Structure of weather prediction errors in stably-stratified atmospheric conditions

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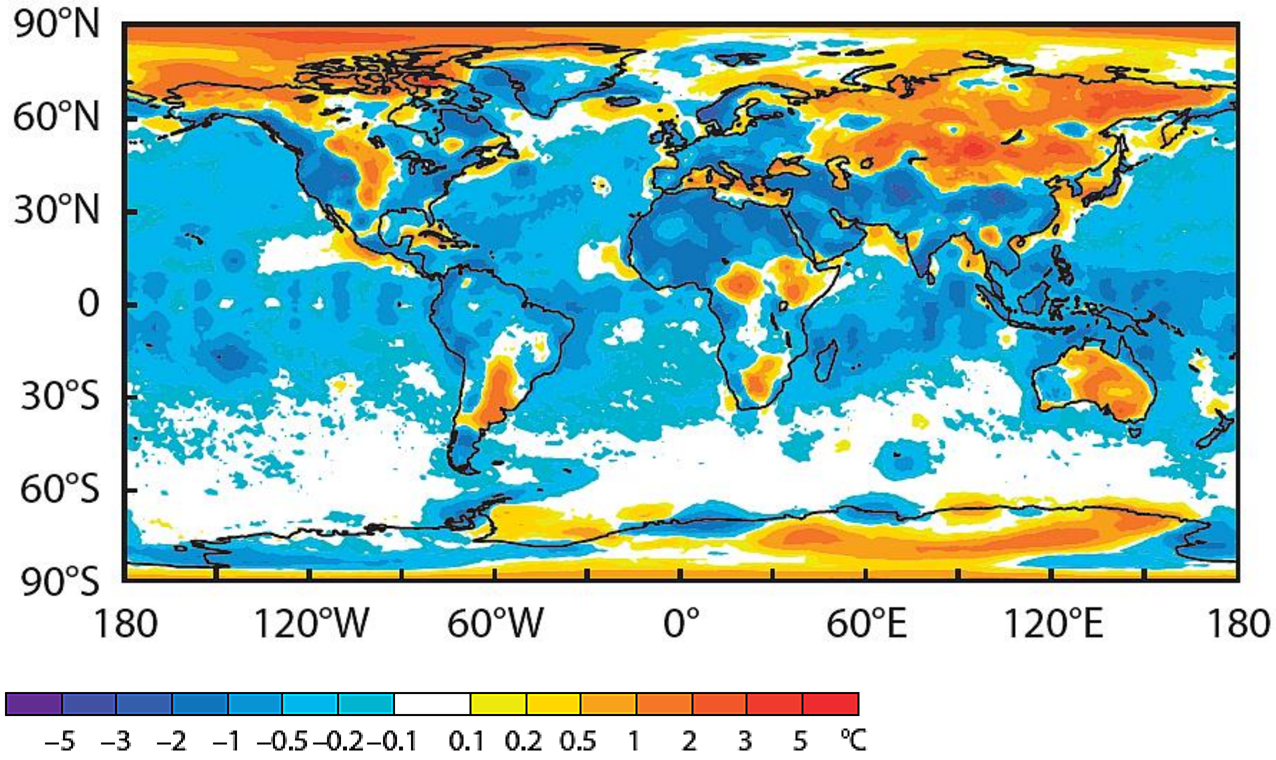
Challenge: Inaccurate weather prediction in cold climate regions



Mean 2-metre temperature error (°C) for the CTL daily forecasts performed for January–March 2012 with respect to the analyses from which the forecasts were initialized (Sandu et al., doi:10.21957/kdvw4lub)

In the Numerical Weather Prediction (NWP) models:

- **Stable boundary layers are often too deep**, h_{PBL} is large
- Low-level jets are too weak and located too high above the surface – **consequence** of the large h_{PBL}
- Near-surface ageostrophic wind angles are too small, so that the wind turning between the surface and the boundary layer top is underestimated – **consequence** of the large h_{PBL}
- Normalized 2m air temperature error, under conditions that $(T^{mod} - T^{obs})|_{t\ onset\ of\ SBL} = 0$, is positive, i.e. the SBL is more thermally inertial than observed

The cause of these errors is well-known:

- **Turbulence schemes require more diffusion in stable conditions than justified by observations or very high-resolution simulations**
- It is often argued that the artificial enhancement of the mixing in stable conditions is needed to account for contributions to vertical mixing associated with surface heterogeneity, gravity-waves and mesoscale variability which are not explicitly represented in models. But it is difficult to estimate by how much the mixing in stable conditions should be enhanced

Methodology: Turbulence Schemes in Meteorological Models

(1) Flux – gradient approach, the turbulent flux, F_ϕ is proportional to the vertical gradient of the large-scale quantity ϕ, in a typical First-Order turbulence diffusion scheme of the NWP model

$$F_\phi = K\frac{\partial\phi}{\partial z}$$

(2) The proportionality coefficient, K – turbulent diffusion is given through the wind shear as

$$K = \left|\frac{\partial U}{\partial z}\right| l^2 f(Ri)$$

The turbulent diffusion depends on the mixing length scale, l – prescribes its changes with height; and stability correction function, $f(Ri)$ – prescribes its changes with statis stability (the Richardson Number)

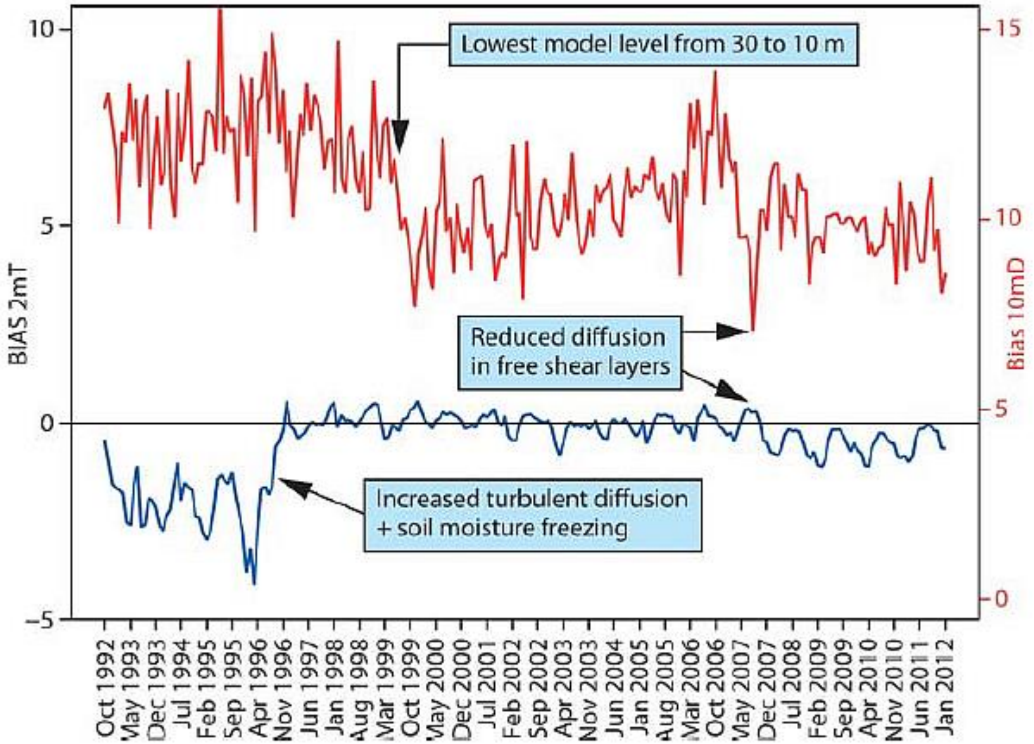
(3) The PBL thickness (depth) is defined as a height where turbulent mixing becomes small

$$h_{PBL}: z, F_\phi(z) \ll F_\phi(z=0)$$

(4) The PBL depth, h_{PBL}, and turbulent diffusion near the surface, $K(z=0)$, are linked through F_ϕ in this approach with the following consequences:

- Reduction of the PBL thermal inertia requires reduction of h_{PBL}, and hence, reduction of $K(z=0)$
- Reduction of $K(z=0)$ threatens surface-PBL coupling; and detereorate the forecast

Methodology: Turbulence Schemes in Meteorological Models



Historic evolution of 2 m temperature (blue curve) and 10 m wind direction errors (red curve) of the operational ECMWF IFS. These are monthly values of mean errors at a lead time of 60 h of the daily forecasts initialized at 1200 UTC (verifying time 0000 UTC). The verification includes 800 SYNOP stations over Europe (30–72N, 22W–42E).

*“ We find that **reduced turbulent diffusion in stable conditions improves the representation of winds in stable boundary layers, but it deteriorates the large-scale flow and the near-surface temperatures**. This suggests that enhanced diffusion is still needed to compensate for errors caused by other poorly represented processes (e.g. orographic drag), which influences the large-scale flow in a similar way to the turbulence closure for stable conditions, and the strength of the land-atmosphere coupling, which partially controls the near-surface temperatures. We demonstrate that the turbulent diffusion in stable conditions affects the large-scale flow by modulating not only the strength of synoptic cyclones and anticyclones, but also the amplitude of the planetary-scale standing waves.”*

Sandu et al., 2013, doi:10.1002/jame.20013.

(5) A new turbulent scheme must satisfy both:

- Reduce the PBL depth
- Keep enhanced turbulence diffusion across the PBL, especially near the surface

Model: Turbulence scheme in the Single-Column Model MUSC – HARATU

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

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

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

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.

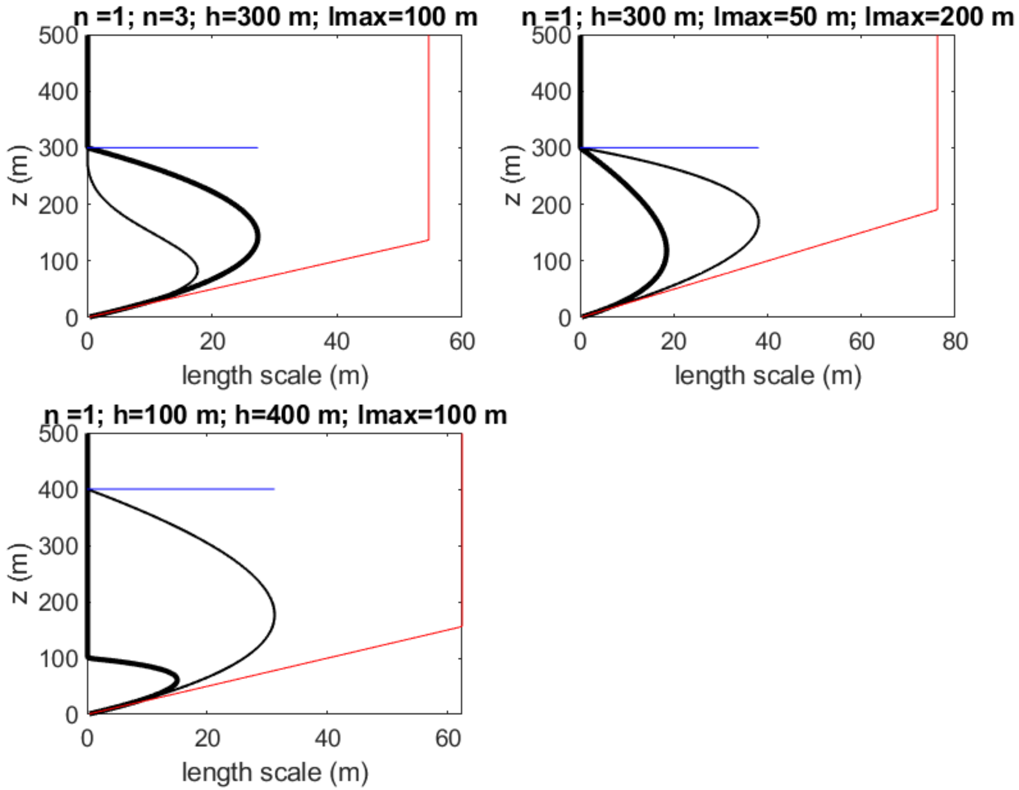
Model: Length scale in MUSC – HARATU

$$l_{M,H}(z,t) = \lambda(z) f_{M,H}(Ri)$$

The length-scale formulation in HARATU for stable conditions consists of two parts (Lenderink 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, $c_{Ri} = 2$ (Baas et al., 2008).

Theory: Energy-Flux – Balance (EFB) scheme (1)

$$\frac{DE_K}{Dt} = \frac{\partial}{\partial z} K_E \frac{\partial E_K}{\partial z} + \tau_x \frac{\partial U}{\partial z} + \tau_y \frac{\partial V}{\partial z} + \beta \tau_\theta - \frac{E_K}{t_T}$$

$$\frac{DE_P}{Dt} = \frac{\partial}{\partial z} K_E \frac{\partial E_P}{\partial z} - \beta \tau_\theta - \frac{E_P}{C_P t_T}$$

$$where\ E_P = \left(\frac{\beta}{N}\right)^2 E_\theta = \frac{1}{2}\left(\frac{\beta}{N}\right)^2 \overline{\theta'^2} = c_{Ep\theta} N^{-2} \overline{\theta'^2}$$

The turbulence diffusion coefficients are given as

$$K_M = 2C_\tau A_z E_K t_T$$

$$K_H = 2C_F \left(1 - C_\theta \frac{E_P}{A_z E_K}\right) A_z E_K t_T$$

In the MUSC realization, the anisotropy was kept constant, $A_z = 0.2$.

A measure (energy-based) of the static stability is given by $\Pi = \frac{E_P}{E_k} = \frac{C_P R_f}{1 - R_f}$ where $\Pi_{inf} = 0.14$ is its asymptotic limit.

Theory: Realization of the Energy-Flux – Balance (EFB) scheme (2)

Short name	References	Comments	Model
Z13	Zilitinkevich et al. (2013)	The original scheme/TTE, additional prognostic equation for TPE/temp fluctuations	NA
QNSE	Tastula et al. (2015)	1.5-order scheme: Corrections on the length scales and stability functions	WRF
TEMF	Angevine et al. (2010)	Total energy – mass balance scheme	NA
SBP	Wilson (2015)	EFB-based mixing length scheme	NA
TOUCANS	Ďurán et al. (2018)	EFB-based pTKE scheme including TPE equation	ALARO
MUSC-FMI	Fortelius and Kadantsev (2014)	Simplified EFB	MUSC
LMDZ-EFB	Vignon etal. (2017)	Simplified and reduced EFB	LMDZ
ECHAM6-EFB	Pithan et al. (2015)	Elements of the EFB	ECHAM-6

Simplifications in the MUSC-FMI realization: The relaxation (prognostic) equation for the dissipation time scale

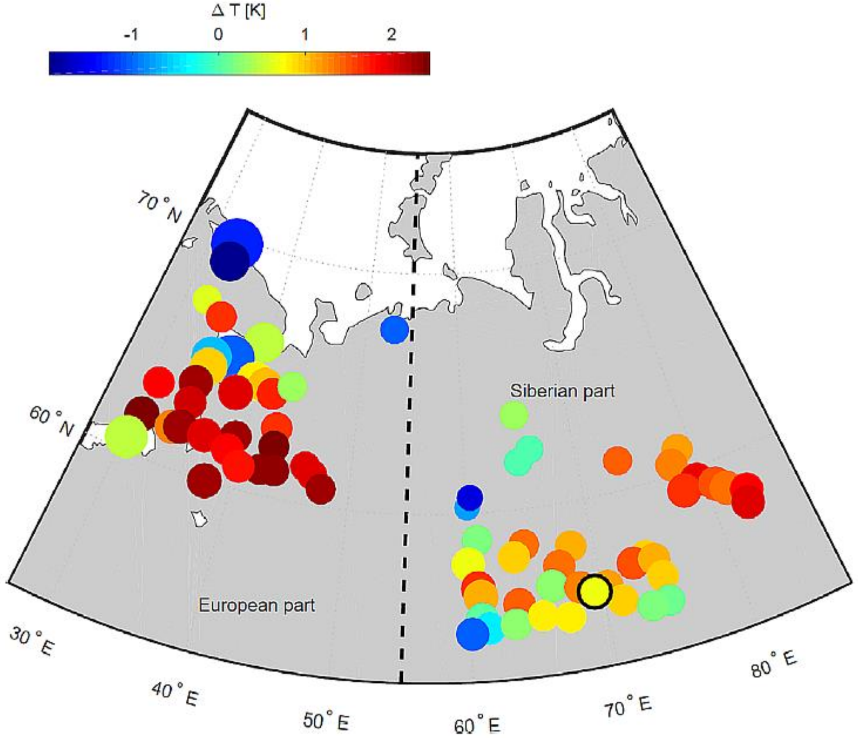
$$\frac{dt_T}{dt} = t_T(t) - t_T(t-\delta t) = \min\left(0.2, \frac{\delta t}{t_{TE}}\right)\left(t_{TE}(t) - t_T(t-\delta t)\right)$$

t_{TE} is an equilibrium time scale, associated with the length scale $l = t_{TE}\sqrt{E_K}$, its diagnostic expression is given by

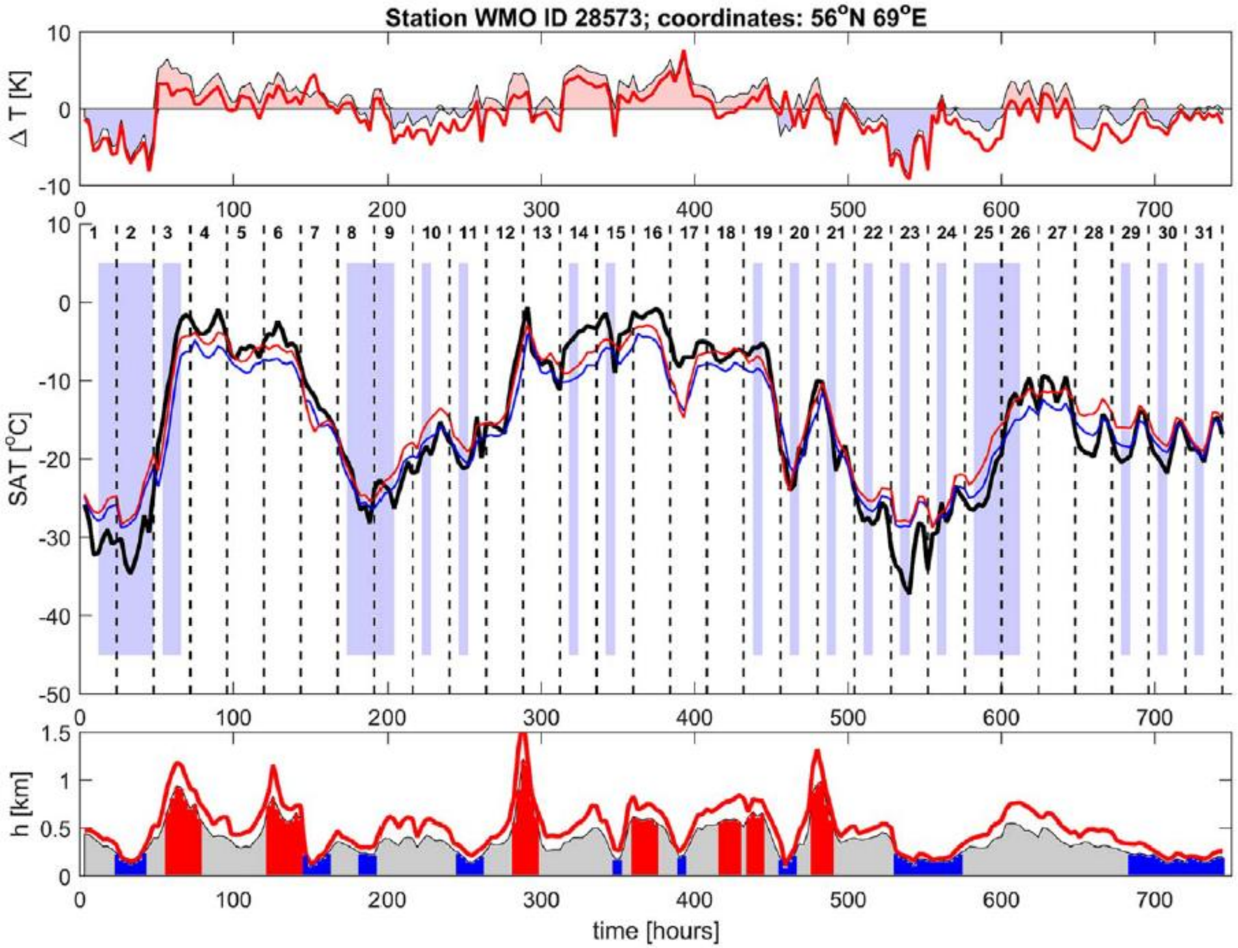
$$t_{TE} = kz\frac{1}{\sqrt{E_K} + C_\Omega \Omega z}\left(\frac{E_K}{\tau}\right)^{\frac{3}{2}}\left(1 - \frac{\Pi}{\Pi_{inf}}\right)$$

the Earth rotation set $C_\Omega = 0$.

Results: Systematic temperature bias in the SL-AV model with the TOUCANS and pTKE schemes (1)



The meteorological stations (circles) in the study of the systematic biases in the northern European part and western Siberian part of Russia. Colors correspond to the mean SAT errors, ΔT, averaged over diurnal cycle, in January 2015 in the forecasts with the pTKE scheme. The circle size indicates the monthly mean ABL thickness in the model. The black ring marks the selected WMO station with ID 28573.



Results: Systematic temperature bias in the SL-AV model with the TOUCANS and pTKE schemes (2)

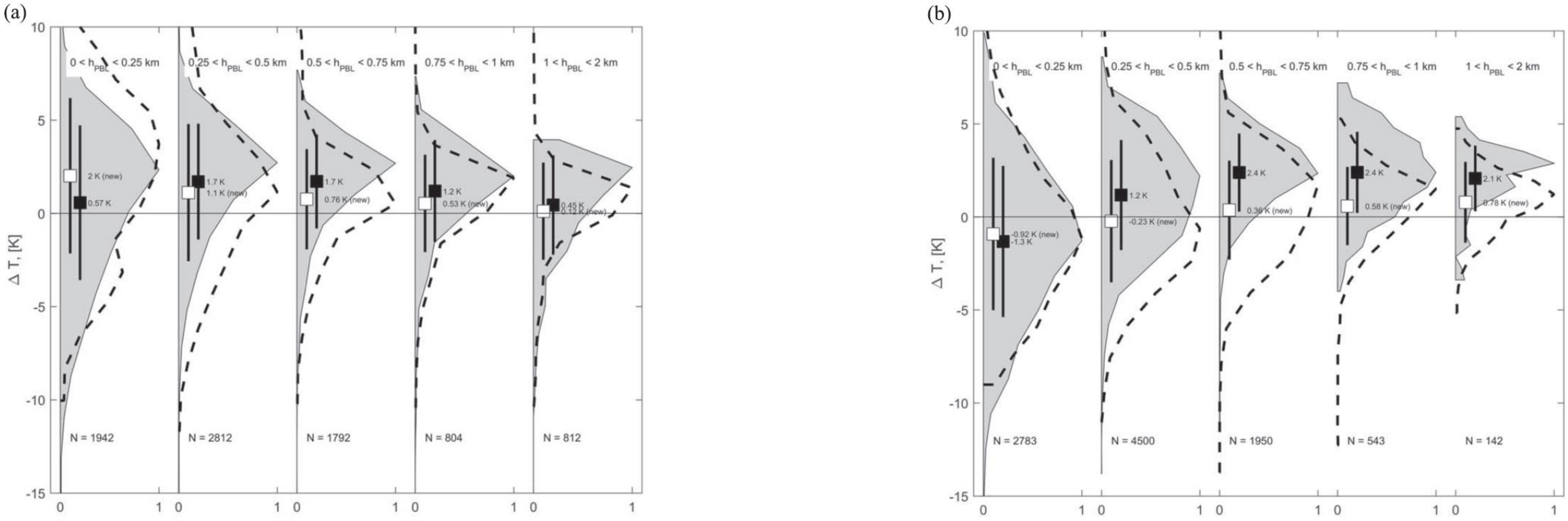
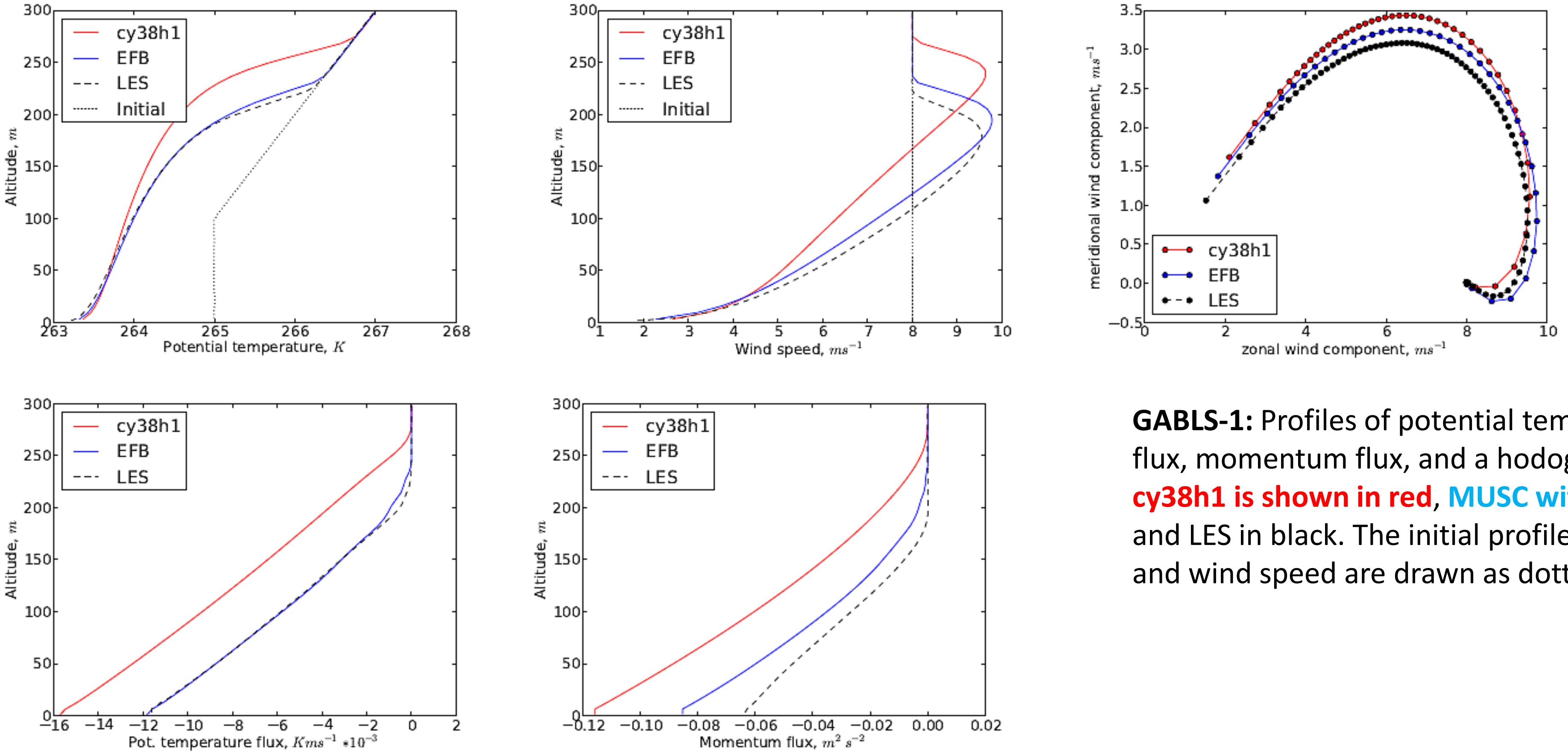


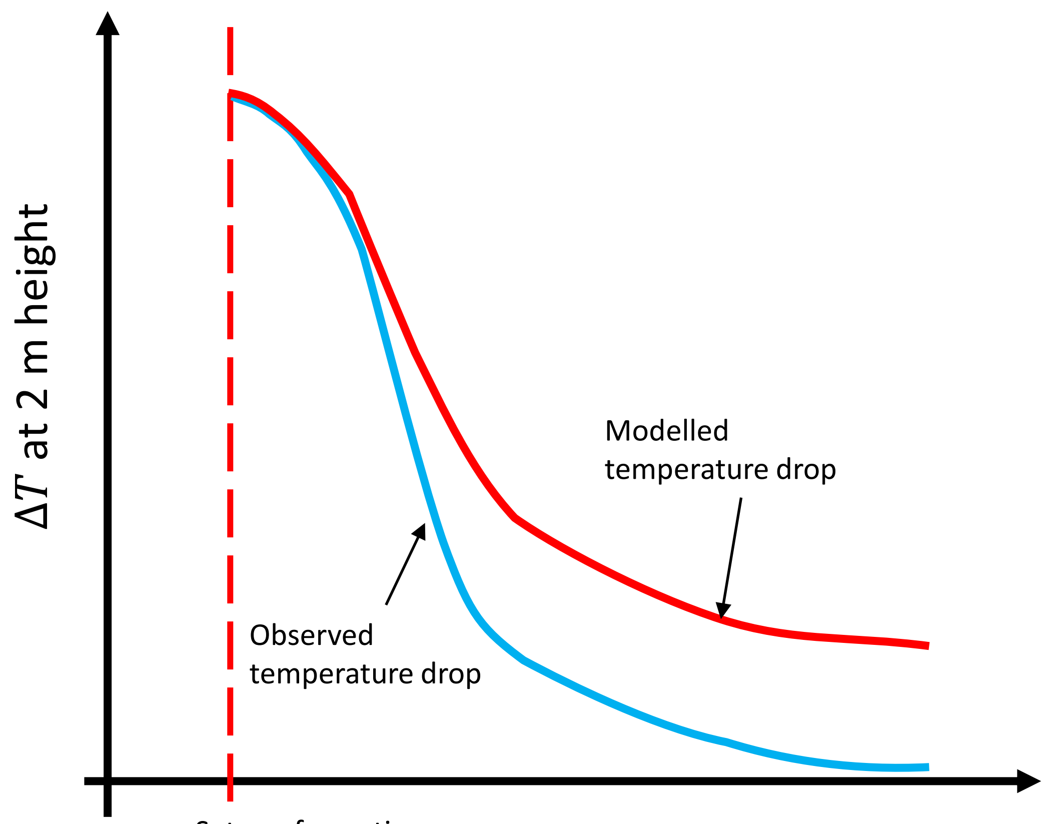
Figure 7. The model errors, $\Delta T = T_{obs} - T_{\mathrm{mod}}$, split in the five bins with the following h_{PBL} thicknesses: <0.25 km, $0.25 < h_{PBL} < 0.5$ km, $0.5 < h_{PBL} < 0.75$ km, $0.75 < h_{PBL} < 1.0$ km and $h_{PBL} > 1.0$ km. The European stations are shown in panel (a) and the Siberian ones in panel (b). Histograms of the model errors for each bin are shown by gray shading for the old scheme and by dashed lines for the new scheme. The mean ΔT and its standard deviations are shown by squares and vertical black lines. The mean values and numbers of 3-hourly observations in each bin are given on the plots. The histograms are normalized by their maximum values in each bin.

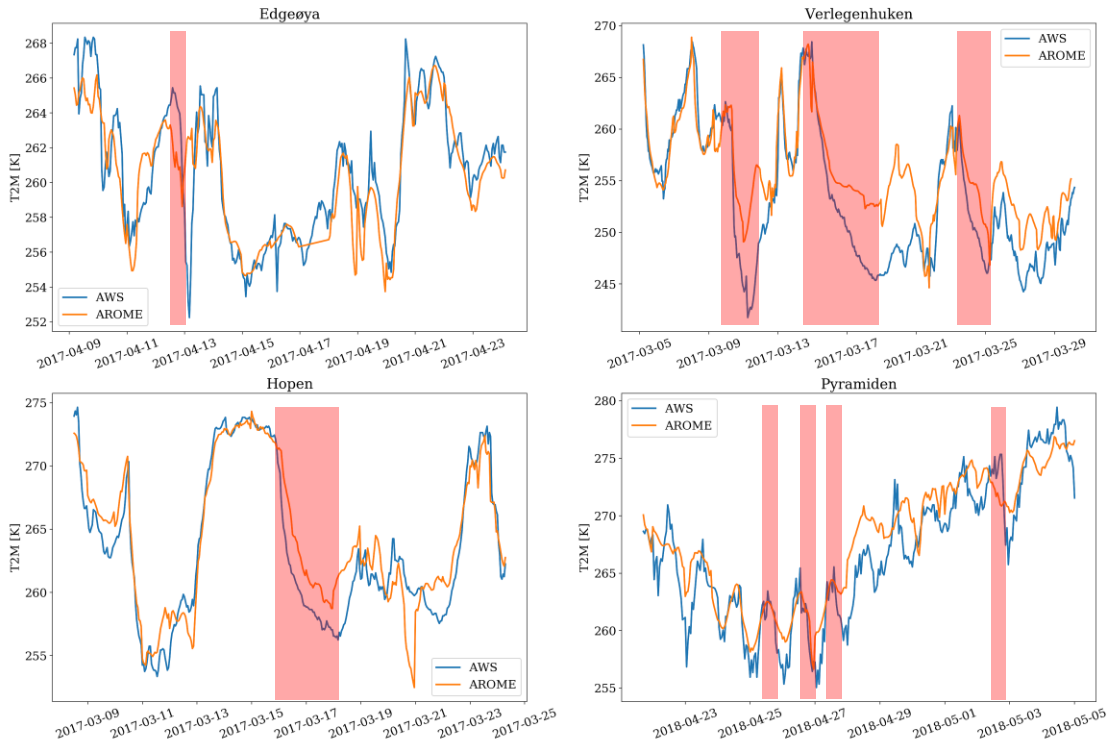
Results: GABLS-1 experience with MUSC-EFB (cy38.h1)



GABLS-1: Profiles of potential temperature, wind speed, heat flux, momentum flux, and a hodograph, plotted at 9h. **MUSC cy38h1 is shown in red**, **MUSC with the EFB closure in blue**, and LES in black. The initial profiles of potential temperature and wind speed are drawn as dotted lines.

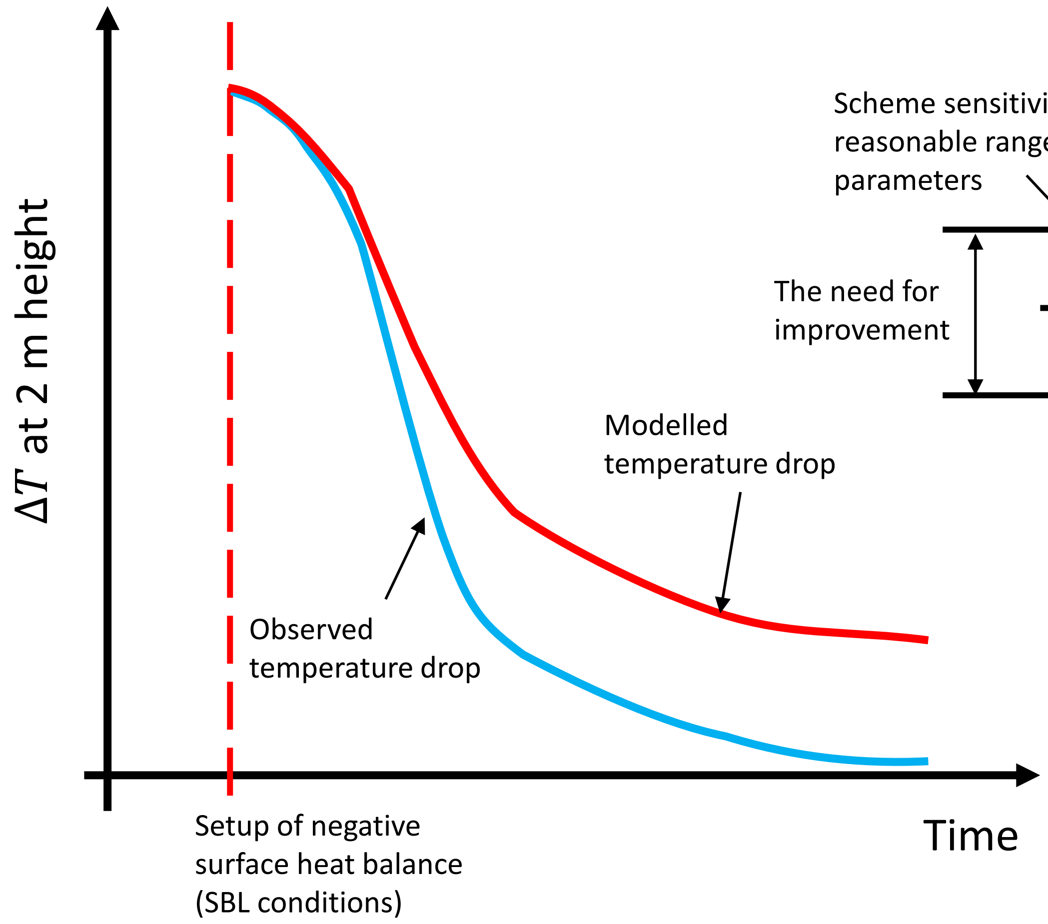
Results: On the origins of the systematic warm temperature biases

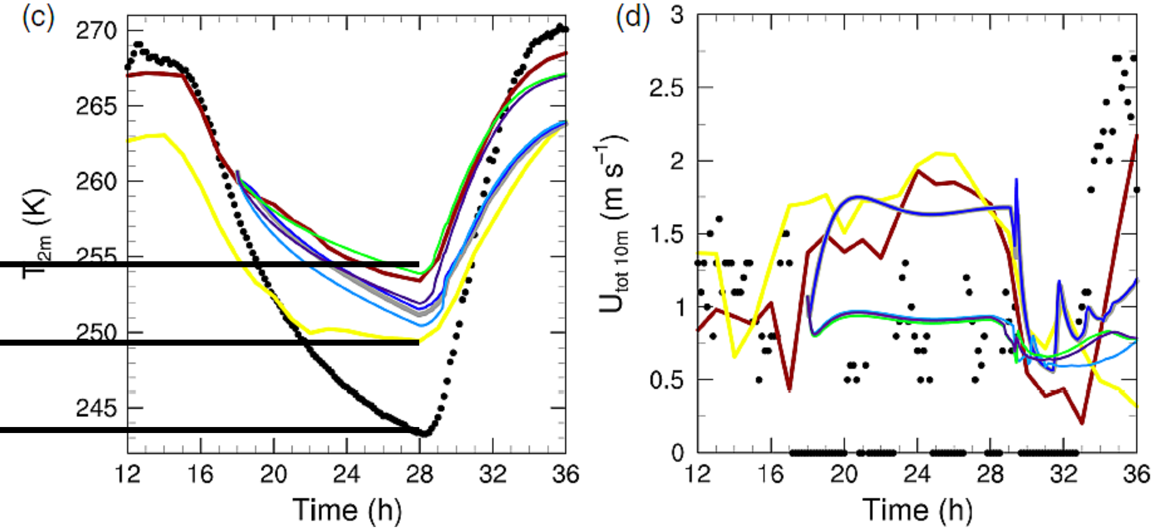




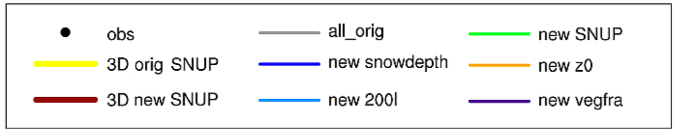
Comparing observed and predicted temperature fluctuations. Results from the partner in the ALERTNESS project (the HIRLAM-HARMONIE model with the HARATU scheme)

Results: Rethinking of the errors and biases in common theoretical frameworks

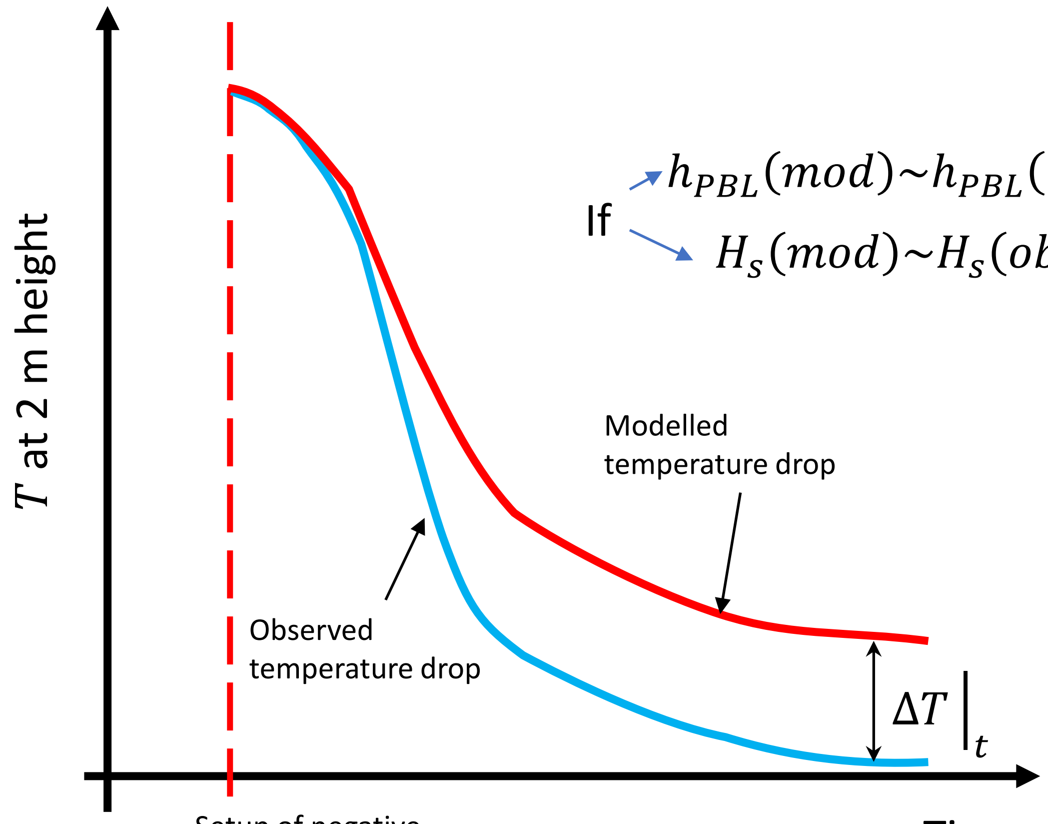




Sterk et al. (2015) study of the PBL scheme sensitivity



Results: Rethinking of the errors and biases in common theoretical frameworks



$$\frac{dT}{dt} = (\rho c_p)^{-1} \frac{1}{h_{PBL}} H_s$$

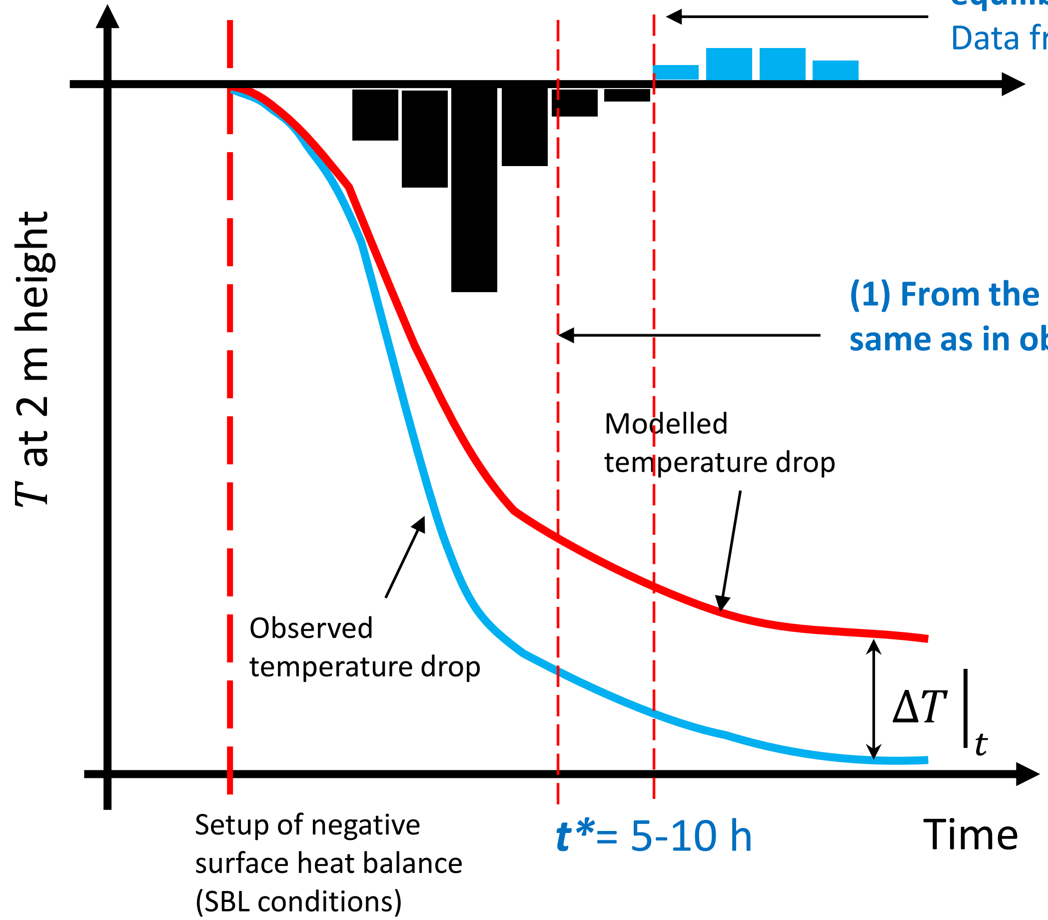
If $h_{PBL}(mod) \sim h_{PBL}(obs) \rightarrow \quad \Delta T = \big(T(mod) - T(obs)\big)|_t \sim H_s(mod) - H_s(obs)$

If $H_s(mod) \sim H_s(obs) \rightarrow \quad \Delta T = \big(T(mod) - T(obs)\big)|_t \sim \frac{1}{h_{PBL}(mod)} - \frac{1}{h_{PBL}(obs)}$

- Air is warmed/cooled at the surface (simplification for a thin PBL)
- Sensible heat is transported by turbulent flux, H_s
- The PBL, h_{PBL}, is assymptotically controlled by an equilibrium H_s (in agreement with the LES runs in Esau & Zilitinkevich, 2006)

Results: Rethinking of the errors and biases in common theoretical frameworks

(2) In long run with unchanged boundary conditions, the model equilibrate; and the temperature error decreases
Data from MUSC experiment in METCOOP domain (Kemi, Finland)



So that, in long run, the MUSC-HARATU-Lederink scheme is accurate (Baas et al., 2008)

(1) From the time moment *t, temperature drop is almost the same as in observations, but the error has accumulated already**

- Contribution to the total model temperature bias (replotted from MUSC runs with varying wind speed): % of the total ΔT (mod – obs) accumulated by the given time after the SBL setup

Conclusions and future work

- Systematic errors in forecast near-surface air temperature (SAT) still constitute a considerable problem for numerical weather prediction (NWP) at high latitudes.
- We compared several attempts to implement elements of the new EFB turbulence scheme in different models – no significant progress was reported
- We looked in more details into implementations in ALARO (SL-AV; TOUCANS) and AROME-HARATU (MUSC; EFB-FMI) physical modules – results are controversial, no significant progress in the most stable PBL cases
- We analyzed structure of the systematic temperature bias – the errors are accumulated after switch of the surface flux, thus, suggesting dependence on thermal inertia of the PBL
- We suspect that new implementations of the EFB scheme must allow for more independence between the PBL depth and the turbulent diffusion

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