The stable boundary layer in the ECMWF model

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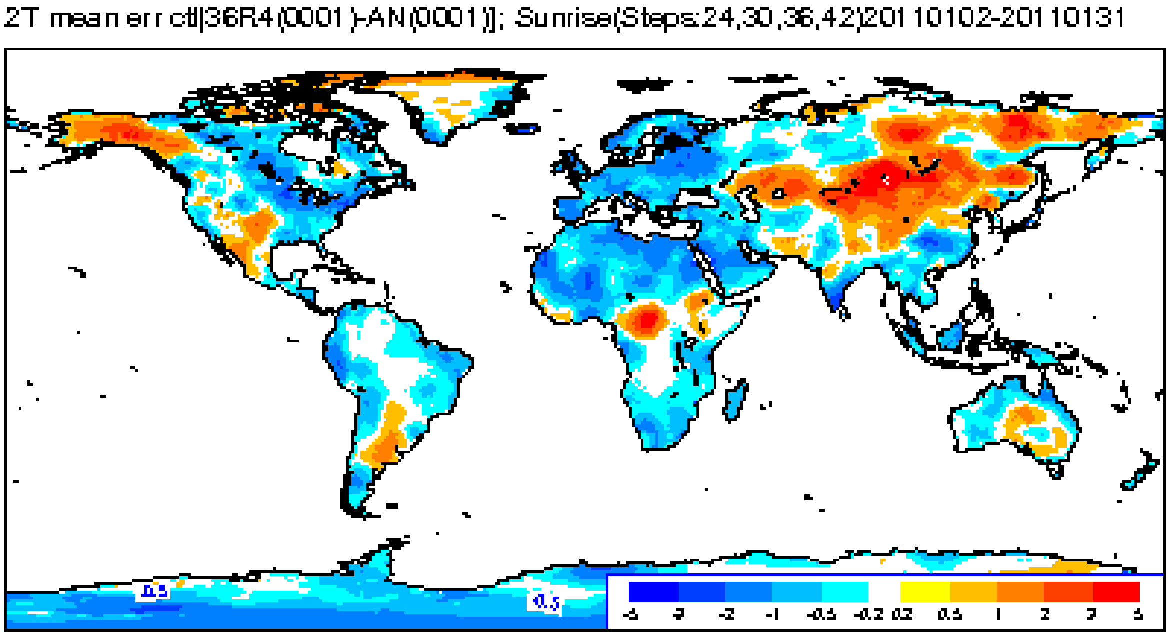
(ECMWF)

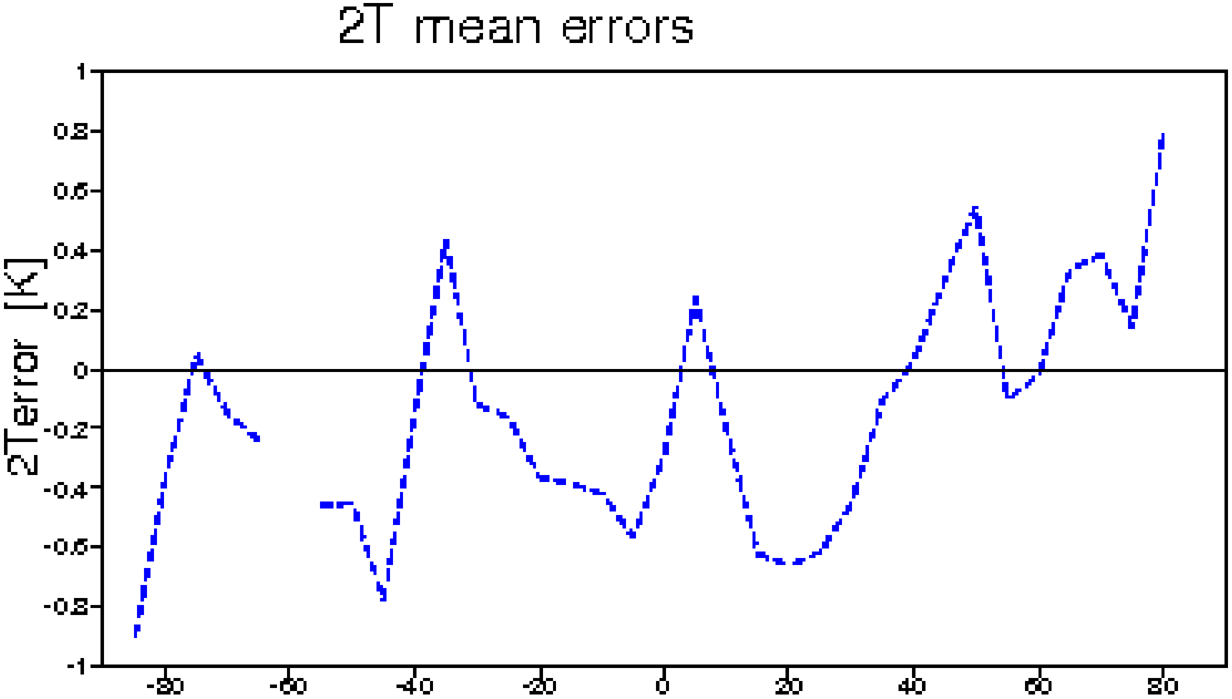
**Thanks to: Gianpaolo Balsamo, Alan Betts, Emanuel Dutra,
Martin Koehler, Irina Sandu, Soumia Serrar, Pedro Viterbo**

- **Introduction**
- **Thermal coupling of the atmosphere to the surface**
- **Momentum transport**

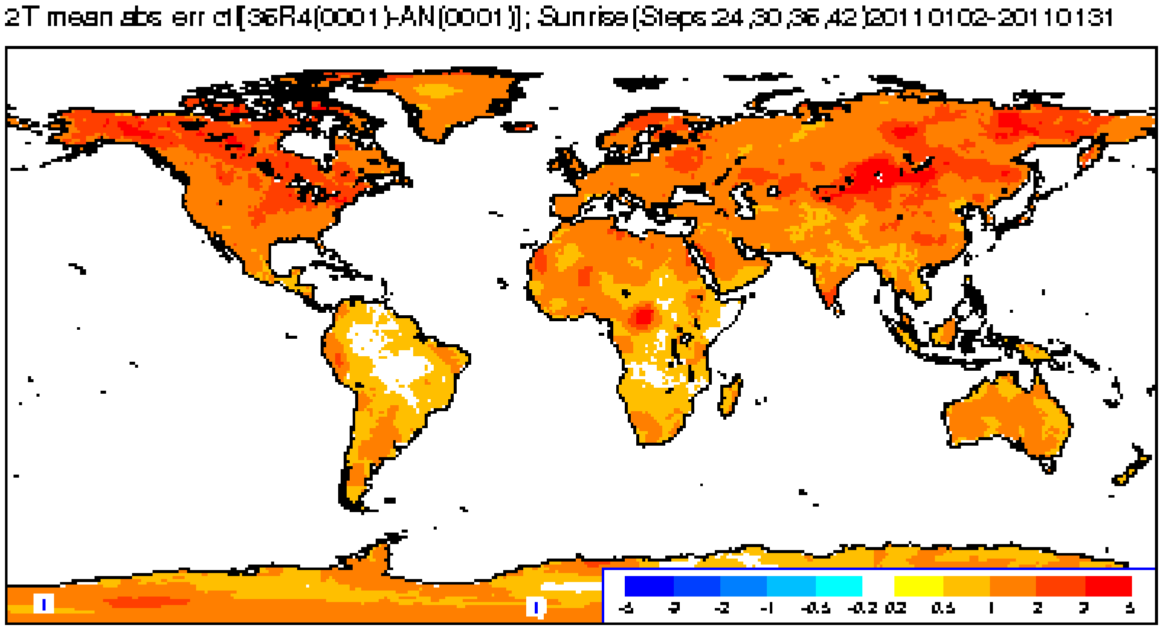
Mean error of minimum temperature at 2m for January 2011



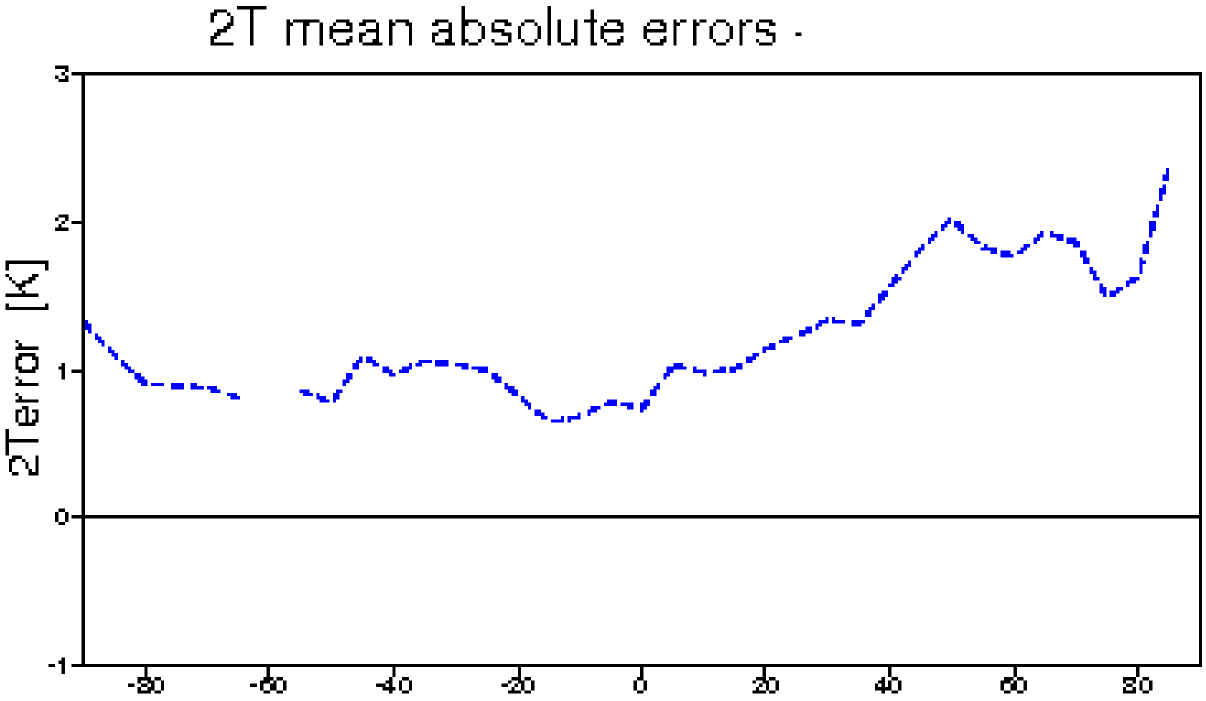
Zonal average over land



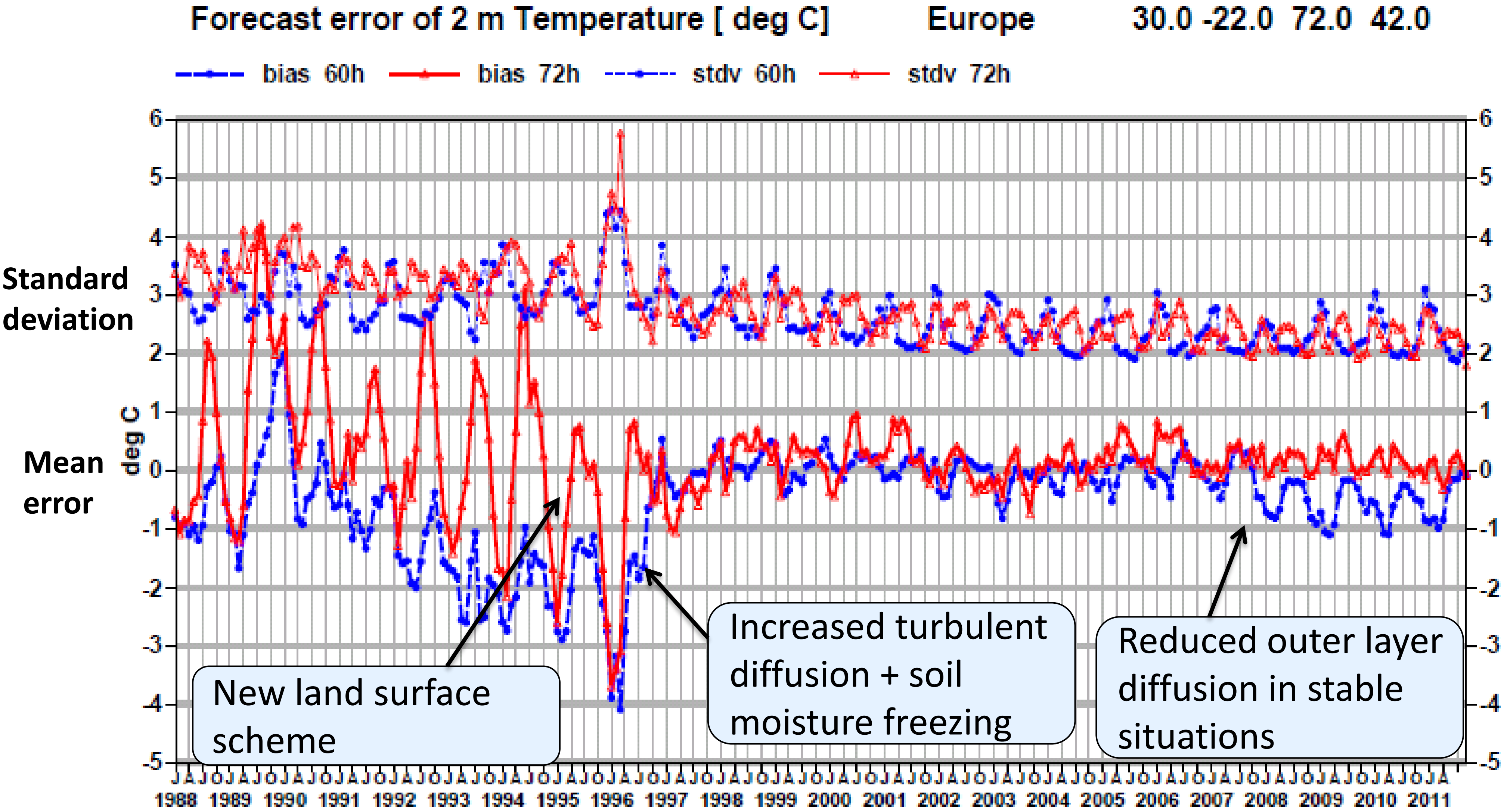
Mean absolute error of minimum 2T for January 2011



Zonal average over land



History of day and night time temperature errors
Monthly averages over Europe

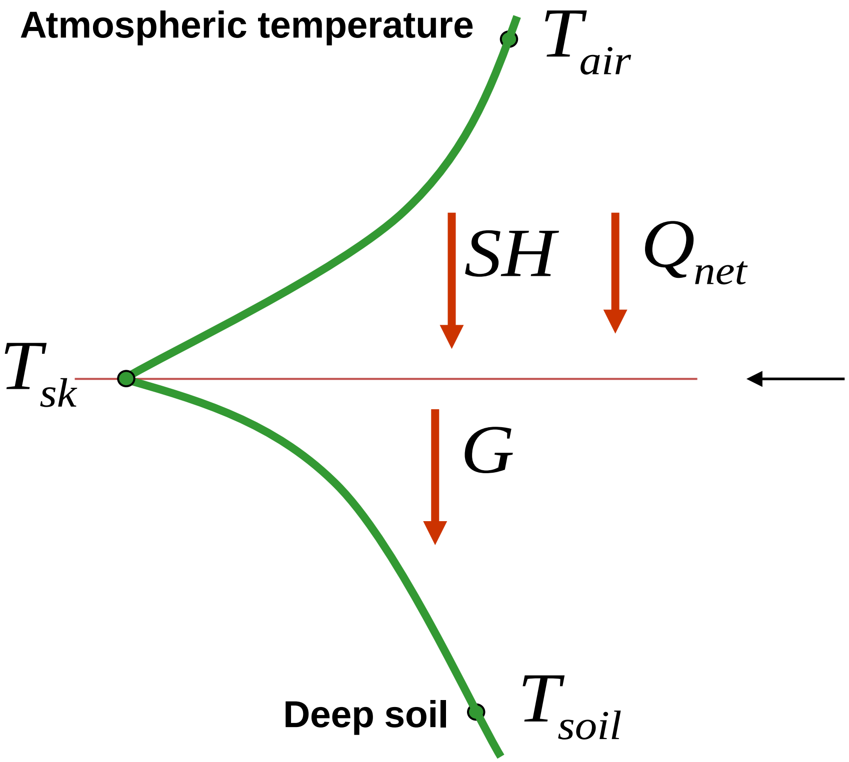


New land surface scheme

Increased turbulent diffusion + soil moisture freezing

Reduced outer layer diffusion in stable situations

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

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

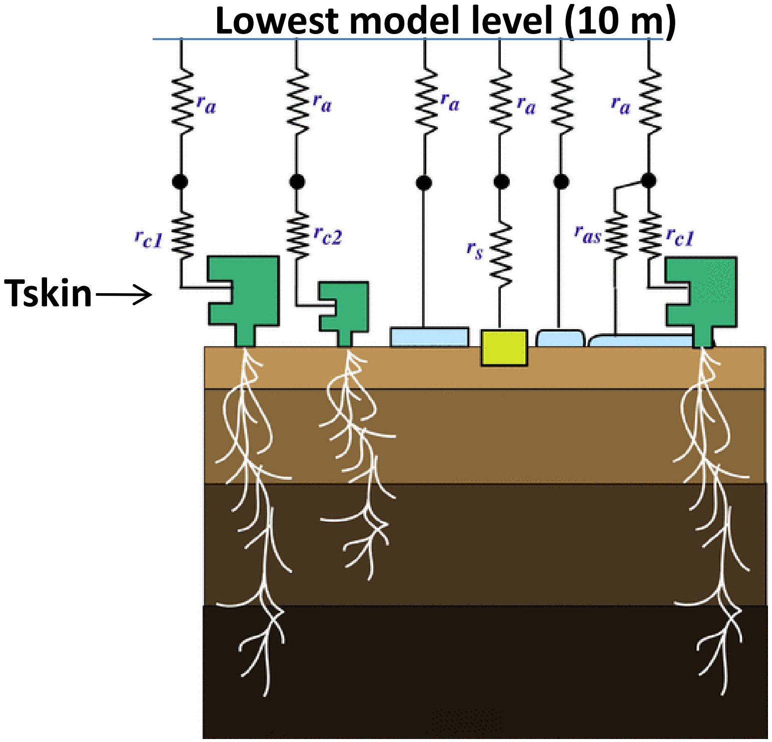
$$w'\theta' = -K_H \frac{d\theta}{dz}, \quad K_H = l^2 \left\{ \left| \frac{dU}{dz} \right| + S_m \right\} f_H(Ri)$$

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

Coupling coefficients are hidden in a number of parametrizations

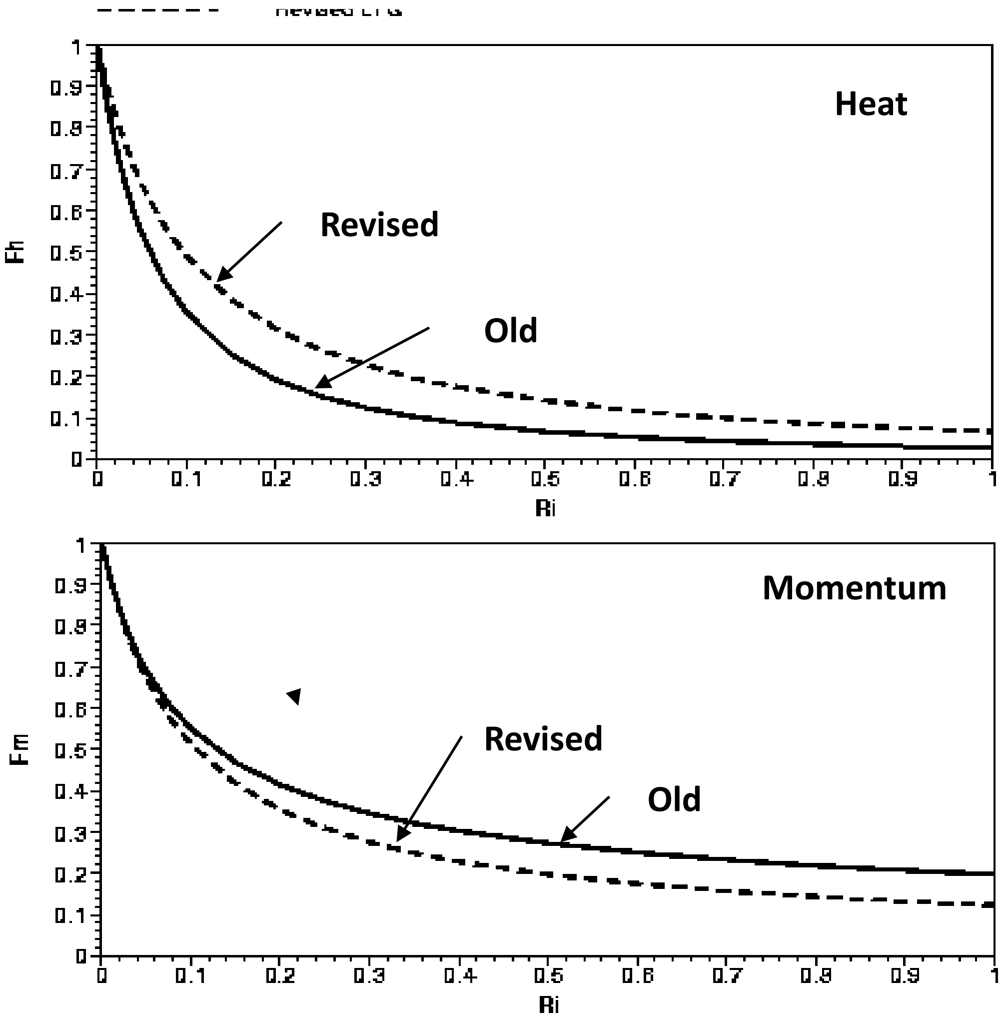
Coupling between skin level and deep soil is affected by all the details of the land surface scheme:

- **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**

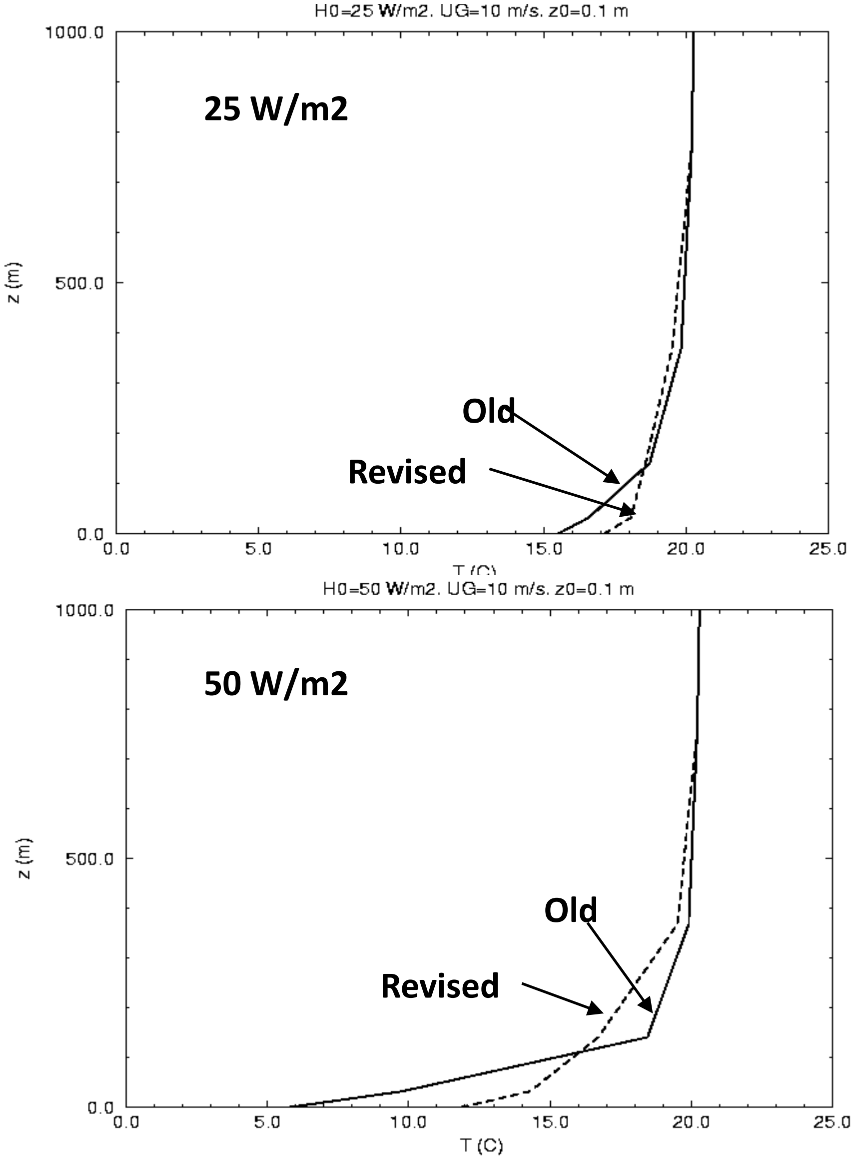


Increased diffusion of heat in stable situations

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



Soil water freezing

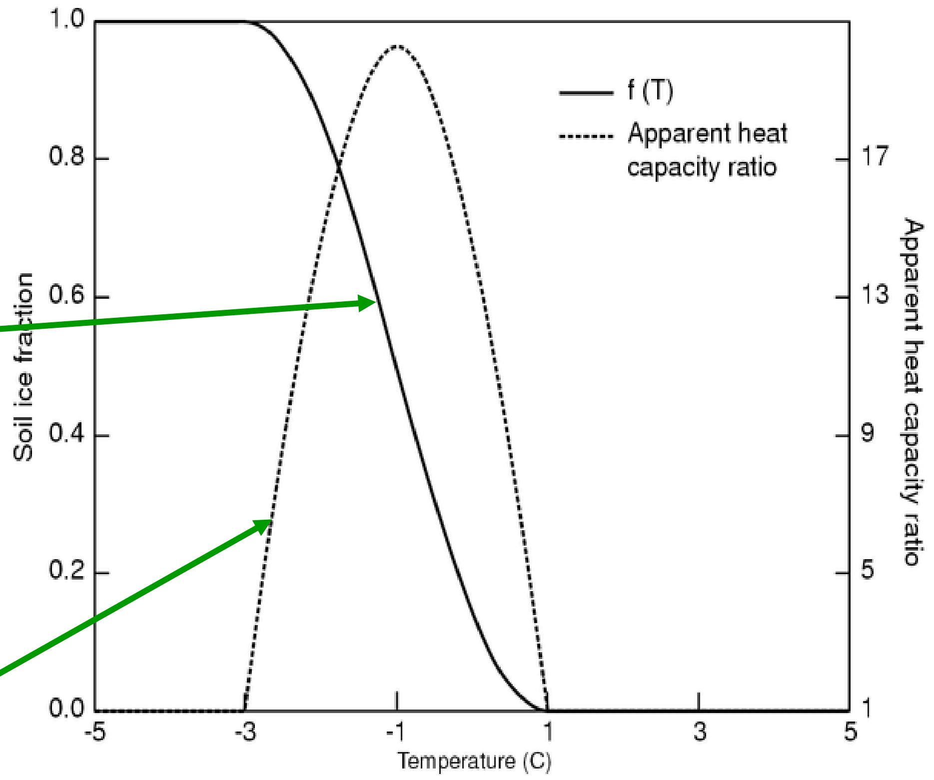
Soil heat transfer equation during freezing

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

θ_I Soil frozen water

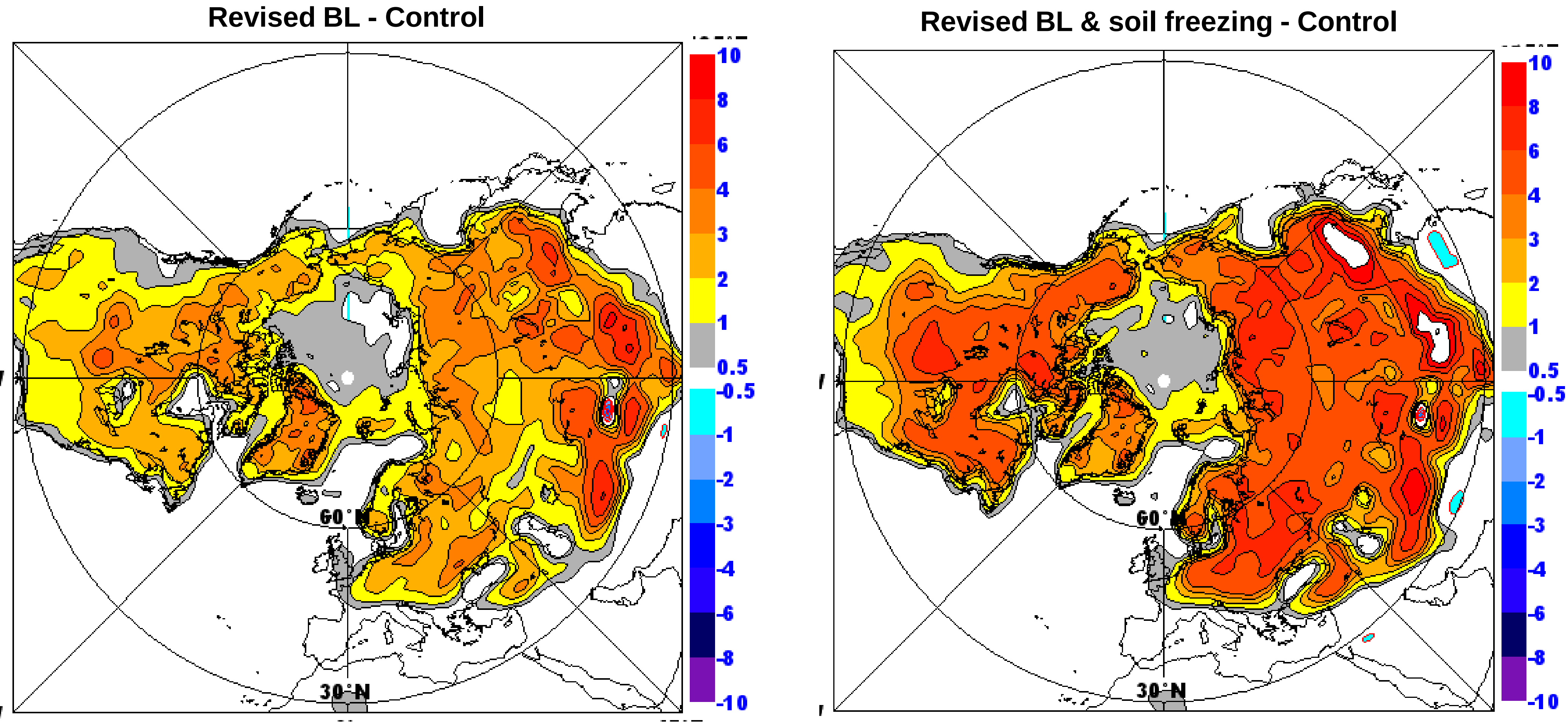
$$\theta_I = \theta_I(T) = f(T)\theta$$

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



Difference in 2m temperature for January 1996

From long “relaxation” integrations starting 1 Oct 1995
1994 model version

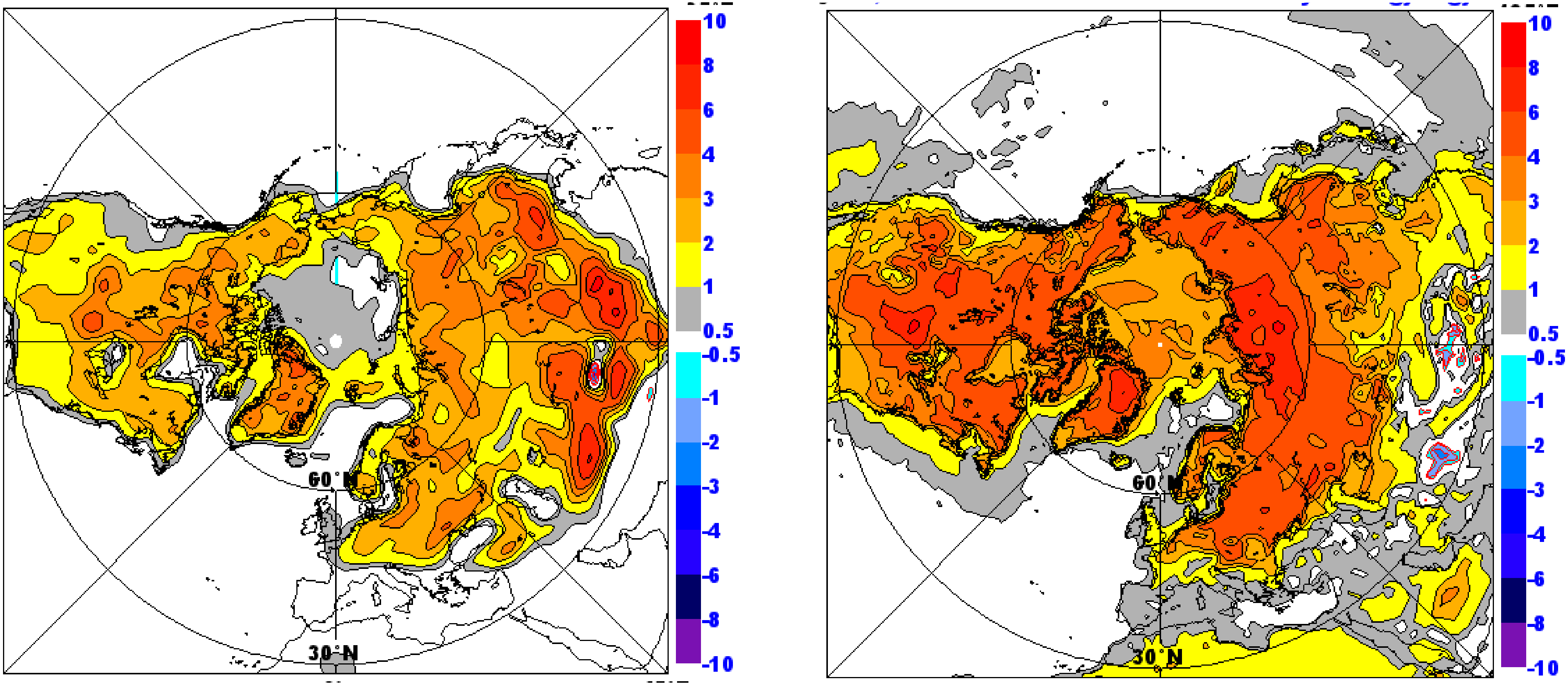


Revised BL - Control

Revised BL & soil freezing - Control

Difference in 2m temperature for January 1996

From long “relaxation” integrations starting 1 Oct 1995

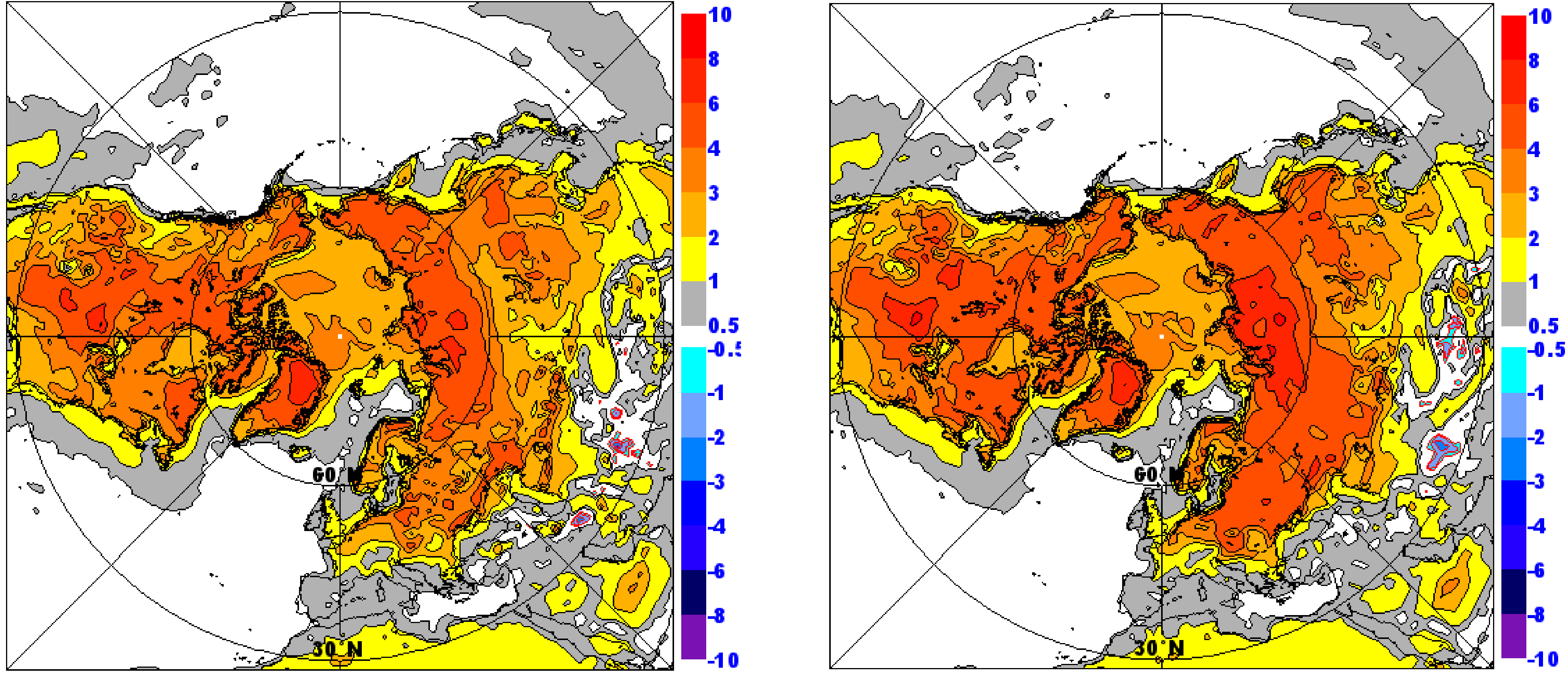


Effect of revised LTG in 1994 model version

Effect of revised LTG in 2011 model version

Difference in 2m temperature for January 1996

From long “relaxation” integrations starting 1 Oct 1995

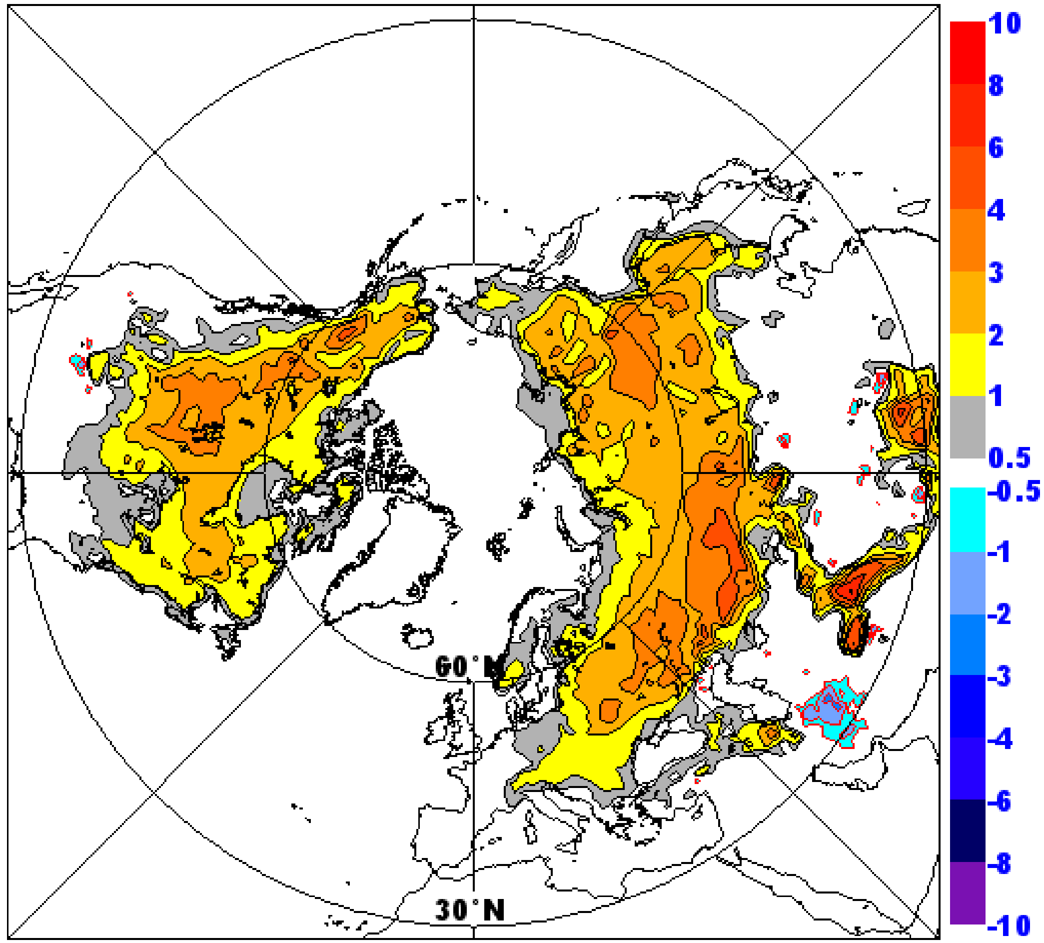


Effect of revised LTG in 2011 model but old snow

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

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

Betts (2006): JGR, 111, D07105

Diurnal temp range

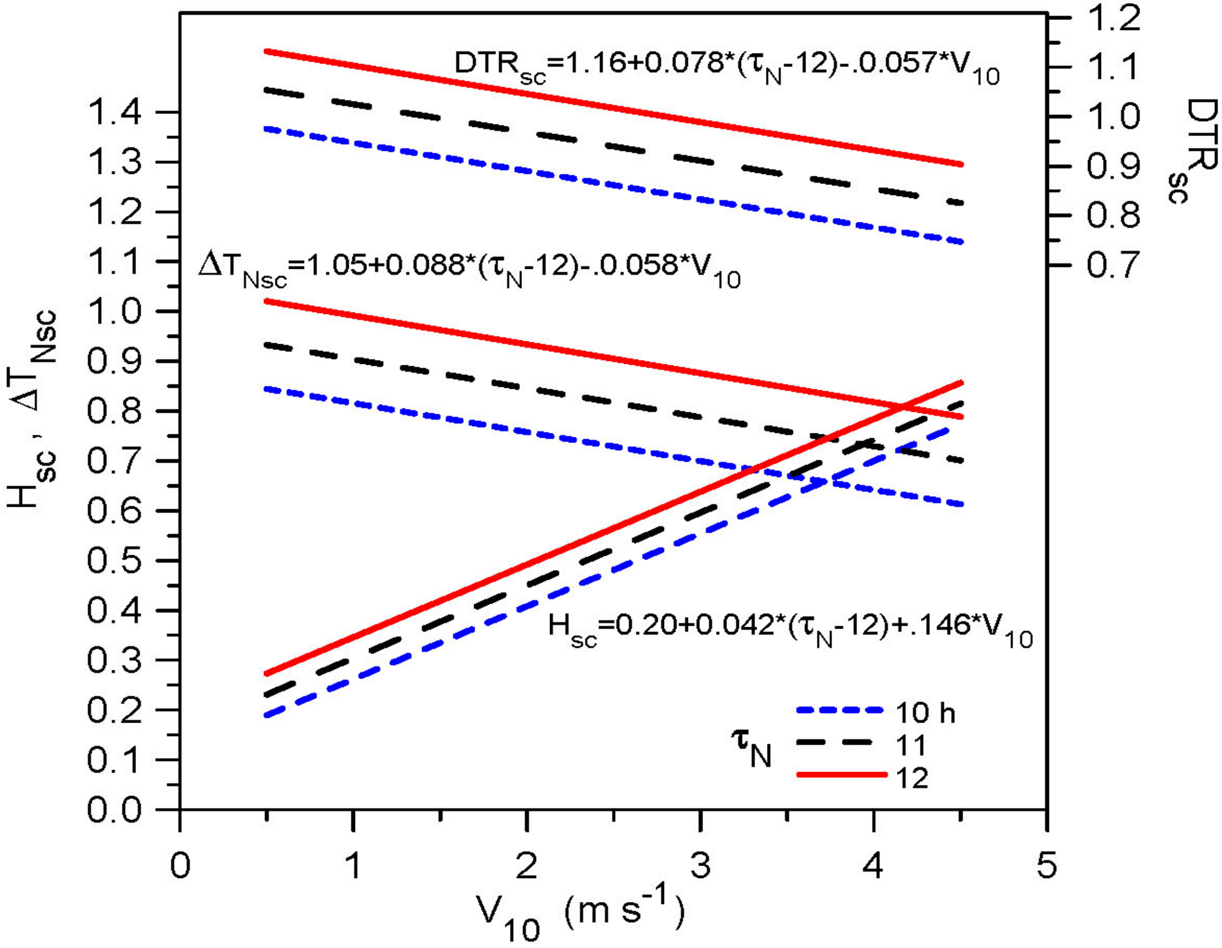
$\mathbf{DTR_{sc} = DTR / \Delta T_R}$

Strength of NBL

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

Scaled heat flux

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

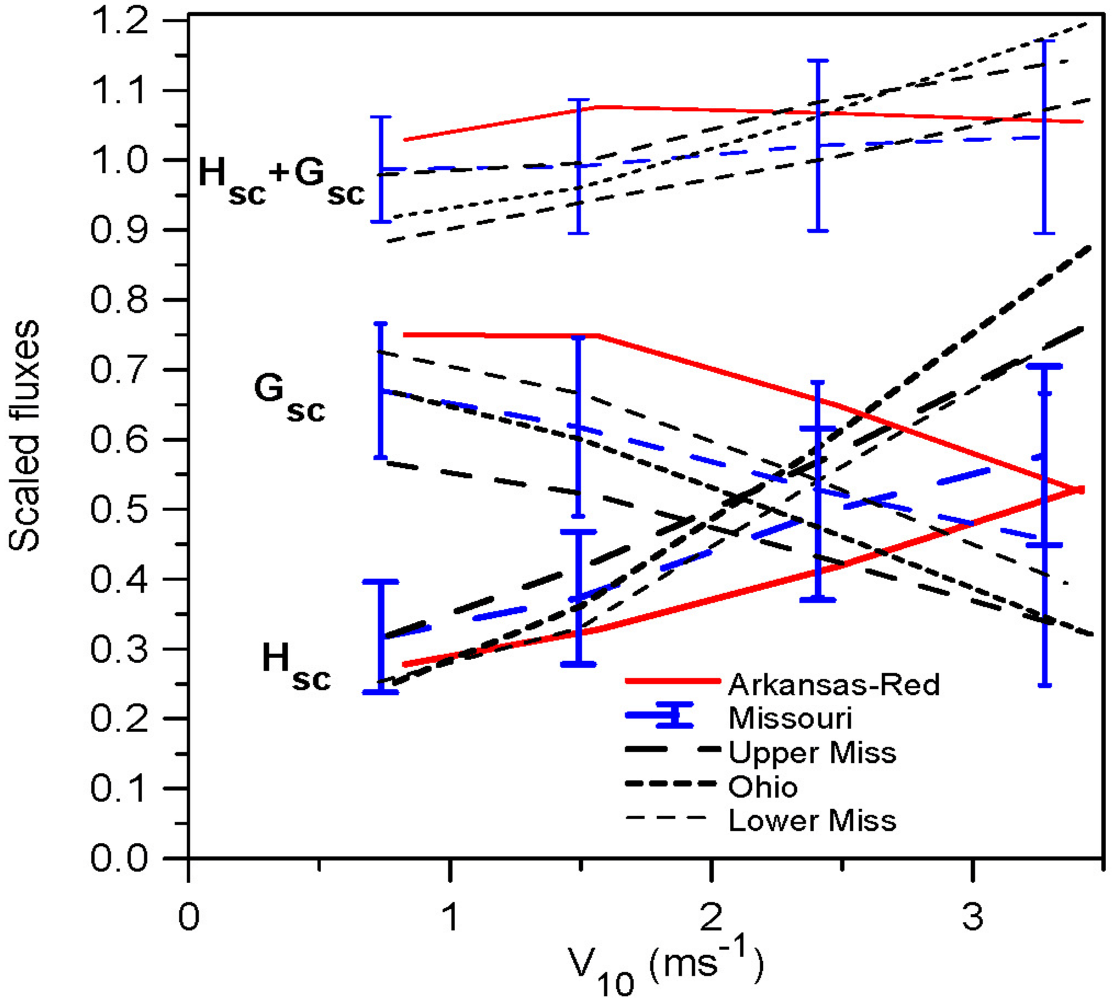


Dependence of scaled energy budget on wind speed

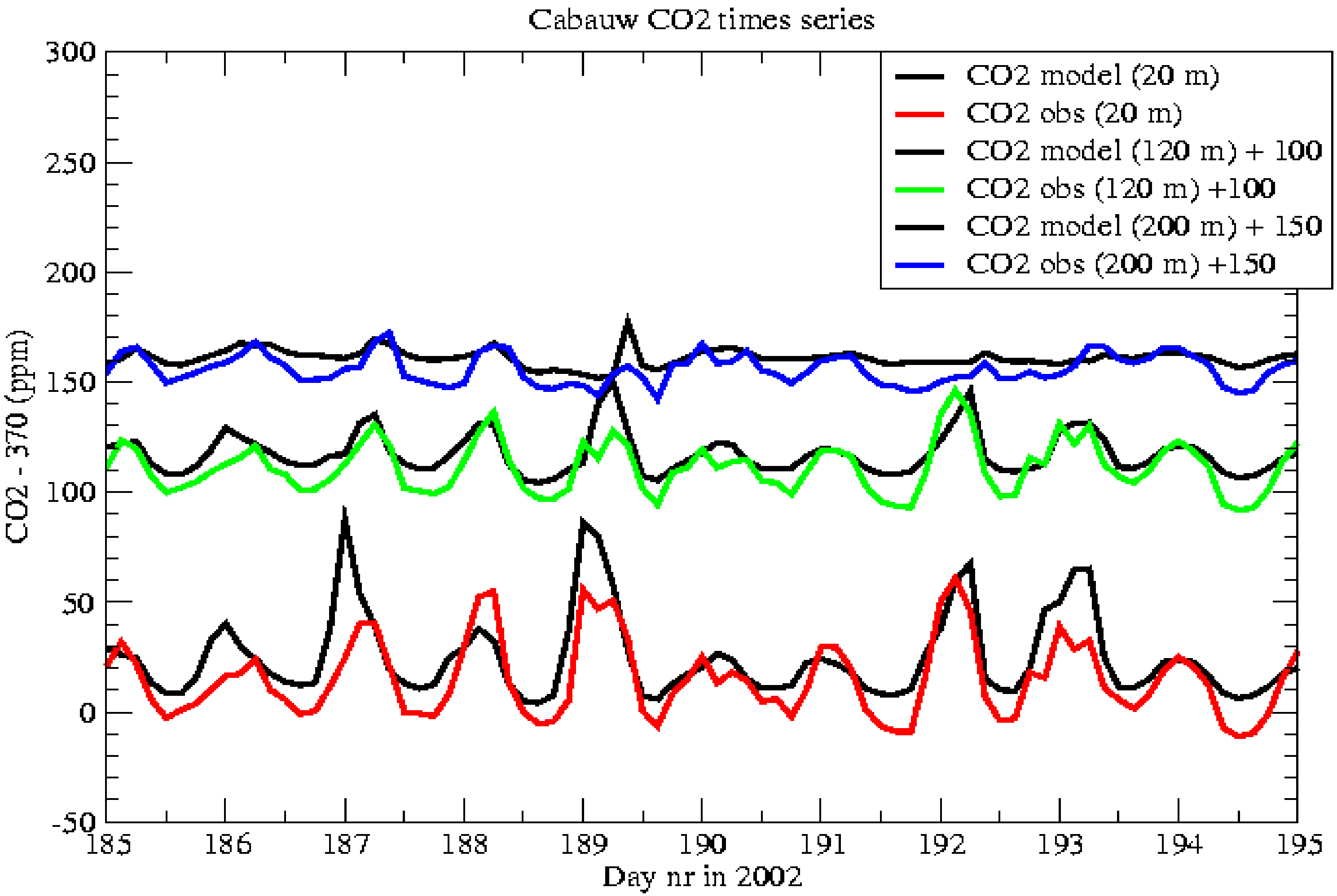
For NBL:

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

Partitioning changes with wind speed, but basins show different slope



Model and observations at Cabauw (3-hourly)



Data kindly provided by
ECN/KNMI

Conclusions on atmosphere land coupling

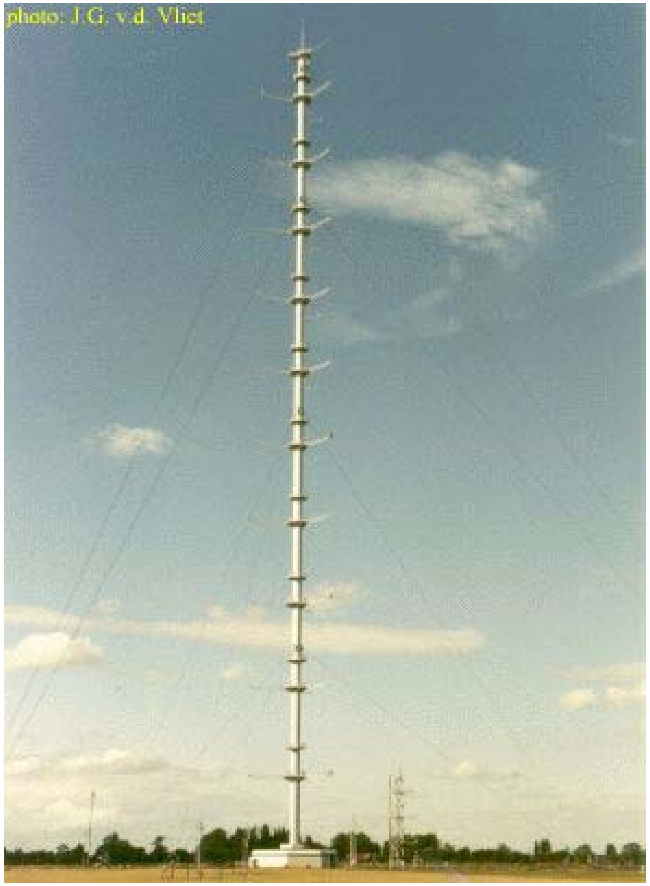
- Boundary layer, radiation, clouds, and surface climate are a tightly coupled system
- True but still largely ignored
- Models help to understand the coupling of complex processes
- Links in the coupled system need careful evaluation against observables

How to reduce uncertainty in atmosphere to surface coupling ?

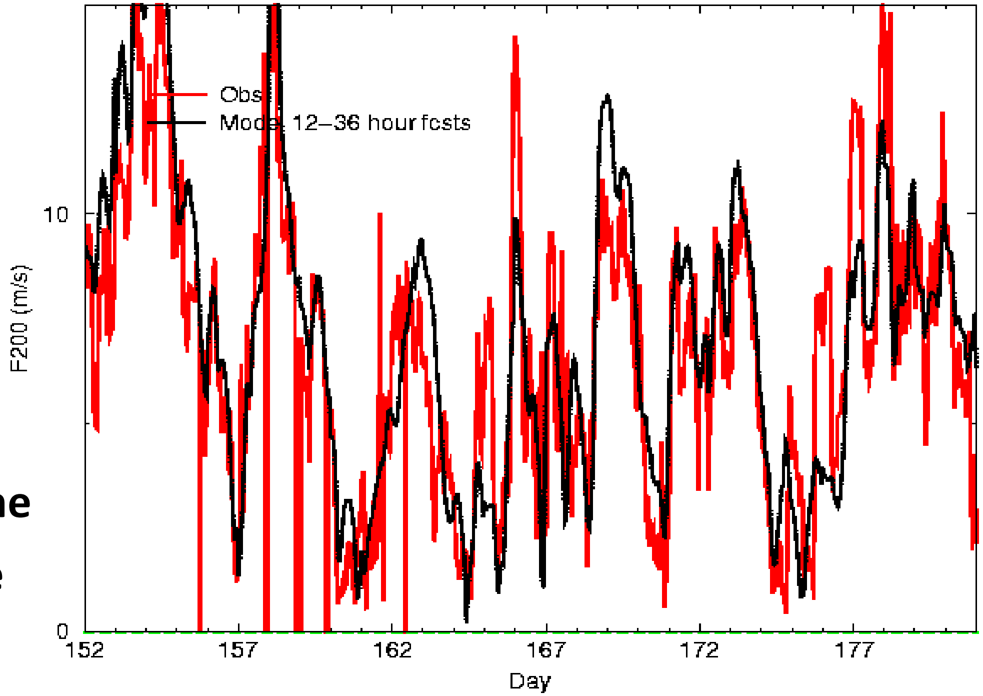
- Analyze relations between variables of the coupled system for observations and models. Relevant variables are:
  - Night time temperature drop
  - Long wave cooling
  - Boundary layer depth
  - Wind speed
  - Night time CO2 increase
  - Sensible heat flux
  - Ground heat flux
- Analysis is needed for observational sites characterizing different types of terrain

Model issues related to wind and momentum fluxes

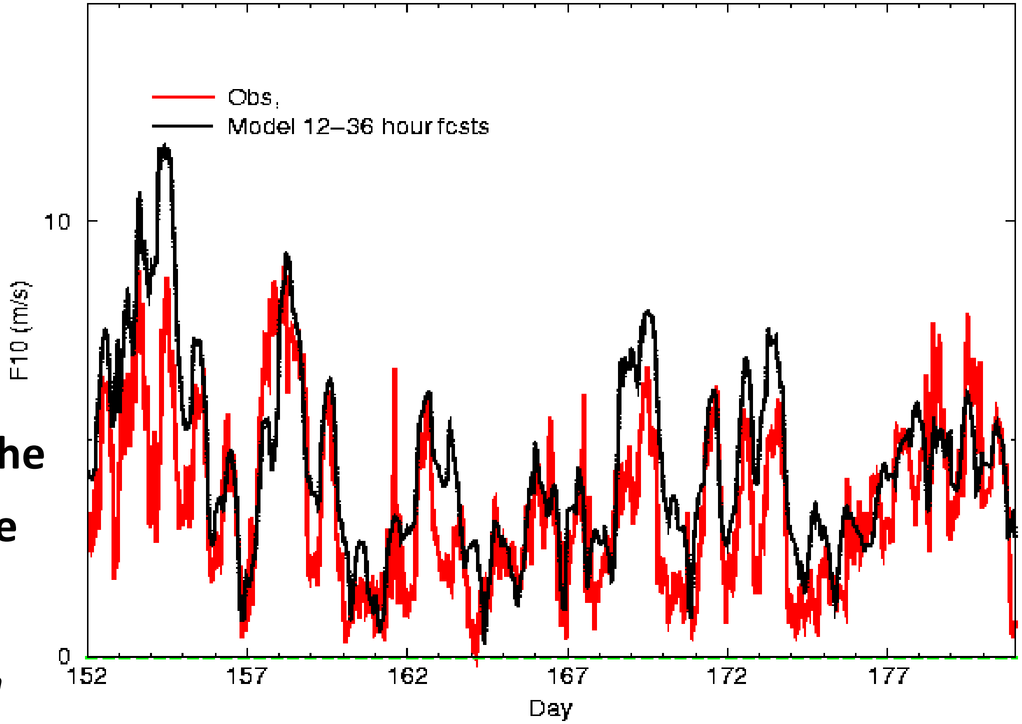
Time series of wind speed at Cabauw (Netherlands) for the month of June 2001: Observations (10 min averages) & ERA-Interim



200 m above the surface

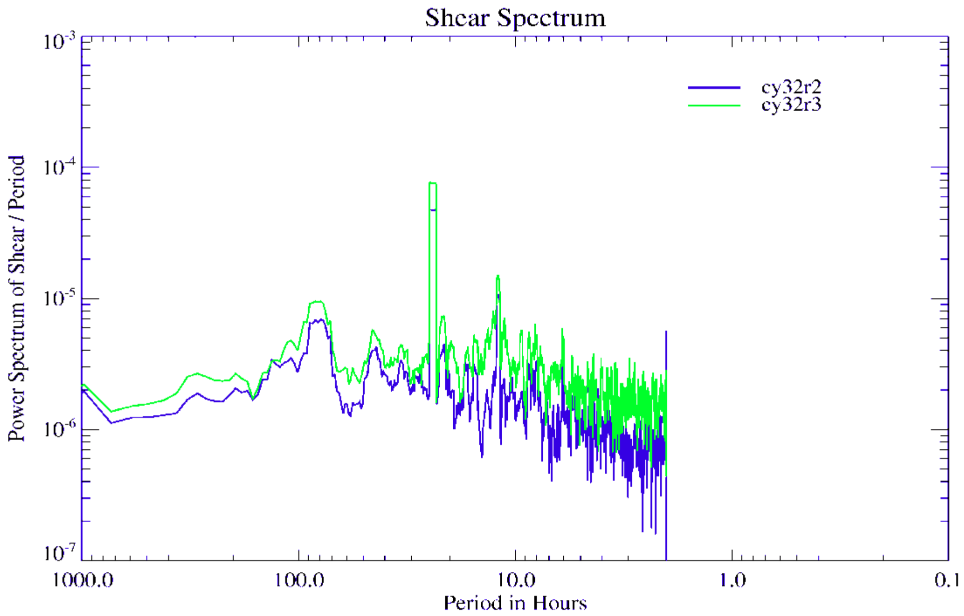


10 m above the surface

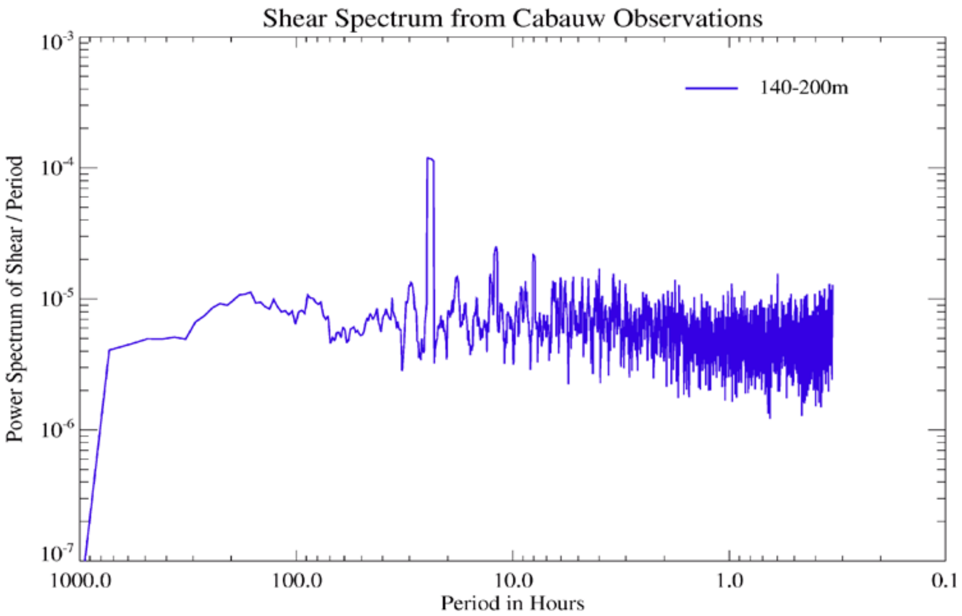


Data: Fred Bosveld, KNMI

Shear Spectrum at Cabauw Tower


Shear Spectrum

Model: L86/87 (160/220 m)

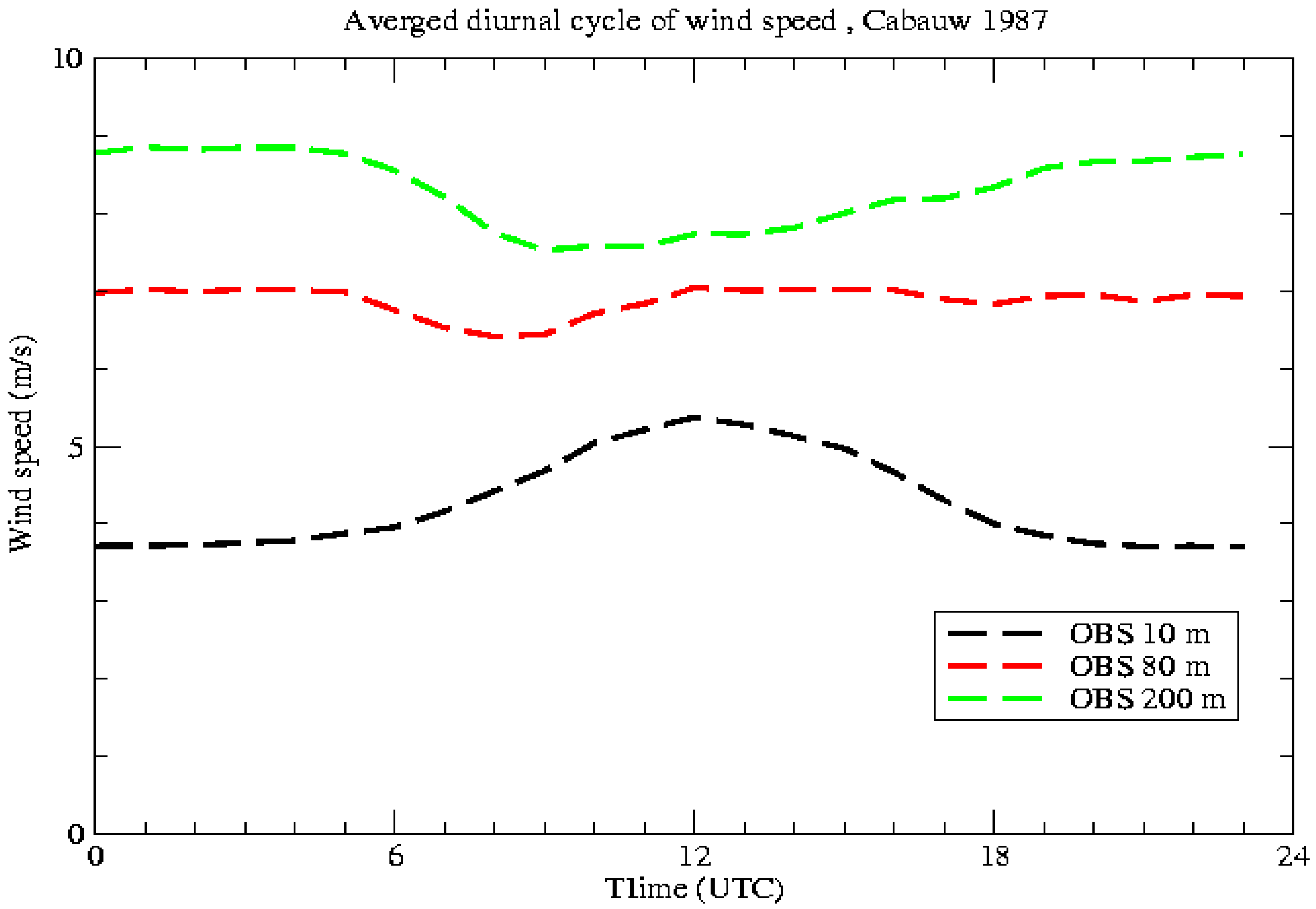

Shear Spectrum from Cabauw Observations

From observed 10-min averages: (140/200 m)

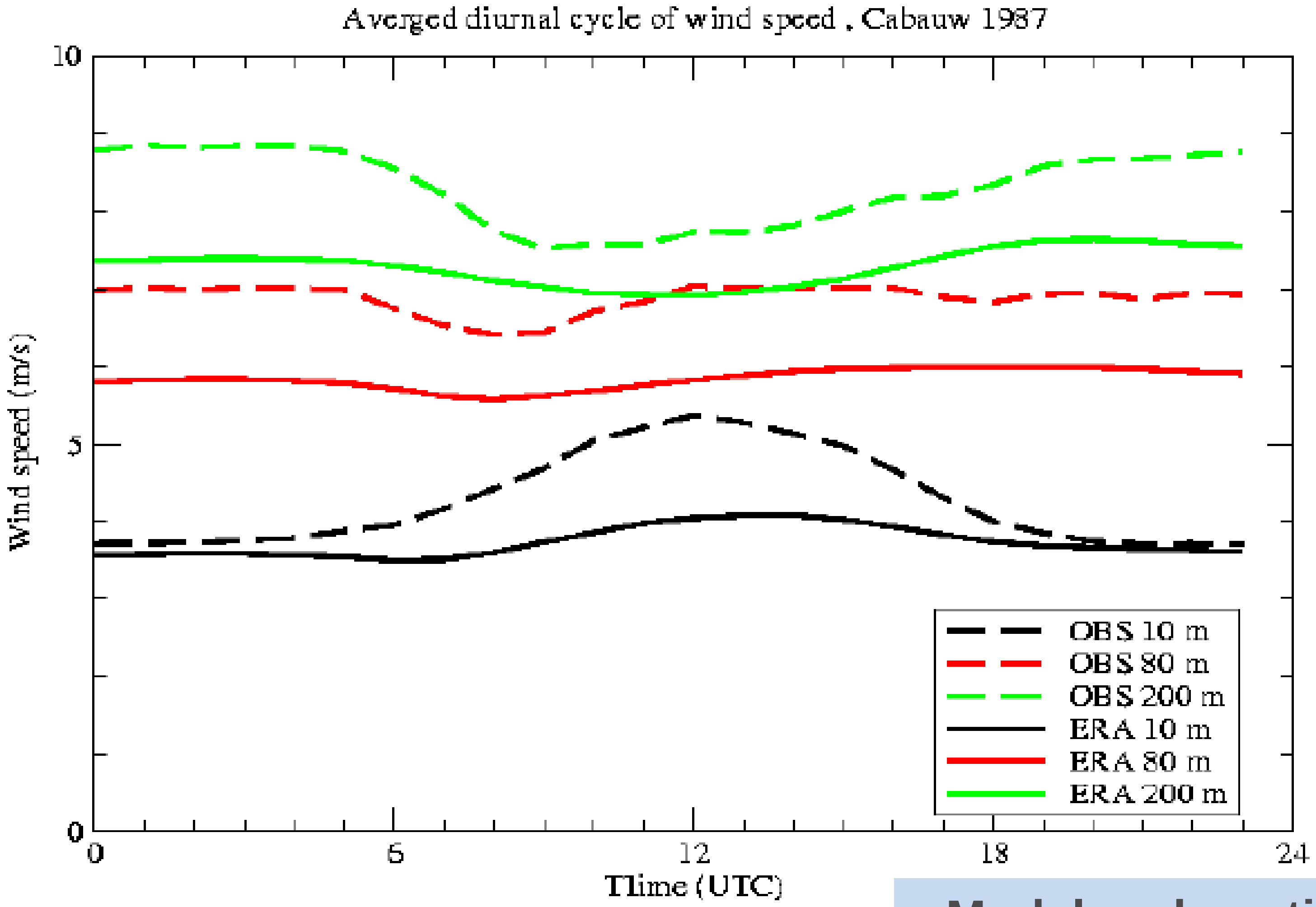
Is this term needed and how does it scale?

$$K_H = l^2 \left\{ \left| \frac{dU}{dz} \right| + S_m \right\} f_H(Ri)$$

Diurnal cycle over land: Cabauw 1987 annual average

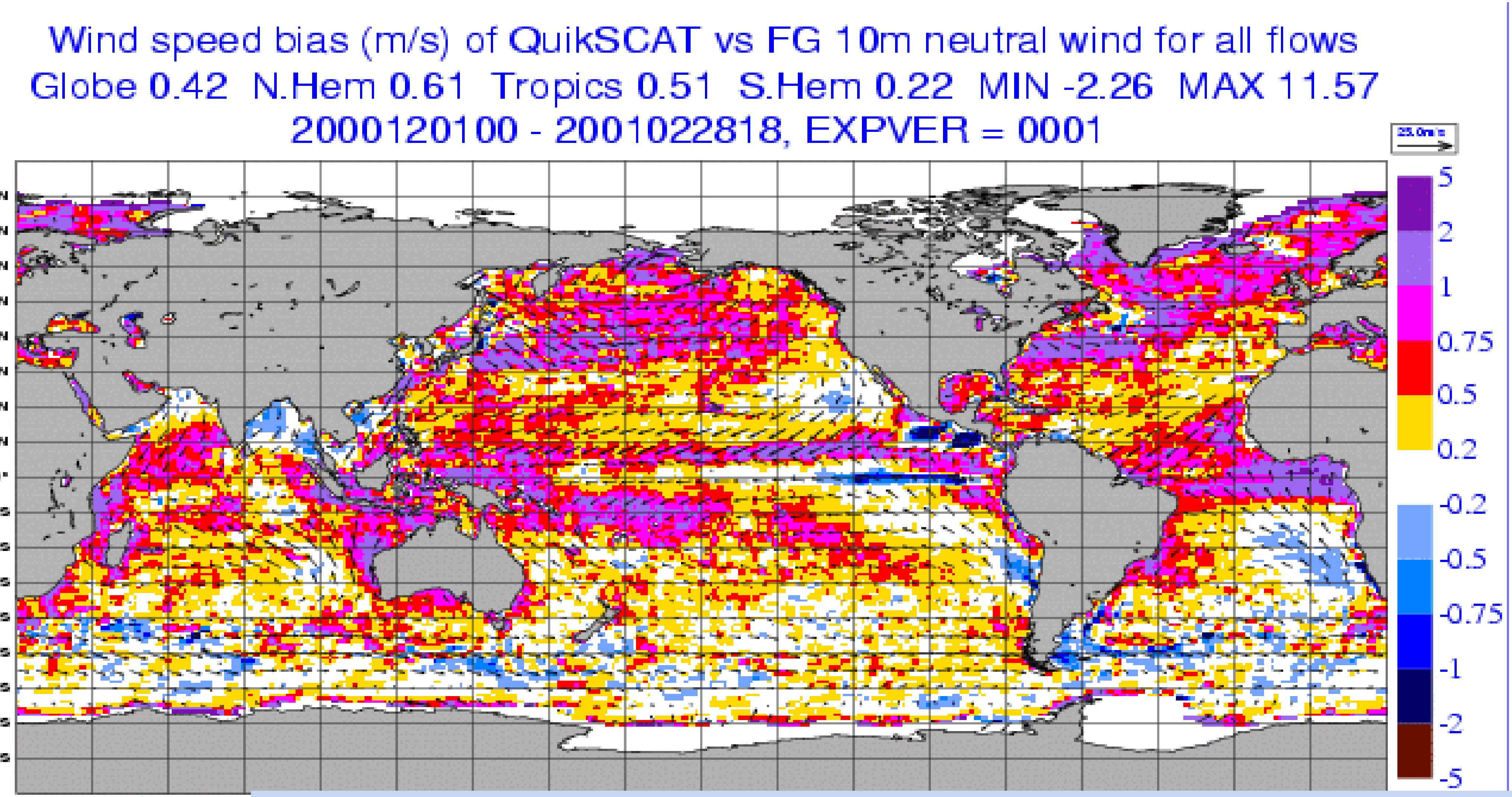


Diurnal cycle: Cabauw 1987 vs. ERA-40 12-36 hour daily forecasts



Model underestimates diurnal cycle at 10 m and at 200 m

QuikSCAT neutral wind speed – model (all)

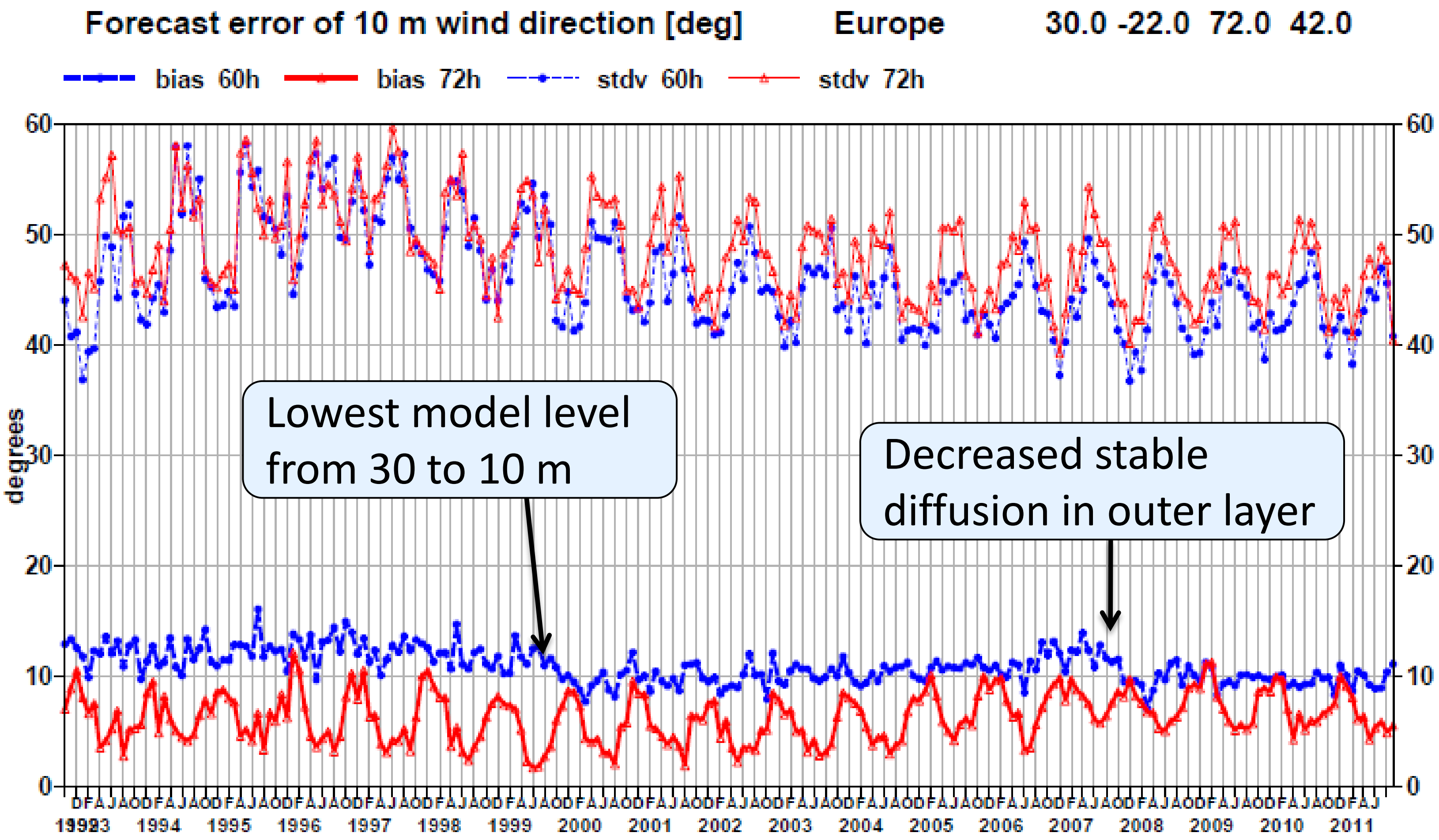


Wind speed bias (m/s) of QuikSCAT vs FG 10m neutral wind for all flows
Globe 0.42 N.Hem 0.61 Tropics 0.51 S.Hem 0.22 MIN -2.26 MAX 11.57
2000120100 - 2001022818, EXPVER = 0001

Courtesy, Hans Hersbach

Model slightly underestimates winds over the ocean. Further analysis shows that model underestimates stability effects on surface wind

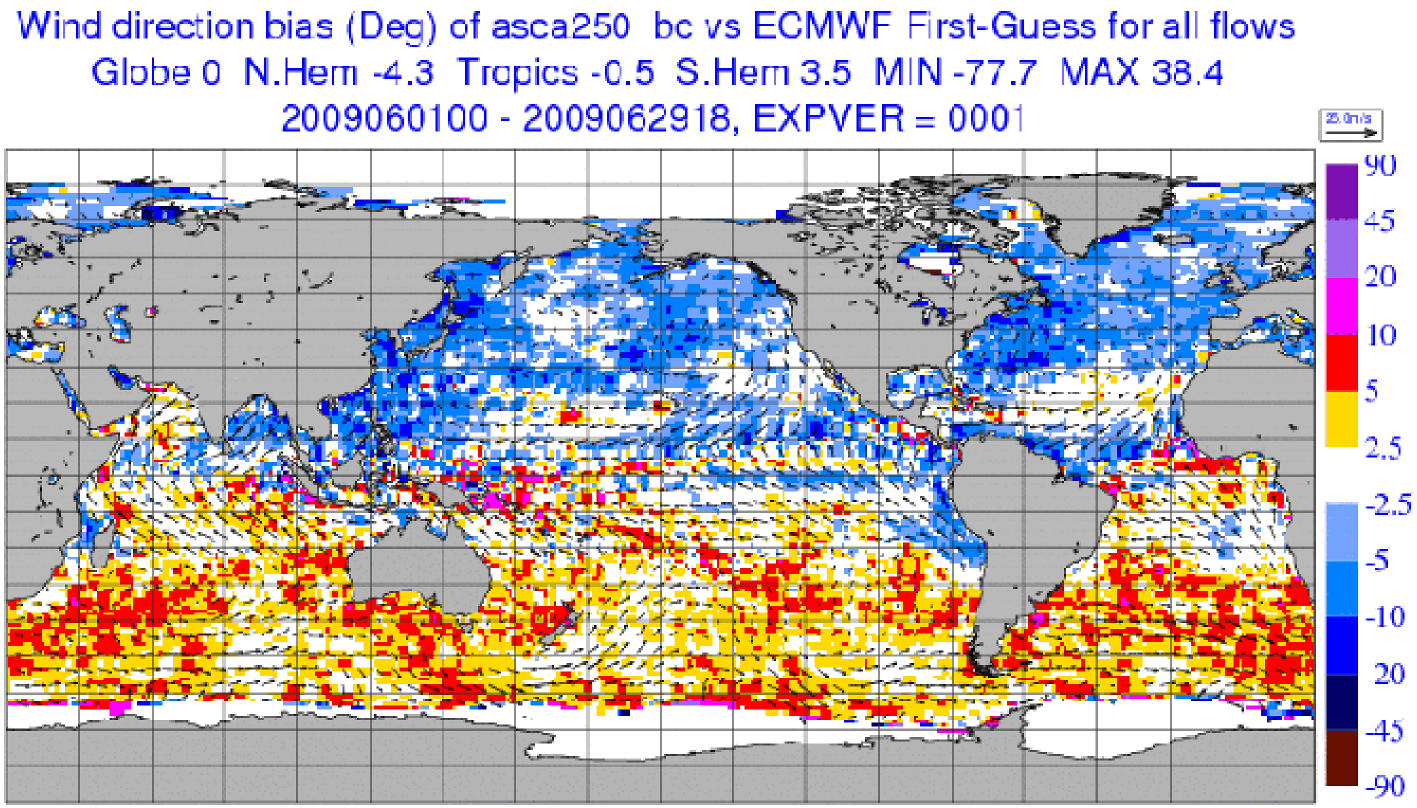
Wind direction errors compared to SYNOP over Europe



Lowest model level from 30 to 10 m

Decreased stable diffusion in outer layer

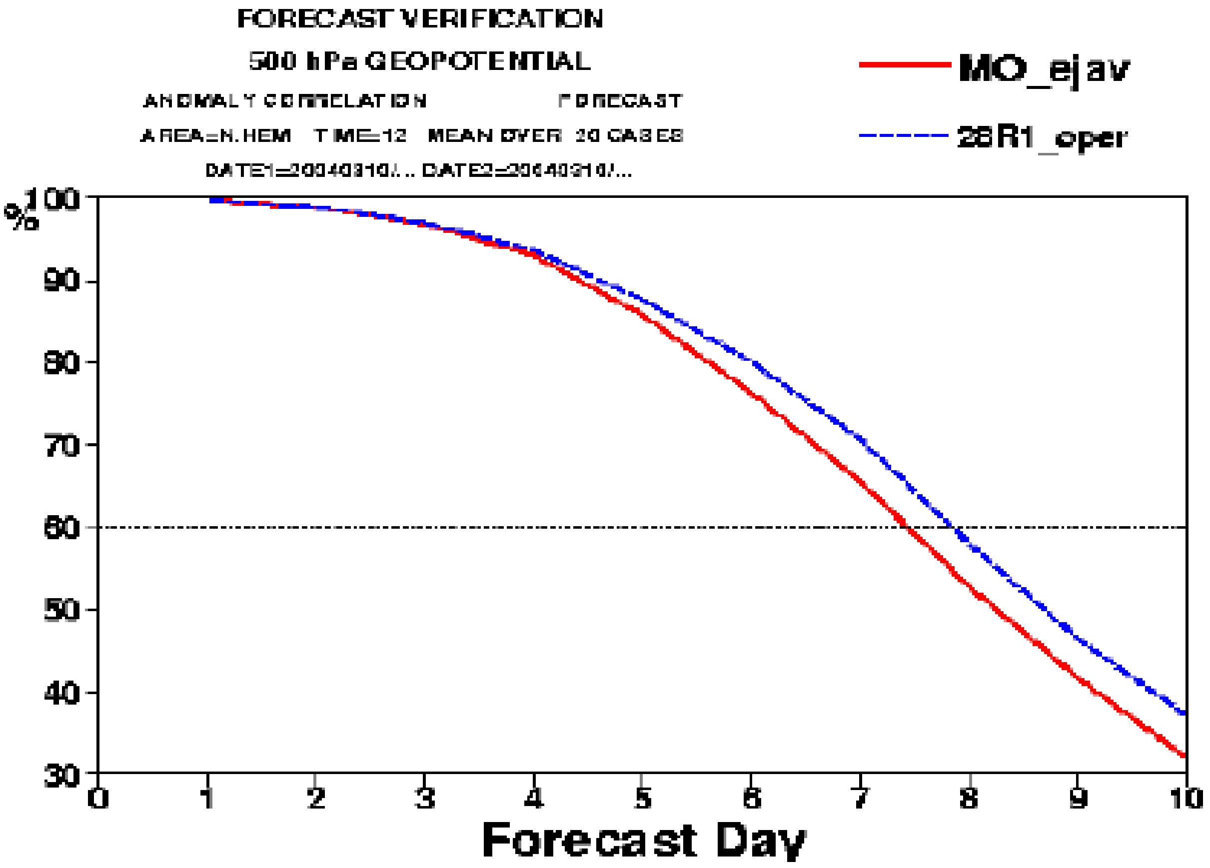
Wind direction error compared with QuikSCAT neutral wind (all)



Wind direction bias (Deg) of asca250 bc vs ECMWF First-Guess for all flows
Globe 0 N.Hem -4.3 Tropics -0.5 S.Hem 3.5 MIN -77.7 MAX 38.4
2009060100 - 2009062918, EXPVER = 0001

Model underestimates a-geostrophic angle. Stratification by stability shows that problem is worse in stable situations

Stable boundary layer diffusion affects large scale scores



Effect of MO-stability functions (reduced diffusion) instead of operational formulation, on 500hPa NH height scores

Model somehow needs larger drag over land than can be obtained from schemes that produce reasonable stable boundary layer structure.

Ground truth for drag over land does not exist.

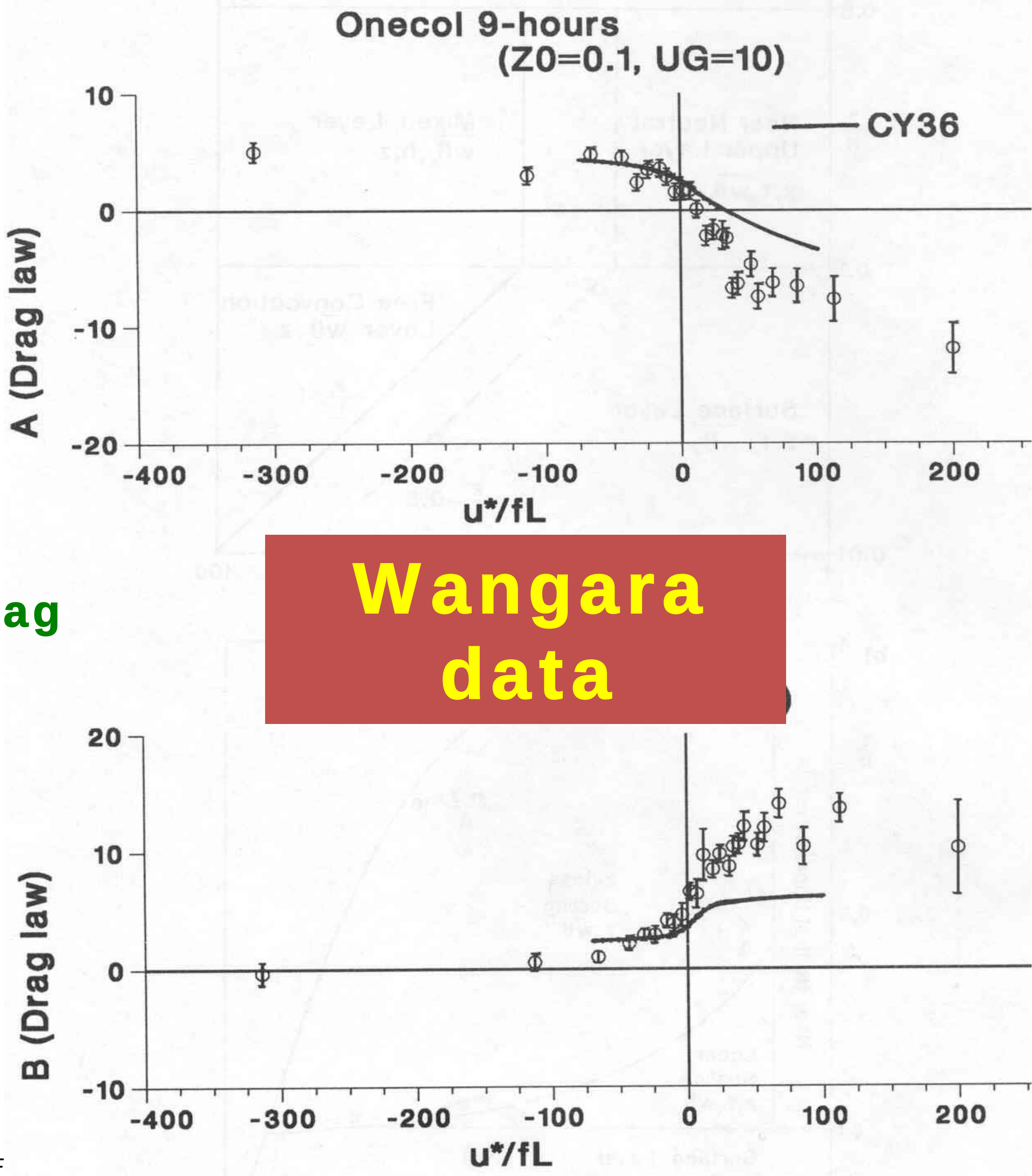
Geostrophic drag law

$$\frac{U_G}{u_*} = \frac{1}{\kappa}\ln\left(\frac{u_*}{f\, z_{om}}\right) - \frac{A}{\kappa}$$

drag

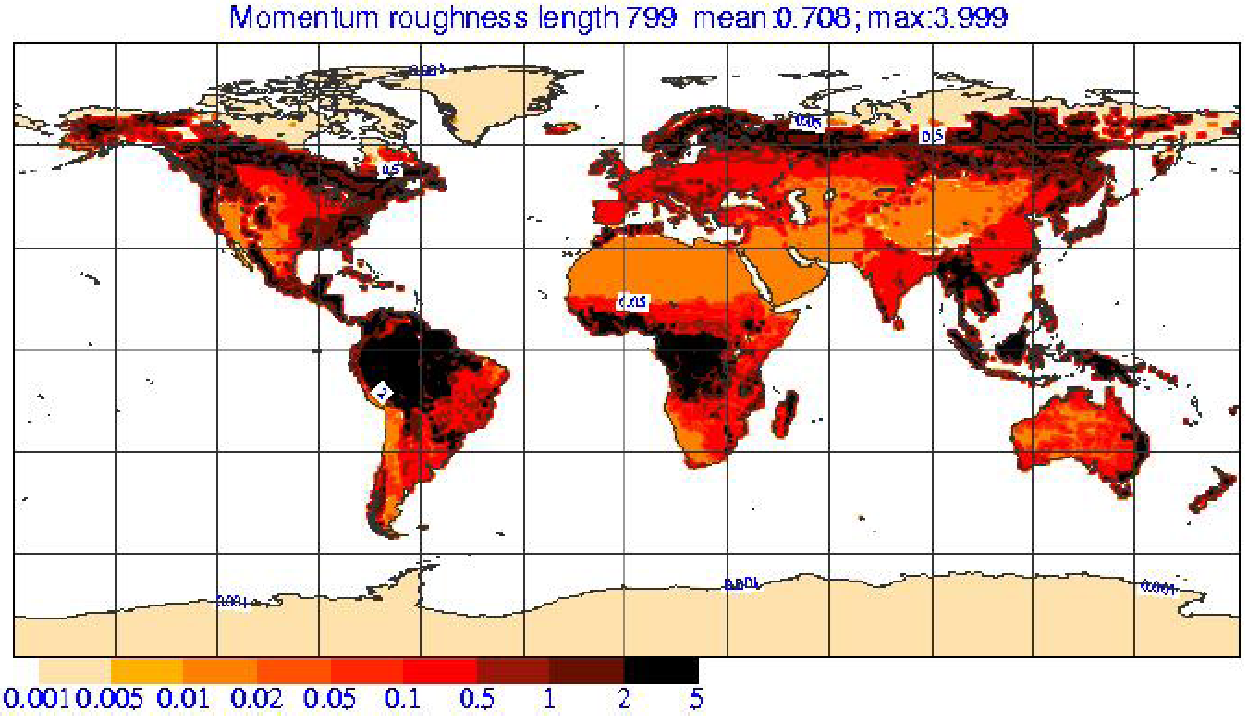
$$\frac{V_G}{u_*} = \frac{B}{\kappa}$$

a-geostrophic angle

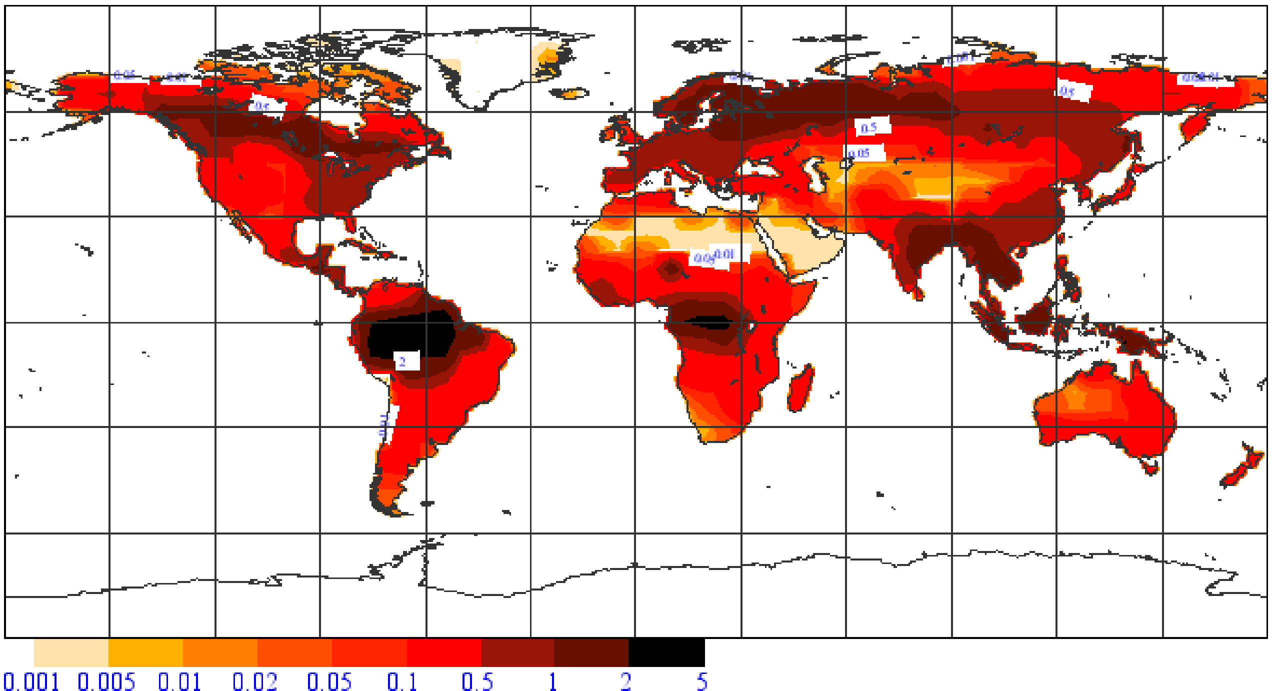


Wangara data

Roughness length for momentum



CY31R2; ERA-Interim; (Derived from vegetation type)

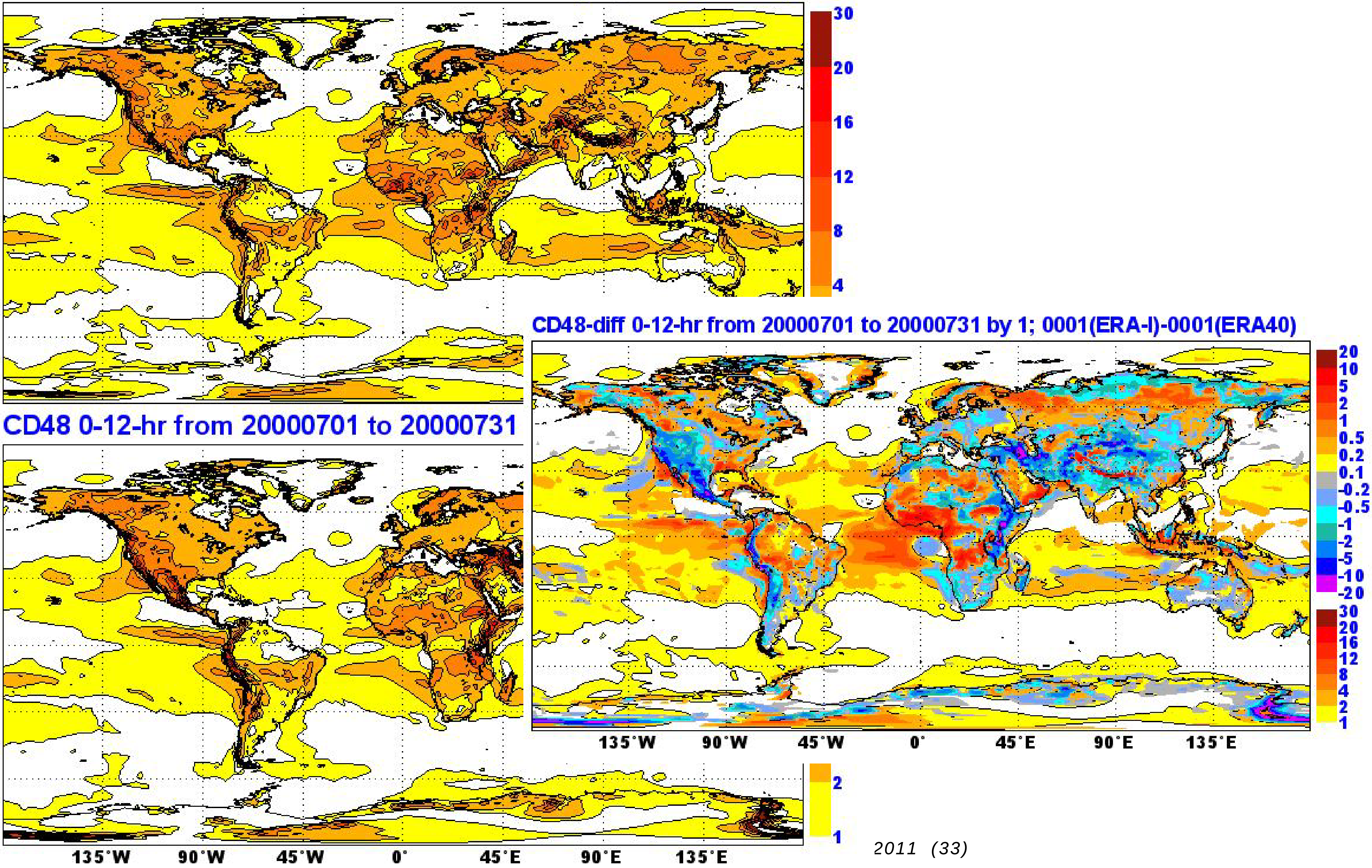


CY23R4; ERA-40; 5x5 deg. (Baumgartner et al. 1977)

CD48 0-12-hr from 20000701 to 20000731 by 1; 0001(ERA-I)

CD48 0-12-hr from 20000701 to 20000731

CD48-diff 0-12-hr from 20000701 to 20000731 by 1; 0001(ERA-I)-0001(ERA40)



Conclusions on wind and momentum issues

- Diurnal cycle of wind is attenuated in the ECMWF model by the stable diffusion scheme
- The momentum boundary layer is too deep resulting in a too weak low level jet
- Large scale model performance is very sensitive to surface drag (Irina will provide more detailed results)
- Observed wind has a lot of variability at all scales which the ECMWF model does not have
- Uncertainty in specifying surface drag is large e.g. due to inhomogeneous terrain effects

How to progress?

- Parameter optimization in NWP is possible (e.g. by using data assimilation techniques) provided that the surface and the boundary layer can be characterized by a limited set of parameters (e.g. through a suitable scaling framework)
- LES simulations applied to real terrain (including heterogeneous canopy and small scale topography) might help to shed light on the role of meso-scale variability