Comparison of HIRLAM and QNSE turbulence closures for Stratified Atmospheric Boundary Layer

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Outline

- Background
- HIRLAM and QNSE closure
- QNSE closure for 1D-model
- Results and comparisons
- Conclusions

Background

Atmospheric Boundary Layer

- The transition layer within which surface-air interaction takes place
- Physical processes in ABL determine the surface fluxes of the momentum, temperature and humidity

Stable Boundary Layer

- Inversions of temperature
- Damped vertical heat fluxes
- Could be very shallow, down to 10 meters or less
- Can maintain well developed turbulence
- **Effect of the negative buoyancy**
  - Suppresses vertical heat fluxes
  - Increases wind velocity gradient, resulting in mixing adjacent flows
- Least friendly to mathematical modeling
- Not possible to treat within analytical theories

Background

HIRLAM turbulence closure

- TKE-l scheme

- The turbulence closure
  - based on formulation of $K_{m,h}$ coefficients via $l_{m,h}$ and E
  - Derived with assumption of near-neutral conditions and isotropic turbulence
  - SBL is presented in form of the dependence on E and buoyancy flux
  - The integral form for ABL is averaging between SBL conditions and near-neutral conditions

- **Nordic Temperature Problem of HIRLAM**

- Large errors in prediction of T2m in
  - Nordic regions
  - Statically stable Boundary layer
  - Cold conditions

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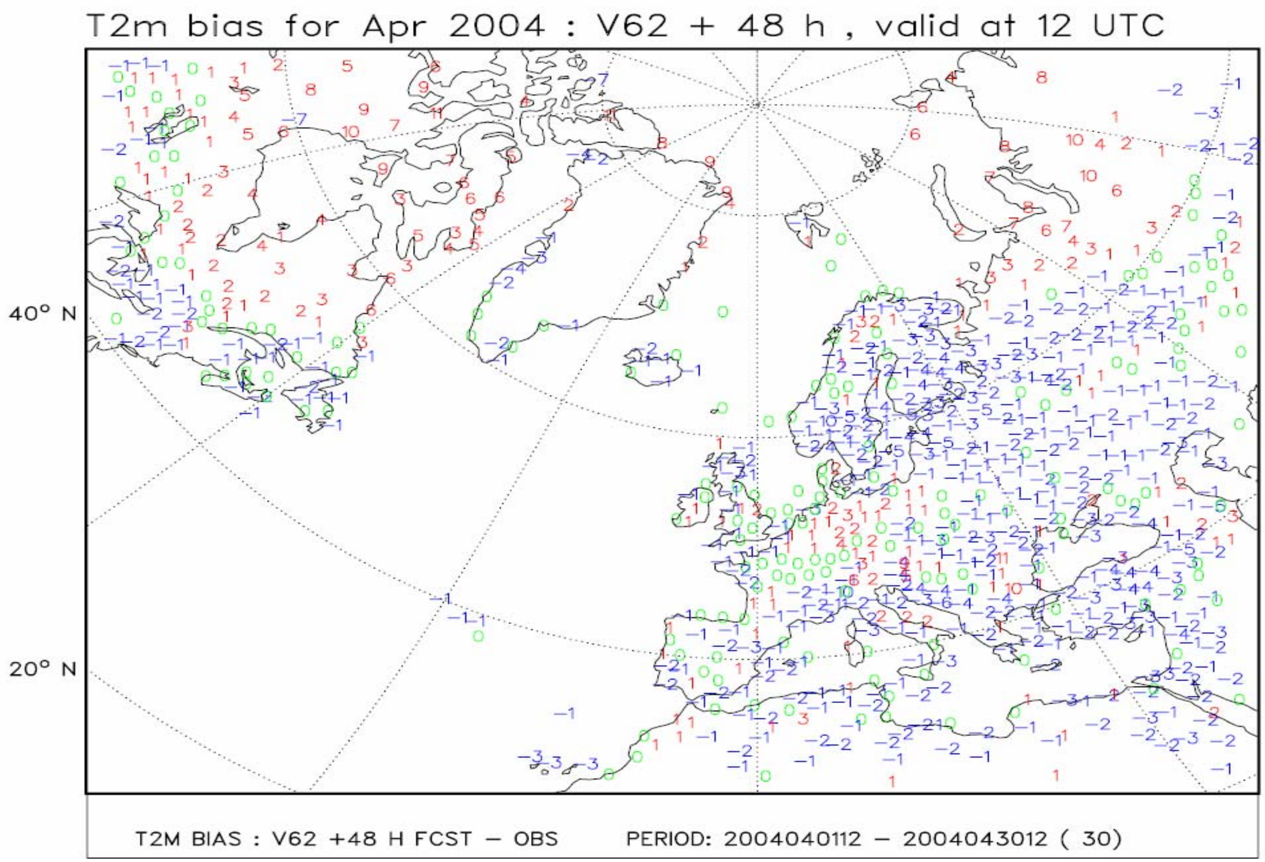
Background

- **Nordic Temperature Problem**

  - T_{2m} BIAS distribution

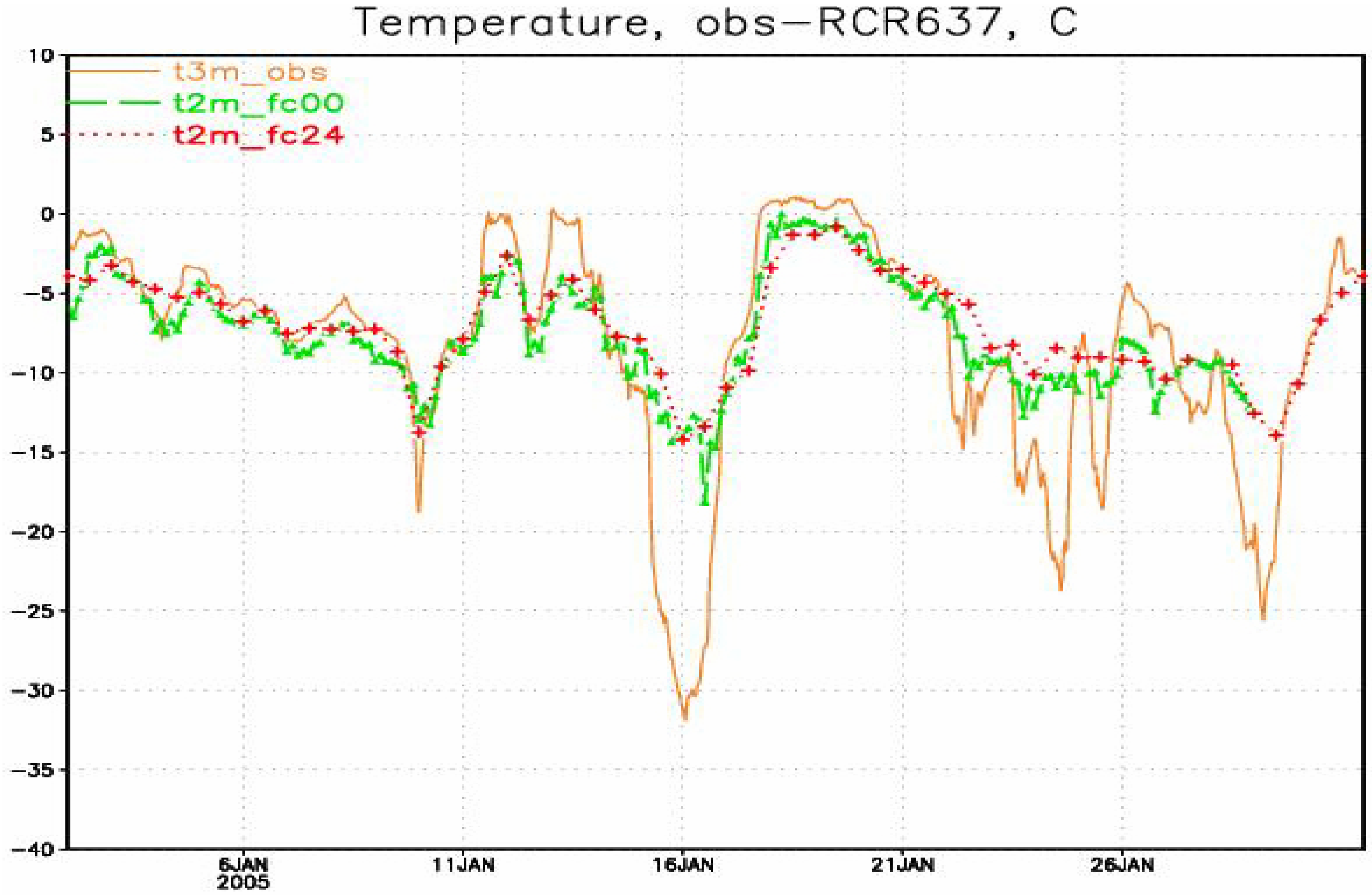
S.Järvenoja / FMI



Background

- **Nordic Temperature Problem**

T_{2m} time series : forecast / measurements (Sodankyla)



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Background

QNSE turbulence closure

- Mapping of the velocity field onto quasi-Gaussian field whose modes are governed by the Langevin equation

- $K_{m,h}$ formulations are added by the dependence on stability function of Fourier space wavenumber and frequency

Modified 1D HIRLAM closure for SBL

- $l_{m,h}$ formulation is made with assumption of SBL conditions

- $K_{m,h}$ are taken with QNSE stability functions

- The modified closure scheme has been developed and tested in 1D HIRLAM

- Experiments
  - 1D HIRLAM system 6.3.4
  - Sodankyla region
  - Very Stable Boundary Layer condition

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Reference and QNSE closure

HIRLAM turbulence closure TKE-l scheme

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

$$\varepsilon = c_d \frac{E^{3/2}}{l_{m,h}}; \qquad K_{M,H} = l_{m,h}\sqrt{E}$$

The turbulent length scale combines the length scales for near-neutral condition and for stable condition

QNSE theory for TKE-l scheme gives

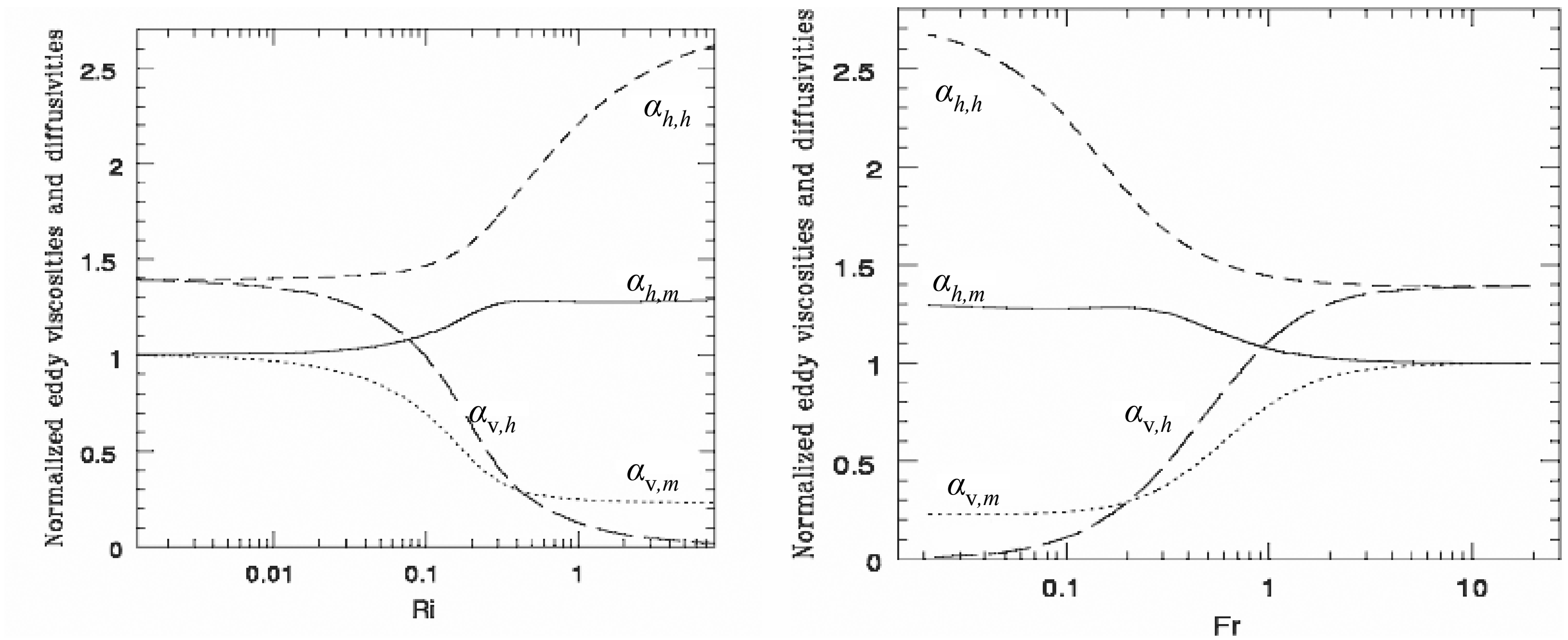
$$K_{M,H} = \alpha_{m,h} l \sqrt{E}$$

$$\alpha_{m,h} = \frac{K_{M,H}}{K_{M,neutr}}$$

- non-dimensional stability functions for viscosity and diffusivity resulted from QNSE theory

Results from the spectral models theory

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



- Normalized turbulent exchange coefficients
- For *Ri* > 0.1, both vertical viscosity and diffusivity decrease, with the diffusivity decreasing faster than the viscosity
- Horizontal mixing increases with increasing *Ri*. The model accounts for flow anisotropy
- The crossover from neutral to stratified flow regime is replicated

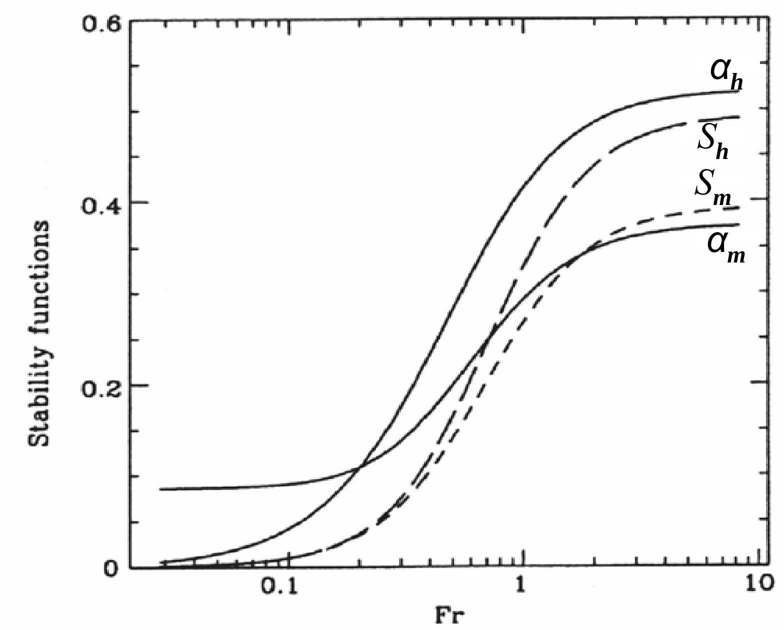
QNSE closure for 1D-model

Eddy viscosity and diffusivity formulation in the modified CBR scheme

$K_{M,H} = S_{m,h} l \sqrt{E}$ instead of $K_{M,H} = \alpha_{m,h} l \sqrt{E}$

$S_{m,h} \sim G(Fr^{-2})$ - are stability functions of Fr, $Fr = \frac{\varepsilon}{NE}$

Comparisons of stability functions calculated from the spectral theory and from QNSE



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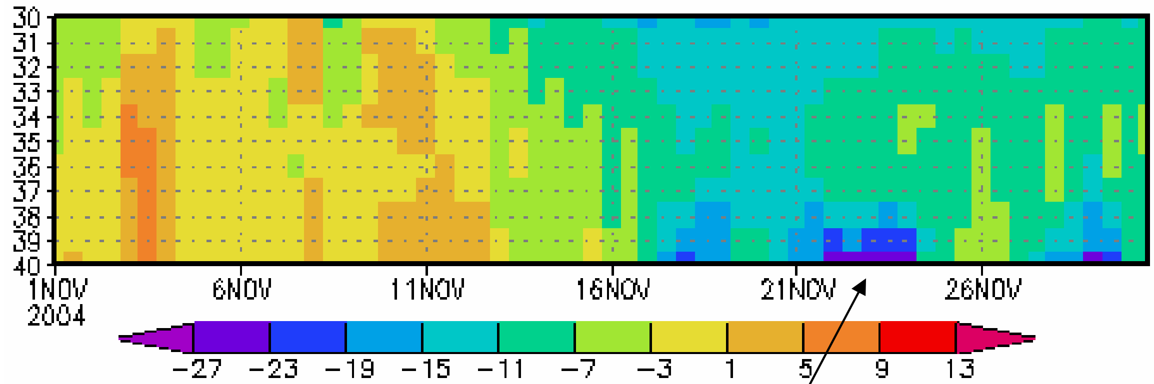
Sodankyla data utilization in 1d-model experiments

- Location: Northern Finland 67.22ºN, 26.38 ºE - Nordic region
- Occurrence of (very) stable boundary layer
  - Cold conditions
  - Temperature inversions
- HIRLAM large T2m errors
- Data:
  - Soil measurements
  - Mast measurements
  - Soundings (interpolation to model levels)

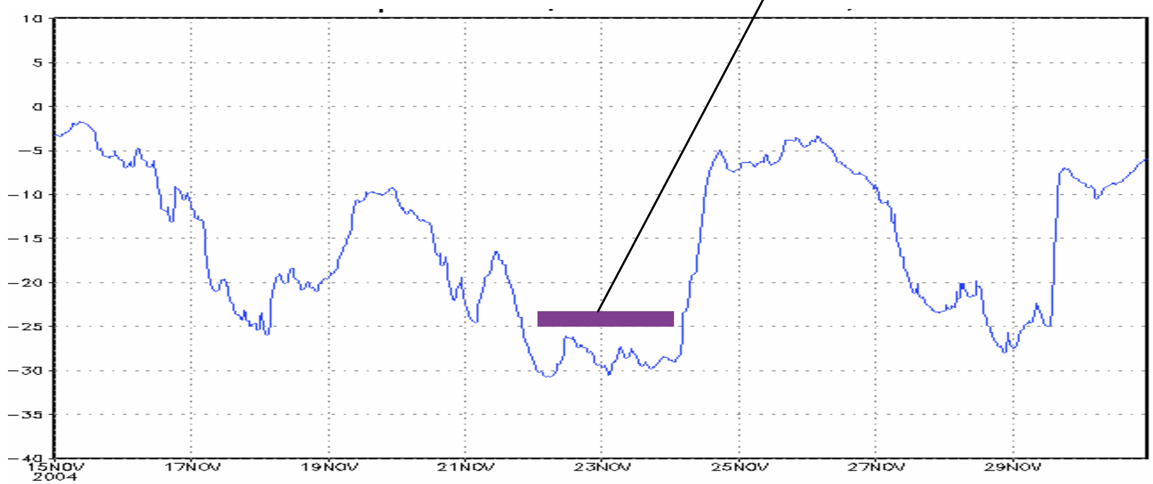
Case of Very Stable Boundary Layer in Sodankyla

22-24 November 2004

Temperature at model levels



T2m



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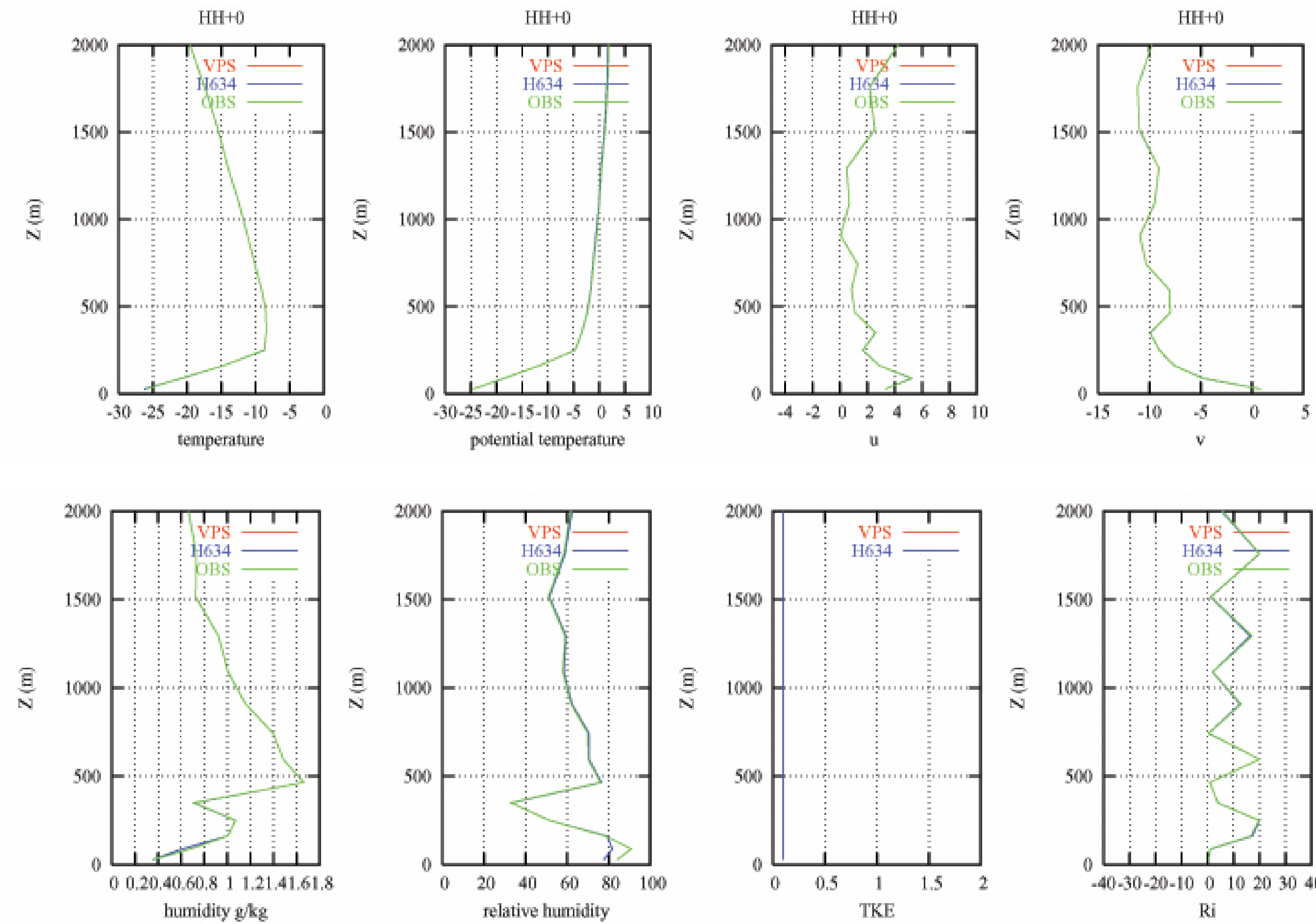
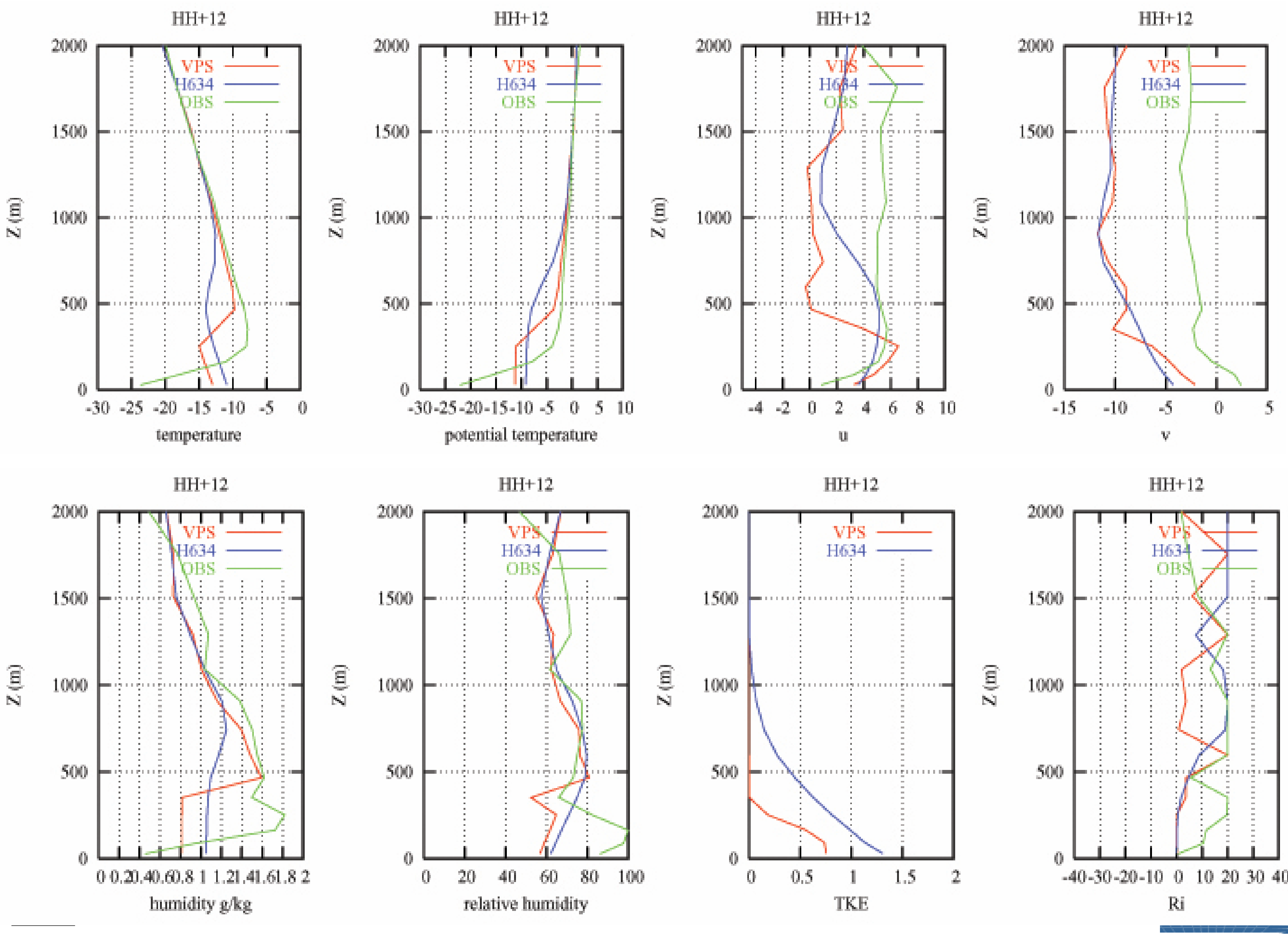
Results and comparison



Results and comparison



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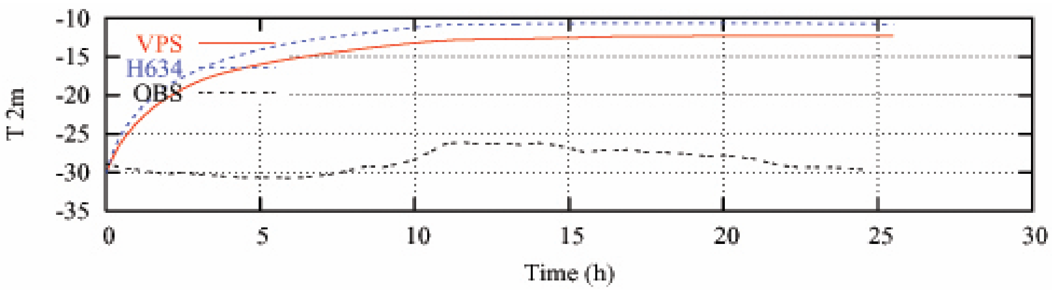

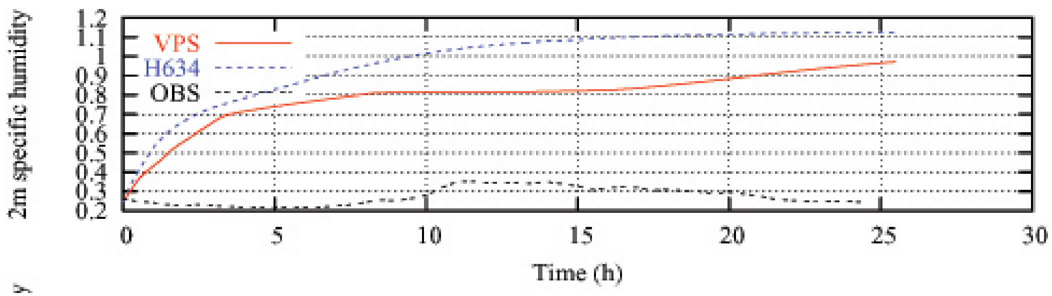

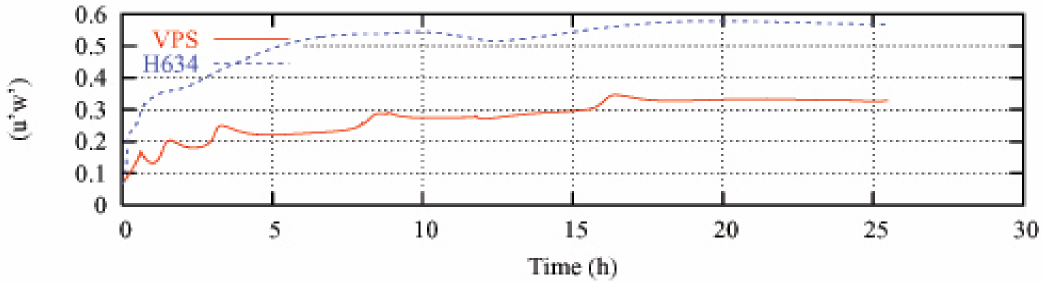

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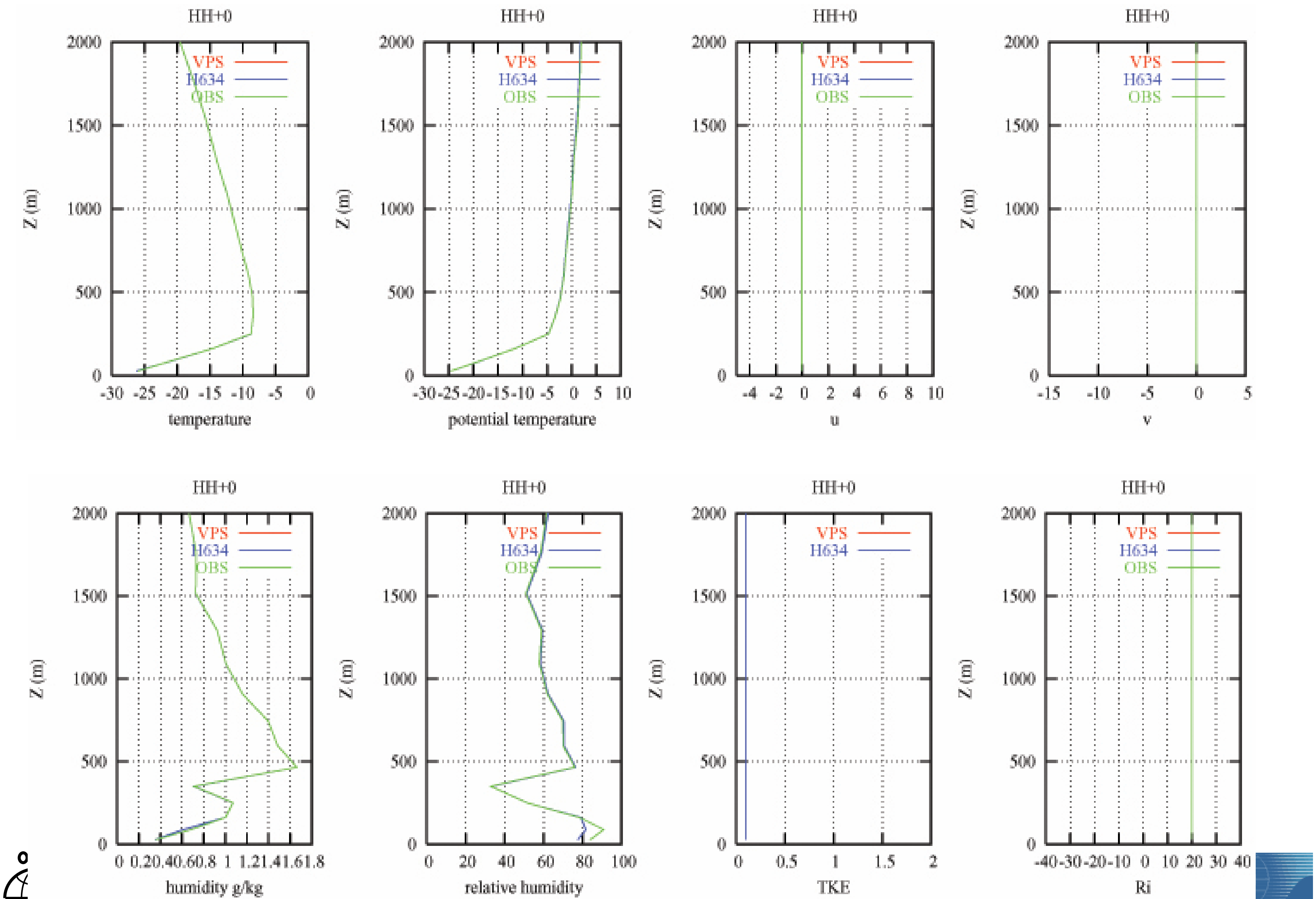
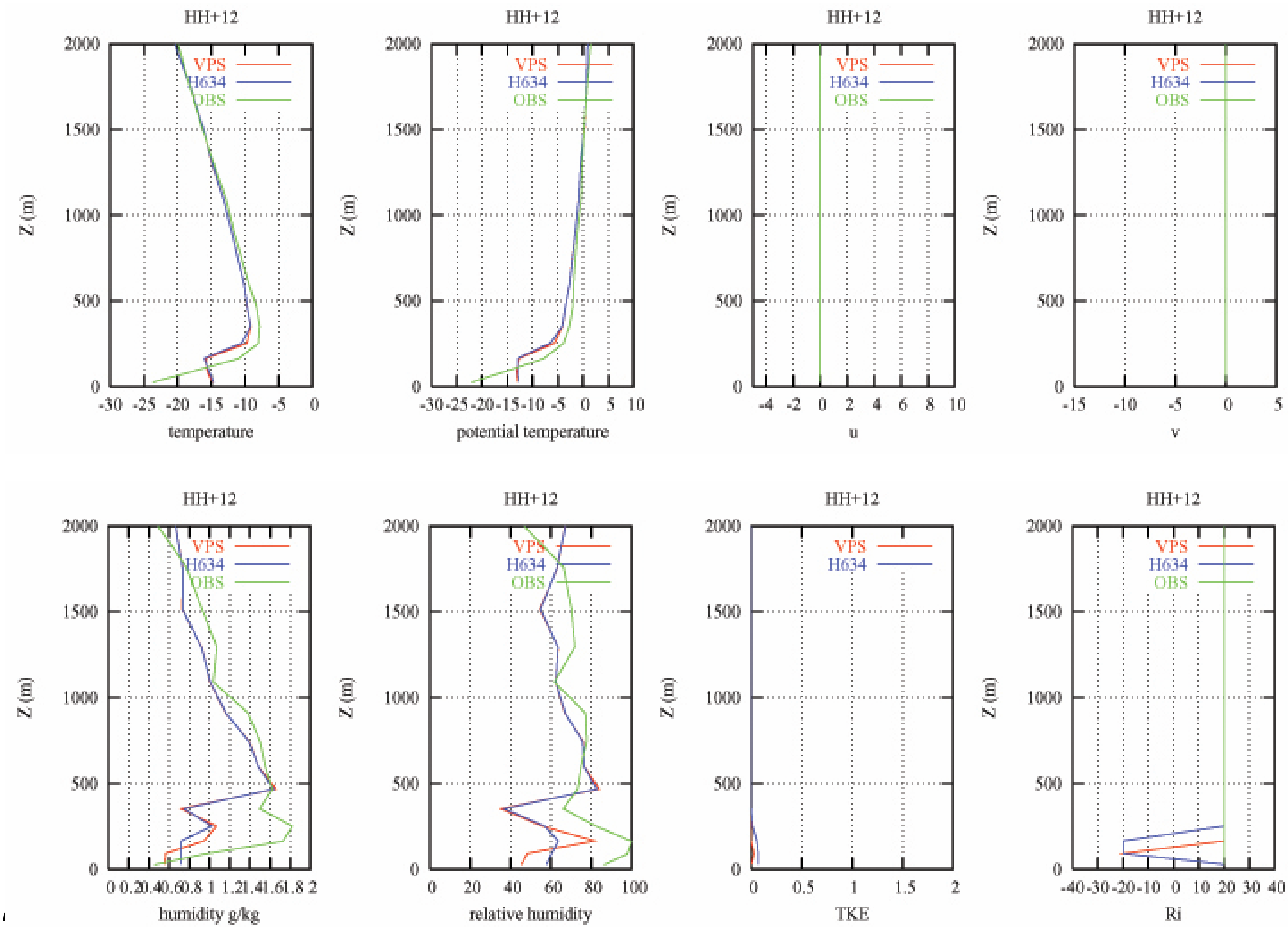
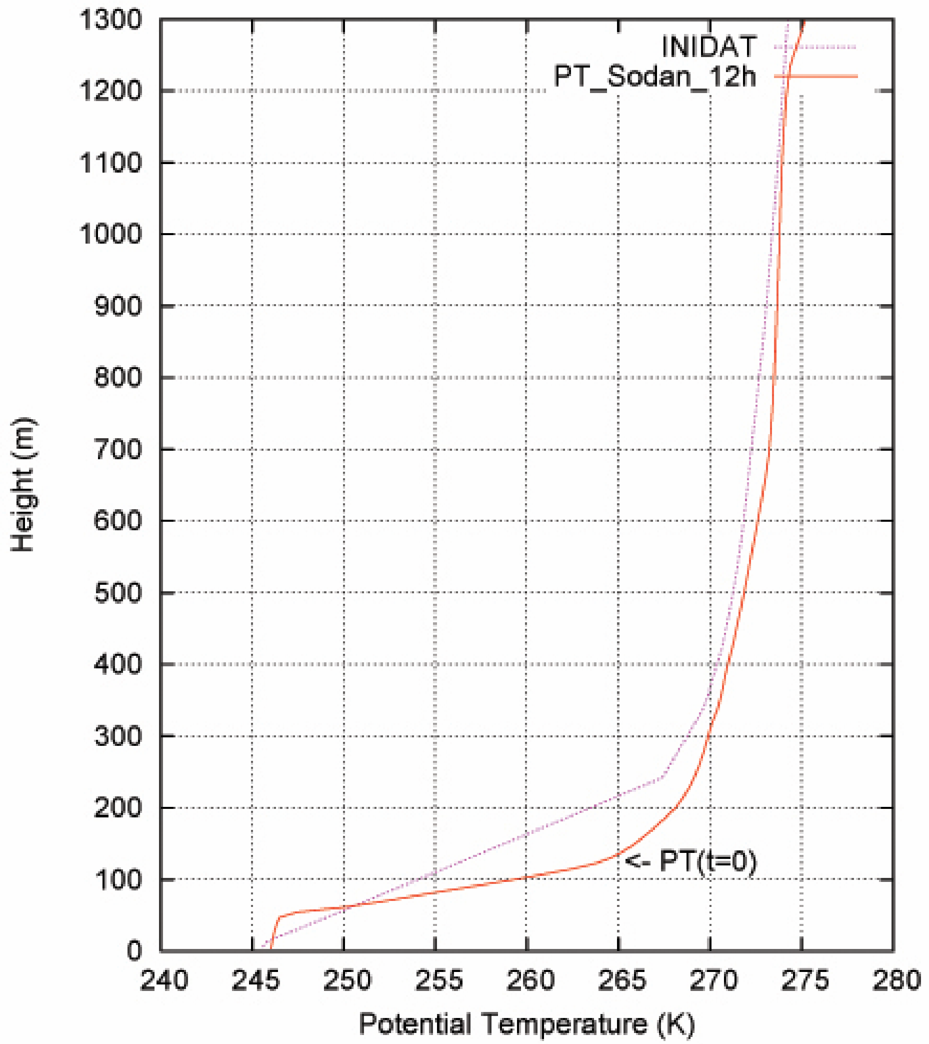
Results and comparison (no wind)



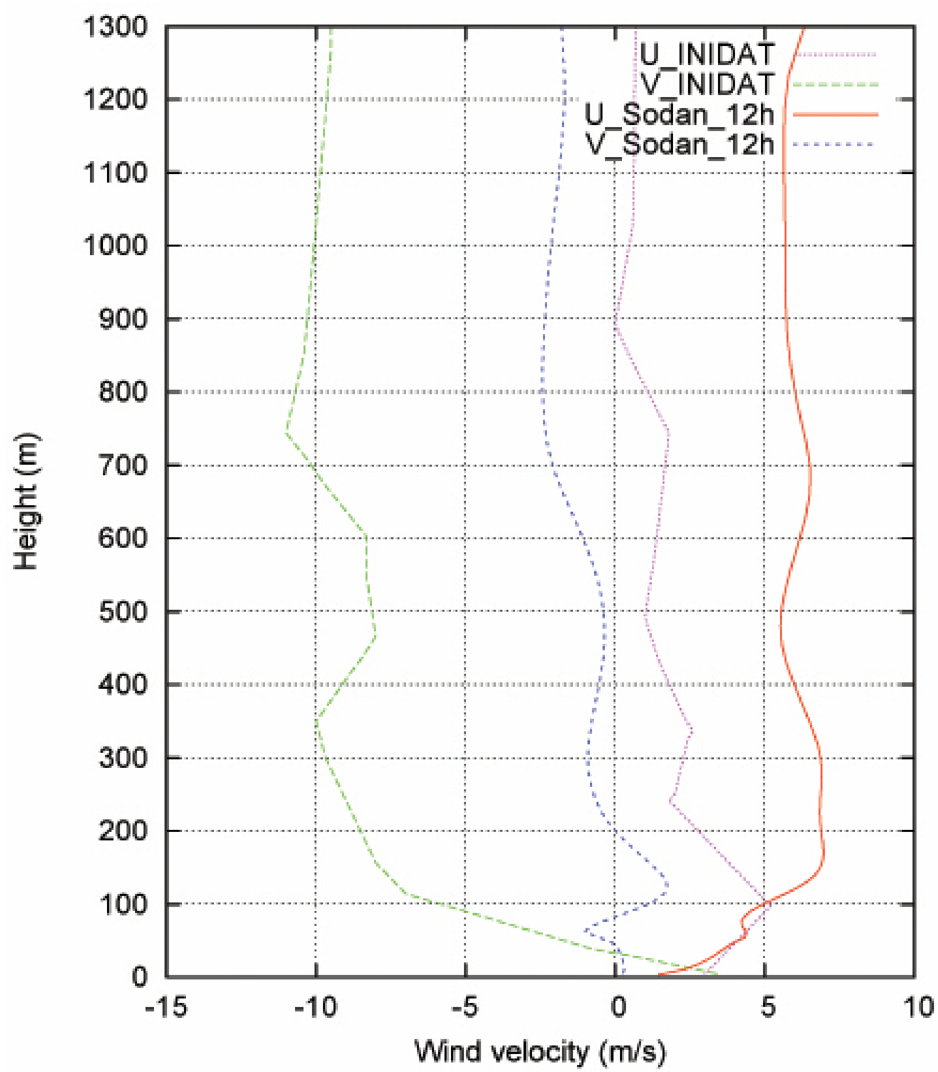
Results and comparison (no wind)



Temperature:
12 hour forecast with T_S taken from observation / obs



Wind velocity:
12 hour forecast with T_S taken from observation / obs



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Conclusions

- The modified TKE-l (QNSE-based) scheme brings the near surface parameters closer to the observations

- The new model better accounts for effects of stable stratification

- Nordic Temperature Problem
  - Large temperature errors are not related to turbulence scheme rather to
    - Surface-air interaction (heat exchange) processes
    - Moist processes
    - Long wave radiation

- Upcoming investigations:
  - Implementation of QNSE scheme in 3D non-hydrostatic models
  - More comparisons are needed for combined stable-unstable conditions
  - Tests for strato-cumulus clouds within ABLs

Thank you for your attention

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