# Toward improved correlations between WRF model and remotely-sensed PBL height retrievals for the Southern Appalachian Mountains

Chris Thaxton (thaxtoncs@appstate.edu)
Appalachian State University, Boone, NC

Ad-Hoc Mixing Layer Working Group Meeting, April 11, 2018

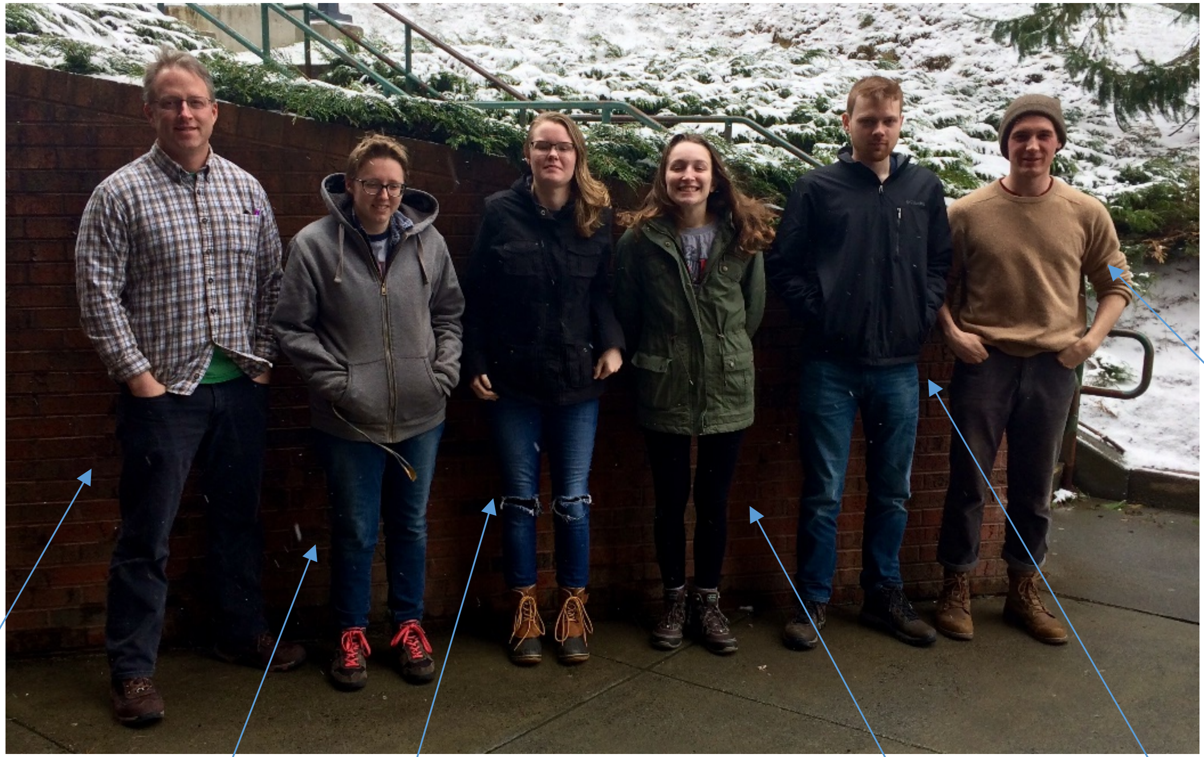
U.S. NAVAL RESEARCH LABORATORY

Appalachian STATE UNIVERSITY.

UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

# Applied Fluids Laboratory, 2018

## Appalachian State University



Chris Thaxton

Elliott McMillan
UG-Computer Science

Katie Steffen
UG-Environmental Science

Amelia Bellanger
UG-Environmental Science

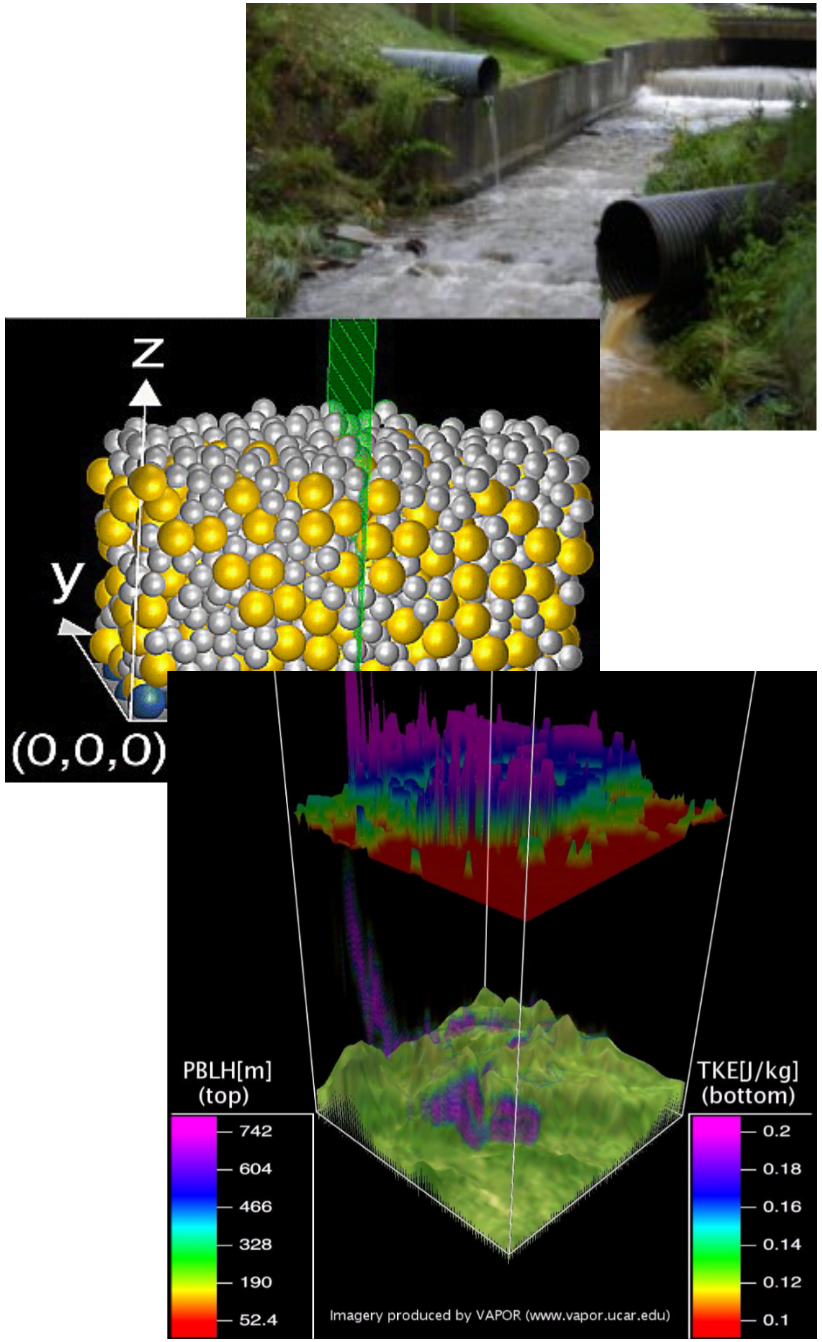
Preston Wilson
UG-Computer Science

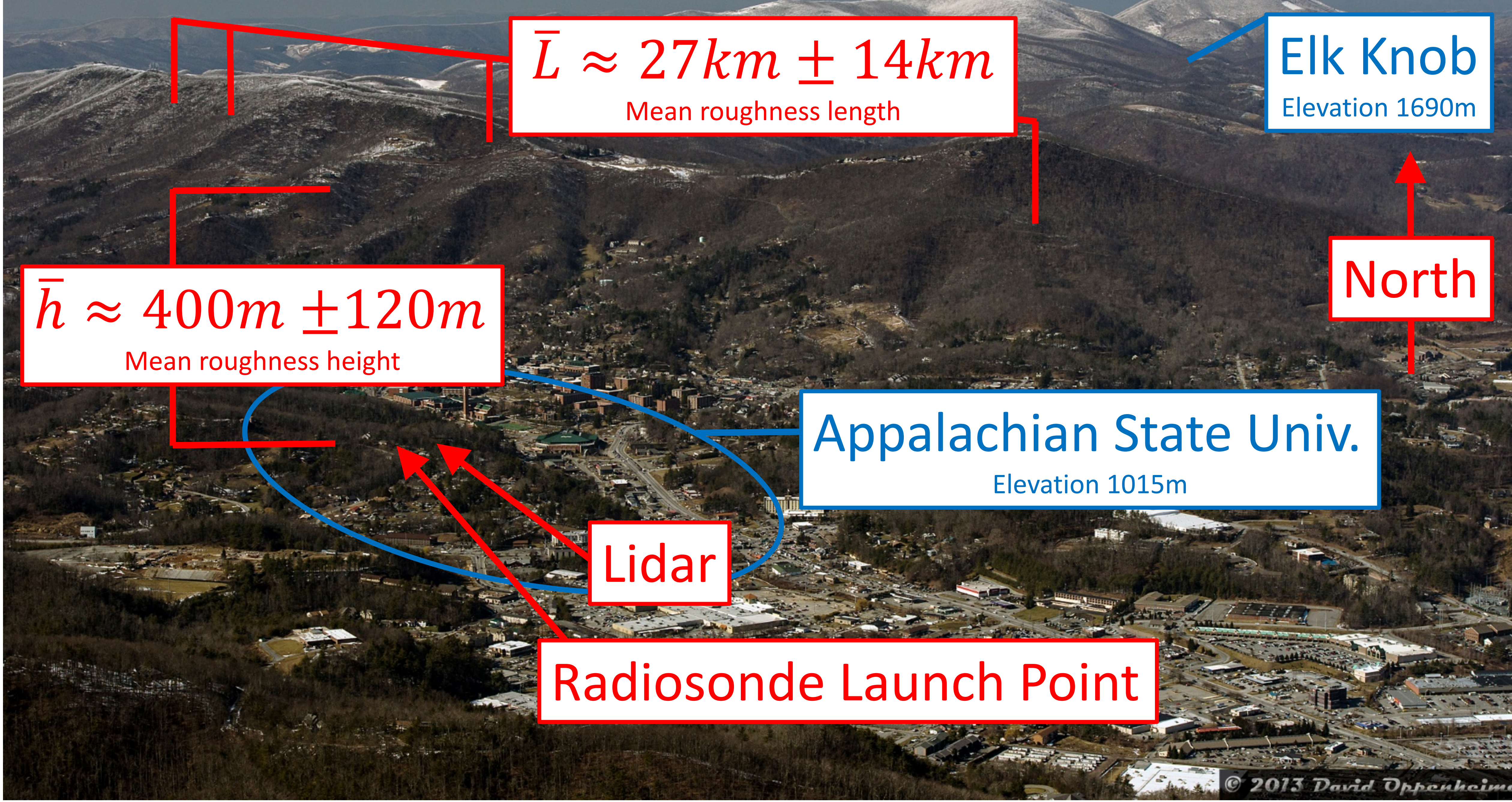
Quinlin Riggs
Graduate Student
Physics

Not shown
Sophia Barron
UG-Physics

# AFL@appstate – Active Projects

- **Optimizing planetary boundary and surface layer schemes in the WRF model for the Southern Appalachian Mountains (SAM).**
  - **Support aerosol-based investigations (e.g. Sherman, Swarthout, etc.)**
  - **Inform operational forecasting in complex terrain.**
  - **Foundation for WRF-Chem (Summer, 2018)**
- **Characterizing turbulence sourcing over the SAM.**
- **Theory for Incipient Motion in Oscillatory Flows.**
- **Stochastic analysis of mountain stream temperatures (10+ years)**
- Emergent projects:
  - Cold season precipitation events in the SAM.
  - "Big data" analysis of climate forcings in Peru and Bolivia
  - …





$\bar{L} \approx 27km \pm 14km$
Mean roughness length
Elk Knob
Elevation 1690m
North
$\bar{h} \approx 400m \pm 120m$
Mean roughness height
Appalachian State Univ.
Elevation 1015m
Lidar
Radiosonde Launch Point
© 2013 David Oppenheimer

**WRF v3.9 w/hybrid vertical coordinate**

Resolutions: d01=27km; d02=9km; d03=3km; d04=1km

60 vertical layers

dt(d01)=90;

Microphysics: Thompson scheme

LW /SW rad: RRTM schemes

Surface: Unified Noah land-surface model

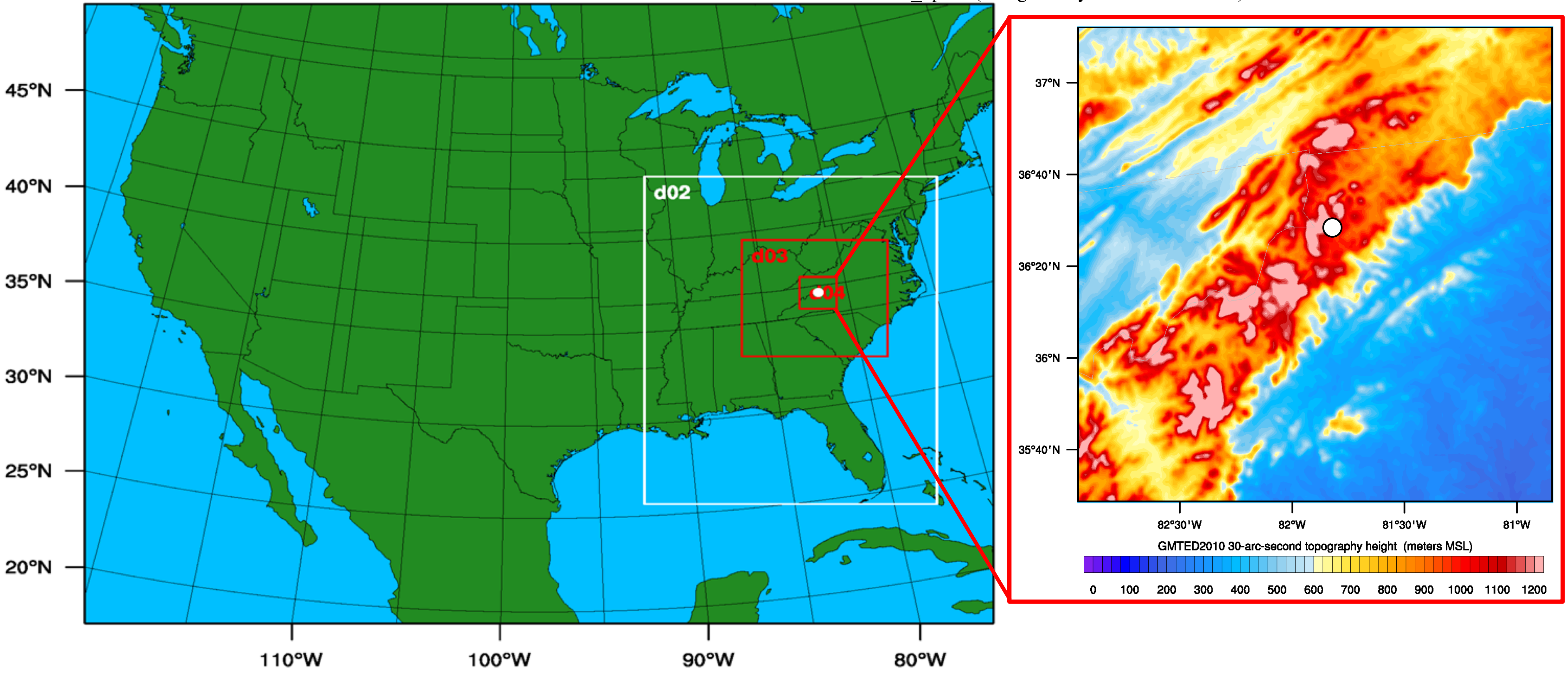
Cumulus physics: Kain-Fritsch (new Eta) scheme

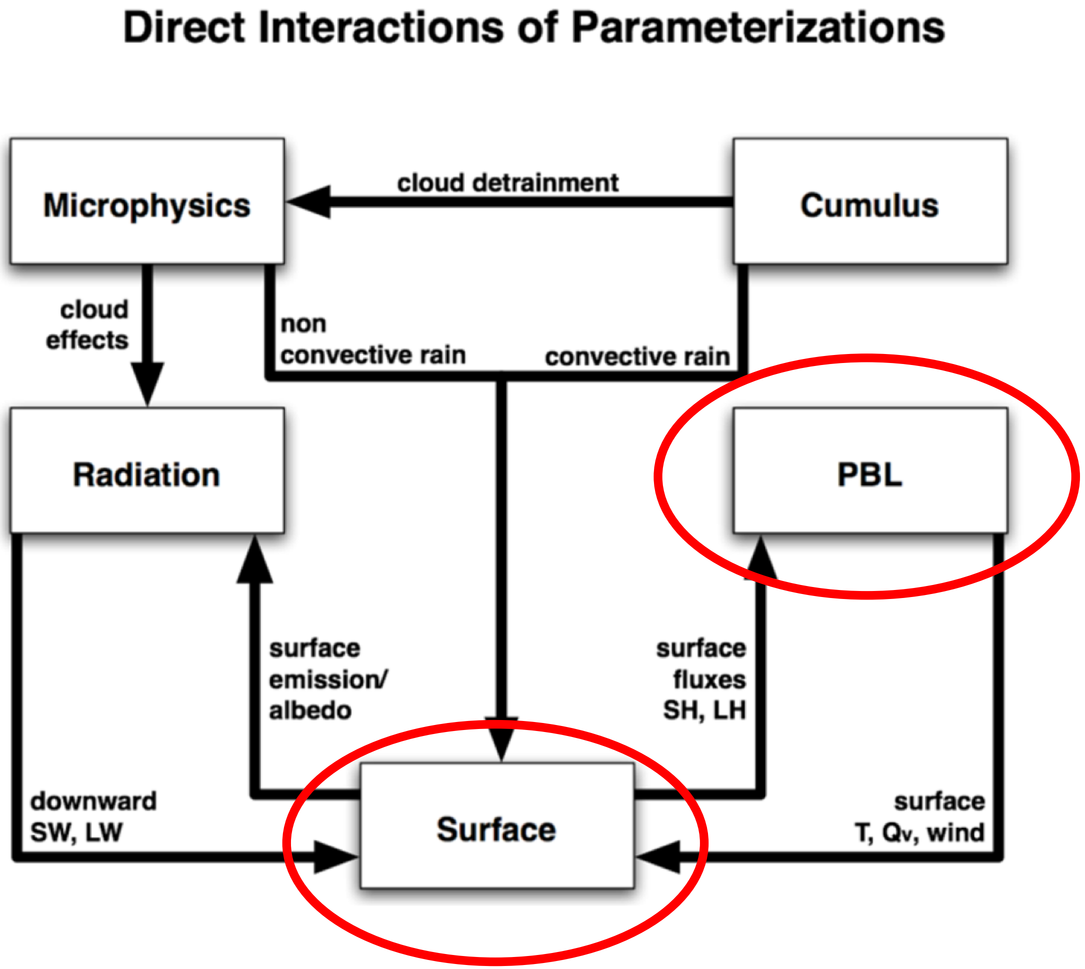
(outer 2 domains only); cu-rad feedback=.true.

Dynamics:

No 6thO diff; diff_opt=0/1/2 (turbulence); Rayleigh damping;

km_opt=4 (Smagorinsky first order closure)



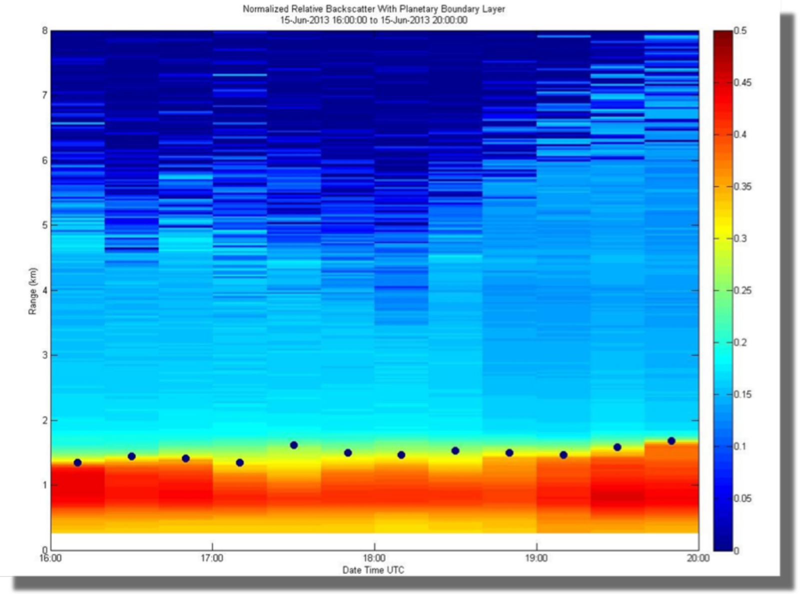



| PBL Scheme | bl_pbl _physics | Closure Scheme | Surface Scheme | sf_sfclay _physics | As in… |
|---|---|---|---|---|---|
| MYNN2.5 | 5 | 1.5 local | MYNN | 5 | [1, 2] |
| MYJ | 2 | 1.5 local | Eta Similarity | 2 | [1,2,3,8] |
| YSU | 1 | 1.0 non-local | MM5 | 1 | [1,2,3,8] |
| ACM2 | 7 | 1.0 non-local | MM5 | 1 | [1,2,3,8] |

**The on-site Micro Pulse LiDAR** (MPL-4B-532, Sigma Space Corporation, Lanham, MD), uses a 532nm laser with a minimum range of 150m and a maximum range of 25km to receive the relative backscatter signal from aerosols, clouds, and clean air. The time of flight resolution for the Micro Pulse LiDAR signal is 30m.

The Normalized Relative Backscatter (NRB) signal was processed through a wavelet covariance transform algorithm**. Three dilation windows of varying widths, 60-120m, 360-540m, **480-660m** were used to identify the location of the steepest gradient corresponding to the PBL height.

****  Brooks J., *J. Atmo & Oceanic Techn*. (20), 2003**
**Compton et al, *J. Atmo & Oceanic Techn*. (30), 2013**



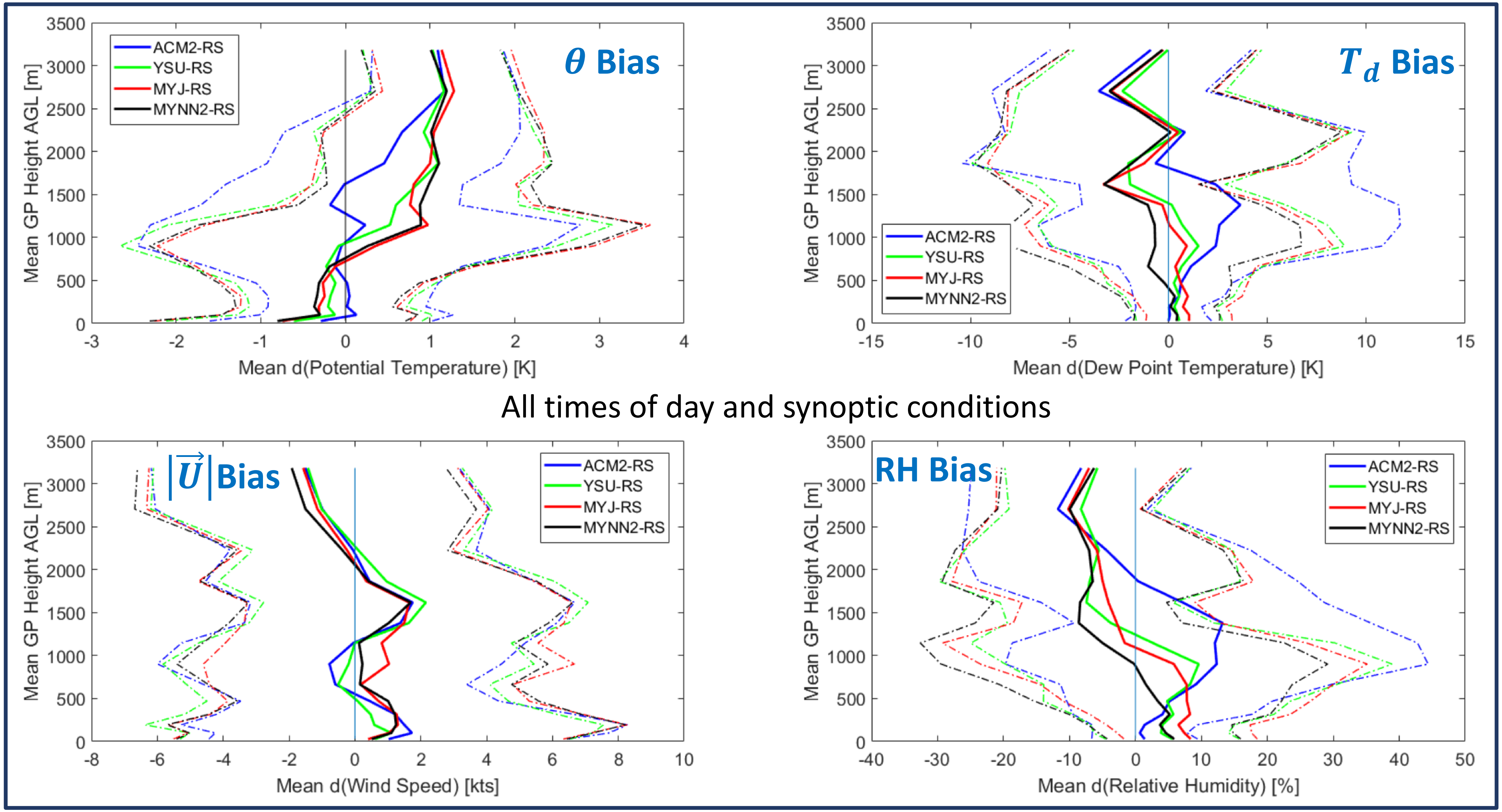

76 radiosonde launches during the warm months of 2013

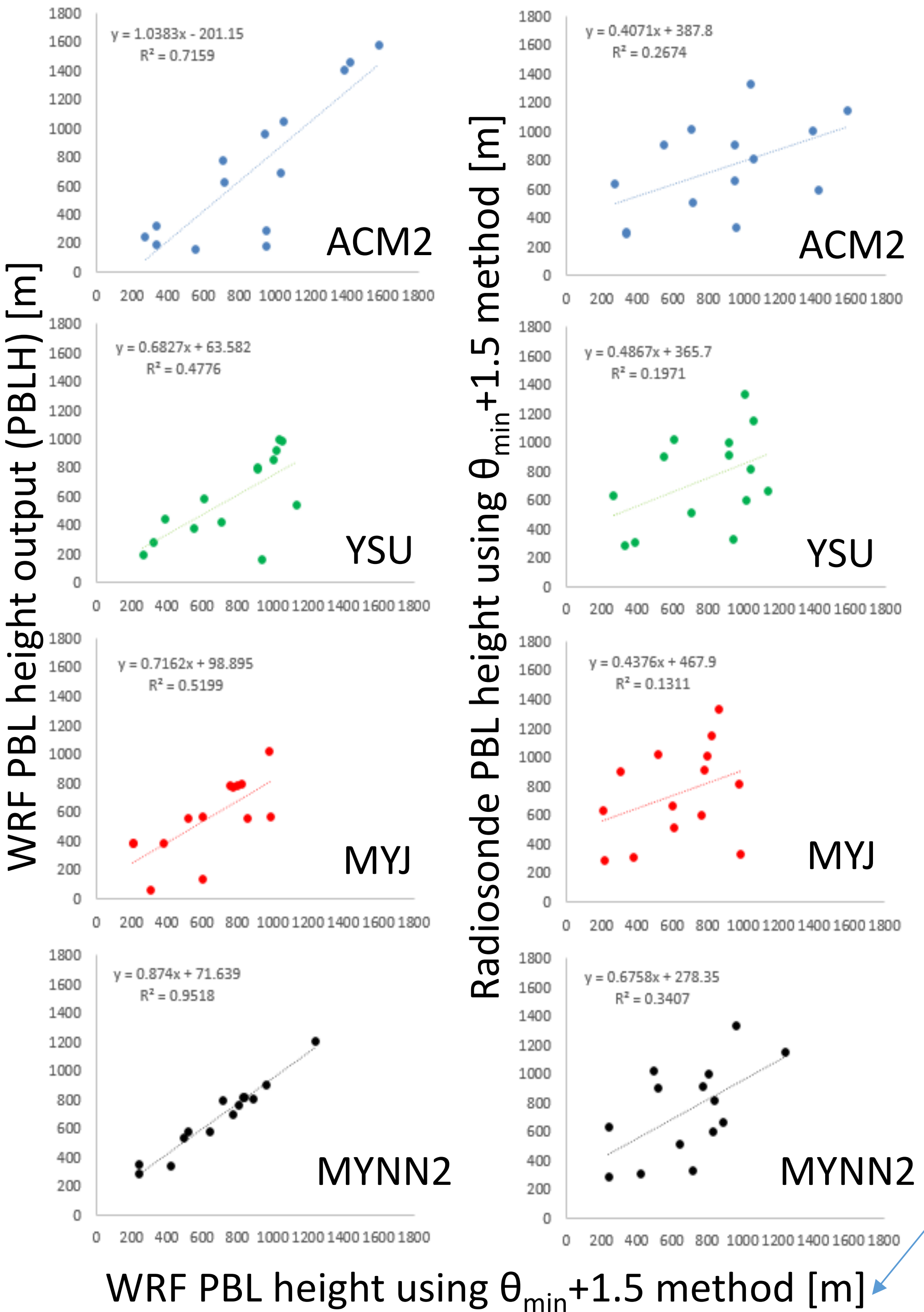
iMet-1 radiosondes (IMET-1-AV-403MHz, International Met Systems, Grand Rapids, MI

Ongoing launch campaign – Winter 2018

Focus: Shear-dominated flows

# Preliminary WRF results – subset of Su2013





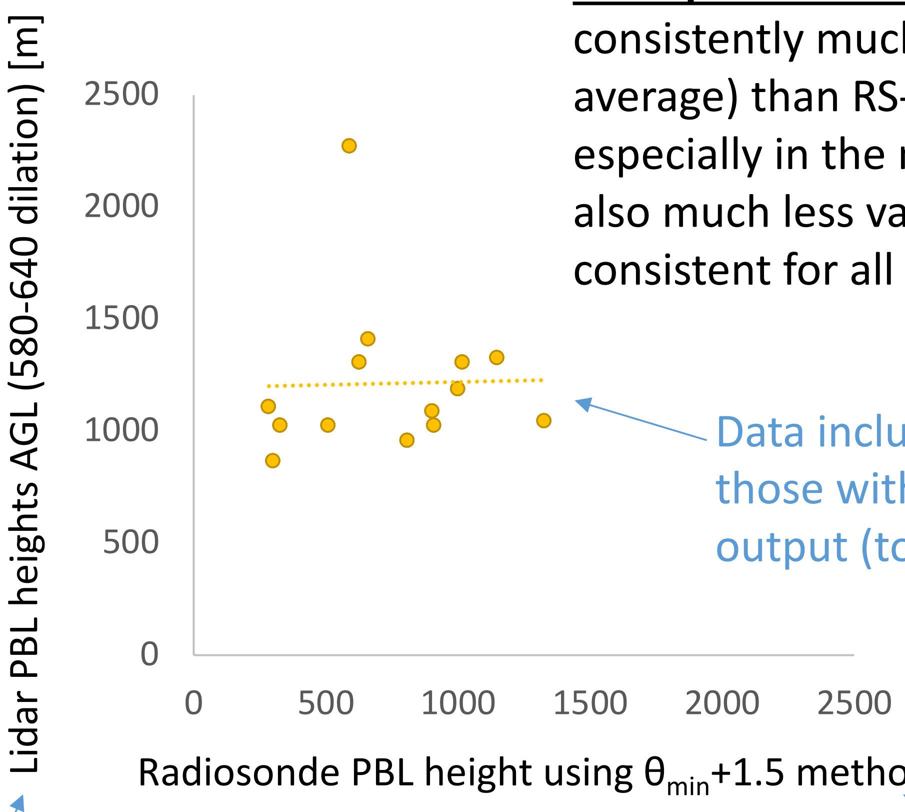

PBL height is determined in various ways by each PBL scheme:

- **ACM2:** PBLH = the height where the bulk Richardson number calculated above neutral buoyancy exceeds a critical value of 0.25.
- **YSU:** PBLH = Using a bulk Richardson method but starts from the surface. A threshold value of 0.25 is used for unstable flow; threshold of 0.00 for stable conditions.
- **MYJ:** PBLH = the height at which the TKE decreases to a value of 0.2 $m^2s^{-1}$.
- **MYNN2.5:** Adaptive PBLH scheme

We have many more runs – need to update analysis

**Garcia-Diez, M., J. Royal Met. Soc., 2013; Nielsen-Gammon, J.W., et al, , JAMC. (47) 2007**

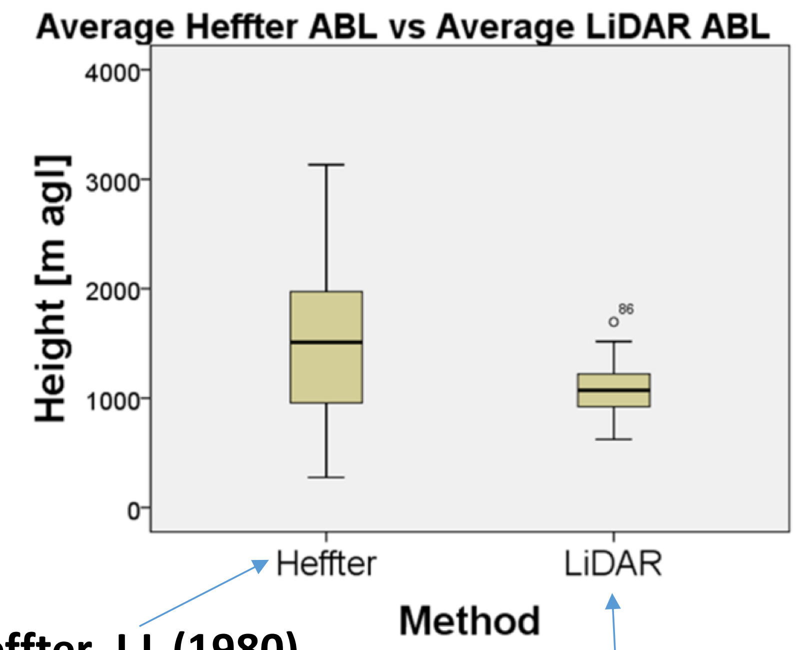
# Prelim LIDAR comparison – Summer 2013 data, correlated to radiosonde launch date:time




**<u>Lidar-predicted PBL heights</u>** were consistently much higher (40% on average) than RS-derived PBL heights, especially in the mornings. They were also much less variable. Results were consistent for all dilation windows.

Data include only those with WRF run output (to date)

All summer 2013 data




**Heffter, J.L (1980)**

Mean over all dilation window sizes

Wavelet covariance method, e.g.
**Brooks J., *J. Atmo & Oceanic Techn*. (20), 2003**
**Compton et al, *J. Atmo & Oceanic Techn*. (30), 2013**

**Garcia-Diez, M., J. Royal Met. Soc., 2013**
**Nielsen-Gammon, J.W., et al, , JAMC., 47, 2007**

Mean PBL height and StDev from WRF and using the $\theta_{min} + 1.5$ method(++) to radiosonde profiles, broken down by synoptic code(**).

| Mean | Mean | Stdev | SC1 Mean | SC1 Stdev | SC4 Mean | SC4 Stdev | SC6 Mean | SC6 Stdev | SC7 Mean | SC7 Stdev | SC66 Mean | SC66 Stdev |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ACM2** | 706 | 508 | 541 | 343 | 872 | 823 | 1095 | 672 | 573 | 537 | **781** | 881 |
| **YSU** | 594 | 293 | 573 | 313 | **536** | 536 | 698 | 400 | **620** | 251 | 583 | 296 |
| **MYJ** | 550 | 268 | 503 | 294 | 674 | 155 | 674 | 159 | 573 | 275 | 421 | 513 |
| **MYNN2** | 673 | 252 | **612** | 263 | 805 | 17 | **889** | 448 | 516 | 251 | 670 | 127 |
| **Radiosonde** | **744** | **326** | **600** | **343** | **459** | **186** | **828** | **451** | **605** | **431** | **951** | **70** |

| SC** | Type |
|---|---|
| 1 | Dry moderate |
| 2 | Dry polar |
| 3 | Dry tropical |
| 4 | Moist mod. |
| 5 | Moist polar |
| 6 | Moist tropical |
| 7 | Transition |
| 66 | MT+ |
| 67 | MT++ |

**MYNN and YSU are emerging as best options**

**All WRF PBL schemes generally under-predict PBLh.**
**WRF is not mixing enough?**

** http://sheridan.geog.kent.edu/ssc.html
Sherdian, 2002, The redevelopment of a weather-type classification scheme for North America, Int. J. Climatol. 22: 51–68 (2002) DOI: 10.1002/joc.709.
++ Garcia-Diez, M., J. Royal Met. Soc., 2013; Nielsen-Gammon, J.W., et al, , JAMC., 47, 2007

The turbulent kinetic energy per unit mass:

$$TKE \equiv (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})/2$$

....changes in time due to the following processes:

$$\frac{\bar{D}\,(TKE)}{Dt} = MP + BPL + TR - \varepsilon$$

Redistribution of turbulence by advection and pressure forces

Dissipation of turbulence to molecular scale

Mechanical Production


Buoyancy Production or Loss

vs.


(Wallace & Hobbs, 2006, eq. 9.7)

# Focus on shear-driven stable boundary layer (Winter, NW flows); Isolate mechanical production

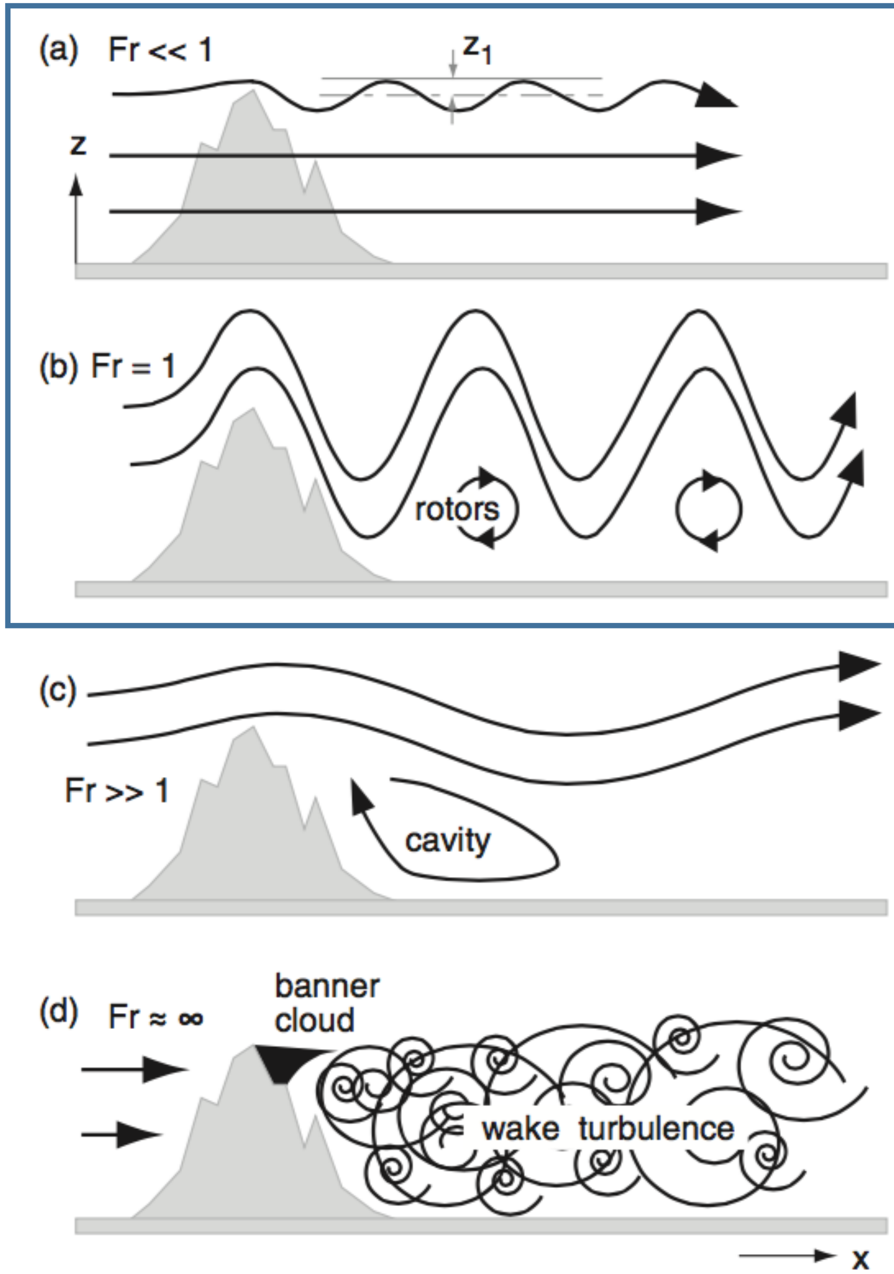
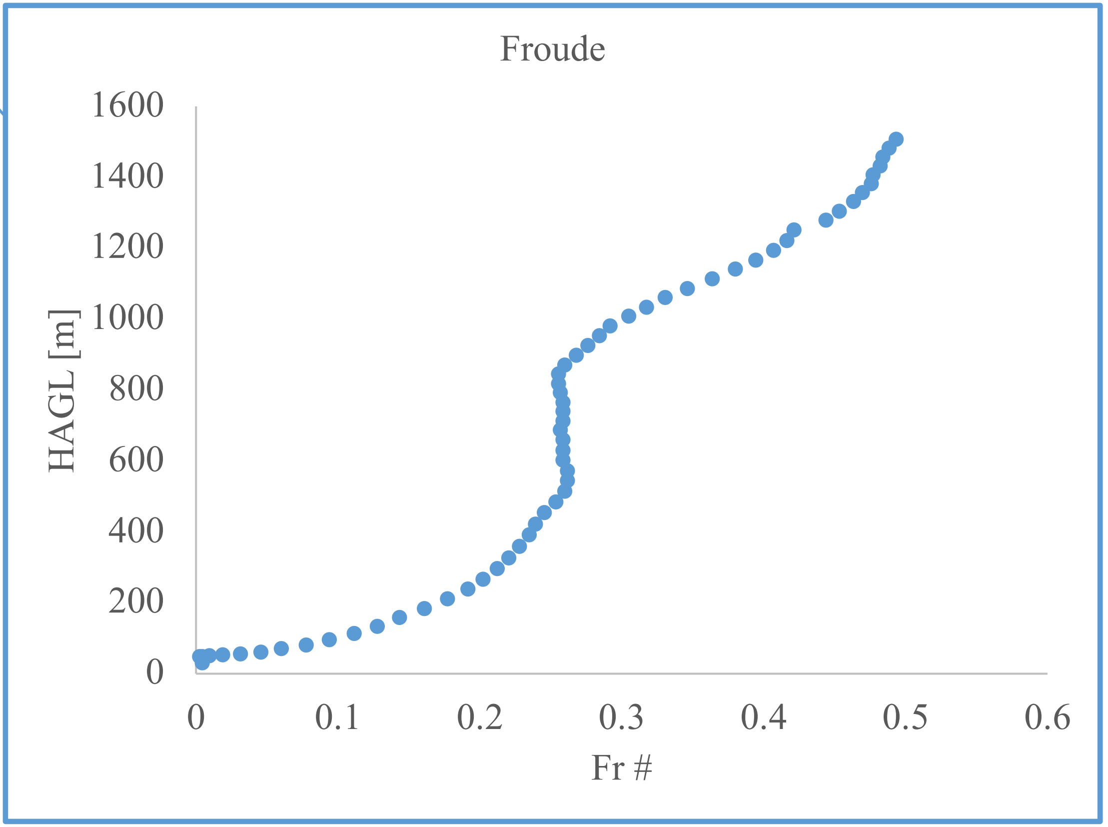
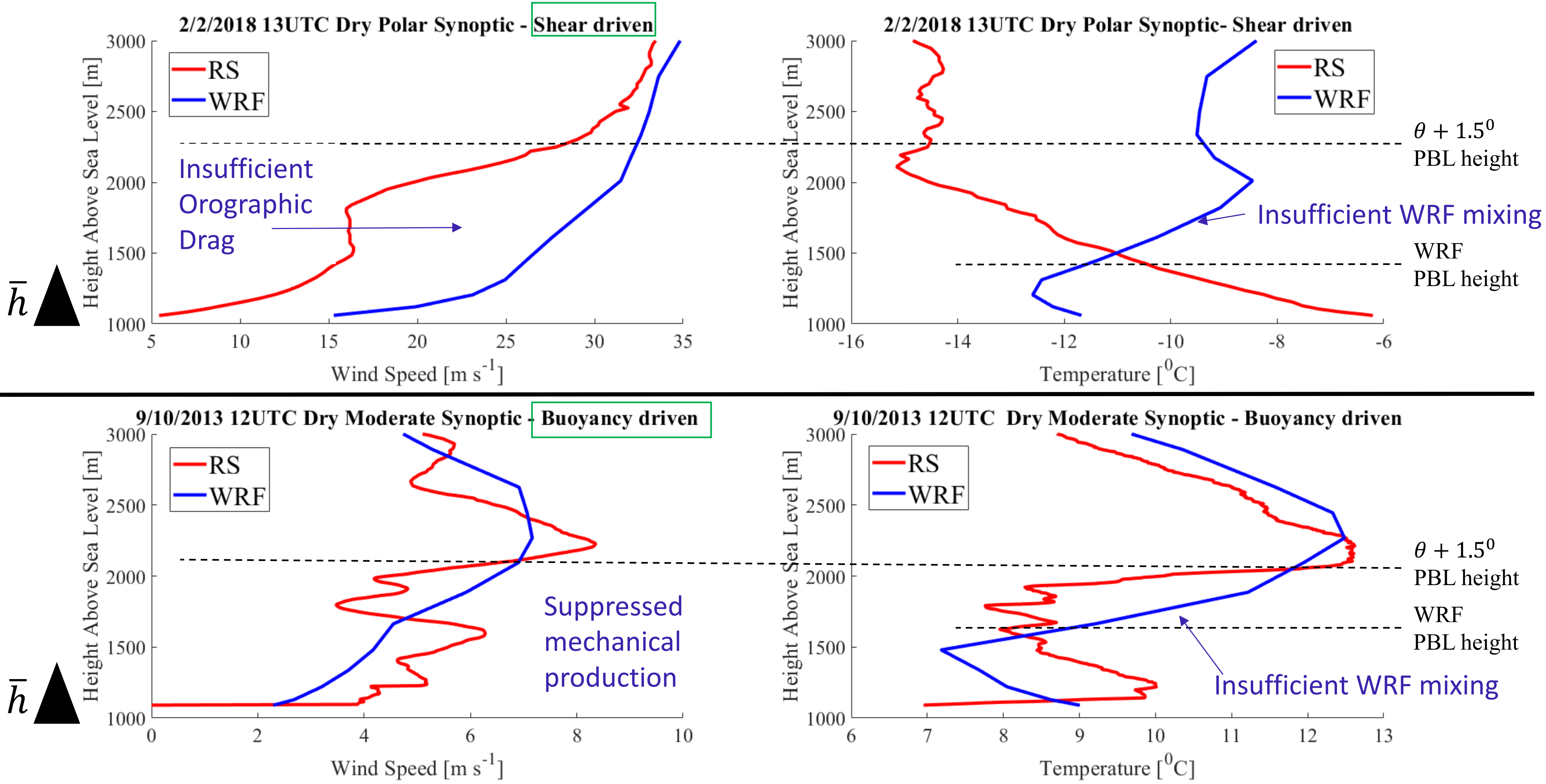



**Figure 17.30**
*Mountain wave behavior vs. Froude number, $Fr_3$.*

2/1/2018 0830 local time
Surface WS: 10 m/s; Patchy clouds
Synoptic WD: $310^0$ (Northwesterly)
Surface Temp: $-4^0C$



# WRF runs – YSU (with TOPOWIND=1; Jimenez & Dudhia, 2012), at 1.0km resolutions



$$\frac{\bar{D}\bar{u}}{Dt} = -\frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial x} + f\bar{v} - \left[\frac{\partial \overline{u'u'}}{\partial x} + \frac{\partial \overline{u'v'}}{\partial y} + \frac{\partial \overline{u'w'}}{\partial z}\right] + \bar{F}_{rx}$$

$$\frac{\bar{D}\bar{v}}{Dt} = -\frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial y} - f\bar{u} - \left[\frac{\partial \overline{u'v'}}{\partial x} + \frac{\partial \overline{v'v'}}{\partial y} + \frac{\partial \overline{v'w'}}{\partial z}\right] + \bar{F}_{ry}$$

$$\frac{\bar{D}\bar{w}}{Dt} = -\frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial z} + g\frac{\bar{\theta}}{\theta_0} - \left[\frac{\partial \overline{u'w'}}{\partial x} + \frac{\partial \overline{v'w'}}{\partial y} + \frac{\partial \overline{w'w'}}{\partial z}\right] + \bar{F}_{rz}$$

$$\frac{\bar{D}\bar{u}}{Dt} = -\frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial x} + f\bar{v} - \frac{\partial \overline{u'w'}}{\partial z}$$

$$\frac{\bar{D}\bar{v}}{Dt} = -\frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial y} - f\bar{u} - \frac{\partial \overline{v'w'}}{\partial z}$$

Just look at horizontal for now

WRF: Horizontal turbulence variations neglected – BAD for mountains!!

Neglect molecular diffusion – we assume that turbulence greatly dominates above a viscous sublayer.

# Flux-gradient Theory (K-Theory)

- WRF boundary layer schemes are based on K-theory.
- “Closure” achieved by assuming eddies “behave” like molecular diffusion…turbulent flux is proportional to local gradient

$$\overline{u'w'} = -K_m\left(\frac{\partial \bar{u}}{\partial z}\right); \quad \overline{v'w'} = -K_m\left(\frac{\partial \bar{v}}{\partial z}\right)$$

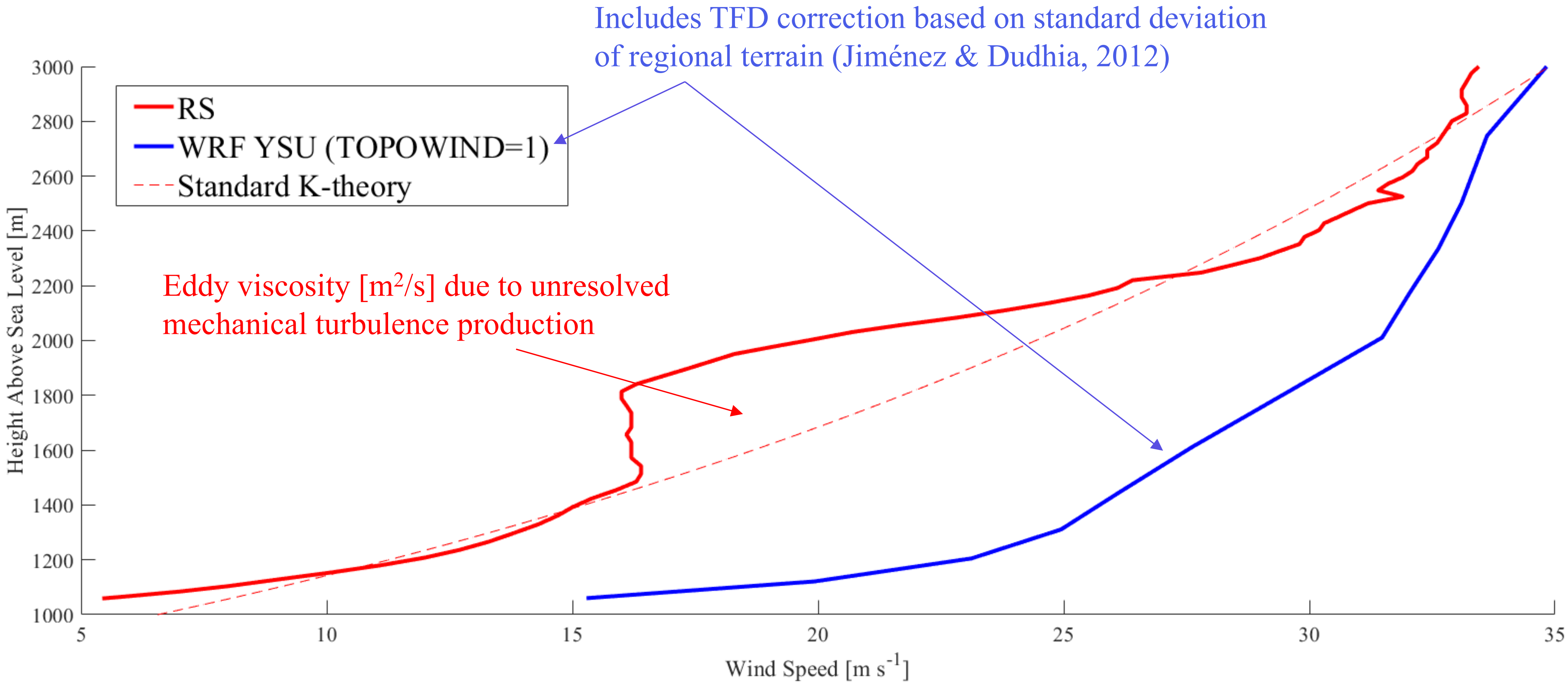
$$\overline{\theta'w'} = -K_h\left(\frac{\partial \bar{\theta}}{\partial z}\right)$$

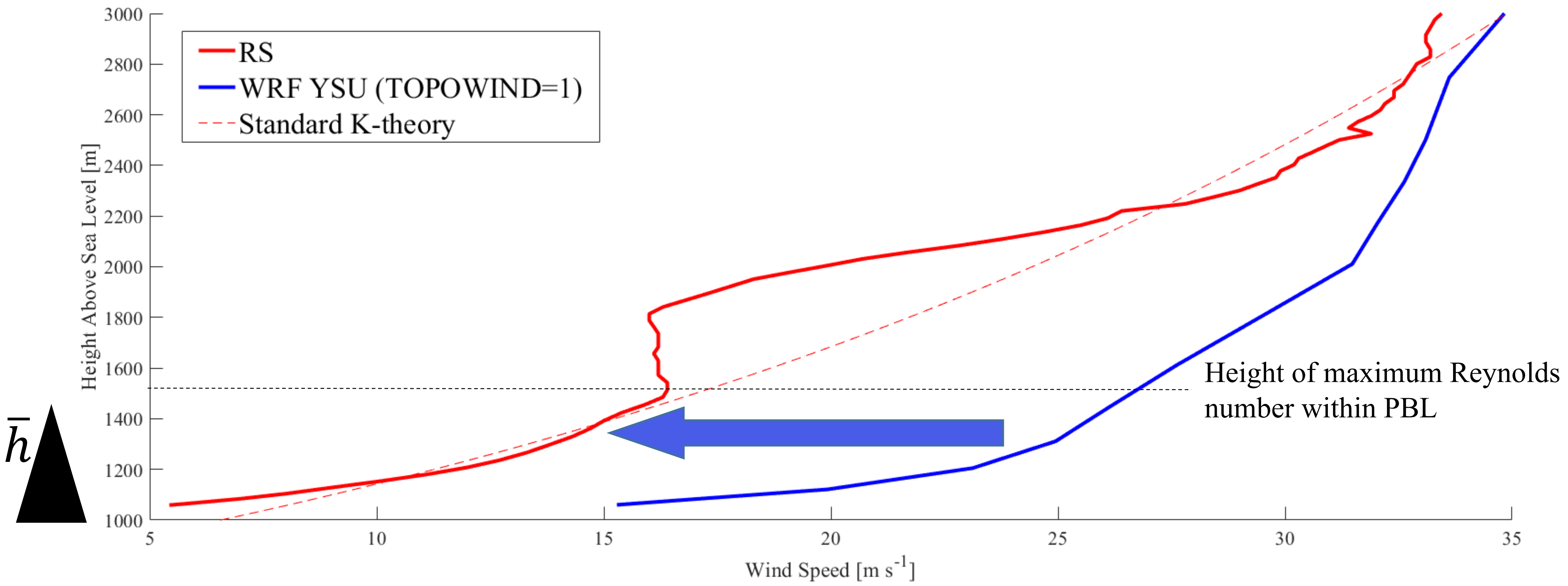
Eddy viscosity is defined as

$$K_m = \overline{\xi'^2}\left|\frac{\partial \vec{V}}{\partial z}\right| = \overline{l^2}\left|\frac{\partial \vec{V}}{\partial z}\right|$$

Boundary layer profile

$$\overline{U} = \frac{u_*}{k} ln\left(\frac{z}{z_0}\right) \qquad u^{*2} = K\left|\frac{\partial \vec{V}}{\partial z}\right|; \quad \mathrm{k} = 0.4; \quad z_0 = h$$

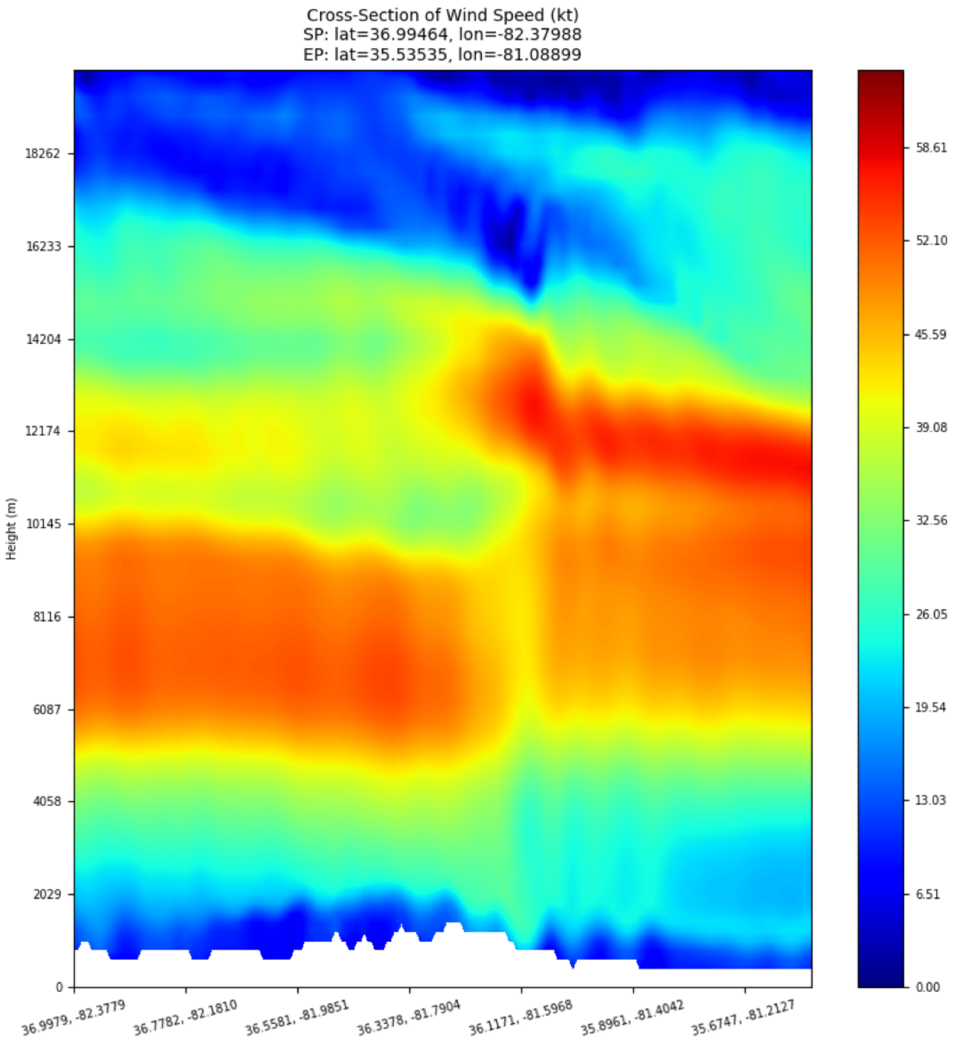

Includes TFD correction based on standard deviation of regional terrain (Jiménez & Dudhia, 2012)
RS
WRF YSU (TOPOWIND=1)
Standard K-theory
Eddy viscosity [m2/s] due to unresolved mechanical turbulence production
Height Above Sea Level [m]
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
5
10
15
20
25
30
35
Wind Speed [m s-1]




For shear driven stable boundary layers, modify WRF PBL closure with increased TFD based on flow diagnostics (e.g. mean flow speed, maximum Re, etc.)

# We know we're only concerned with OFD (for now):

- Orographic form drag
- Gravity wave drag
    - Well above PBL
- Blocking
    - Need to include, generally
    - Pending proposal for field campaign across SAM region (2018/19)



# Example:
# MYNN modification

- Mixing length:

$$\frac{1}{l} = \frac{1}{l_s} + \frac{1}{l_t} + \frac{1}{l_b}$$

- Conditional modification based on flow regime (Re) and stability (Ri)?

The surface layer length scale $l_s$:

$$l_s = \begin{cases} kz(1+\text{cns}\zeta)^{-1} & \text{if } 0 \le \zeta \le 1 \\ kz(1-\alpha_4\zeta)^{0.2} & \text{if } \zeta < 0 \end{cases}$$

The turbulent length scale $l_t$:

$$l_t = \alpha_1 \frac{\int_{z=0}^{PBLH} zq\,dz}{\int_{z=0}^{PBLH} q\,dz}$$

The buoyancy length scale $l_b$:

$$l_b = \alpha_2 \frac{q}{N}$$

where $q = \sqrt{(2\times TKE)}$nd $N$ is the Brunt-Vaisala frequency.

The cloud-specific length scale $l_c$ (Teixeira and Cheinet, 2003, *BLM*):

$$l_c = \tau\sqrt{TKE}$$

where τ is a cloud timescale.

The "BouLac" length scale, $l_{BL}$ (Bougeault and Lacarrere 1989, *MWR*).

From: Olson, et al., 2016, WRF Workshop, Boulder, CO

# Future Applications

- Improved aerosol-meteorology coupling over complex terrain
  - Rainfall enhancement / suppression
  - Cloud height and cloud duration
- Mountain cold weather precipitation modeling
- Improve correlations between lidar-derived PBLh and other methods and models
- Inform correlations in optical products derived from lidar and satellite data

Thank you!