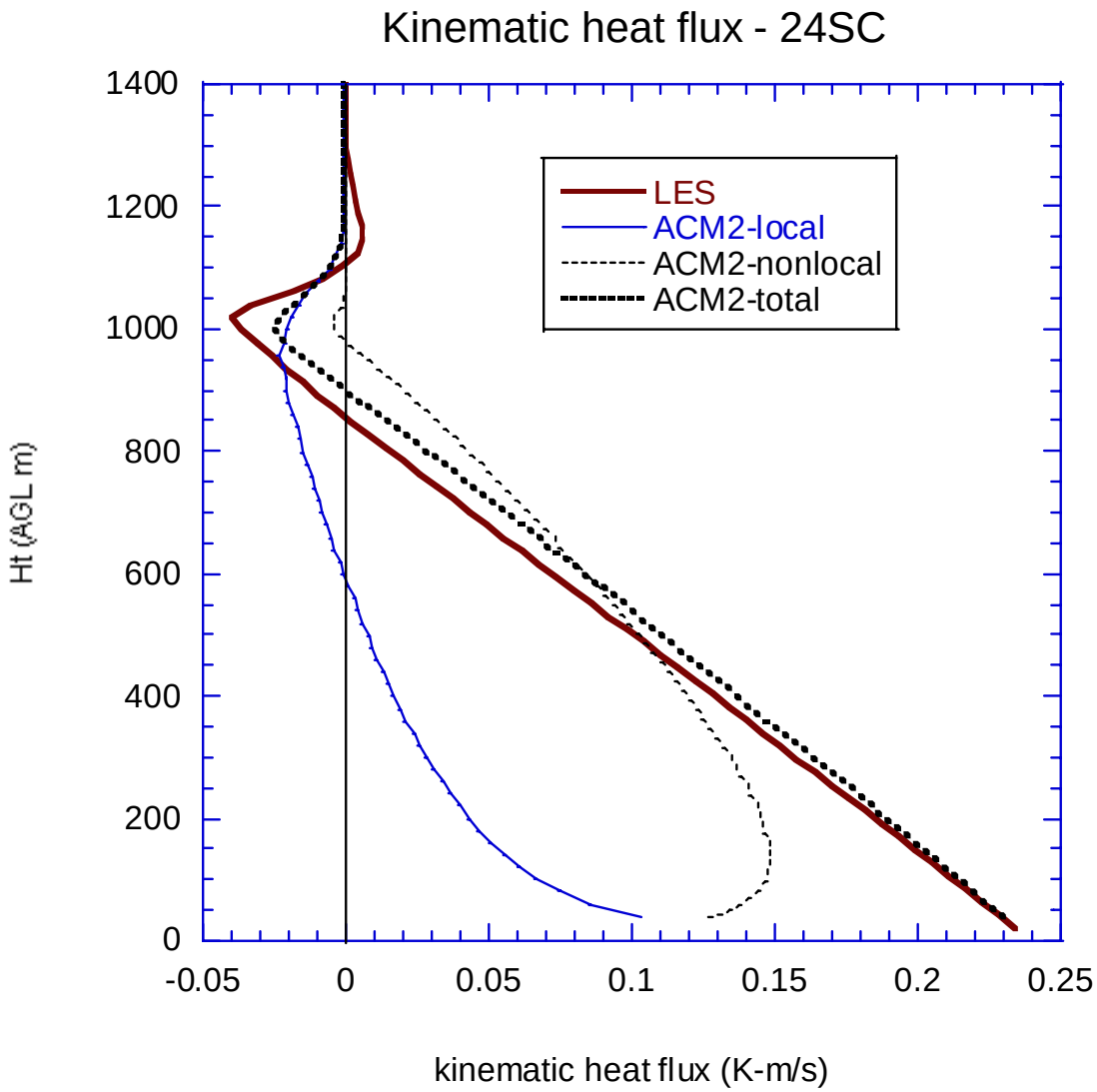
LES experiment high heat flux (Q = 0.24 K m s-1), strong cap*



Comparison of ACM2, ACM1 and EDDYNL (based on HB93) for 05WC case



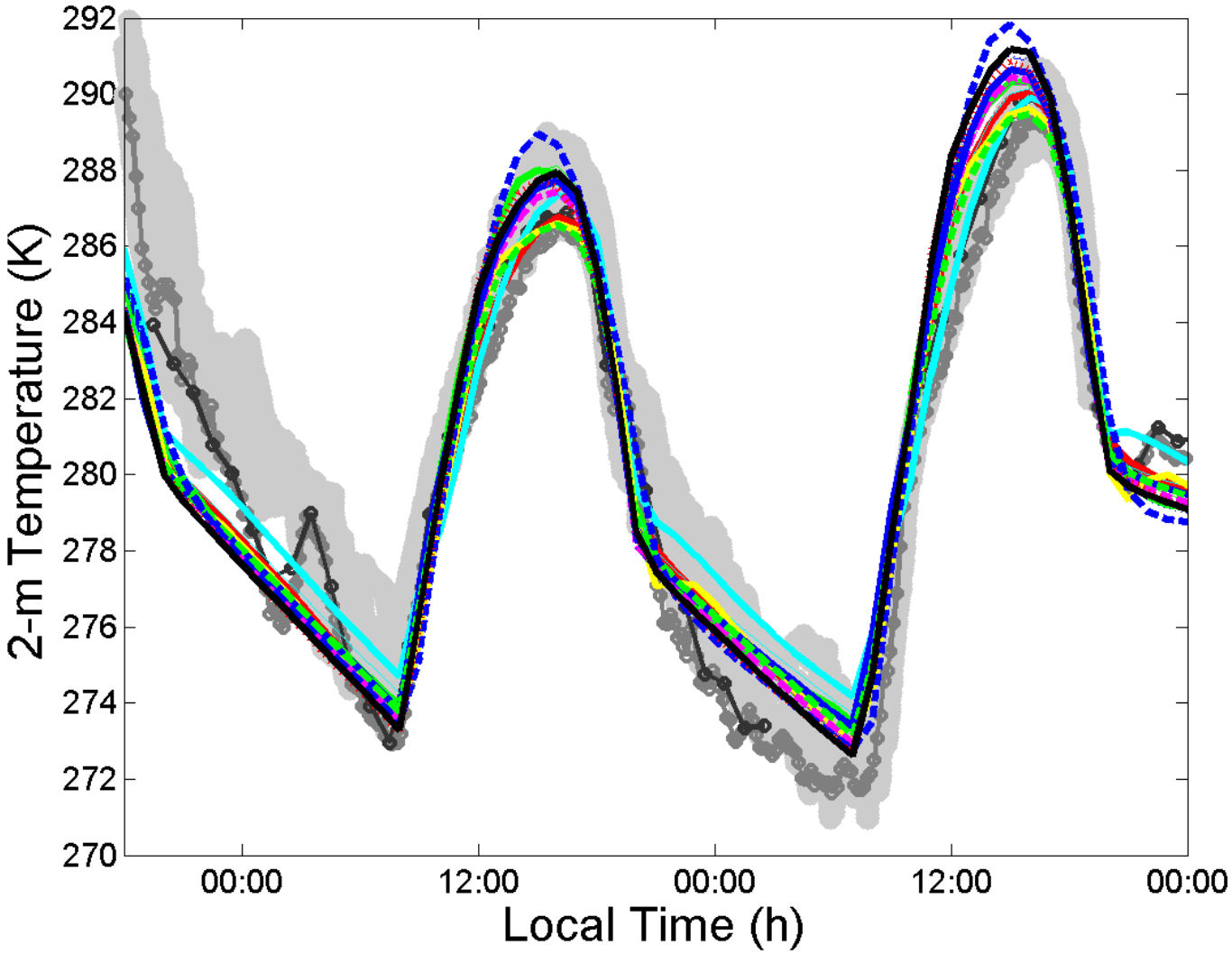
Profiles of sensible heat flux. Local, non-local, and total sensible heat flux compared to LES



The second GABLS model intercomparison

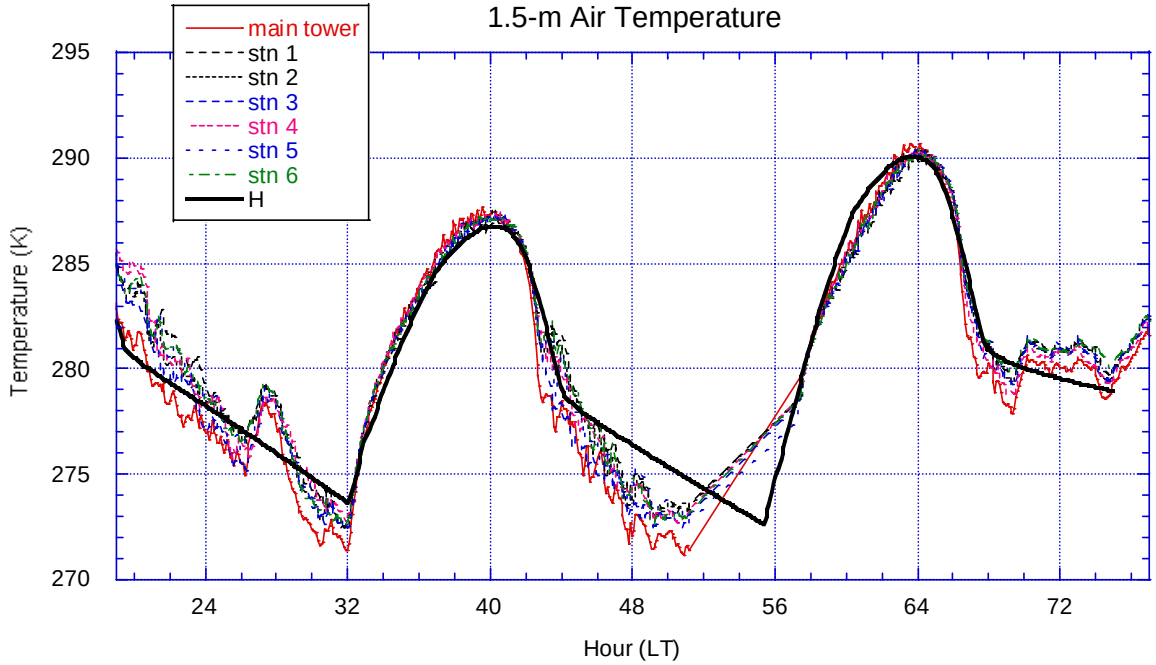
- Multi-day Intercomparison of 23 PBL models for CASES99 field study
  - Given initial profiles
  - T_g time series
  - Constant geostrophic wind
  - Large scale subsidence
  - 2.5% of potential evaporation
  - P, z_o

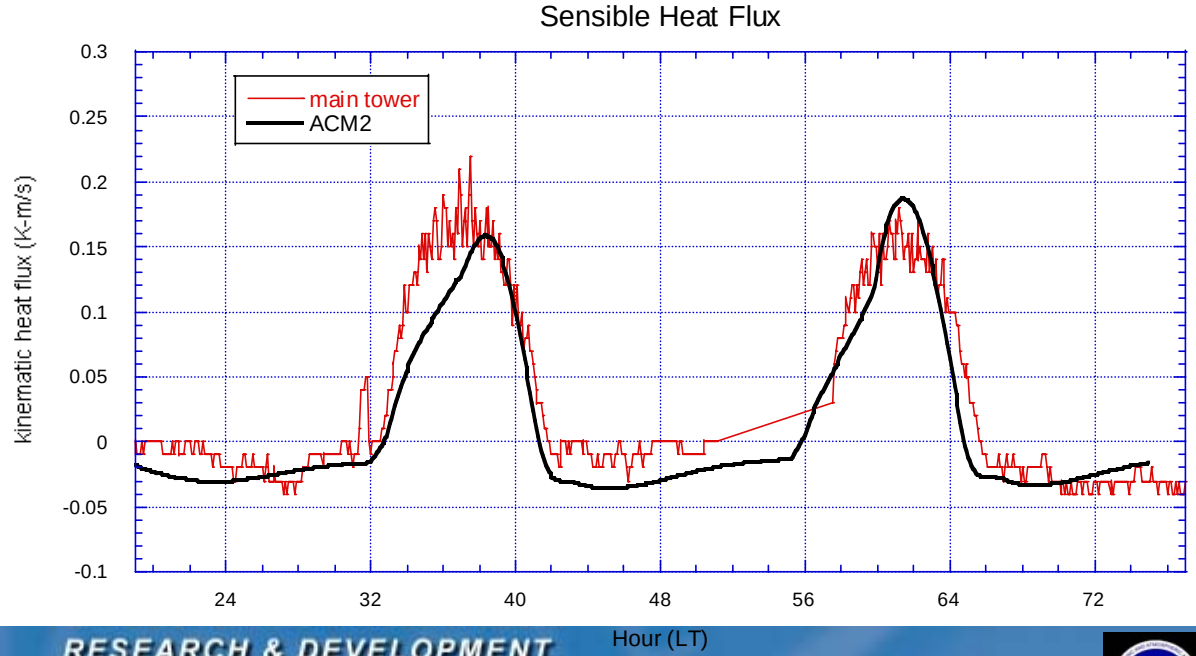
GABLS T-2m Intercomparison



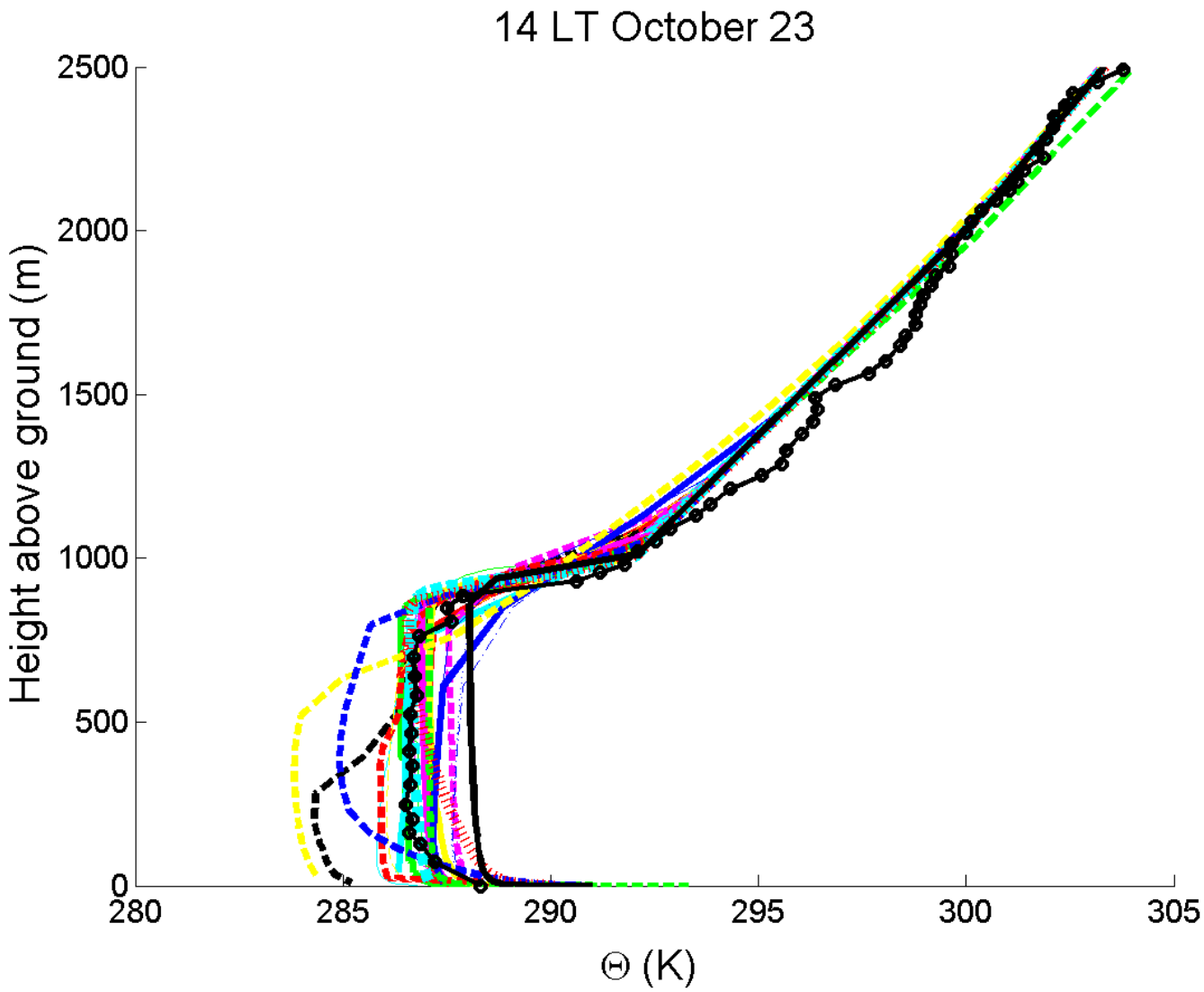
GABLS Experiment – Simulation of CASES99

October 22-24, 1999

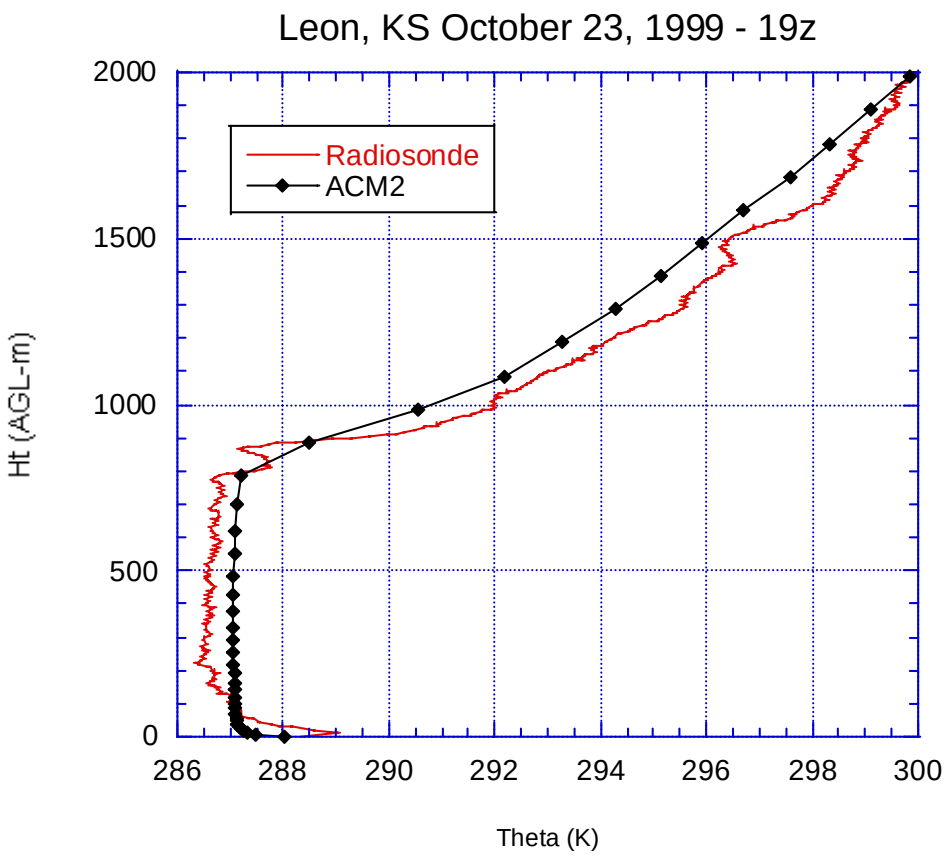


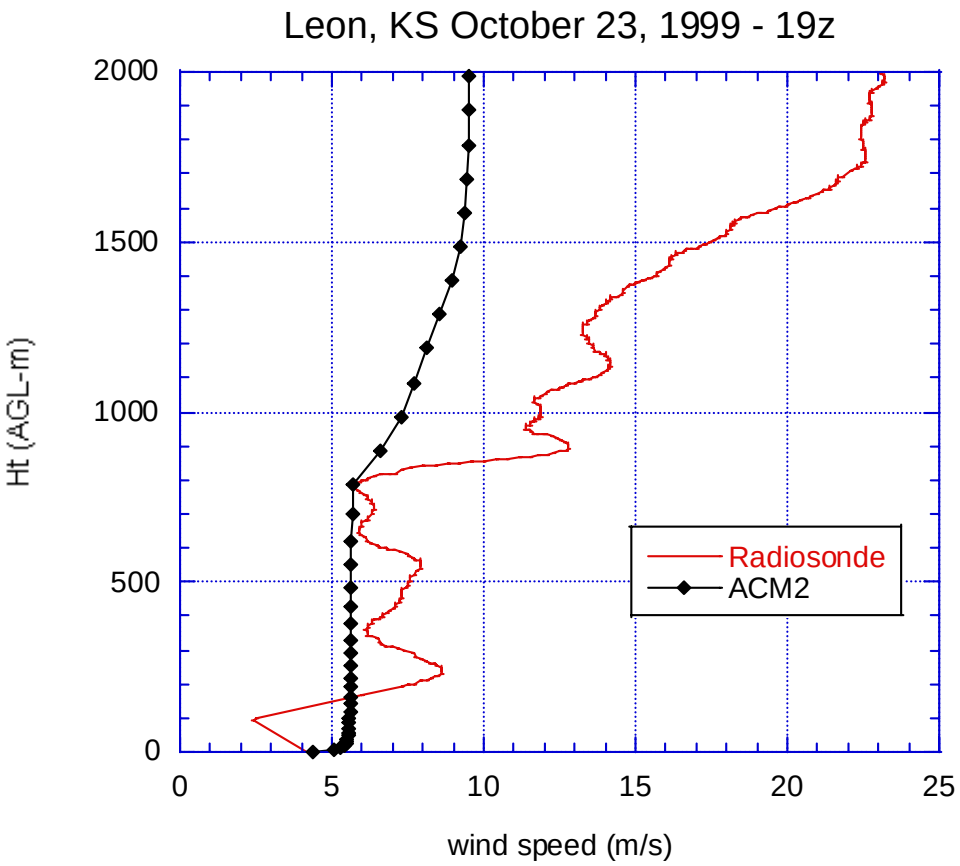


GABLS Profile intercomparison

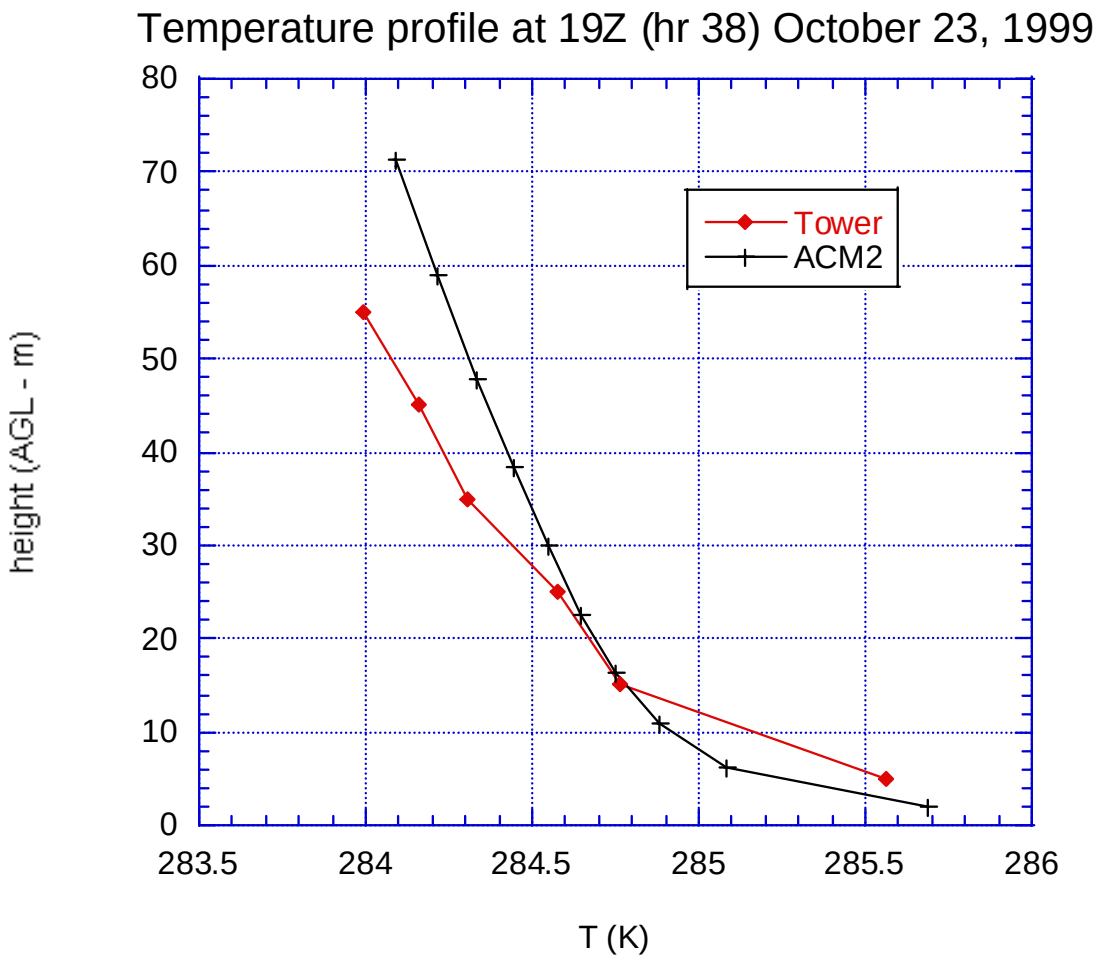


CASES99 profiles





Near surface Temperature profile from CASES99 main tower



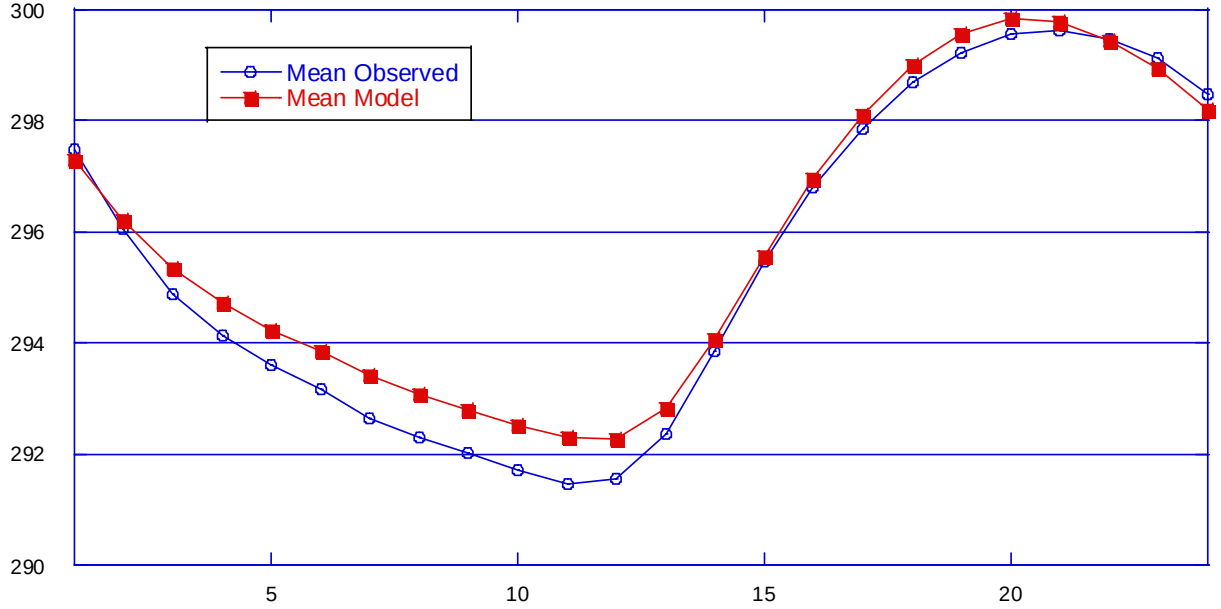
MM5 Evaluations

- Domain: 202 x 208 x 34 @ 12 km res
- Physics:
  - ACM2
  - PX LSM
  - KF2
  - Reisner 2
  - RRTM w/ Dudhia SW
- Data Assimilation:
  - Winds at all levels, T and q_v above PBL
  - Indirect soil moisture nudging
- July 13 – August 18, 2004

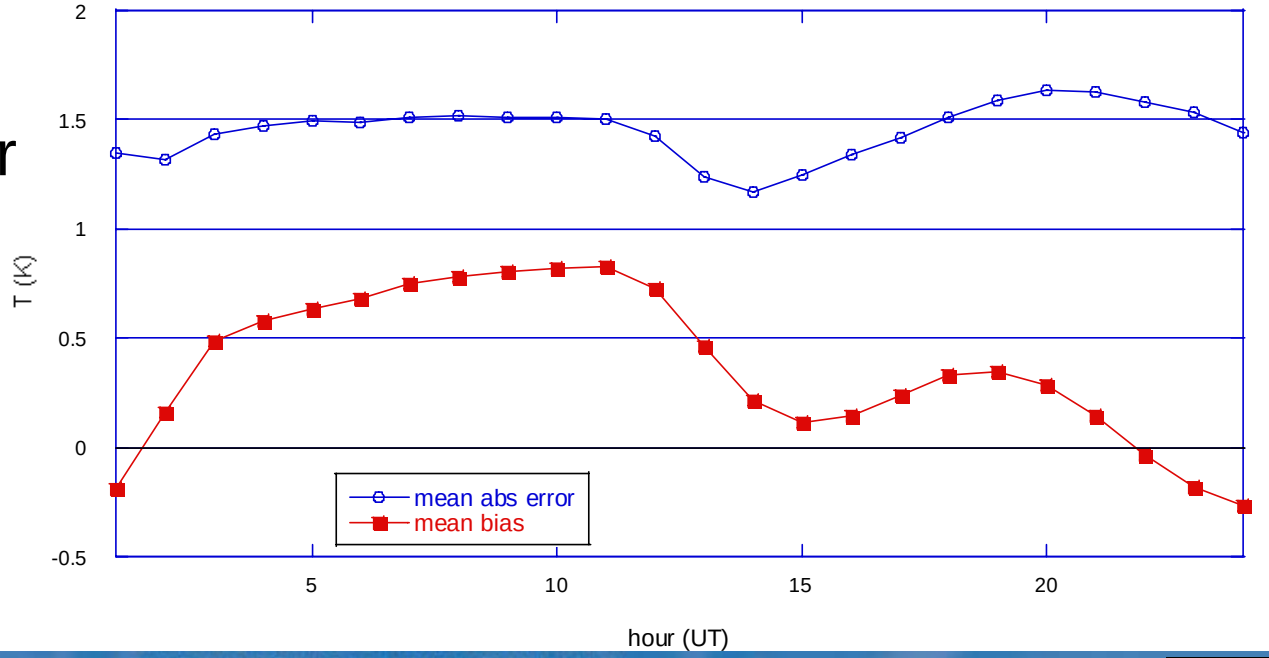
Model performance statistics for the 12 km MM5-ACM2 simulations over the period of July 13 – August 18, 2004

	T	q_v	ws	wd
Data count	398848	398848	398848	398848
Correlation	0.934	0.915	0.612	---
MAE	1.42 K	1.14 g/kg	1.026 m/s	31.8 deg
MB	0.369 K	0.109 g/kg	-0.211 m/s	10.2 deg
Index of Ag	0.931	0.911	0.606	---

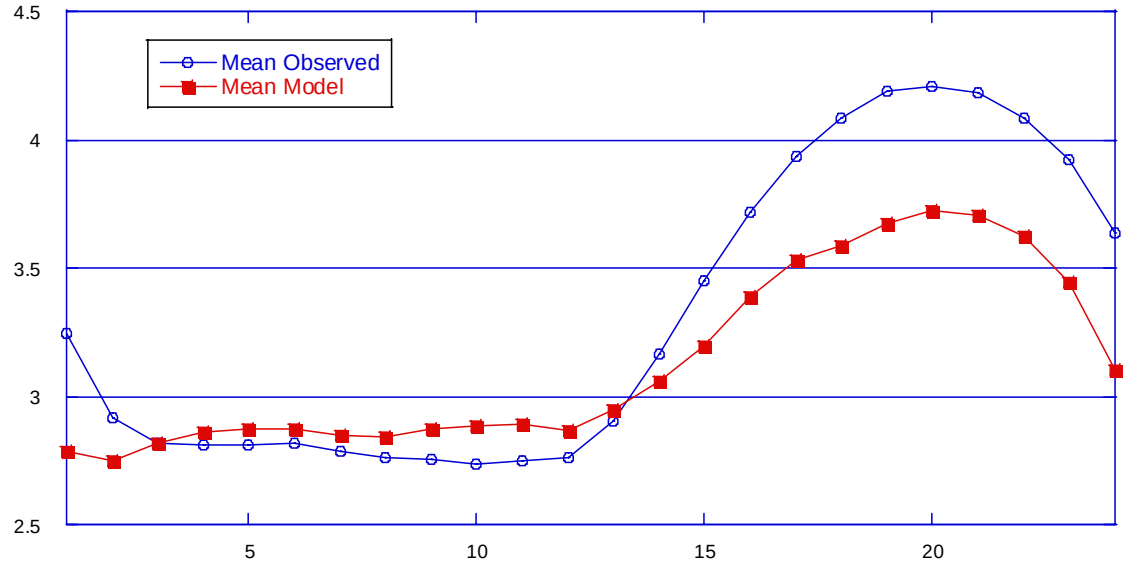
2 m Temperature Averaged over all NWS/FAA sites 7/15 – 8/18 2004

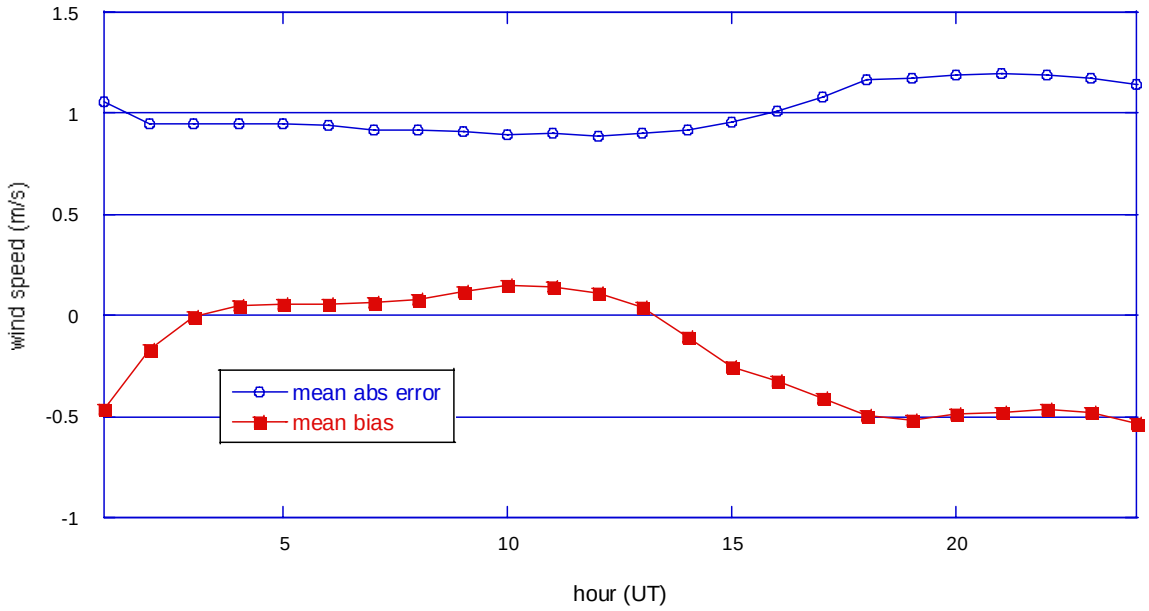


Mean Absolute Error
Mean Bias



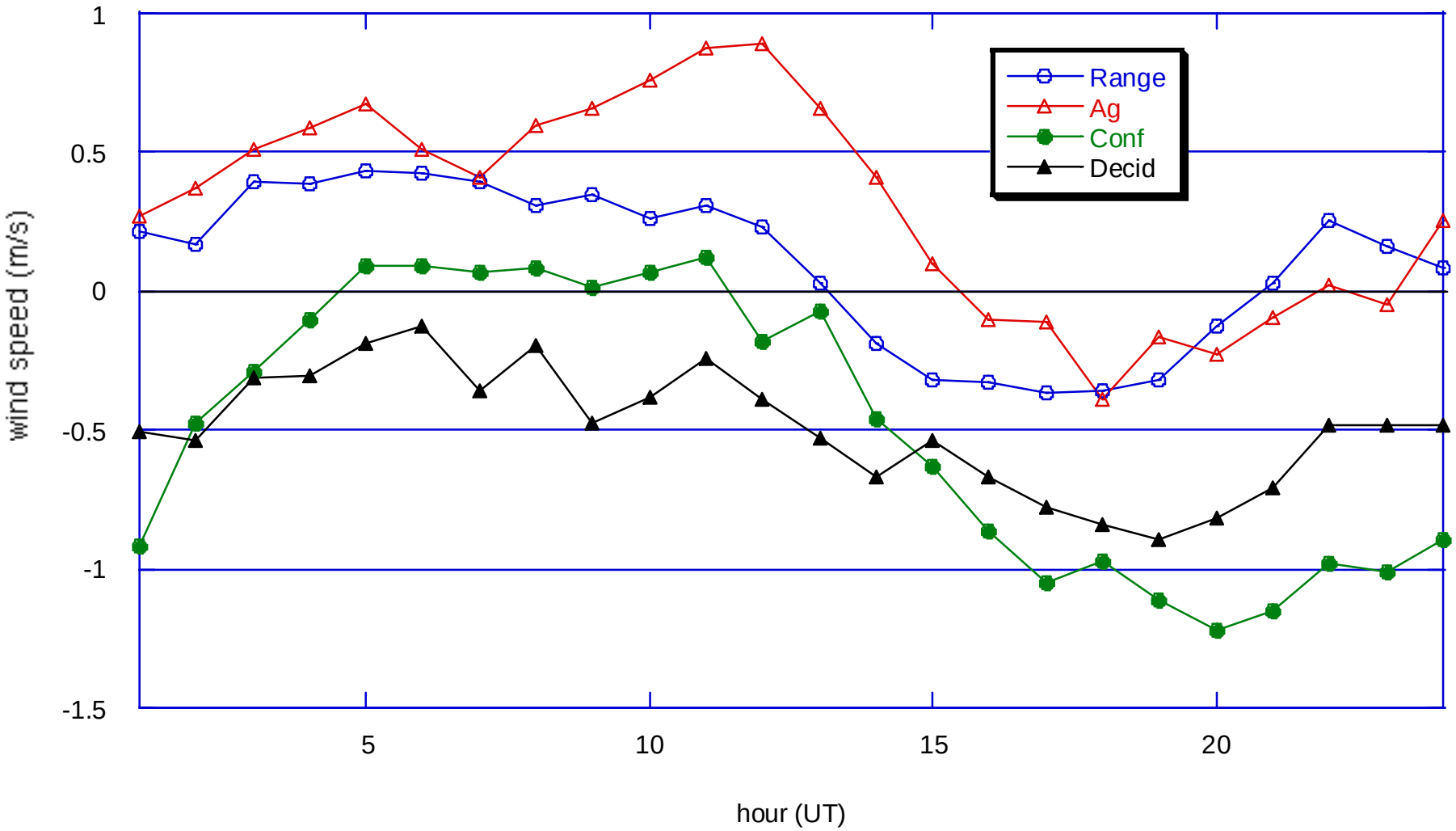
10 m Wind speed Averaged over all NWS/FAA sites 7/15 – 8/18 2004





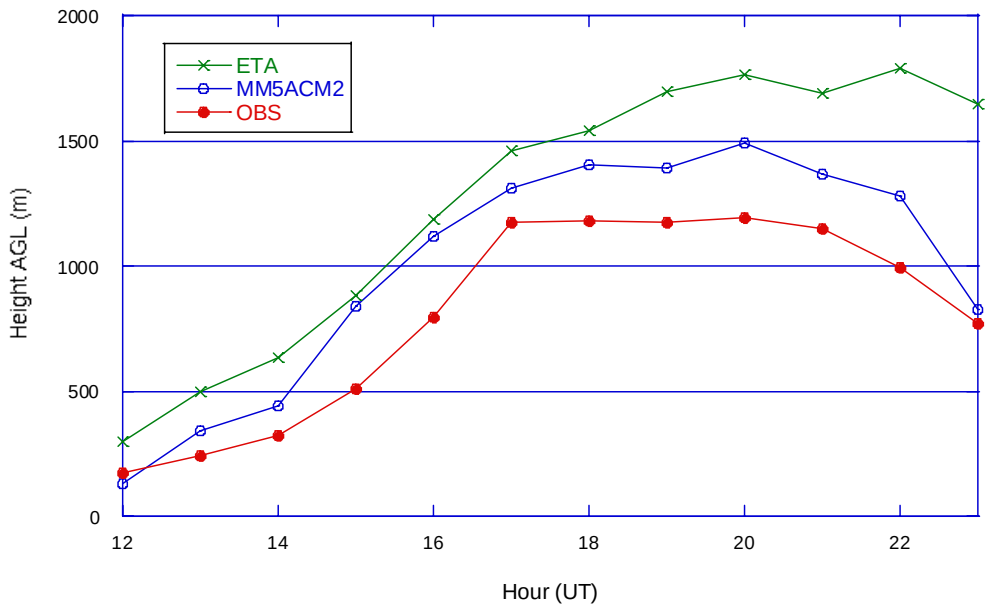
Mean Absolute Error
Mean Bias

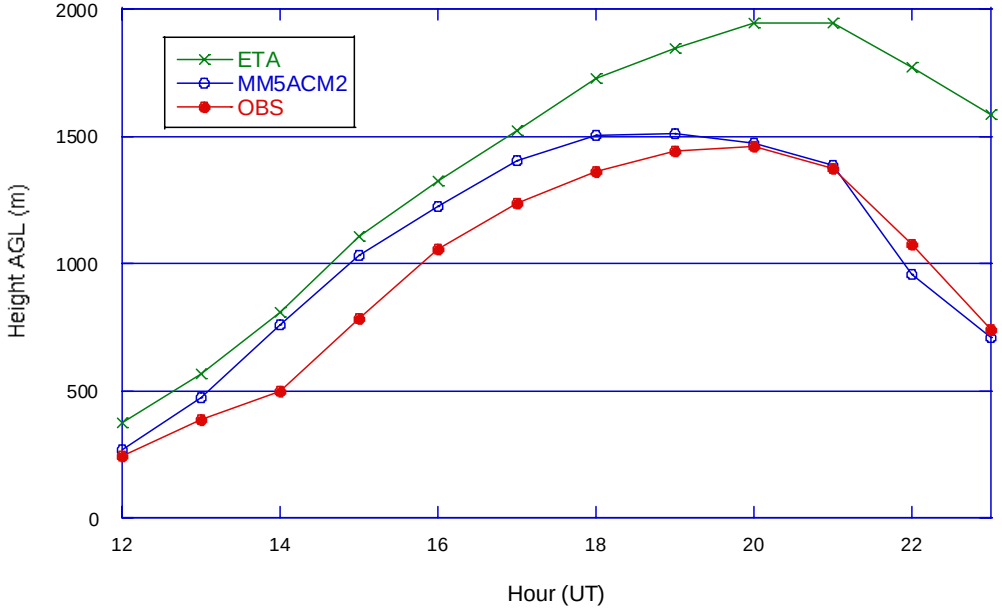
Wind speed bias segregated by Landuse



PBL Height from Radar wind Profilers (from Jim Wilczak)

Pittsburgh, PA



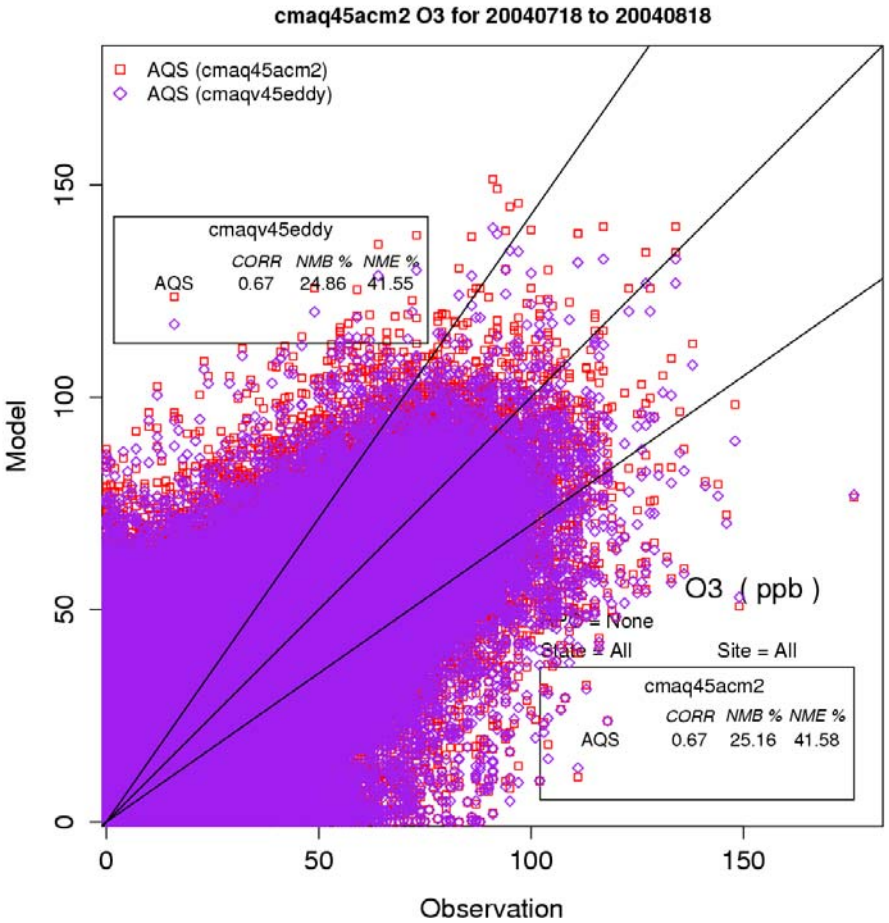


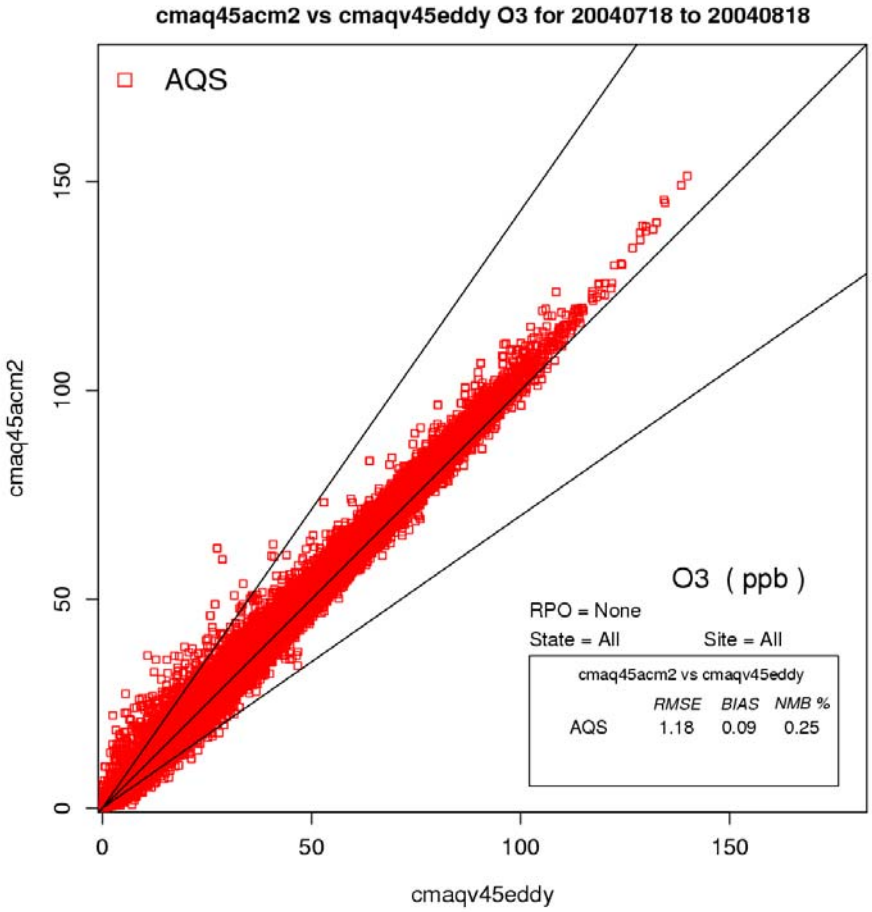
Concord, NH

CMAQ

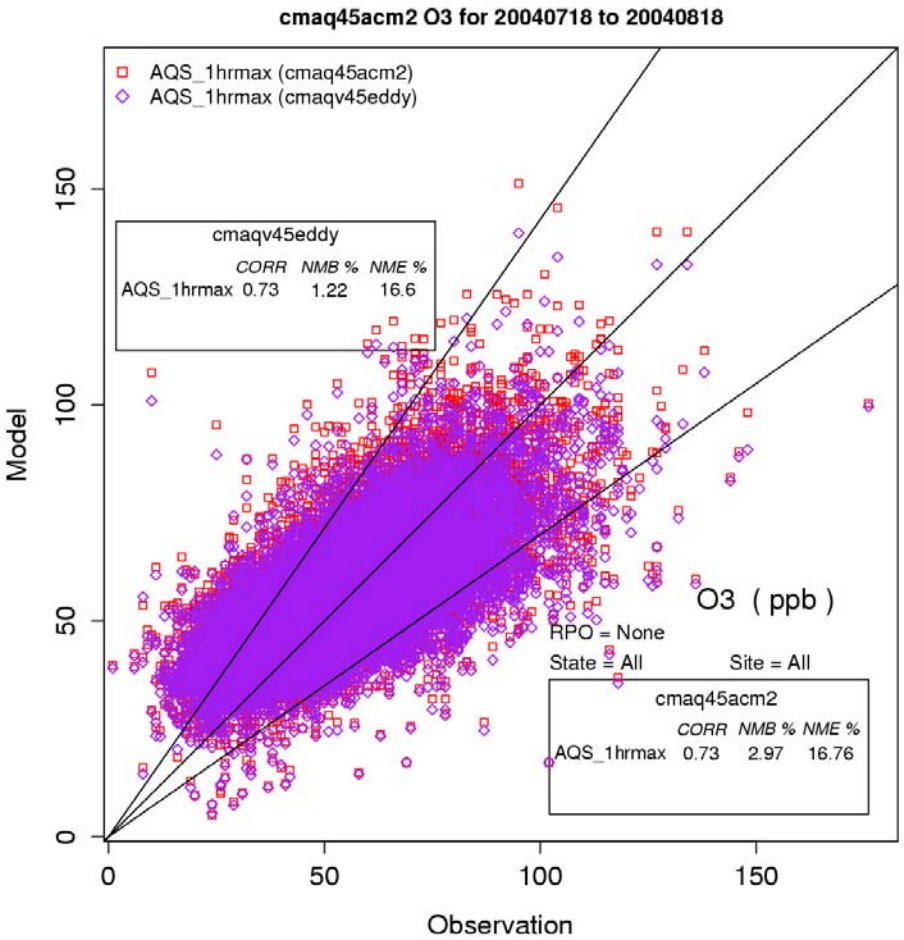
- Configuration:
  - Domain: 199 x 205 x 34 @ 12 km res
  - V4.5 CB4 AE3
  - ACM2 vs Eddy
- Preliminary evaluation
  - Ground level statistics (AMET)
  - Ozonesondes from ICARTT 2004

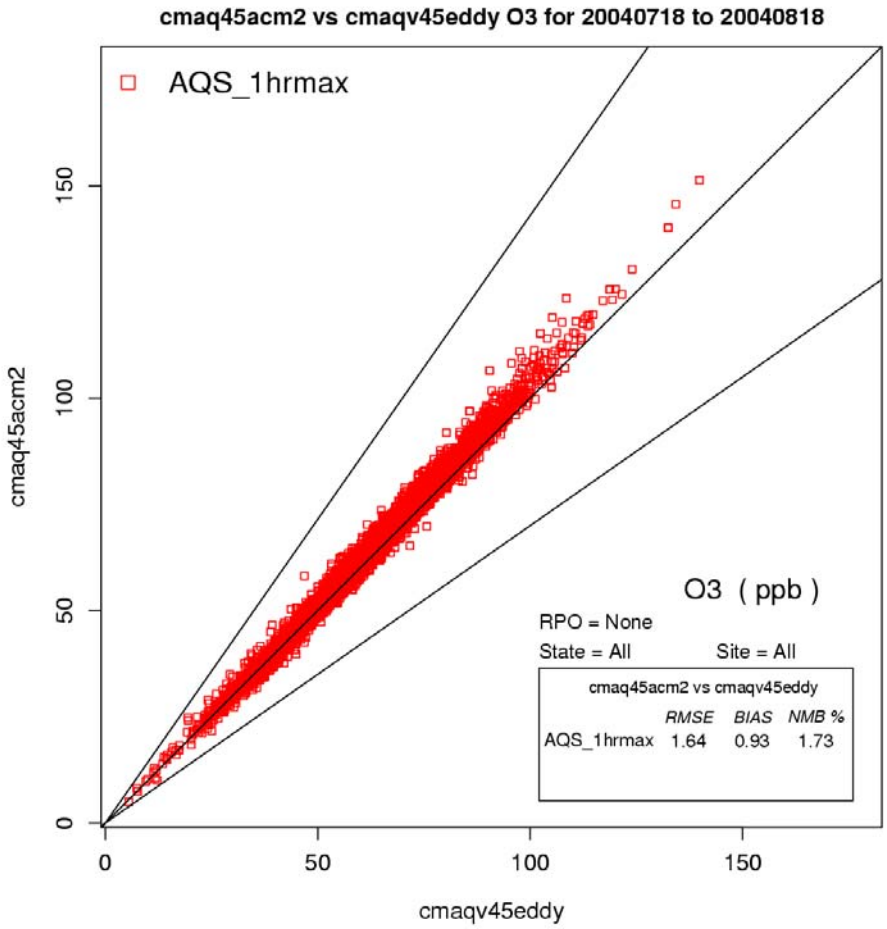
Hourly Ozone comparisons



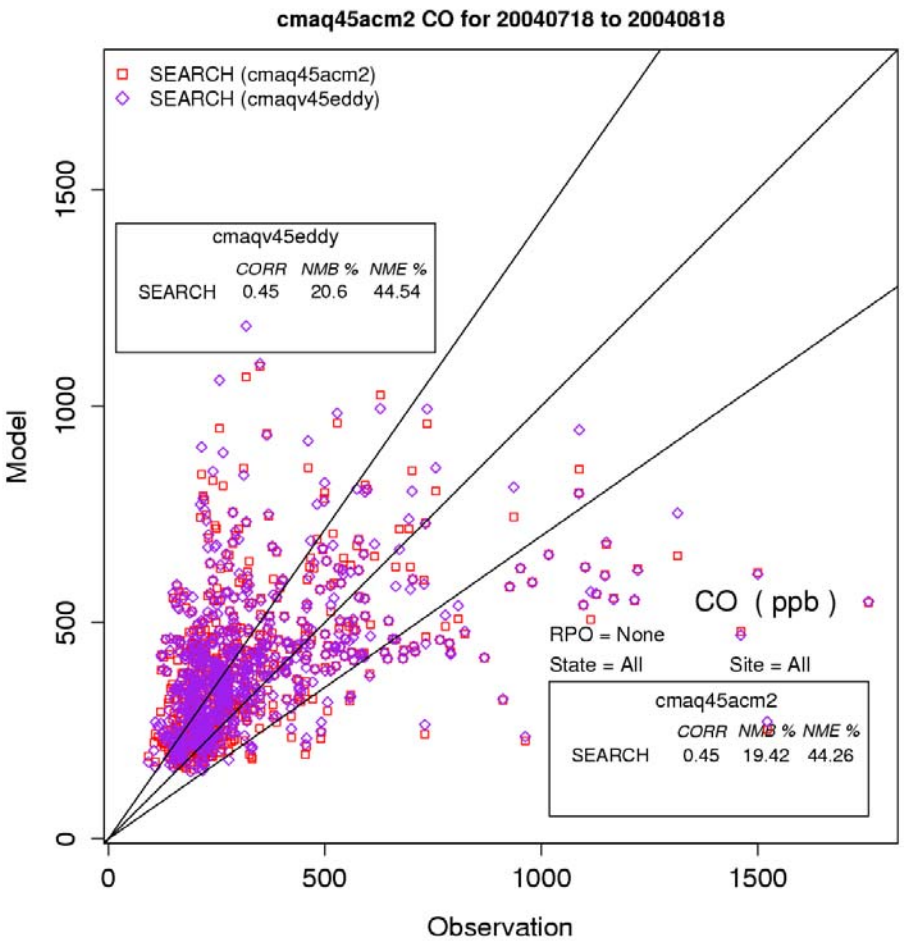


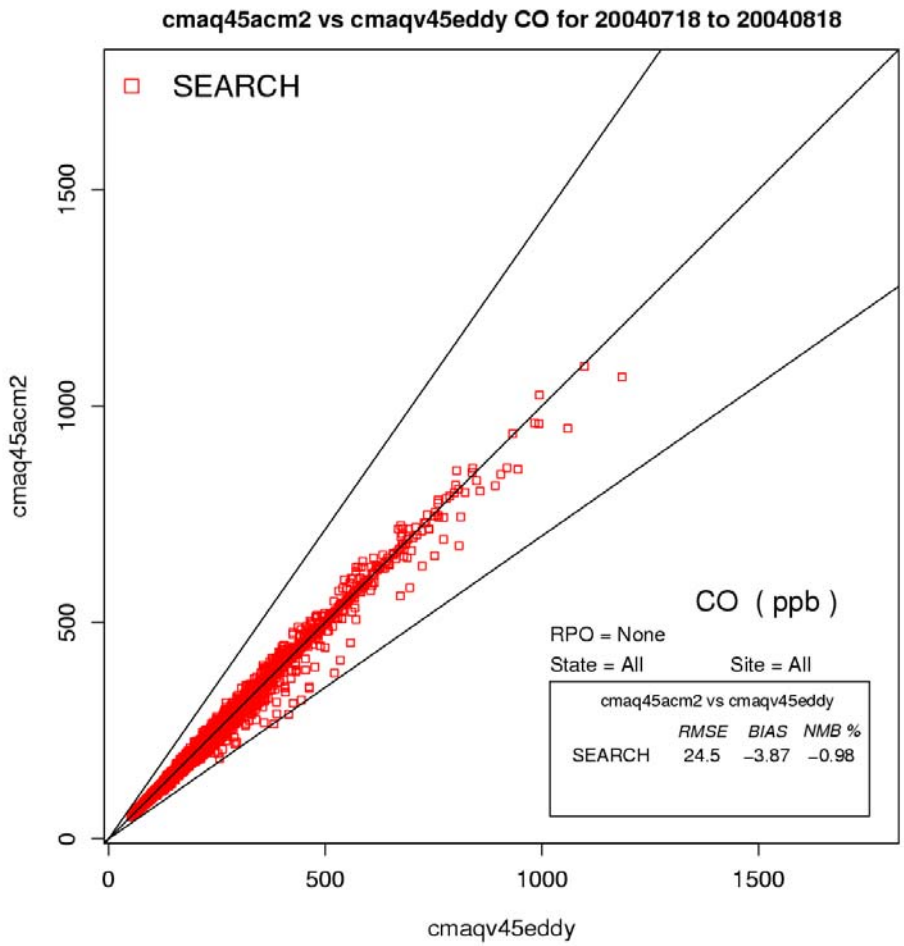
Maximum 1-hr Ozone comparisons



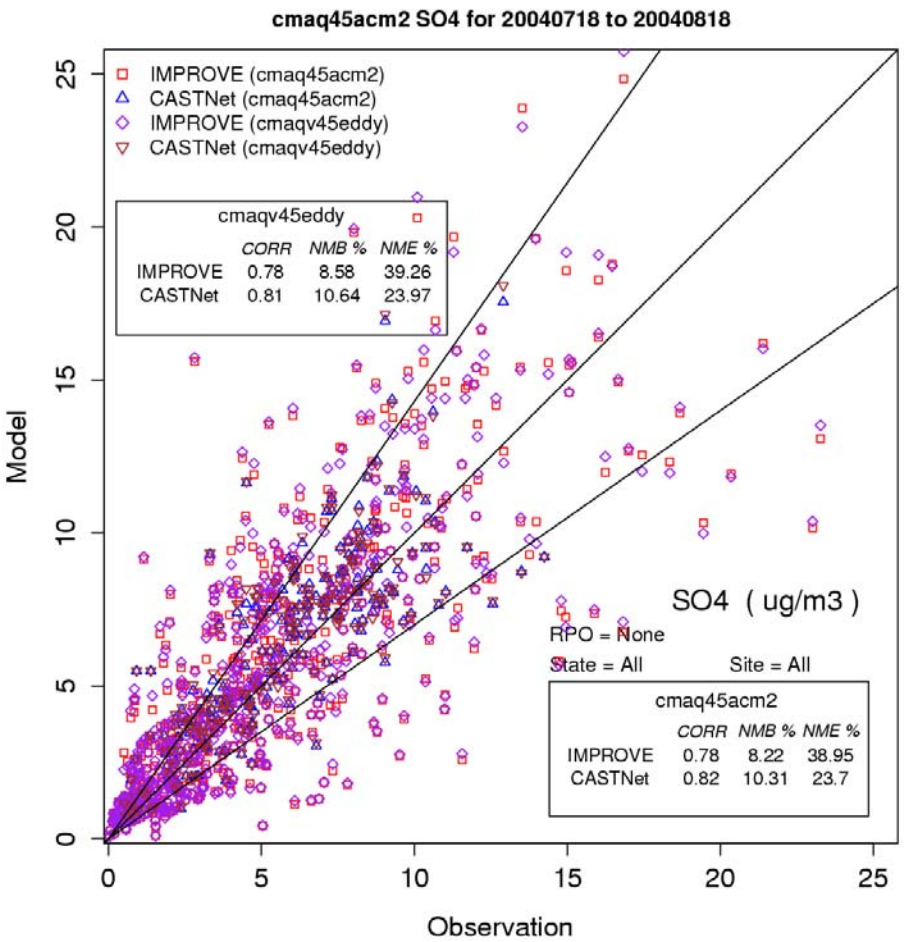


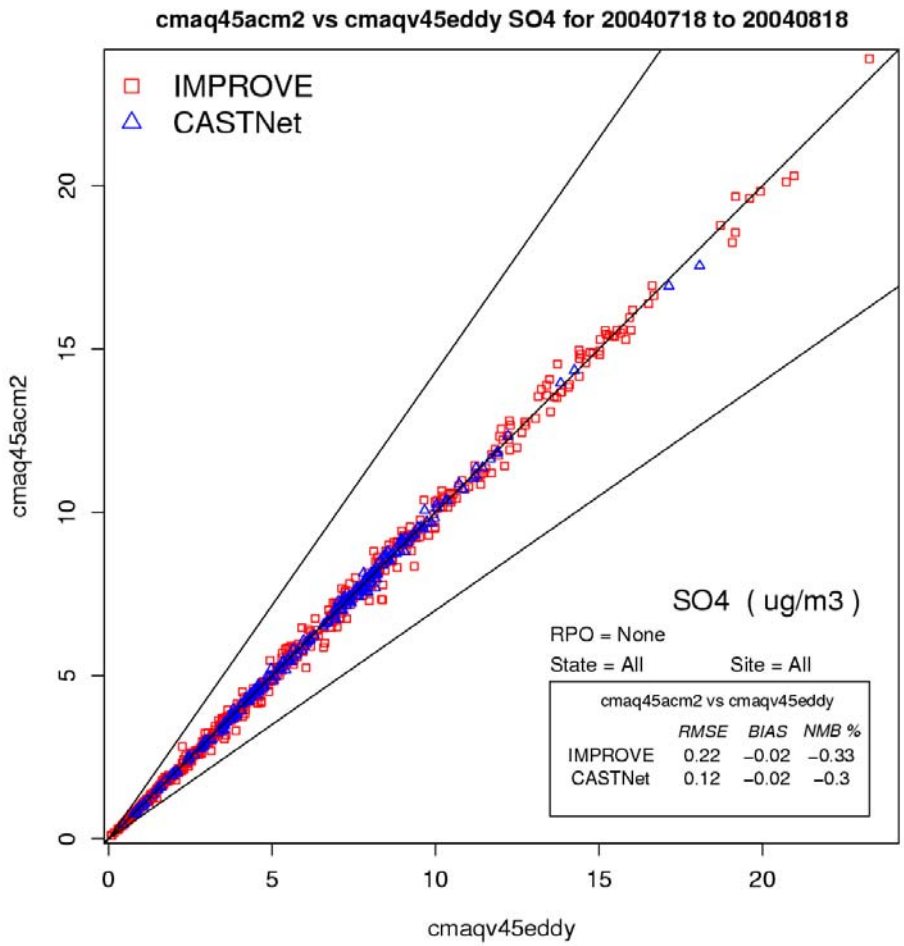
Hourly CO comparison



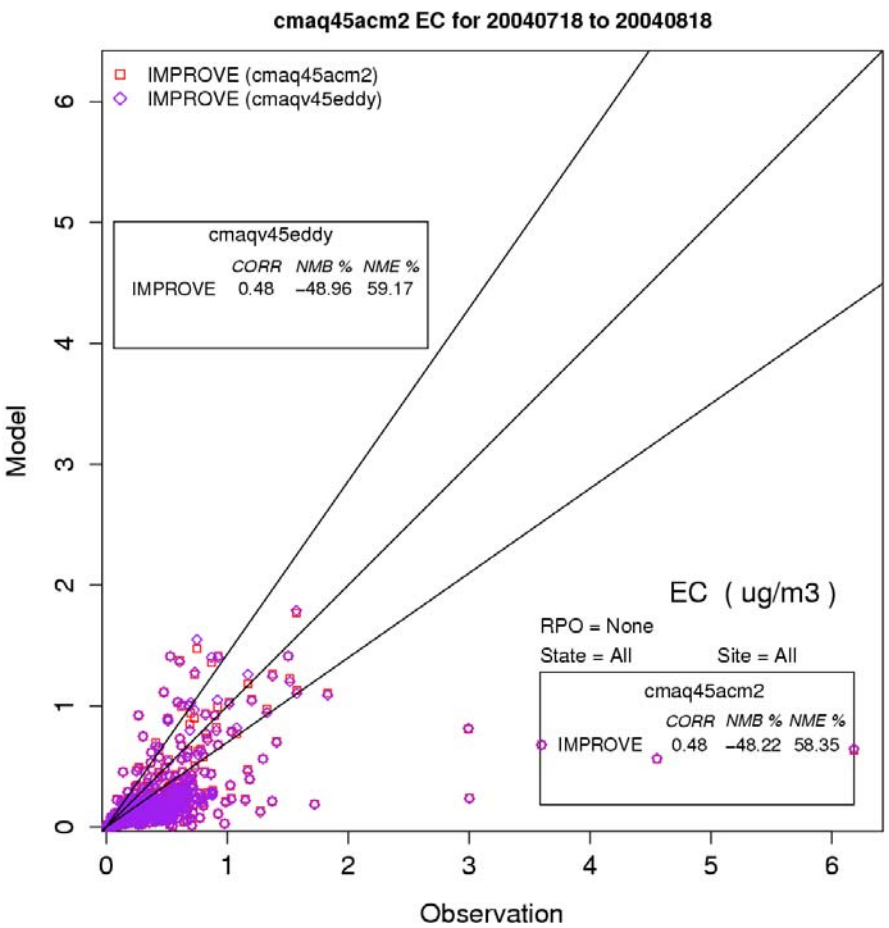


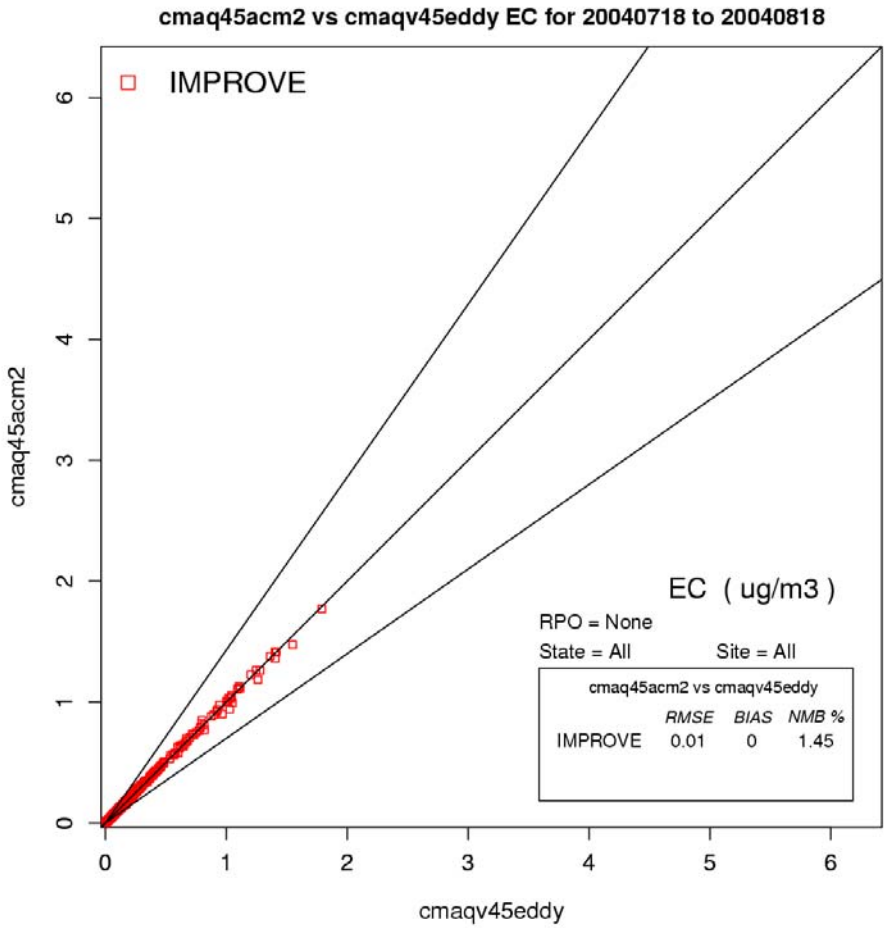
Sulfate comparison



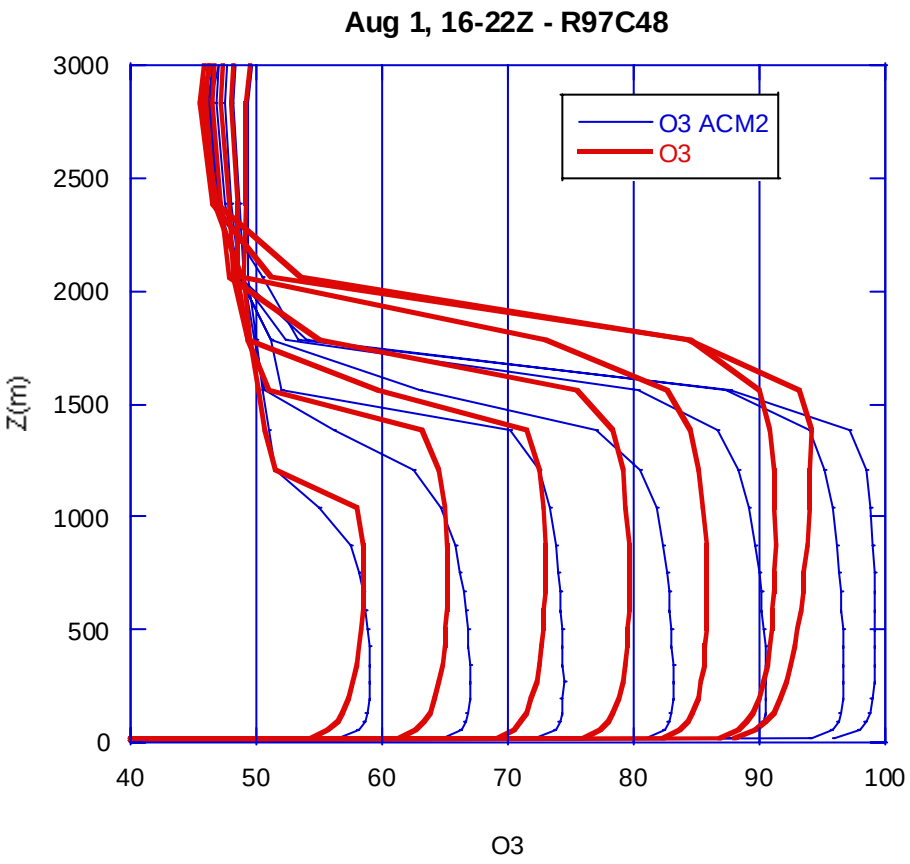


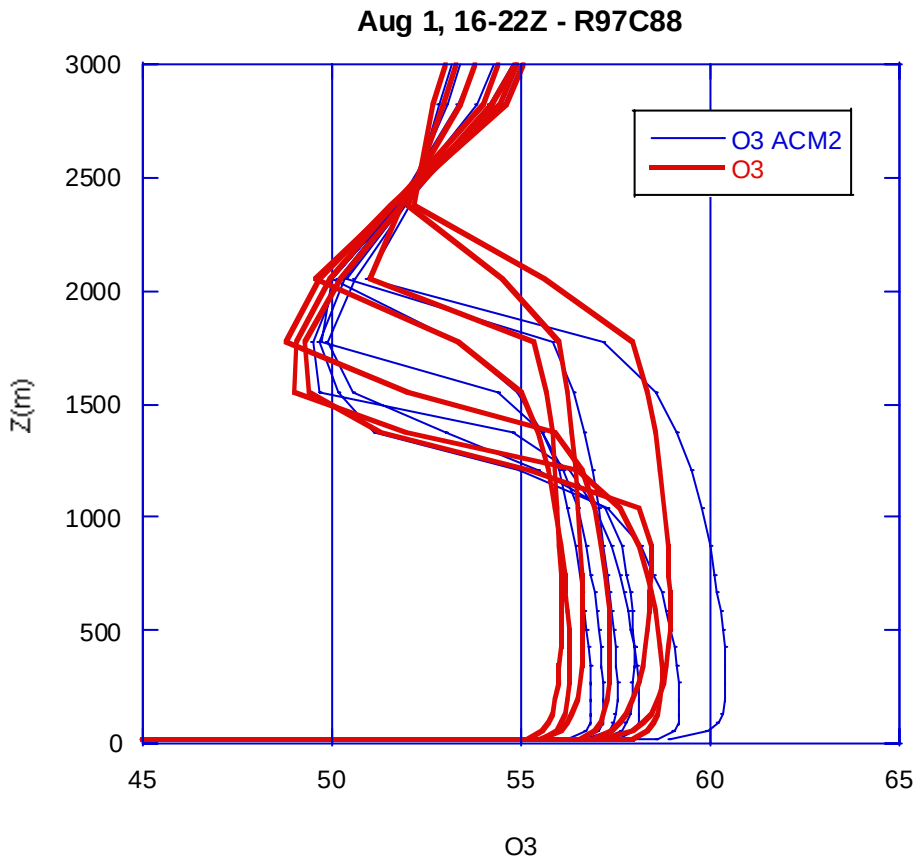
EC Comparison



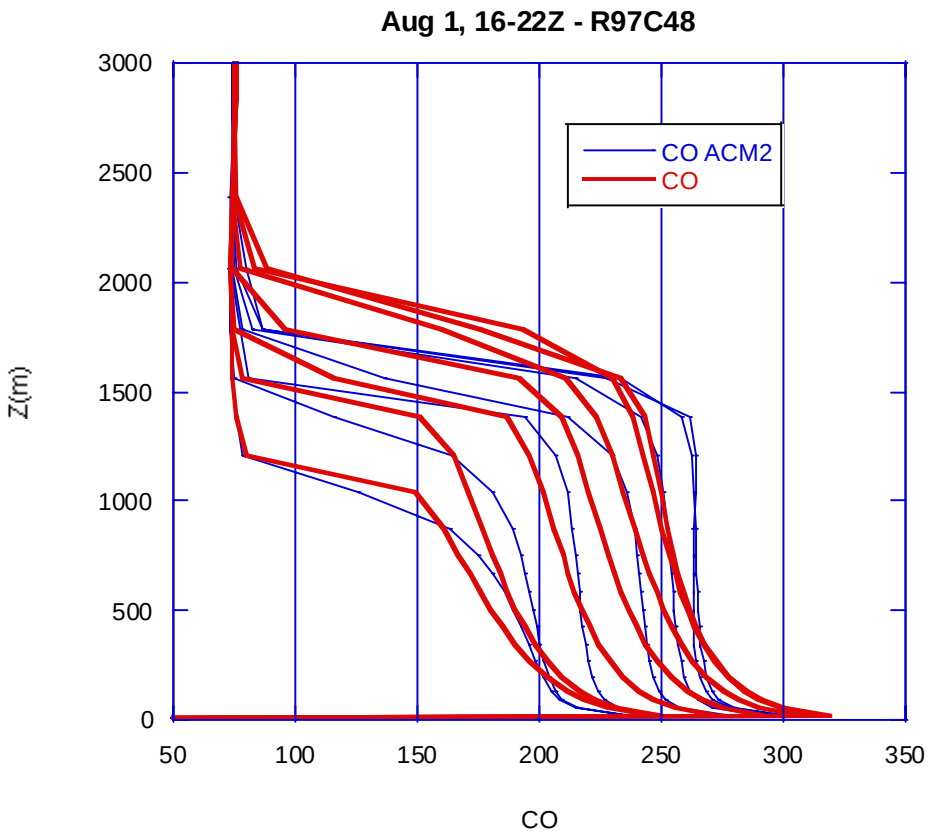


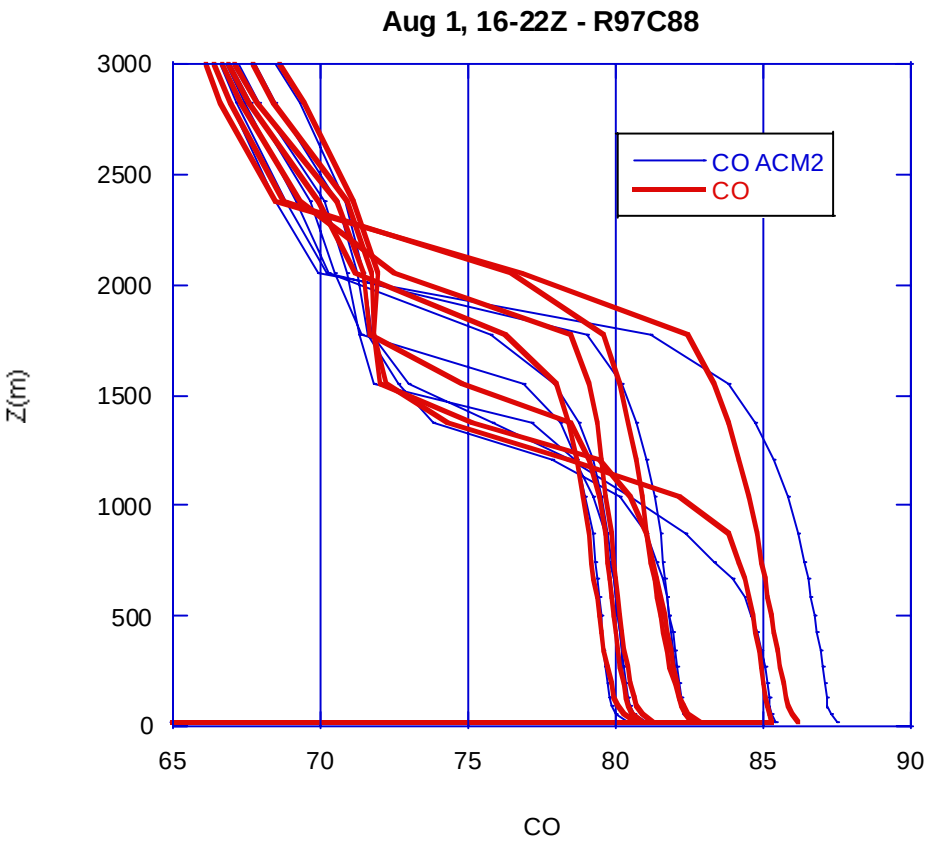
O_3 Vertical Profiles for urban and rural grid cells





CO


Aug 1, 16-22Z - R97C48
3000
2500
2000
1500
1000
500
0
Z(m)
50
100
150
200
250
300
350
CO
CO ACM2
CO


Aug 1, 16-22Z - R97C88
3000
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Z(m)
65
70
75
80
85
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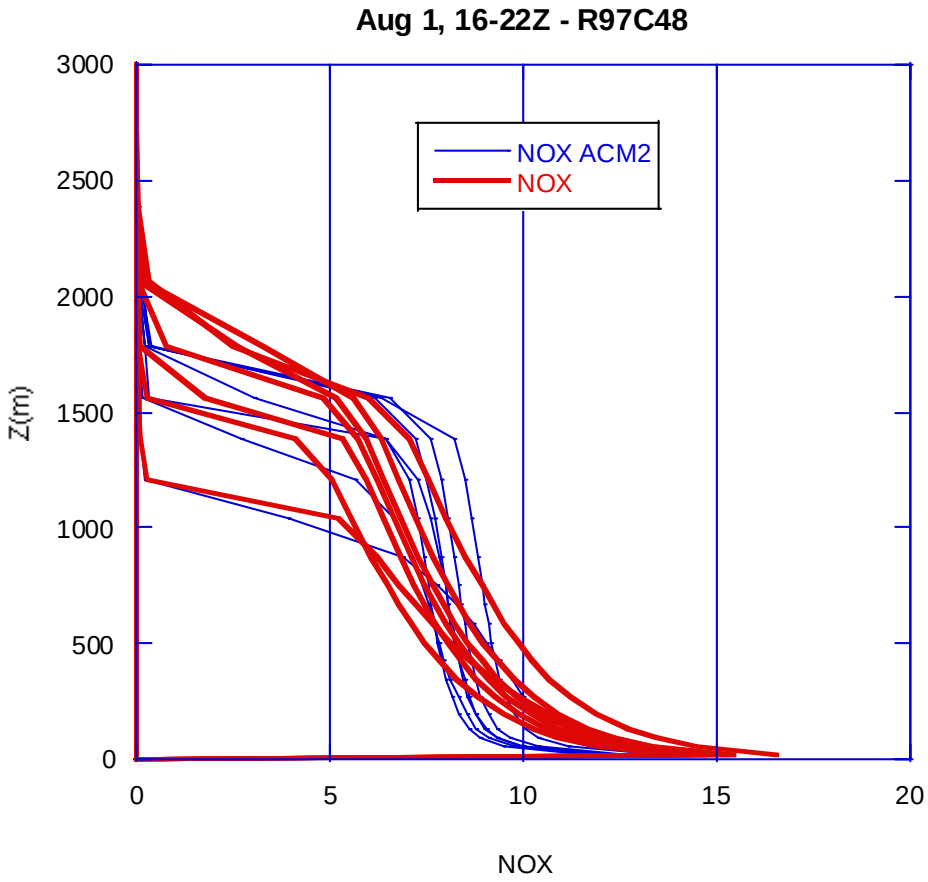
Aug 1, 16-22Z - R97C48
NOX ACM2
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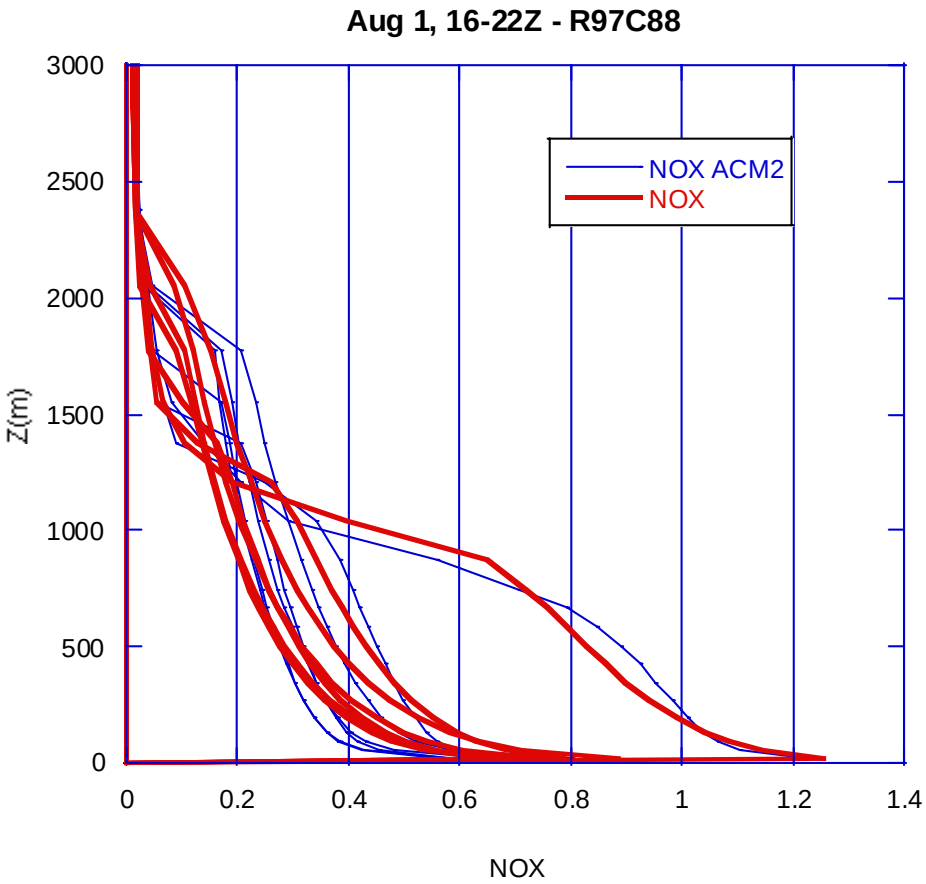
Aug 1, 16-22Z - R97C88
NOX ACM2
NOX
Z(m)
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2500
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1000
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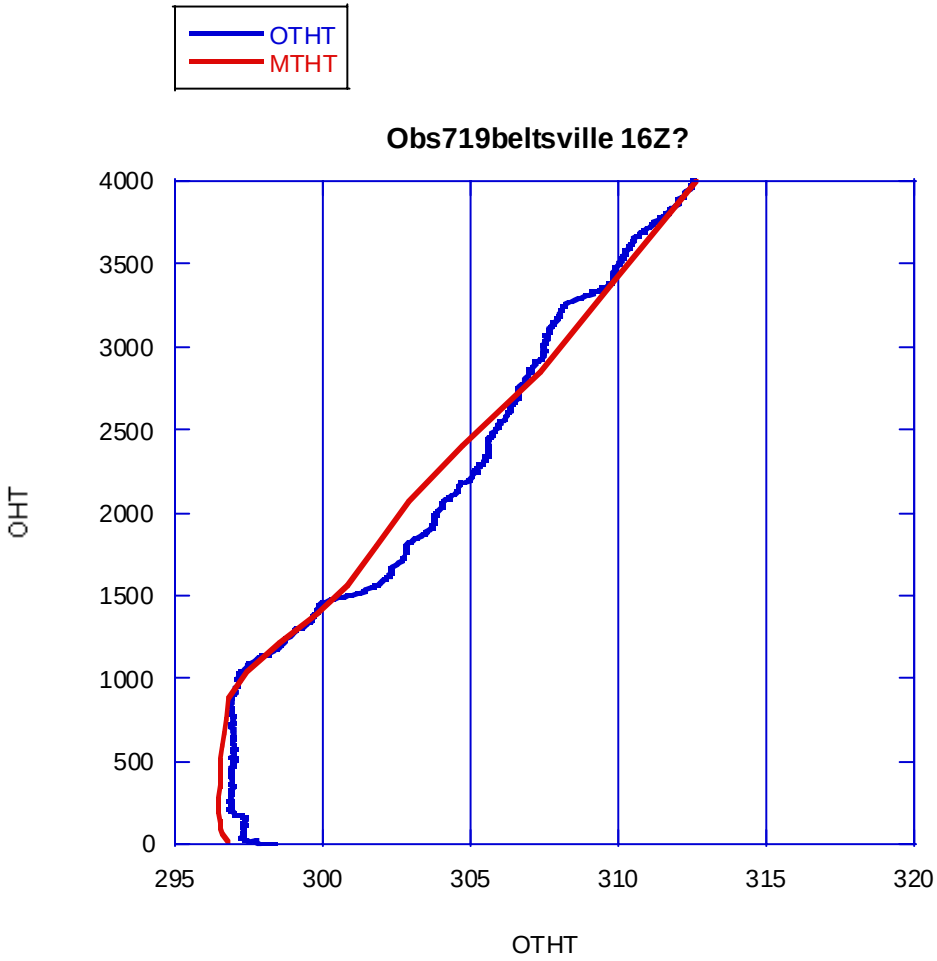
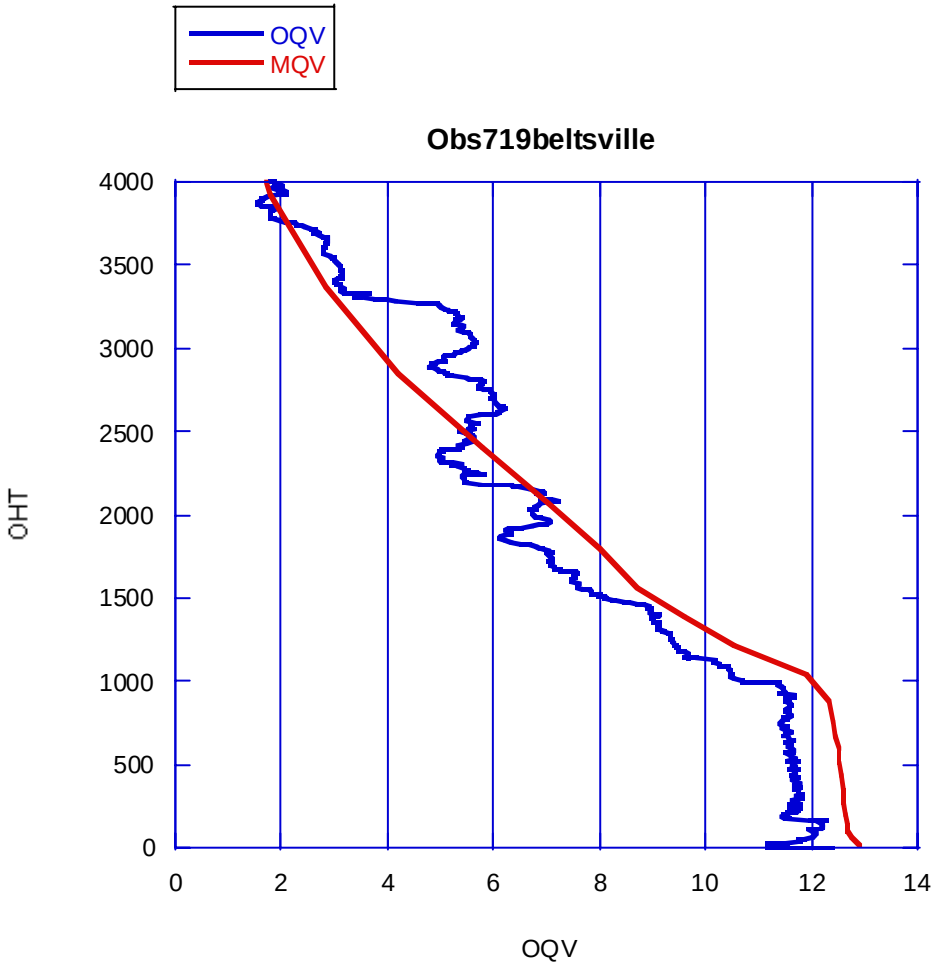
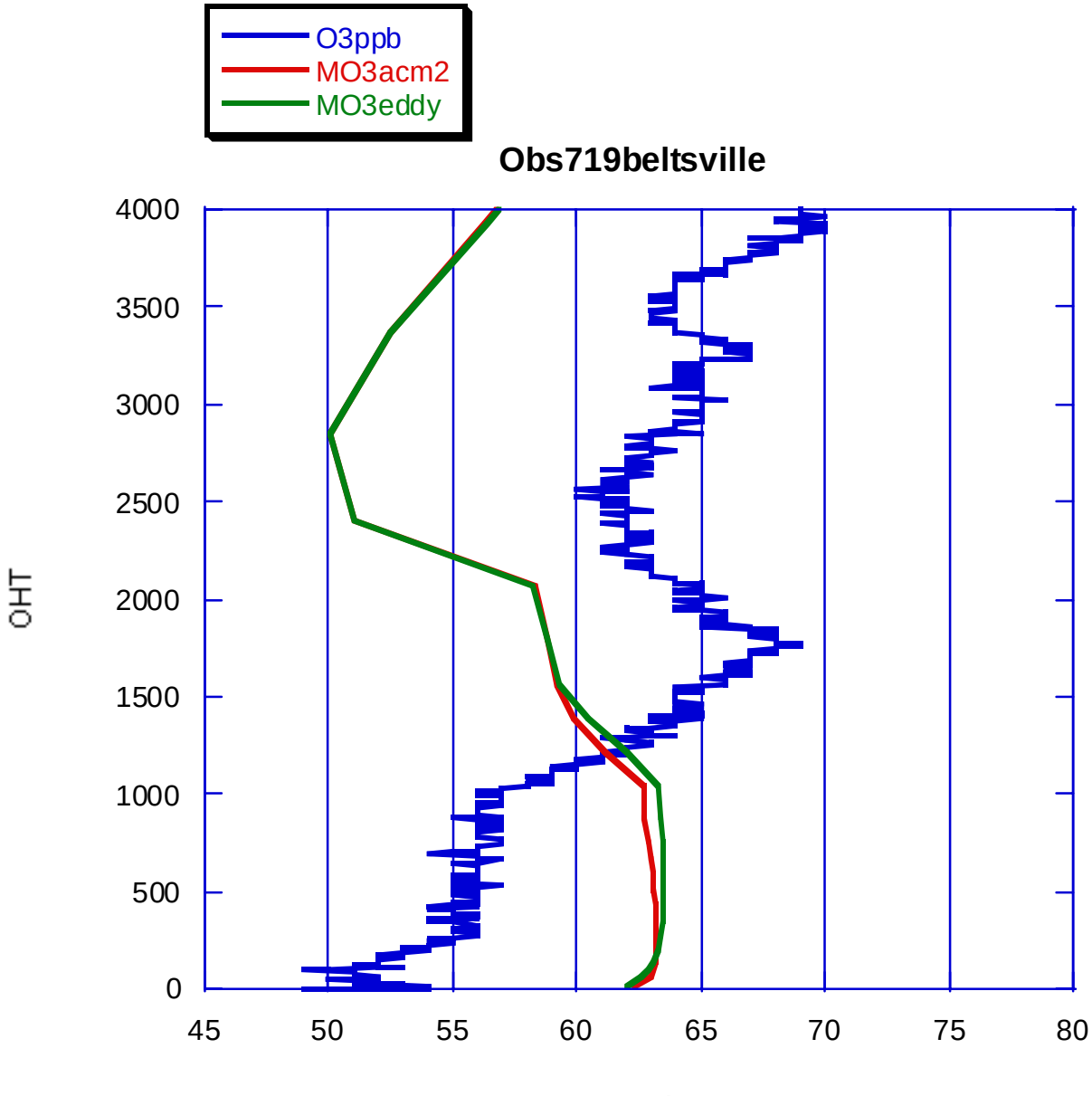
NOX

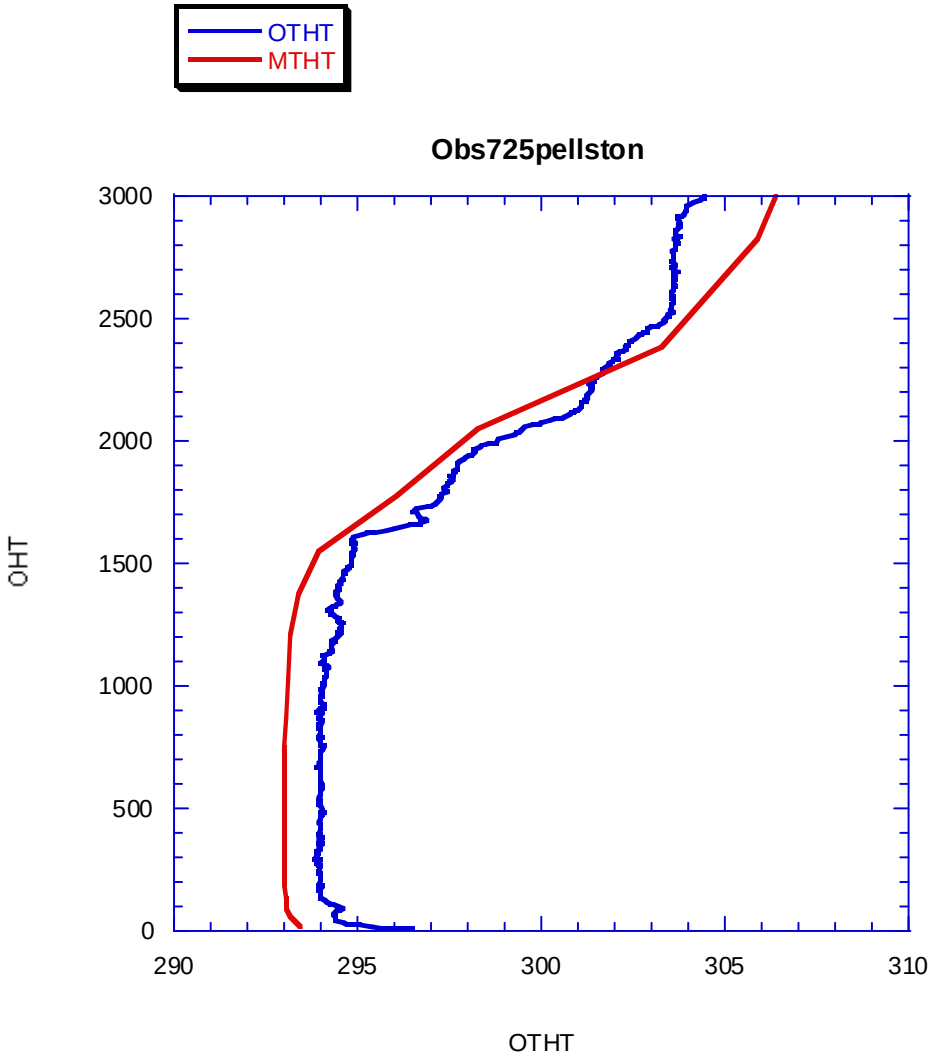
Ozonesonde at Beltsville
July 19, 16 Z

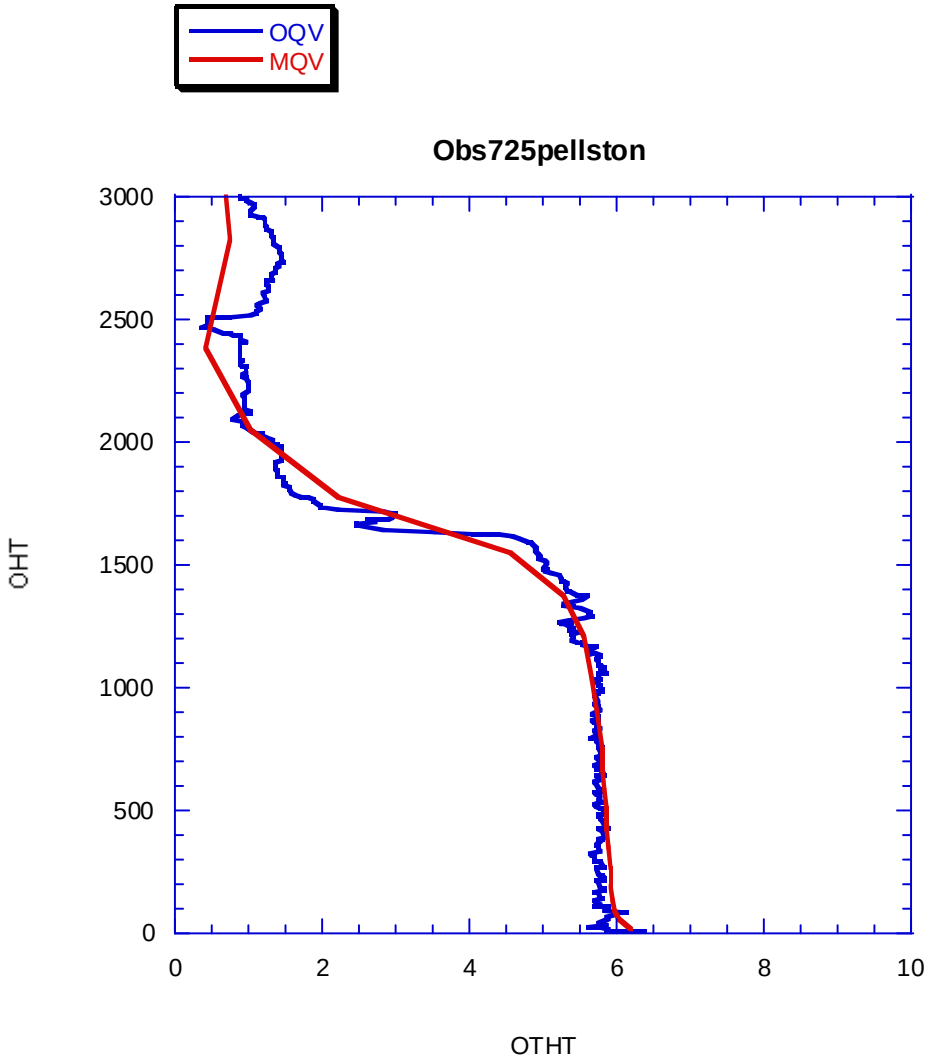


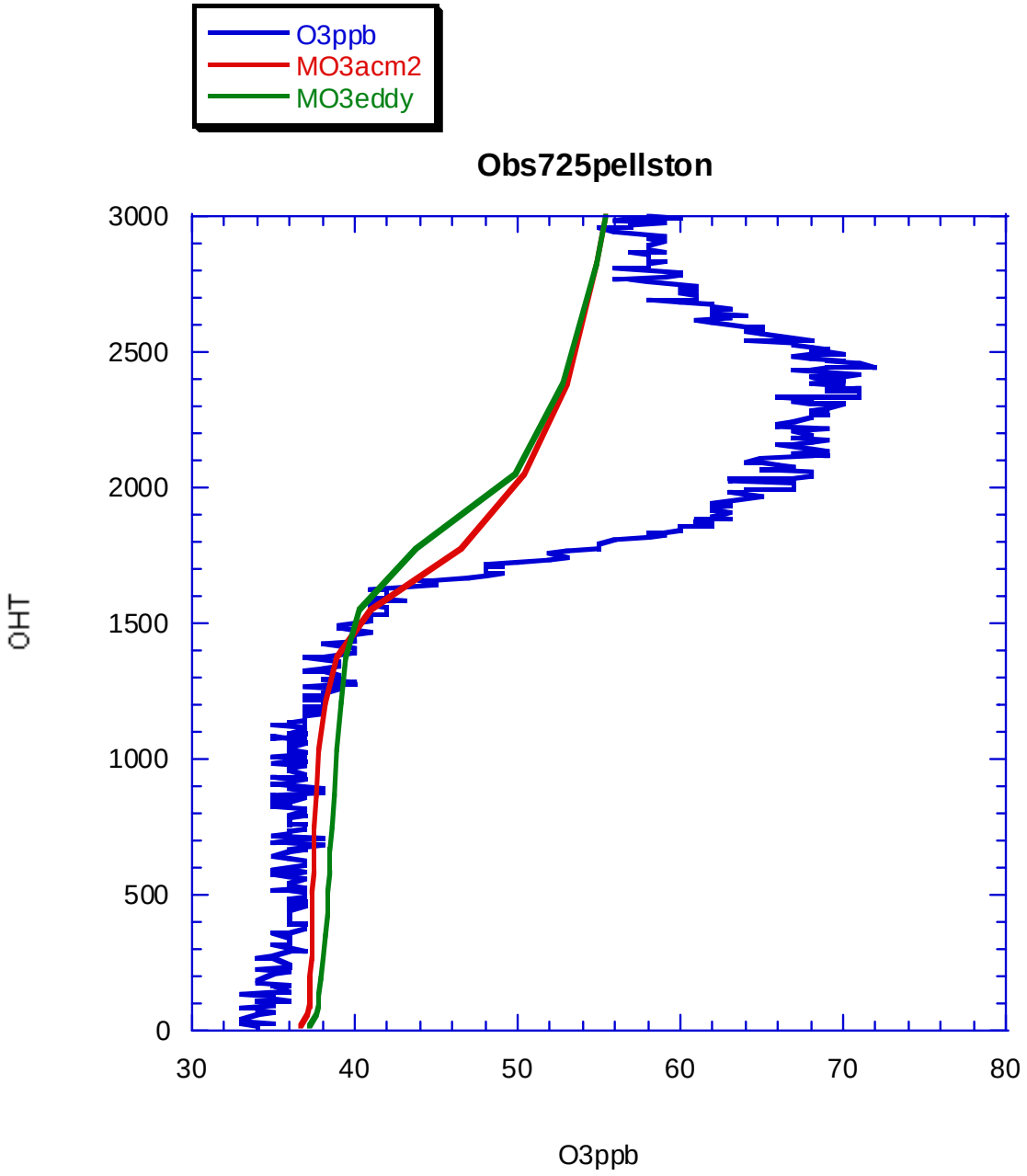



O3ppb
MO3acm2
MO3eddy
Obs719beltsville
4000
3500
3000
2500
2000
1500
1000
500
0
OHT
45
50
55
60
65
70
75
80
O3ppb

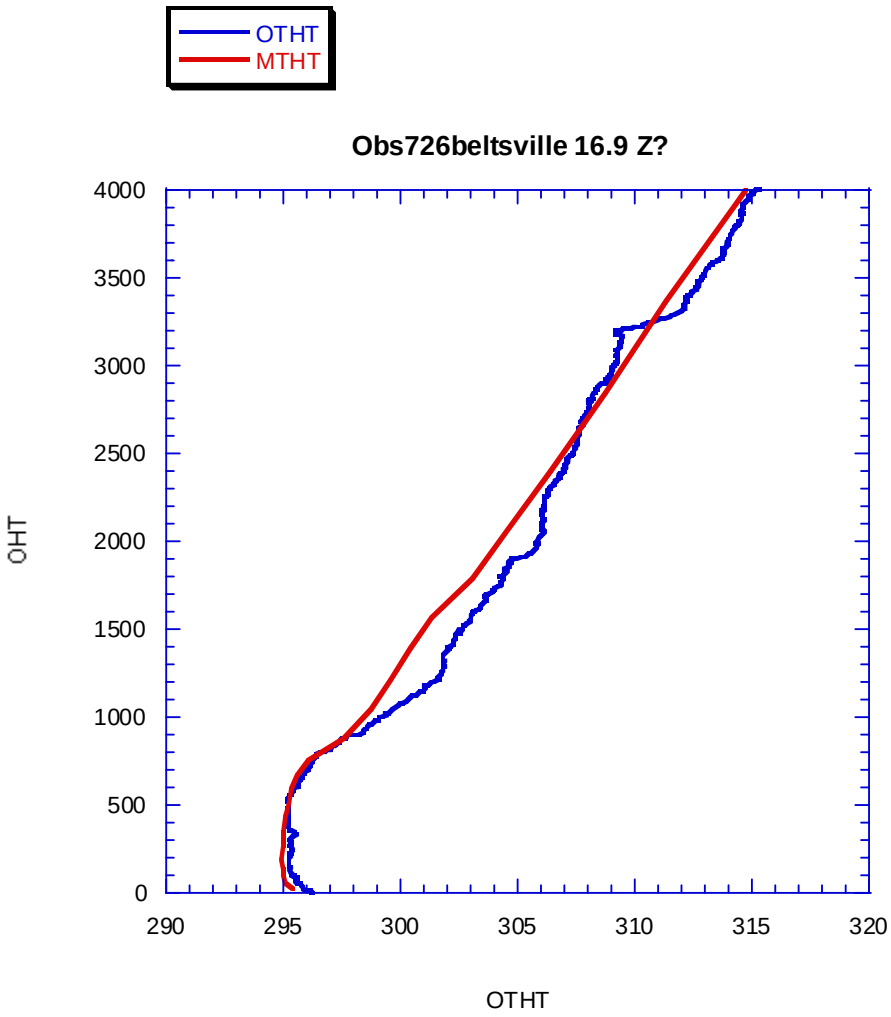
Pellston, MI July 25, 18Z

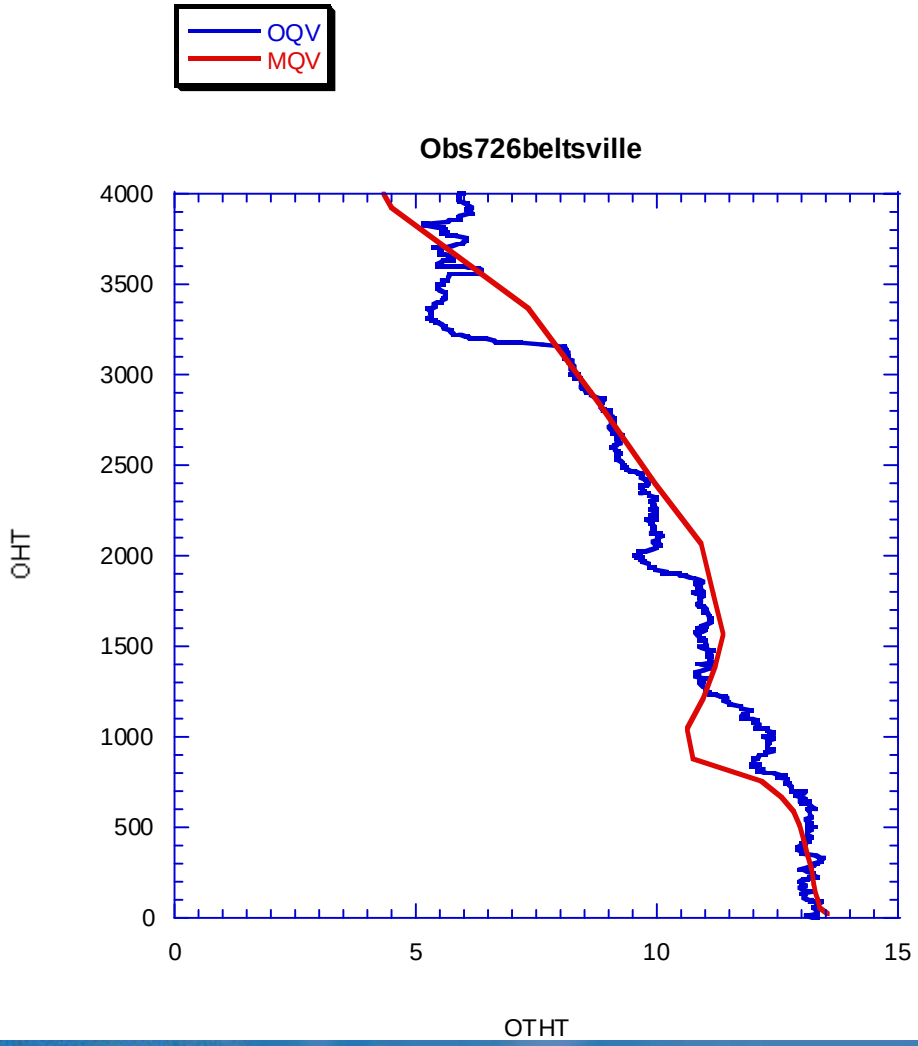


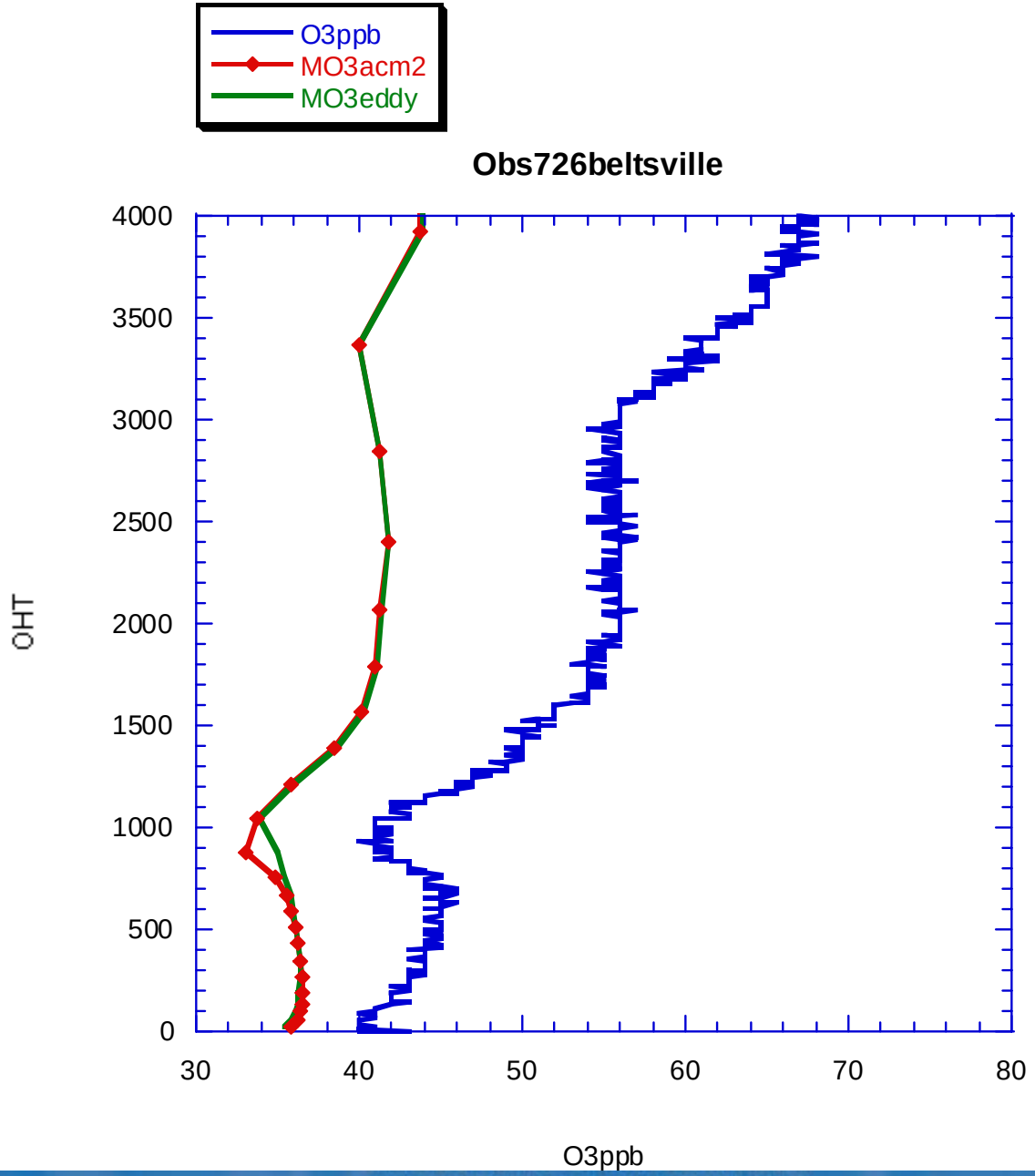



O3ppb
MO3acm2
MO3eddy
Obs725pellston
3000
2500
2000
1500
1000
500
0
OHT
30
40
50
60
70
80
O3ppb

Beltsville July 26, 17Z






O3ppb
MO3acm2
MO3eddy
Obs726beltsville
4000
3500
3000
2500
2000
1500
1000
500
0
OHT
30
40
50
60
70
80
O3ppb

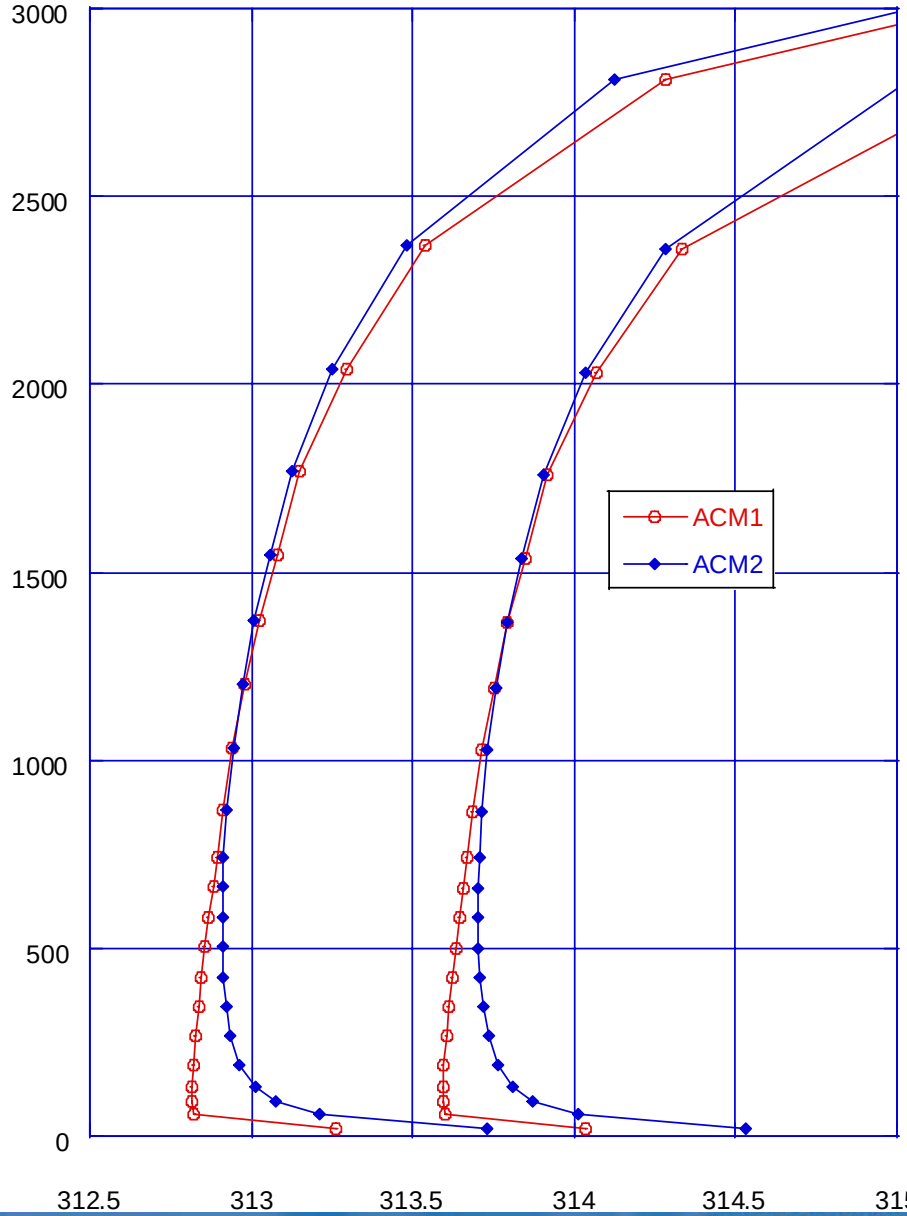
Conclusions

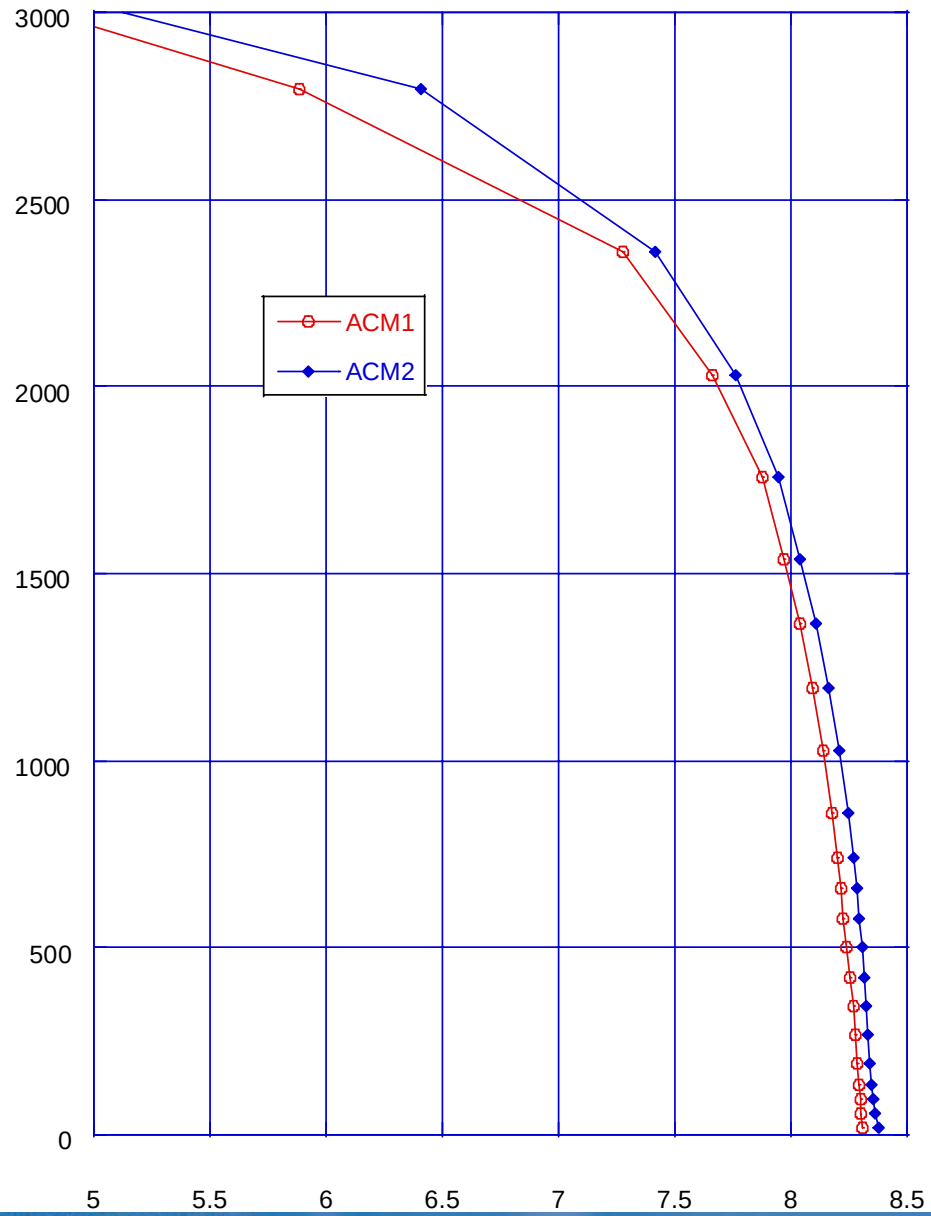
- ACM2 is a combination of local and non-local closure techniques
  - Similar capabilities to eddy diffusion w/ counter-gradient adjustment but more readily applicable to any quantity (e.g chemistry)
  - ACM2 produces more realistic superadiabatic surface layer than ACM1
- LES and 1-D tests show accurate simulation of vertical profiles and PBL heights
- MM5 tests show good ground level performance and accurate PBL heights

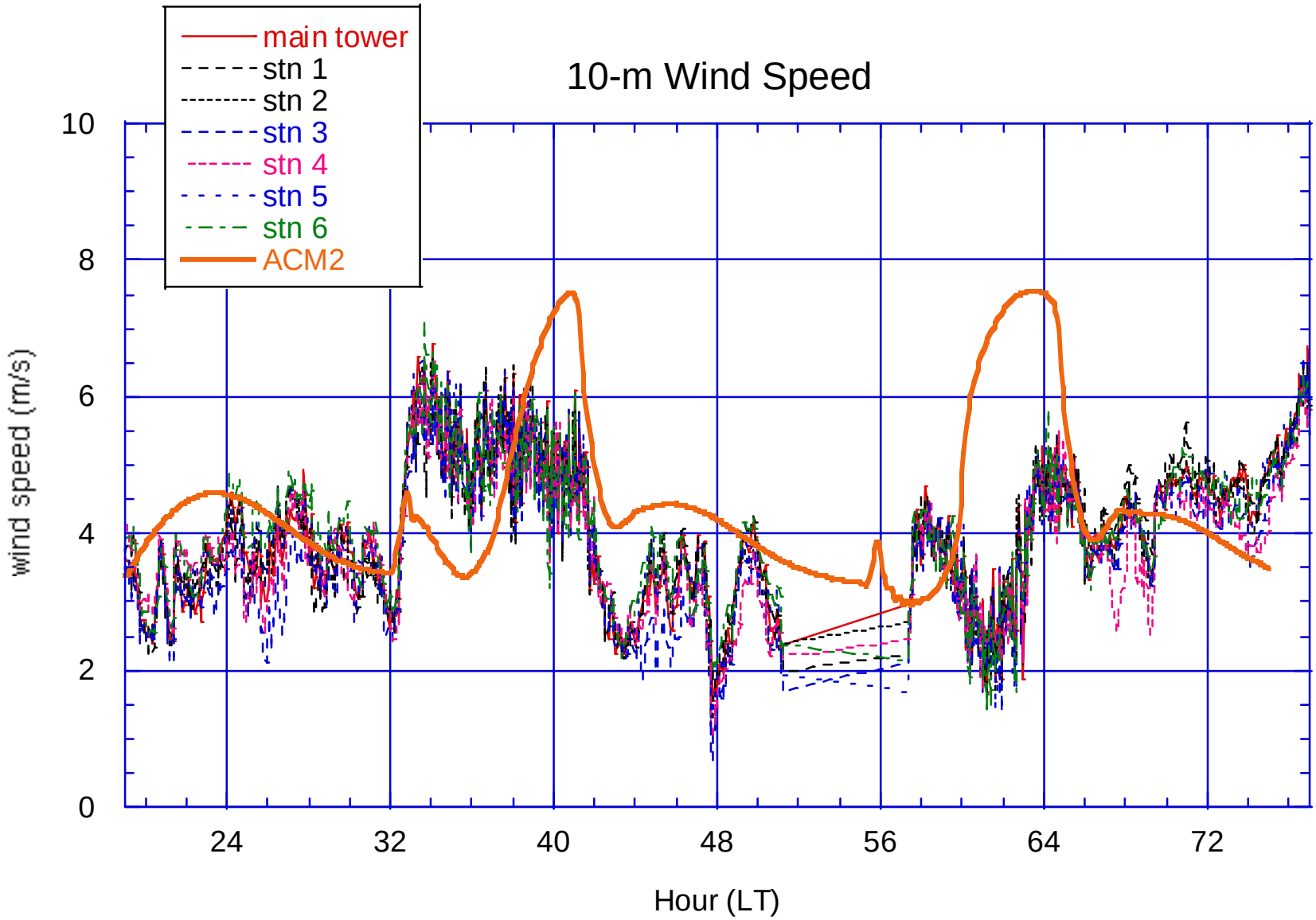
More Conclusions

- CMAQ testing shows comparable ground level performance as the current eddy diffusion model
- Vertical profiles show larger differences from eddy diffusion with shallower and more well mixed CBL
- Ozonesonde comparisons often show good agreement for θ and q_v but not as often for O_3
- *Given the meteorological verification and comparable CMAQ ground level statistics, ACM2 should be used in both meteorology and chemistry modeling*

MM5v3.6 Profiles over southern OK on August 5 18Z






10-m Wind Speed
main tower
stn 1
stn 2
stn 3
stn 4
stn 5
stn 6
ACM2
wind speed (m/s)
0
2
4
6
8
10
24
32
40
48
56
64
72
Hour (LT)