Atmosphere/surface interactions in the ECMWF model at high latitudes

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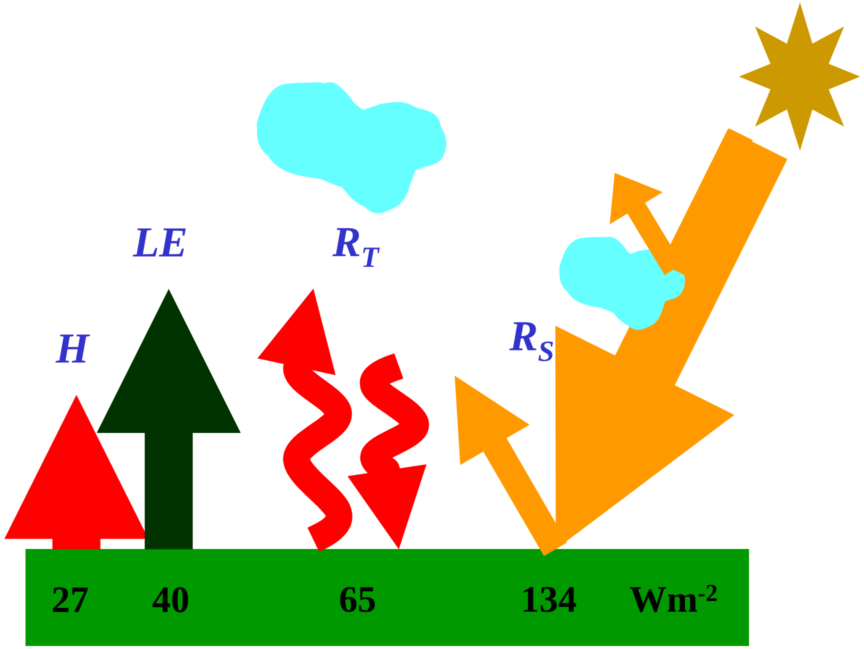
- Introduction
- Soil freezing and stable boundary layer diffusion
- Snow albedo
- TESSEL
- Sea ice
- Snow
- ERA-40 data assimilation increments
- ERA-40 and BERMS

Thanks to many colleagues

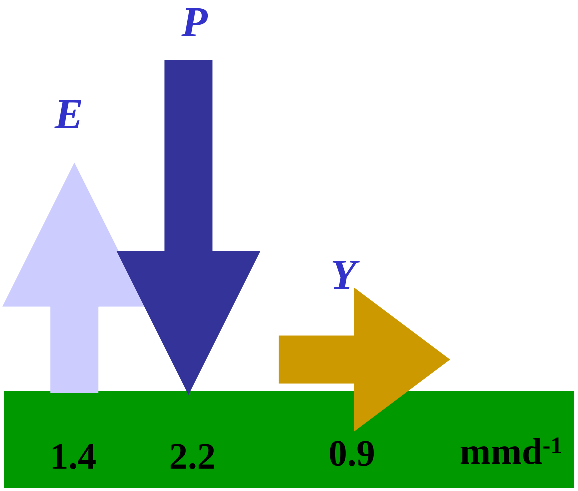
Role of land or sea ice model

- Atmosphere needs boundary conditions for the enthalpy, moisture (and momentum) equations: Fluxes of energy, water (and stress) at the surface.

Energy budget



Water budget

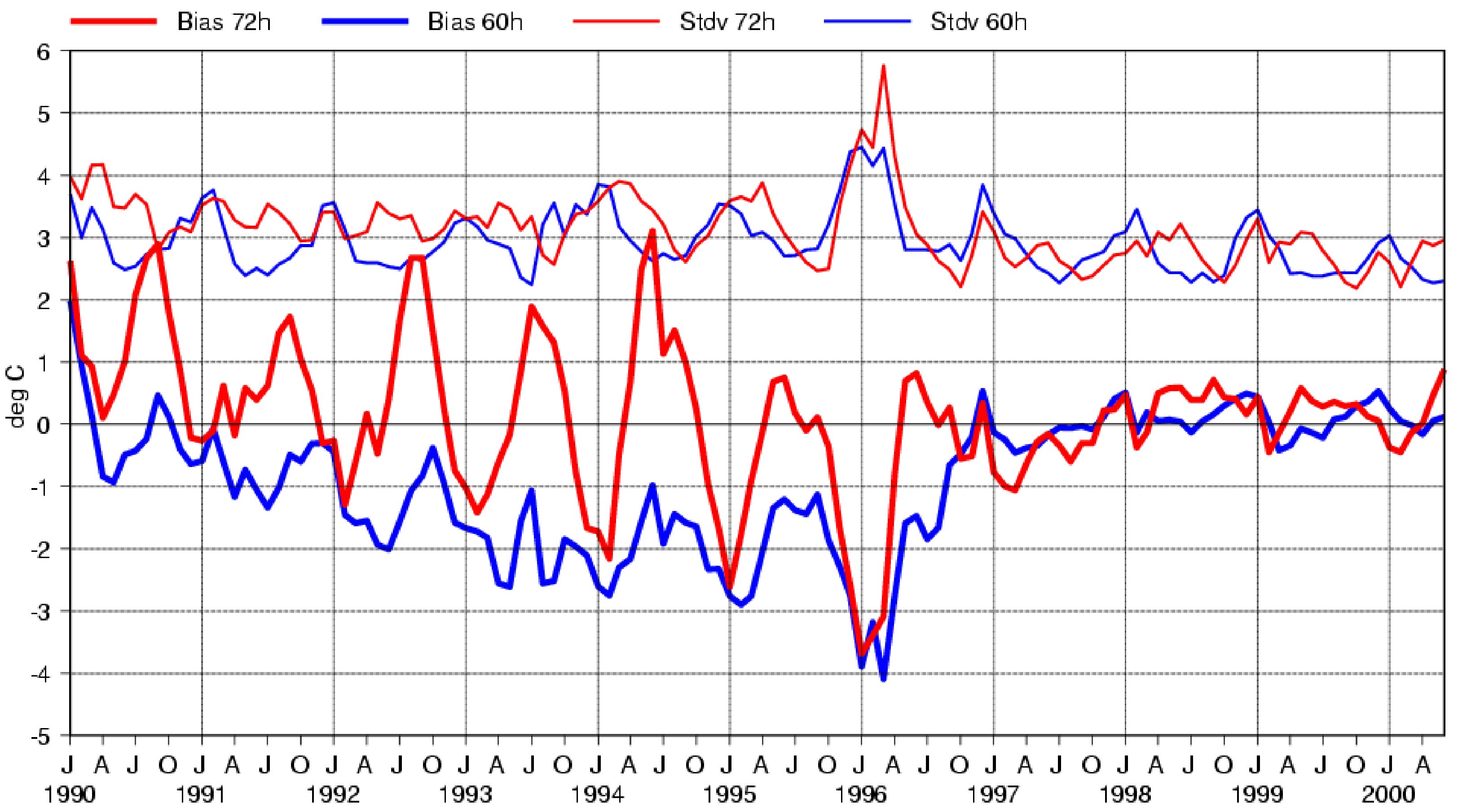


ERA40 land-averaged values 1958-2001

History of the land surface scheme at ECMWF

- 2-layer soil model with deep climatological boundary condition for soil moisture and temperature
- 1993: free running 4-layer soil model with free drainage for water and no flux for heat as lower boundary condition
- 1994: soil moisture nudging
- 1996: soil moisture freezing +stable boundary layer + snow albedo in forest areas
- 1999: soil moisture OI
- 2000: Tiled surface scheme (TESSEL): ERA-40

History of ECMWF 2m T errors



4-LAYER
SOIL MODEL

RESETTING
OF SOIL
MOISTURE

SOIL
MOISTURE
ANALYSIS

PROGNOSTIC
CLOUD
SCHEME

SOIL
FREEZING

SNOW
ALBEDO

REVISED
SOIL
MOISTURE
ANALYSIS

TILES
SURFACE
SCHEME

- Introduction
- **Soil freezing and stable boundary layer diffusion**
- Snow albedo
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Soil freezing + stable boundary layer

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

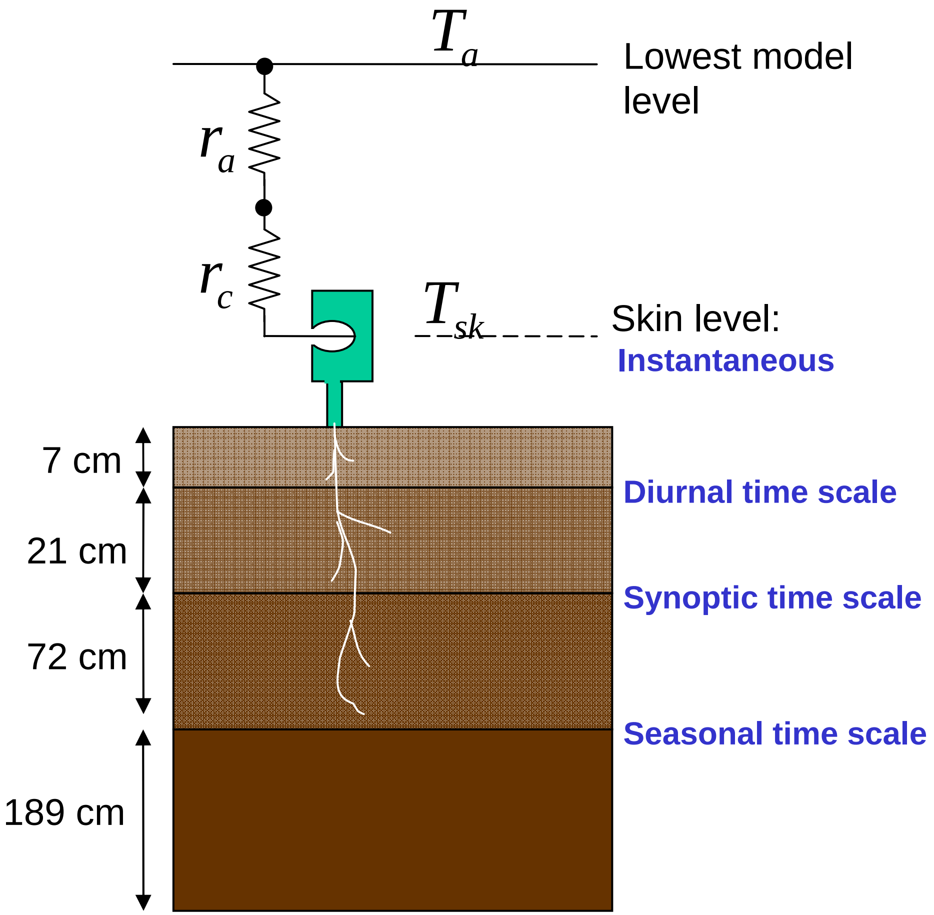
$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \lambda \frac{\partial T}{\partial z}$$

- **Boundary conditions:**

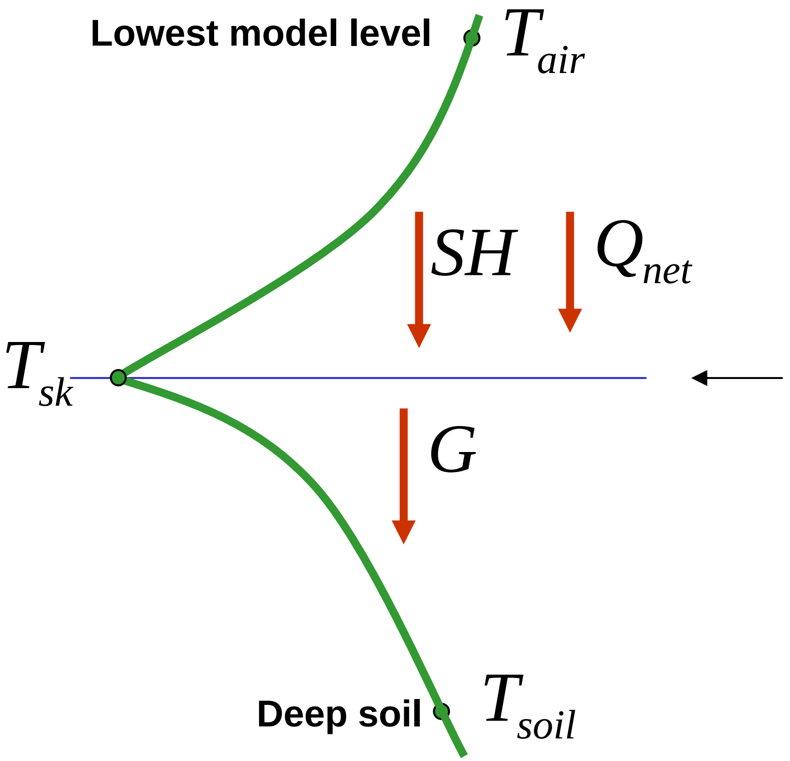
$$surface: \quad G = \Lambda_{sk} (T_{sk} - T_1)$$

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

$$deep\ layer: \quad no\ heat\ \ flux$$



Winter and night time cooling at the surface: How is it 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

$$SH \quad + \quad Q_{net} \quad = \quad G$$

$$C_{air}(T_{air}-T_{sk})+Q^{\downarrow}_{solar}(1-A)+Q^{\downarrow}_{therm}-\in\sigma T_{sk}^{4}=C_{soil}(T_{sk}-T_{soil})$$

Coupling coefficients are hidden in a number of parametrizations

Coupling between lowest model level and surface (skin layer) is affected by:

- Wind speed
- Roughness lengths
- Stability function
- Heterogeneity

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

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

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

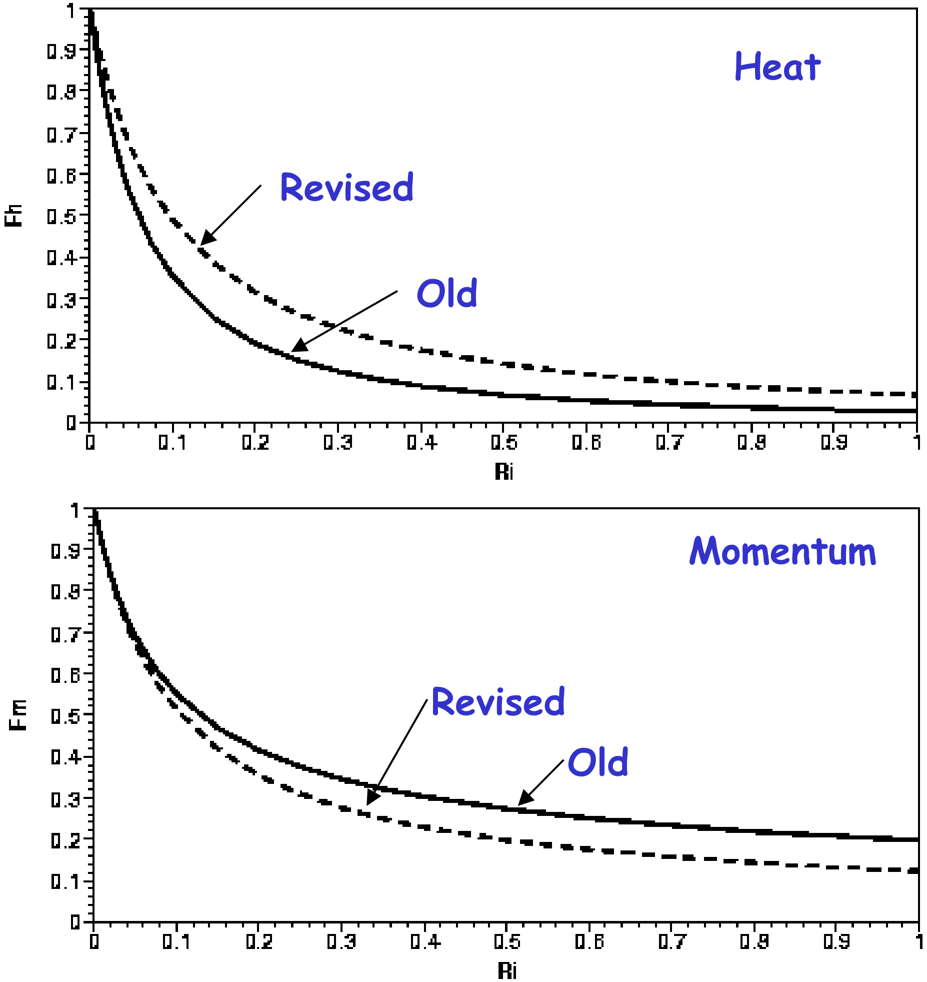
- Soil thermal properties
- Presence of snow and snow properties
- Representation of land cover
- Soil water freezing and thawing
- Heterogeneity

Radiation as affected by:

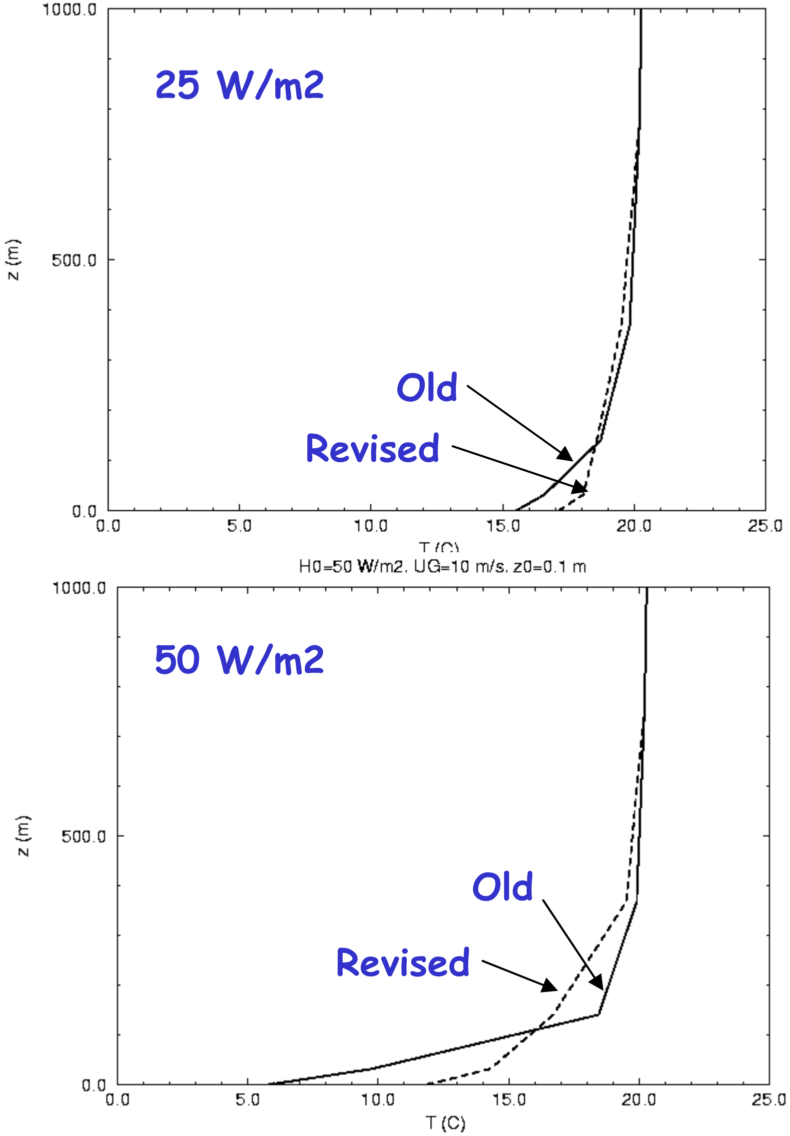
- Clouds
- Aerosols
- Albedo

Increased stable boundary layer

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



Soil water freezing

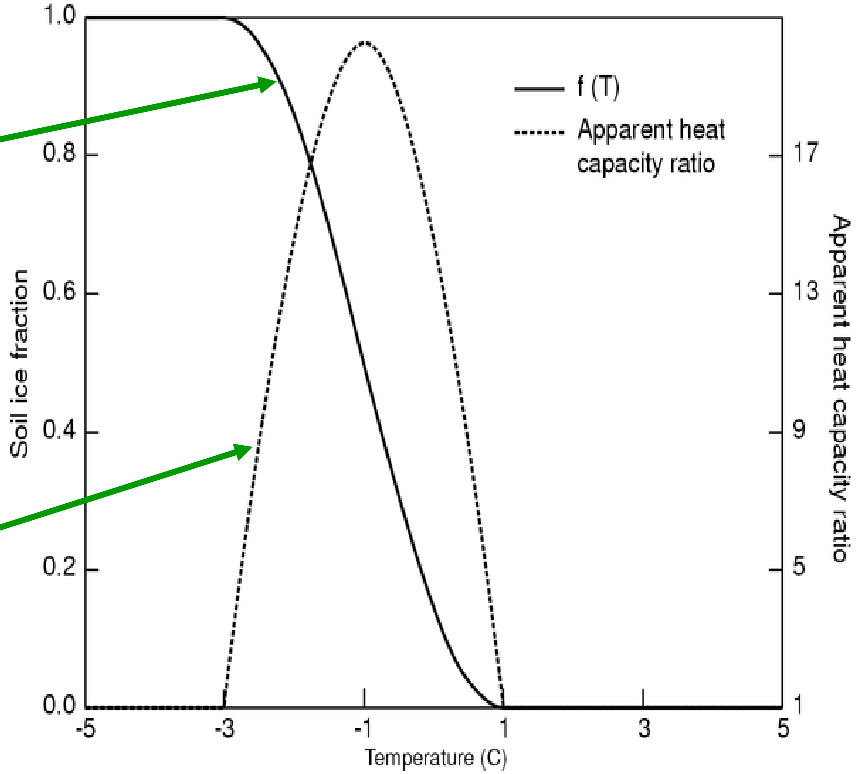
Soil heat transfer equation in soil freezing condition

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

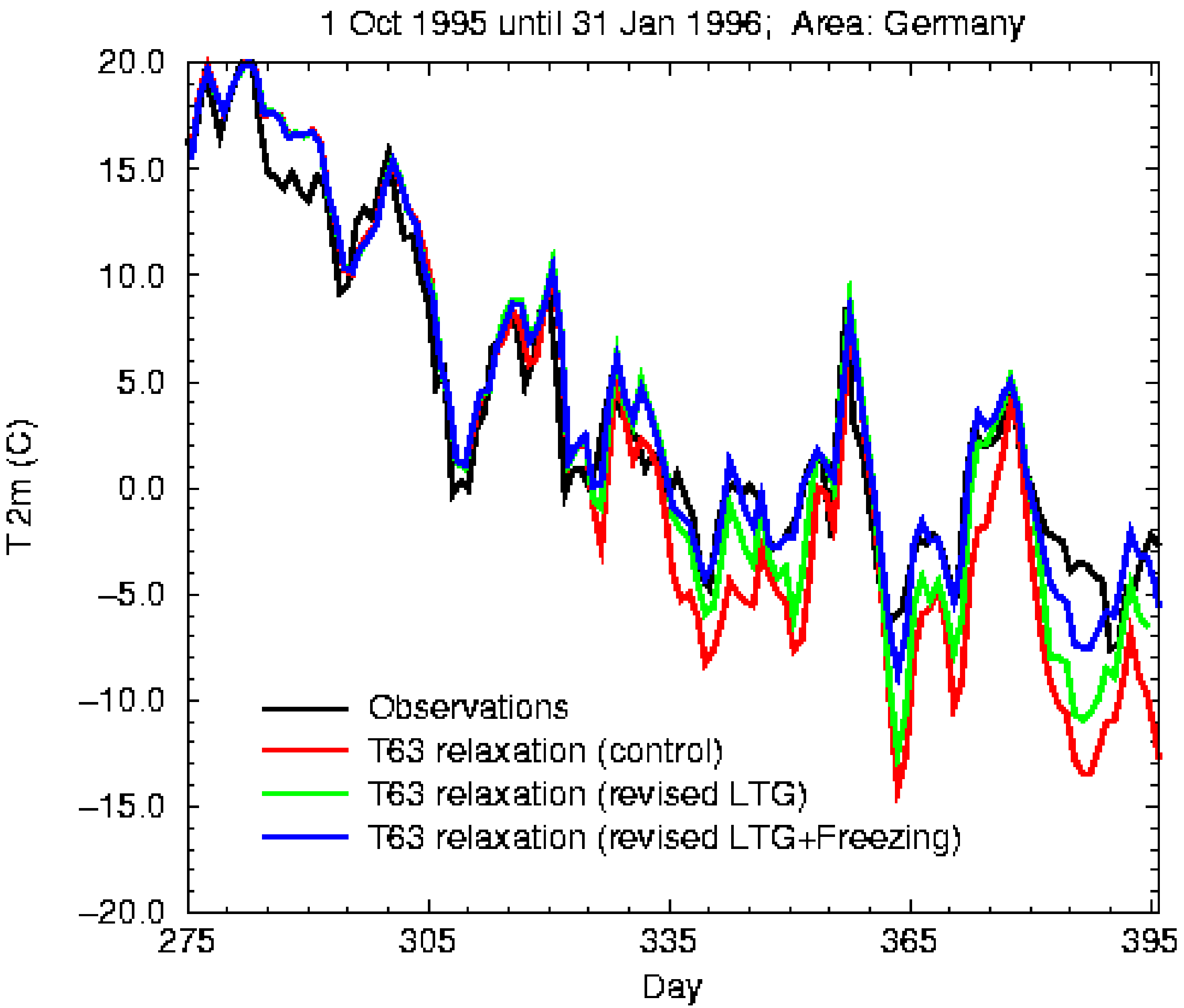
θ_I **Soil frozen water**

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

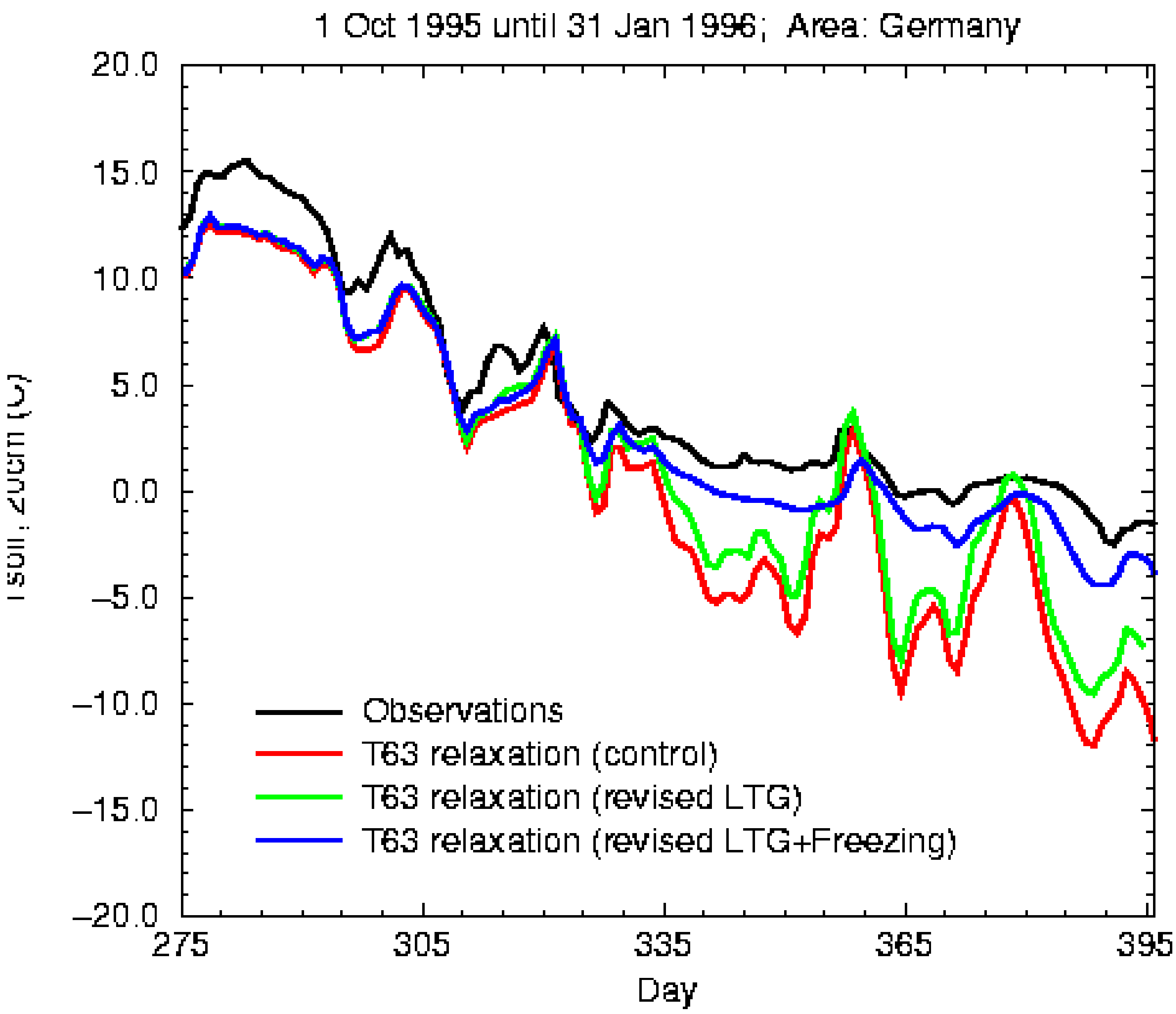
$$\underbrace{\left[(\rho C)_s - L_f \rho_w \theta \frac{\partial f}{\partial T} \right]}_{\text{Apparent heat capacity}} \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \lambda_T \frac{\partial T}{\partial z}$$



Time series of 12 UTC 2m temperatures over Germany

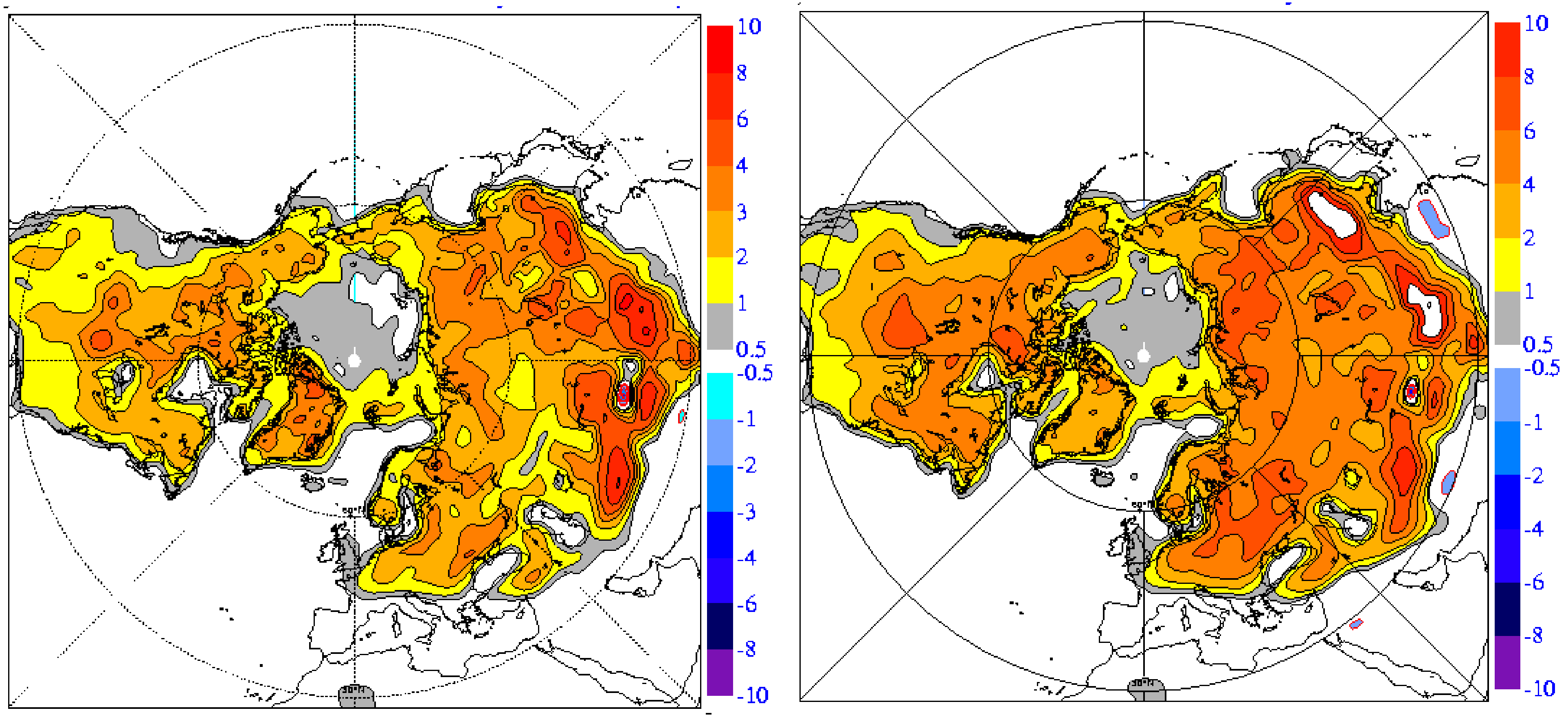


Time series of soil temperatures over Germany



Difference in 2m temperature for January 1996

From long “relaxation” integrations starting 1 Oct 1995

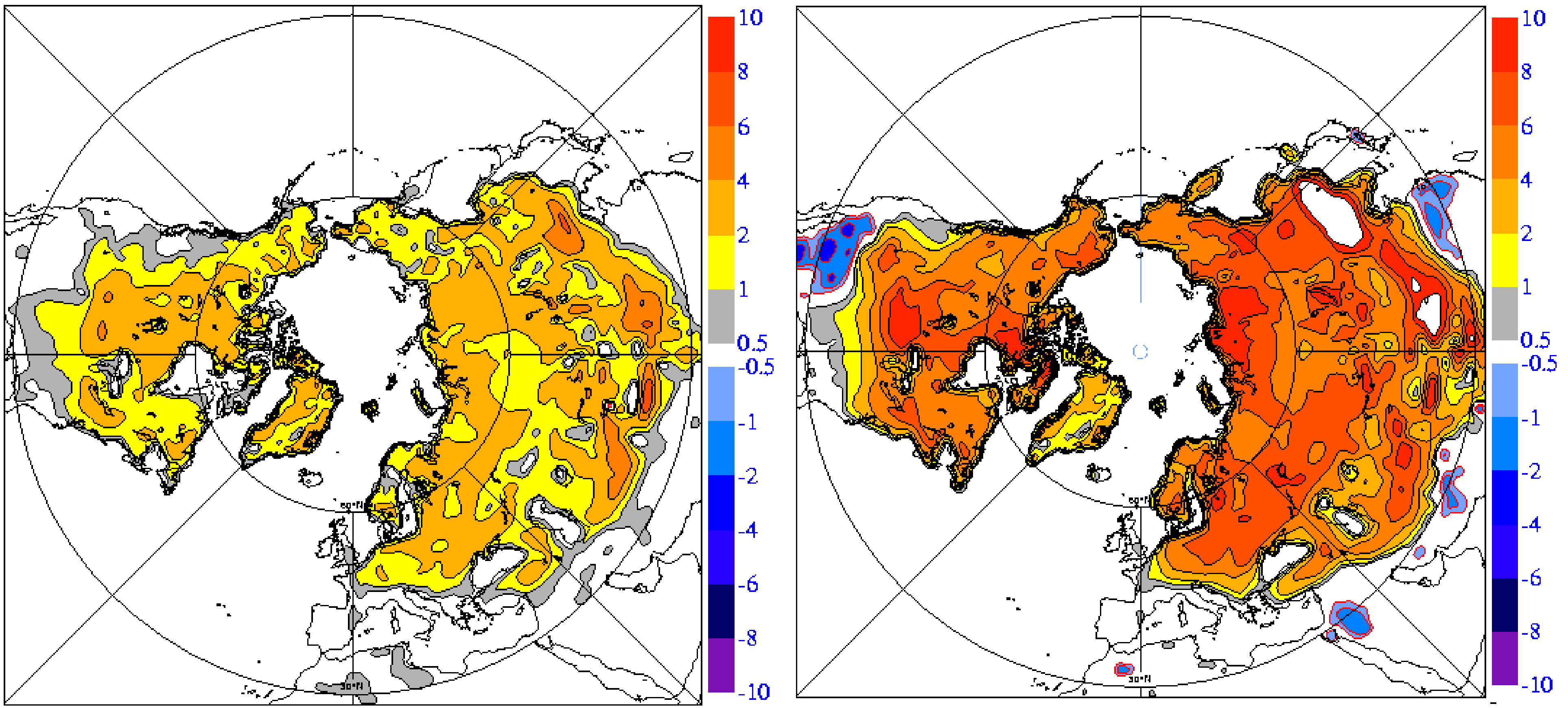


Revised BL - Control

Revised BL & soil freezing - Control

Difference in soil temperature layer 2 (7-28 cm deep) for January 1996

From long “relaxation” integrations starting 1 Oct 1995



Revised BL - Control

Revised BL & soil freezing - Control

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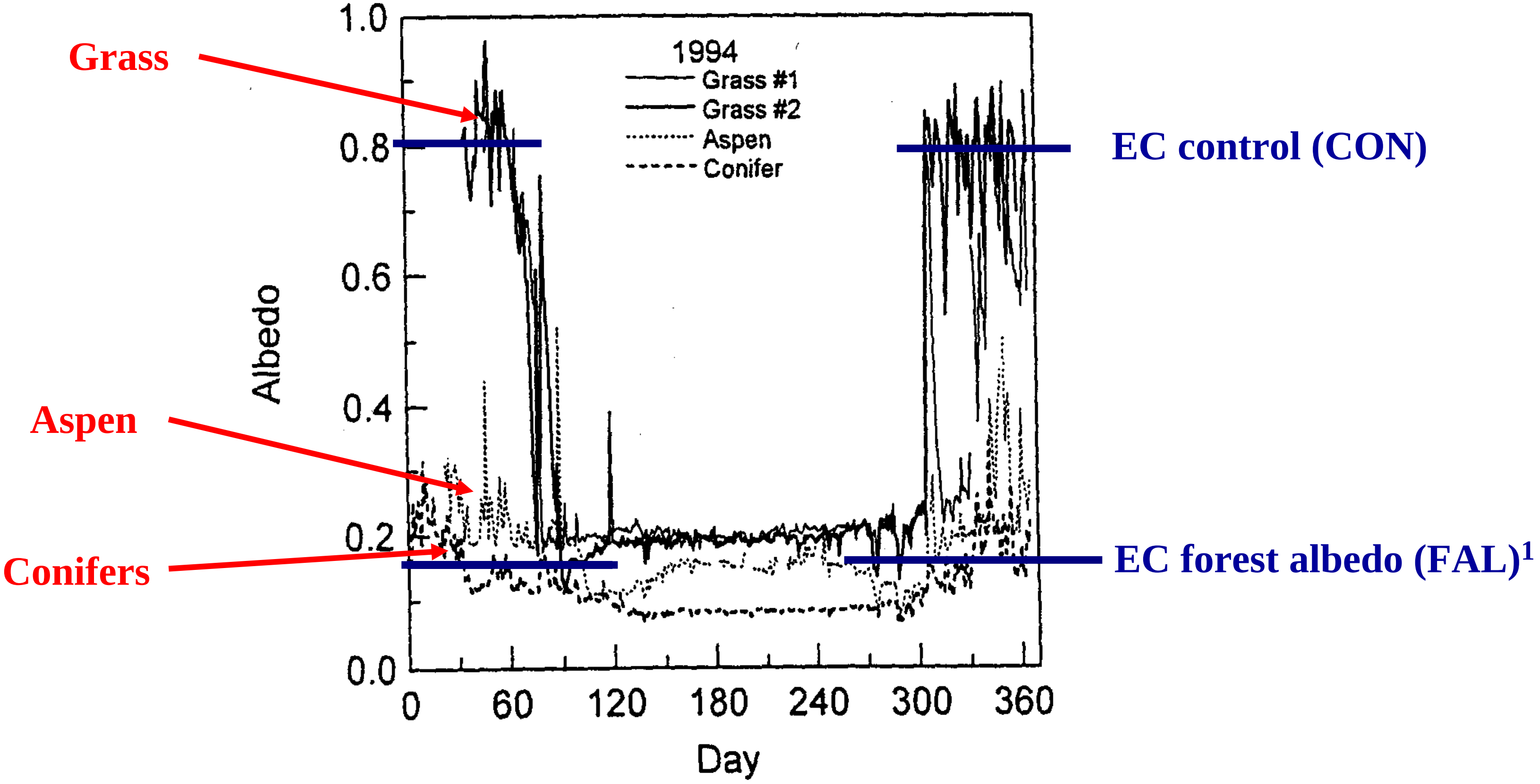
Spring: Boreal forest albedo (BOREAS)

Observed albedo BOREAS 1994



Grass

Aspen

Conifers

EC control (CON)

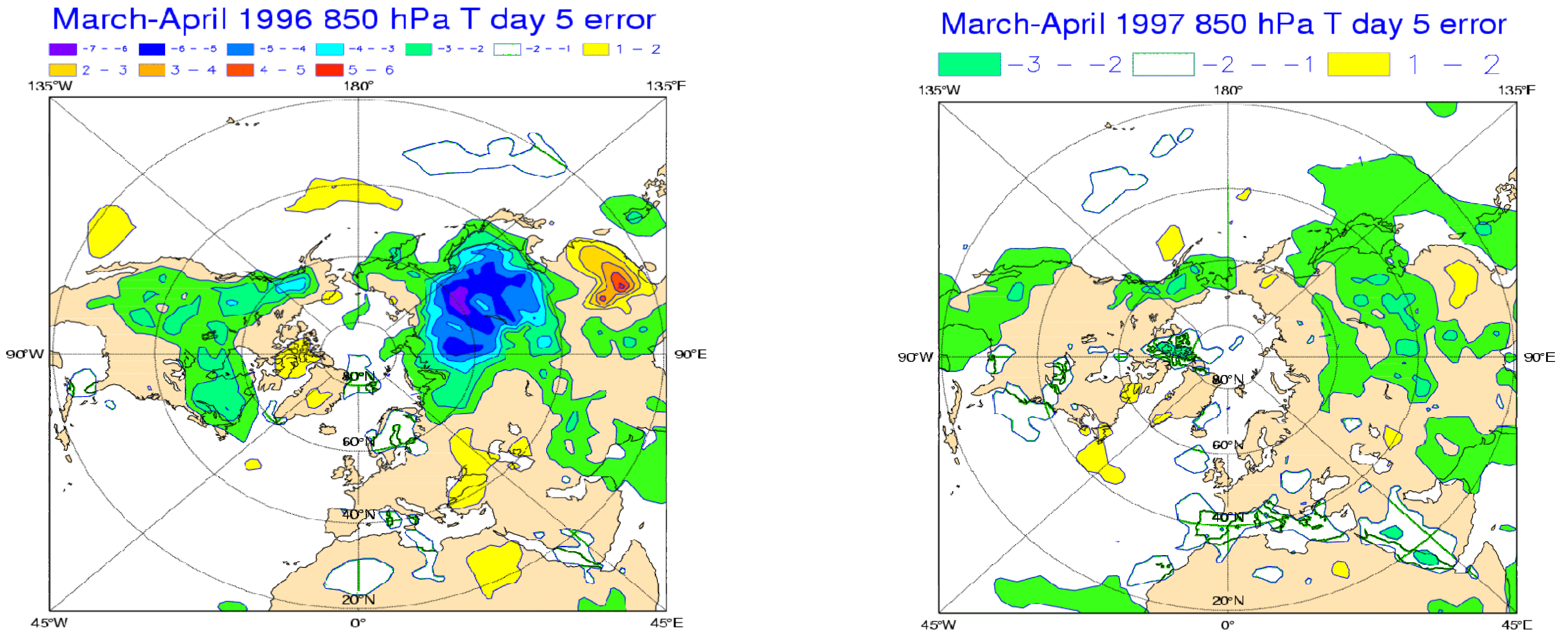
EC forest albedo (FAL)^1

Figure 4. Daily average albedo for 10 BOREAS mesonet sites for 1994; showing two grass sites, the aspen site, and an average of the seven conifer sites.

Viterbo and Betts, 1999: J. Geophys. Res., 104D, 27,803-27,810.

Radiation energy budget is important e.g. through albedo

operational day-5 T bias at 850 hPa



March/April 1996

March/April 1997

Viterbo and Betts, 1999

- *A smaller albedo of snow in the boreal forests (1997) reduces dramatically the spring (March-April) error in day 5 temperature at 850 hPa*

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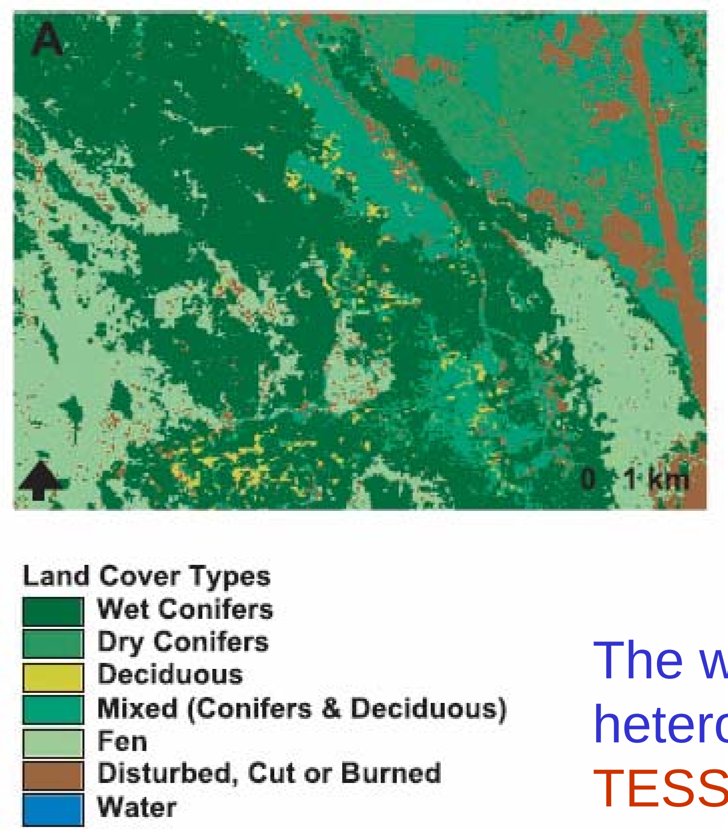
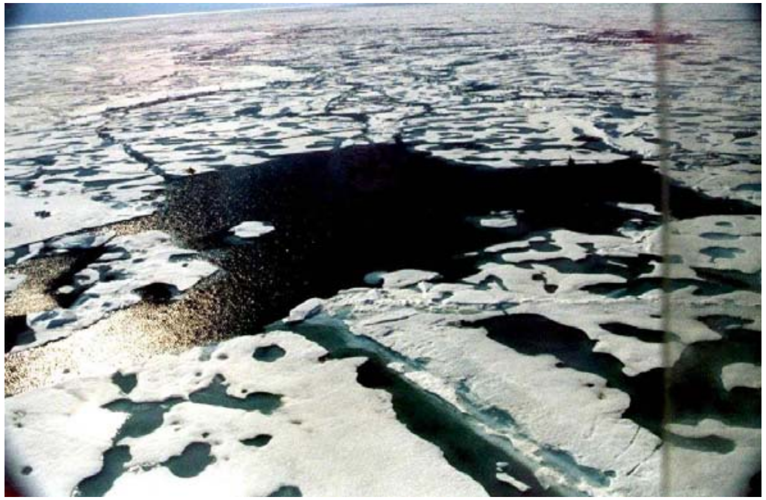
Land surfaces and ocean surfaces are often heterogeneous

- **Details of the land surface can not be resolved by NWP models**



Portion of BOREAS Southern Study Area (about 10x10 km; Gamon et al. 2004)

- **Heterogeneities in e.g. sea ice, land cover type, albedo, leaf wetness may play an important role.**



SHEBA Photo of sea ice

The wish to have a simple representation of heterogeneity, motivated the development of TESSEL (Tiled ECMWF Scheme for Surface Exchanges over Land) which has 6 tiles for land surfaces and 2 tiles for ocean/lake points

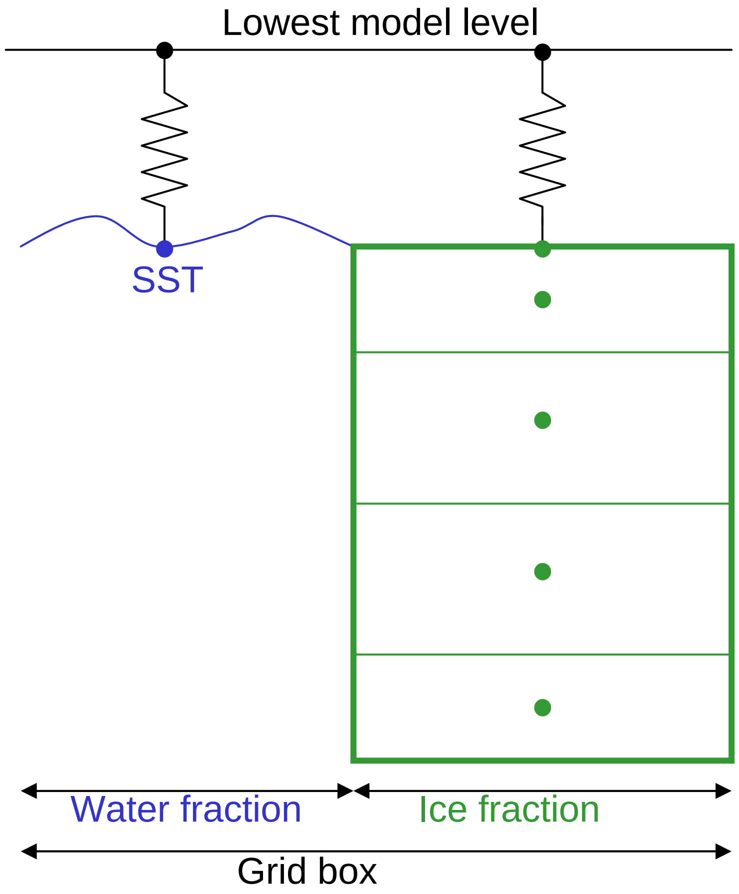
Model for sea ice temperature

Purpose of sea ice model:

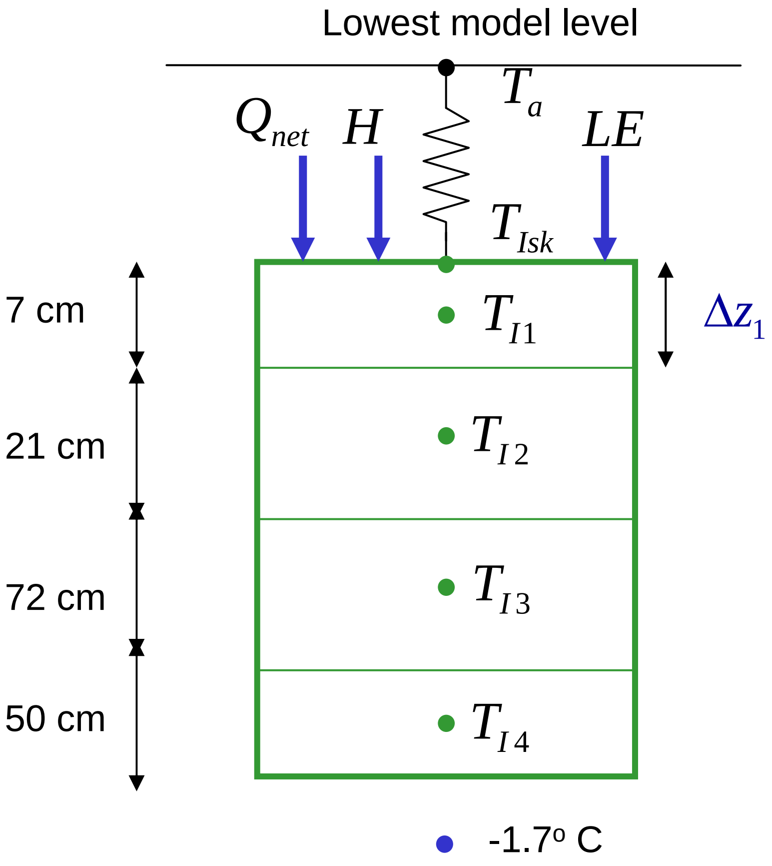
- **To provide fluxes of heat and moisture to the atmospheric model**
- **To provide a surface temperature for thermal radiation and as a background for satellite retrievals**
- **Provide albedo for solar radiation**

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:

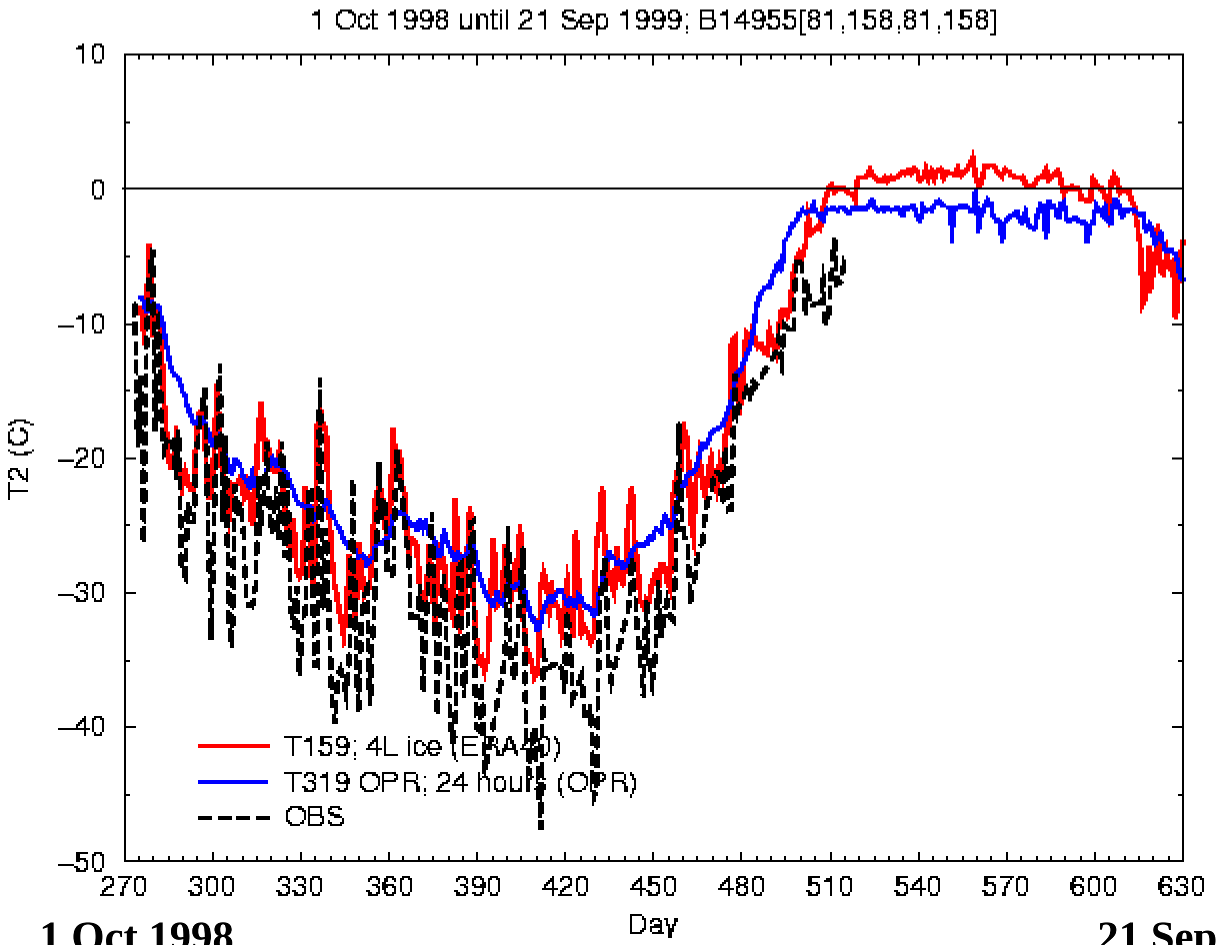
$$surface: \quad G = \lambda_I \frac{(T_{Isk} - T_{I1})}{\Delta z_1 / 2}$$

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

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

- Thickness of deep layer adjusted to obtain good agreement with ice buoy data
- Surface albedo monthly climatology prescribed according to Ebert and Curry (1993)

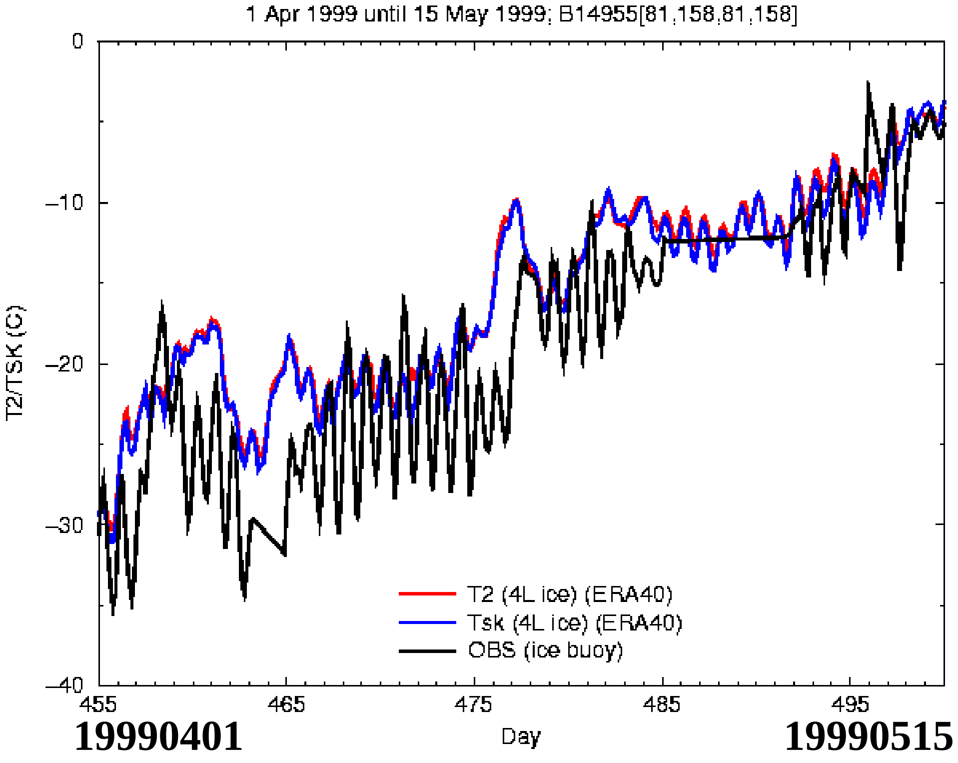
Temperature at 2m compared to ice buoy data (12 UTC)

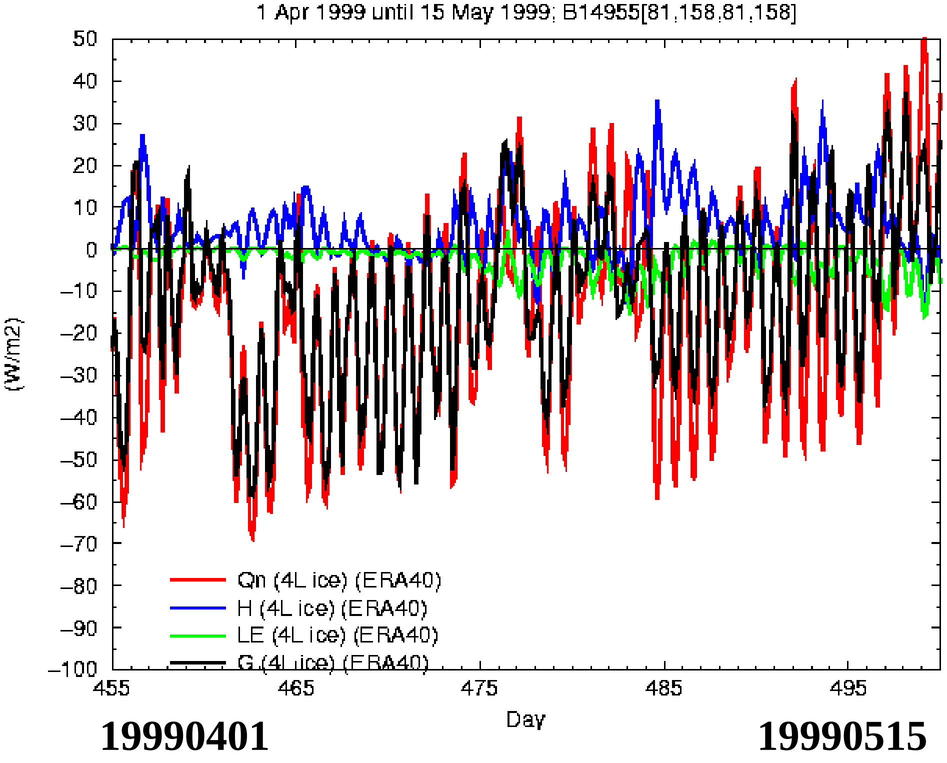


1 Oct 1998 **21 Sep 1999**

- 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)

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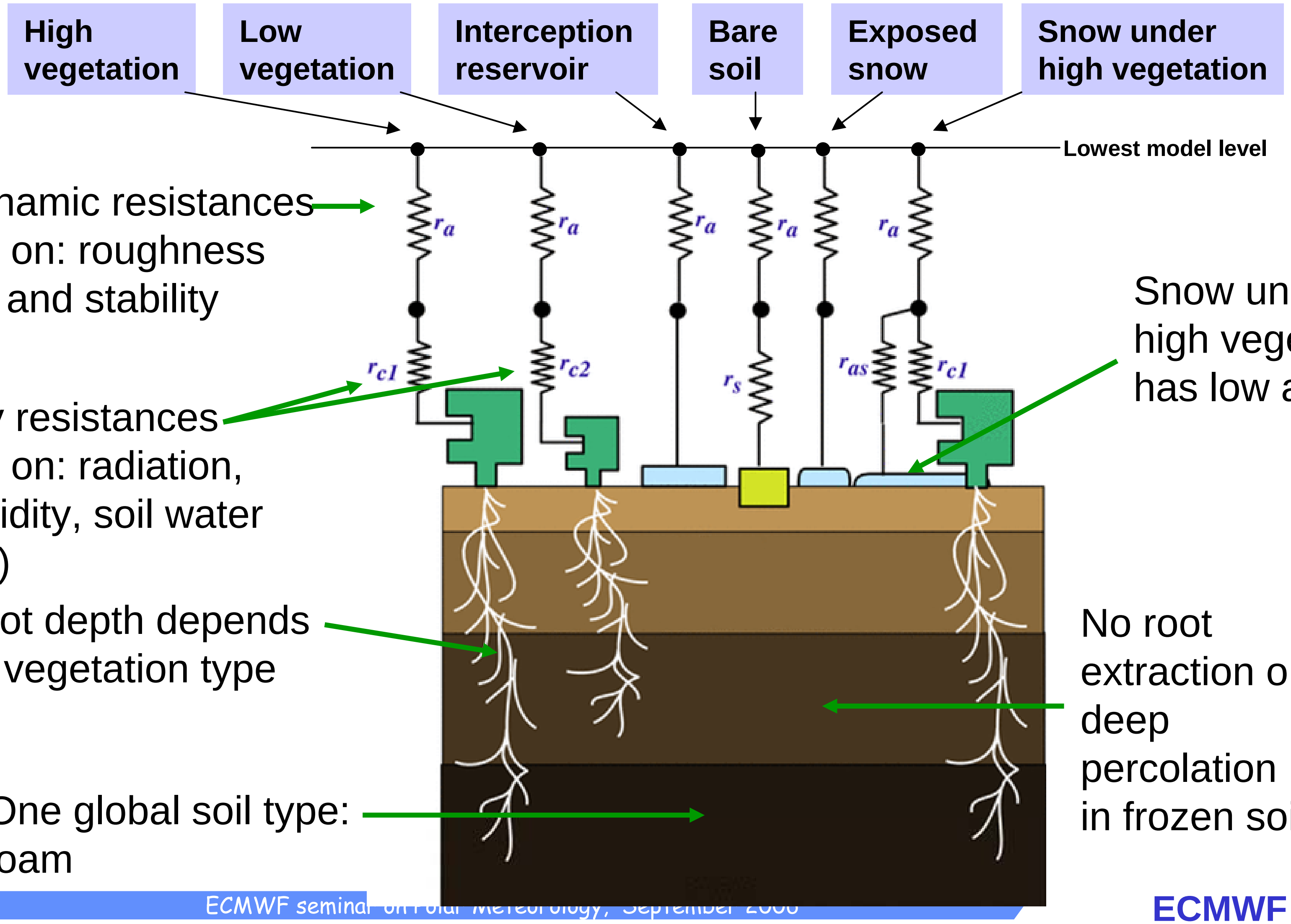
The land surface scheme (TESSEL)

Climatological land use data fields derived from 2’30” GLCC:

Low vegetation cover	High vegetation cover
Low vegetation type	High vegetation type



Aerodynamic resistances depend on: roughness lengths and stability

Canopy resistances depend on: radiation, air humidity, soil water (not ice)

Root depth depends on vegetation type

One global soil type: loam

Snow under high vegetation has low albedo

No root extraction or deep percolation in frozen soils

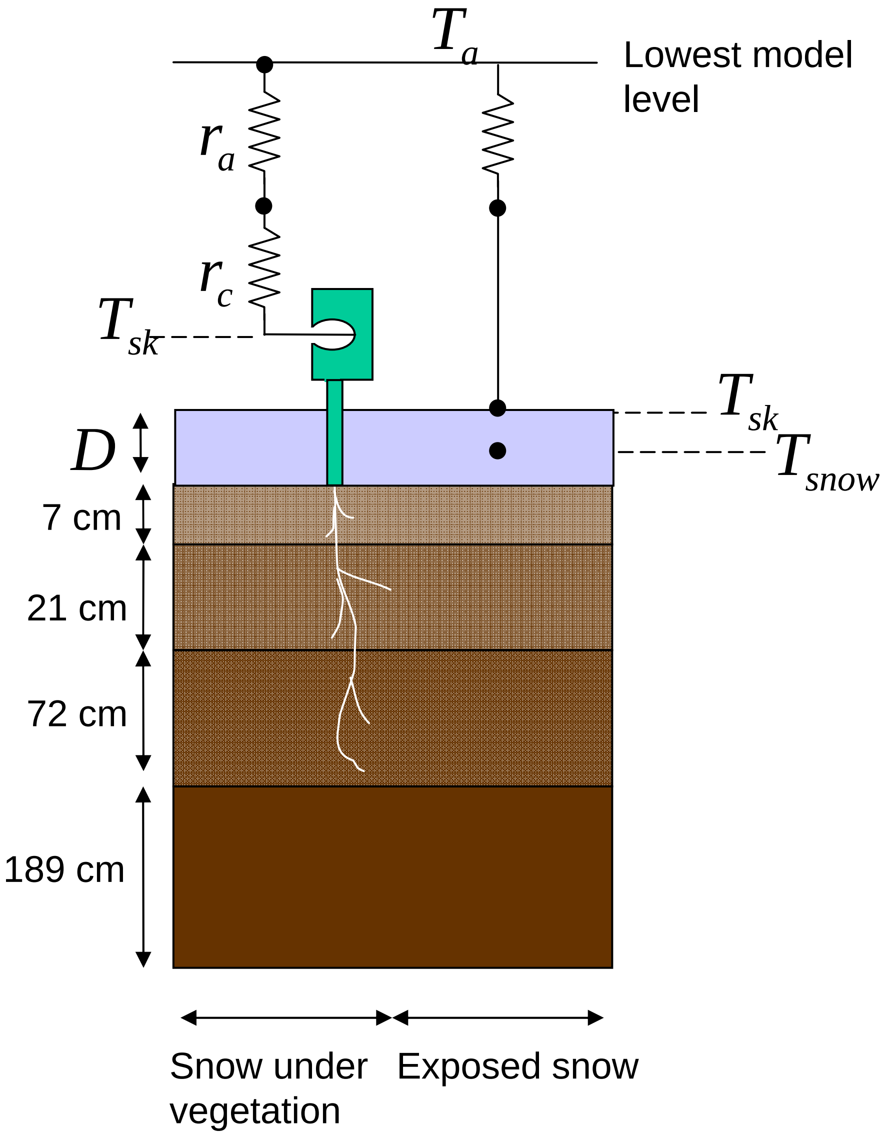
Snow model in TESSEL (2 tiles)

Single layer snow pack with prognostic equations for (Douville et al. 1995):

- Snow mass (right hand side : snow fall, snow melt and snow evaporation)
- Snow temperature (right hand side: radiative heating, turbulent fluxes, basal heat flux)
- Snow density (right hand side: decrease to min 100 kg/m2 for fresh snow; relaxation to 300 kg/m2 in 3 days)
- Snow albedo (right hand side: reset to 0.85 for fresh snow, relaxation to 0.50 with a time scale of a month for cold snow and about 4 days for melting snow)
- Snow depth **D** from mass and density
- Snow cover increases linearly with snow mass (total cover at 15 kg/m2)

Snow albedo is only used for "exposed snow" tile

Tile with snow under high vegetation has albedo of 0.2 (Viterbo and Betts, 1999)



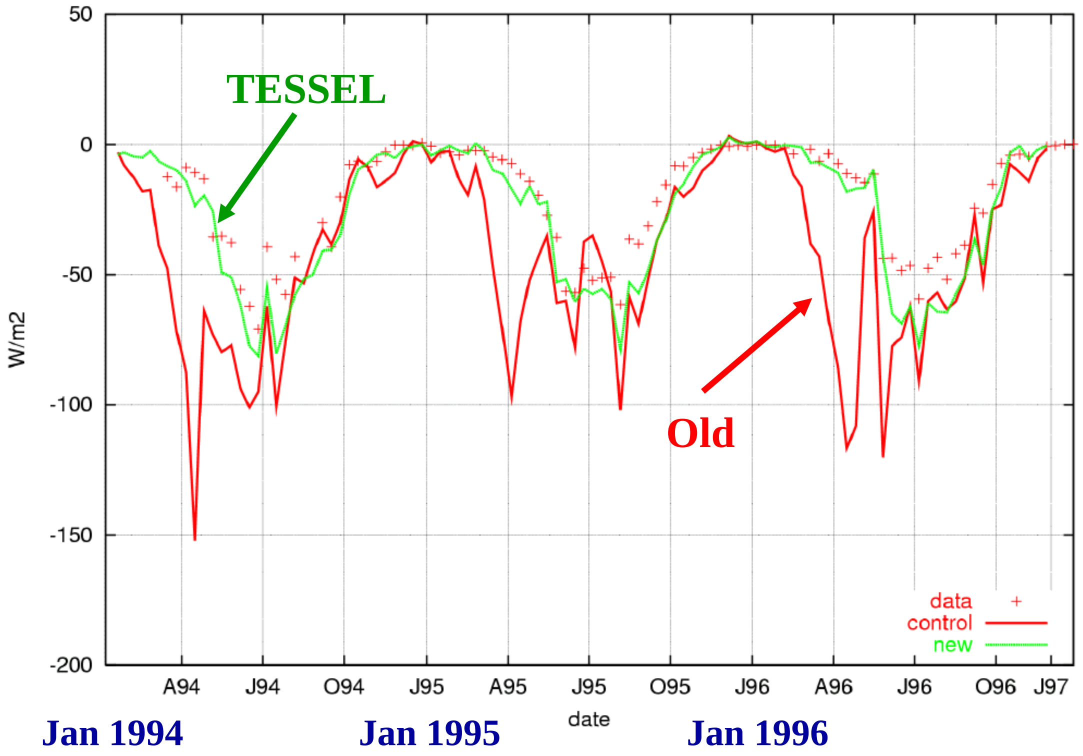
Offline TESSEL evaluation with BOREAS data

Used 9 different datasets for offline testing:

...

- BOREAS 1994-1996
- NOPEX 1994-1996
- Torne-Kalix (PILPS2E)

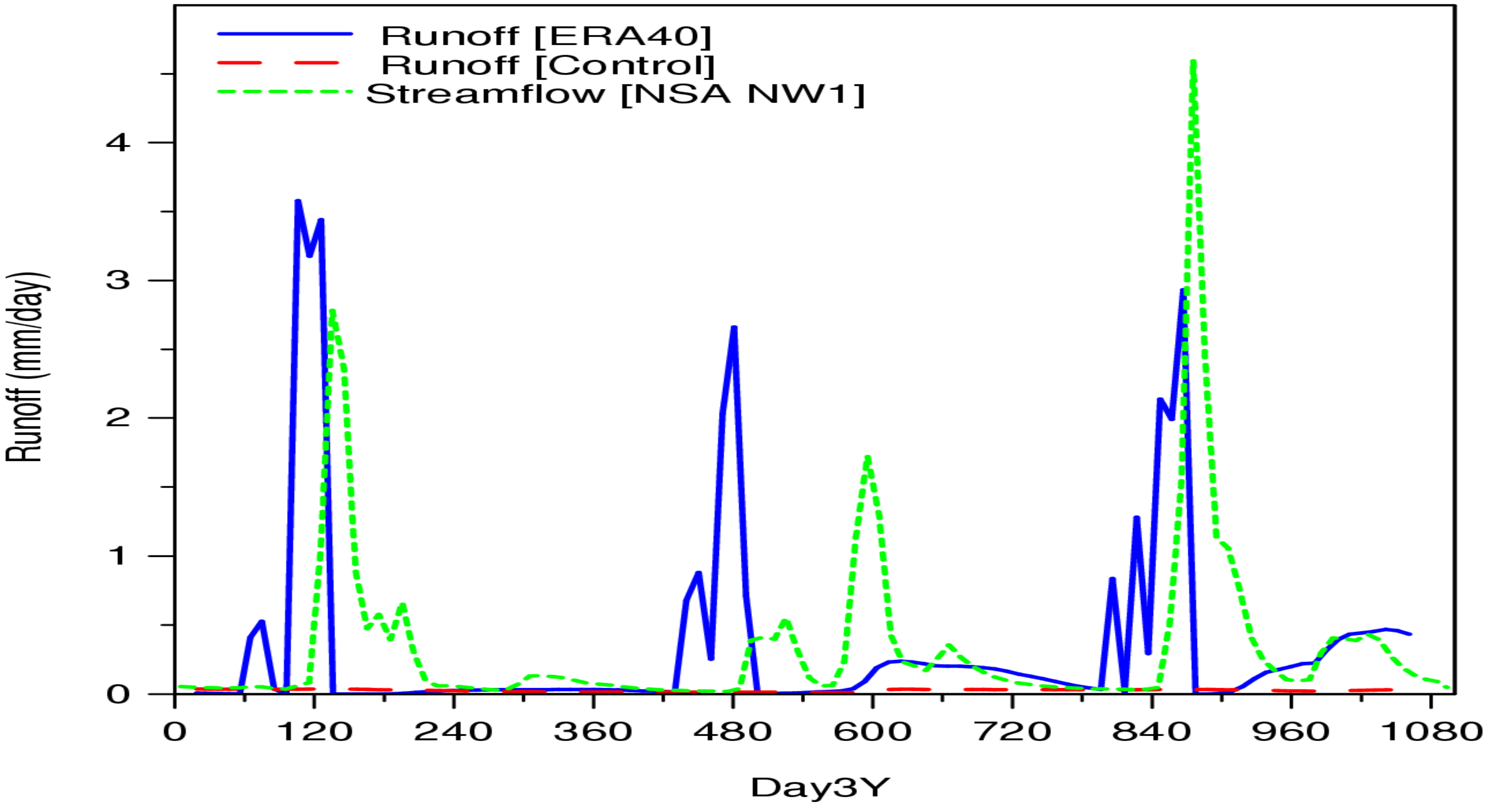
BOREAS evaporation: One-column integration



Van den Hurk et al, 2000. ECMWF Tech. Mem. 295, 42 pp.

- The old model erroneously transform the available energy into evaporation. However, plants have limited transpiration in winter/spring, when the roots are frozen.
- The TESSEL model simulates this because the stress function relies on available water (excluding ice).

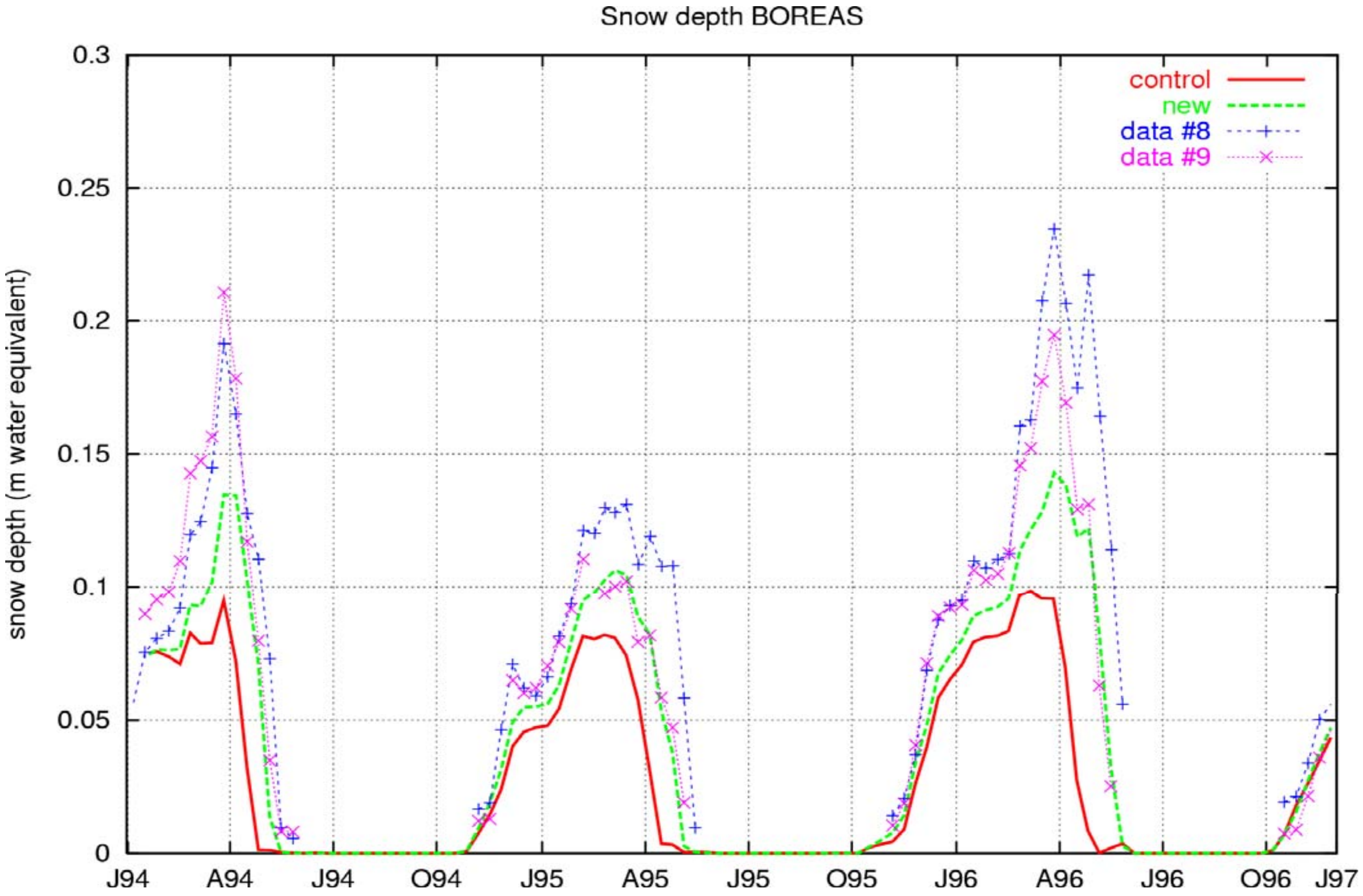
BOREAS: runoff vs observations



Betts et al, 2001. *J. Geophys. Res.*, BOREAS special issue.

- Deep drainage is the only mechanism for runoff in the old (ERA15) model (control). There is no mechanism for fast runoff and no peak associated to spring snowmelt.
- TESSEL (ERA40) restricts vertical water transfer in frozen soils. Fast runoff due to: (a) snowmelt over frozen soils, and (b) Soil water melt.

BOREAS snow depth

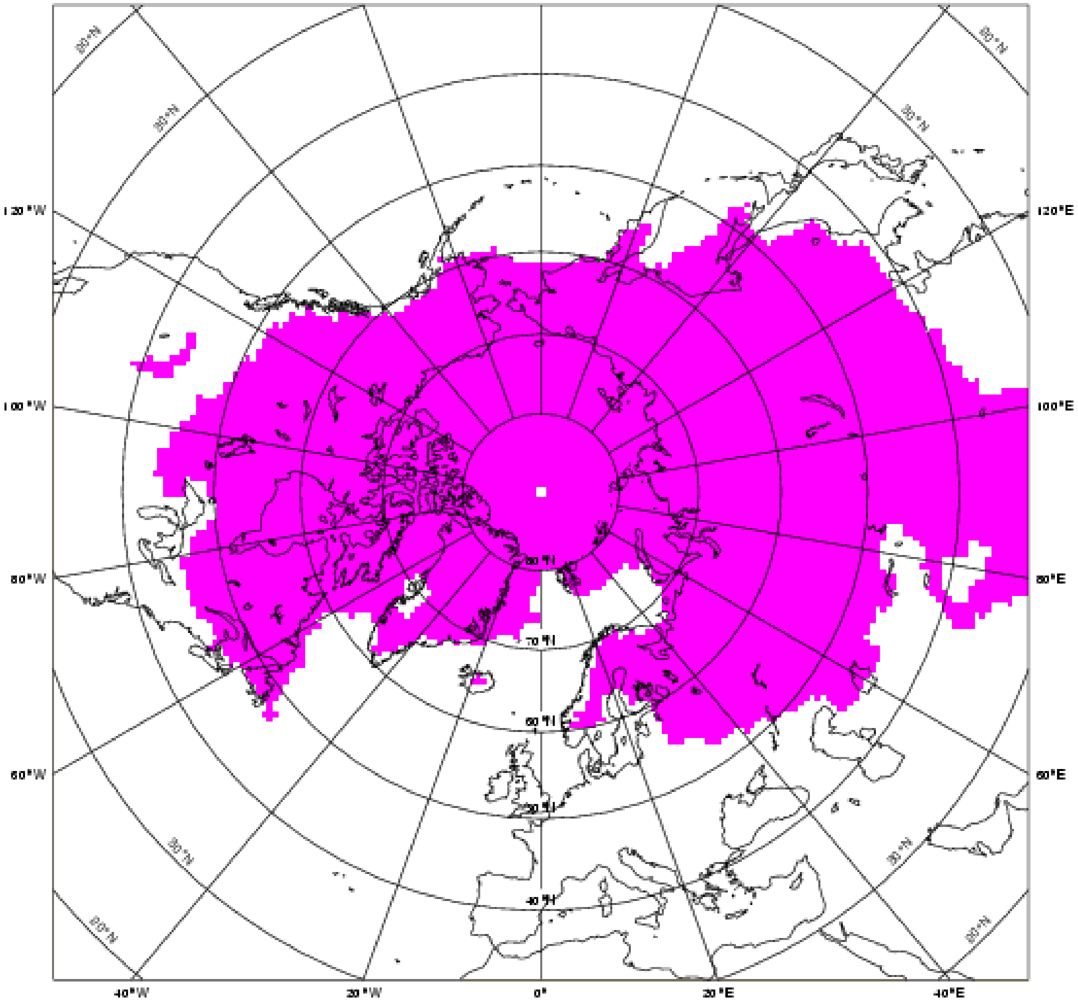


Van den Hurk et al, 2000. ECMWF Tech. Mem. 295, 42 pp.

- In the old (control) model, evaporation causes too early depletion of snow
- TESSEL (new) model limits snow evaporation, and depletion of snow (by melting) occurs later

Freezing/melting cycle in the soil column

Freeze extension in layer 3 [28 cm to 1 m], JAN



Deep and surface freezing extension from ERA-40 monthly mean min and max

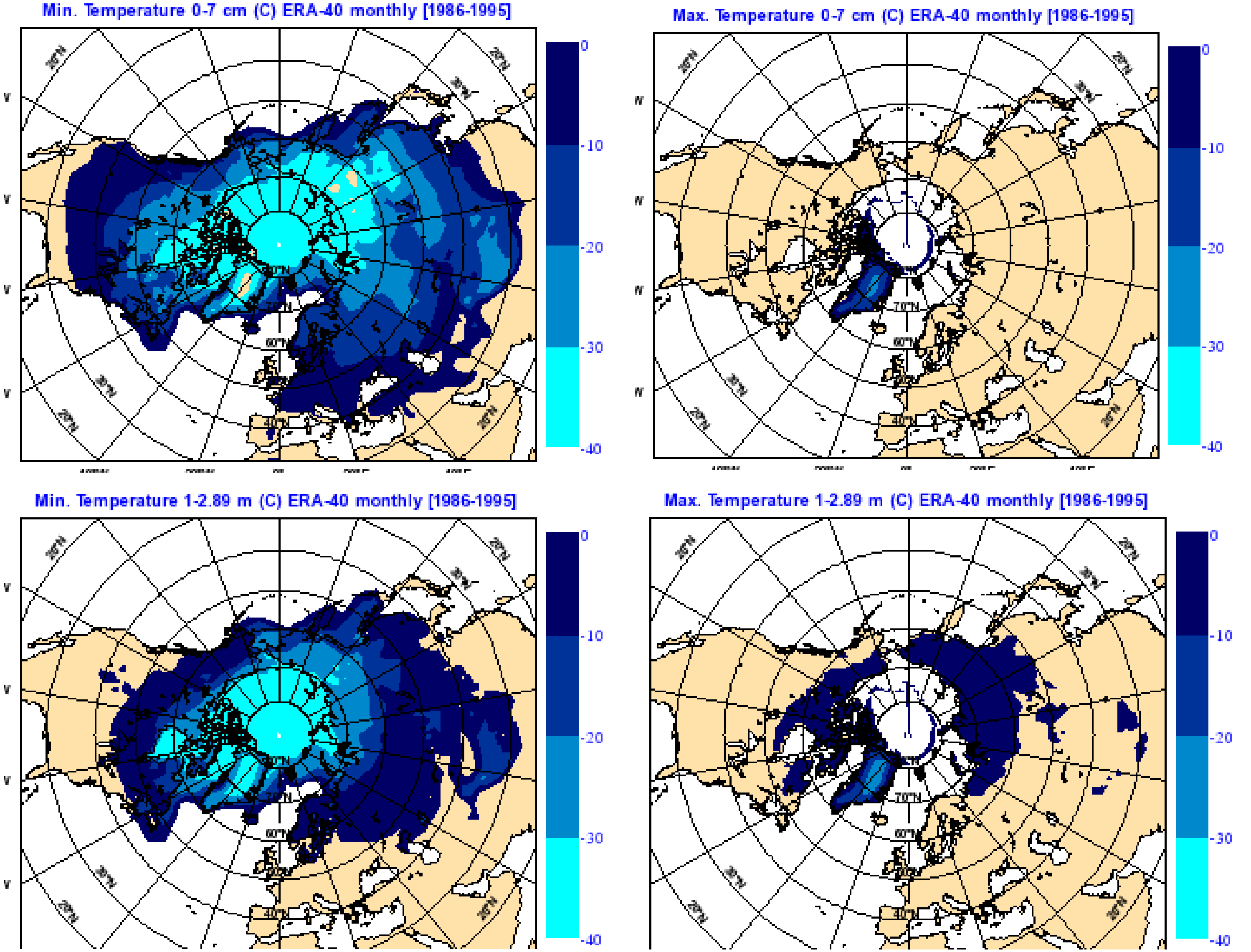
Min

Shading below zero only

Max

0-7 cm

100-289 cm


Min. Temperature 0-7 cm (C) ERA-40 monthly [1986-1995]

Max. Temperature 0-7 cm (C) ERA-40 monthly [1986-1995]

Min. Temperature 1-2.89 m (C) ERA-40 monthly [1986-1995]

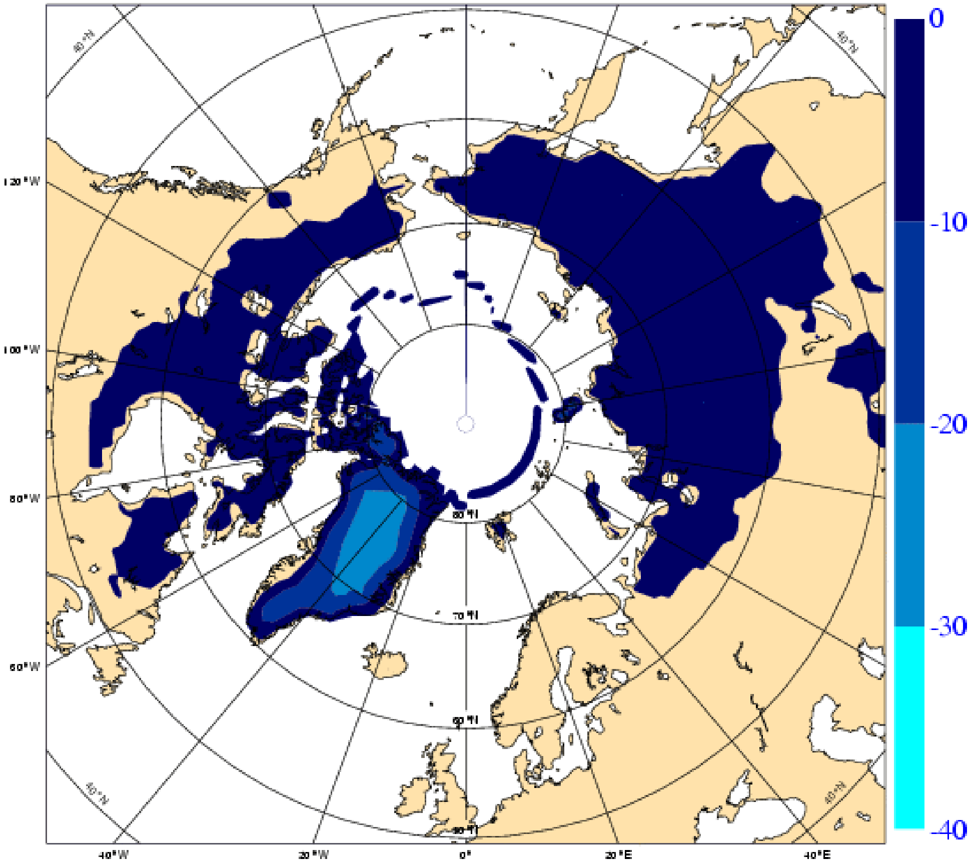
Max. Temperature 1-2.89 m (C) ERA-40 monthly [1986-1995]

0-7 cm

100-289 cm

Permafrost in ERA-40

Max. Temperature 1-2.89 m (C) ERA-40 monthly [1986-1995]



Source:International Permafrost Association, 1998.
Circumpolar Active-Layer Permafrost System (CAPS), version 1.0.

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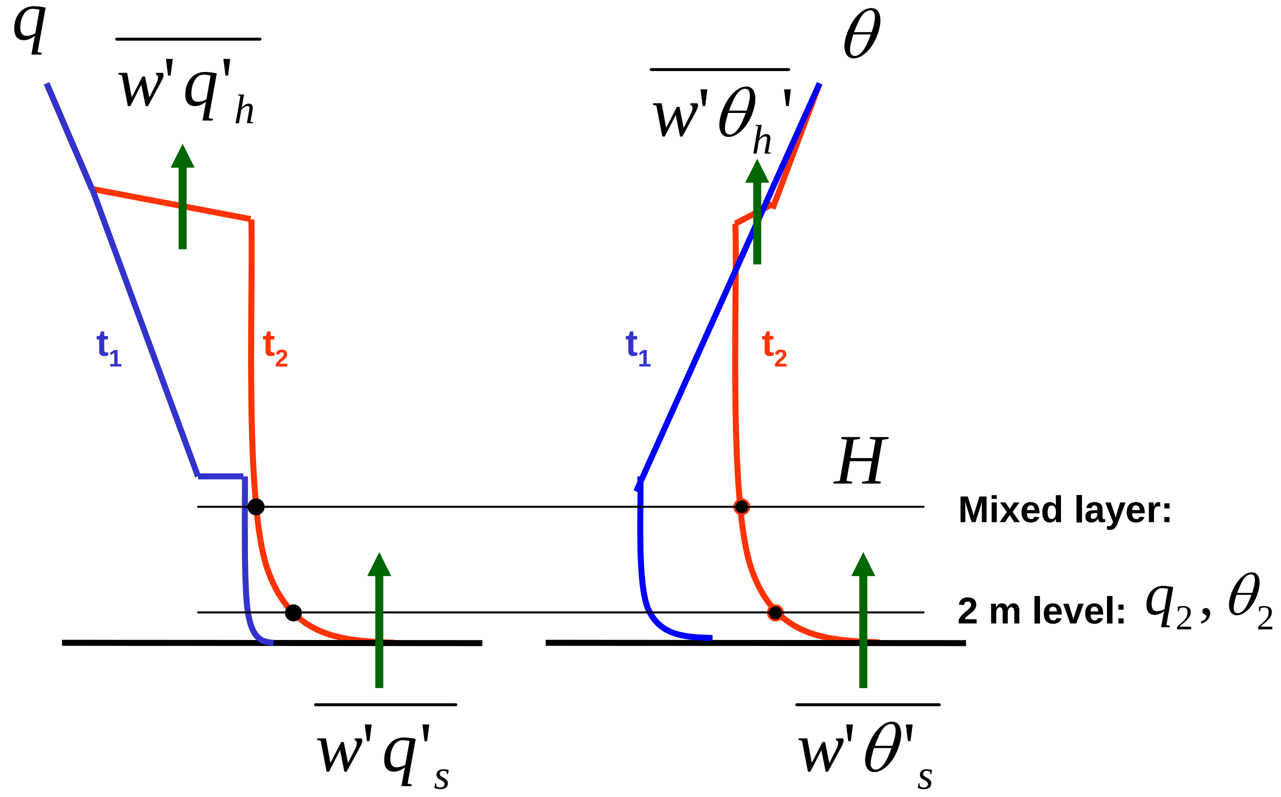
Land surface data assimilation in the ECMWF system

Short range forecast errors of 2m temperature and moisture (compared to SYNOP observations) depend on surface fluxes through two effects:

- Time evolution of mixed layer budgets depend on surface fluxes

- Near surface vertical gradients depend on surface fluxes

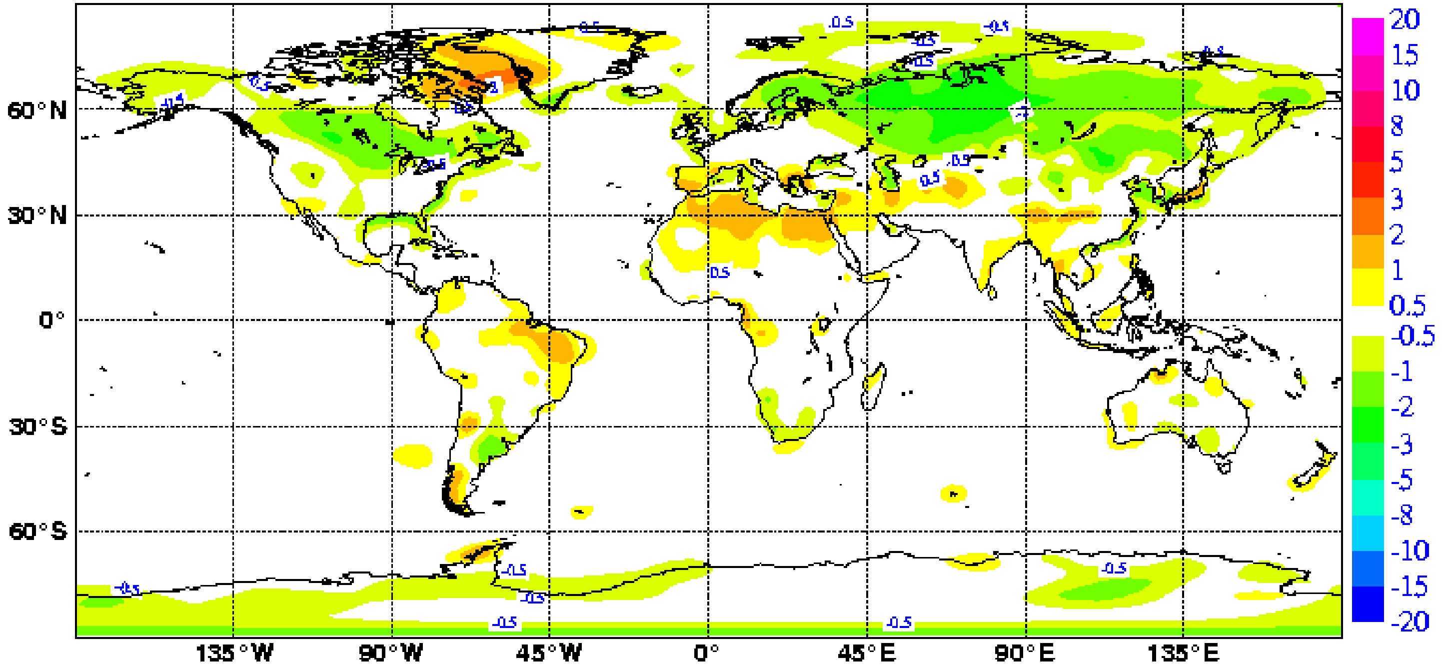


$$h\frac{dq_m}{dt} = \overline{w'q'}_s - \overline{w'q'}_h \qquad h\frac{d\theta_m}{dt} = \overline{w'\theta'}_s - \overline{w'\theta'}_h$$

$$q_2 - q_m \sim \overline{w'q'}_s \qquad \theta_2 - \theta_m \sim \overline{w'\theta'}_s$$

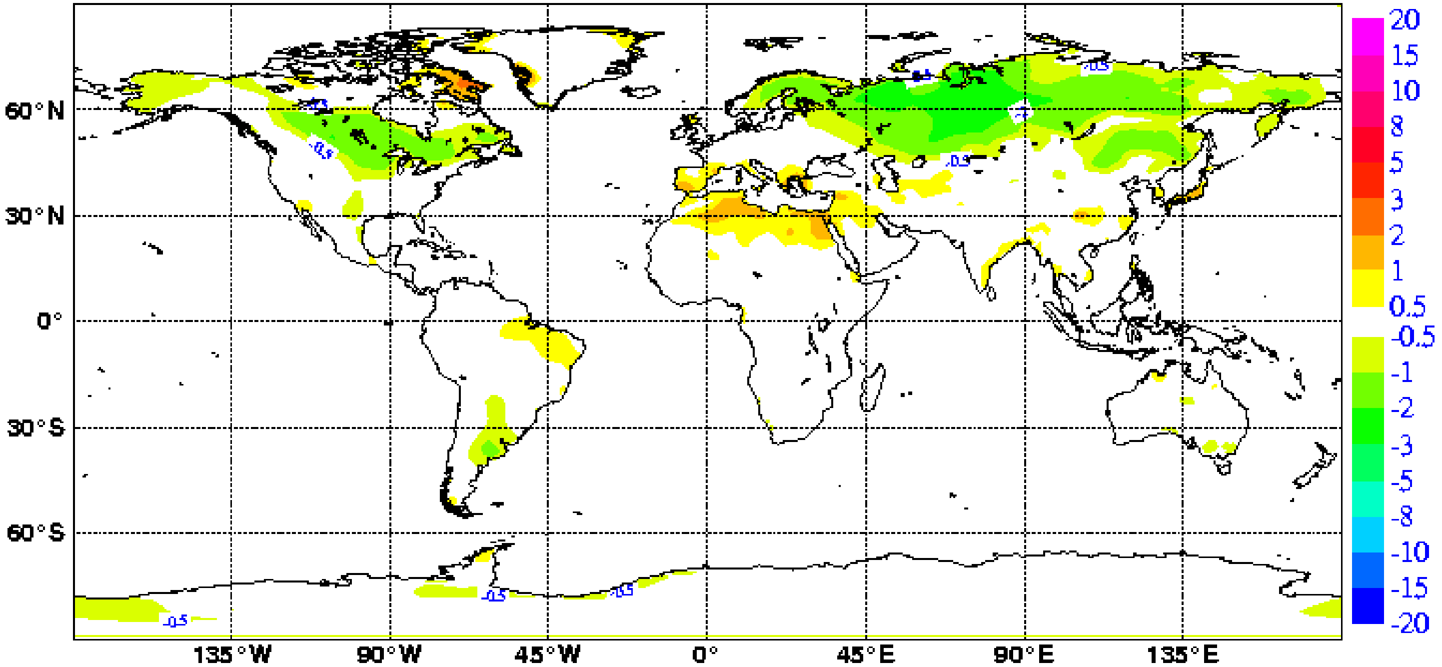
- Unstable situations are used to correct soil moisture
- Stable situations are use to correct temperature of soil layer 1

2m temperature analysis increments in ERA-40 January 1986-1995



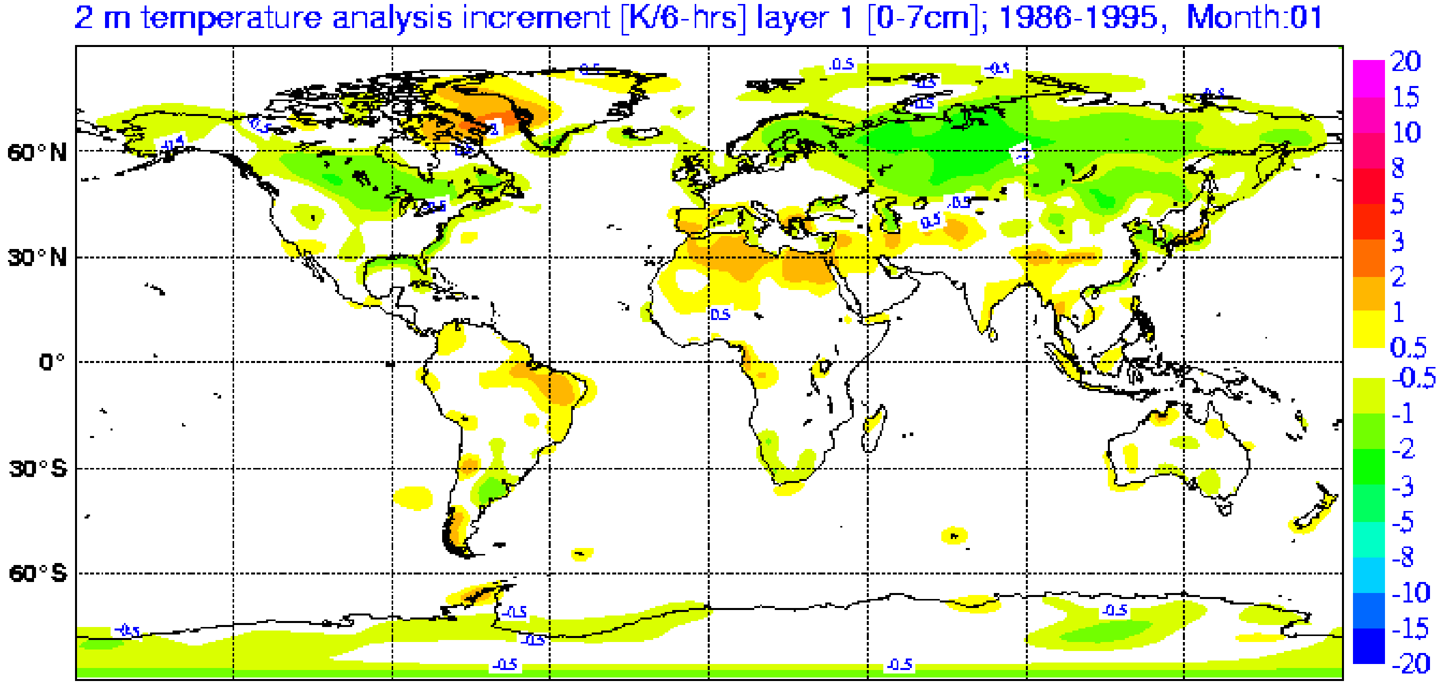
2 m temperature analysis increment [K/6-hrs] layer 1 [0-7cm]; 1986-1995, Month:01

Soil temperature analysis increments in ERA-40 January 1986-1995

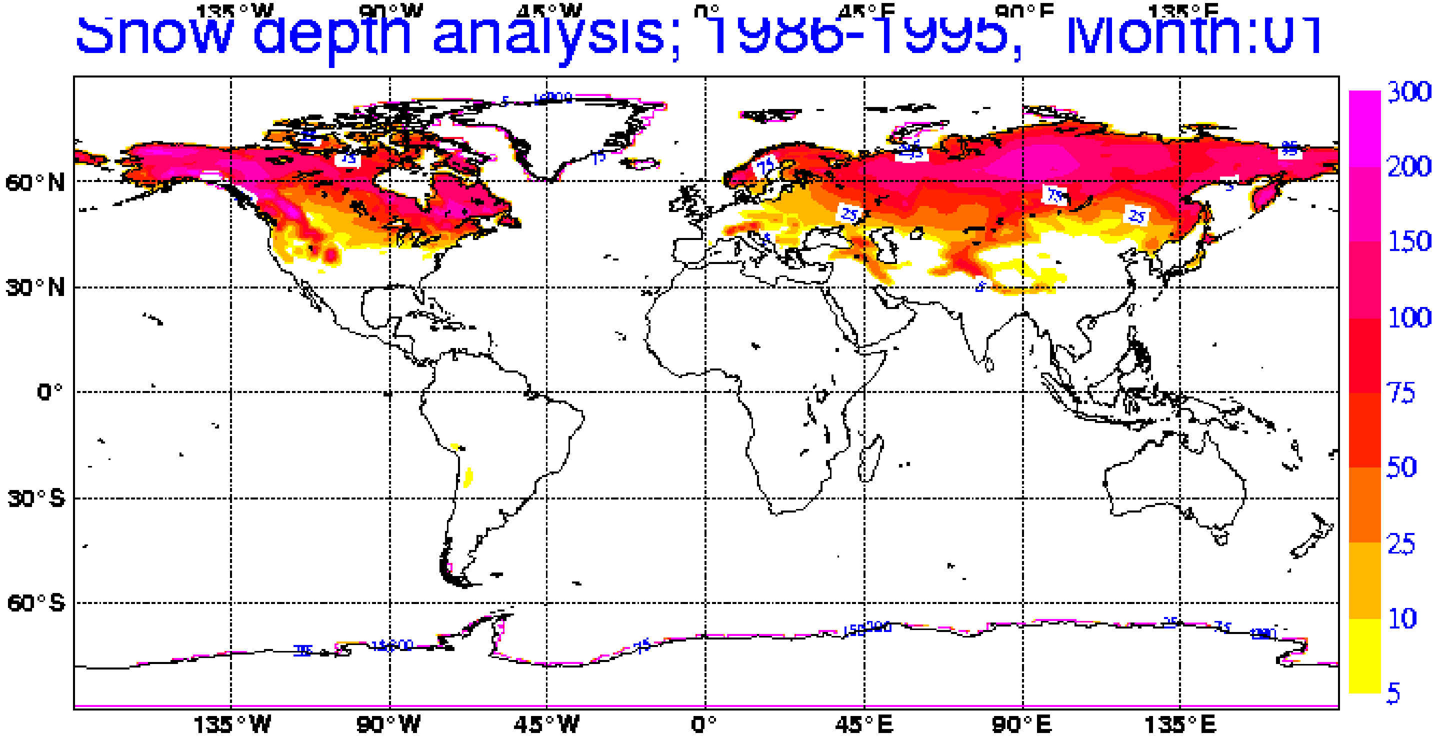


Soil temperature analysis increment [K/6-hrs] layer 1 [0-7cm]; 1986-1995, Month:01

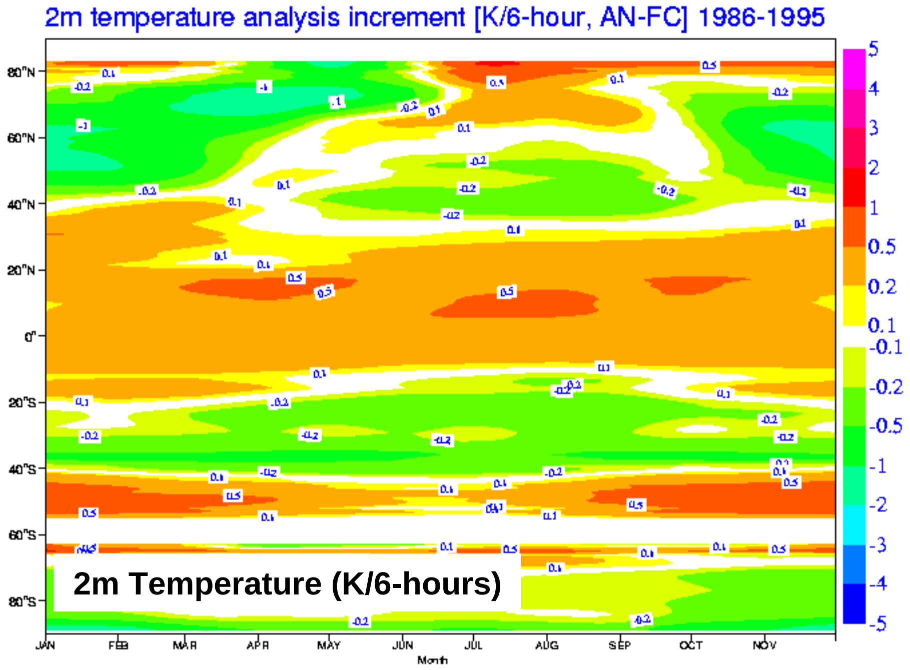
2m temperature analysis increments in ERA-40 January 1986-1995



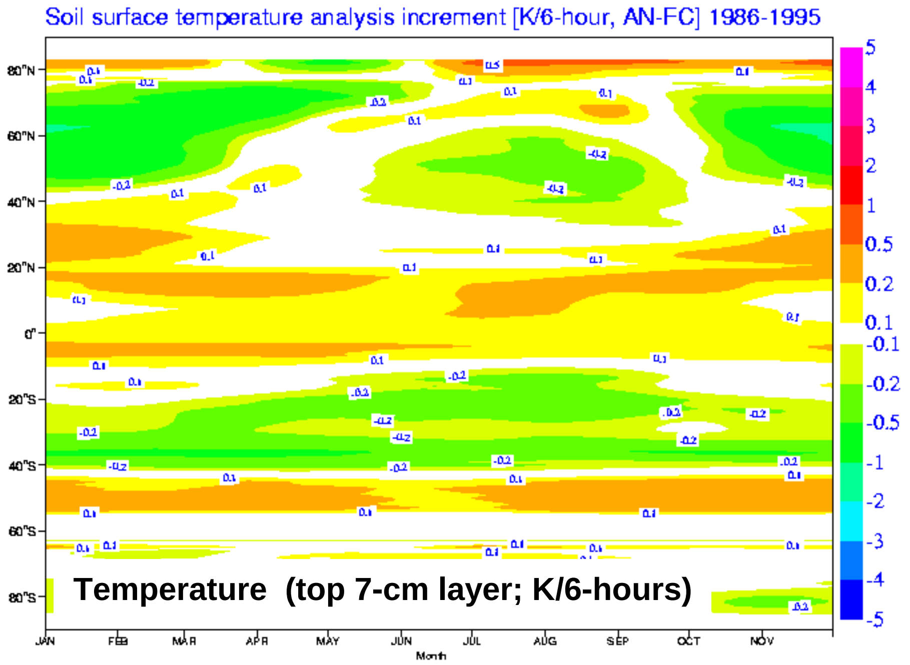
Snow depth analysis in ERA-40 January 1986-1995



Surface analysis increments in ERA-40 (1986-1995)



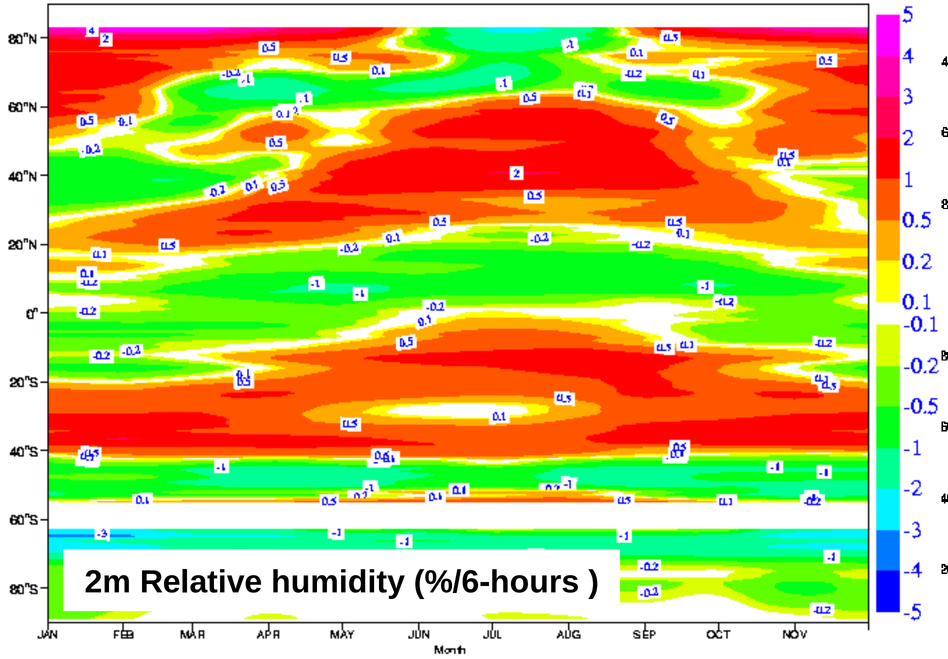
2m Temperature (K/6-hours)



Temperature (top 7-cm layer; K/6-hours)

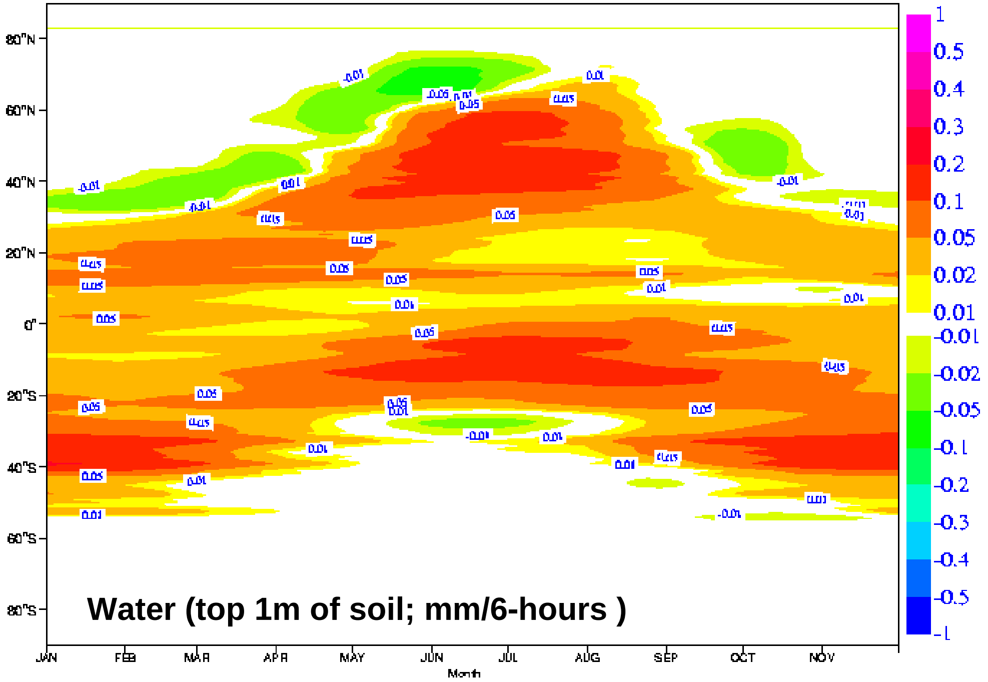
Surface analysis increments in ERA-40 (1986-1995)

2m relative humidity analysis increment [%/6-hour, AN-FC] 1986-1995



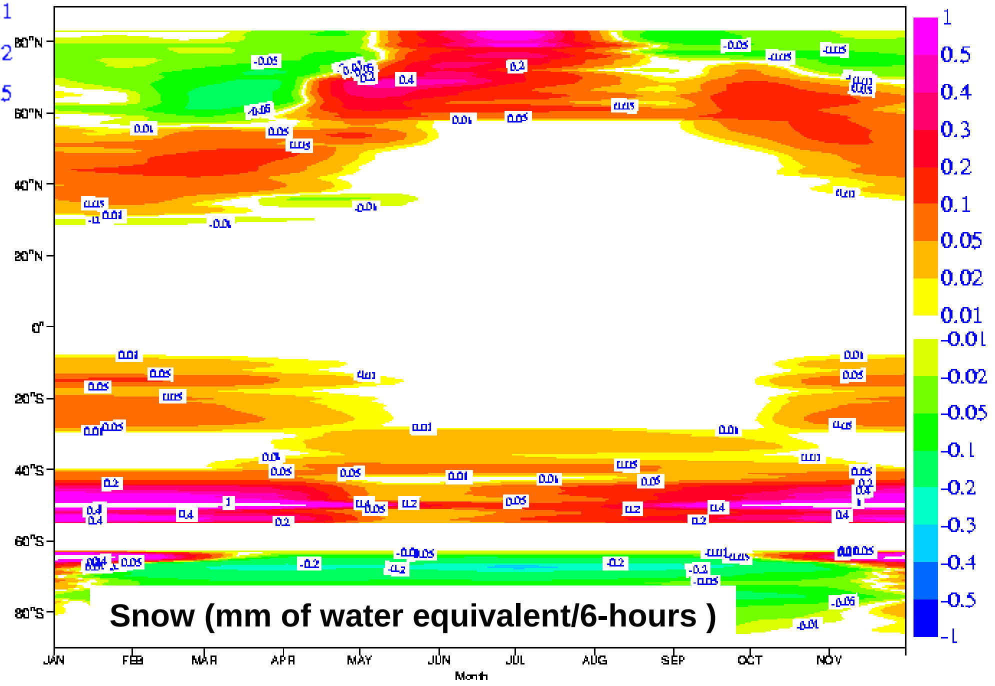
2m Relative humidity (%/6-hours)

Top 1-m soil moisture analysis increment [mm/6-hour, AN-FC] 1986-1995



Water (top 1m of soil; mm/6-hours)

Snow water equivalent analysis increment [mm/6-hour, AN-FC] 1986-1995



Snow (mm of water equivalent/6-hours)

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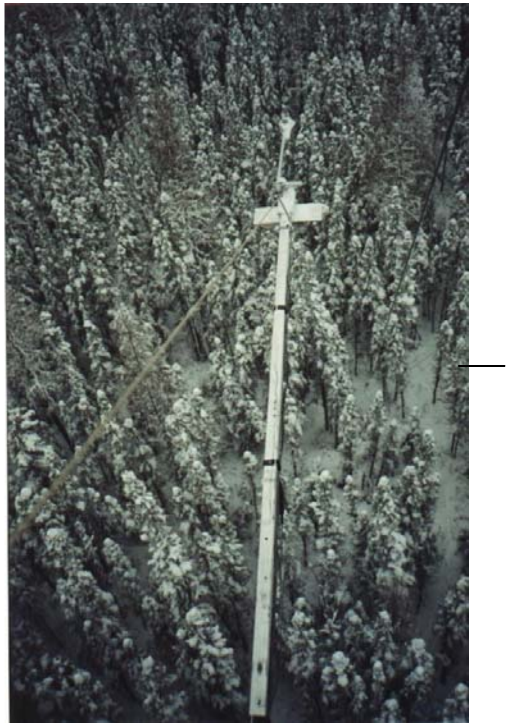
- **ERA-40 and BERMS**

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



Three different sites less than 100 km apart in Saskatchwan at the southern edge of the Canadian boreal forest (at about 54ºN/105^{0}W) :

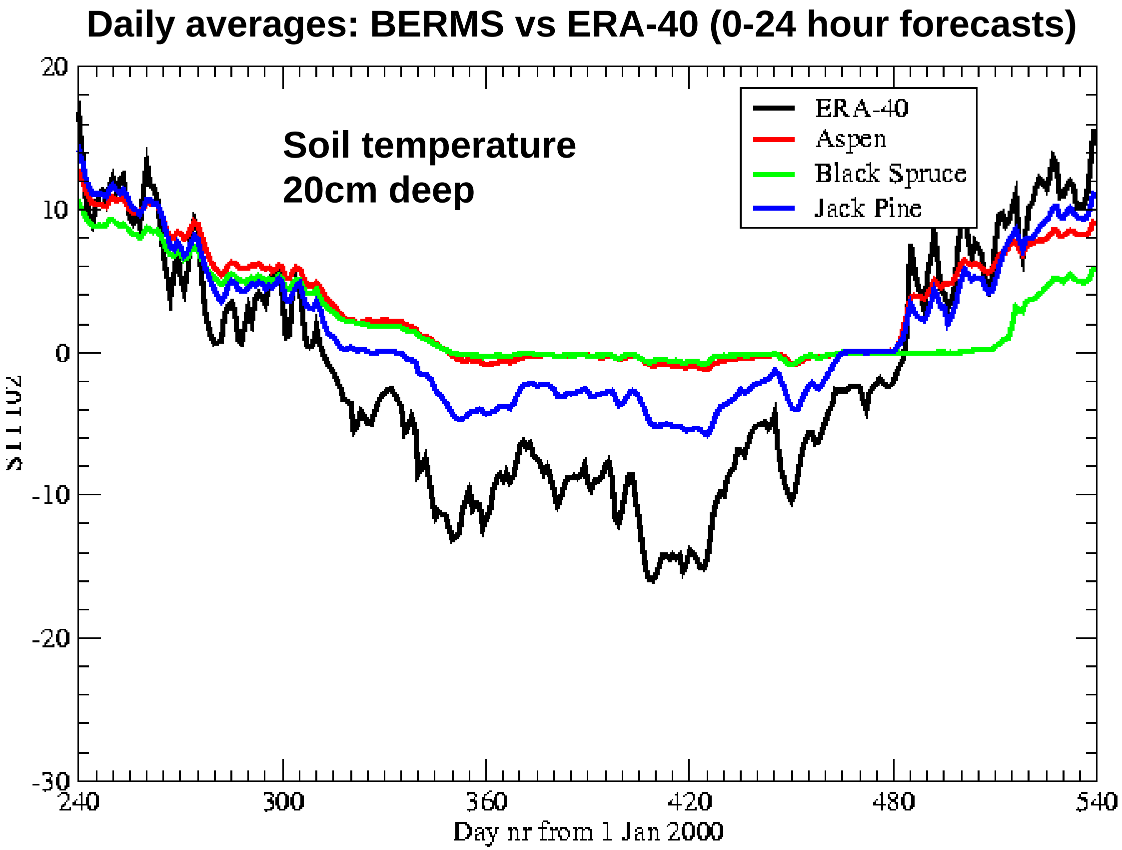
Old Aspen (deciduous, open canopoy, hazel understory, 1/3 of evaporation from understory)

Old Black Spruce (boggy, moss understory)

Old Jack Pine (sandy soil)

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

Soil temperatures from BERMS and ERA-40

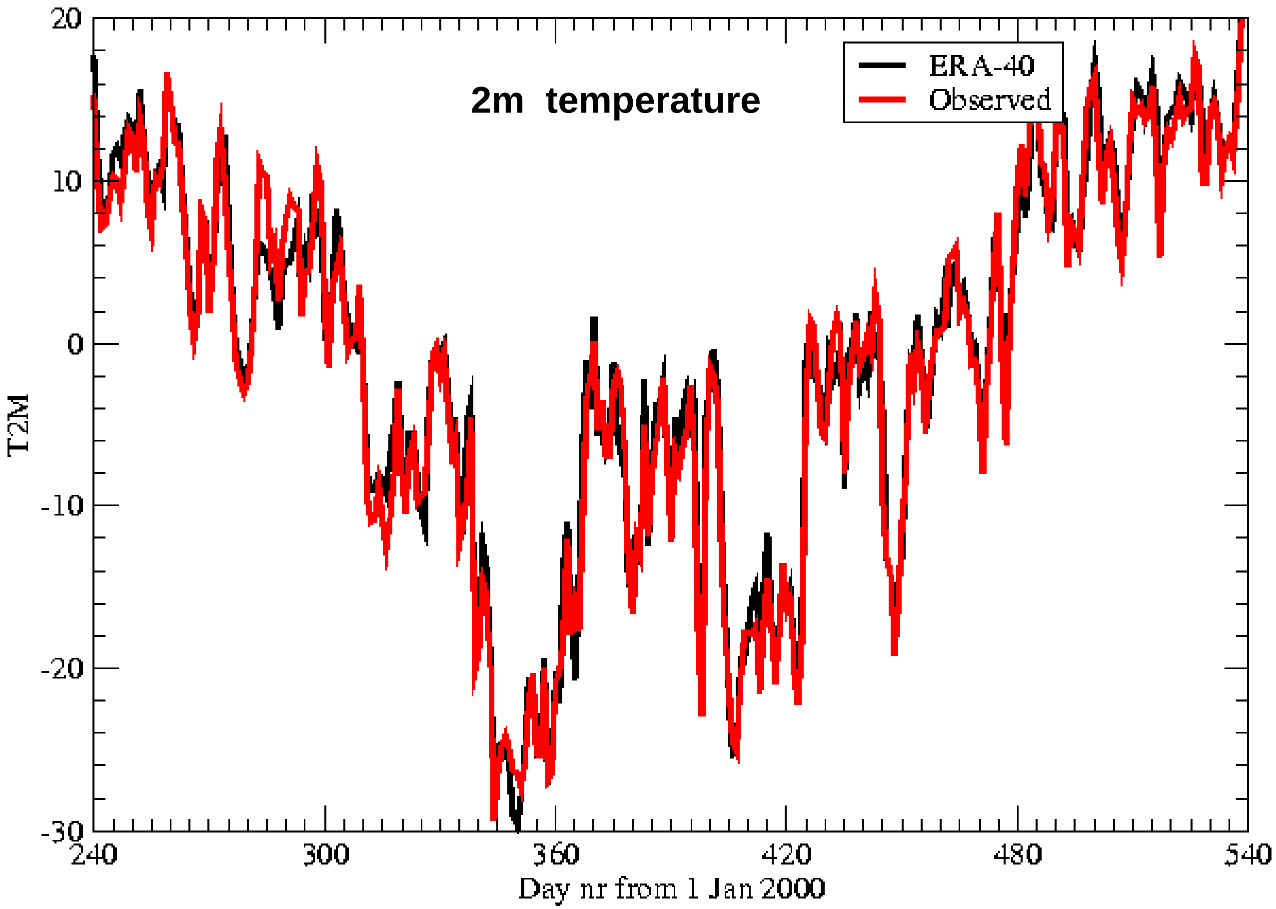


Daily averages: BERMS vs ERA-40 (0-24 hour forecasts)

Data processed to daily averages
and gap filled by Betts et al. (2005)

Differences between sites are non-negligible, but the differences tend to be smaller than the model errors

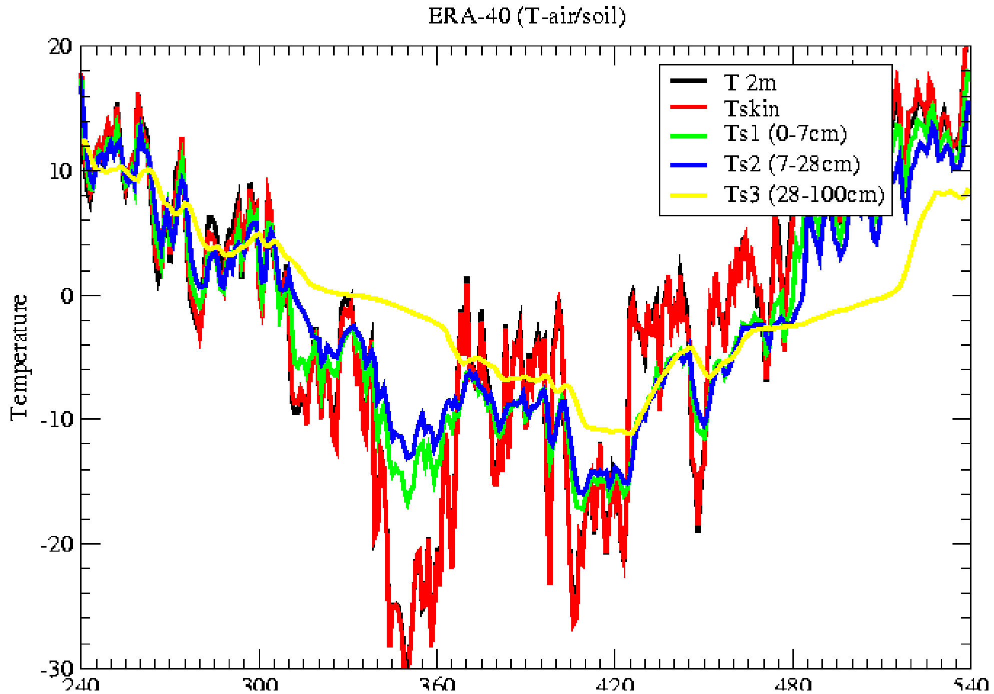
BERMS vs ERA-40



ERA-40 follows observations with RMS error of about 2 K.

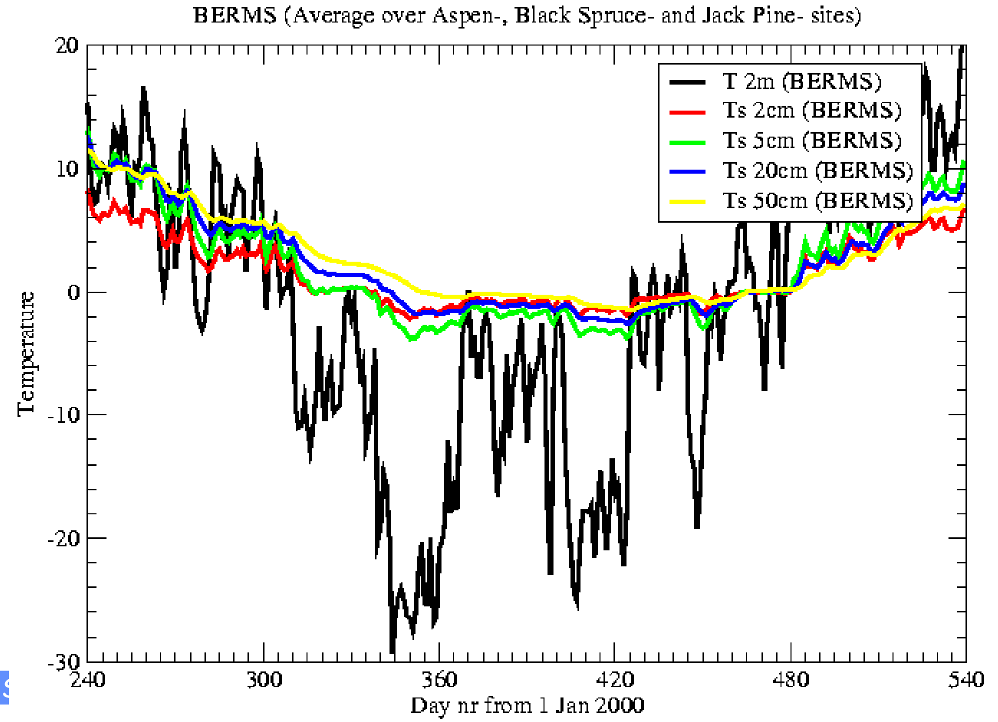
Air/Soil temperatures

ERA-40



ERA-40 (T-air/soil)

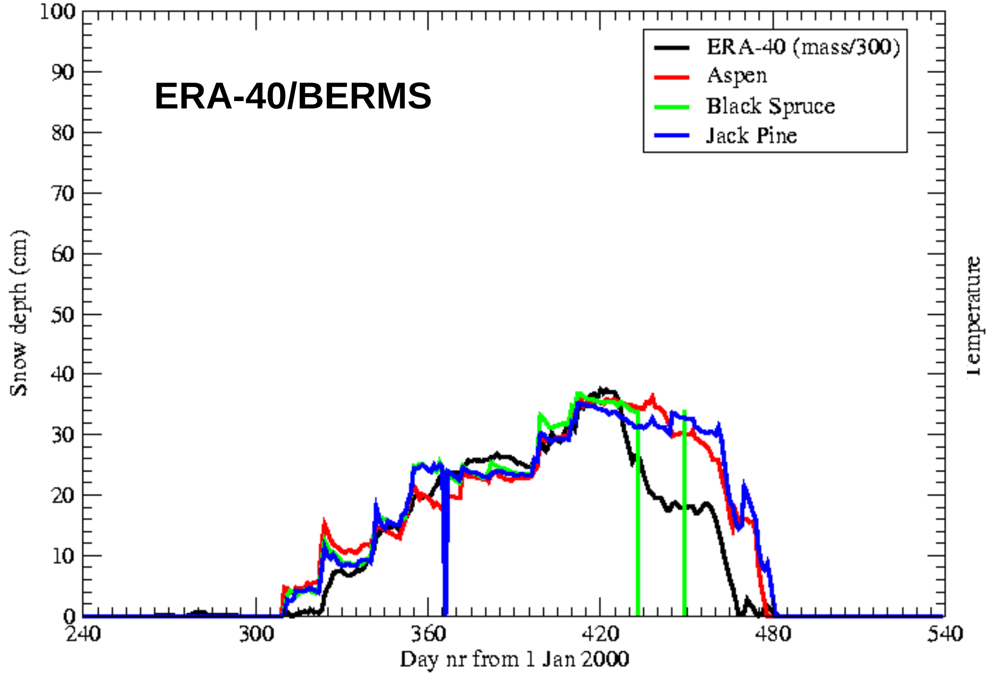
BERMS



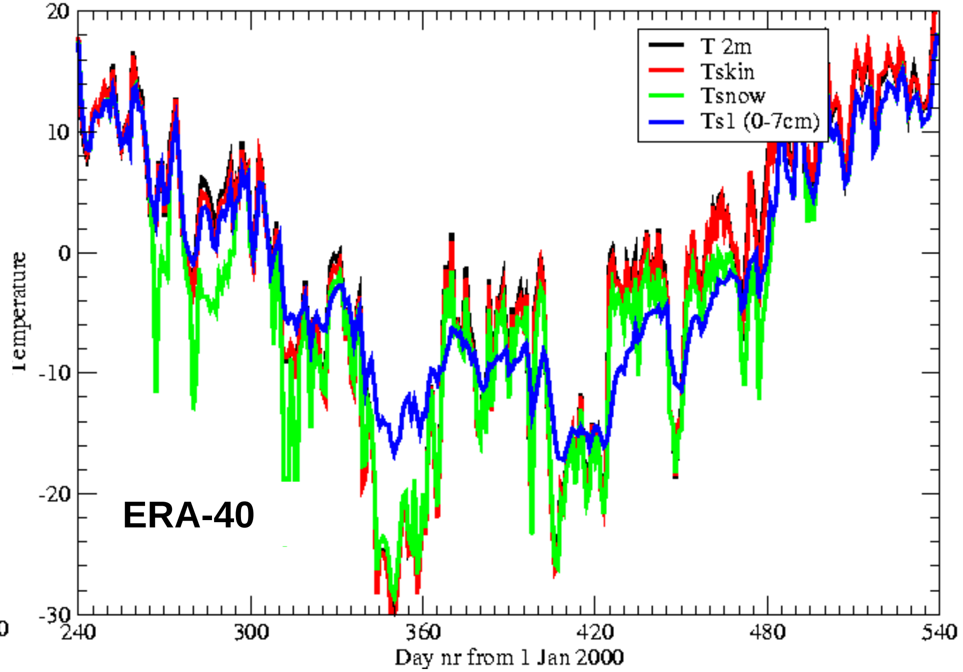
BERMS (Average over Aspen-, Black Spruce- and Jack Pine- sites)

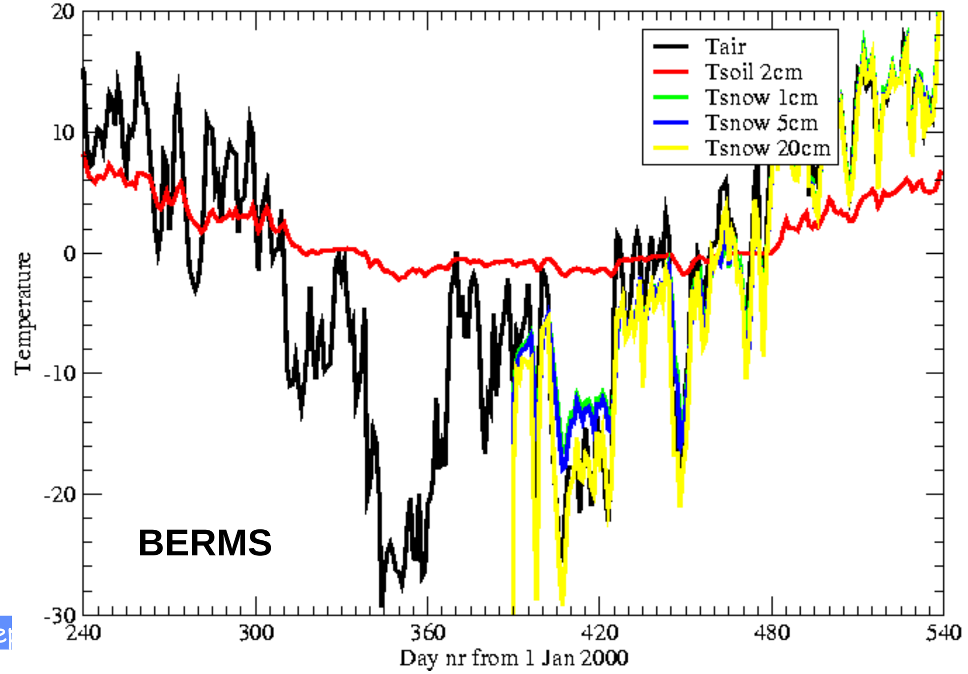
ERA-40 has much more temperature variation in the soil than observed.

Snow depth



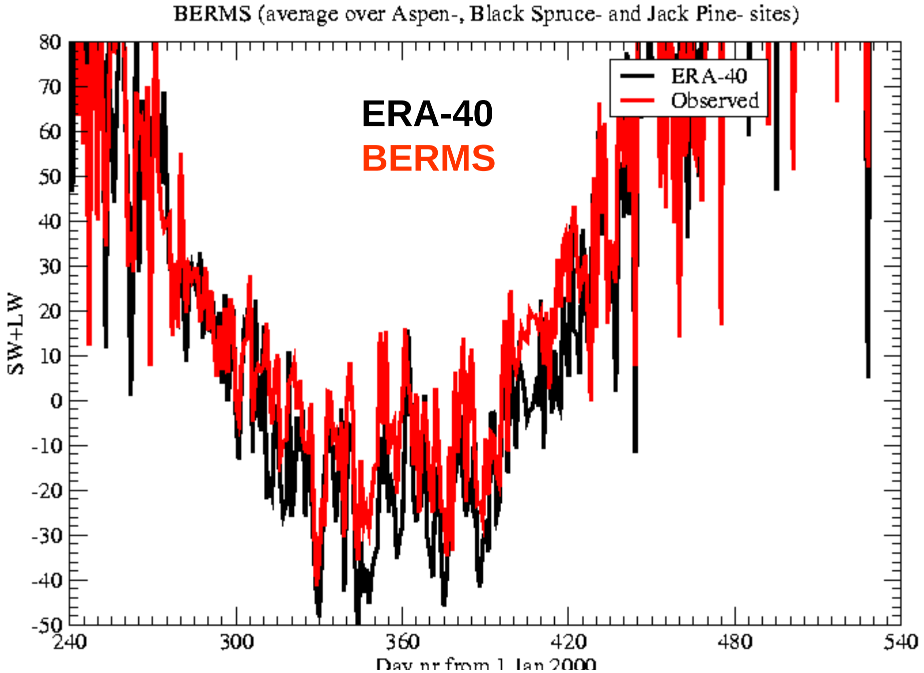
Air/snow/Soil temperatures



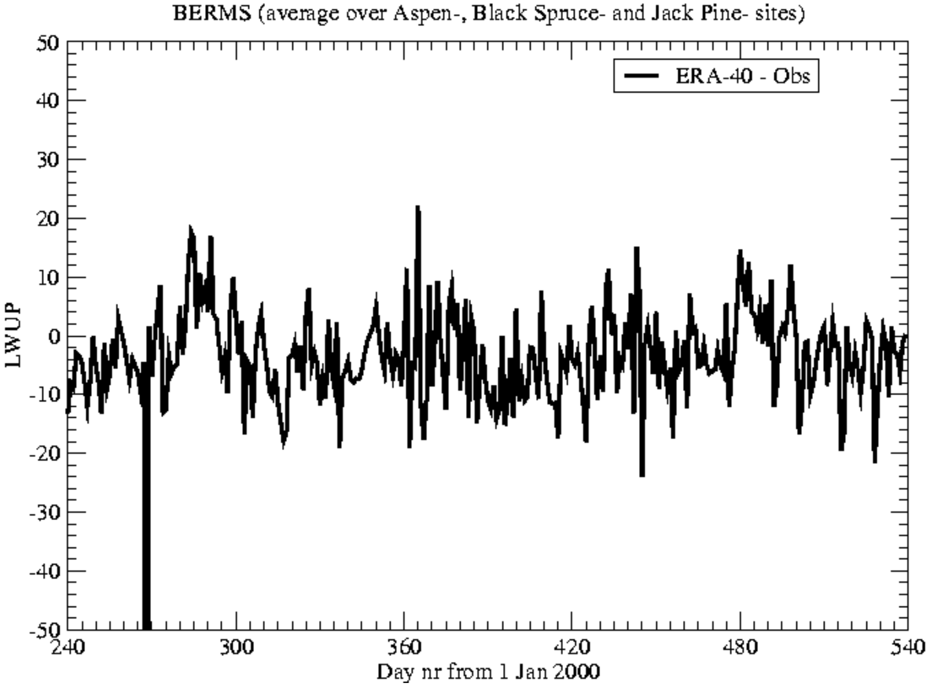


- **Air temperature and snow temperatures are well connected in both ERA-40 and observations**
- **In ERA-40: strong response of soil temperature to air/snow temperature**
- **In observations: weak response of soil temperature to air/snow temperature**
- **Is the undergrowth providing an insulation layer between snow and soil?**

Net radiation

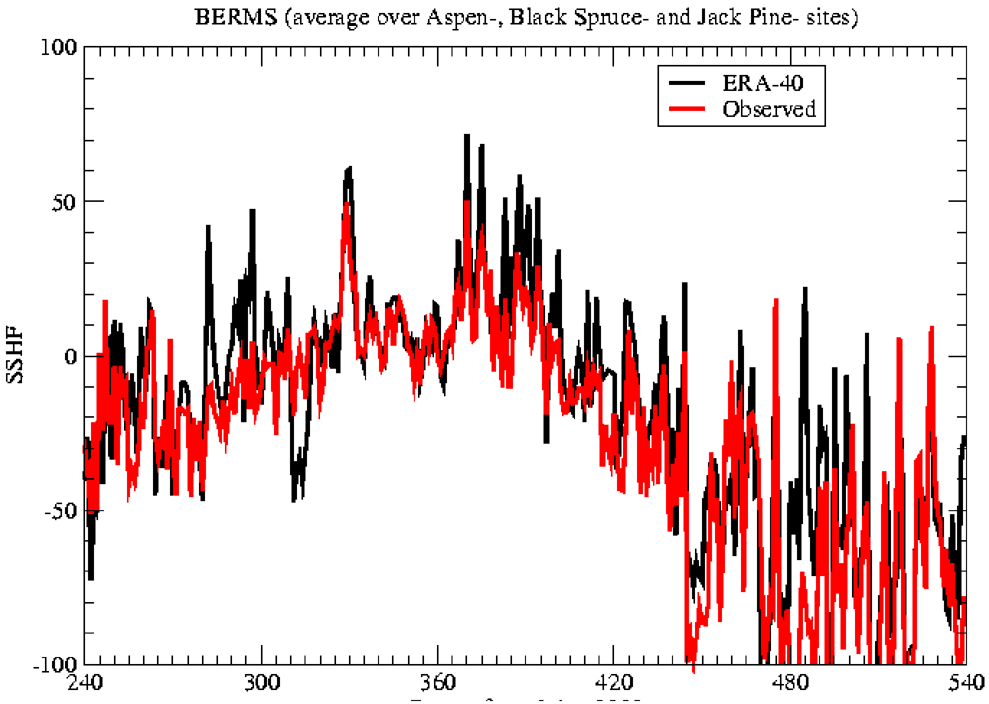


LW-up error (ERA-40 - BERMS

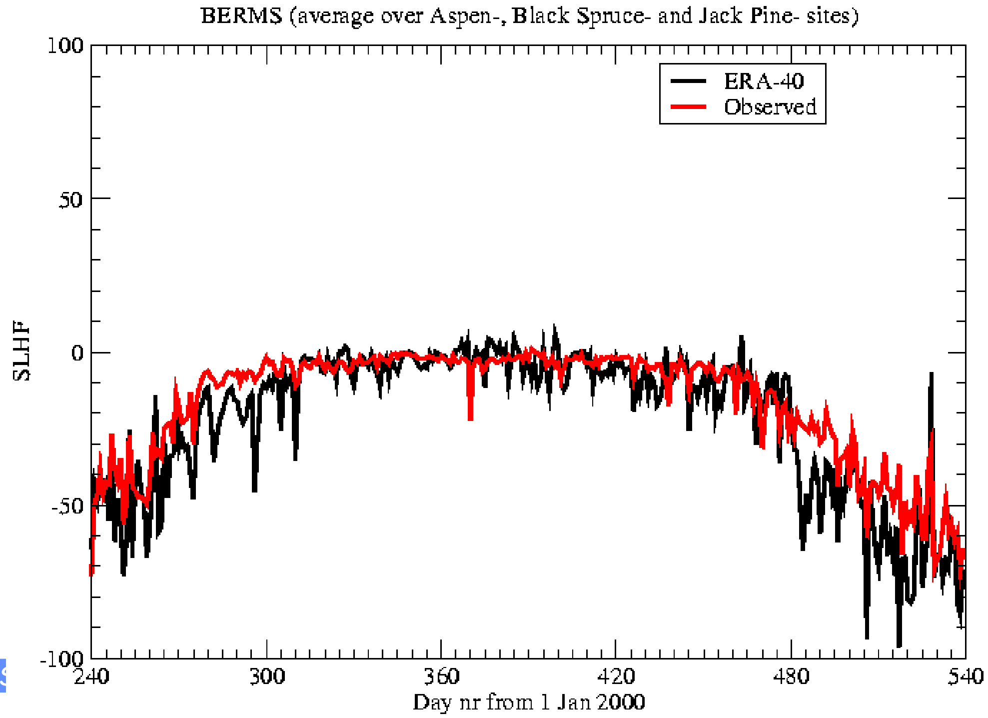


ERA-40 has slightly too much radiative cooling at the surface (mainly from LW-up)

SSHF

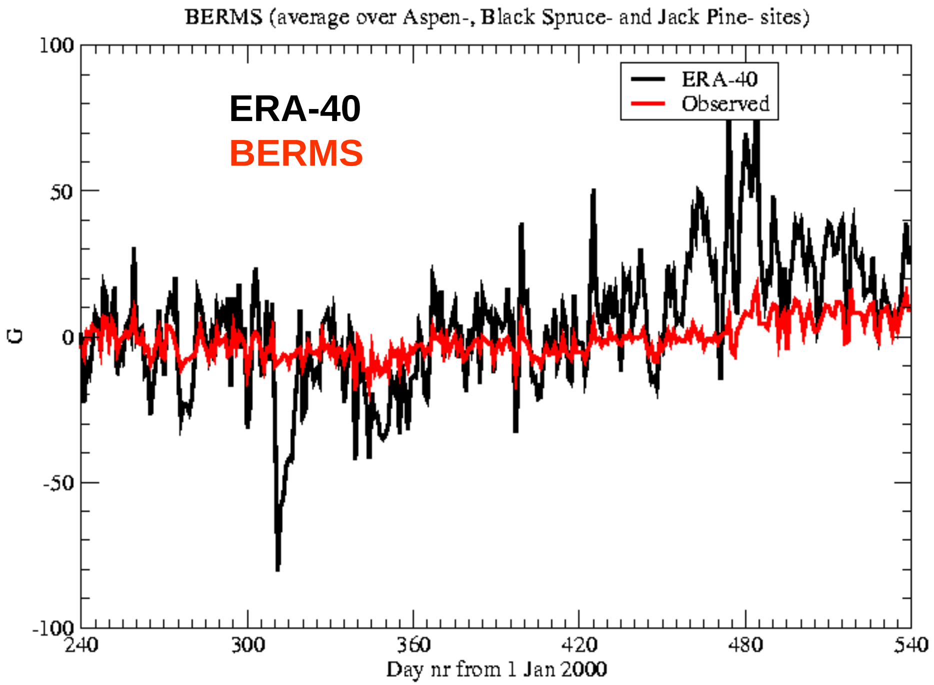


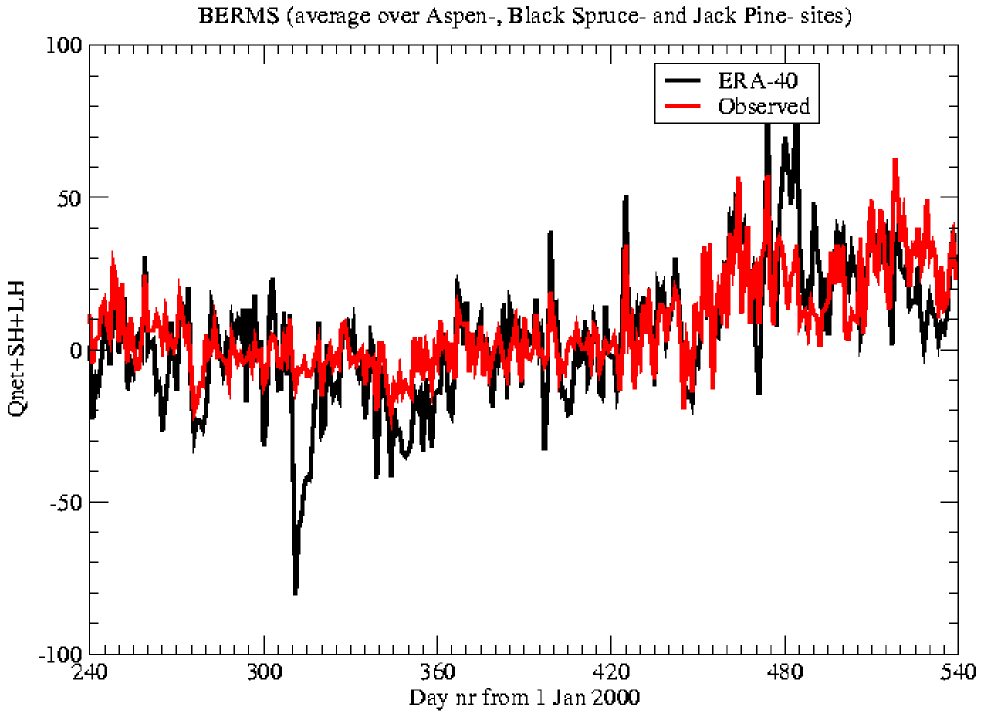
SLHF



Sensible and latent heat fluxes look reasonable

Ground heat flux (residual of Qnet+SSHF+SLHF)



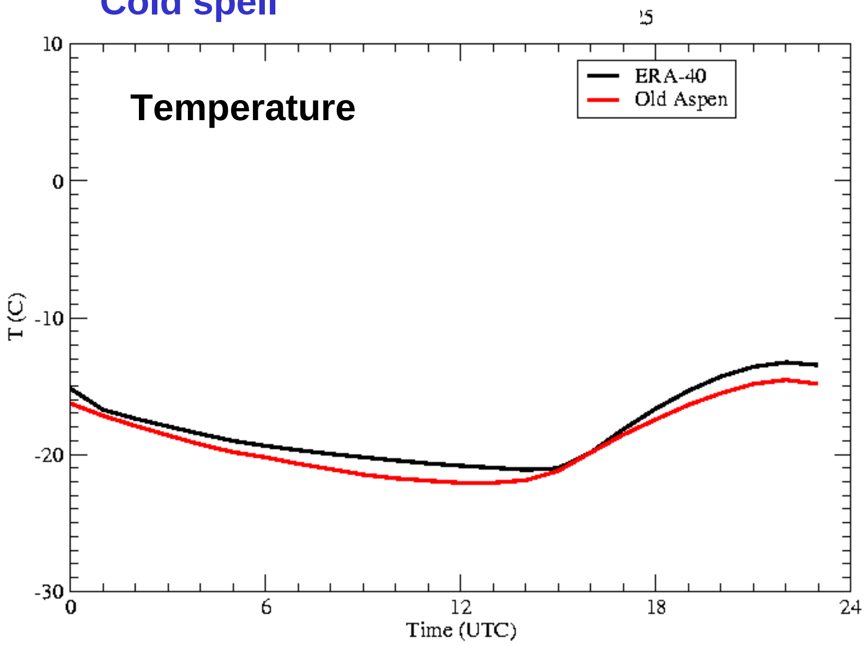


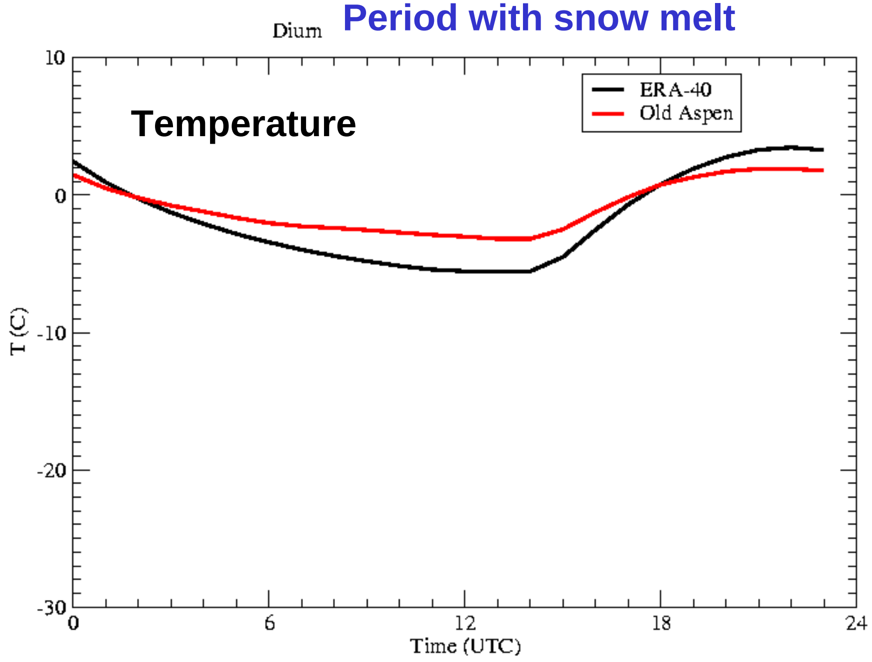
Ground heat flux is excessive in ERA-40; absorbs errors and variability

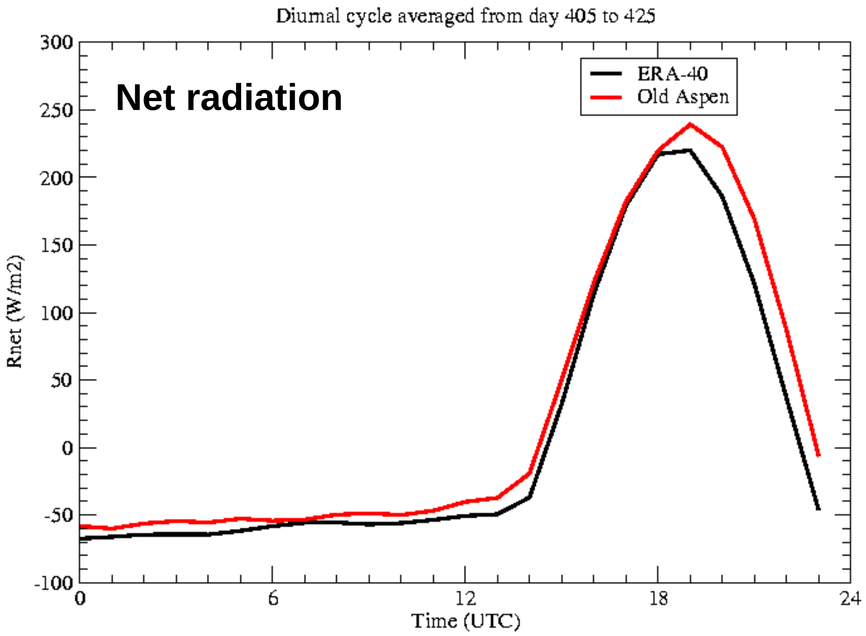
BERMS diurnal cycles (20-day averages)

Cold spell

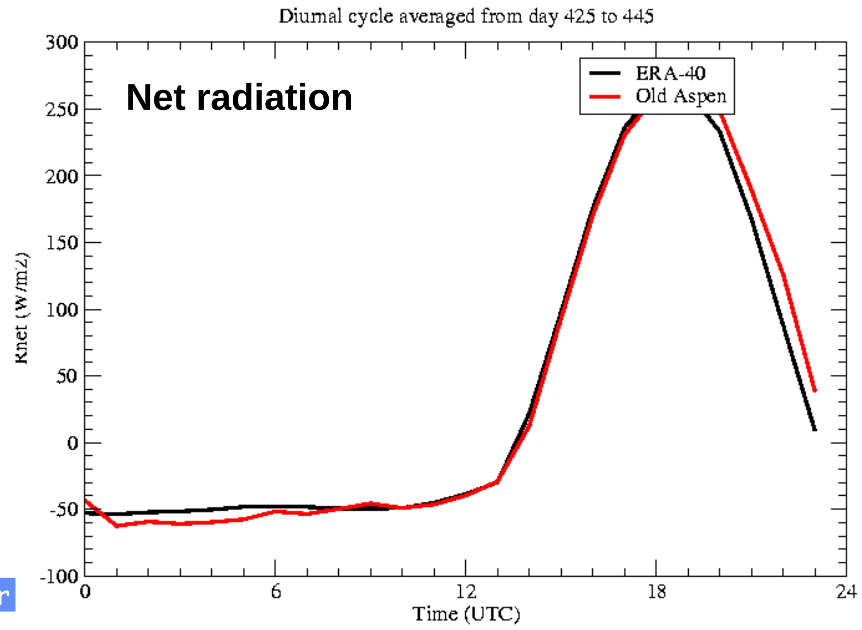
Period with snow melt





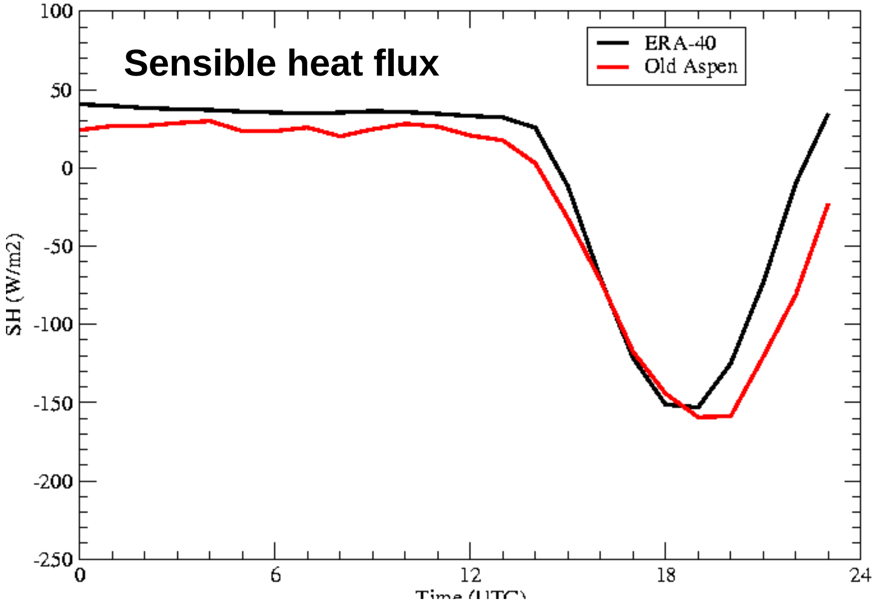


September

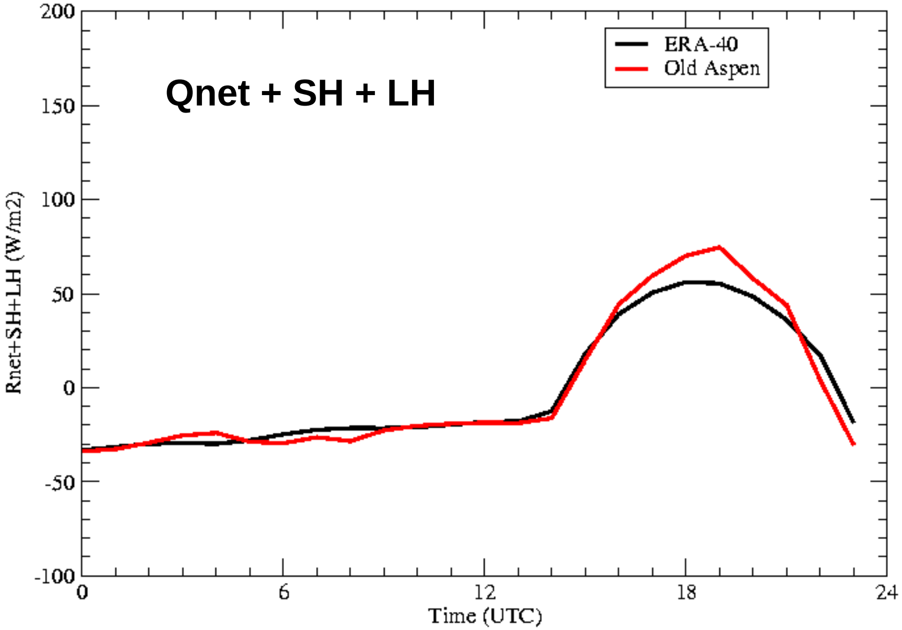


BERMS diurnal cycles (20-day averages)

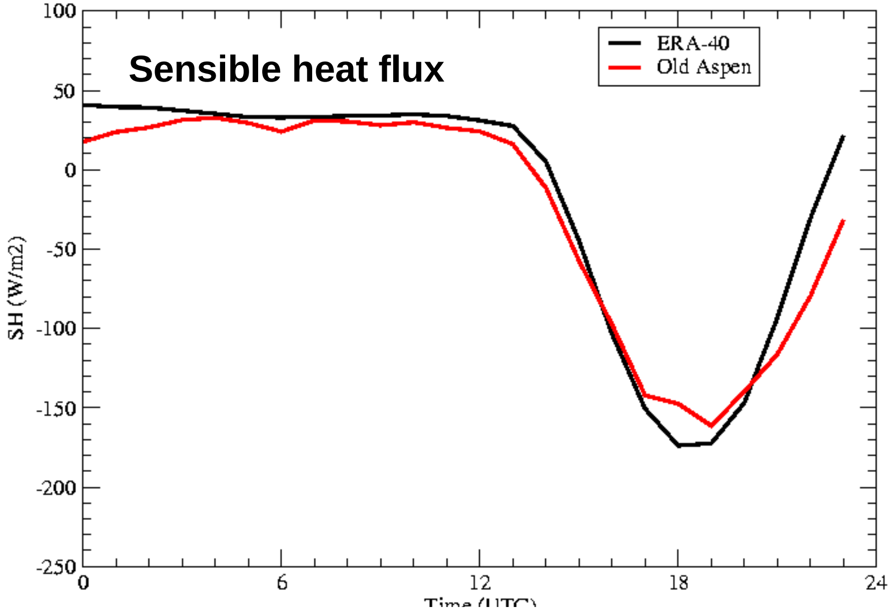
Cold spell



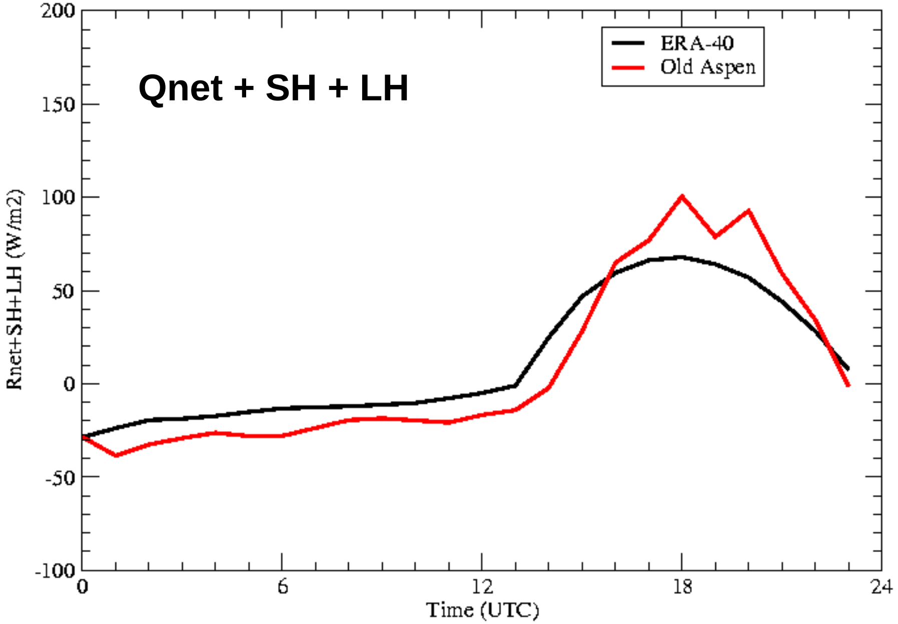
Diurnal cycle averaged from day 405 to 425



Period with snow melt



Diurnal cycle averaged from day 425 to 445

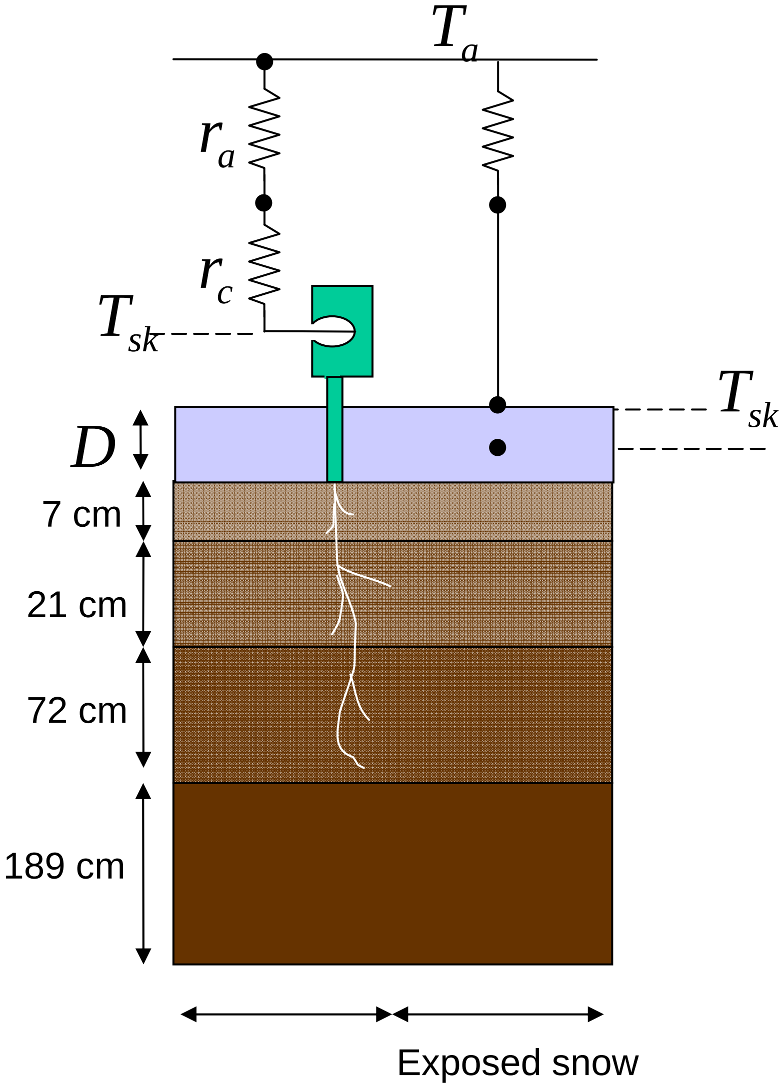


, Septem

So why is TESSEL melting snow too quickly ?

- Diurnal cycle of heat flux into the snow pack looks very reasonable
- Day time energy flux into the surface (snow+vegetation+land) is probably too large (observations typically underestimate turbulent fluxes)

- Day time melt runs off and can not re-freeze because TESSEL does not keep water phase in snow pack
- Canopy/snow coupling may be too strong
- Aerodynamic coupling with the atmosphere may be too strong (Van den Hurk and Viterbo 2002) e.g. too large roughness lengths in snow areas



Summary

- Field experiments have been crucial to the land surface and ice mode developments at ECMWF
- Temperatures at high latitudes are the result of a subtle balance of small energy fluxes
- Radiation (influenced by clouds), and the coupling coefficients in the boundary layer and the surface are crucial
- ECMWF model (TESSEL + boundary layer scheme) has too strong coupling to deep surface; keeps errors under control
- Data assimilation is very efficient in keeping 2m temperature and humidity errors under control at the expense of soil temperature (and soil moisture)
- Field experiments will help to improve model and reduce analysis increments