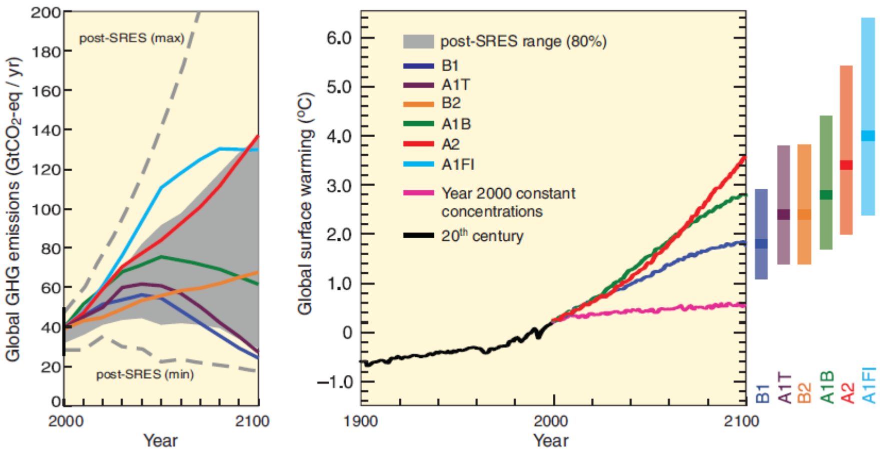
Processes at high latitudes related to near surface temperature

Anton Beljaars, Gianpaolo Balsamo, Emanuel Dutra,
Richard Forbes, Irina Sandu

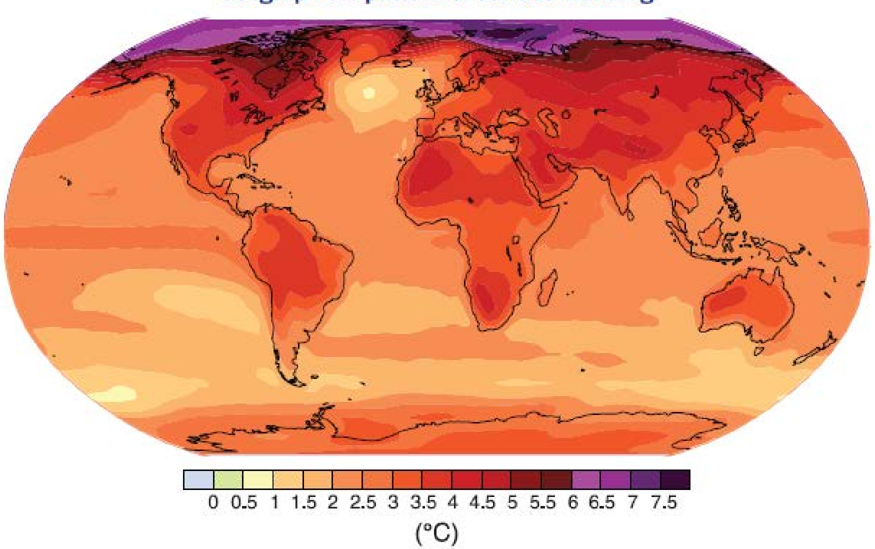
- **Radiation**
- **Clouds**
- **Boundary layer coupling to land and snow**
- **How to disentangle the effects of different processes ?**

IPCC 4th assessment, projection for 2100

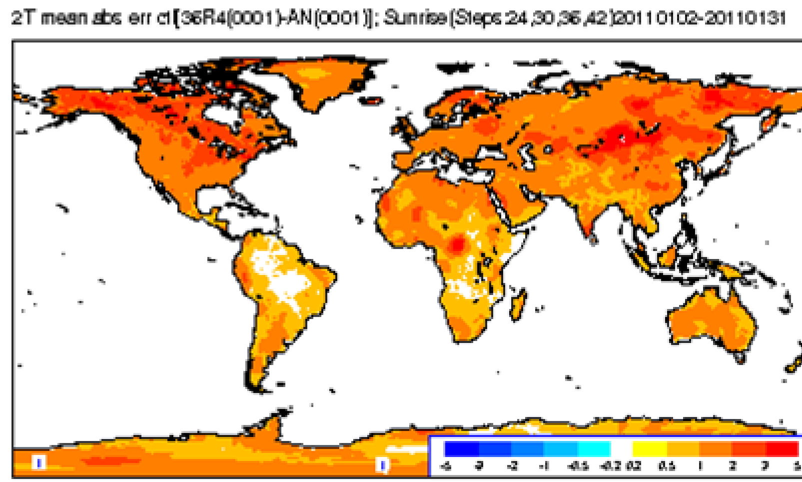
Scenarios for GHG emissions from 2000 to 2100 (in the absence of additional climate policies) and projections of surface temperatures



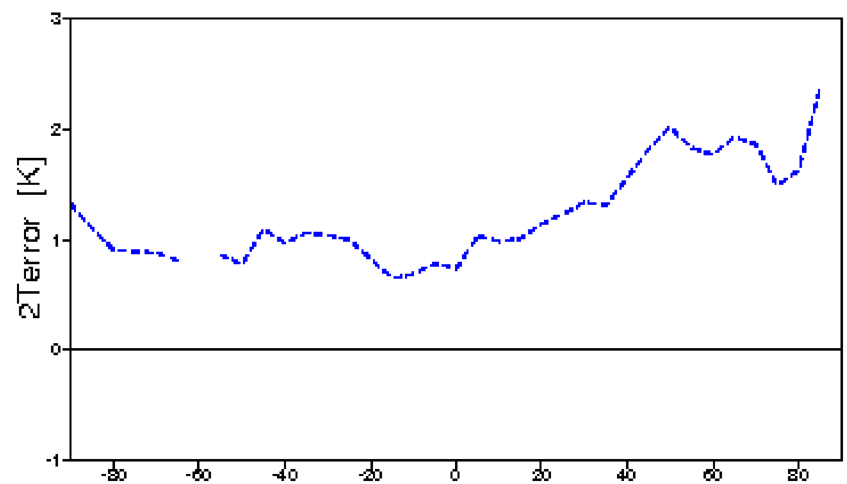
Geographical pattern of surface warming



Mean absolute error of minimum 2T in ECMWF short range forecasts for January 2011

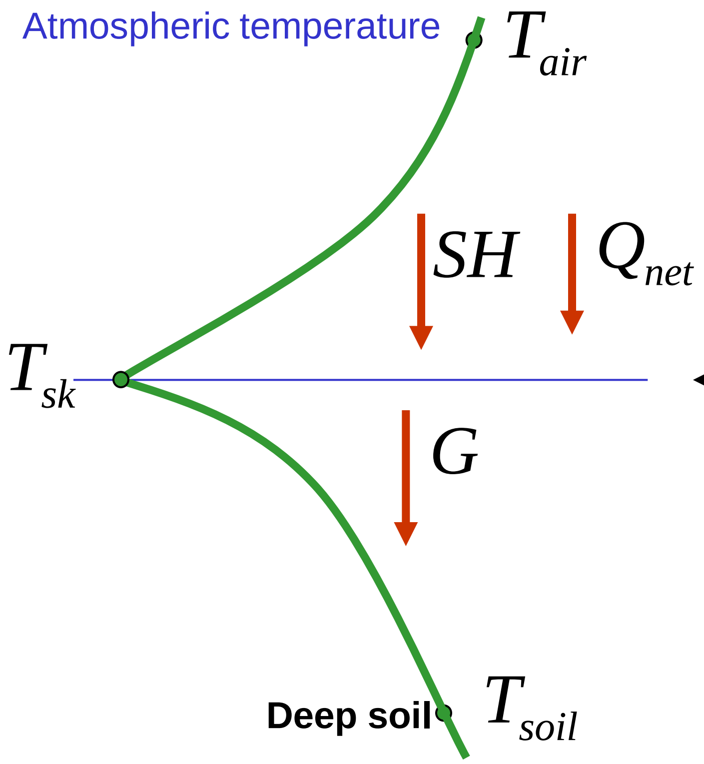


Zonal mean average of absolute error of minimum 2T in ECMWF model



ECMWF

How is the winter and night time cooling at the surface controlled?



Radiation intercepting/emitting level:
e.g. vegetation canopy, litter layer on top of bare soil, snow layer, or combination of these in a heterogeneous configuration

1. **Which fraction of radiative cooling is taken from the atmosphere through sensible heat flux and which fraction from the land surface?**
2. **Over what depth is the cooling distributed in the atmosphere (boundary layer depth)**

ECMWF

The strength of the coupling is hidden in a number of parametrizations

Radiation is affected by:
- Clouds
- Aerosols
- Water vapor

Coupling between lowest model level and surface (skin layer) is affected by:
- Wind speed
- Roughness lengths
- Stability function
- Heterogeneity

$$H = \rho c_p C_H \,|U|\,(\theta_l - \theta_{sk})$$

$$C_H = \frac{k^2}{\ln(z/z_{om})\ln(z/z_{oh})} F_H(Ri_b)$$

Boundary layer diffusion above the lowest model level is affected by:
- Wind shear
- Stability
- Meso-scale variability
- Asymptotic mixing length

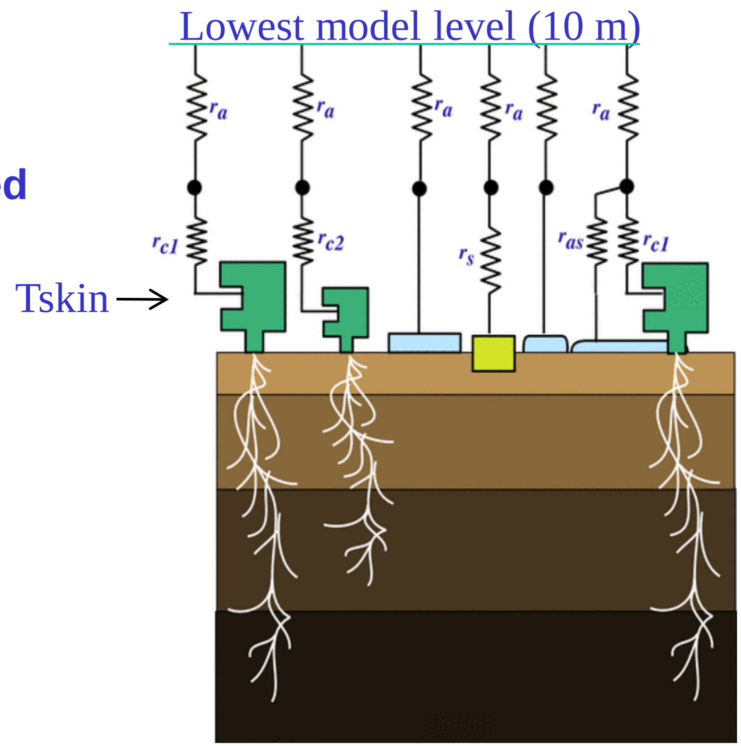
$$w'\theta' = -K_H \frac{d\theta}{dz}, \quad K_H = l^2 \left\{ \left| \frac{dU}{dz} \right| + S_m \right\} f_H(Ri)$$

$$l^{-1} = (\kappa z)^{-1} + \lambda^{-1}$$

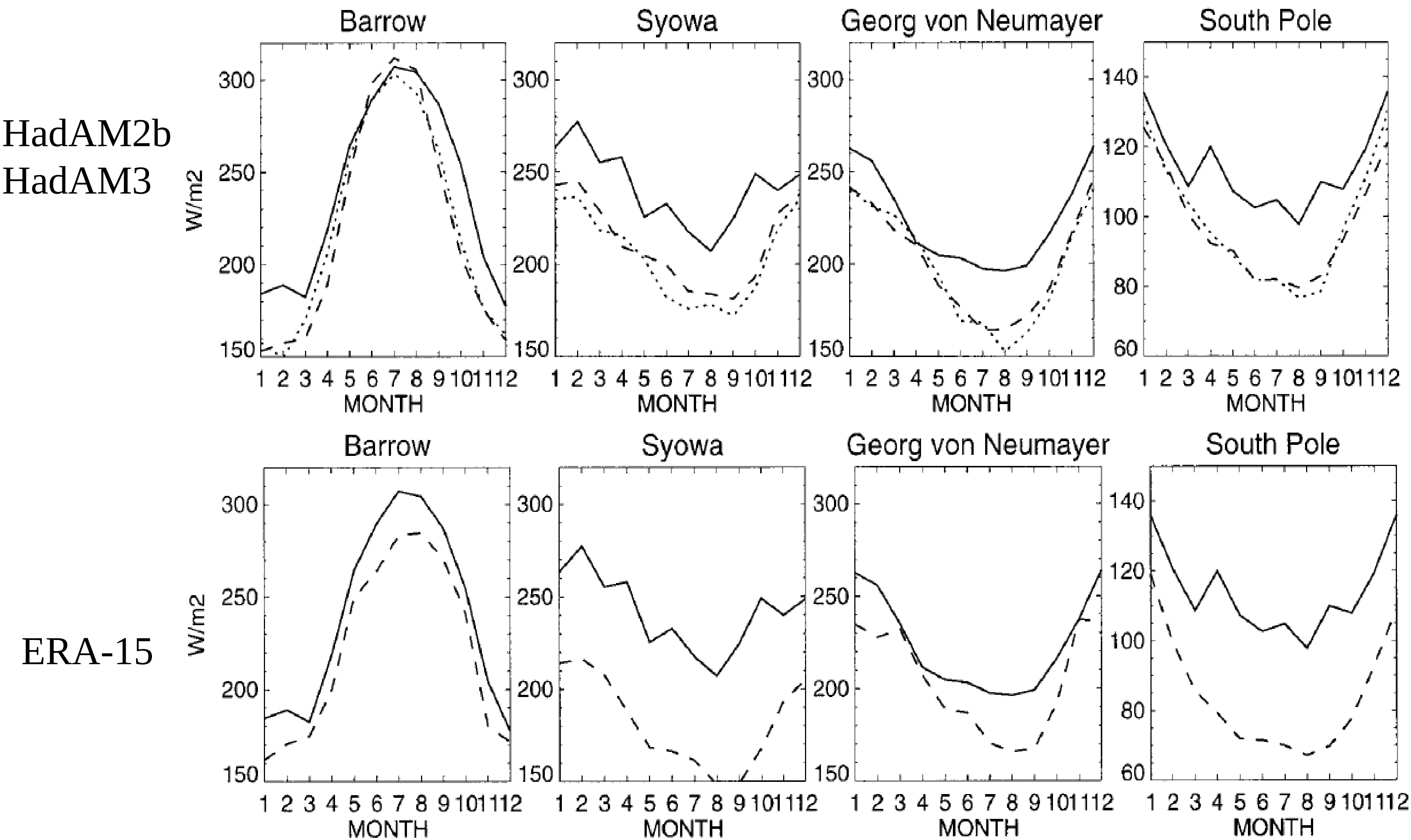
Coupling coefficients are hidden in a number of parametrizations

Coupling between skin level and deep soil is affected by all the details of the land surface scheme:

- **Soil thermal properties**
- **Presence of snow and snow properties**
- **Representation of land cover (skin or canopy to ground conductivity in ECMWF model)**
- **Soil water freezing and thawing**
- **Heterogeneity**

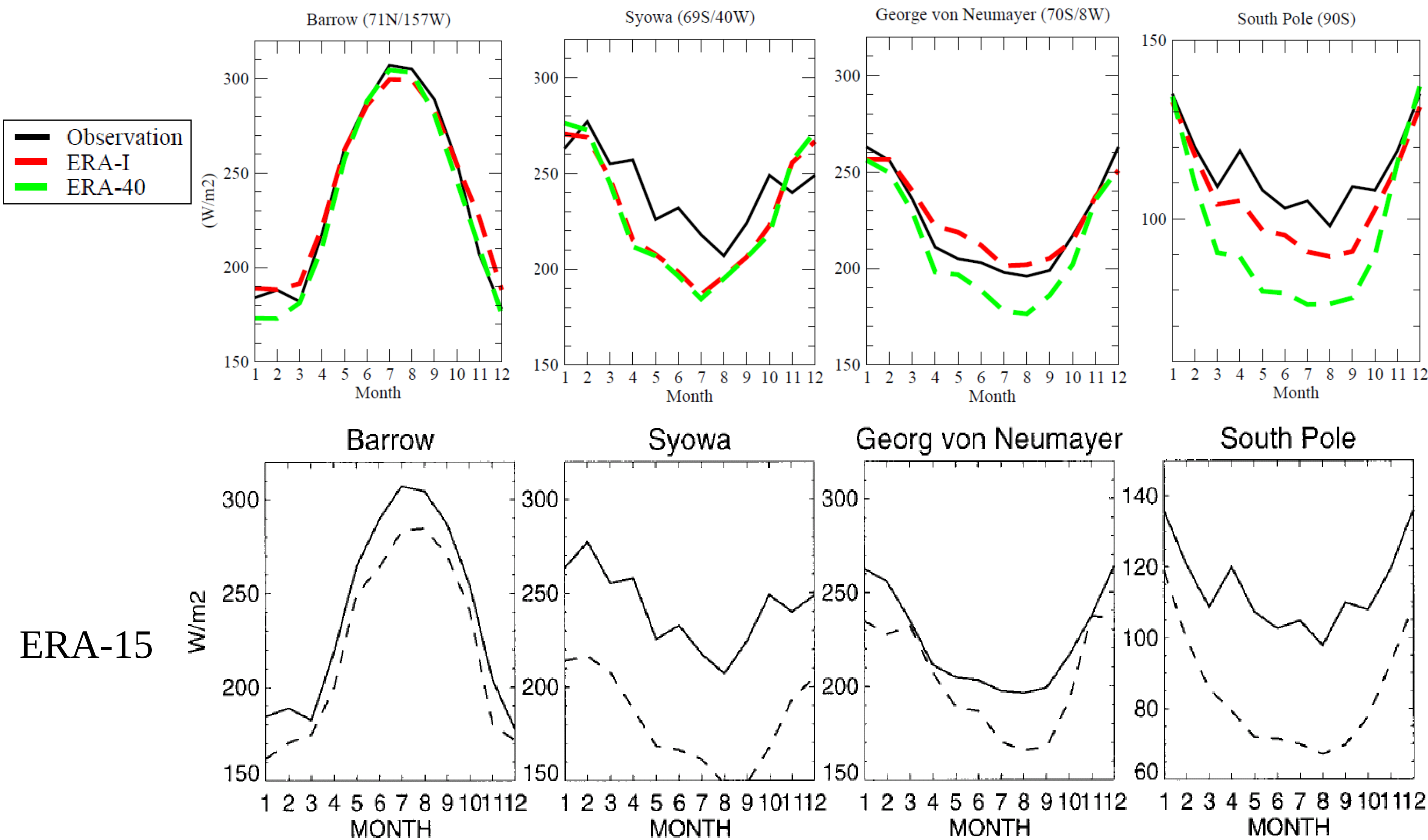


High latitude LW downward radiation: models (dash) compared to observations (solid)



Wild et al., 2001, J. Clim., 14, 3227

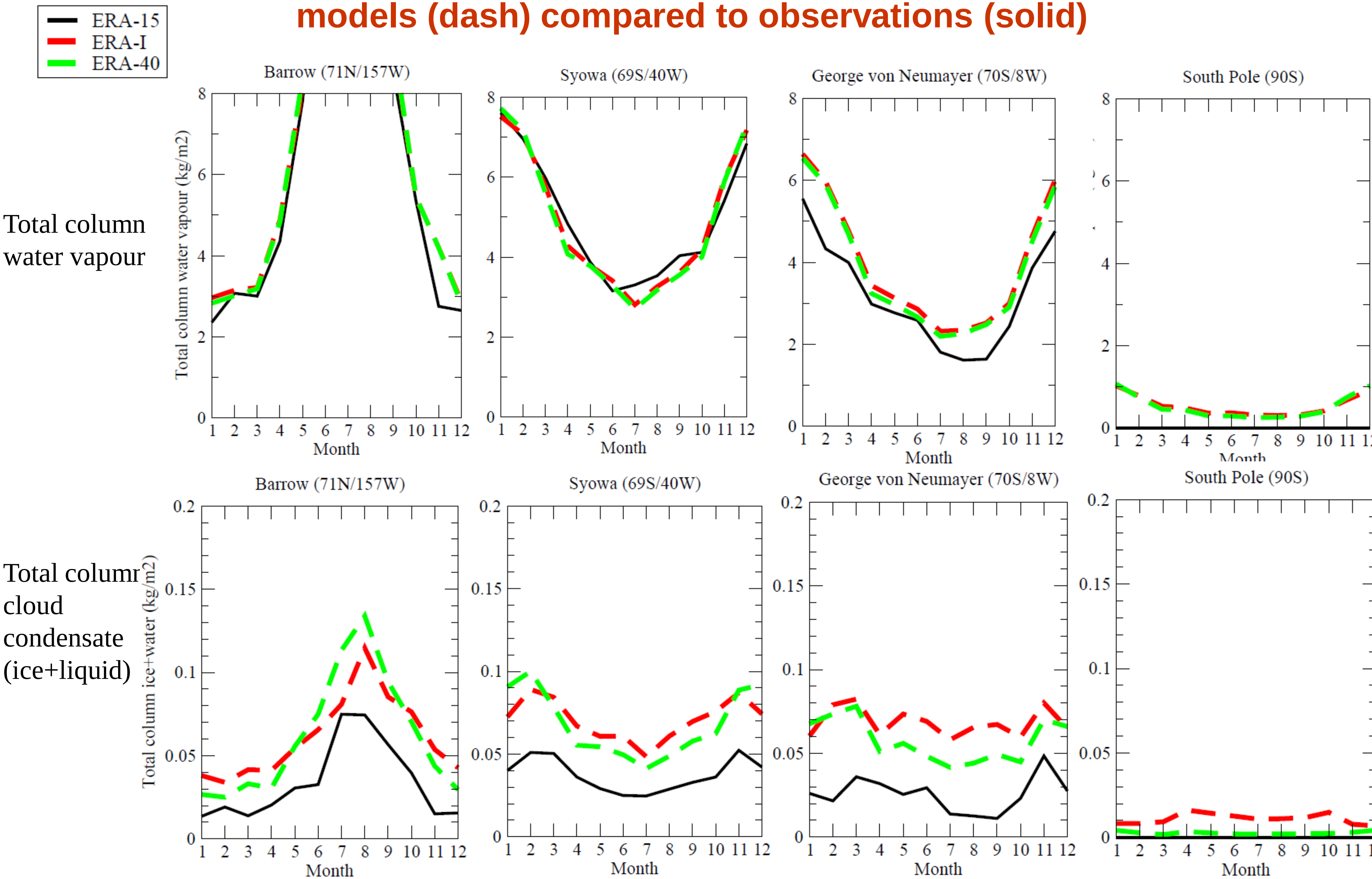
High latitude LW downward radiation: models (dash) compared to observations (solid)



Wild et al., 2001, J. Clim., 14, 3227

ECMWF

High latitude LW downward radiation: models (dash) compared to observations (solid)

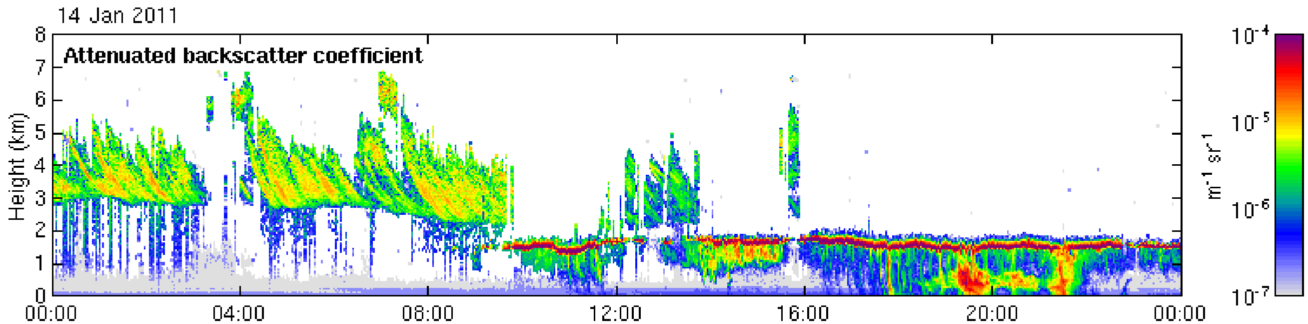


ECMWF

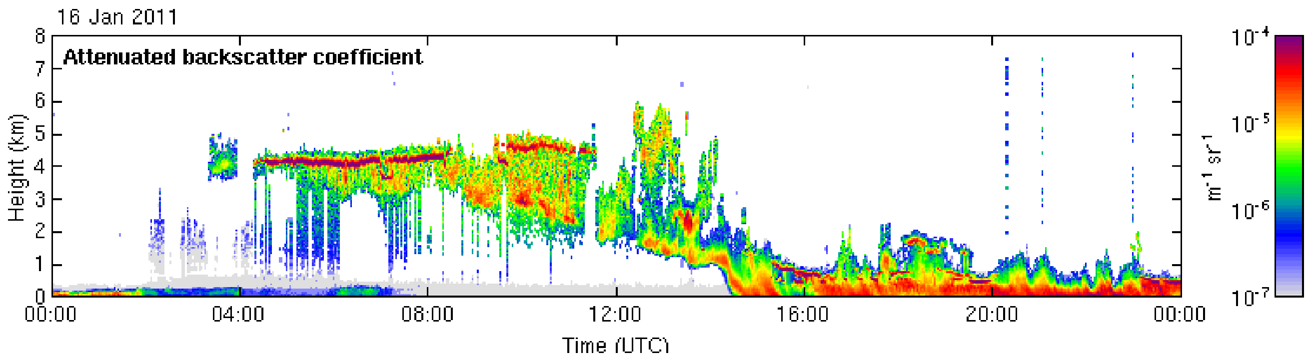
Observations of mixed-phase cloud

Sodankyla – Northern Finland (67N, 38E)

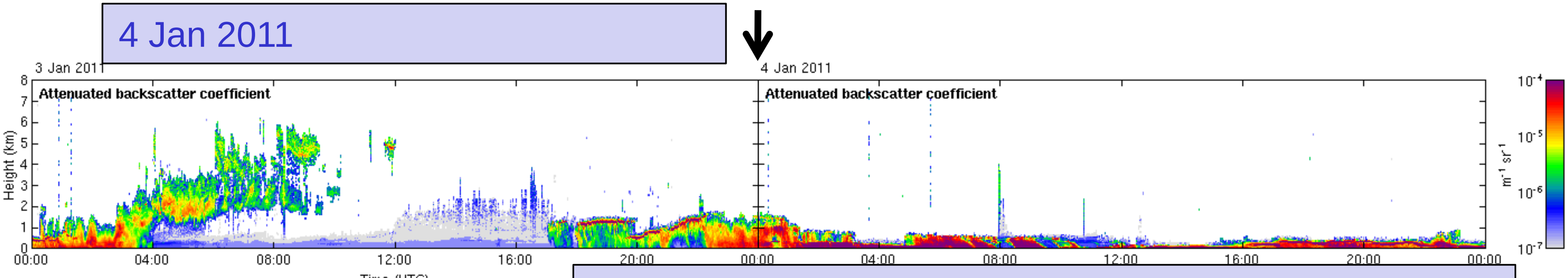
14 Jan 2011
Ice cloud and SLW layer at 2km, ice falling out



16 Jan 2011
SLW layer at 4km, ice falling out



4 Jan 2011

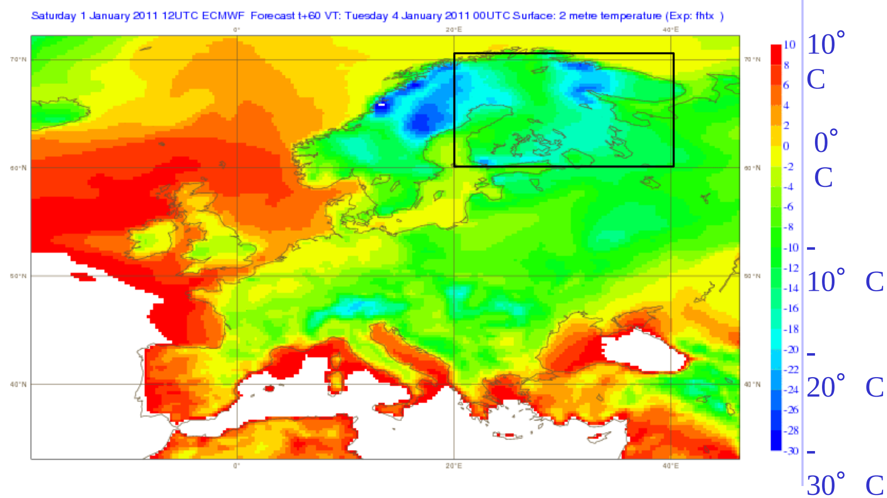


Low-level liquid/ice cloud (fog) observed

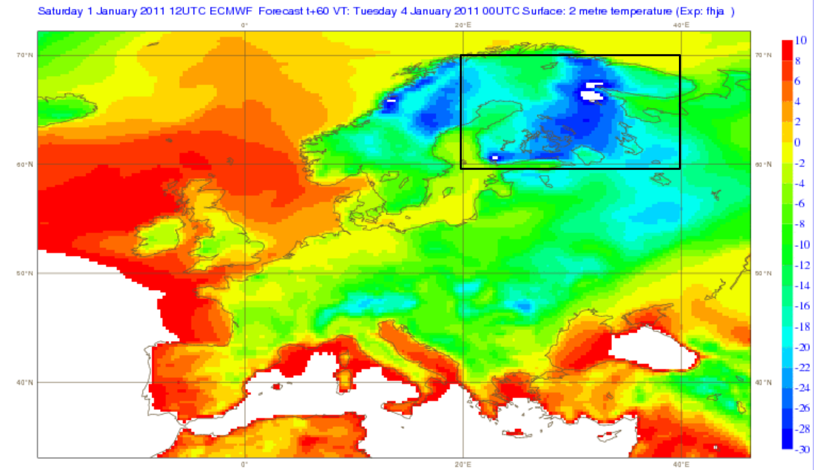
ECMWF

Cold T2m bias in weakly forced mixed-phase after Introduction of cloud scheme with separate variables for cloud ice and cloud water (to replace diagnostic relation between 0 and -23 C) . (Example T2m snapshot from 00Z 4th Jan 2011)

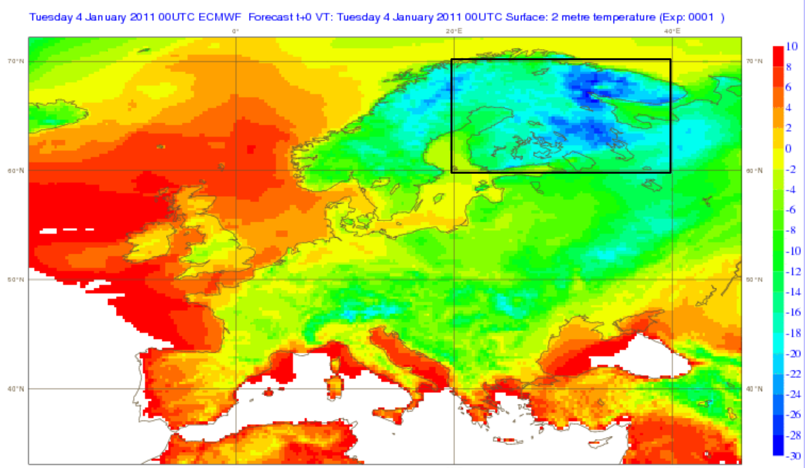
36r3 Diag mixed phase



37r1 Prog mixed phase

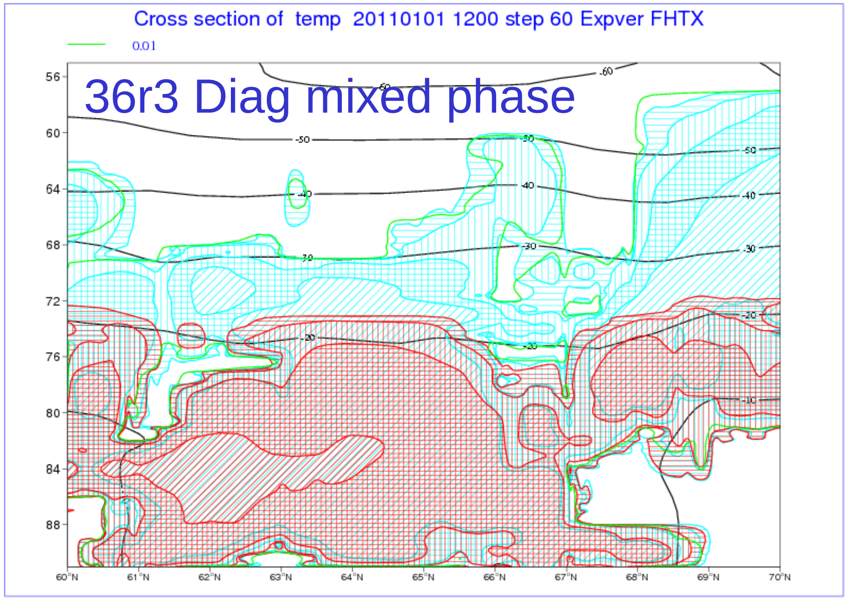


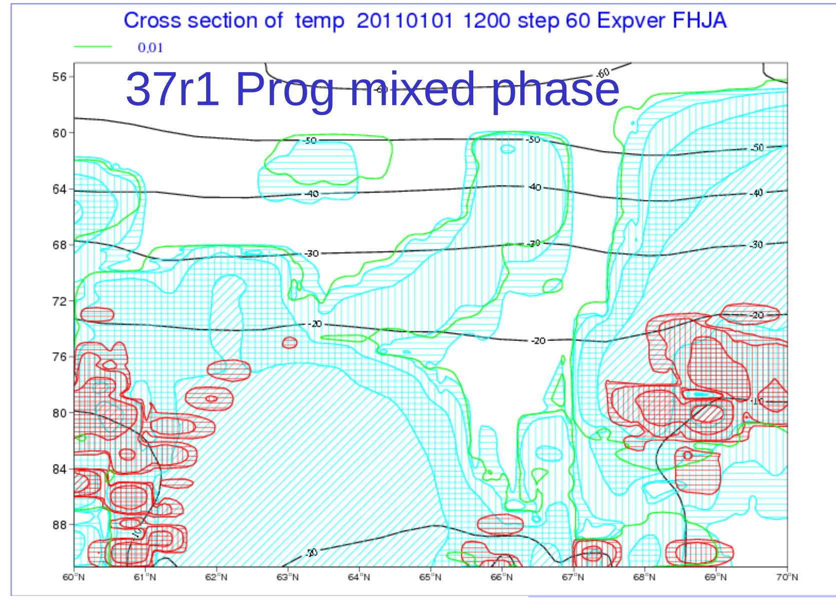
Analysis



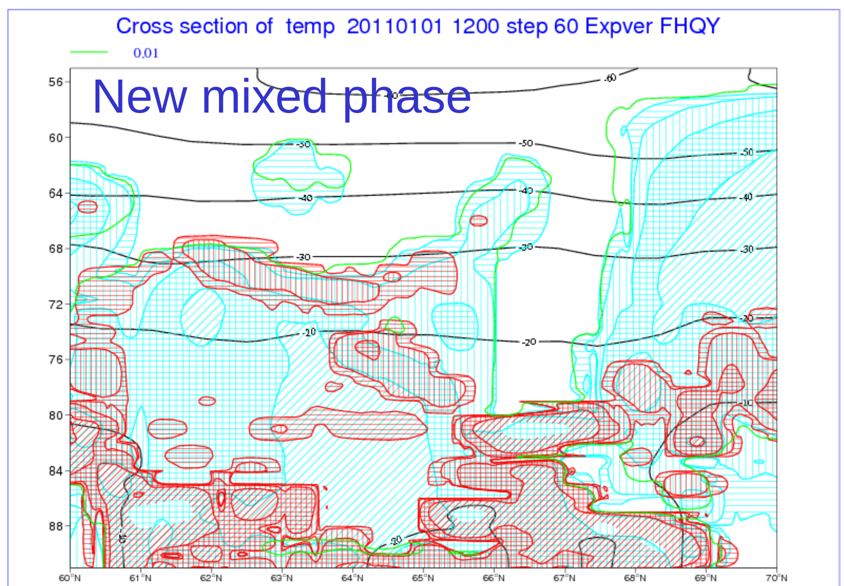
Cold 2mT bias and Total Column Liquid Water

(Example snapshot from 00Z 4th Jan 2011) - Finland





More super-cooled liquid water at cloud top (due to deposition change) and near the surface (due to supersaturation change)

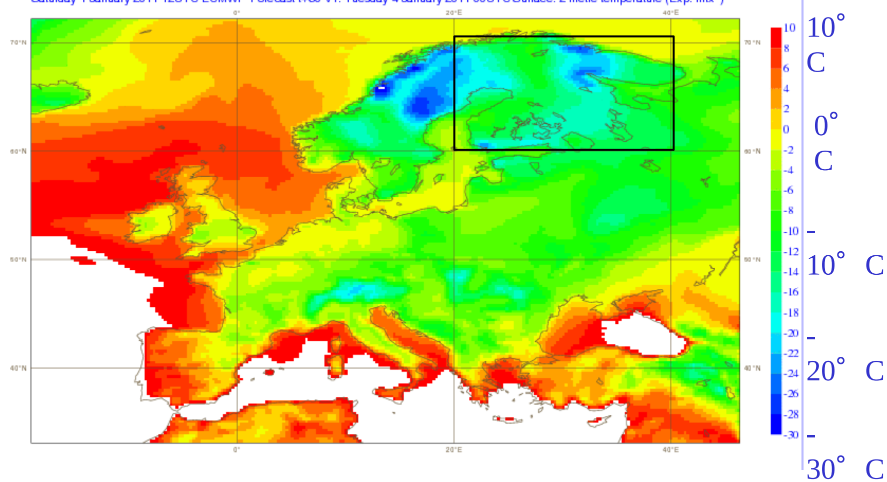


ECMWF

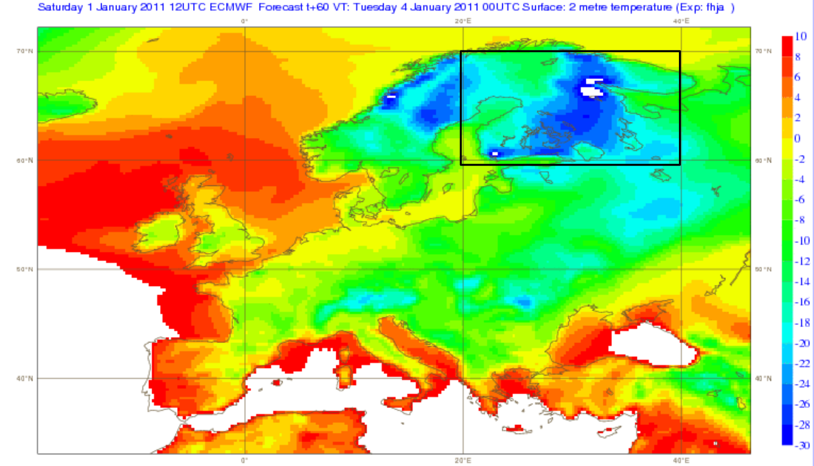
Cold T2m bias in weakly forced mixed-phase

(Example T2mT snapshot from 00Z 4th Jan 2011)

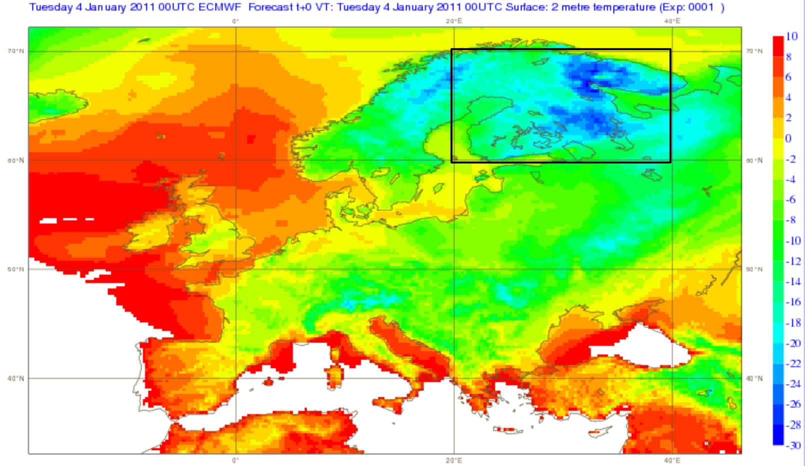
36r3 Diag mixed phase



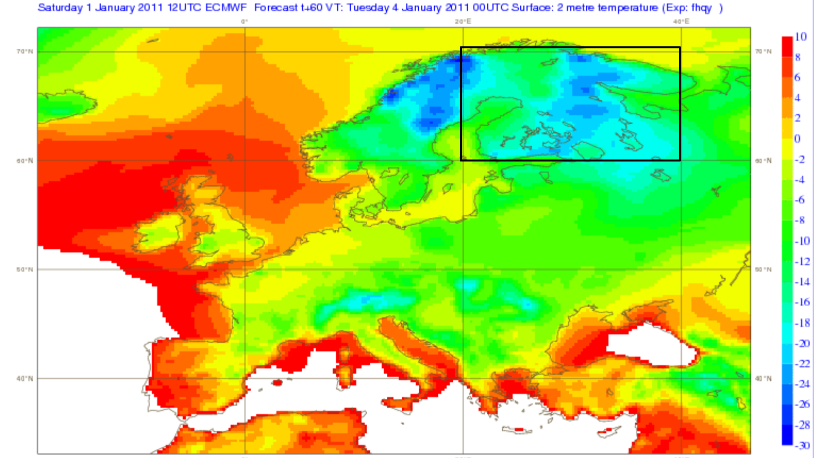
37r1 Prog mixed phase



Analysis



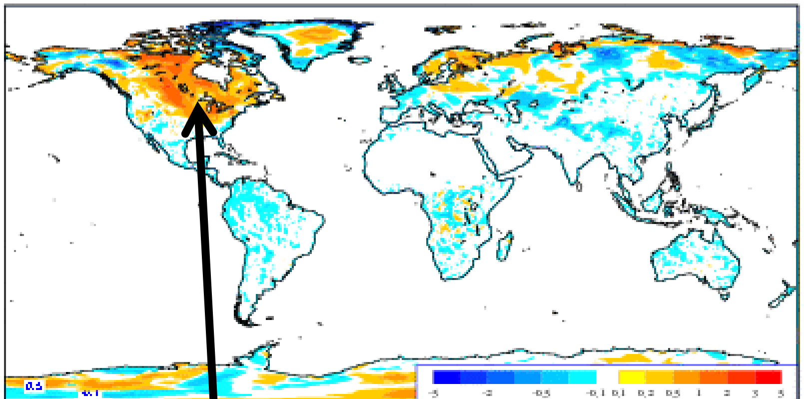
New mixed phase



T2m improvement – Feb 2010

Expt - Control

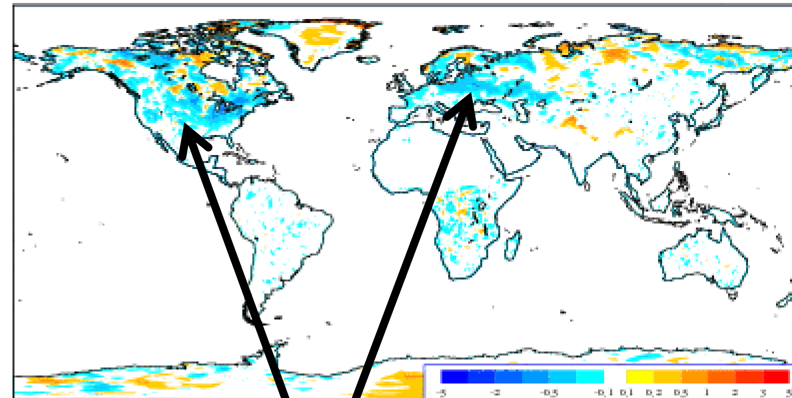
2T mean[CY37R1-new(fhr8)+60-AN(fezj)]-mean[CY36R4(fgio)+60-AN(fezj)]



Warming over Scandinavia and eastern North America, but also cooling elsewhere

Mean Absolute Error

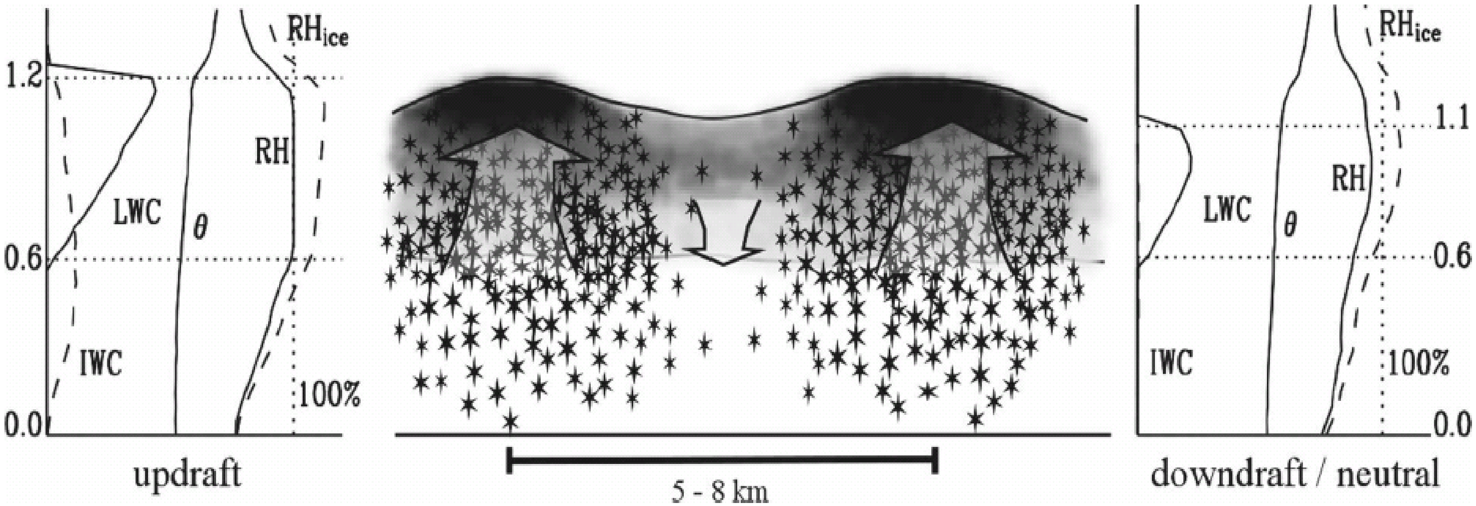
2T mean_abs[CY37R1-new(fhr8)+60-AN(fezj)]-mean_abs[CY36R4(fgio)+60-AN(fezj)]



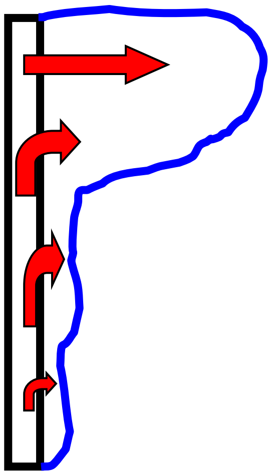
MAE largely reduced in Europe/N. America

What are the necessary ingredients in a cloud scheme to have supercooled liquid layers?

Conceptual picture by Shupe et al. (2008, JAS, 65, 1304)



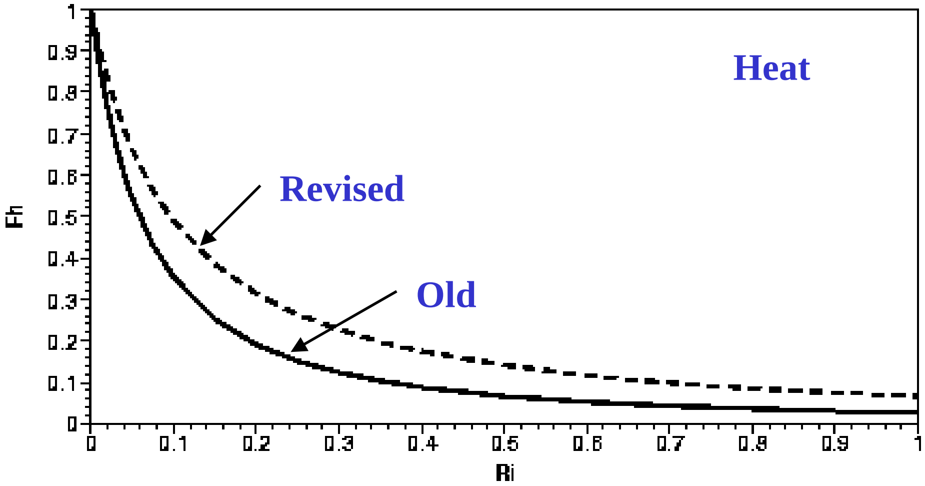
- Time scales related to updraught velocity, ice fall-out and vapour deposition control ratio of liquid/ice. Can PDF based cloud schemes do this ?

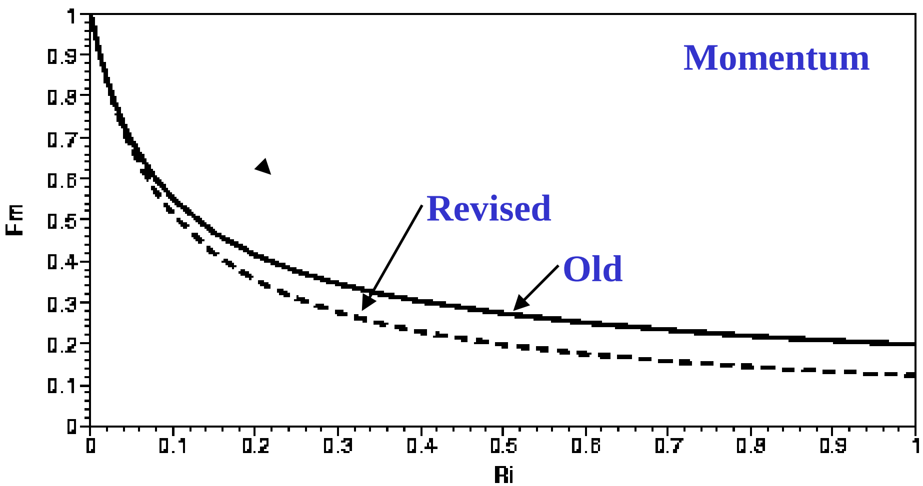


- The Tiedtke scheme in which shallow convection detrainment is coupled to cloud production has the potential but in the ECMWF system stratiform boundary layer clouds are produced by the BL scheme

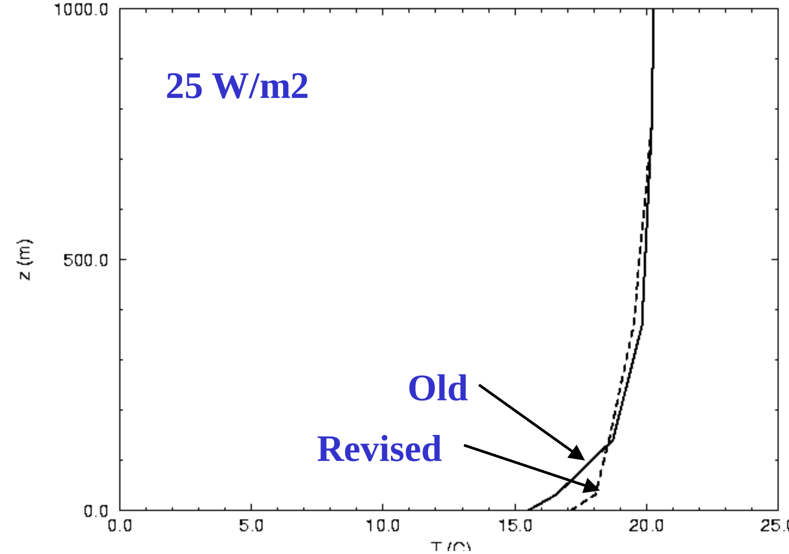
Increased diffusion of heat in stable situations

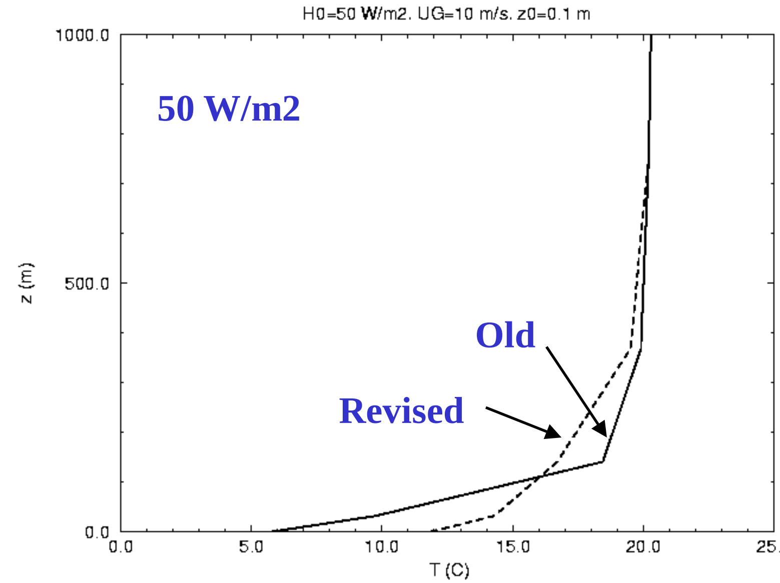
Stability (Richardson number) dependence of heat and momentum diffusion coefficients





T-profiles after cooling a neutral boundary layer profiles for 9 hours with 25/50 W/m2





ECMWF

Soil water freezing

Soil heat transfer equation during freezing

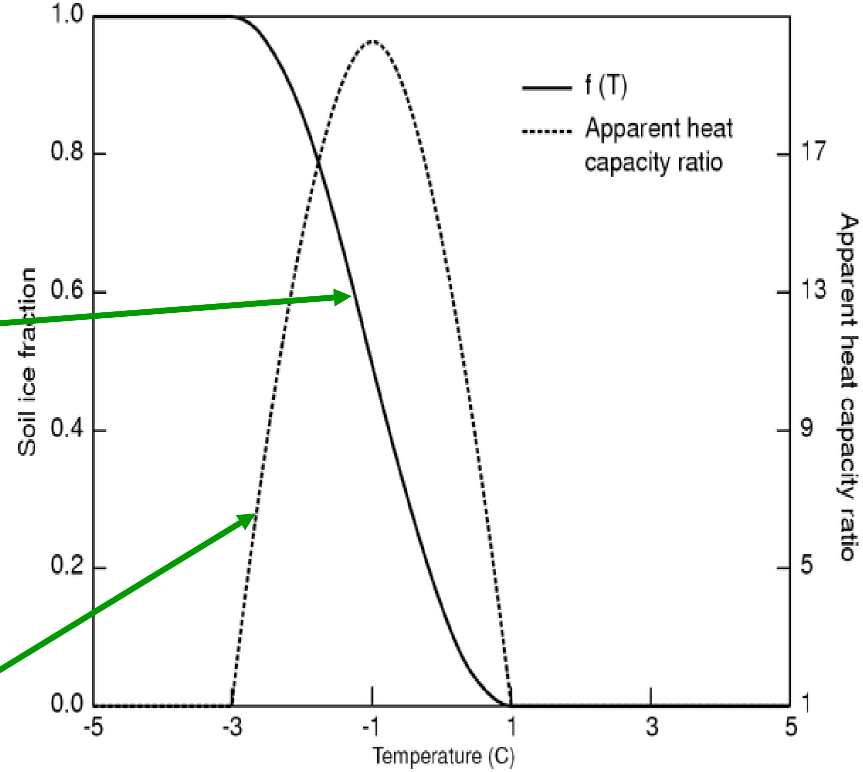
$$(\rho C)_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \lambda_T \frac{\partial T}{\partial z} + L_f \rho_w \frac{\partial \theta_I}{\partial t}$$

θ_I Soil frozen water

$$\theta_I = \theta_I(T) = f(T)\theta$$

$$\left[(\rho C)_s - L_f \rho_w \theta \frac{\partial f}{\partial T} \right] = \frac{\partial}{\partial z} \lambda_T \frac{\partial T}{\partial z}$$

Apparent heat capacity

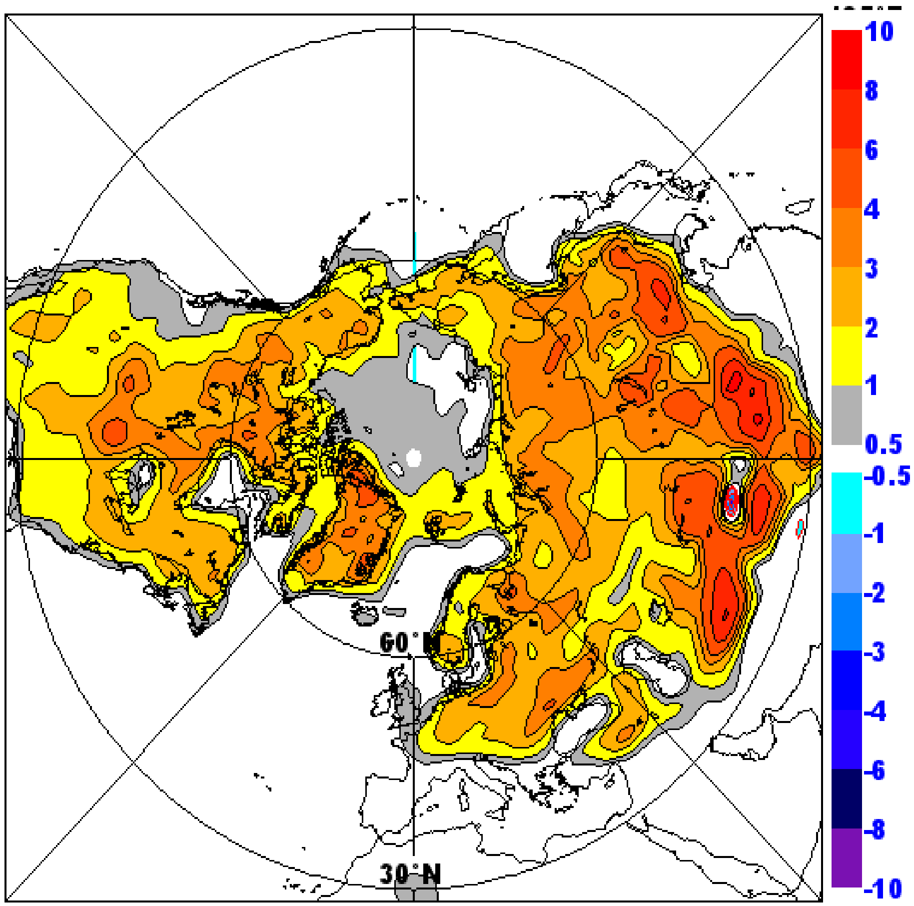


Difference in 2m temperature for January 1996

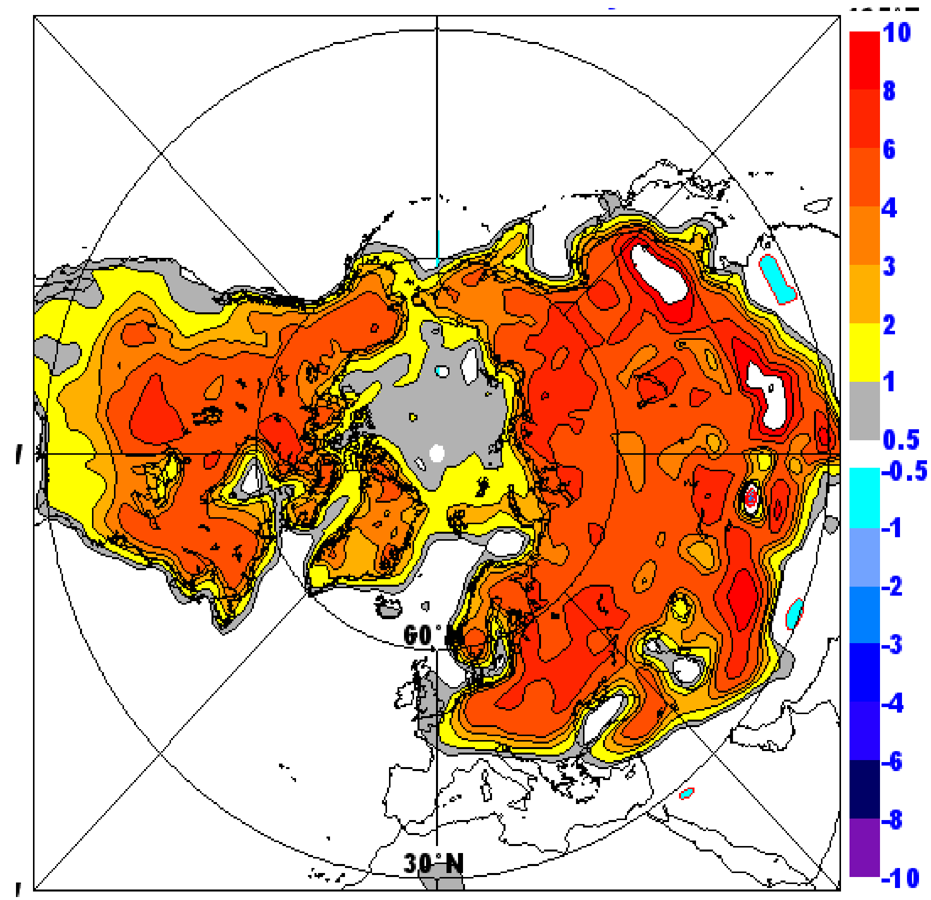
From long "relaxation" integrations starting 1 Oct 1995

1994 model version

Revised BL - Control



Revised BL & soil freezing - Control

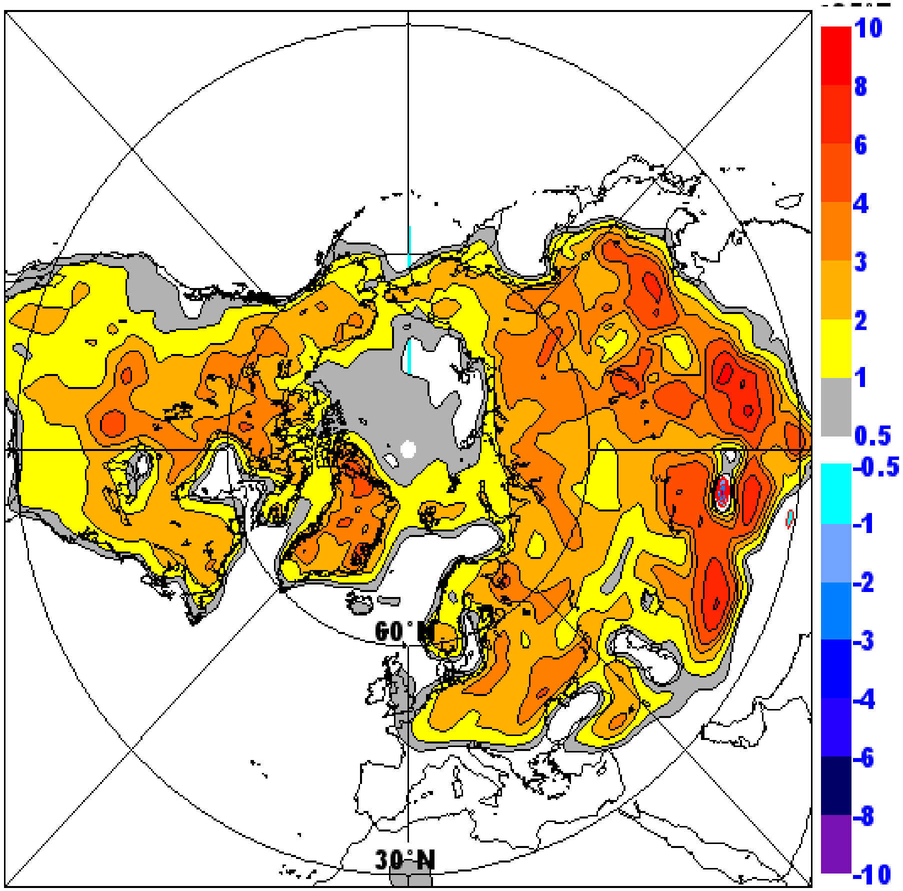


ECMWF

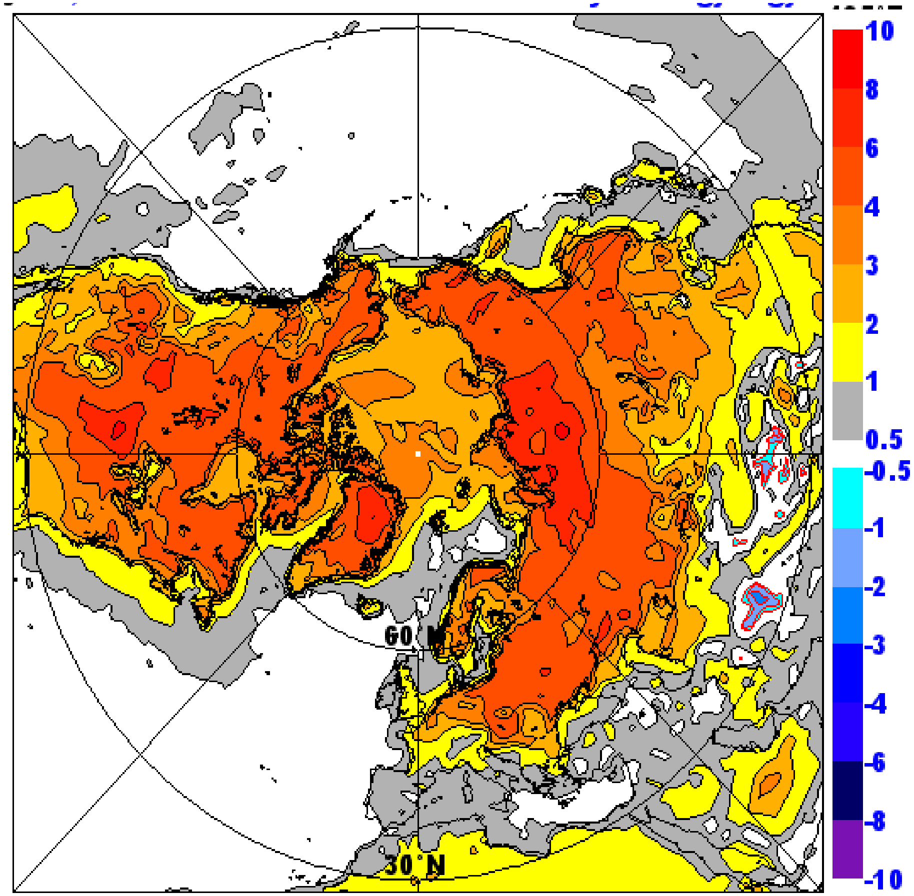
Difference in 2m temperature for January 1996

From long "relaxation" integrations starting 1 Oct 1995

Effect of revised LTG in 1994 model version



Effect of revised LTG in 2011 model version

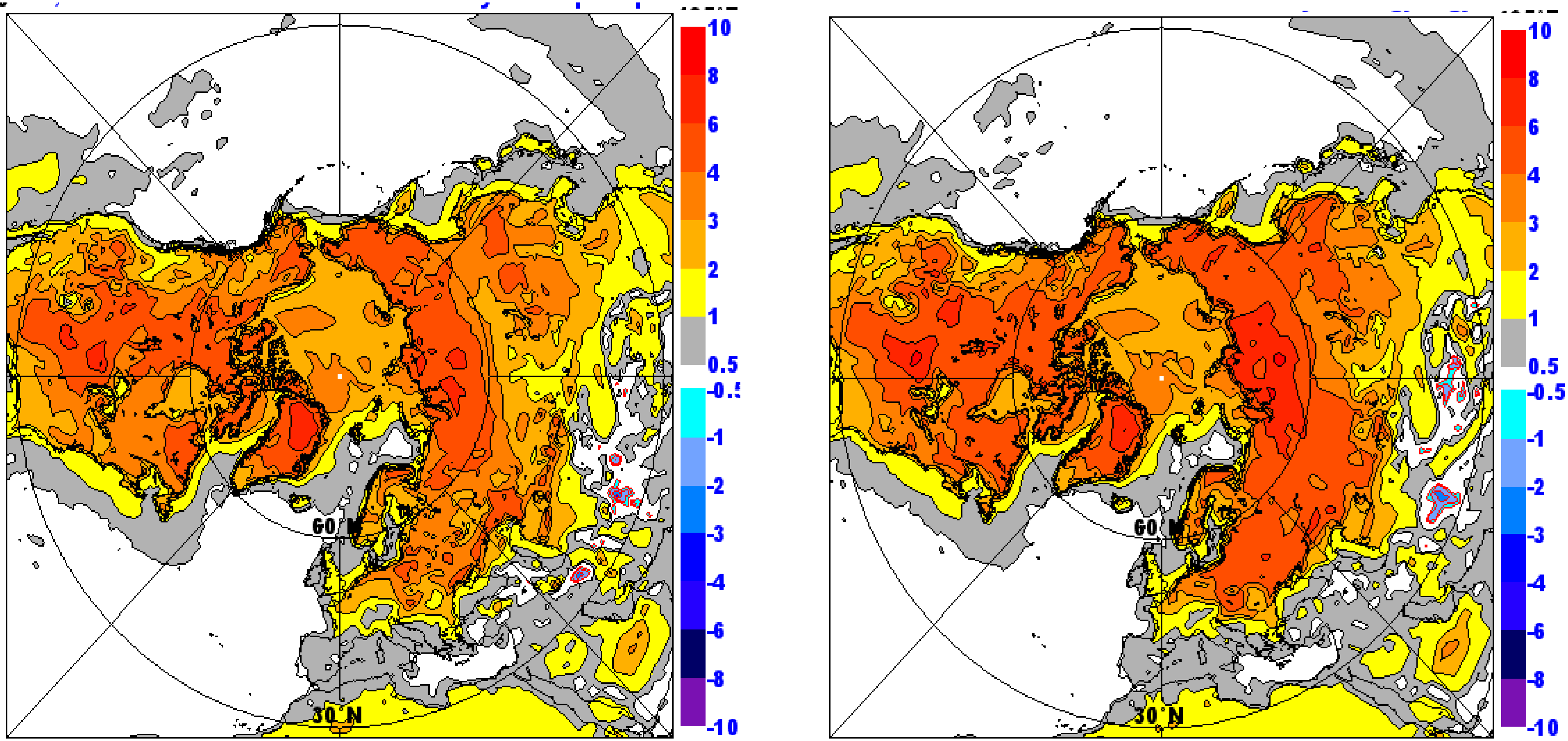


Difference in 2m temperature for January 1996

From long “relaxation” integrations starting 1 Oct 1995

Effect of revised LTG in 2011 model but old snow

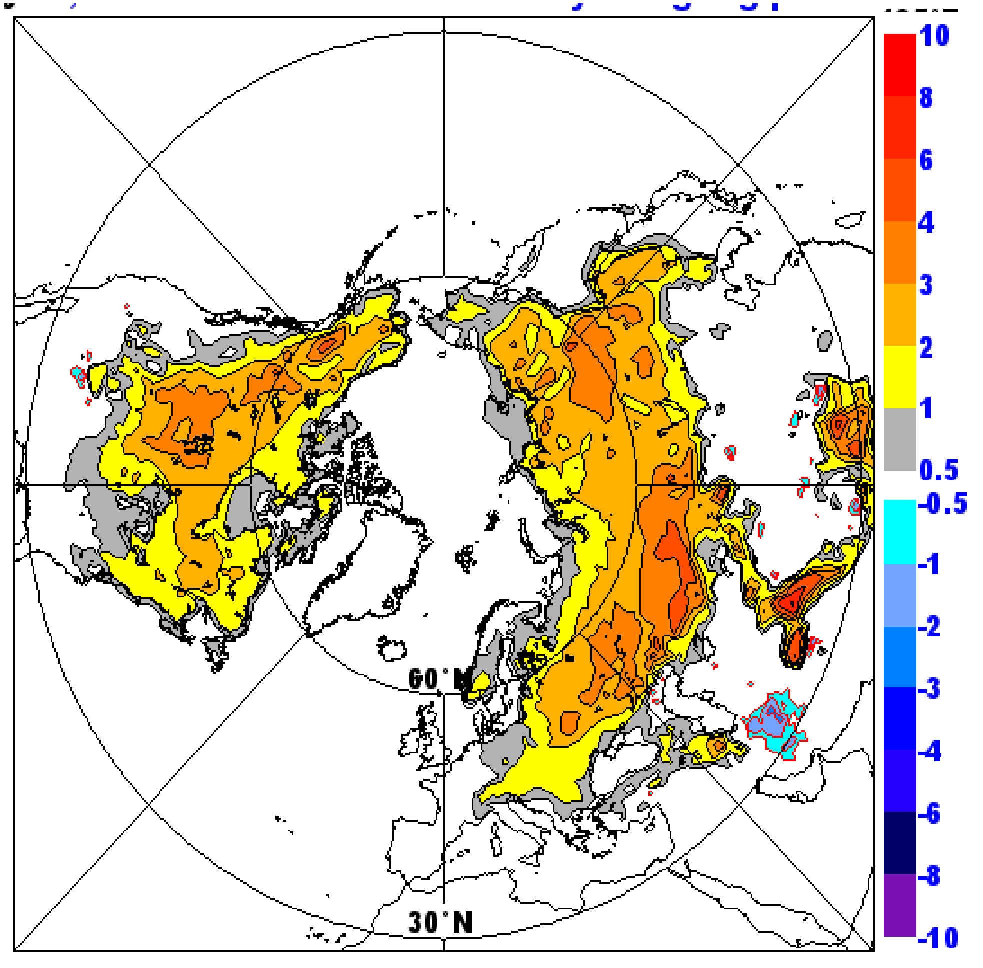
Effect of revised LTG in 2011 model version



Difference in 2m temperature for January 1996

From long “relaxation” integrations starting 1 Oct 1995

old snow scheme – new snow scheme



The new snow scheme (Dutra et al. 2010) has lower conductivity and therefore the winter temperature drops more over snow.

Insulating snow also increases the model sensitivity to boundary layer diffusion.

Summary

- Strong sensitivities have been demonstrated
- Reasonable results for temperature are obtained by optimization
- Errors are still substantial with large-scale geographical patterns in 2m temperature bias
- Given the large uncertainty in a many coupling parameters, it is likely that compensating errors exist
- How to progress?

Way forward:

- Consider atmosphere and land as a coupled problem and analyze relations between variables to demonstrate realism of the full system
- Use tracers as an additional constraint on the problem of atmospheric diffusion

Data from the Boreal Ecosystem Research and Monitoring Sites (BERMS)

Thanks to the Fluxnet-Canada Research Network (A. Barr, T. A. Black, J. H. McCaughey)

Three different sites less than 100 km apart in Saskatchewan at the southern edge of the Canadian boreal forest (at about 54°N/105°W) :

Old Aspen (deciduous, open canopoy, hazel understory, 1/3 of evaporation from understory)

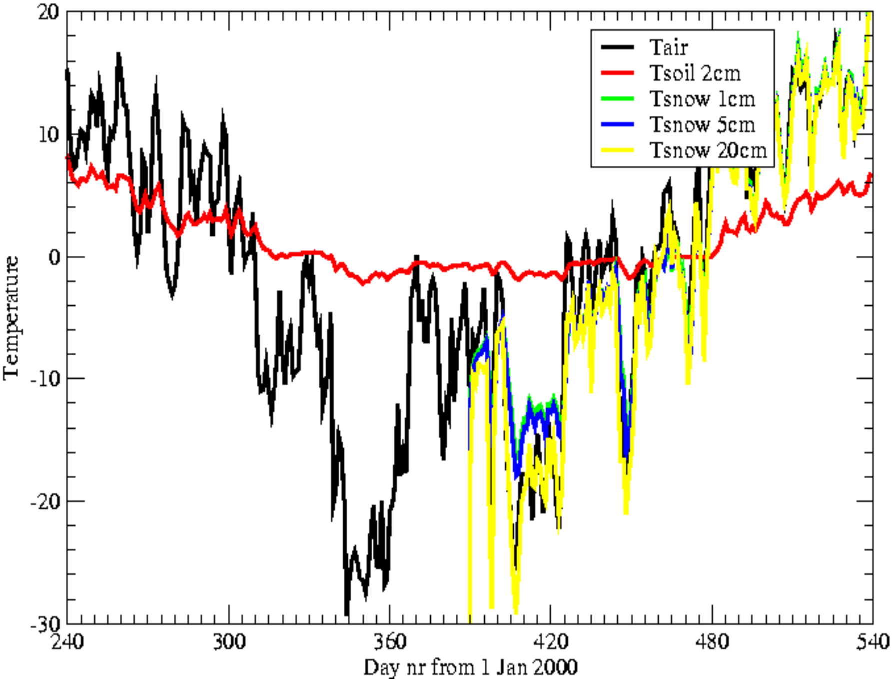
Old Black Spruce (boggy, moss understory)

Old Jack Pine (sandy soil)

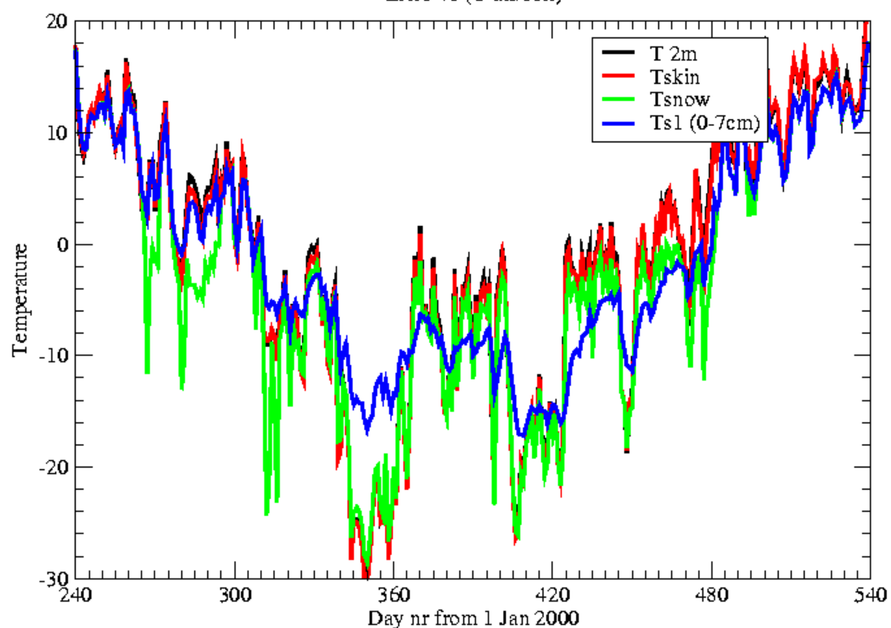
TABLE 1. Mean values of Northern Hemisphere 5-yr (2000–04) broadband surface albedo (in presence of snow) aggregated by high vegetation type (adapted from Moody et al. 2007).

Vegetation type	Albedo
Evergreen needleleaf trees	0.27
Deciduous needleleaf trees	0.33
Deciduous broadleaf trees	0.31
Evergreen broadleaf trees	0.38
Mixed forest–woodland	0.29
Interrupted forest	0.29

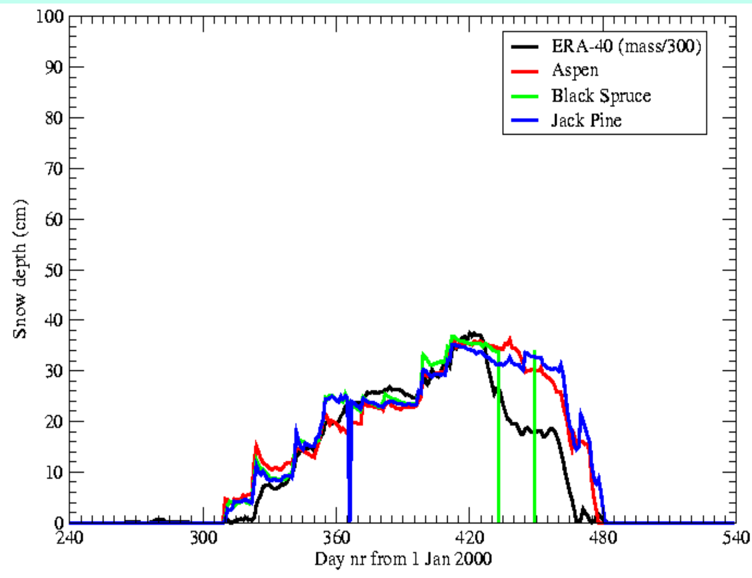
BOREAS observations



ERA-40 (T-air/soil)



- Air temperature and snow temperatures are well connected in observations
- Weak response of soil temperature to air/snow temperature
- Is the undergrowth providing an insulation layer between snow and soil?
- ERA-40 model has too strong coupling with the soil



Regression on daily summer data from the ECMWF model [non-tropical basins: 10700 days]

Betts (2006): JGR, 111, D07105

Diurnal temp range

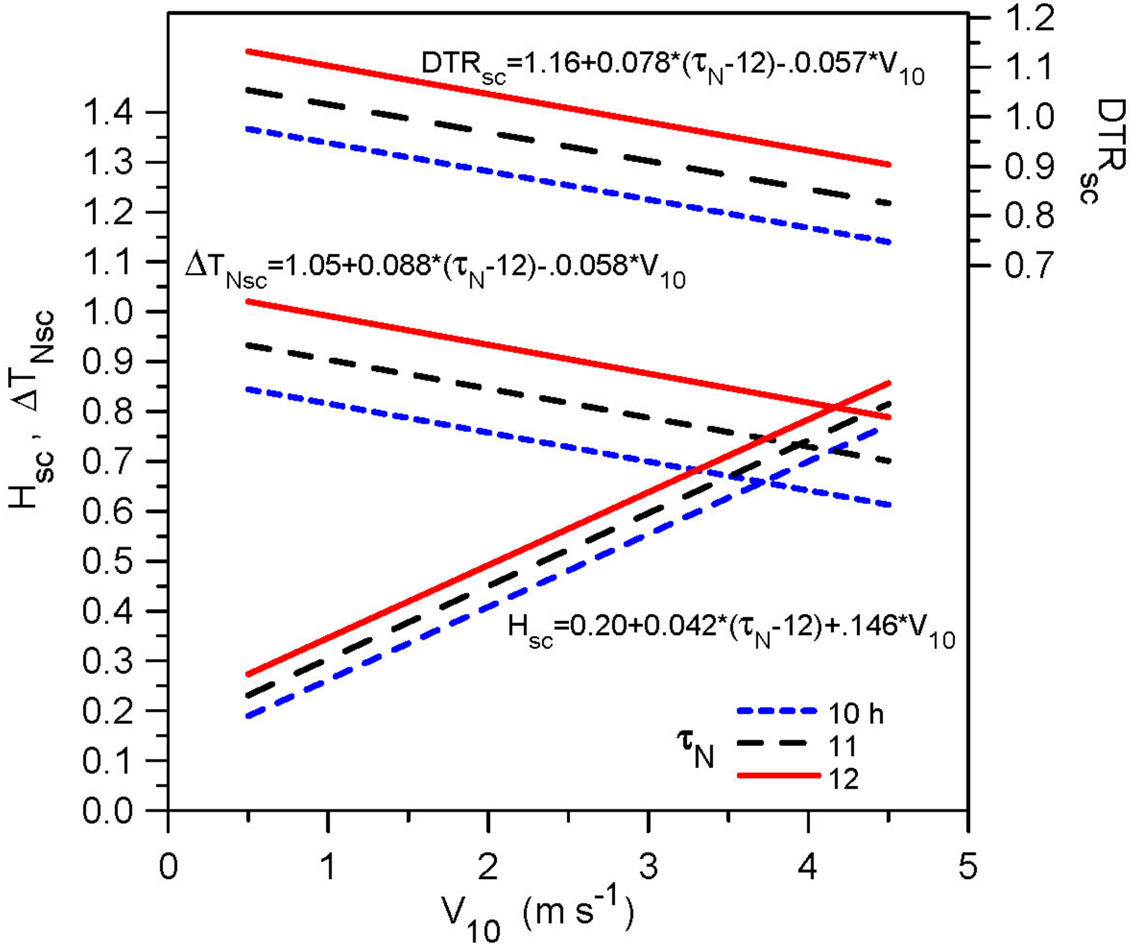
$DTR_{sc} = DTR/\Delta T_R$

Strength of NBL

$\Delta T_{Nsc} = \Delta T_N/\Delta T_R$

Scaled heat flux

$H_{sc} = H_N/(-LW_{netN})$



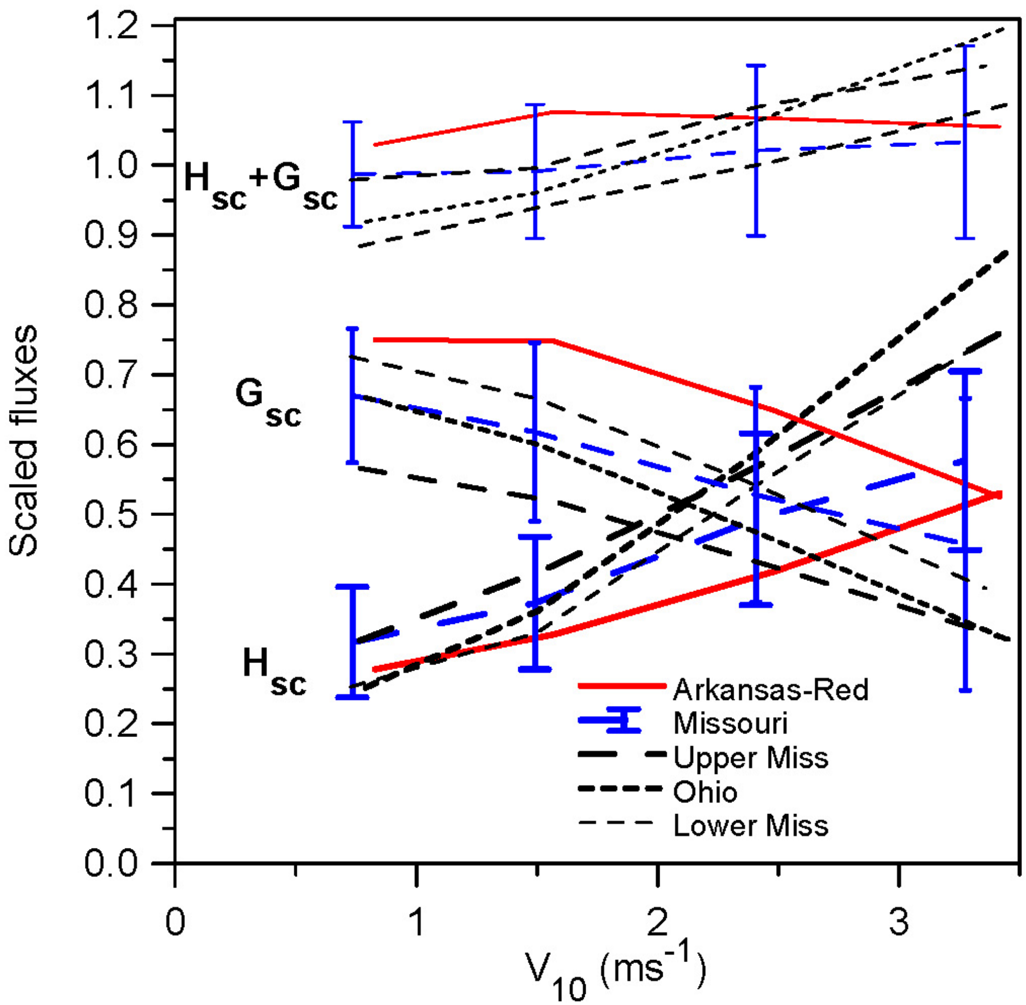
ECMWF

Dependence of scaled energy budget on wind speed

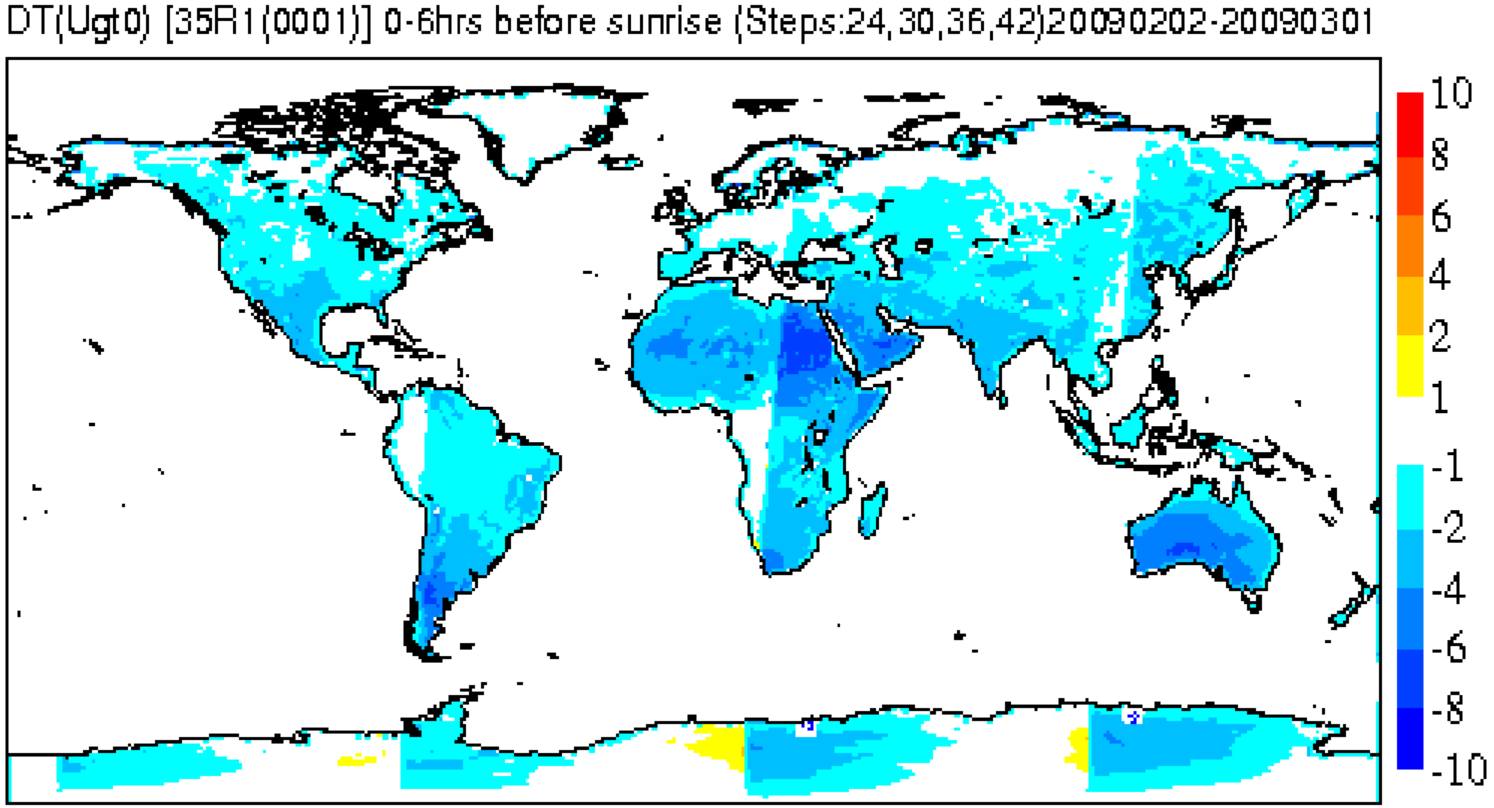
For NBL:

$H_{sc} + G_{sc} \approx 1$

Partitioning changes with wind speed, but basins show different slope



Temperature drop over 6 hours before minimum temperature (2m). For every longitude the synoptic time has been selected (0, 6, 12 or 18 UTC) that is closest to the minimum temperature.



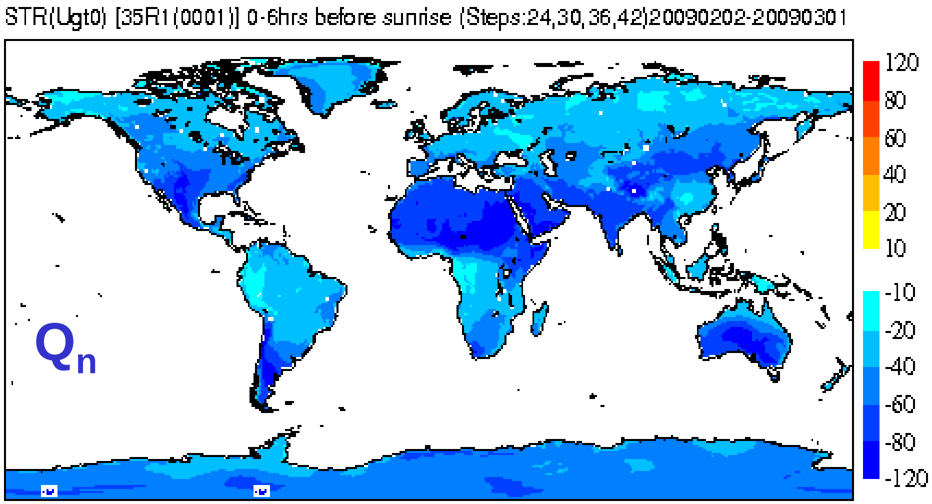
Data has been averaged over a month of daily 24,30,36 and 48-hour forecasts (Operations, Feb 2009)

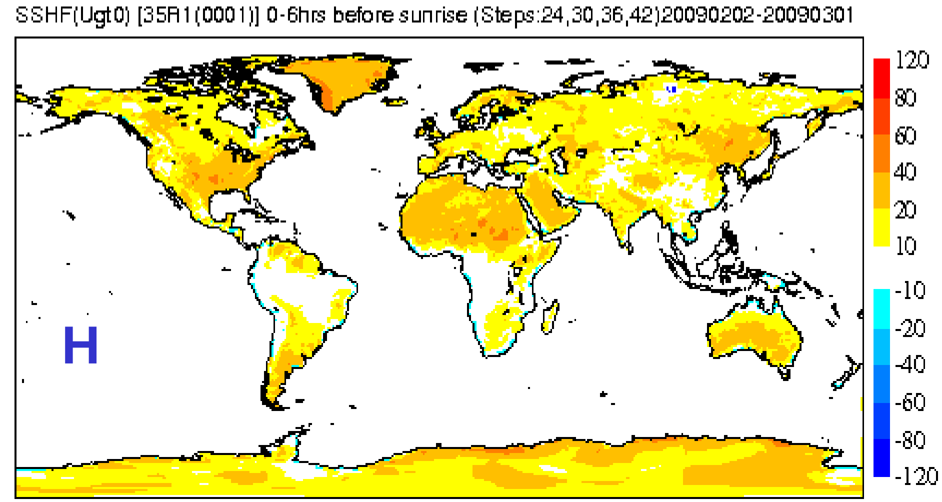
ECMWF

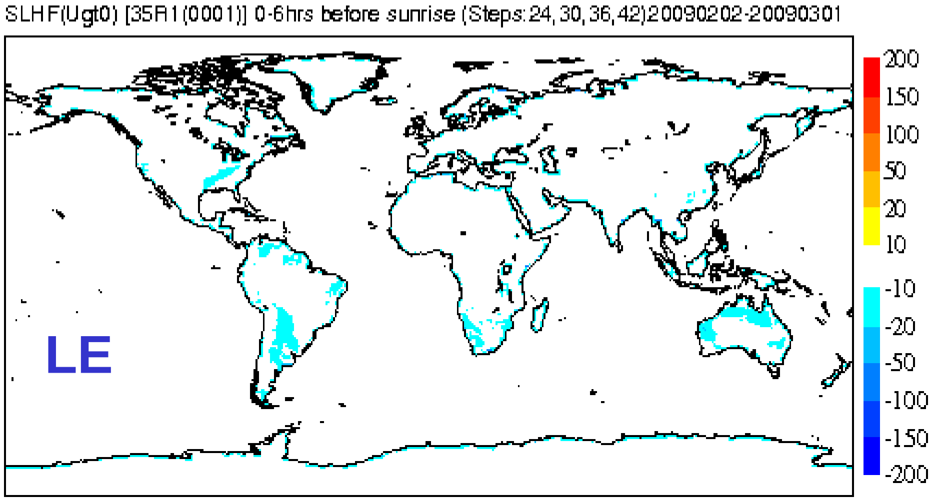
Energy budget over 6 hours before the "minimum temperature" (Feb 2009)

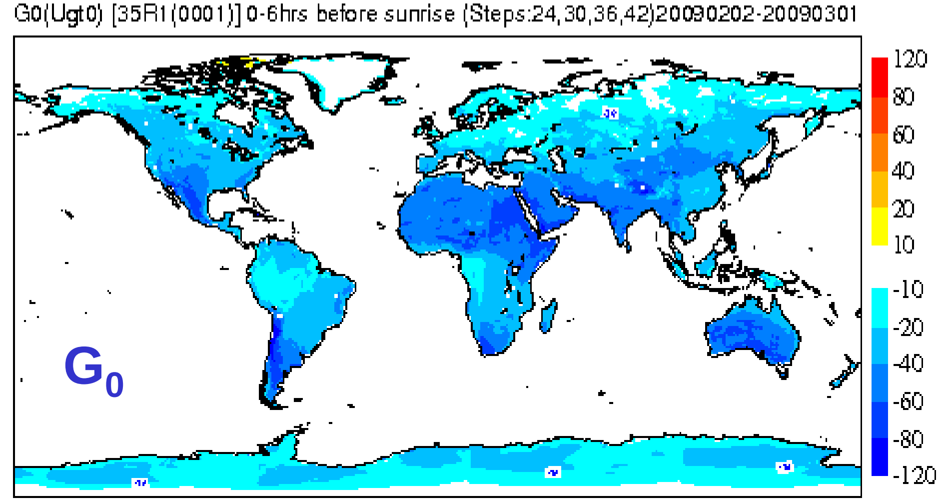
$$Q_n + LE + H = G_0$$

(W/m^2, sign convention: downward is positive)



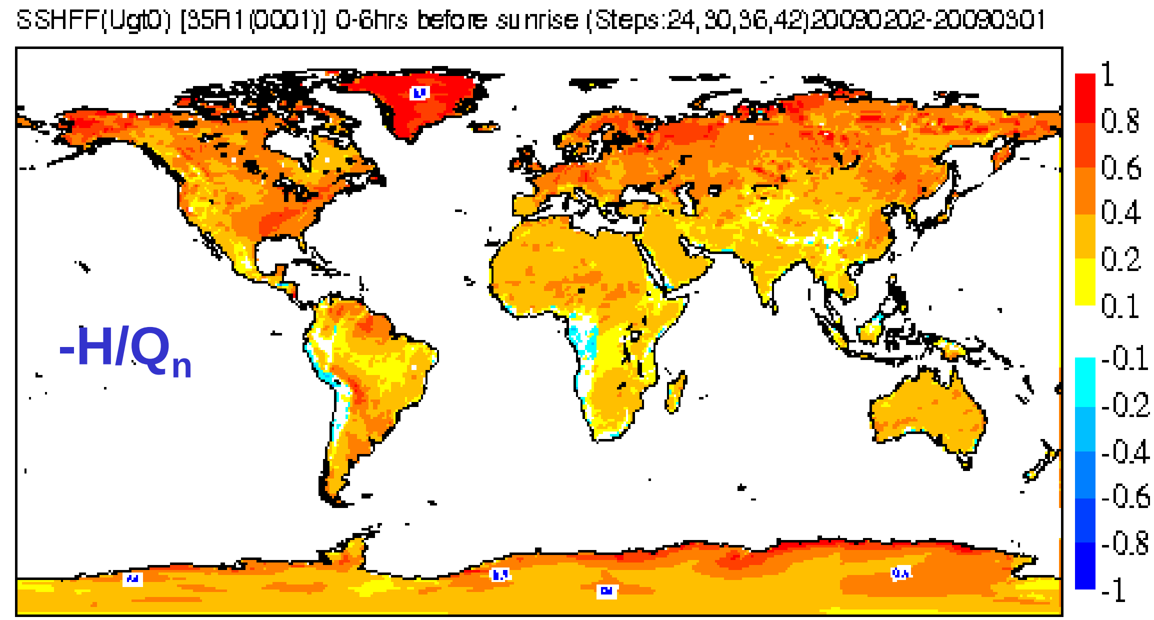


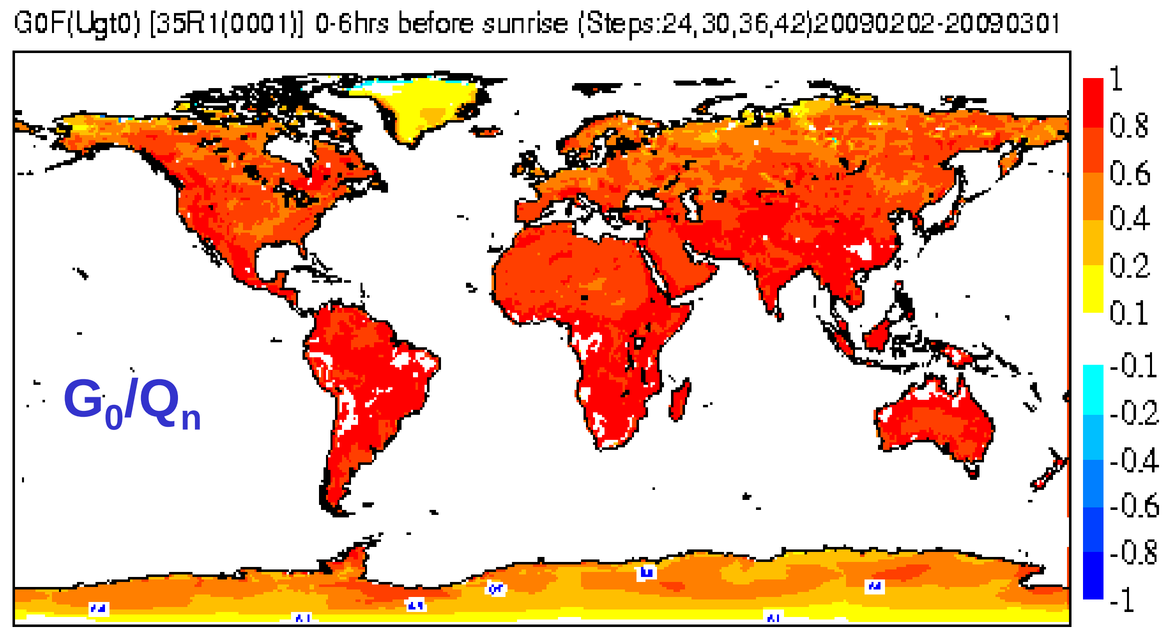




Energy budget over 6 hours before the “minimum temperature” (Feb 2009)

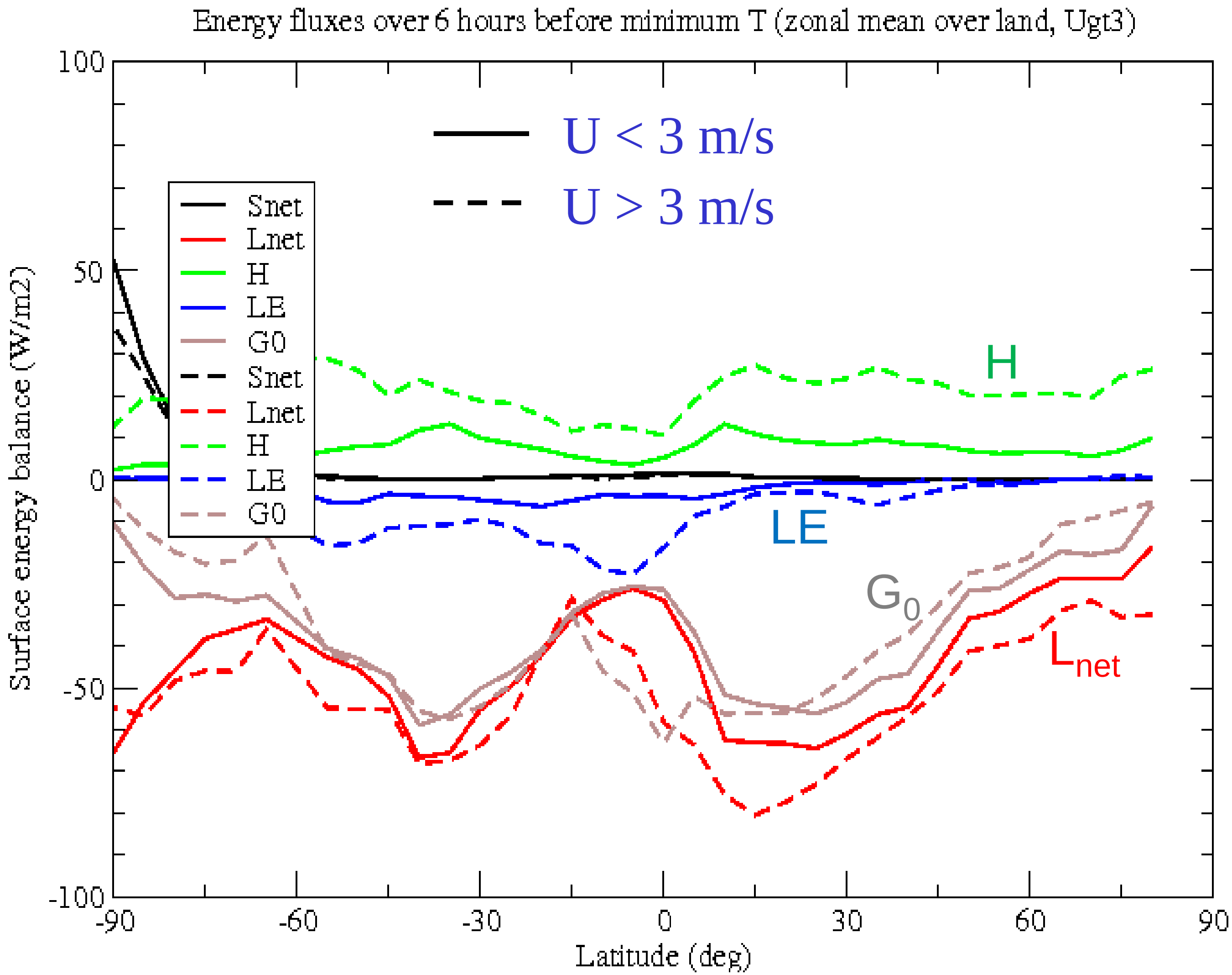
$1 + H/Q_n = G_0 /Q_n$





Energy budget over 6 hours before "minimum temperature" (Feb 2009, land only)

$Q_n + LE + H = G_0$



ECMWF

Conclusions

- To develop models that simulate realistic projections it is required to represent the current climate with the correct mechanisms
- To verify it is necessary to compare with observations at the process level
- Clouds and their phase are crucial for the radiation
- The ratio of sub-surface / atmospheric energy fluxes requires careful evaluation
- NWP environment has advantages for model development because the comparison with observations is simpler than in climate mode

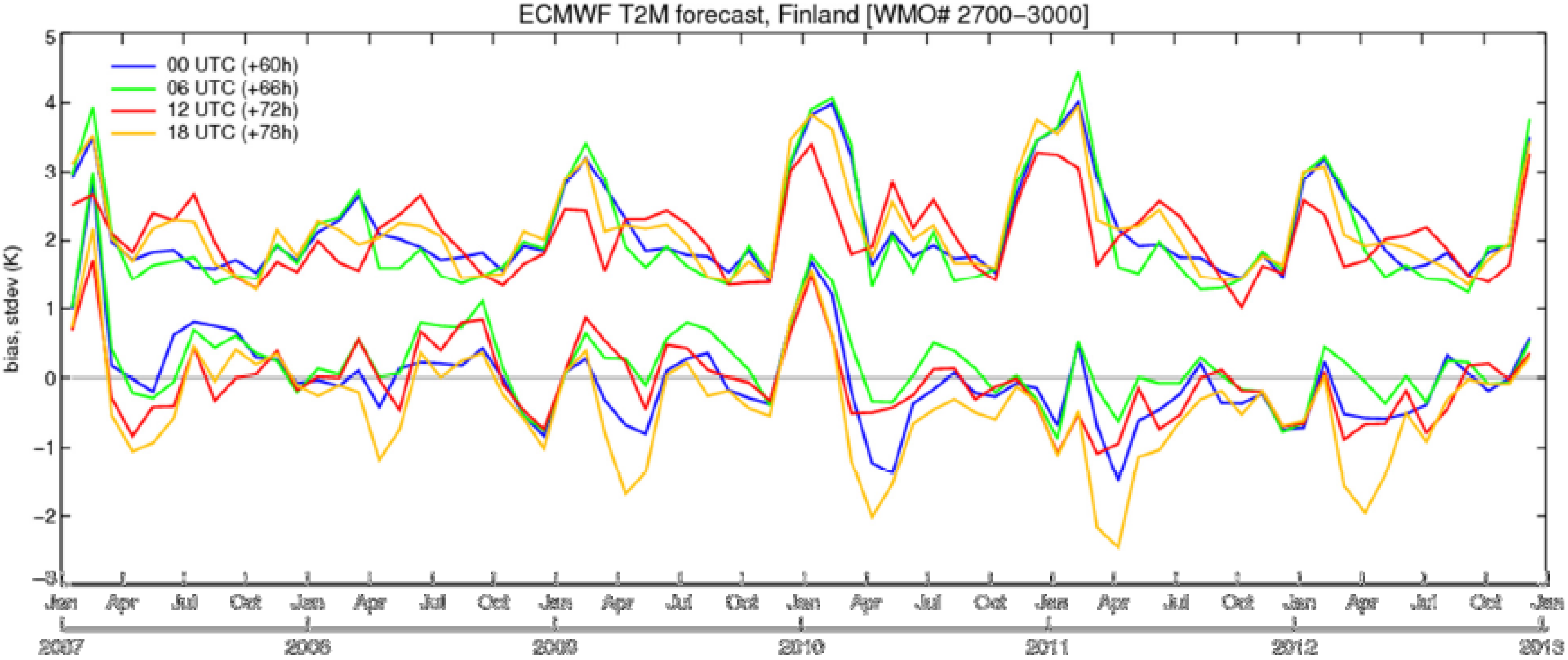
- Priority areas for research and further model development are:
    - Mixed phase clouds (models do not necessarily have a physically realistic representation)
    - Cloud / radiation interaction
    - Boundary layer / Land surface + snow interaction (including heterogeneous terrain)
    - The ECMWF snow model needs more layers to represent different time scales

All these research activities need support from observations,

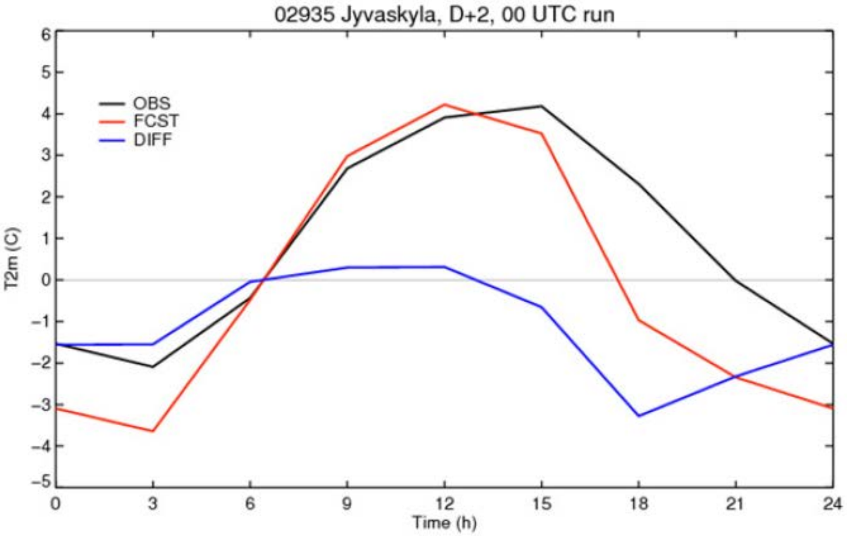
but,
We also need modellers to build the increased knowledge into models.
The Workshop on "The Physics of Weather and Climate Models" (March 2012, Pasadena) concluded that the development of weather and climate models was lagging behind on observations and process science!

Thank you

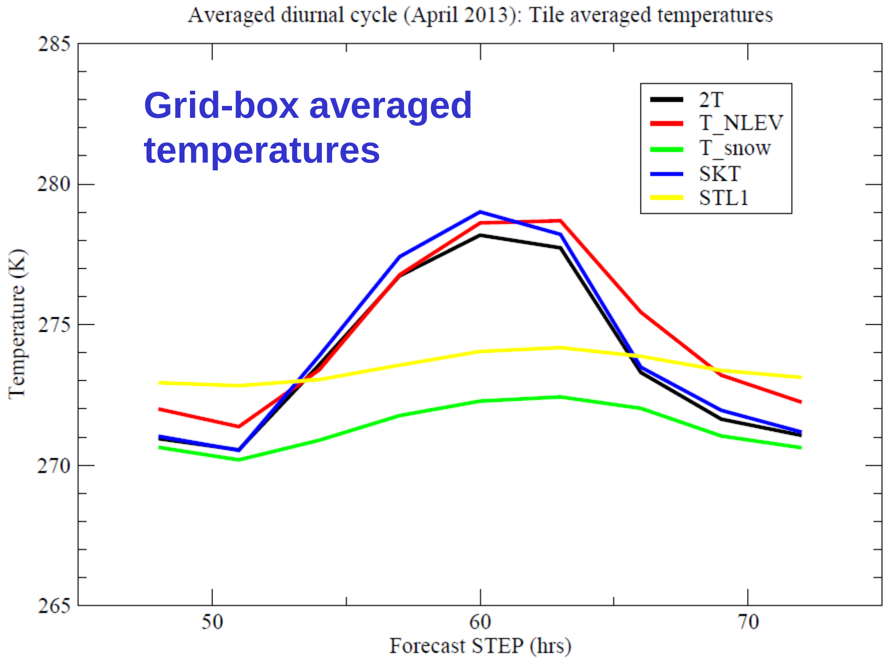
Spring temperature biases over Scandinavia

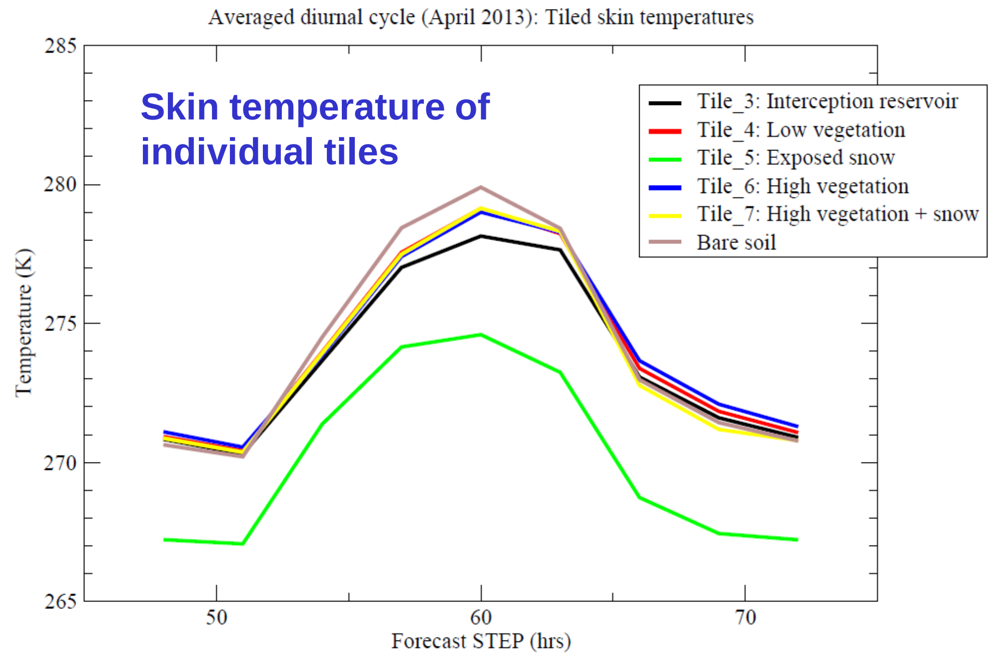


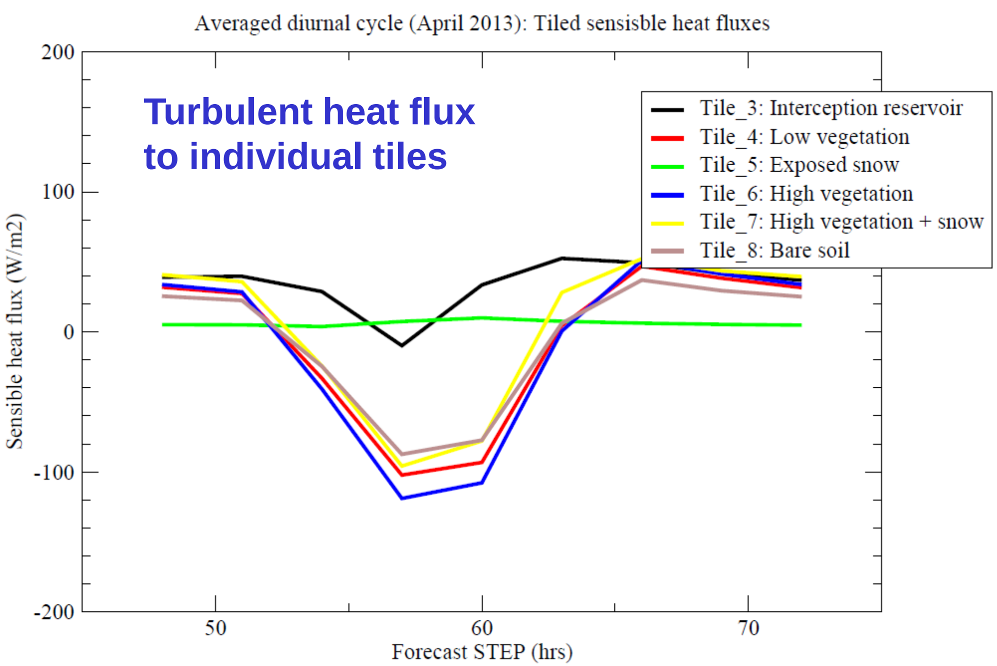
Scandinavian countries show a spring time cold bias mainly at 18 UTC related to snow melt in forested areas. The bias has a distinct diurnal cycle.



Figures: Thomas Haiden

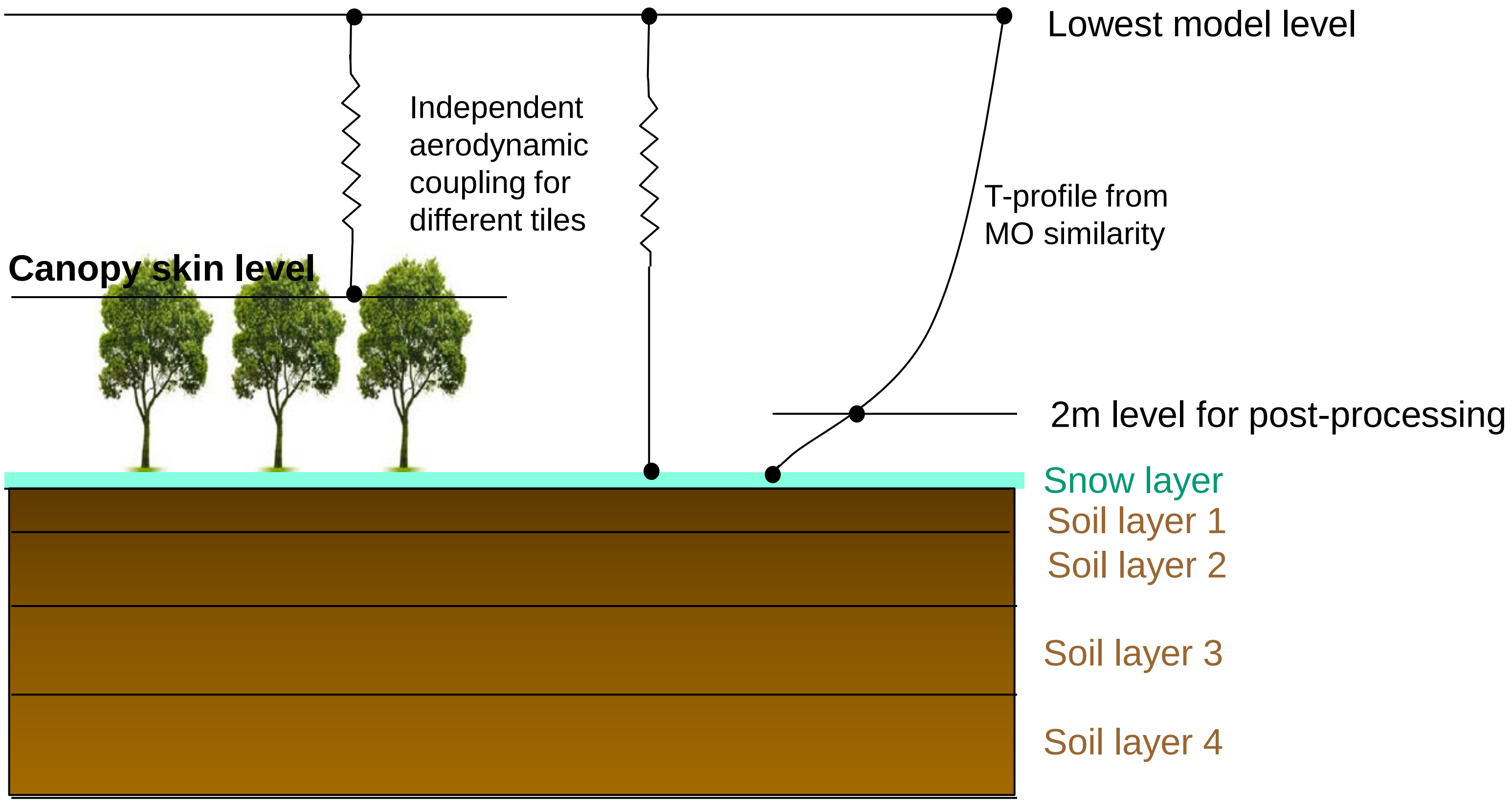






The heat flux towards the exposed snow is nearly zero!

The two relevant tiles are:
(i) tile with snow under vegetation and (ii) tile with exposed snow



Even if the forest is dominant, the vertical interpolation to the 2m level is done for the exposed snow tile (SYNOP stations are always in a clearing).

During day time, the forest heats the atmosphere. At sunset the exposed snow tile becomes very stable cutting off turbulent exchange. Therefore snow temperature and T2 drop too much. In reality forest generated turbulence will maintain turbulent exchange over the clearing and prevent extreme cooling.

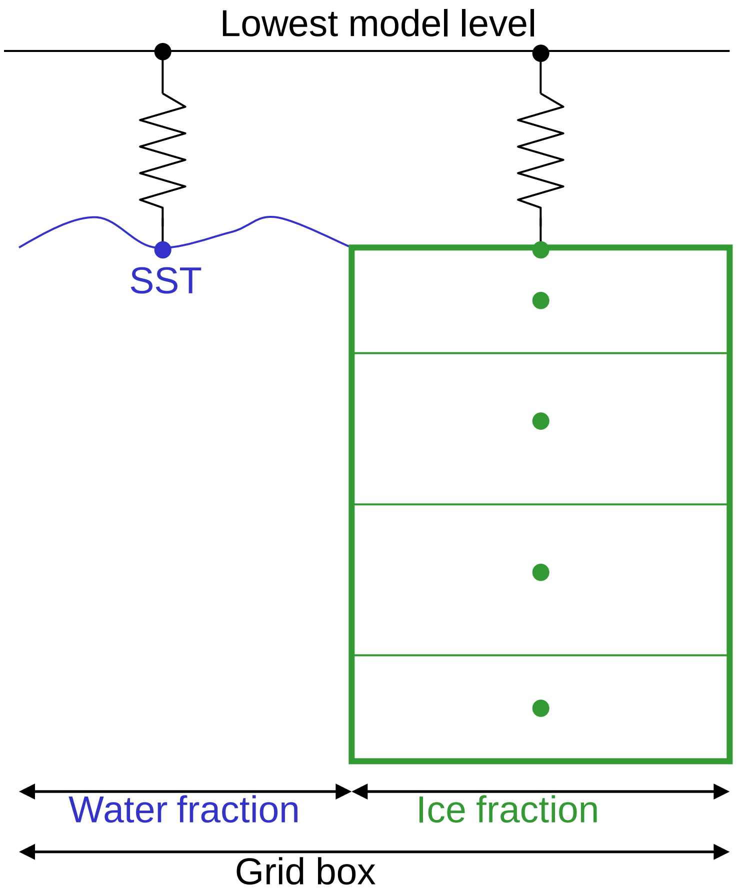
Model for sea ice temperature

Purpose of sea ice model:

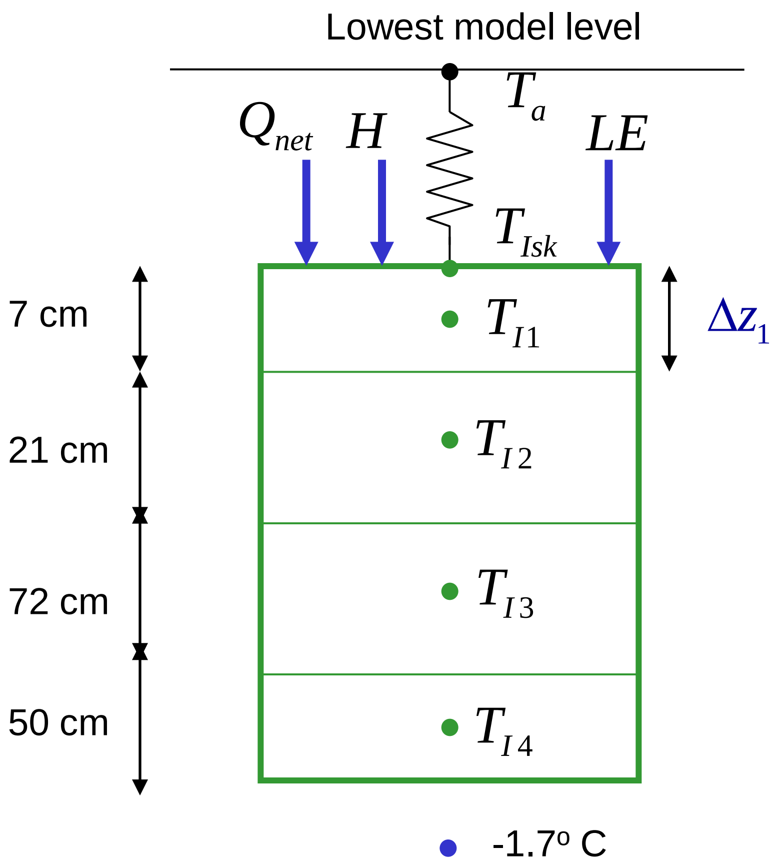
- To provide fluxes of heat and moisture to the atmospheric model
- To provide a surface temperature for thermal radiation and as a background for satellite retrievals
- Provide albedo for solar radiation

Handling of sea ice in ECMWF model:

- Grid boxes with less than 50% land are called sea/lake
- Sea points have 2 tiles: water and ice with variable fractions
- Water temperature (SST) and ice fraction are prescribed from daily analysis and kept constant during the forecasts
- Ice temperature evolves according to ice model
- Ice temperature is not constrained by observations, it cycles through the first guess fields and responds to the atmospheric analysis through ice model



Model for sea ice temperature



- No snow on sea ice
- No parametrized melt ponds (only through climatological albedo)

- 4-layer ice model to describe multiple time scales
- Diffusion equation for ice:

$$(\rho C)_I \frac{\partial T_I}{\partial t} = \frac{\partial}{\partial z} \lambda_I \frac{\partial T_I}{\partial z}$$

- Boundary conditions:

$$surface: \quad G = \lambda_I \frac{(T_{Isk} - T_{I1})}{\Delta z_1 / 2}$$

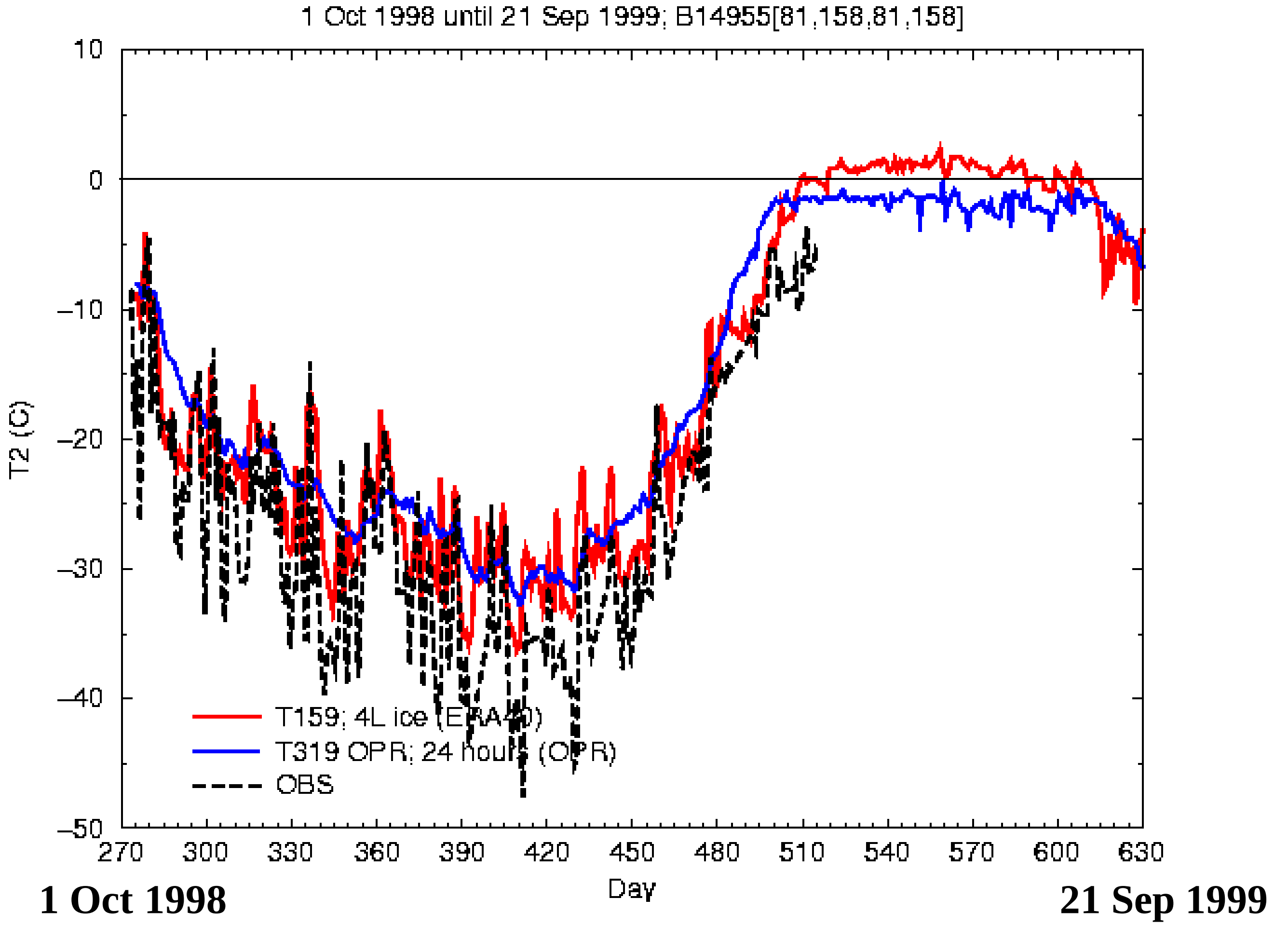
$$G = Q_{net} + H + LE$$

$$deep\ water: \quad T = -1.7^o C$$

- Thickness of deep layer adjusted to obtain good agreement with ice buoy data

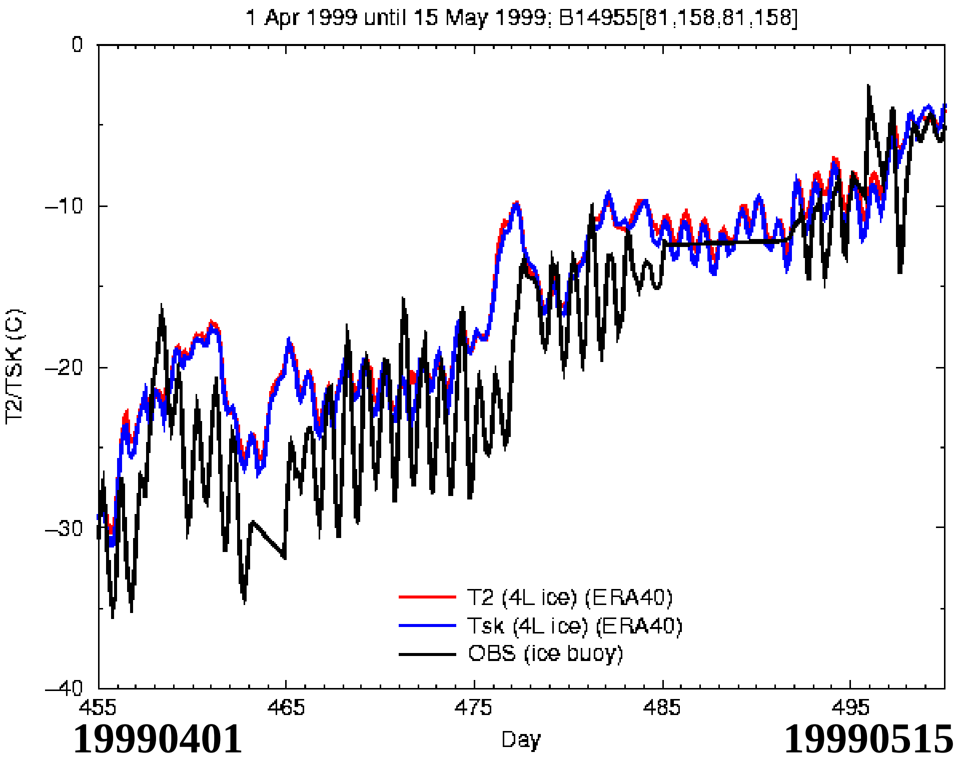
- Surface albedo monthly climatology prescribed according to Ebert and Curry (1993)

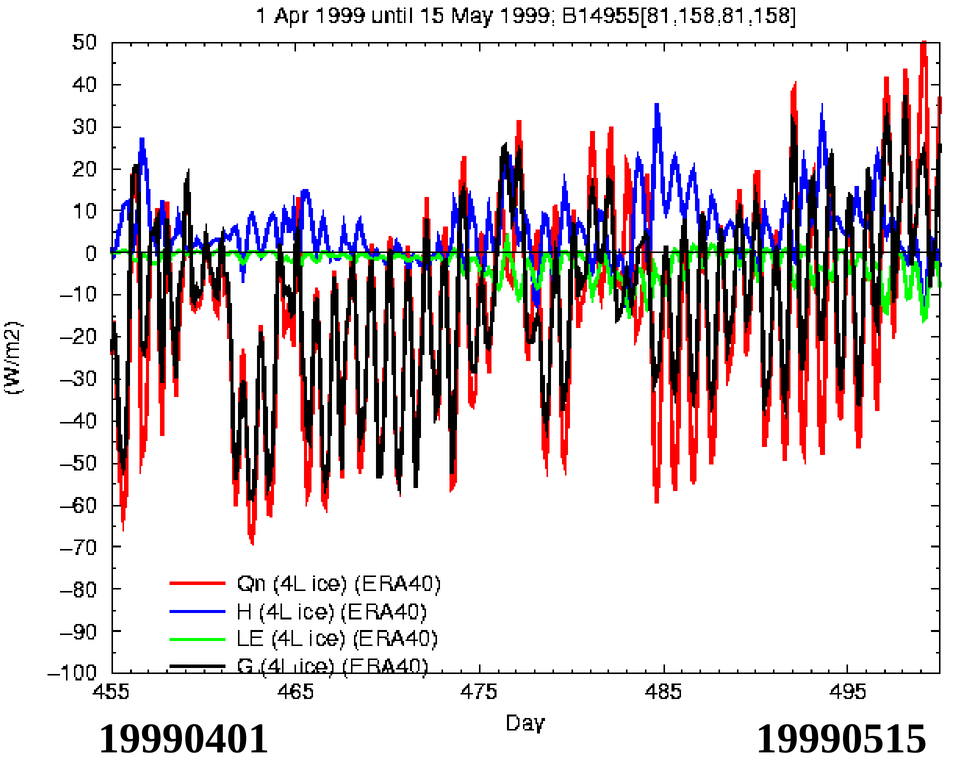
Temperature at 2m compared to ice buoy data (12 UTC)



- Ice layer thickness (1.5 m) was optimized using ice buoy data (Thanks to Ignatious Rigor, M. Serreze, Greg Flato, Judy Curry, Don Perovich)
- Temperatures show much better variability at synoptic time scales than old slab model (although variability is still underestimated)

Diurnal cycle of temperature at 2m and surface energy balance





- Over sea ice the amplitude of the diurnal temperature cycle is underestimated by a factor 3
- Temperature at 2m is nearly identical to skin temperature
- Surface energy balance is dominated by a balance between net radiation and heat flux into the ice

Options for improvement of the sea ice model?

- The underestimation of diurnal cycle suggests a too strong coupling with the surface; the insulating effect of snow might be needed, but how to control the snow without observations?
- Is it possible to make use of satellite observations of surface temperature?
- Is the albedo too high? (a realistic albedo model gives a positive feedback in spring which can not be controlled by observations)