High resolution simulations of the night-time stable boundary layer over snow

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Motivation

- SBL problematic to understand and model
- GCMs: large T_s errors in polar areas
- NWP: warm biases in cold conditions (T2m < -20^{o}C; Atlaskin and Vihma 2012)
- Snow: good insulation, high thermal inertia
  → low night-time T_s, very stable BL, large NWP biases
- How important is Q_{rad} vs Q_{turb} in the SBL, and why?

→ High-resolution idealized 1-D experiments over snow.

- Vary the wind speed V_g, look for $T(z)$, $V(z)$, $Q_{rad}(z)$, $Q_{turb}(z)$, H_0.

- Vary the snow scheme & snow properties.

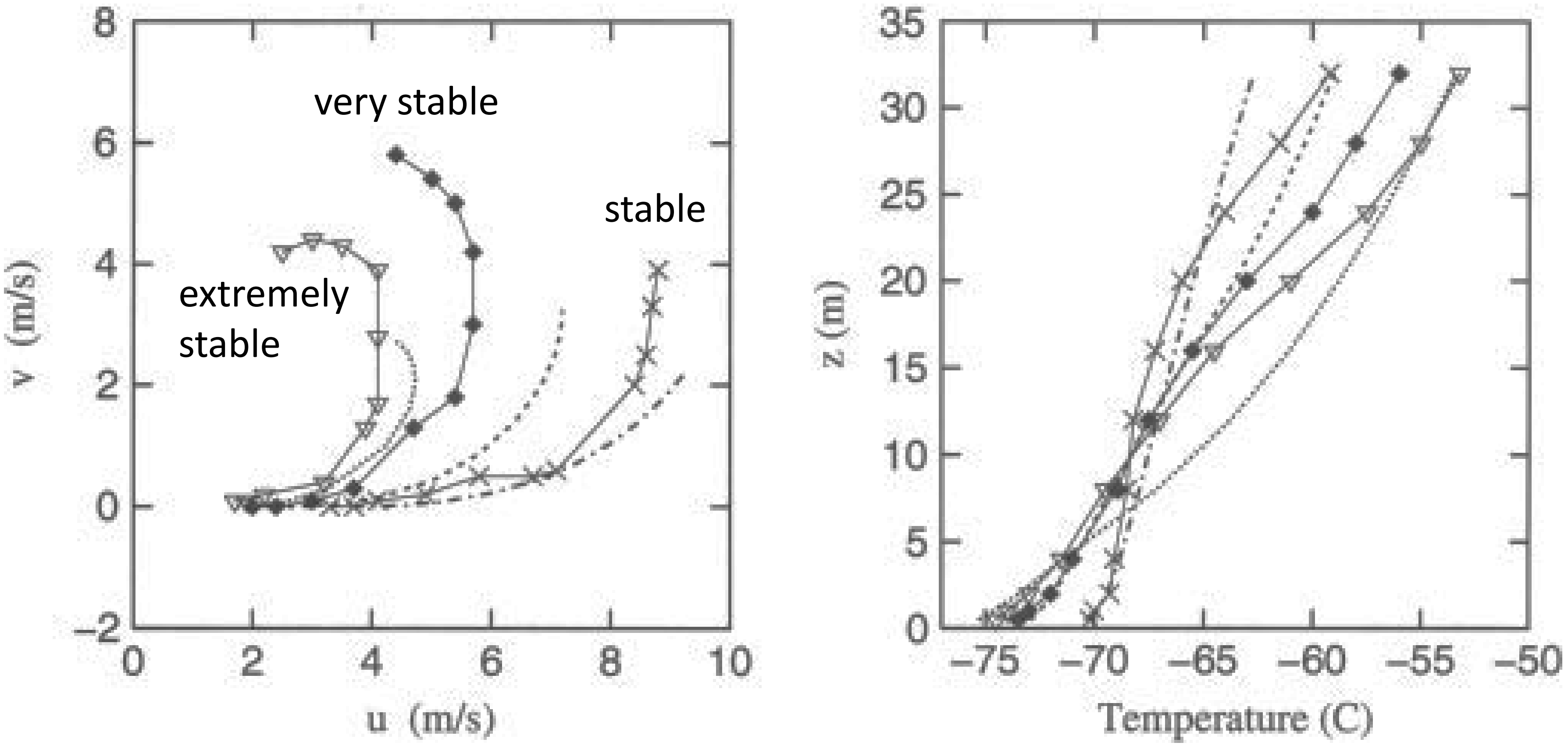
1-D BL model (1)

- 1-D, constant V_g, 10 s time step
- Grid: 0.1 m, 0.3 m, 1, 2, 5, 10, 22 m, ... 30km
- **LW rad**: narrow band model (67 bands, LBL-validated) **SW rad**: HIRLAM-type
- **Turbulence**: mixing length Blackadar closure, λ 150 m, f(Ri) = ’short tails’ for Ri > 0, Dyer-Businger for Ri < 0
- **Cloud physics**: saturation at RH 105% (→ diamond dust in cold air, sedimenting down as observed)

BL model (2)

- **Snow**: thermal diffusion (Crank-Nicholson). **Five optimized depths**: 0, 0.87, 1.85, 6.65, 18.8 cm. Deep snow: $T = T_{ds} = \text{const}$
- **Scheme max T_s error < 1% of amplitude for diurnal square wave forcing** (cf. 14% in a coarse force-restore, 3% in a 50 layer 0.5 cm gridlength scheme)
- 1-D model tested in midlatitude summer (2006 QJ), in Antarctic winter (2009 QJ)

(and in Mars' very stable nighttime BL: 1-S model vs. Phoenix observations (2010 QJ), vs. Spirit obs (2008, 2012 QJ))

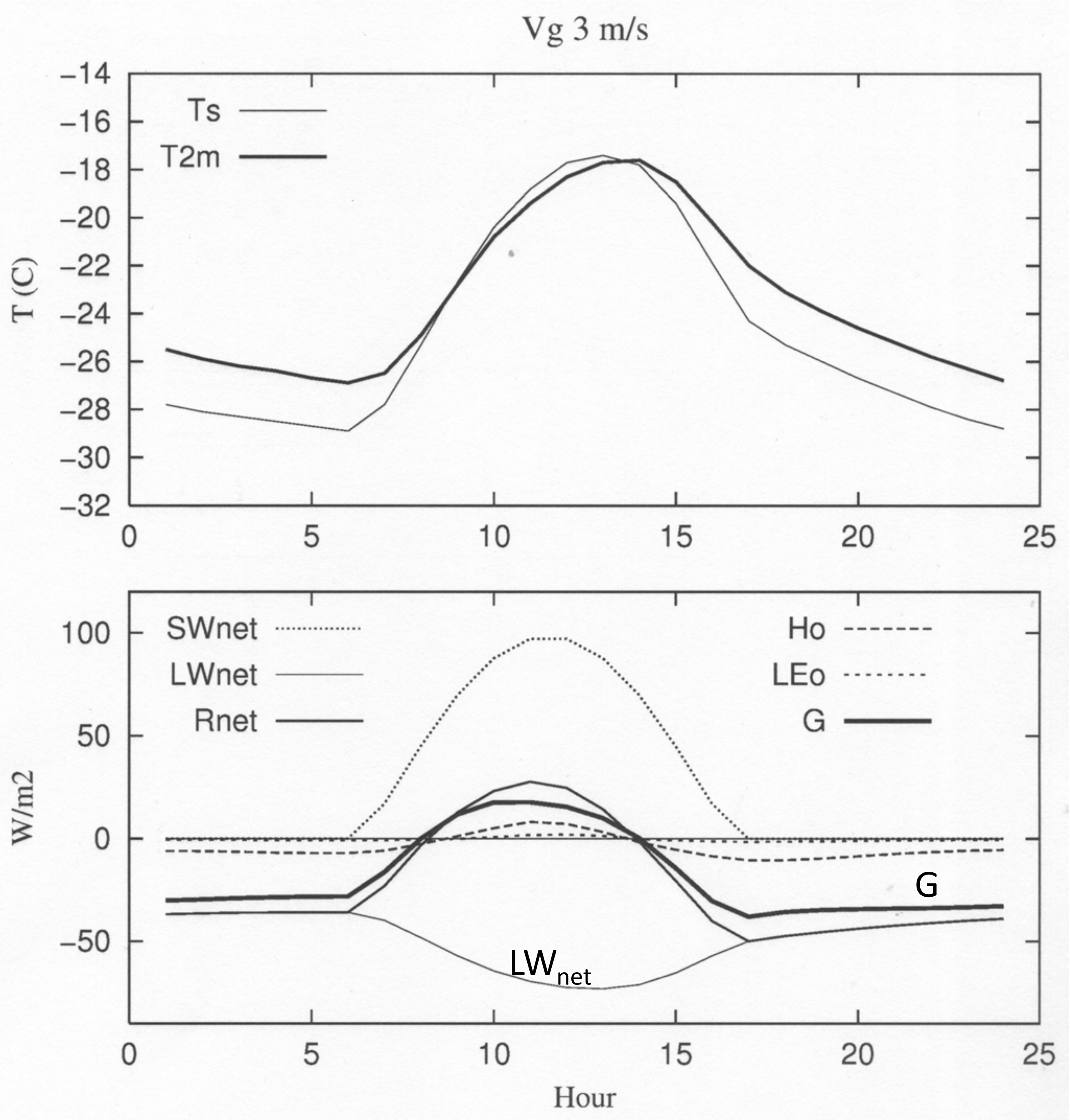


Antarctic High Plateau Station 0-32 m winter mean temperatures and wind hodographs in three stability categories (from King and Turner, 1997) with 1-D simulations (S 2009 QJ)

(non-flat areas & high Ri → local drainage winds → $K=K(\sigma(z_s))$)

Present test case

- 67^oN, clear-sky early March, snow-covered (50 cm) homogeneous field with typical snow ($z_{0m,h}$= 1 cm, α = 70%), T_{ds} = -15°C.
- Initially: mean Sodankylä winter T(z), 40% RH.
- +54h simulation from 00 local solar time (LT).
- First day: a general Arctic clear-sky inversion to about 300 m is formed, as in the Antarctica case.
- Then: Sunny days → shallow well-mixed layer
  Clear nights → shallow diurnal stable layer, T_s down to -25…-34°C depending on winds (V_g = 0/1/2/.. 10 m/s)

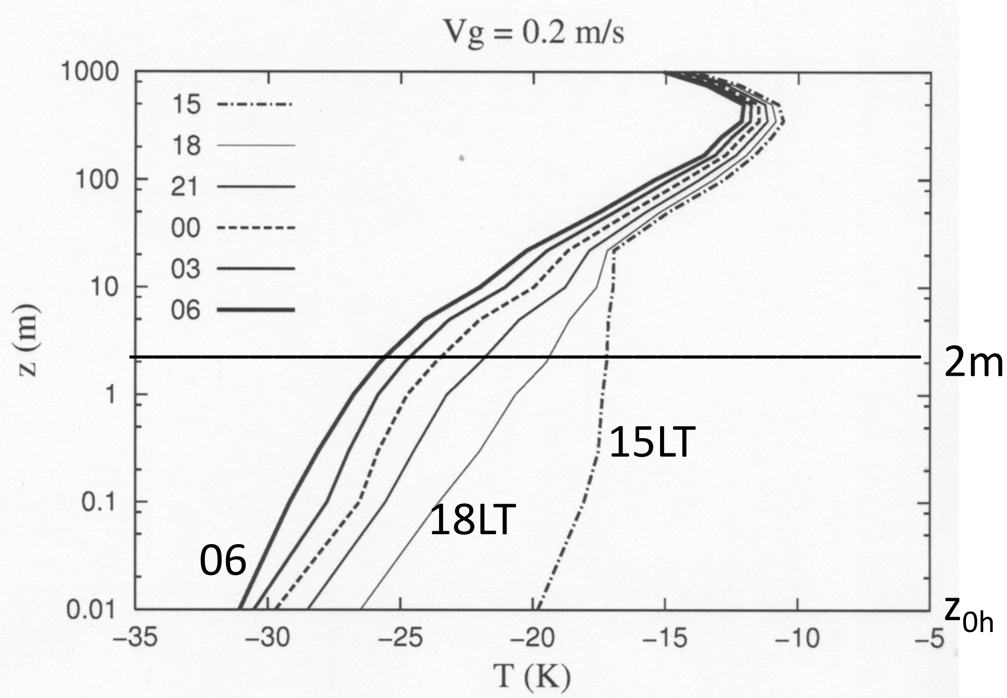


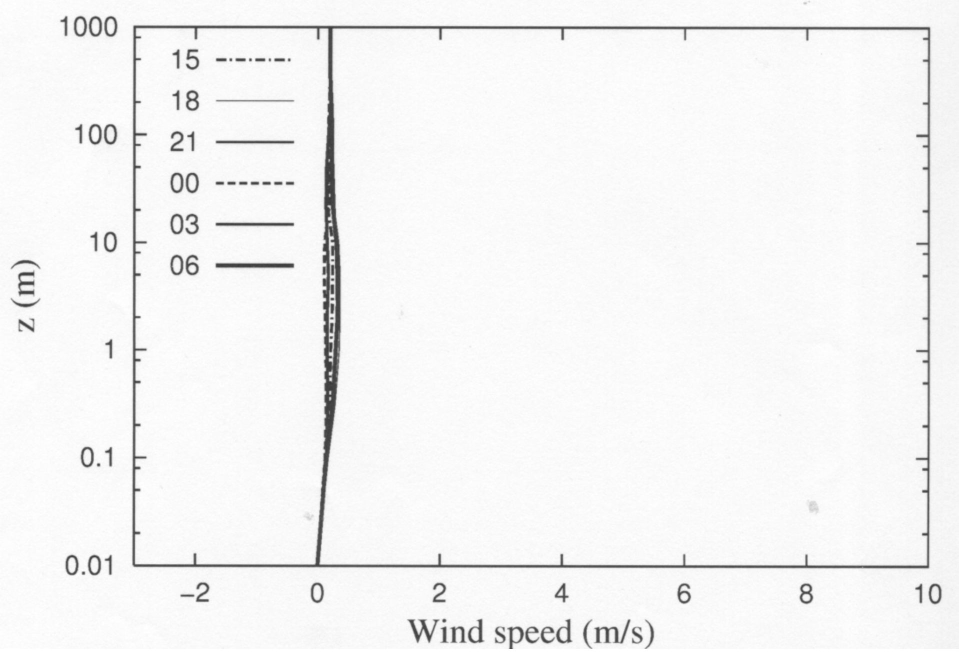
Day 2, clear sky, weak wind:

T2m, Ts:
Unstable at 08-14 LT.
T2m – Ts is about 2 K during the night

Surface heat fluxes:
G: ~ const at night,
H_o, LE_o small,
R_{net} dominates in G

→ downwelling LW radiation should be rather accurate for a good G and a good T_s- and T2m prediction.





<u>Calm</u> clear-sky night, day 2-3

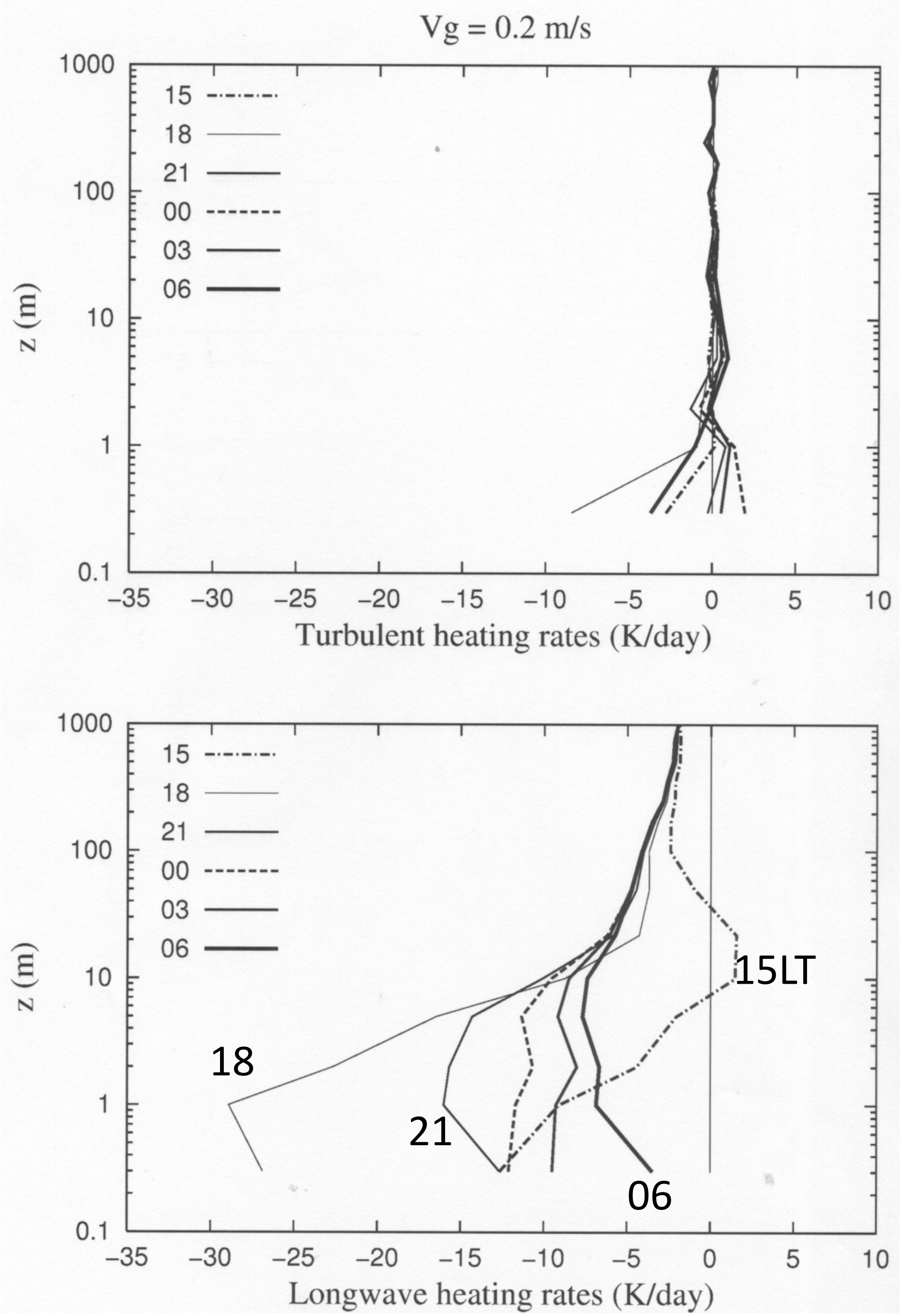
T(log z) 15LT → 06LT:
General inversion to 300 m

Mixed layer to 20 m at 15LT
Then: Steep inversion
Cold surface, quite logarithmic T(z)
T2m –T_s ~ 6 K

Inversion in q(z), too

V(log z):

No wind, calm ”radiative” night



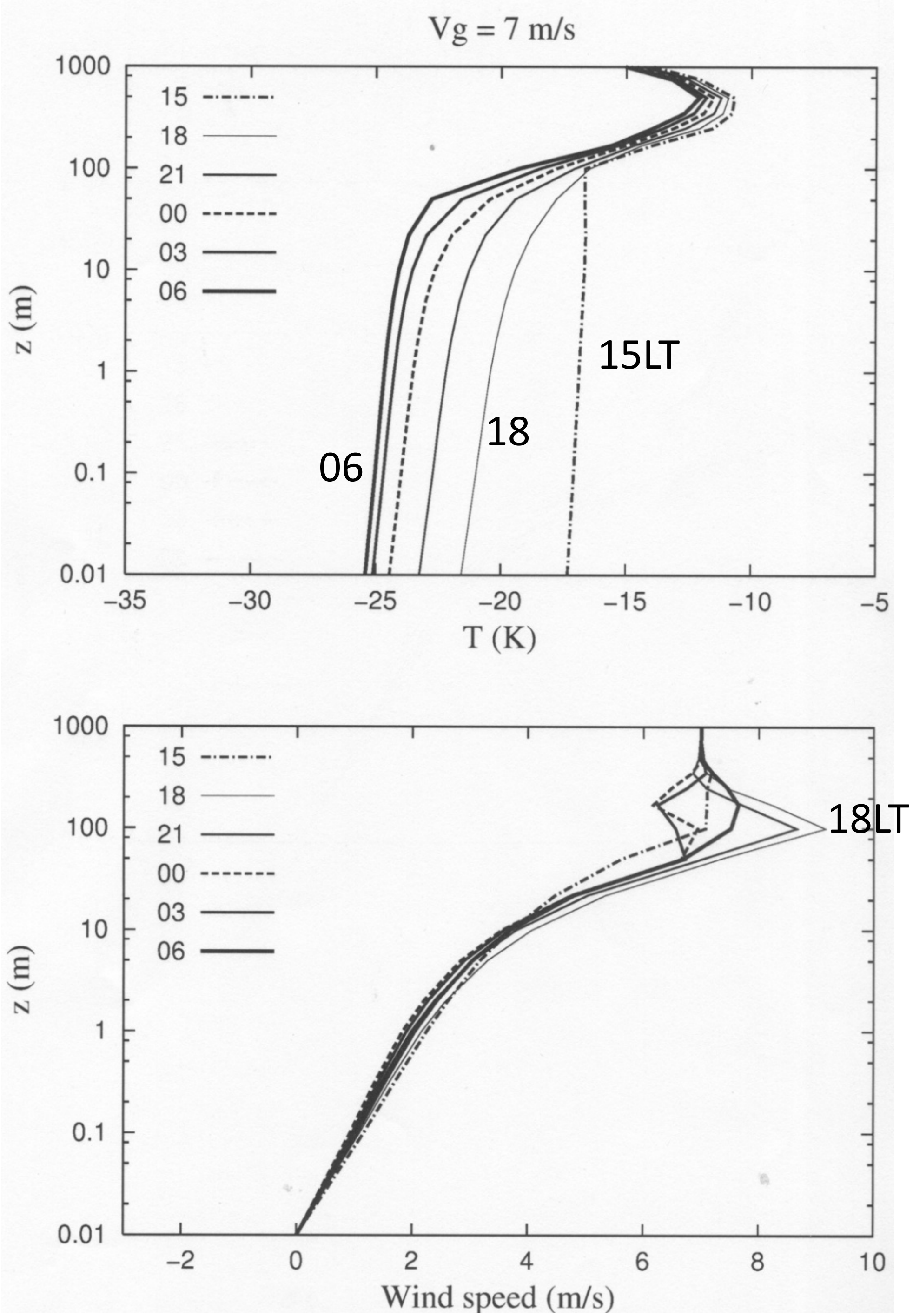
Calm clear-sky night

Q_{turb}(log z) 15LT → 06LT
No wind, no turbulent cooling

Q_{rad} dominates:

In the evening: Strong LW cooling near the surface

During the night: Moderate LW cooling



<u>Windy</u> clear-sky night:

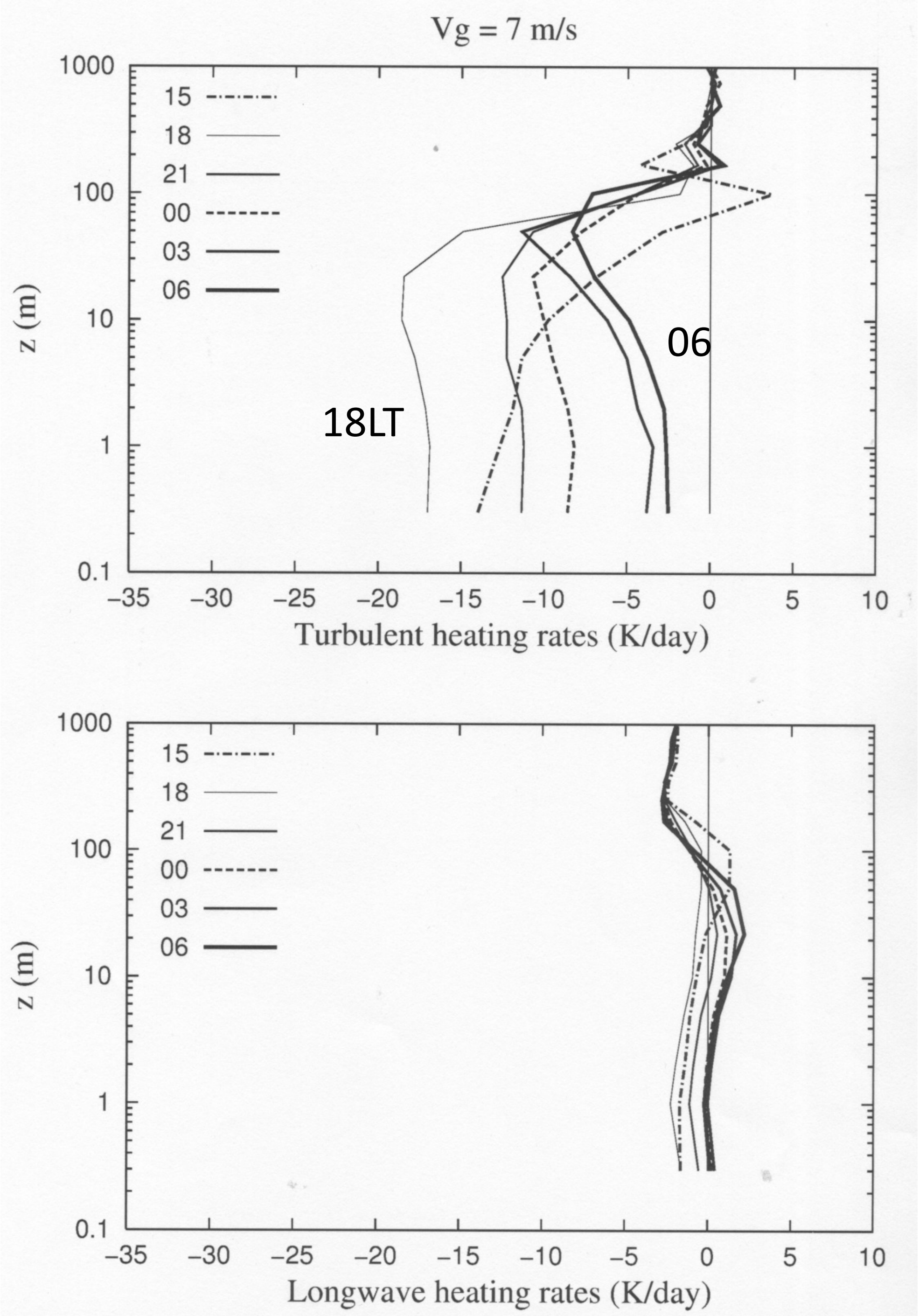
T(log z) 15LT → 06LT:
General inversion to 300 m

Well-mixed BL to 100 m at 15LT.
Nearly isothermal surface layer during the windy night.
T2m is closely coupled to T_s.

V(log z) 15LT → 06LT:

Logarithmic surface layer,
Strong wind shear

Inertial oscillation at 100 m
NLJ at 18-21LT,
Shears time-dependent in the Ekman layer

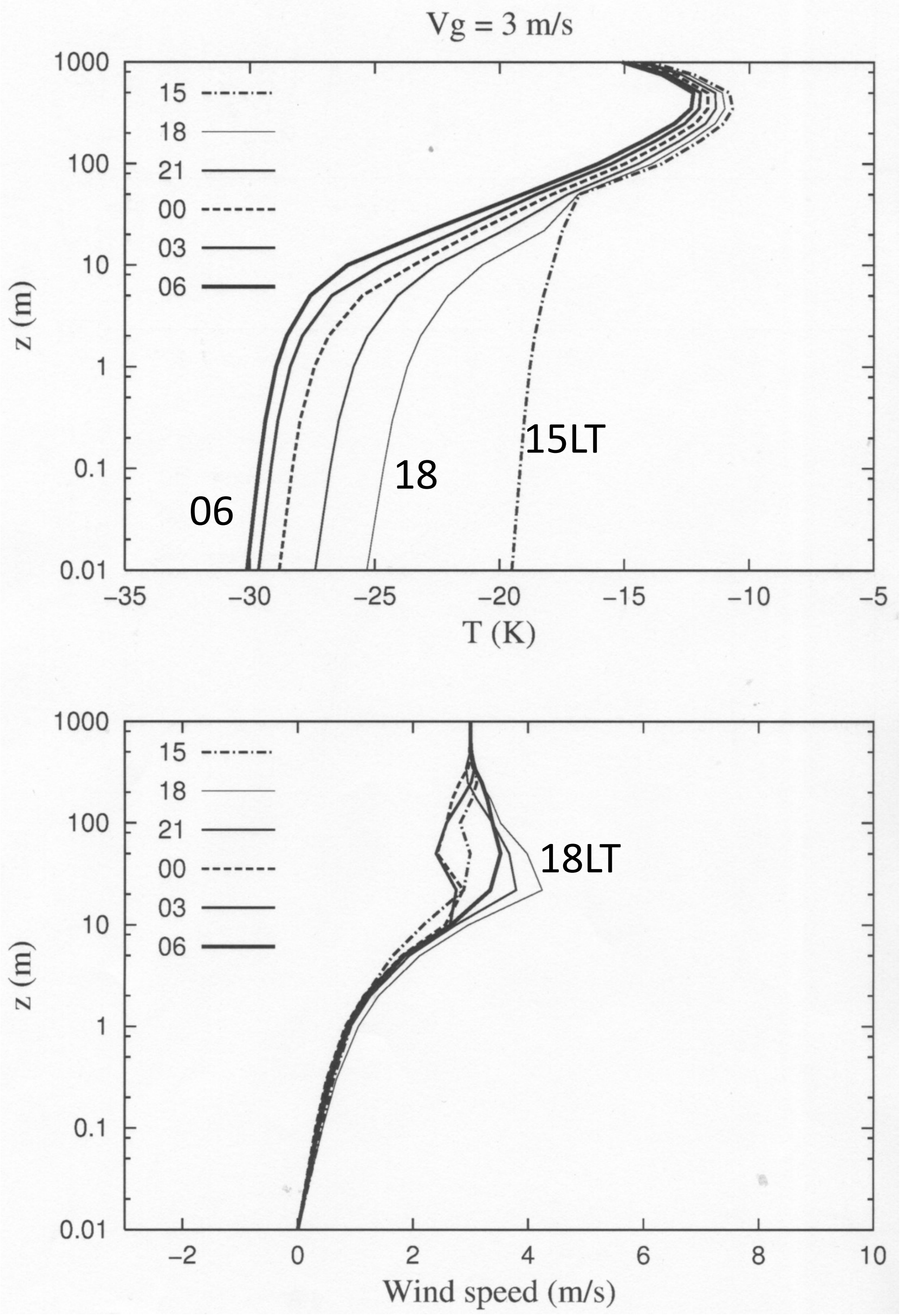


Windy clear-sky night:

Turbulent cooling dominates

(but is only moderate:
wind shears are strong but
T-gradients are weak)

LW cooling is insignificant in
the windy surface layer
(weak T, q -gradients)

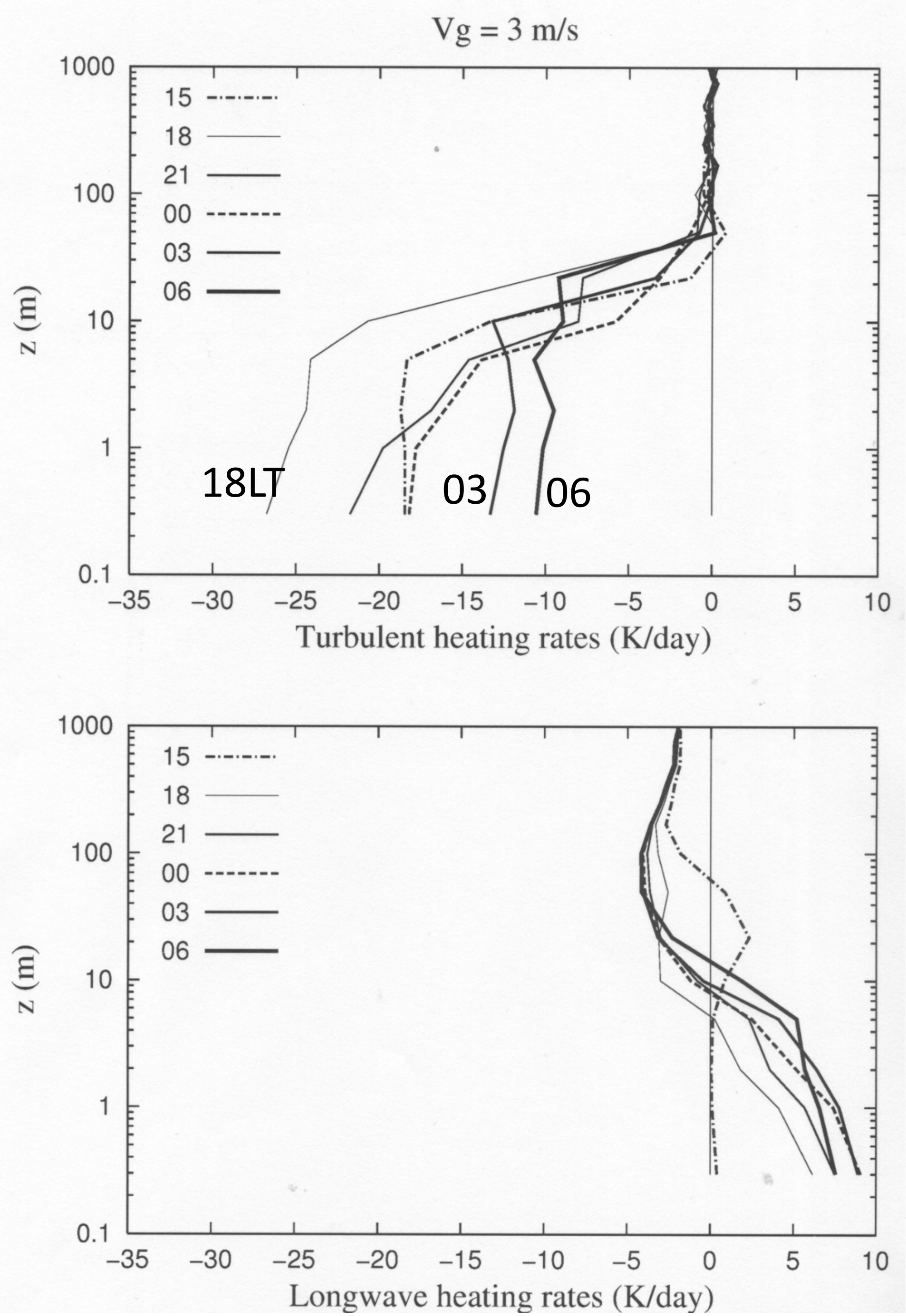


Weak wind, clear sky night:

T(z) is well-mixed to 50 m at 15LT, is between isothermal and logarithmic during the night

T2m - T_s ~ 2 K

Wind speed: logarithmic to 5 m, inertial oscillation with weak NLJ at 20-50 m during the night



<u>Weak wind</u> clear-sky night:

Turbulent cooling is <u>moderate to strong in the surface layer</u>

(moderate shears, moderate T-gradients)

LW cooling is <u>moderate and dominates the mid-inversion and aloft</u>,
but <u>turns to weak heating in the surface layer</u>

(compensates turb cooling!)

The day 2 0600LT V2m, V10m (ms^{-1}) and T_s, T2m, T10m, T100m (^oC) as the function of V_g (ms^{-1}).

V_g	V2m	V10m	T_s	T2m	T10m	T100 m	T2m - T_s
0.0	0	0	**-29.9**	-23.4	-19.2	-11.6	6.5
1.0	0.9	1.4	-29.6	-25.2	-20.2	-11.7	4.4
2.0	1.1	2.3	-29.3	-26.5	-21.8	-11.9	2.8
3.0	1.2	2.8	-28.8	**-26.8**	-23.4	-12.2	2.0
4.0	1.4	2.9	-28.2	-26.6	-24.5	-12.6	1.6
5.0	1.7	3.2	-27.5	-26.0	-24.6	-13.0	1.5
6.0	1.9	3.4	-26.9	-25.6	**-24.7**	-13.9	1.3
7.0	2.2	3.7	-26.1	-24.8	-24.0	-15.7	1.3
8.0	2.6	4.1	-25.4	-24.1	-23.5	**-17.3**	1.3

Surprise in the experiments:

The snow surface was at its coldest after a calm night

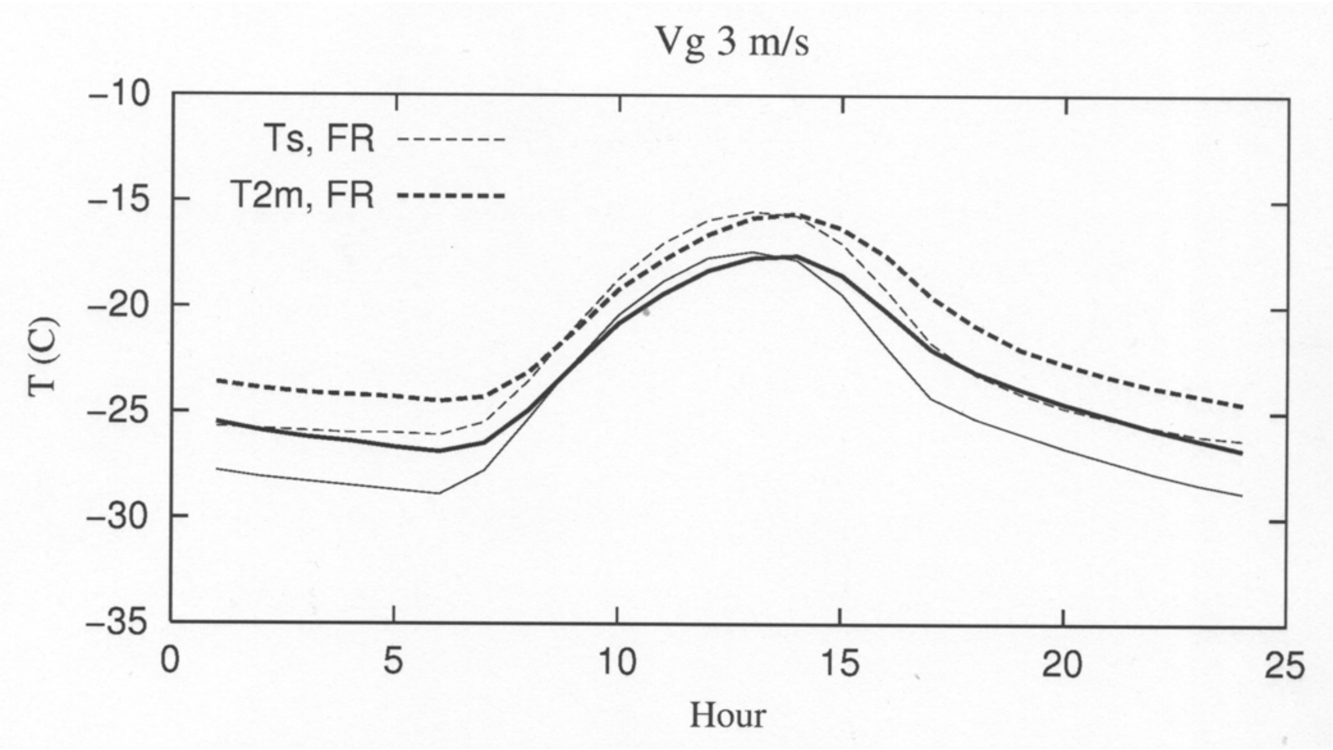
But: T2m was at its coldest during weak wind, V2m of 1.2 m/s (V_g 3 m/s), not during calms,

and T10m was at its coldest for V10m of 3.5 m/s (V_g 6 m/s) as was observed in SHEBA.

Why?

A little bit of wind helps to maximize $|H_0|$ (when using the ’short tails’ f(Ri), not with ’long tails’), so that the coldness of the surface is transported effectively to the air and Q_{turb} can stay strongly negative, against the positive Q_{rad}.

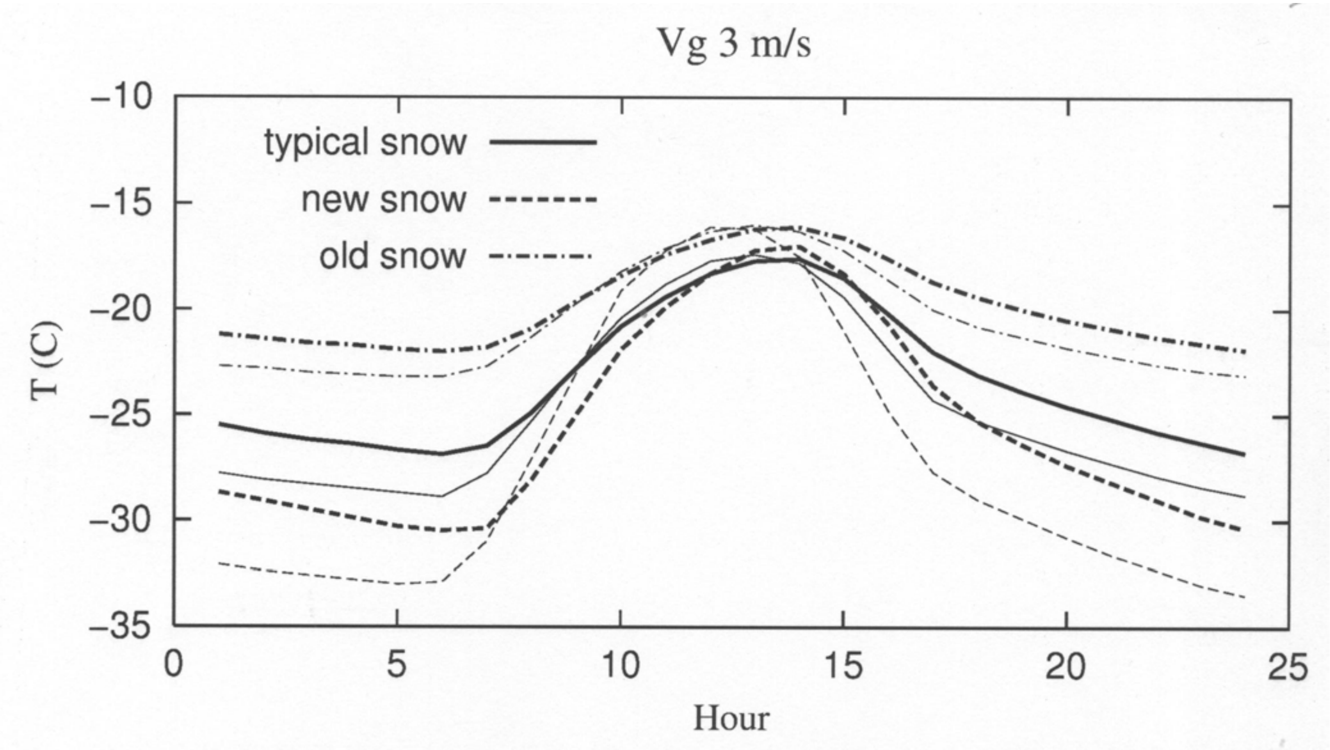
Sensitivity tests: Snow schemes:



A coarse snow scheme (here force-restore = FR) tends to produce too warm night-time temperatures (warm bias).

→ Use multilayer snow schemes

Sensitivity tests: Snow types:



Use of older snow thermal properties (upper curves) when fresher snow actually prevails (lower curves) tends to produce warm bias at night

→ Refresh your snow properties (primarily snow density) by the observed/predicted snowfalls.

Clear-sky nights over snow: conclusions

-**Calm night**: LW cooling dominates, leads to nearly logarithmic T(z).

-**Windy night**: Turb cooling dominates, V(z) is logarithmic with NLJ, surface layer is ~ isothermal.

-**Weak wind**: Turb cooling dominates in the SL against LW warming, LW cooling dominates aloft.

T2m is at its coldest as $|H_0|$ is maximized.

($|E_0|$ is also maximized → danger of road icing!)

-**Coarse snow scheme**: may lead to a warm bias

-**Old snow parameters**: may lead to a warm bias

-**Inaccurate DLR**: may lead to wrong T_s and T2m.