Implementation of the quasi-normal scale elimination (QNSE) theory of turbulence in HIRLAM: Influence on PBL clouds and turbulent fluxes

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- Numerical weather prediction (NWP) models involve eddy viscosity and eddy diffusivity, *Km* and Kh, that account for unresolved turbulent mixing and diffusion.
- The most sophisticated turbulent closure models used today for NWP belong to the family of Reynolds stress models.
- These models are formulated for the physical space variables; they consider a hierarchy of turbulent correlations and employ a rational way of its truncation.
- In the process, unknown correlation are related to the known ones via “closure assumptions” that are based upon preservation of tensorial properties and the principle of invariant modelling

according to which the constants in the closure relationships are universal

- Although a great deal of progress has been achieved with Reynolds stress closure models over the years, these are still situations in which these models fail. The most difficult flows for the Reynolds stress modelling are those with anisotropy and waves because these processes are scale-dependent and cannot be included in the closure assumptions that pertain to ensemble-averages quantities.
- Here we employ an alternative approach of deriving expressions for Km and Kh using the spectral space presentation. The spectral model produces expressions for Km and Kh based upon a self-consistent procedure of small-scale modes elimination.

• This procedure is based upon the quasi-Gaussian mapping of the velocity and temperature using the Langevun equations.

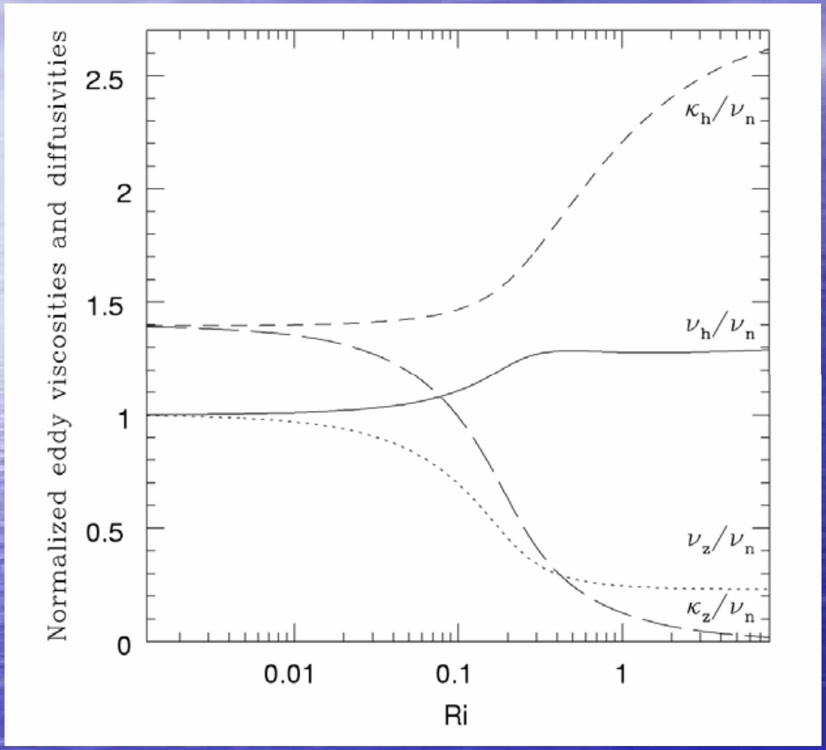
• Turbulence and waves are treated as one entity and the effect of the internal waves is easily identifiable.

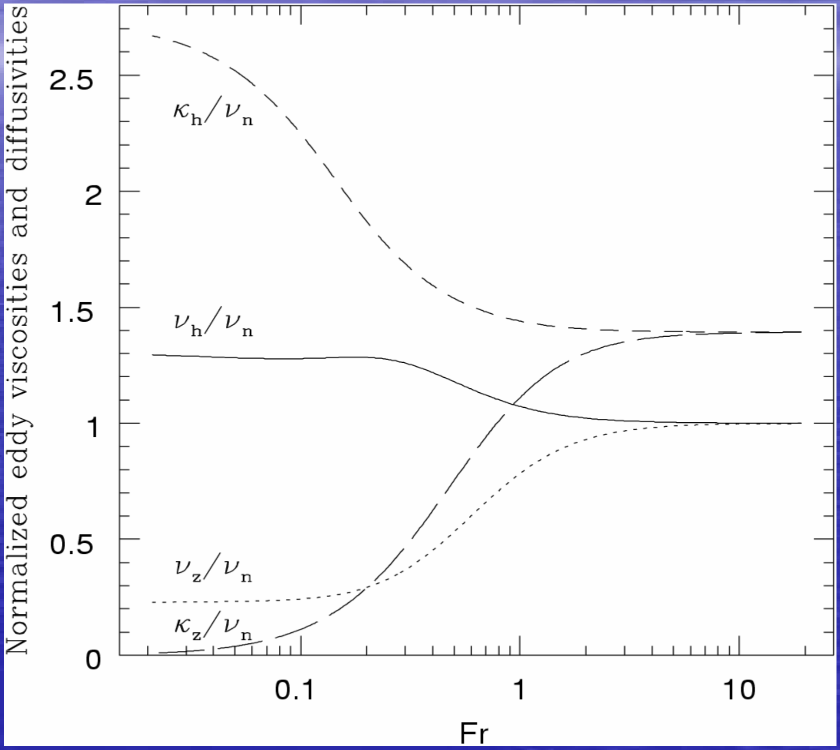
• When averaging is extended to all scales, the method yields a Reynolds-averaged, Navier-Stokes based model.

The details can be found in the paper "Application of a new spectral theory of turbulence to the ABL over sea ice", Boundary_Layer Meteorology, 117, 231-257, 2005, by Sukoriansky S, Galperin B. and Perov V.

Results from the theory

The turbulent coefficients are recast in terms of gradient Richardson number $Ri = N^2 / S^2$ or Froude number $Fr = \varepsilon / NK$





Normalized turbulent exchange coefficients as functions of *Ri* and *Fr.*

For *Ri*>0.1, both vertical viscosity and diffusivity decrease, with the diffusivity decreasing faster than the viscosity ("residual" mixing due to effect of IGW)

- Horizontal mixing increases with Ri. The model accounts for flow anisotropy.
- The crossover from neutral to stratified flow regime is replicated. **No critical Ri.**

Reference HIRLAM K-l scheme of turbulence, stable cases

$$\frac{\partial E}{\partial t} = K_m\left[\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2\right] - \frac{g}{\Theta_0} K_h \frac{\partial \theta}{\partial z} - \varepsilon + \frac{\partial}{\partial z}\left(K_q \frac{\partial E}{\partial z}\right)$$

$$\varepsilon = c_\varepsilon \frac{E^{3/2}}{l}; \quad l_B = \frac{kz}{1 + \frac{kz}{\lambda}}, \quad l_{m,h} = c_{m,h} \frac{E^{1/2}}{N}$$

$$\frac{1}{l} = \frac{1}{l_B} + \frac{1}{l_{m,h}}, \qquad K_{m,h} = l_{m,h} \cdot E^{1/2}$$

Reference HIRLAM K-l scheme of turbulence

$$c_m = c_h * \max(1, \min[\,(1+\gamma Ri * \exp(-Ri^2)) * pfunc, 4]\,)$$

$$pfunc = \max\left(0, \frac{P-100}{P(nlev)-100}\right), \quad c_h = 0.2$$

Increasing of the vertical mixing of momentum under stable stratification. Verification score becames better, but Intercomparison in GABLS shows very deep BL and a wind profile has its maximum at the wrong place (too high)

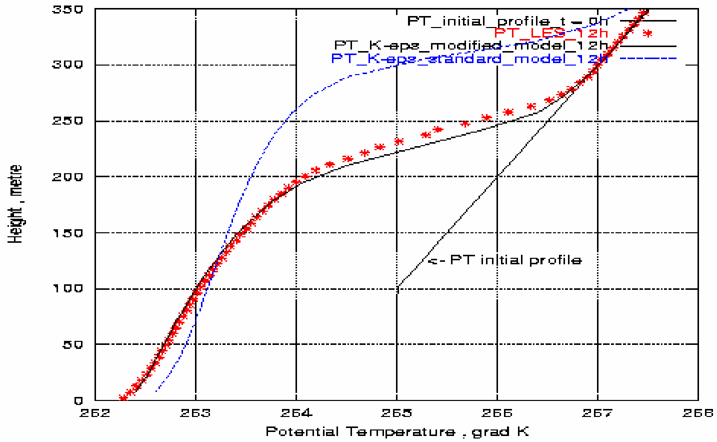
Modification of the HIRLAM turbulent K-l scheme

$$\frac{\partial E}{\partial t} = K_M \left[\left(\frac{\partial U}{\partial z} \right)^2 + \left(\frac{\partial V}{\partial z} \right)^2 \right] - \frac{g}{\theta_0} K_H \frac{\partial \theta}{\partial z} - \varepsilon + \frac{\partial}{\partial z} \left(K_q \frac{\partial E}{\partial z} \right)$$

$$\varepsilon = c_\varepsilon \frac{E^{3/2}}{l}; \quad l_B = \frac{kz}{1 + \frac{kz}{\lambda}}, \quad l_N = c_N \frac{E^{1/2}}{N}; \; c_N = 0.75$$

$$\frac{1}{l} = \frac{1}{l_B} + \frac{1}{l_N}; \qquad K_M = \alpha_M \times l\, E^{1/2}, \quad K_H = \alpha_H \times l\, E^{1/2}$$

Comparison with BASE



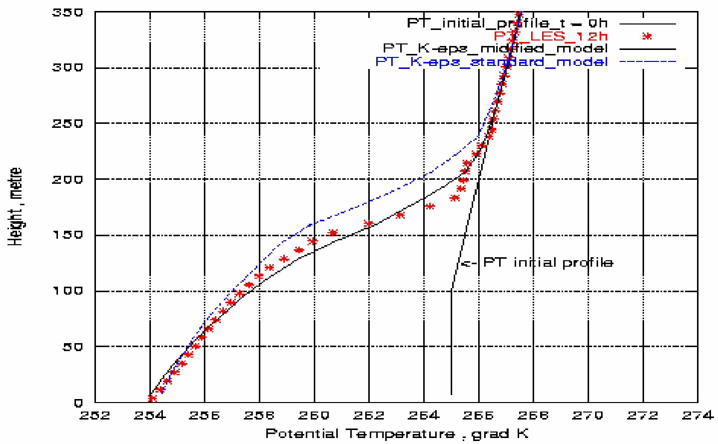


Figure 3: The potential temperature (PT) profiles with new (solid line) and standard (dashed line) $K-\epsilon$ models of turbulence. PT profiles for LES model (Kosović and Curry, 2000) are shown by stars. The initial PTs are shown by solid lines. Case of moderately stable ABL at the top, case of strongly stable ABL at the bottom.

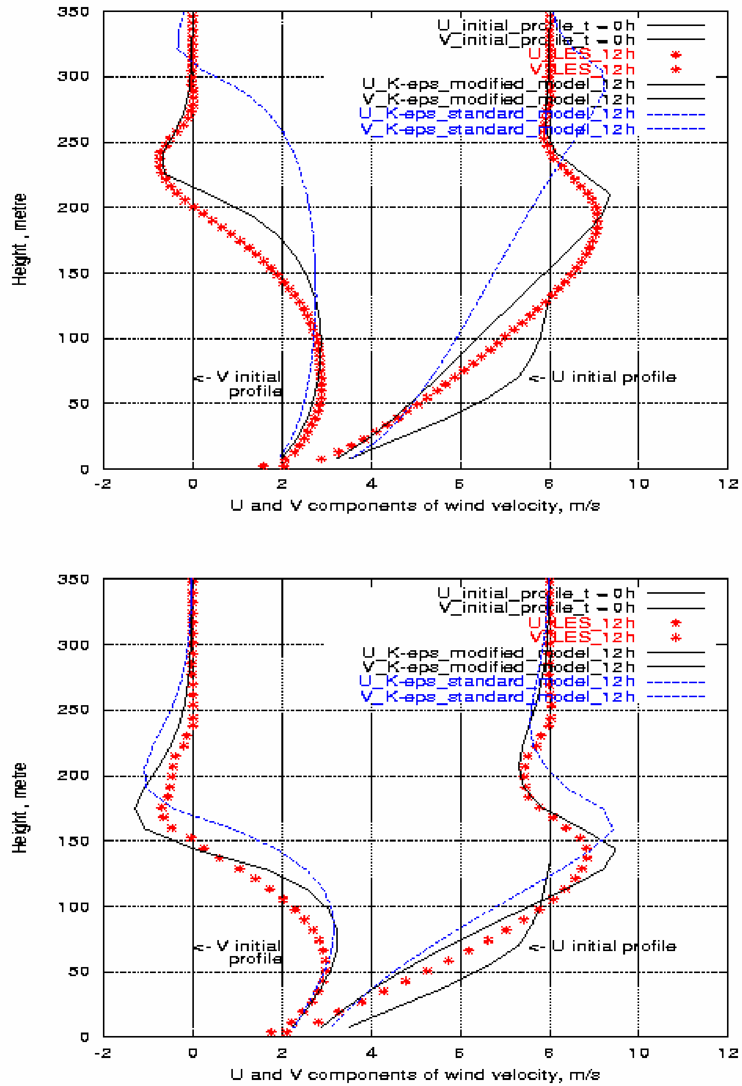
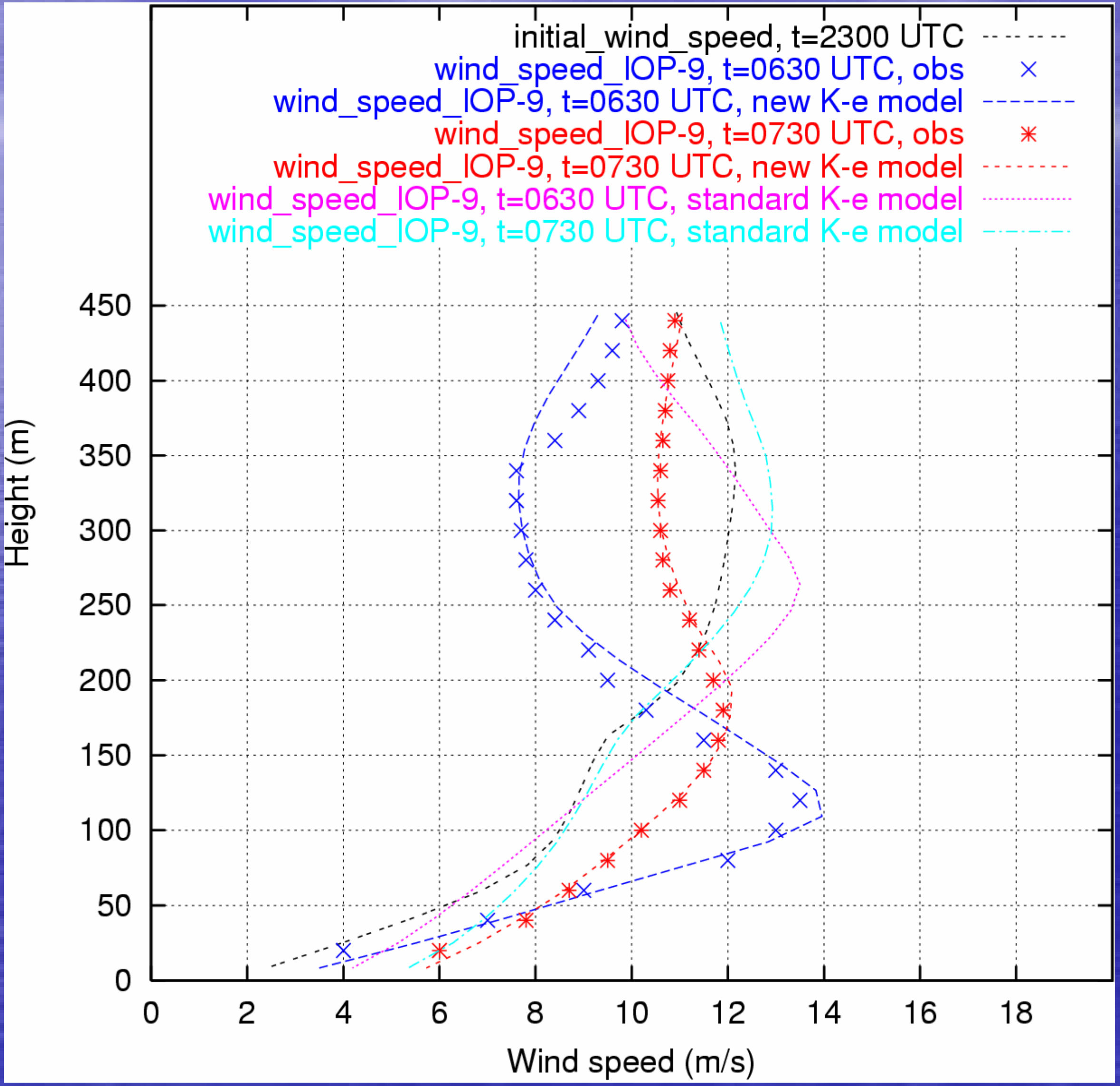
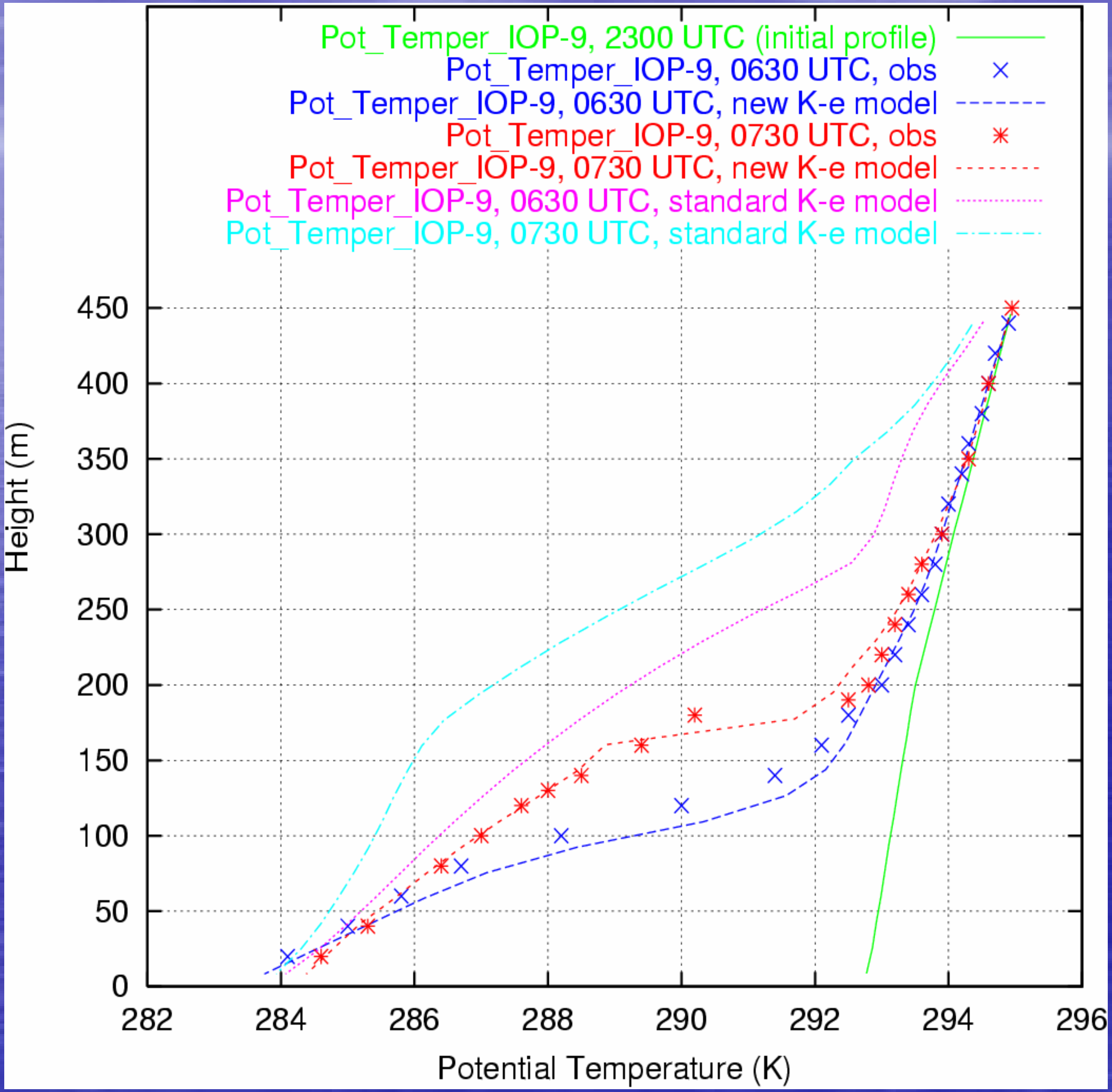


Figure 4: The profiles of U and V components of velocity with new (solid line) and standard (dashed line) $K-\epsilon$ models of turbulence. The profiles of U and V in LES model (Kosović and Curry, 2000) are shown by stars. The initial profiles of U and V are shown by solid lines. Case of moderately stable ABL at the top, case of strongly stable ABL at the bottom.

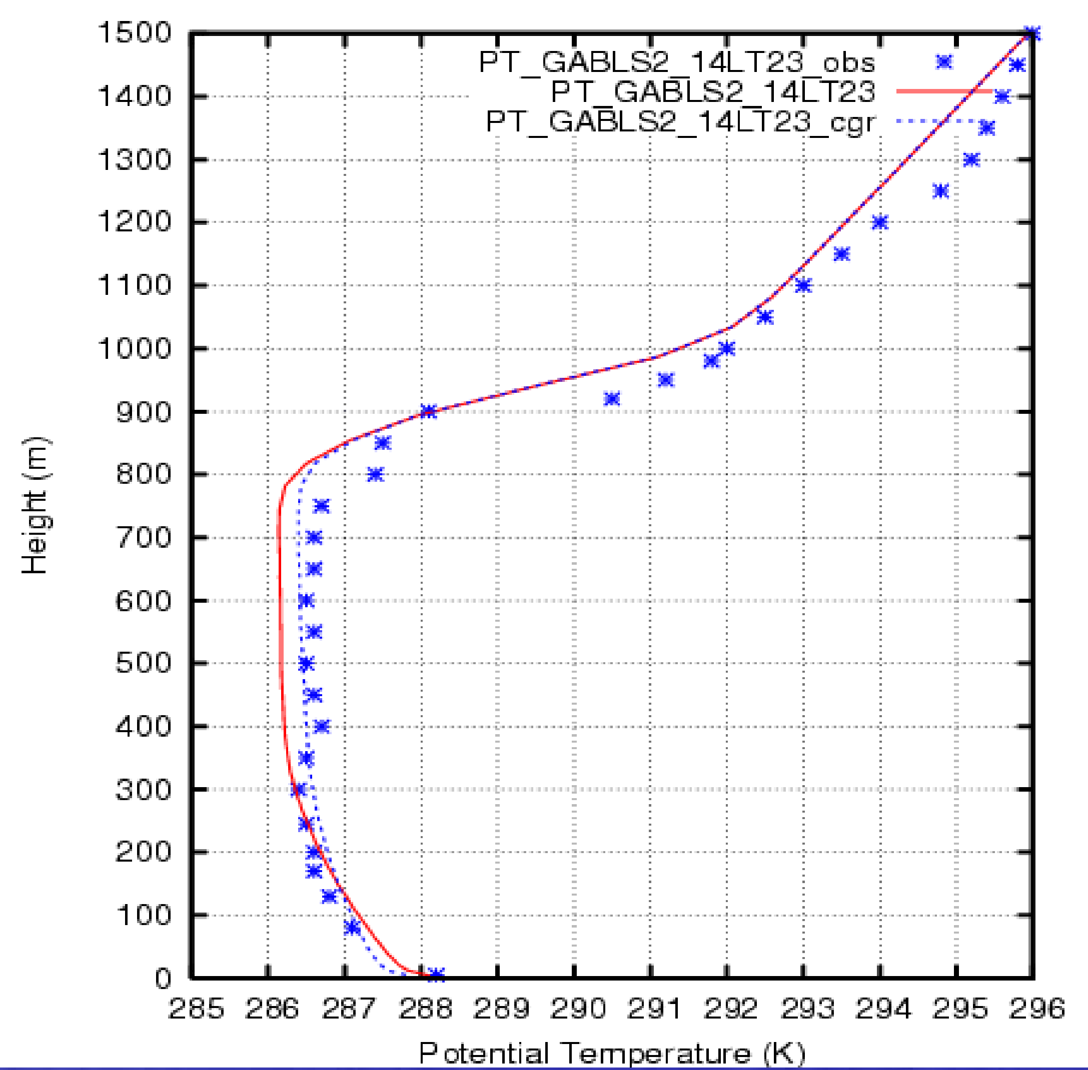
Comparison with CASES-99



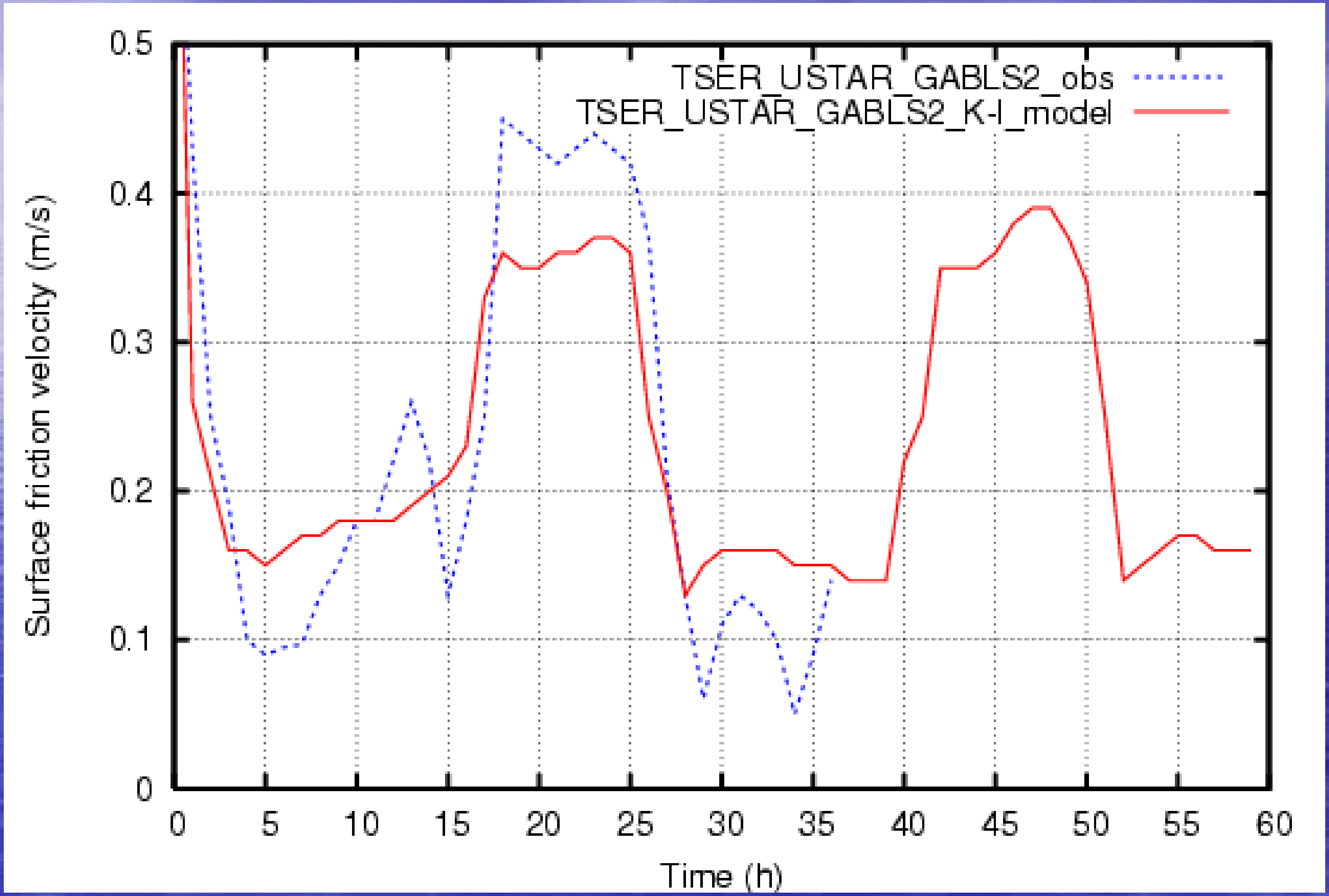
Comparison with CASES-99



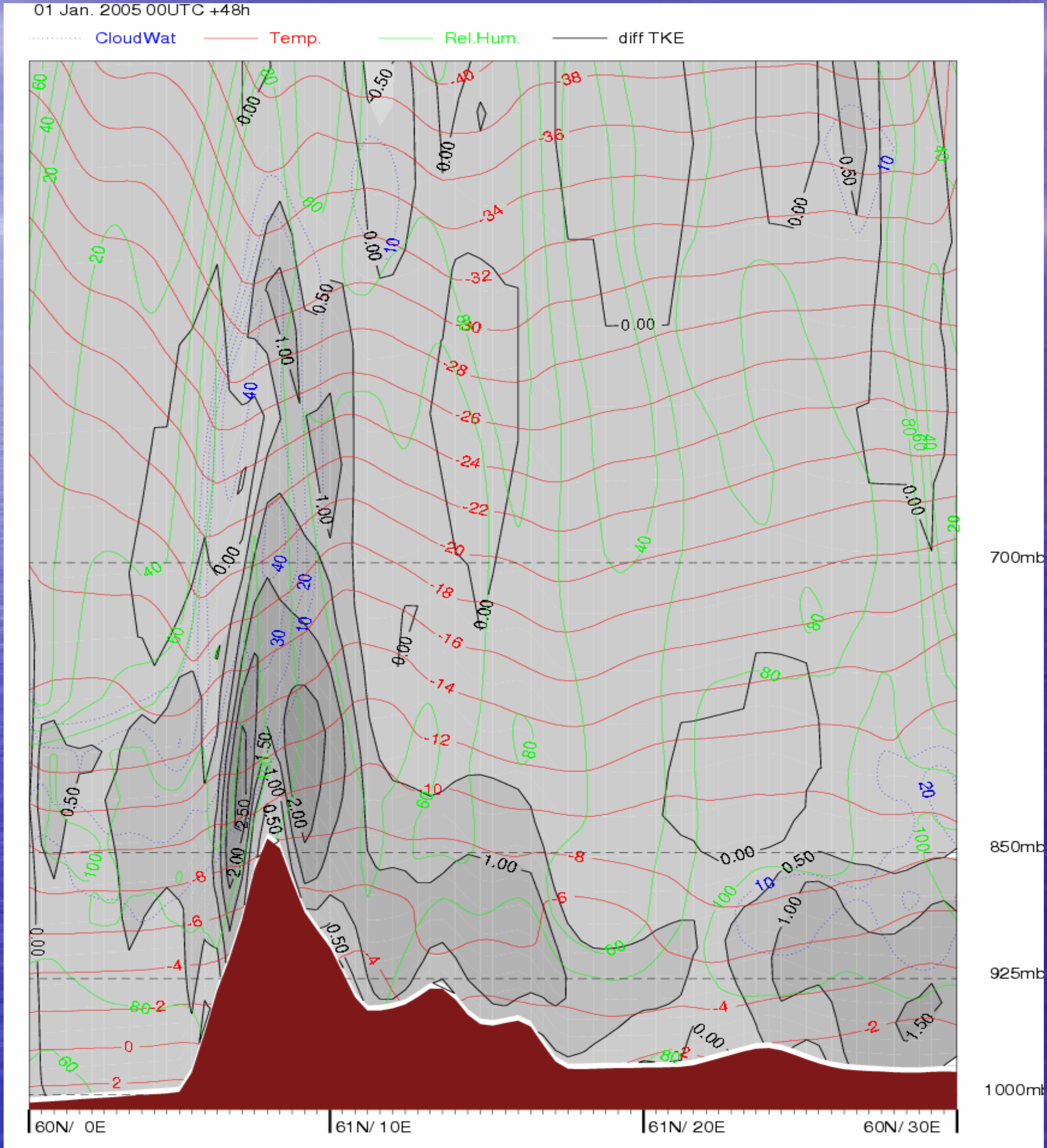
Comparison with GABLS2



Comparison with GABLS2



Cross-section: Difference in TKE



Modification of HIRLAM surface layer parameterization

$$\gamma_m = \ln(\frac{z}{z_0}) + 2.25\frac{z - z_0}{L}(1 - 0.09\frac{z}{L})$$

$$\gamma_h = 0.7\left\{\ln\frac{z}{z_0} + 2\frac{z - z_0}{L}\left[1.02 + 0.07\frac{z}{L}\left((\frac{z}{L})^3 - 2.5(\frac{z}{L})^2 + 2.5\frac{z}{L} - 1.25\right)\right]\right\}$$

$$C_D = \frac{k^2}{\gamma^2_m} \quad ; \quad C_h = \frac{k^2}{\gamma_m \gamma_h}$$

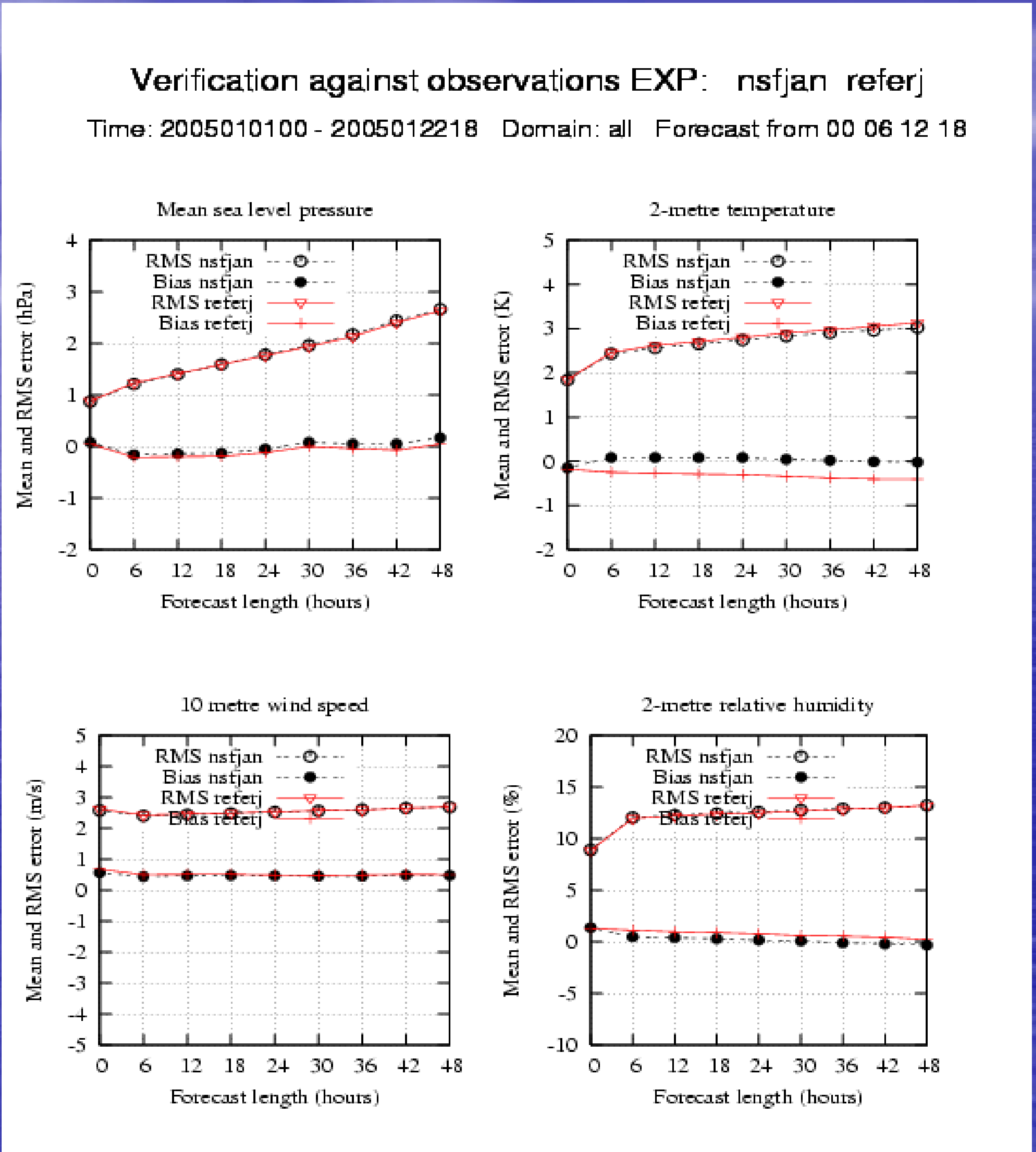
Reference HIRLAM K-l scheme of turbulence. Results of versions 7.0:

-Negative Bias in T2m and positive in Q2M for winter

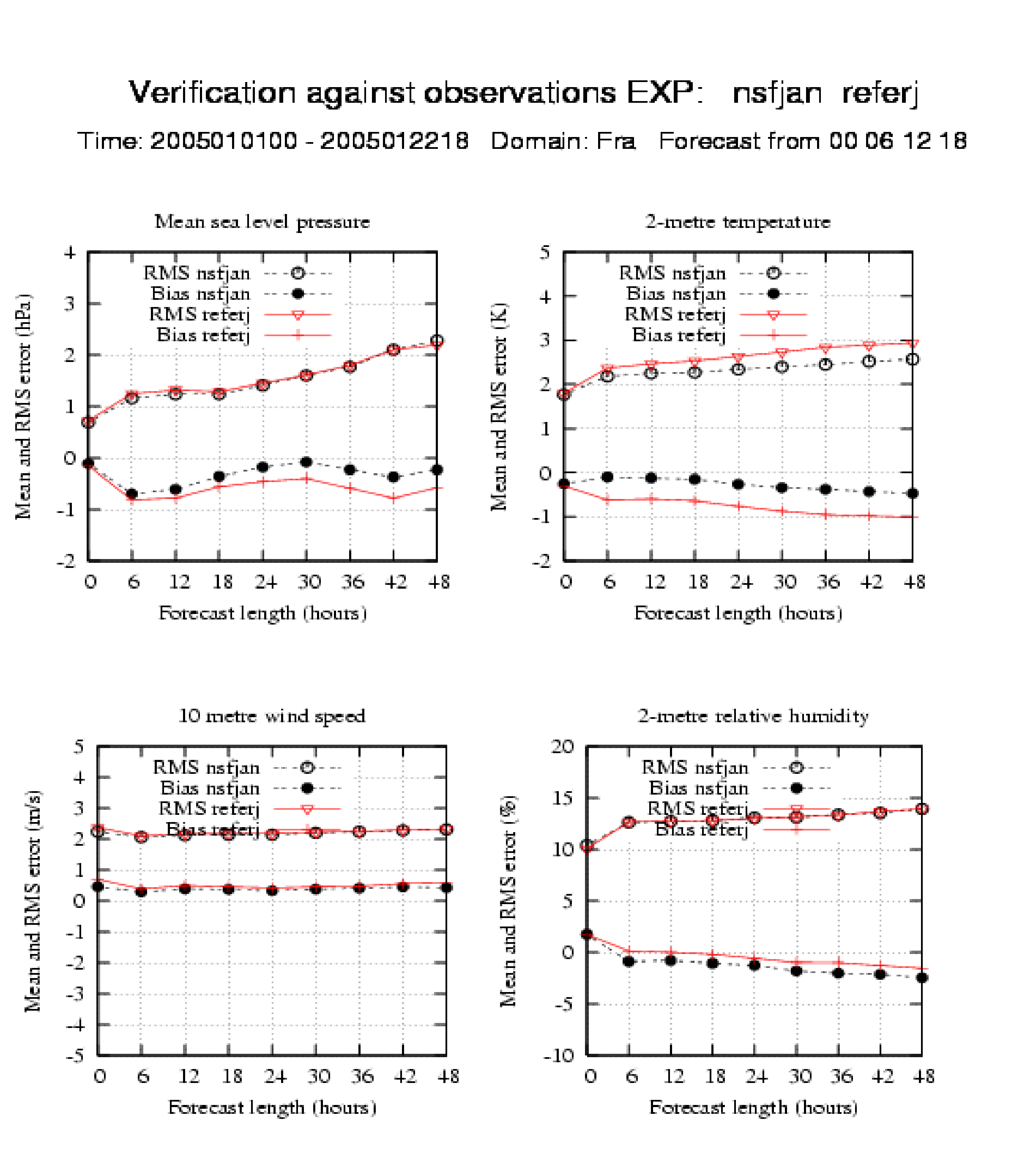
- Positive bias in the wind, accompanied by too strong near surface winds

- Too fast deepening and too slow filling of cyclones, making HIRLAM too active towards the end of the forecast period

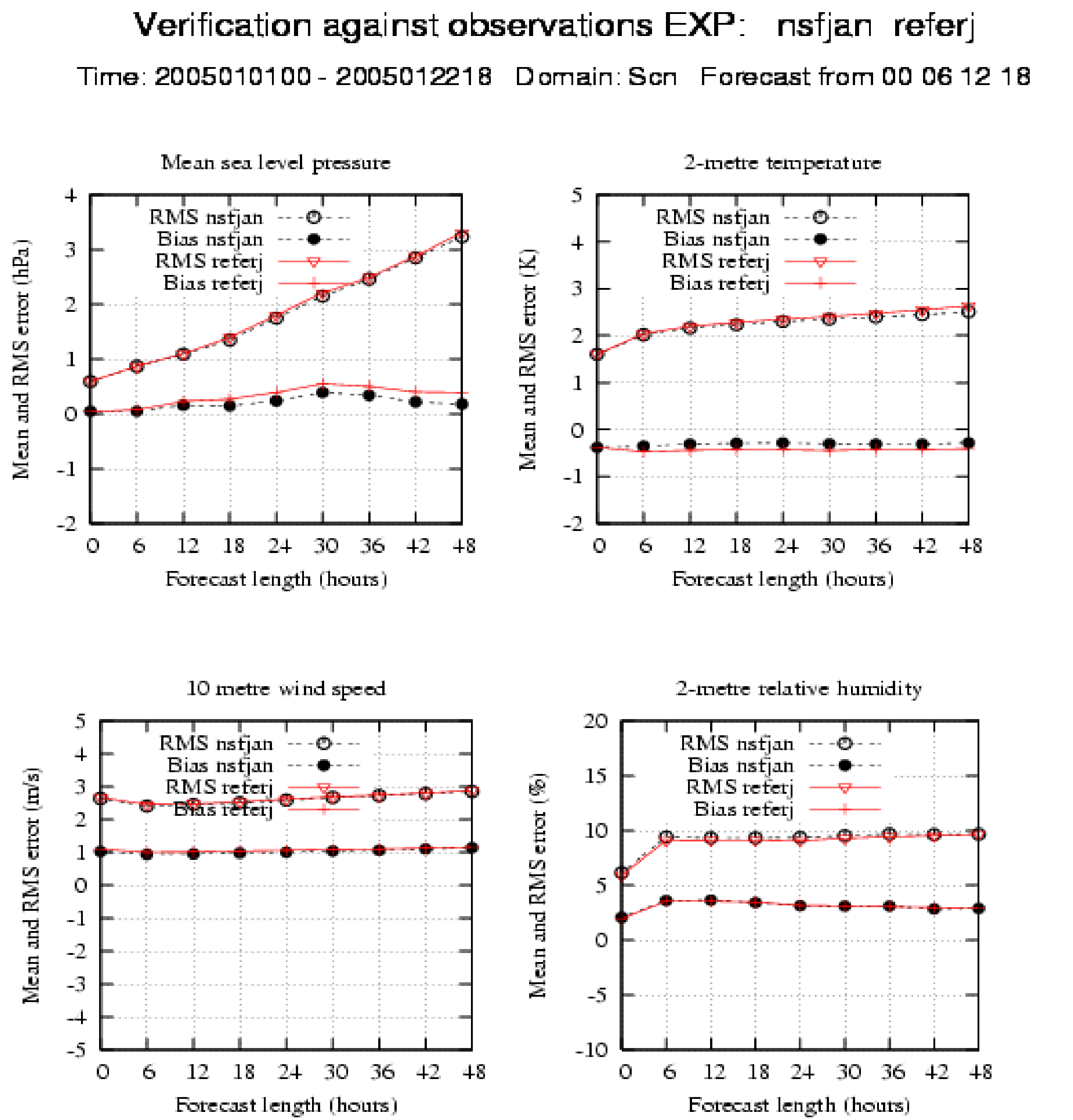
January 2005,
All stations



January 2005, France

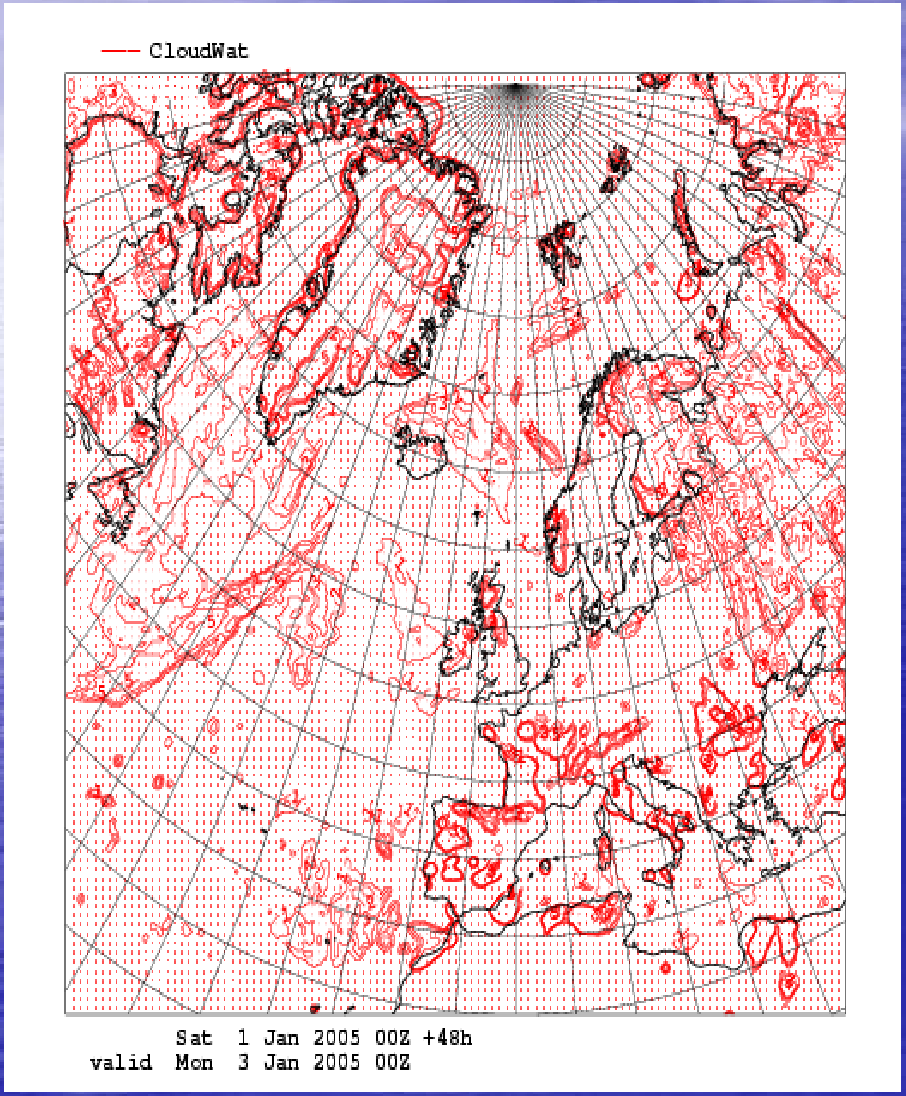


January 2005, Scandinavia

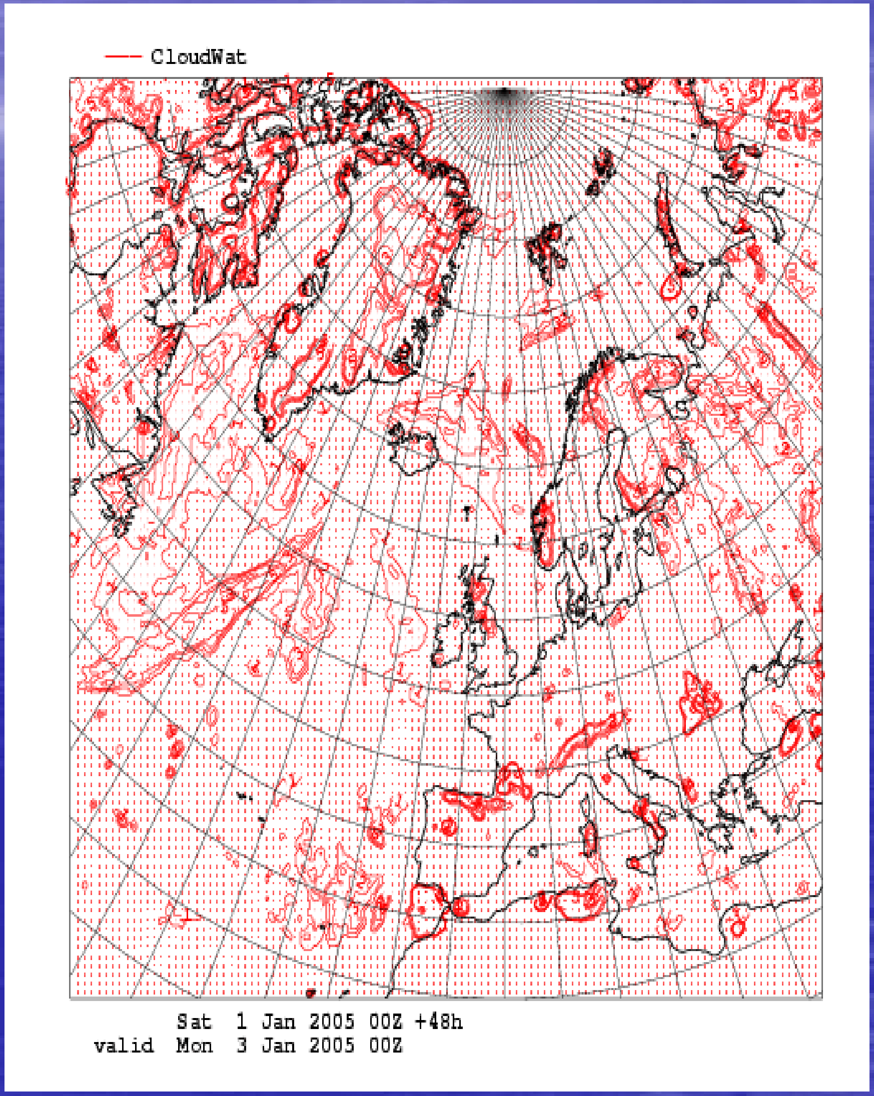


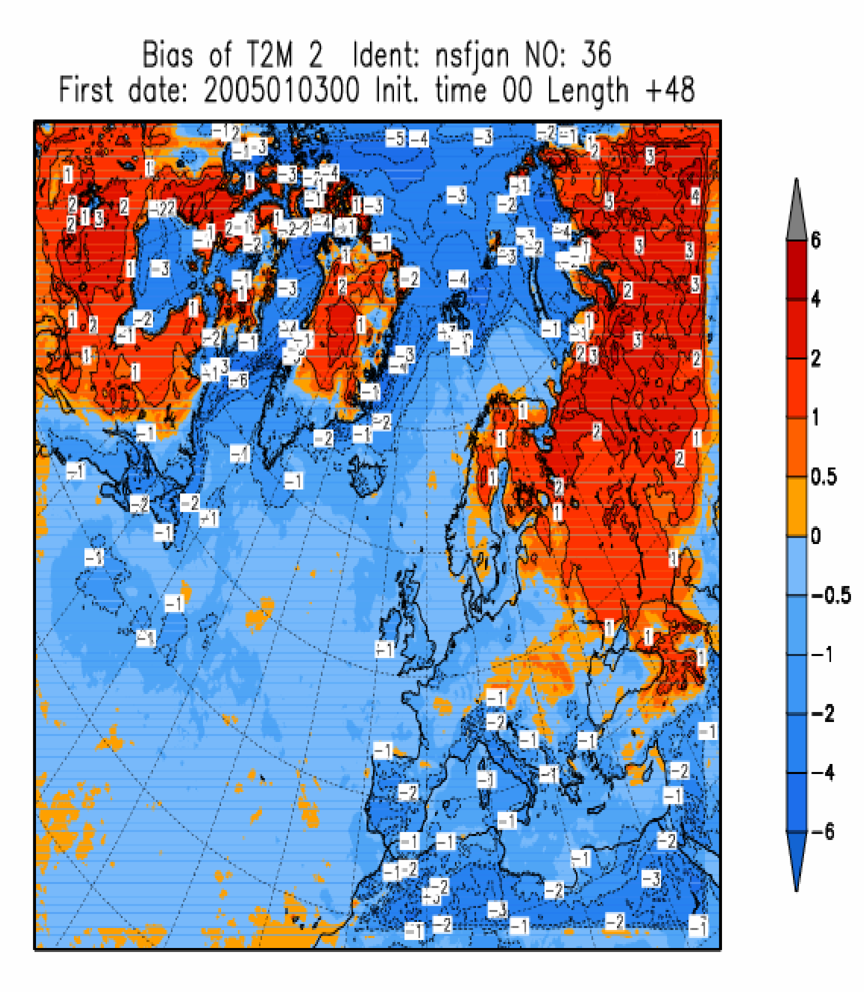
Cloud water at the lowest model level

QNSE model



Reference model

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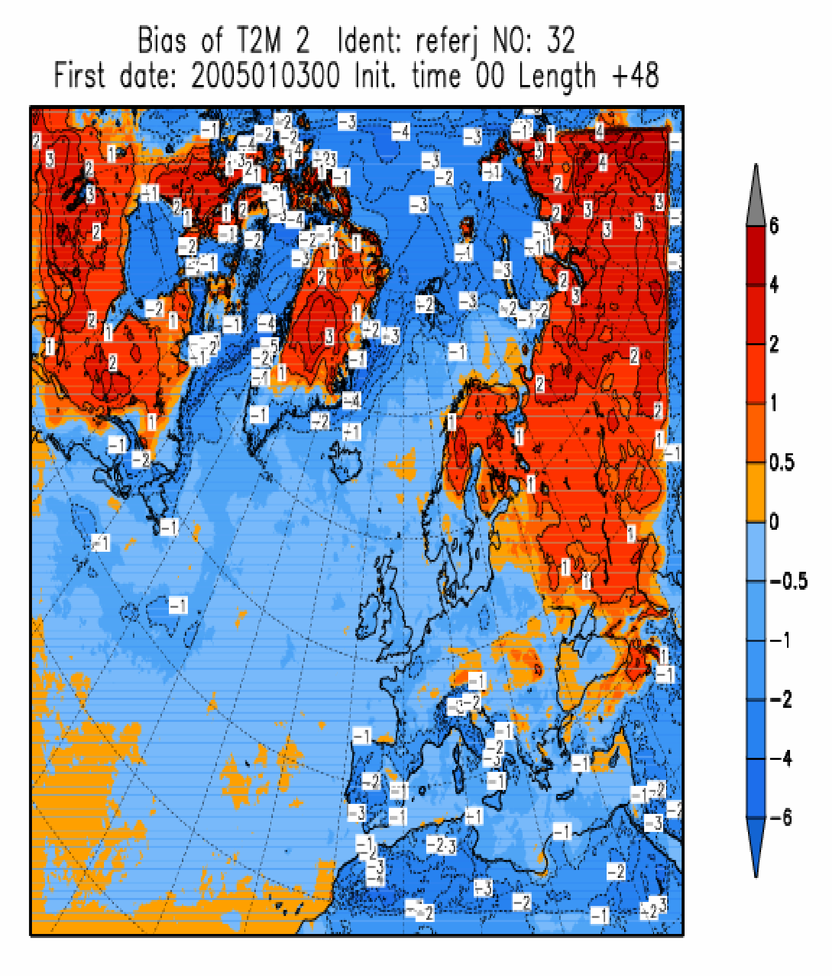
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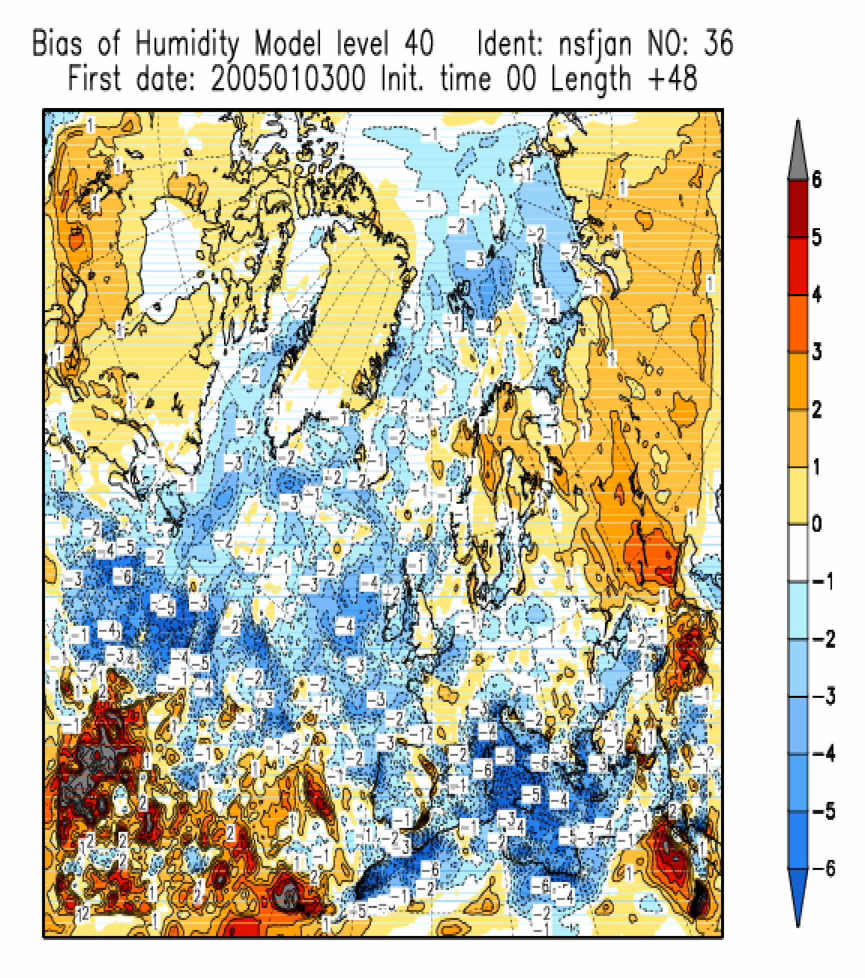
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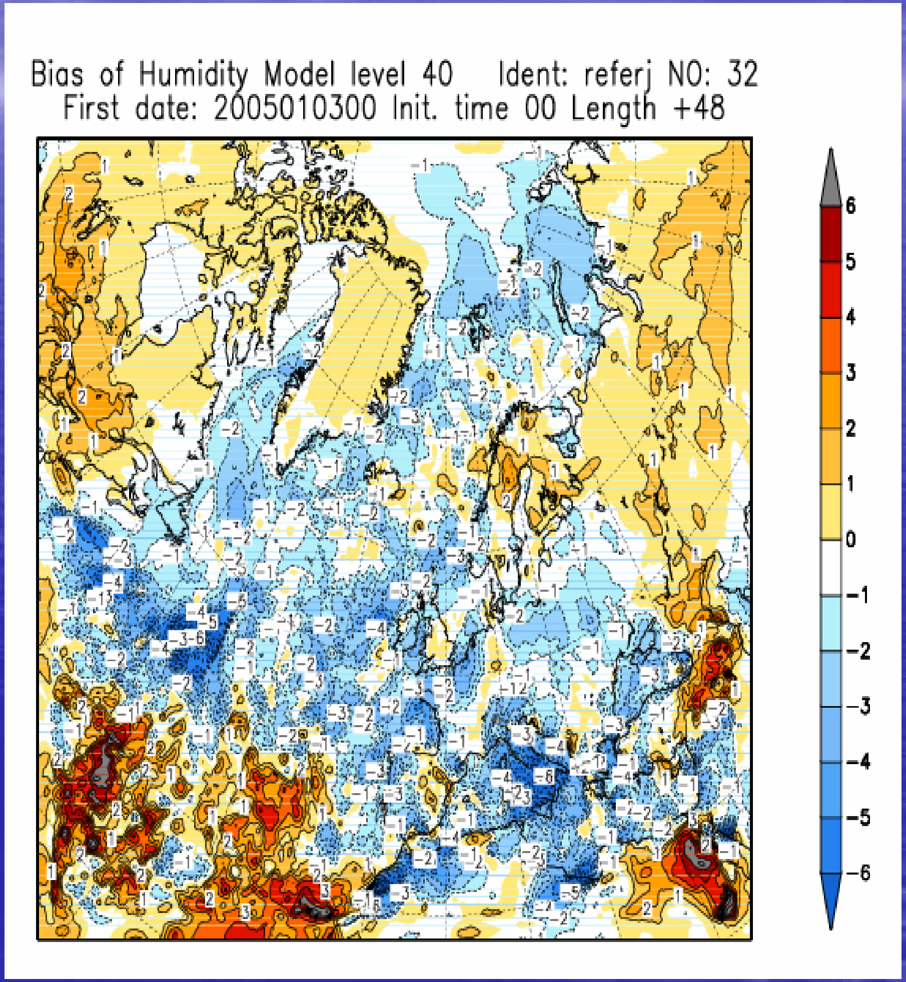
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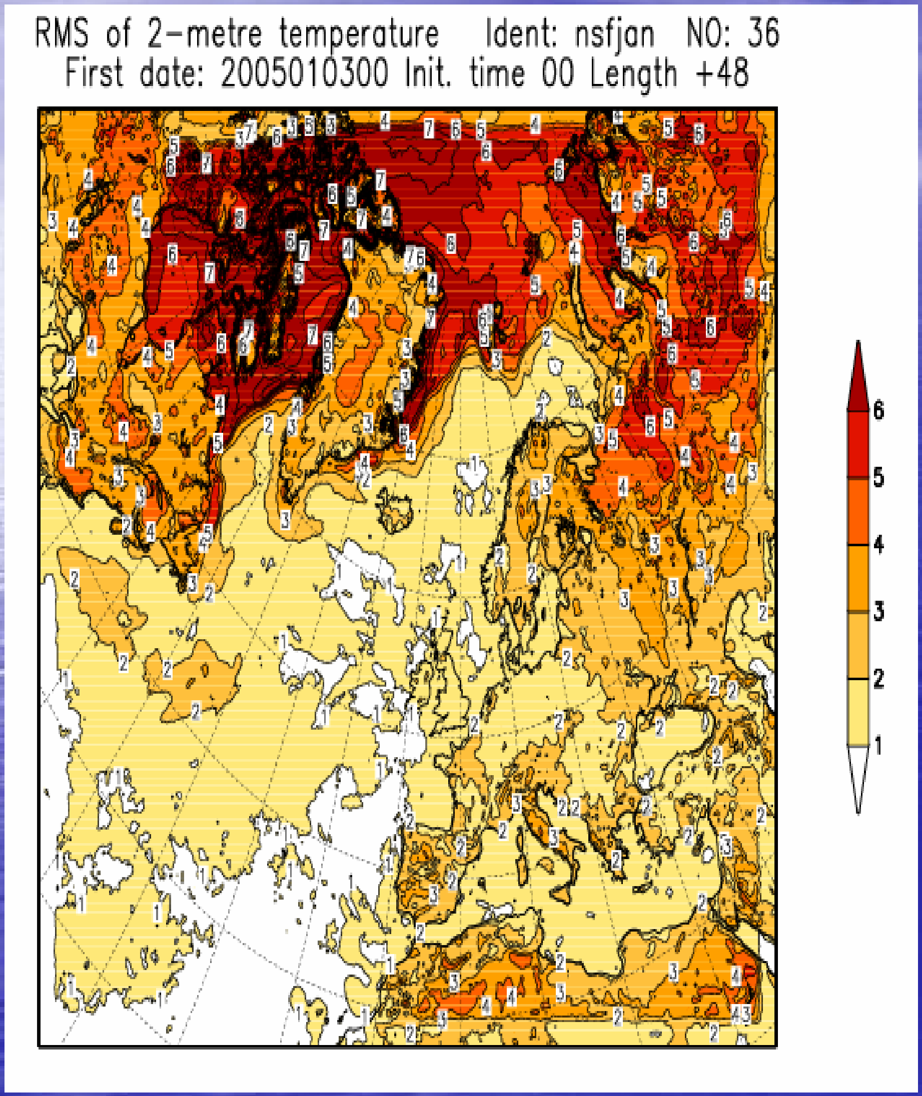
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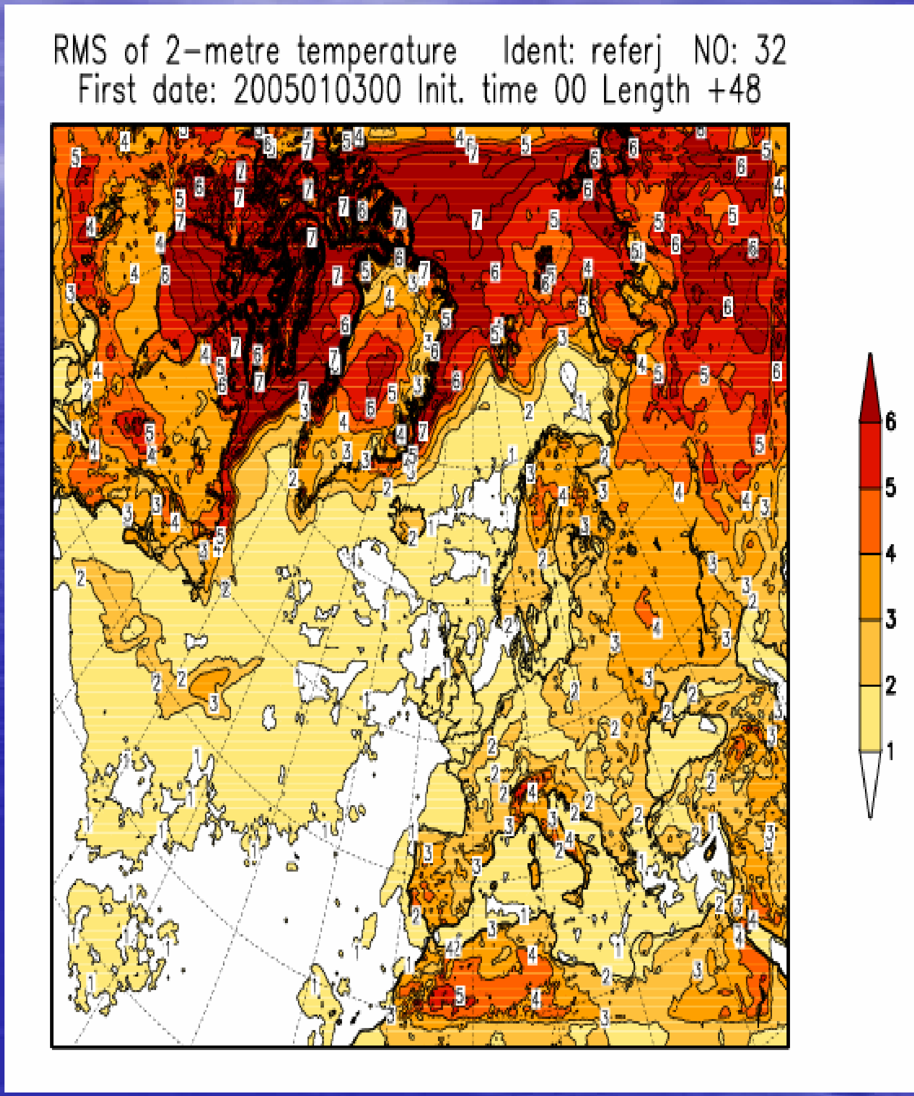
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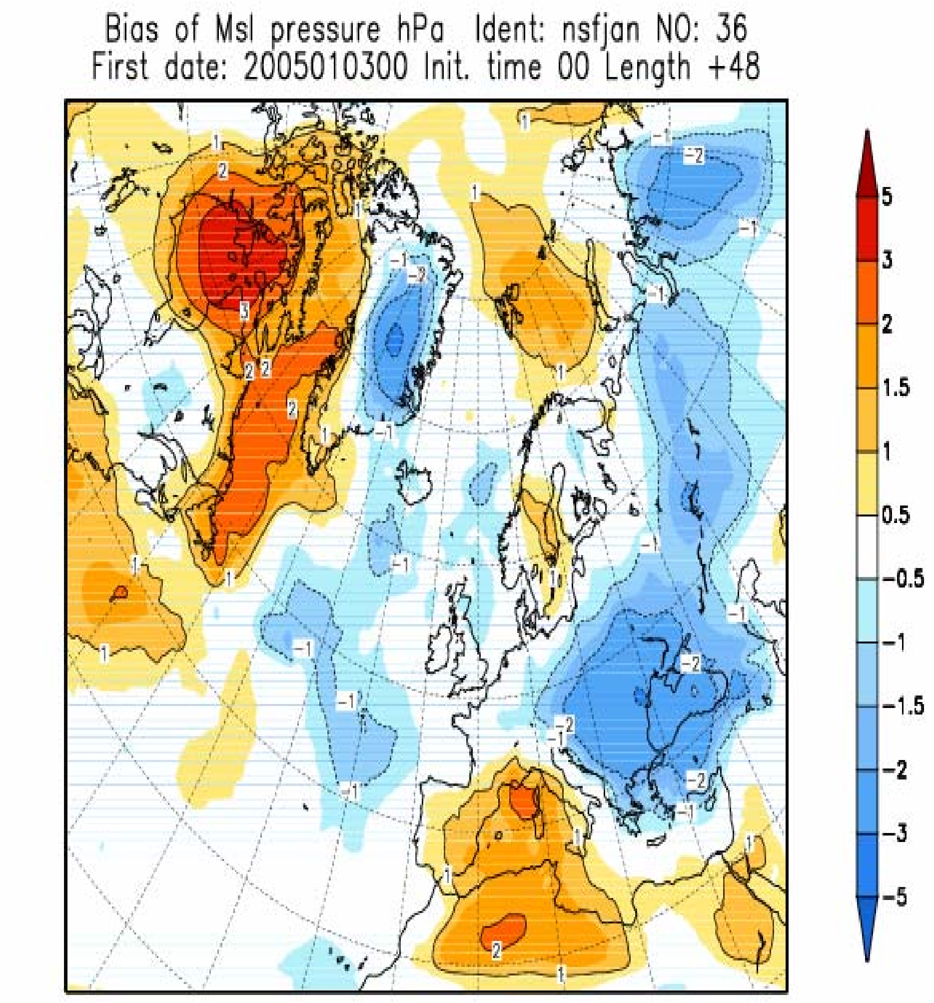
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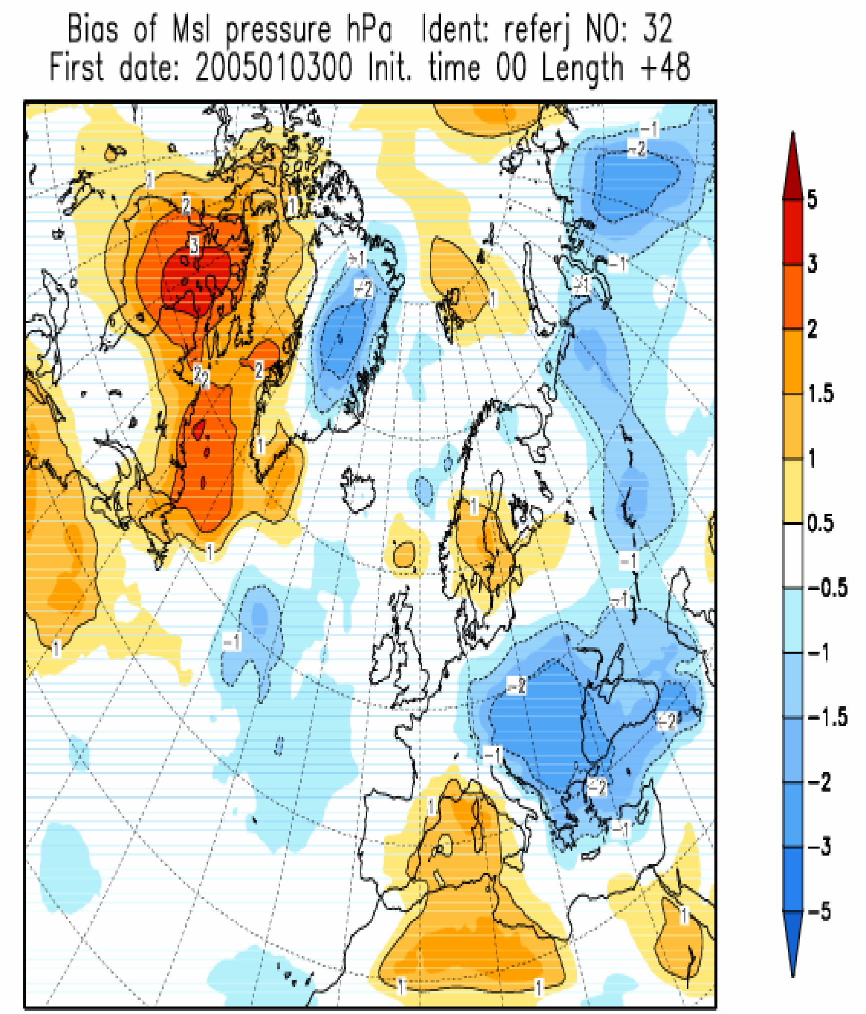
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Conclusions

- Anisotropic turbulent viscosities and diffusivities are in good agreement with experimental data
- The model recognizes the horizontal-vertical anisotropy introduces by stable stratification and provides expressions for the horizontal and vertical turbulent viscosities and diffusivities. This is a real possibility to include 3-D turbulence in NWP and mesoscale models
- Theory has been implemented in 1-D K-ε and K-l models of stratified ABL
- Good agreement with BASE, SHEBA and CASES-99 data sets has been found in 1-D models for cases of stable, neutral and unstable stratifications
- Theory has been implemented in surface layer parameterization of 3-D NWP model HIRLAM, version 7.0
- The new surface layer improves predictive skills of mean sea level pressure and 2M temperature and humidity for +48h weather forecasts over all and EWGLAM stations for January 2005