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Correction of turbulence schemes through atmospheric boundary layer depth limits

Google Scholar

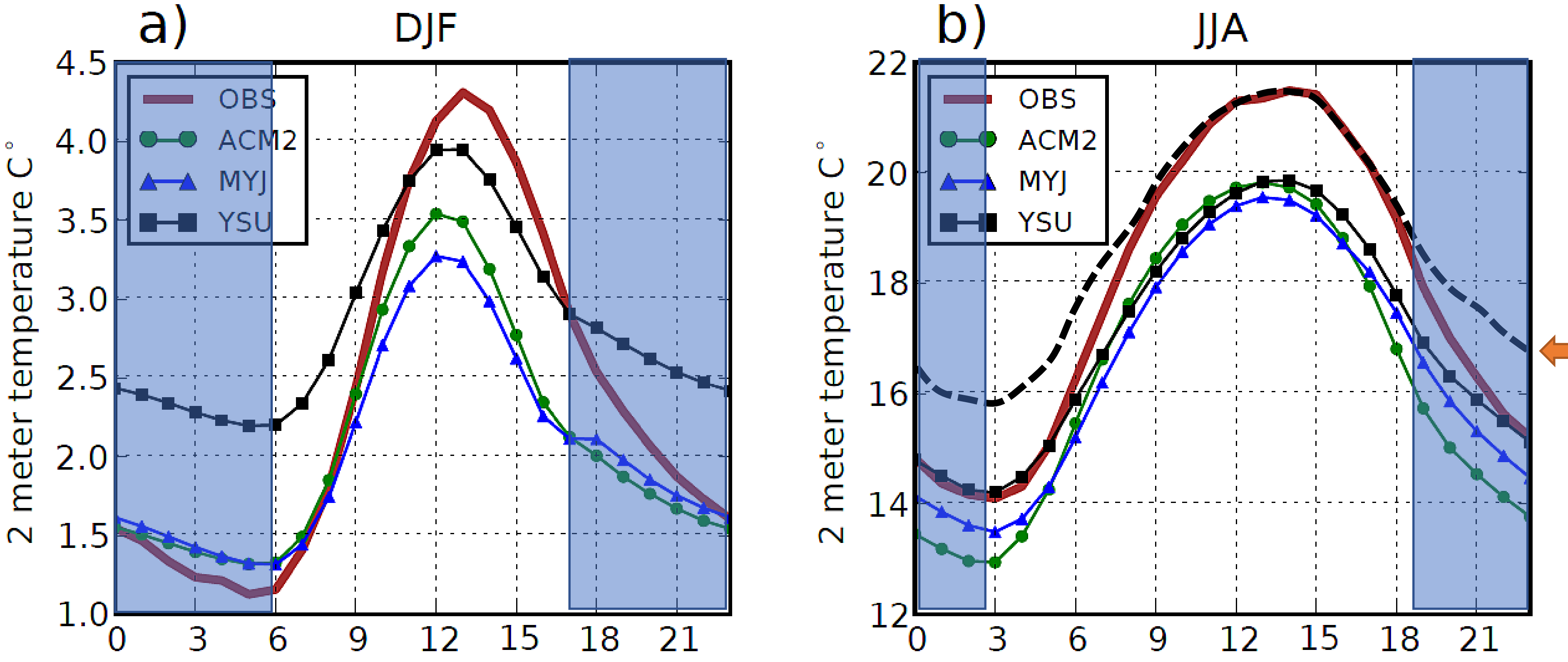
TITLE	CITED BY	YEAR
On the determination of the height of the Ekman boundary layer SS Zilitinkevich Boundary-Layer Meteorology 3 (2), 141-145	423	1972
Energy-and flux-budget (EFB) turbulence closure model for stably stratified flows. Part I: Steady-state, homogeneous regimes SS Zilitinkevich, T Elperin, N Kleeorin, I Rogachevskii Atmospheric Boundary Layers, 11-35	211	2007
Calculation of the height of the stable boundary layer in practical applications S Zilitinkevich, A Baklanov Boundary-Layer Meteorology 105 (3), 389-409	208	2002
Turbulence energetics in stably stratified geophysical flows: Strong and weak mixing regimes SS Zilitinkevich, T Elperin, N Kleeorin, I Rogachevskii, I Esau, T Mauritsen, ... Quarterly Journal of the Royal Meteorological Society: A journal of the ...	184	2008
Resistance laws and prediction equations for the depth of the planetary boundary layer SS Zilitinkevich Journal of Atmospheric Sciences 32 (4), 741-752	149	1975
A hierarchy of energy-and flux-budget (EFB) turbulence closure models for stably-stratified geophysical flows SS Zilitinkevich, T Elperin, N Kleeorin, I Rogachevskii, I Esau Boundary-layer meteorology 146 (3), 341-373	144	2013
Resistance and heat-transfer laws for stable and neutral planetary boundary layers: Old theory advanced and re-evaluated SS Zilitinkevich, IN Esau Quarterly Journal of the Royal Meteorological Society: A journal of the ...	138	2005

A long standing problem ...

- Persistent bias in surface air temperature prediction
    - Some NWP models reveal warm bias
    - Some NWP models reveal cold bias
    - But all biases have somewhat in common

Diagnoses: WRF

Based on:
García-Díez et al. (2013). Seasonal dependence of WRF model biases and sensitivity to PBL schemes over Europe. *QJRMS*, *139*(671), 501–514.



*Originally, **nocturnal bias** is small and negative, but this is because **the model is tuned** to minimum temperatures in the diurnal cycle.*

*If we retune it to maximum temperature, **a warm nocturnal bias emerges***

WRF spatial resolution 15 km

WRF – COLD BIAS

Diagnoses: WRF

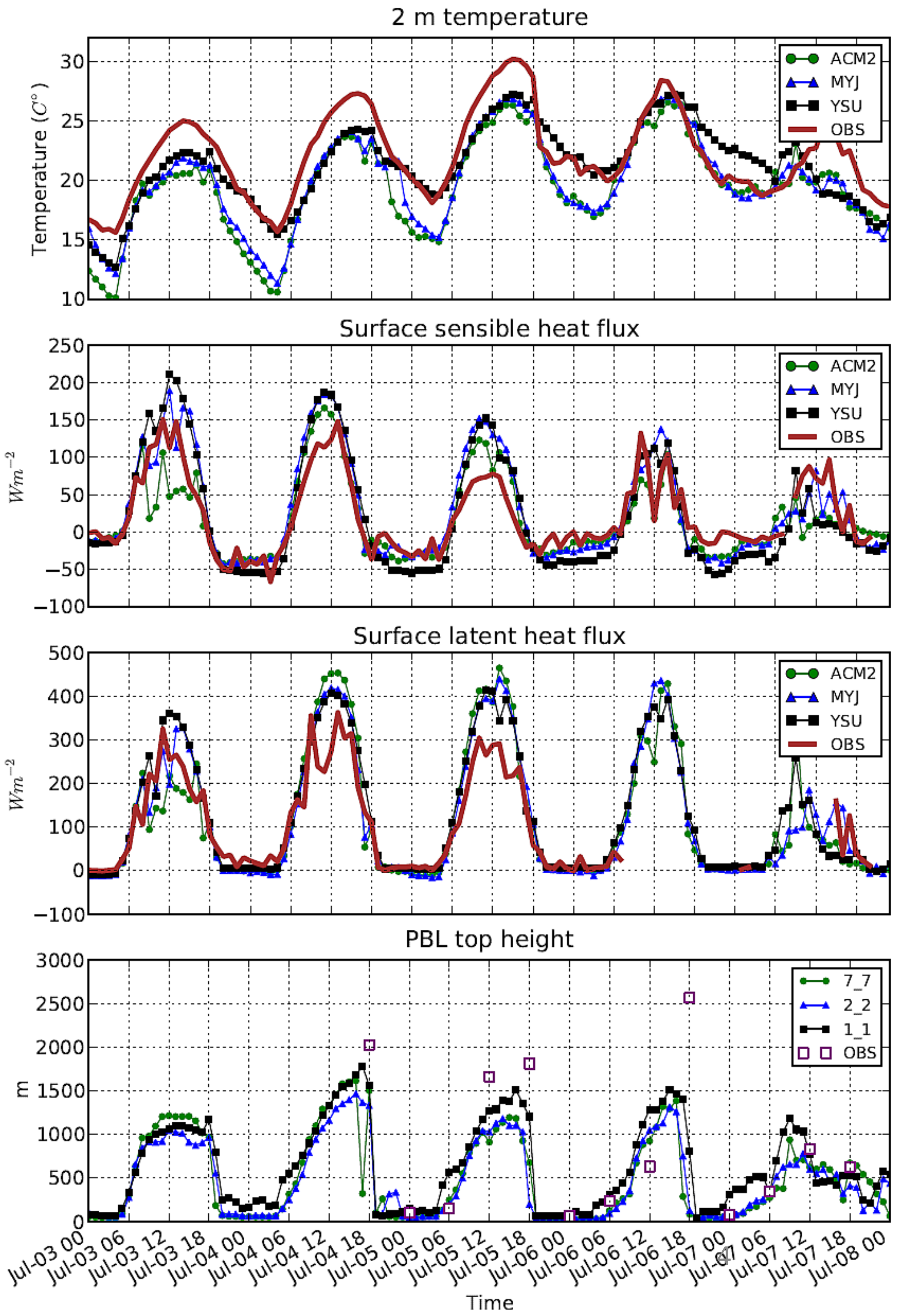
Based on:
García-Díez et al. (2013). Seasonal dependence of WRF model biases and sensitivity to PBL schemes over Europe. *QJRMS*, *139*(671), 501–514.

Hourly time series of the measured and simulated 2 m temperatures, sensible and latent heat fluxes and PBL top height at the CESAR location, for the July 3-7th 2001. Sounding data used to compute PBL top height is taken from De Bilt.

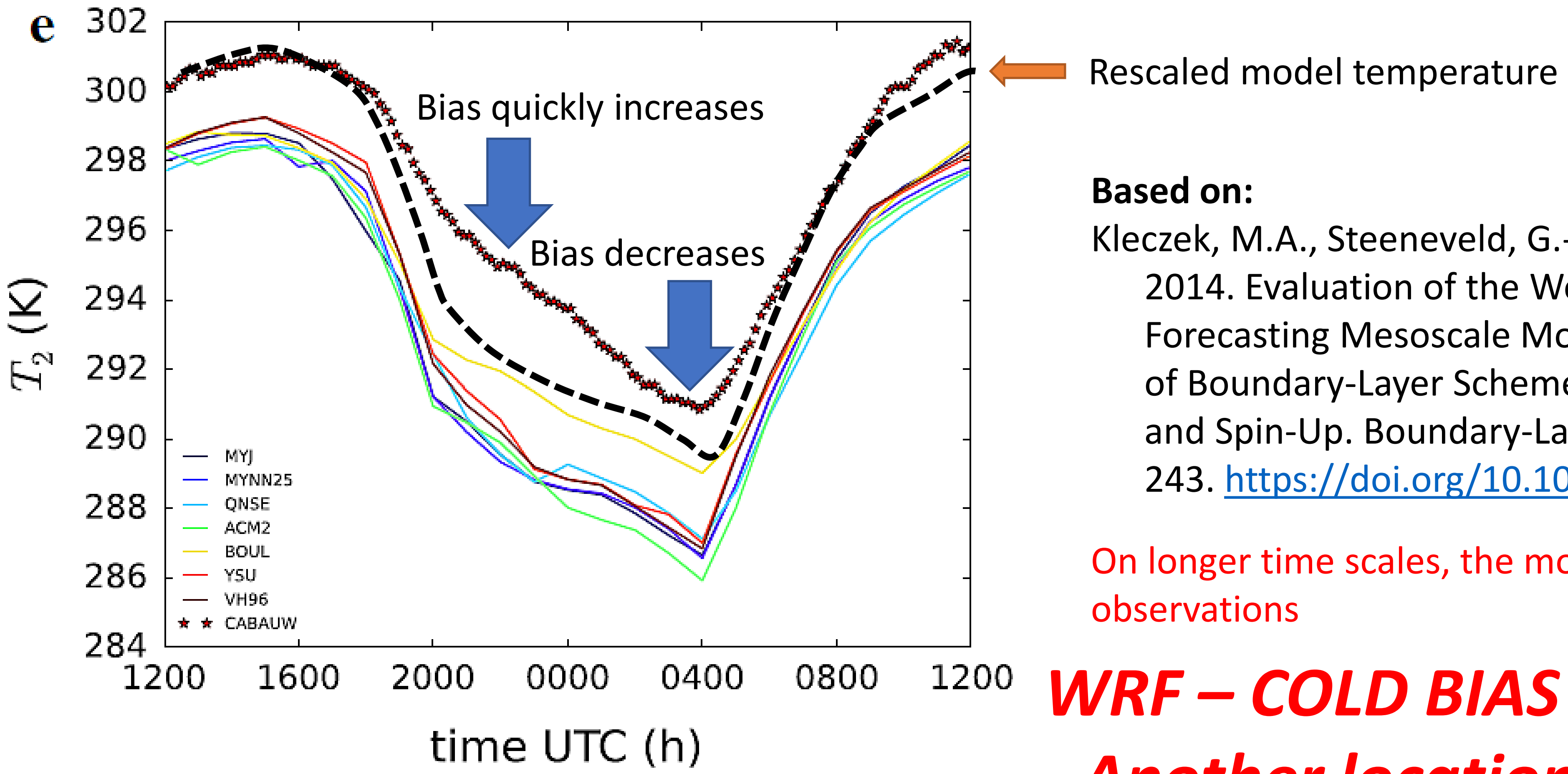
YSU WRF

- tunes to the minimum temperature

- but does not reproduce diurnal cycle despite larger SHFs



Diagnoses: WRF at Cabauw



Based on:

Kleczek, M.A., Steeneveld, G.-J., Holtslag, A.A.M., 2014. Evaluation of the Weather Research and Forecasting Mesoscale Model for GABLS3: Impact of Boundary-Layer Schemes, Boundary Conditions and Spin-Up. Boundary-Layer Meteorol. 152, 213–243. https://doi.org/10.1007/s10546-014-9925-3

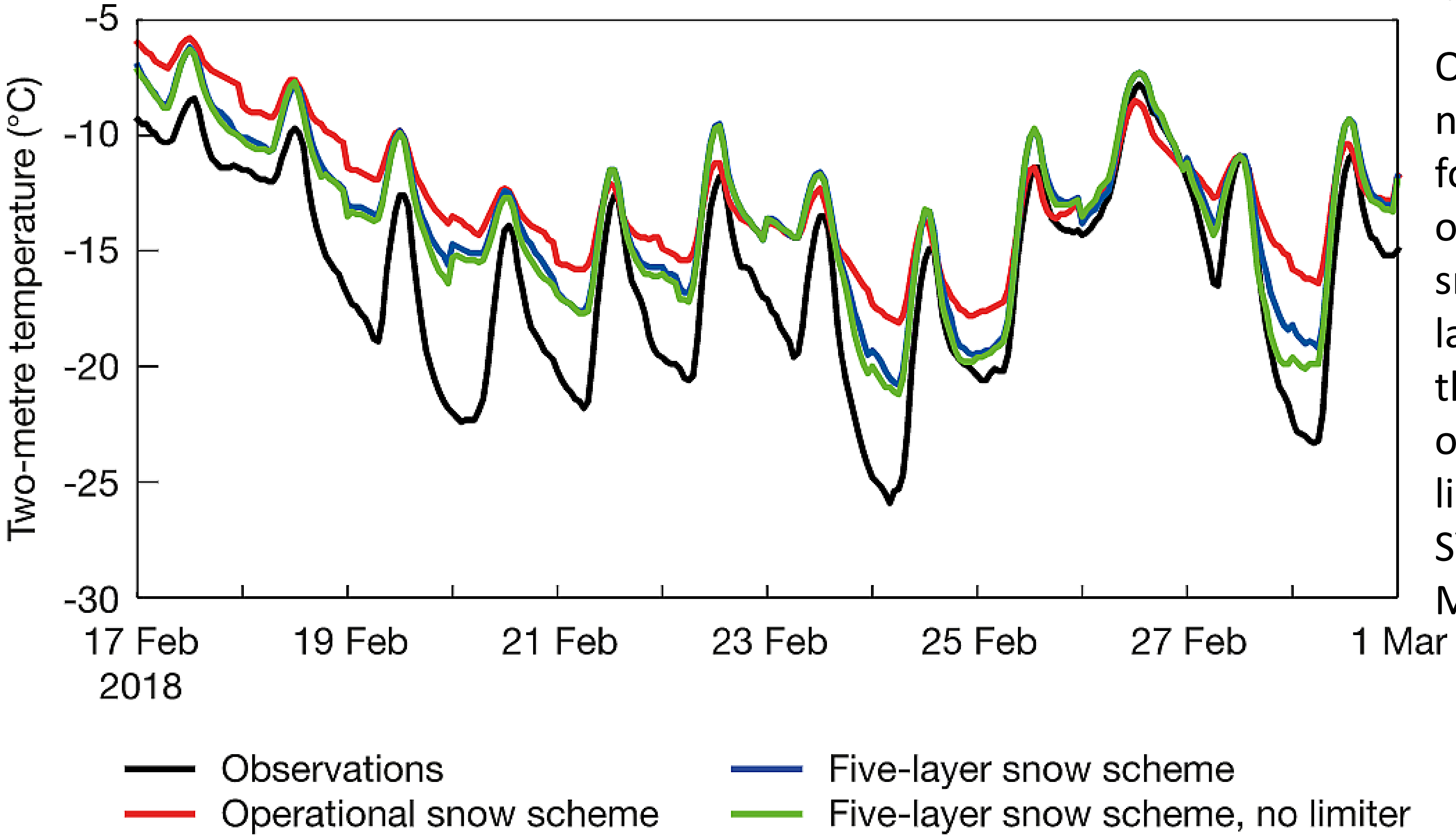
On longer time scales, the model catches up with observations

WRF – COLD BIAS

- Another location – another scheme (BOUL) wins

Diagnoses: ECMWF

Based on:
https://www.ecmwf.int/en/newsletter/157/meteorology/addressing-biases-near-surface-forecasts
By Thomas Haiden, Irina Sandu, Gianpaolo Balsamo, Gabriele Arduini, and Anton Beljaars



Observed and predicted T2m averaged over northern Scandinavia (64–70°N, 15–30°E). The forecasts are a control experiment with the operational snow scheme and two multi-layer snow scheme experiments in which a five-layer vertical discretization is used. In one of them the T2m limiter is active as in the operational model, in the other the T2m limiter is deactivated. Verification is against SYNOP stations for the period 17 February – 1 March 2018

HINT: Forecast has improved by making the surface snow layer thinner!

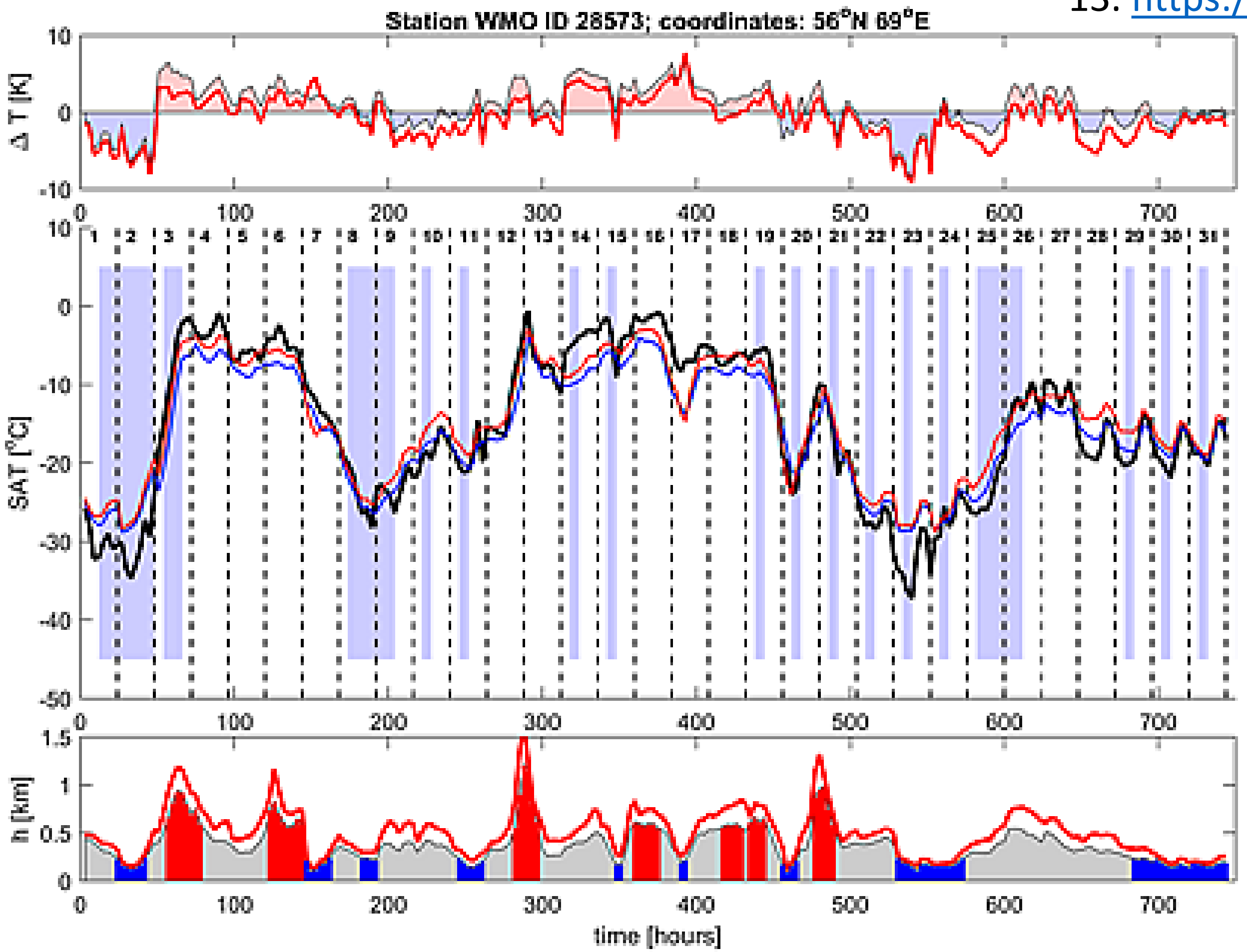
WRF – WARM BIAS

- The scheme is better for daytime maximum temperature

Diagnoses: SL-AV

Based on:

Esau, I., Tolstykh, M., Fadeev, R., Shashkin, V., Makhnorylova, S., Miles, V., Melnikov, V., 2018. Systematic errors in northern Eurasian short-term weather forecasts induced by atmospheric boundary layer thickness. Environ. Res. Lett. 13. https://doi.org/10.1088/1748-9326/aaecfb



Observations and model predictions of the SAT, h, ΔT, and the surface heat budget from the selected Siberian station with WMO ID 28573.
(upper panel) Differences, ΔT, between observed and predicted SAT. Color shading shows ΔT for the prediction with the old scheme. The red curve shows ΔT for the new scheme.
(central panel) Three curves are: the observed temperature (black); the SAT predicted with the old (pTKE) scheme (blue); the SAT predicted with the new (TOUCANS) scheme (red). Blue shading shows the periods of time with the negative modeled surface heat budget accumulated over 6 hours in the prediction with the old scheme. The vertical dashed lines mark the end of the calendar days (1-31 Jan. 2015).
(lower panel) The ABL thickness, h; color shading shows h for the old scheme; the red curve – for the new scheme. Blue bars highlight episodes of the shallow SBL (h<250 m); red bars – episodes of the thick ABL (h>550 m). All data were resampled at 3-hour intervals.

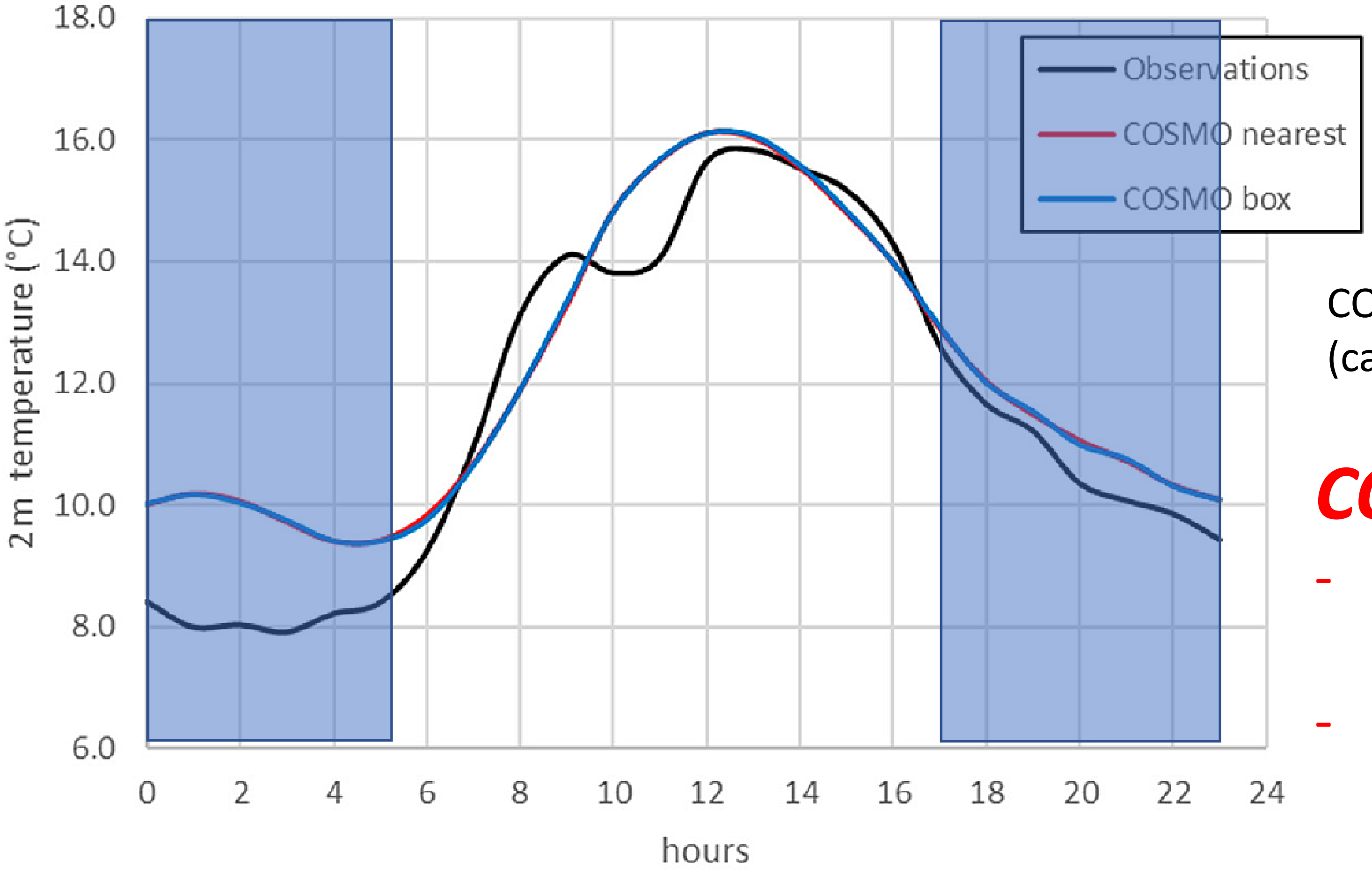
SL-AV – WARM BIAS

- ***Enhancement of surface fluxes does not solve the problem (pTKE vs TOUCANS)***
- ***Similar to WRF YSU diagnosis***

Diagnoses: COSMO

Based on:

Bucchignani, E., Mercogliano, P., 2021. Performance evaluation of high-resolution simulations with COSMO over south Italy. Atmosphere. 12. https://doi.org/10.3390/atmos12010045

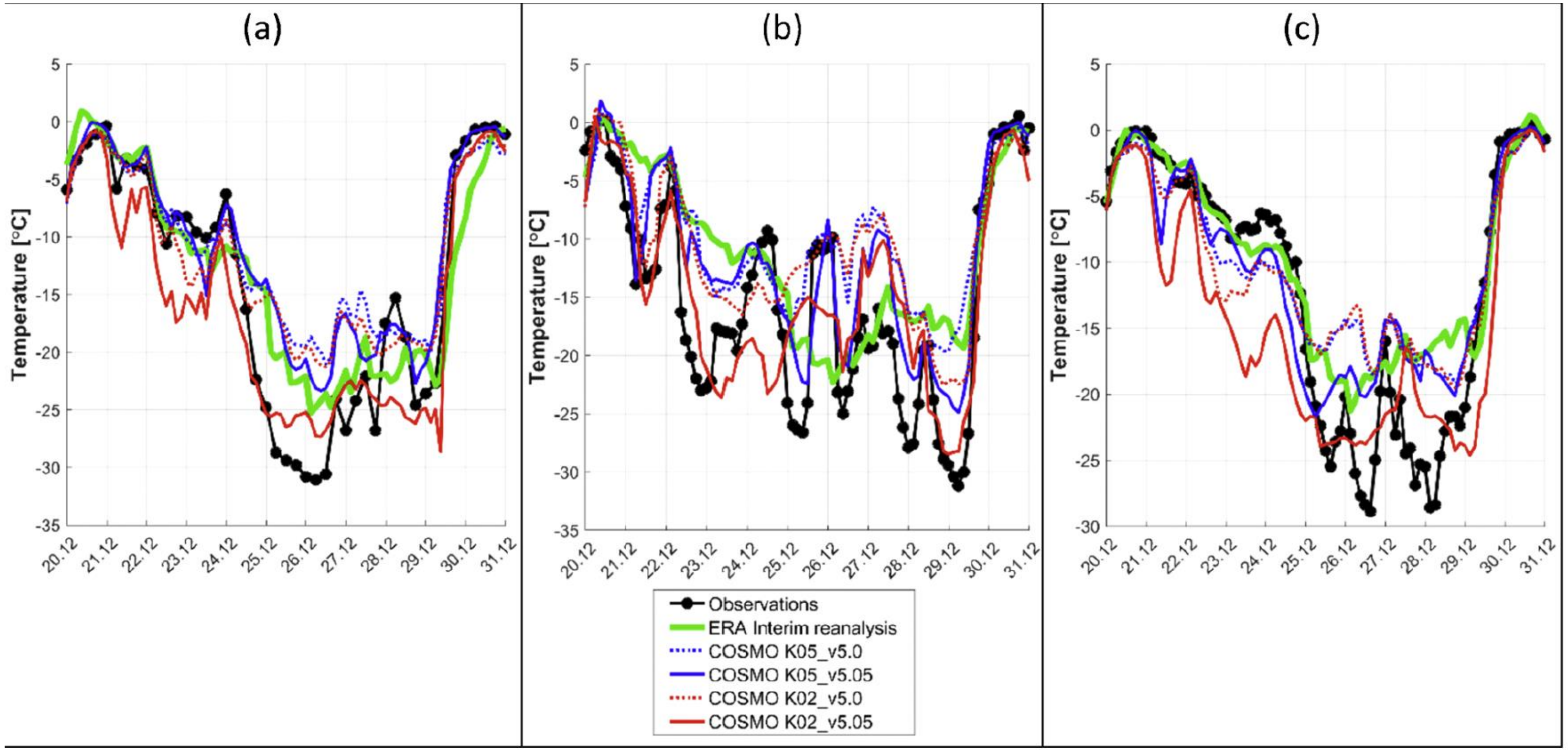


COSMO 1 km resolution averaged for 140 days (cases).

COSMO – WARM BIAS

- *Bias depends on resolution and scheme*
- *But little effect on agility (swiftness of model response) is found*

Diagnosis: COSMO



Based on:

Esau, I., Bobylev, L., Donchenko, V., Gnatiuk, N., Lappalainen, H.K., Konstantinov, P., Kulmala, M., Mahura, A., Makkonen, R., Manvelova, A., Miles, V., Petäjä, T., Poutanen, P., Fedorov, R., Varentsov, M., Wolf, T., Zilitinkevich, S., Baklanov, A., 2021. An enhanced integrated approach to knowledgeable high-resolution environmental quality assessment. *Environ. Sci. Policy* 122, 1–13. https://doi.org/10.1016/j.envsci.2021.03.020

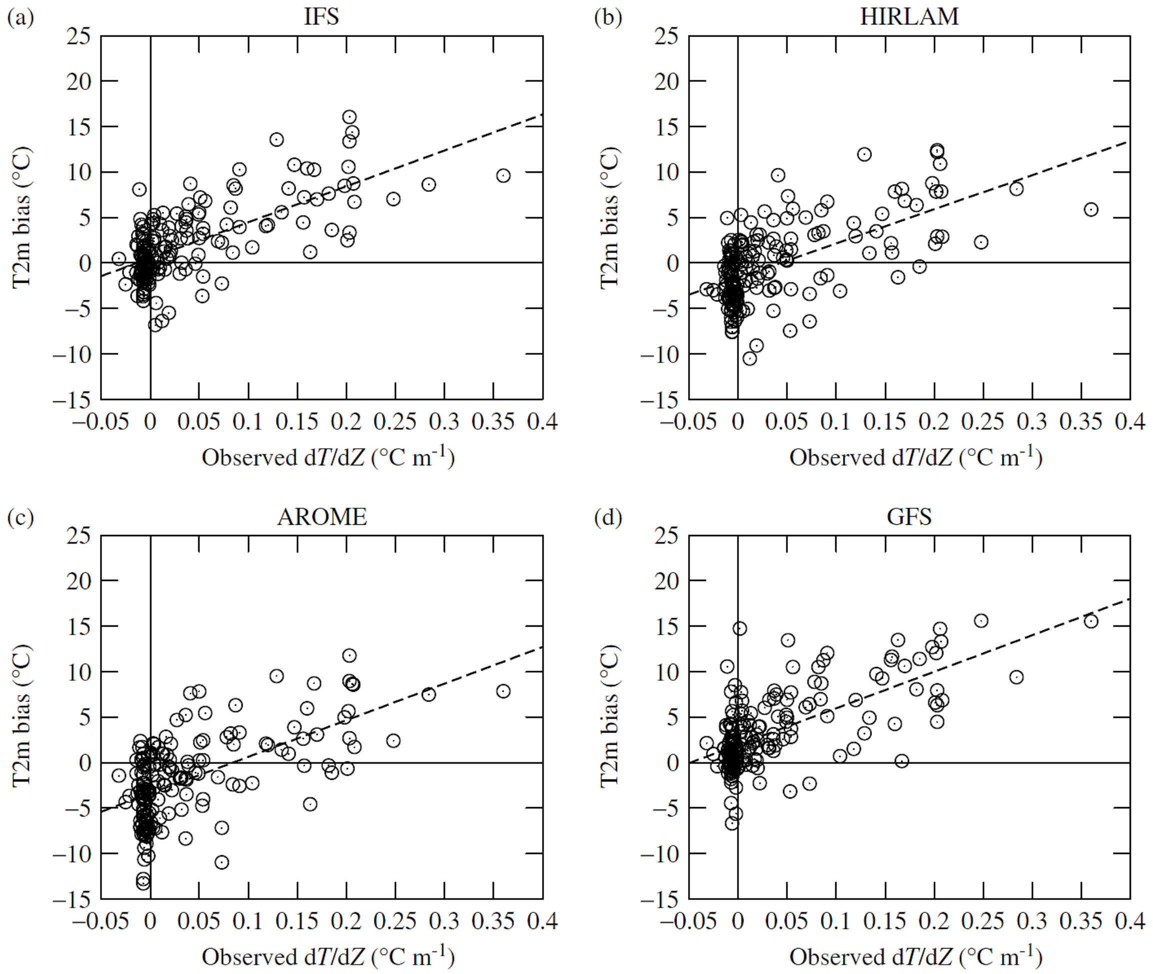
COSMO – WARM BIAS

Comparison of the air temperature at 2 m. Blue lines represent the COSMO-CLM model runs of the version 5.0 (dotted) and 5.05 (solid) in the domain with 5 km horizontal resolution (K05); red lines – in the domain with 2 km horizontal resolution (K02). The green line represents the ERA-Interim reanalysis data in the corresponding locations. Three panels show the comparison for the following locations: (a) the Apatity weather station (WMO ID 22213); (b) Lovozero (WMO ID 22127); (c) Krasnoshchelye (WMO ID 22235). The data observed at the WMO stations are given by black line and dots.

Diagnoses

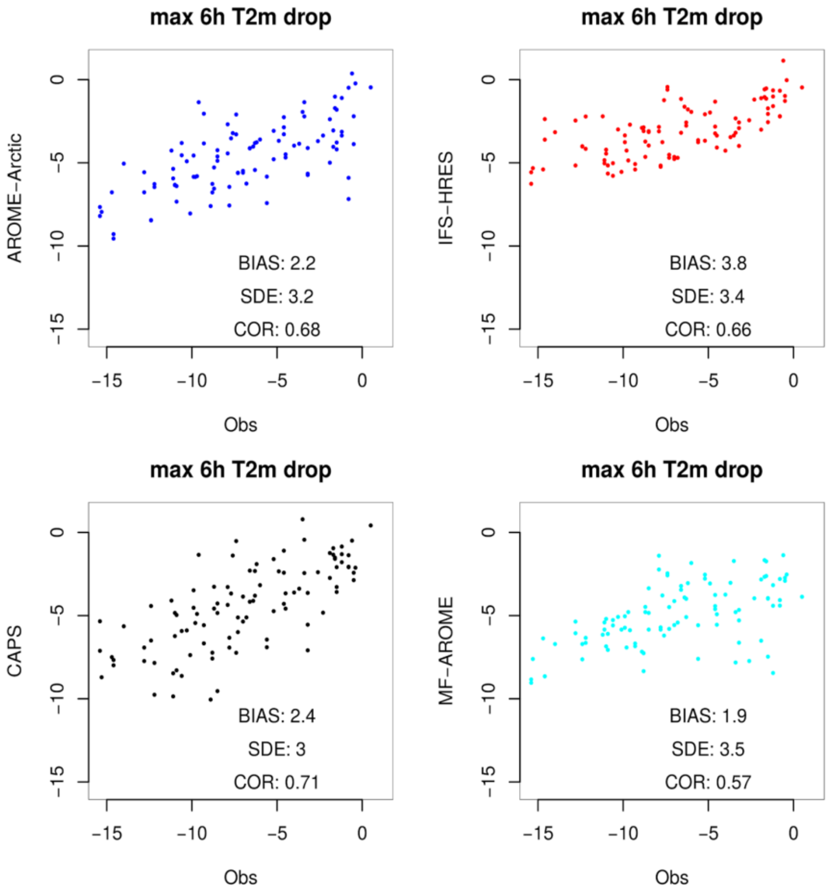
Based on:

Atlaskin, E., Vihma, T., 2012. Evaluation of NWP results for wintertime nocturnal boundary-layer temperatures over Europe and Finland. Q. J. R. Meteorol. Soc. 138, 1440–1451. https://doi.org/10.1002/qj.1885



IFS, HIRLAM, AROME, GFS – WARM BIAS - becomes more pronounced with increasing atmospheric stability

Diagnosis: AROME-ARCTIC (HIRLAM)



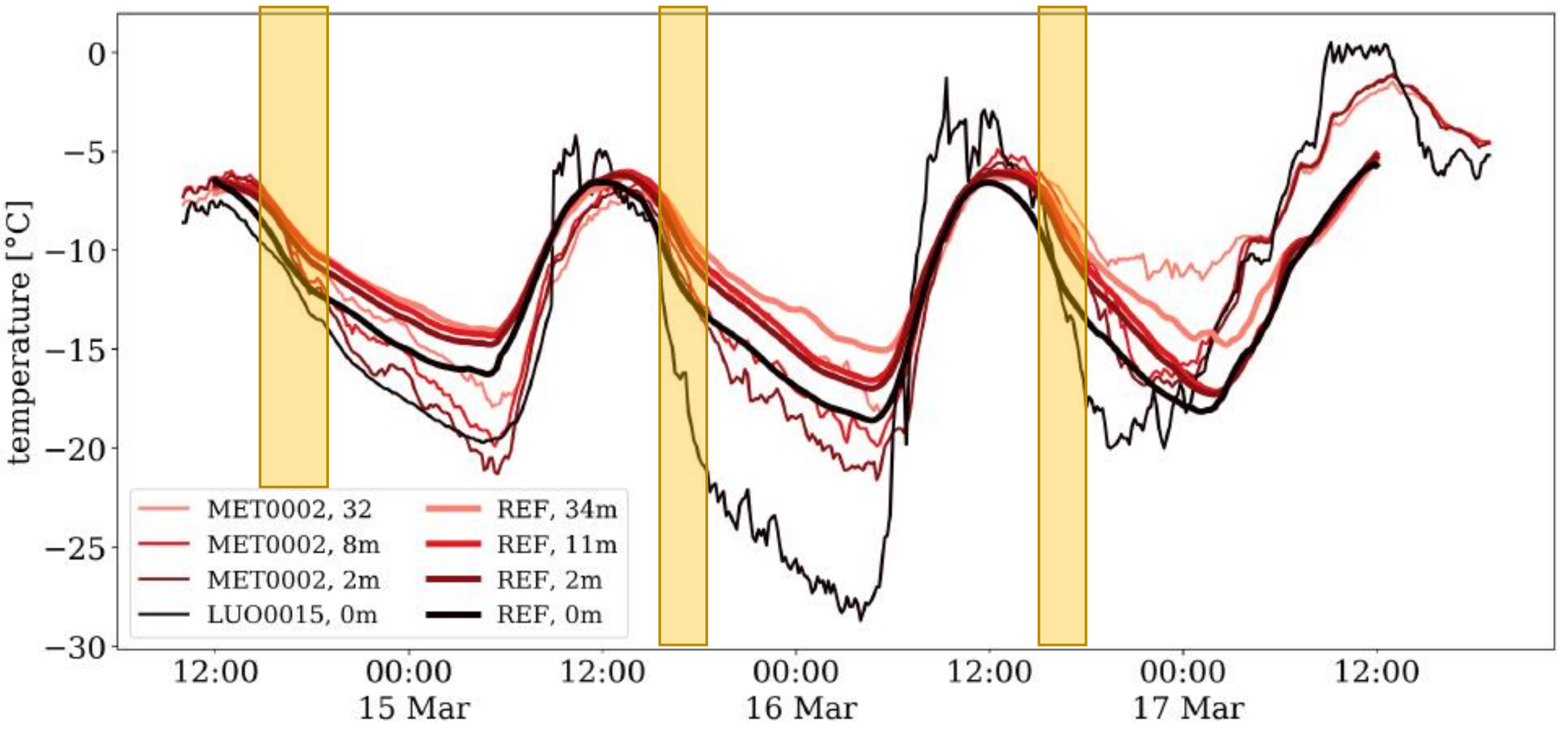
maximum 6h temperature drop during nighttime 4 models vs observations during YOPP-SOP-NH1

Based on:

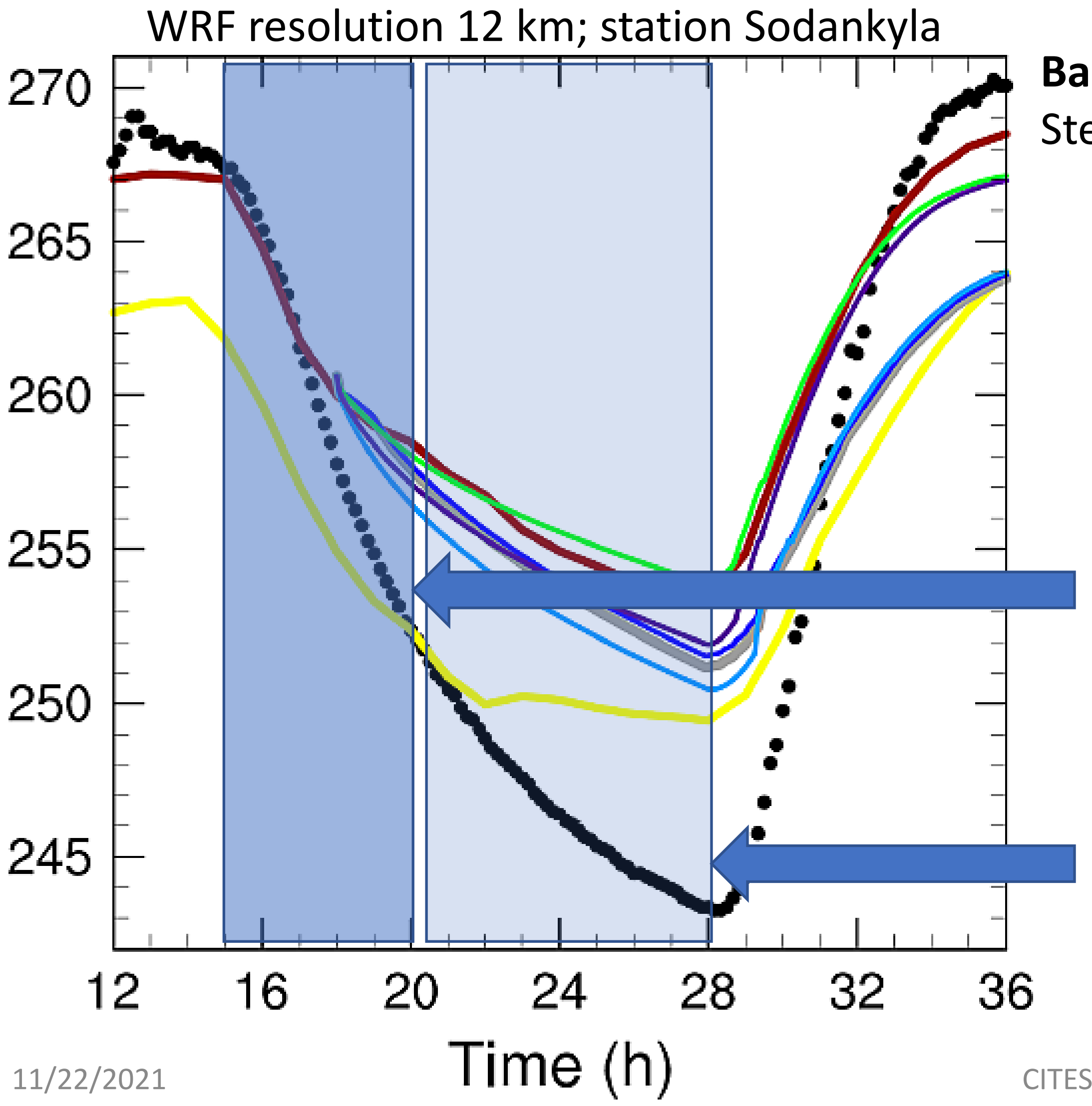
M. Kahnert – ALERTNESS project collaboration

AROME-ARCTC – WARM BIAS

OBS: Model bias depends on transitional temperature fall in cooling periods



A typical bias pattern emerges …



Based on:

Sterk, H.A.M., Steeneveld, G.J., Vihma, T., Anderson, P.S., Bosveld, F.C., Holtslag, A.A.M., 2015. Clear-sky stable boundary layers with low winds over snow-covered surfaces. Part 1: WRF model evaluation. Q. J. R. Meteorol. Soc. 141, 2165–2184. https://doi.org/10.1002/qj.2513

Early cooling stage: Observed cooling is rapid; Models do not reproduce such cooling; **Bias increases**

Late cooling stage: Observed cooling is slowed down and eventually sits on the Budyko-Sellers linear radiation balance asymptote $\sim -(A+BT)$.
Models may catch up due to differences in parametrization constants; **Bias decreases**

Constructive theory of the model bias

Temperature response on instant perturbation;
$T = 0$ is equilibrium temperature; T_0 at $t = 0$

$$C\frac{dT}{dt} = -BT \qquad\qquad C = \rho c_p h$$

Solution: $T = T_0 e^{-\frac{B}{C}t} = T_0 e^{-t/\tau}$

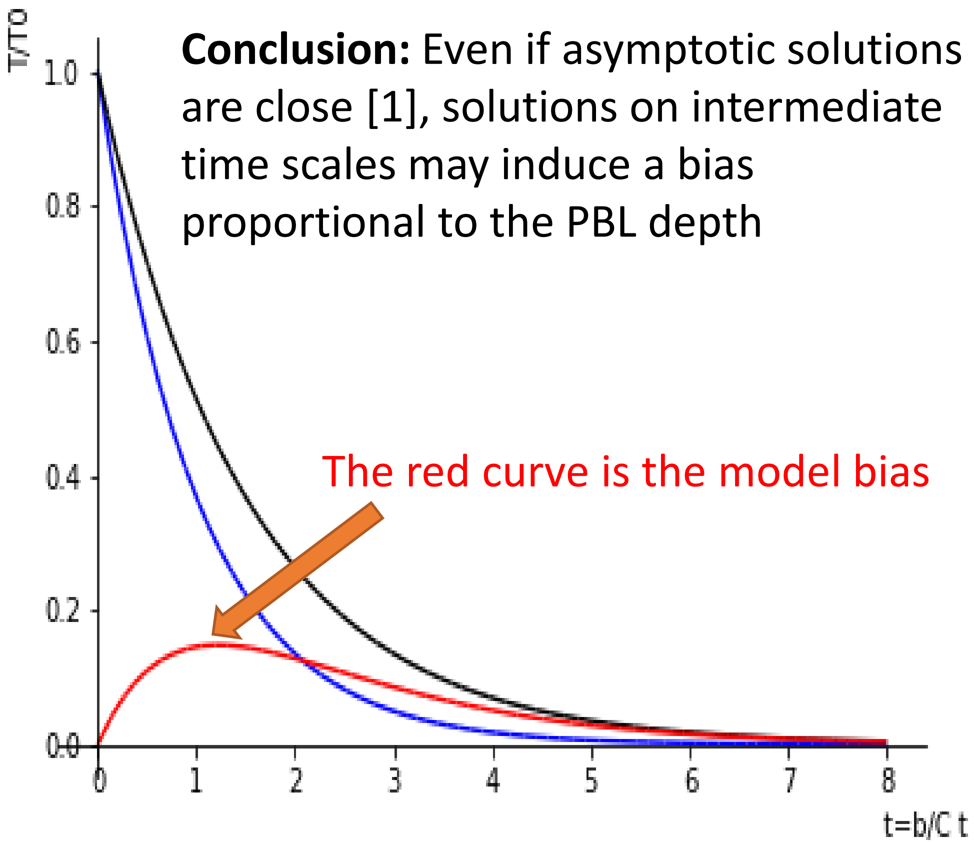
Response time scale depends on the heat capacity, $\tau = B/C \propto \frac{1}{h}$

Temperature bias depends on the heat capacity and relative error in heat capacity,

$$R = \frac{\Delta C}{C} = \frac{C^{mod} - C^{obs}}{C^{obs}} = \frac{h^{mod} - h^{obs}}{h^{obs}} = \frac{\Delta h}{h}$$

The model bias becomes

$$\Delta T(t, C, R) = T^{mod} - T^{obs} = T_0\left(e^{-t/\tau^{mod}} - e^{-t/\tau^{obs}}\right)$$



Conclusion: Even if asymptotic solutions are close [1], solutions on intermediate time scales may induce a bias proportional to the PBL depth

The red curve is the model bias

[1] Baas et al. (2018). From Near-Neutral to Strongly Stratified: Adequately Modelling the Clear-Sky Nocturnal Boundary Layer at Cabauw. *Boundary-Layer Meteorology*, **166**(2), 217–238.

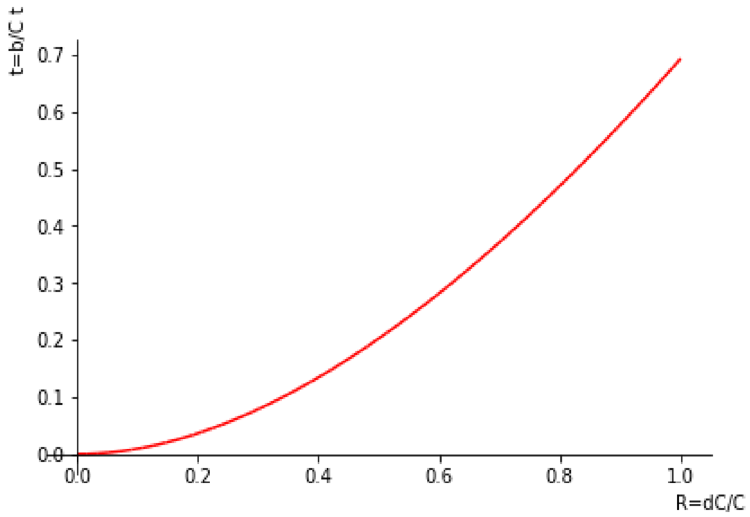
Why do models reveal persistent temperature bias despite verified accuracy of PBL schemes?

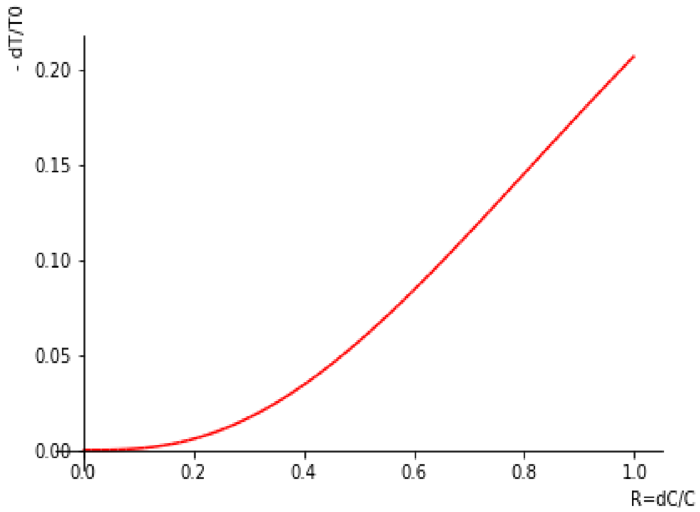
Hypothesis: Due to frequent fluctuations of the surface heat balance, models do not catch up and bias does not decrease

$$\max(\Delta T'(t', R)) = \exp\left(-R \cdot \ln(1+R)\right) - \exp\left(-\frac{R \cdot \ln(1+R)}{1+R}\right)$$

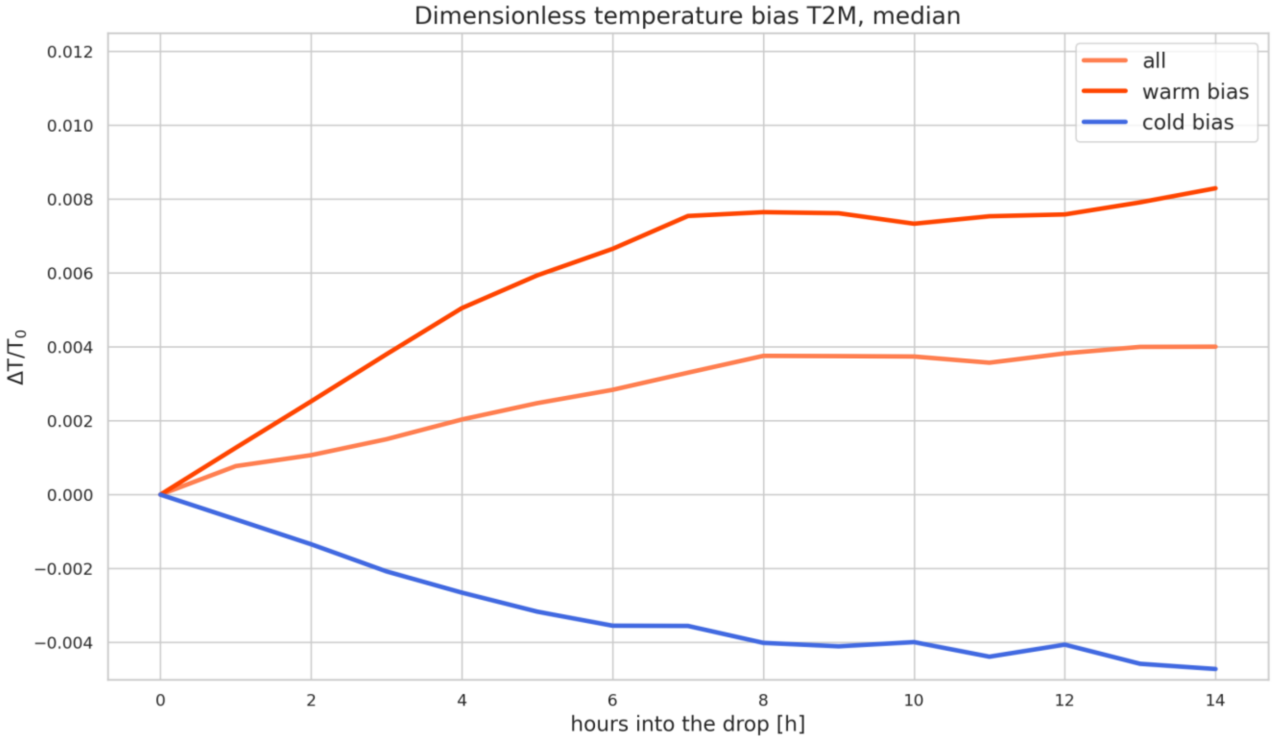
$$R = \frac{\Delta h}{h} \sim 1\ (100\%)$$

$$\max t' = \max\left(\frac{\beta}{h} t\right) = R \cdot \ln(1+R)$$

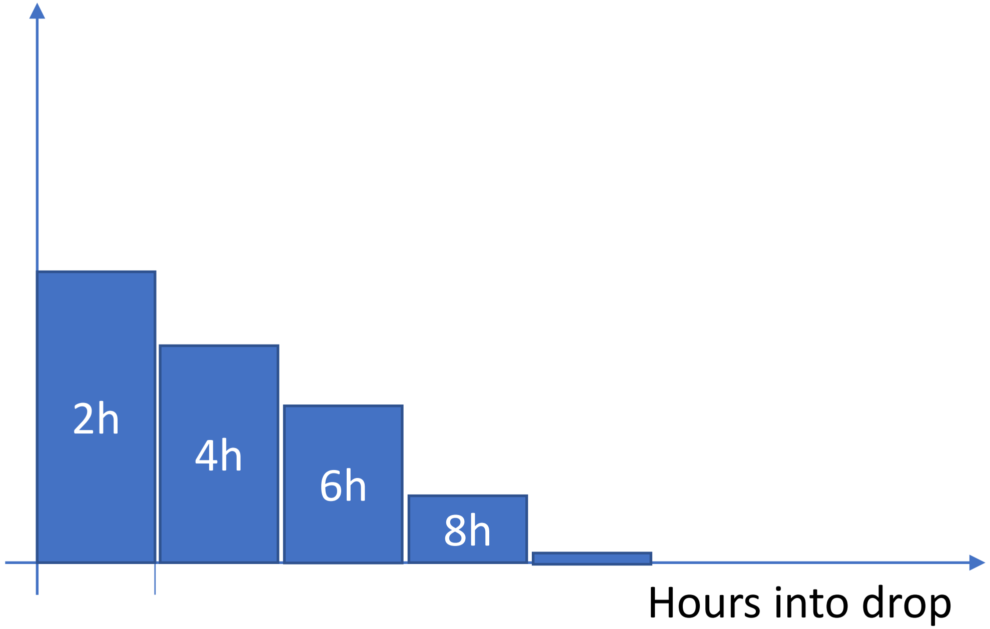




Diagnosis: AROME-ARCTIC at Sodankyla



Based on:
M. Kahnert – ALERTNESS project collaboration



Where could changes be introduced?: Turbulence Scheme in MUSC

$$\frac{\partial \theta_V}{\partial t} = \frac{\partial}{\partial z} K_H \frac{\partial \theta_V}{\partial z} + F_T$$

$$\frac{\partial U}{\partial t} = \frac{\partial}{\partial z} K_M \frac{\partial U}{\partial z} + F_U$$

Comments: F_U is a given external forcing; F_T is the external cooling or warming rates.

If the turbulence scheme causes difficulties, one shall look at eddy diffusivity coefficients
… and further at the mixing length scale

$$l_{M,H}$$

The parametrized form of the TKE equation is

$$\frac{\partial E_k}{\partial t} = K_M S^2 - K_H N^2 + 2K_M \frac{\partial E_k}{\partial z} - \epsilon$$

$$\epsilon = c_d \frac{(E_k)^{3/2}}{l_M}$$

$$K_M = K_H = l_{M,H} \sqrt{E_k}$$

The mixing length scales $l_{M,H}$ absorbed all coefficients.

Mixing length scale (HARATU)

The mixing length-scale in HARATU under stable conditions (Linderink and Holtslag, 2004)

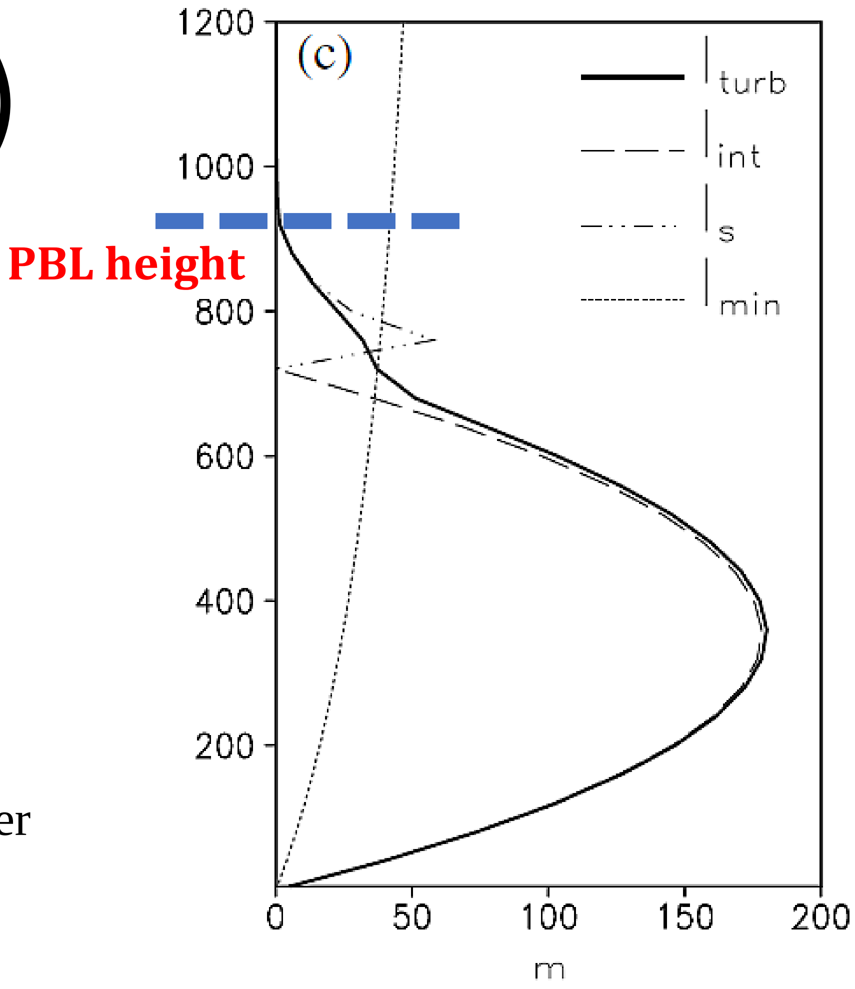
$$\frac{1}{(l_{M,H})^2} = \frac{1}{((l_{int})^2 + (l_{min})^2)} + \frac{1}{(l_s)^2}$$

$$\frac{1}{l_{min}} = \frac{1}{l_{inf}} + \frac{1}{0.5 c_n k z}$$

$$l_s = \frac{c_{M,H}\sqrt{E_k}}{N}$$

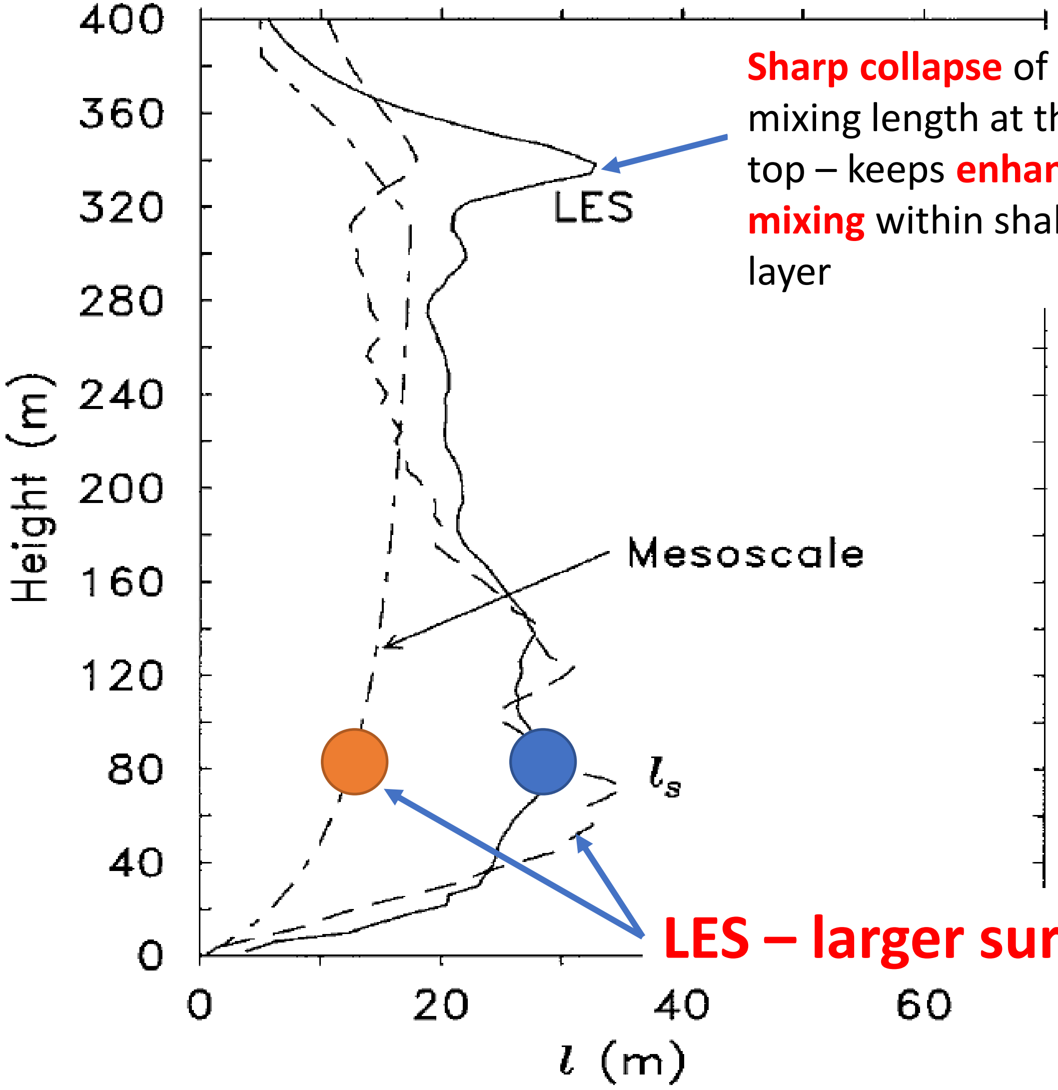
$c_n = (c_n)^{1/4}$,$c_M = c_H(1 + c_{Ri} Ri)$ where l_{inf} = 75 m, c_H = 0.2, $c_{Ri} = 2$ after (Deardorff, 1980; Baas et al., 2008).

The current **operational values**: c_H = 0.2, $c_{Ri} = 1$; The best fit to the SBL conditions: c_H = 0.13, $c_{Ri} = 1$.



The resulting length scale l_{turb}, and its components l_{int}, l_{min} and l_s.

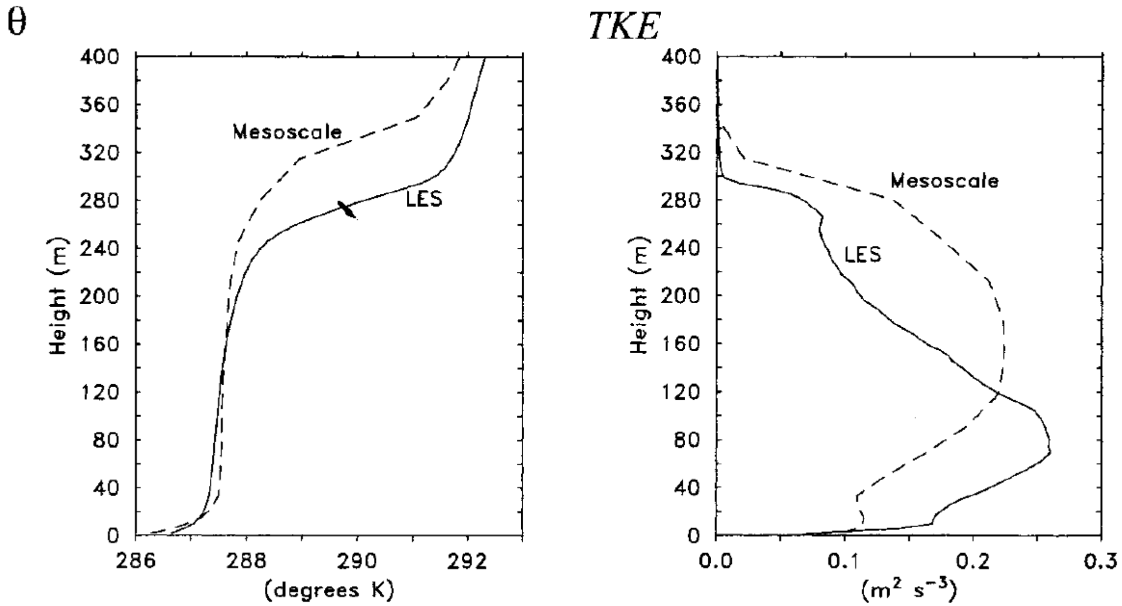
Diagnosis: Mixing length scales



Sharp collapse of the mixing length at the PBL top – keeps **enhanced mixing** within shallower layer

Based on:

Skyllingstad, E.D., Samelson, R.M., Mahrt, L., Barbour, P., 2005. A Numerical Modeling Study of Warm Offshore Flow over Cool Water. Mon. Weather Rev. 133, 345–361. https://doi.org/10.1175/MWR-2845.1



LES – larger surface layer mixing in a more shallow PBL

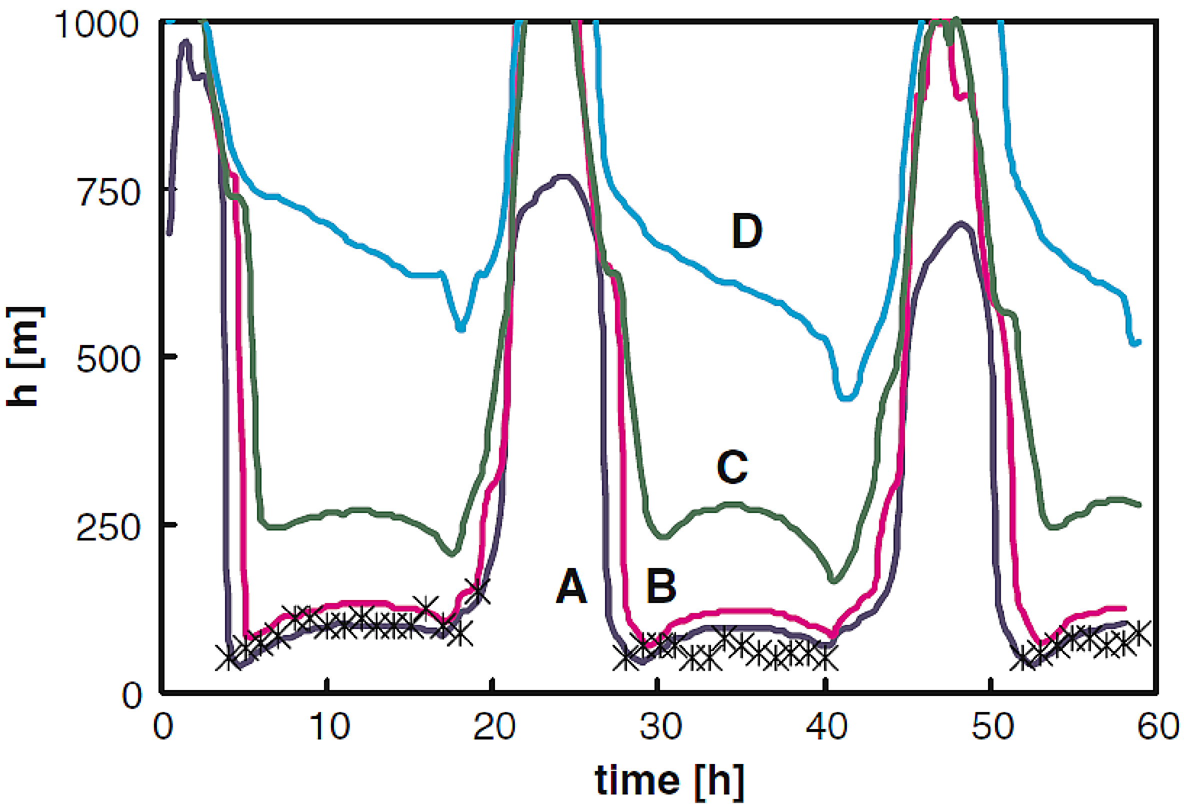
Diagnosis: Analytical

Based on:

Baas, P., de Roode, S.R., Lenderink, G., 2008. The Scaling Behaviour of a Turbulent Kinetic Energy Closure Model for Stably Stratified Conditions. Boundary-Layer Meteorol. 127, 17–36. https://doi.org/10.1007/s10546-007-9253-y

	c_h	c_p	Remarks
A	0.13	0	No Pr dependency; $\phi_m = \phi_h = 5\zeta$ in the stable limit
B	0.13	1	$\mathrm{Pr} = 1 + Ri_g$
C	0.2	1	Current operational values
D	0.2	2	No analytical solution

Characteristics of model runs



PBL is too deep (about 100% deeper) for the current operational values for the run "C"

The mixing length scale IMPLICITLY sets up the PBL height

- So that surface flux and PBL depth are coupled in the scheme

Discussion: How could one decouple surface fluxes and mixing layer depth?

Developing of ideas from Sergej Zilitinkevich

Based on:

Zilitinkevich, S., Esau, I., Baklanov, A., 2007. Further comments on the equilibrium height of neutral and stable planetary boundary layers. Q. J. R. Meteorol. Soc. 133, 265–271. https://doi.org/10.1002/qj.27

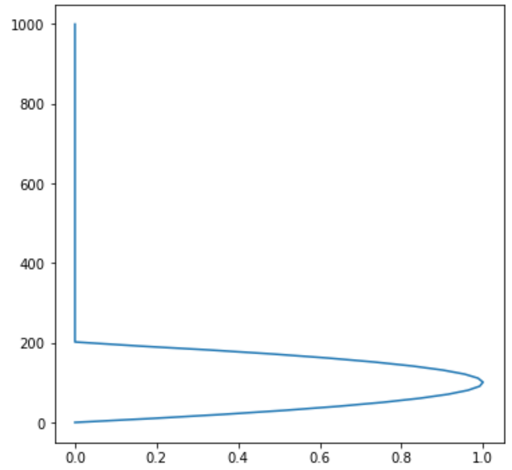
$$h_{PBL} = \frac{1}{\sqrt{\frac{1}{h_{EBL}^2} + \frac{1}{h_{CNL}^2} + \frac{1}{h_{NSL}^2}}}$$

where

$$h_{EBL} = C_R \frac{u_*}{|f|},$$

$$h_{CNL} = C_{CN} \frac{u_*}{\sqrt{|N_v f|}},$$

$$h_{NSL} = C_{NS} \frac{u_*^2}{\sqrt{|B_s f|}}.$$



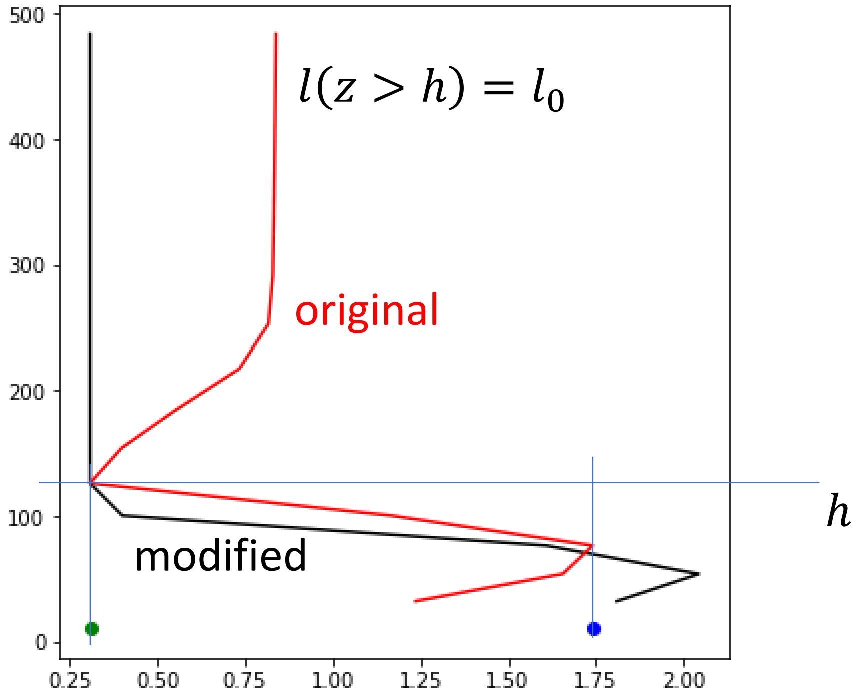
$$l_{m,h}(z > h_{PBL}) = 0.$$

$$l_{max} = \max l_{m,h}$$

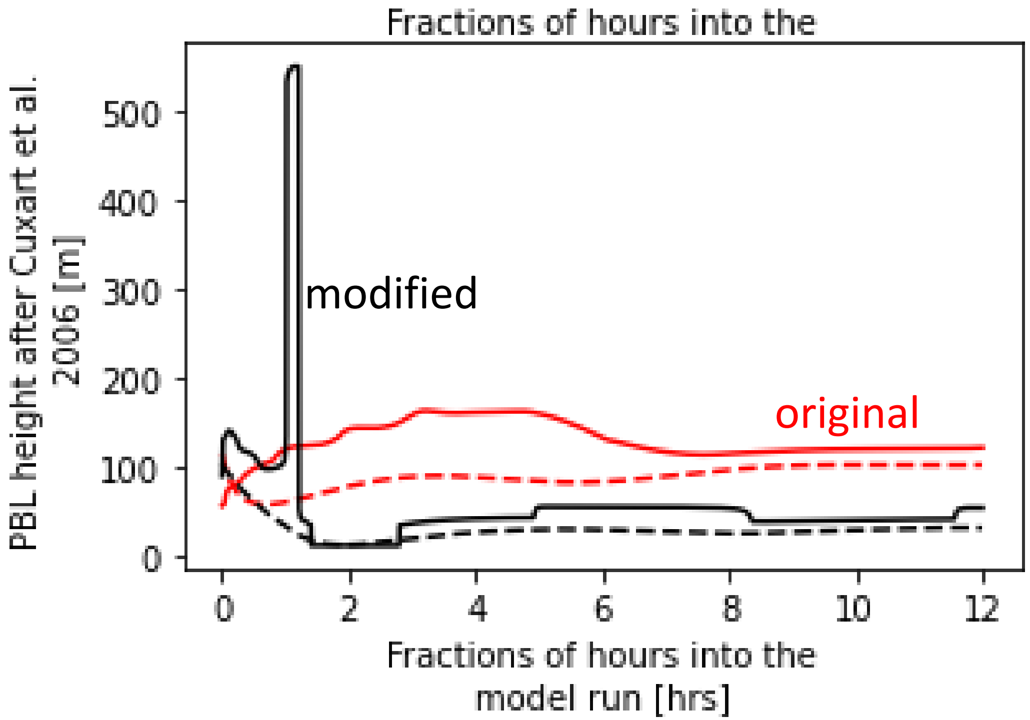
We introduce the following re-scaling (correction) function:

$$l_{m,h}^* = l_{min} + l_{max} \cdot \frac{4}{h_{PBL}} \cdot z \cdot \left(1 - \frac{z}{h_{PBL}}\right).$$

The current status: Diagnostic and prognostic runs of MUSC



$l_{min} \neq l_0$



Modified PBL collapses, why?