Current state of QNSE PBL model in WRF

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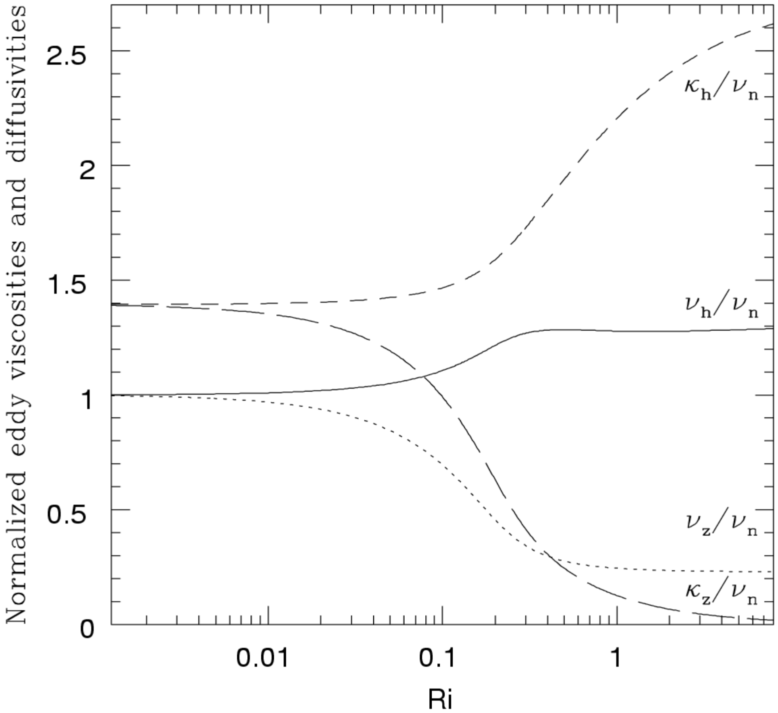
What is QNSE?

- QNSE = Quasi-Normal Scale Elimination
- Spectral theory of turbulence based upon successive ensemble averaging over small shells of Fourier modes
- Every step of scale elimination takes full account of all physical processes that take place within those shells
- Every step shrinks the domain of definition of the governing equations and generates compensating corrections to viscosities and diffusivities
- The QNSE model systematically accounts for anisotropization of turbulence and the effect of internal waves. The model does not separate turbulence and waves and treats them as one entity
- The model accurately predicts various flow characteristics unavailable in Reynolds stress models (RSM): turbulence spectra, flow anisotropization, dispersion relation of IW with turbulence, etc.
- Partial scale elimination yields SGS schemes for LES while elimination of all fluctuating scales produces QNSE-based RSM
- The model is maximally proximate to first principles, free of adjustable parameters, its final results are straightforward to implement, is free of many limitations of RSM, and generally is a viable alternative to this class of models

QNSE-based RANS modeling

Eliminate all fluctuating scales; recast turbulent exchange coefficients as functions of the gradient Richardson number, $Ri = N^2/S^2$

$$\nu_z = K_M$$
$$\kappa_z = K_H$$



ν_z and κ_z decrease with Ri while ν_h and κ_h increase with Ri

Momentum mixing by internal waves ➔ ν_z decreases slower than κ_z

ν_z remains finite even at very large Ri

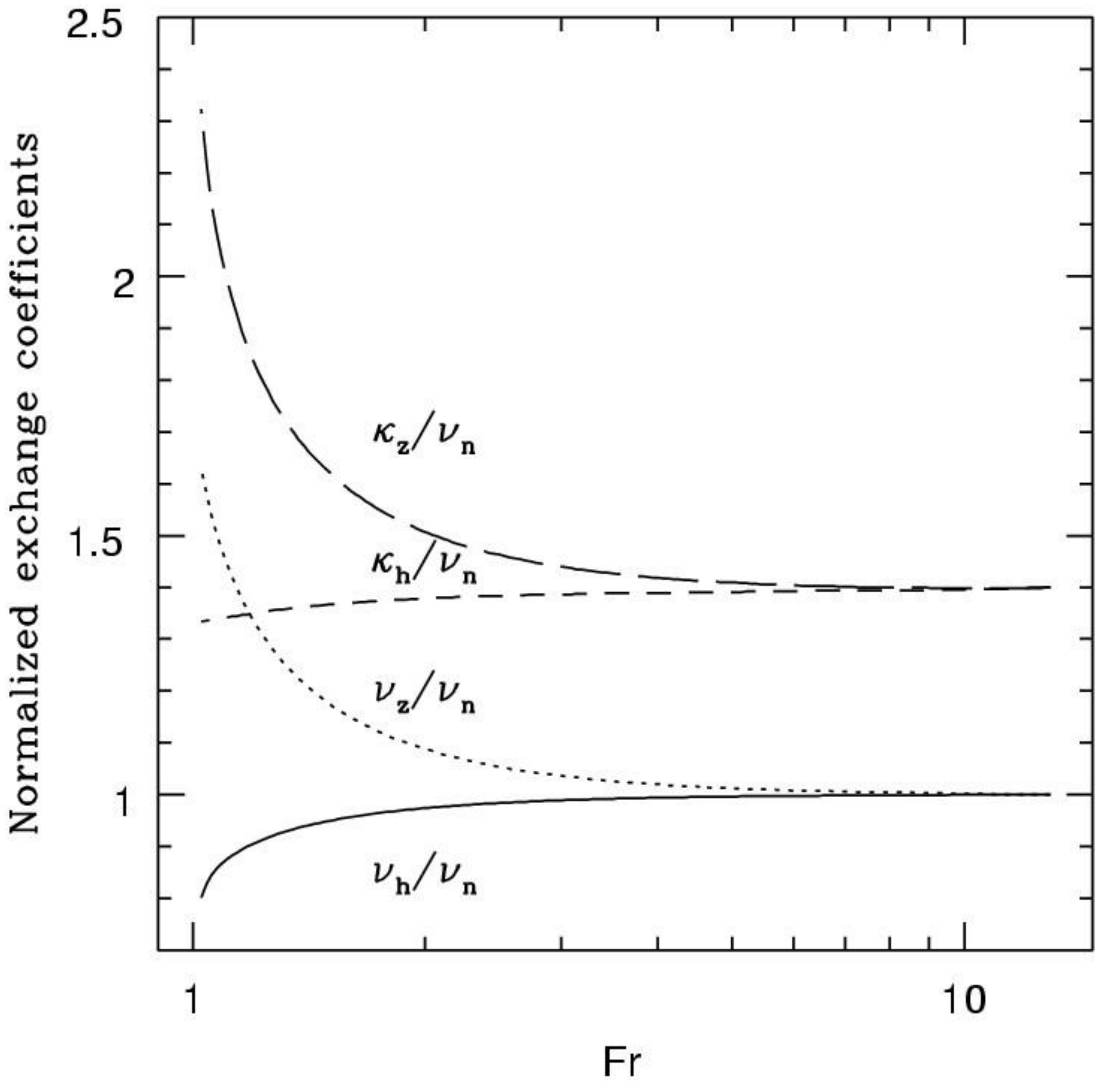
This dependence agrees with the local scaling by Nieuwstadt (1984)

The model does not have critical Ri

Regarding yesterday's presentations,

- QNSE produces horizontal viscosities and diffusivities that depend on stratification
- Takes into account that turbulence is 3D but anisotropic
- QNSE-generated expressions are readily available for implementation
- Preliminary comparisons with ocean models support QNSE results

Unstable stratification (convection)



Curve fitting functions

For implementation in PBL schemes, the theoretically derived stability functions, $\alpha_M = K_M/K_0$ and $\alpha_H = K_H/K_0$, were approximated by a fraction-polynomial fit (K_0 is the eddy viscosity at Ri=0):

$$\alpha_M = \frac{1+8\,Ri^2}{1+2.3\,Ri+35\,Ri^2}$$

$$\alpha_H = \frac{1.4-0.01\,Ri+1.29\,Ri^2}{1+2.344\,Ri+19.8\,Ri^2}$$

The fitting functions are valid for $Ri<1.5$. For larger values, flux Richardson number R_f approaches limiting value <0.5

Monin-Obukhov similarity theory

Monin-Obukhov length scale

$$L = \frac{u_*^2}{\kappa \beta \theta_*} = \frac{z\, \alpha_M^2 (Ri)}{Ri\, \alpha_H (Ri)}$$

ζ = z/L can be presented as a function of Ri and vise versa.
Velocity and temperature at the lower grid point are

$$u_1 = \frac{u_*}{\kappa} \int_{z_0}^{z_1} \frac{dz}{z \alpha_M}$$

$$\theta_1 = \theta_0 + \frac{\theta_*}{\kappa} \int_{z_0}^{z_1} \frac{dz}{z \alpha_H}$$

The integrals are computed analytically as functions of z/L:

$$u_1 = \frac{u_*}{\kappa} (\ln \frac{z_1}{z_0} + c_u \frac{z_1}{L} + \ldots), \qquad c_u = 2.25$$

$$\theta_1 = \theta_0 + \frac{\theta_*}{1.4\kappa} (\ln \frac{z_1}{z_0} + c_\theta \frac{z_1}{L} + \ldots), \qquad c_\theta = 2.04$$

QNSE-based surface layer parameterization

Using theoretically derived stability functions α_M, α_H and approximations of constant flux layer, we derived the drag coefficients for momentum and heat, C_D, C_H, that replace the Louis formulation. The corresponding expressions are:

$$C_D = \frac{\kappa^2}{\left(\ln\frac{z}{z_0} + \psi_M(\zeta) - \psi_M(\zeta_0)\right)^2}, \quad \zeta = z/L, \quad \zeta_0 = z_0/L$$

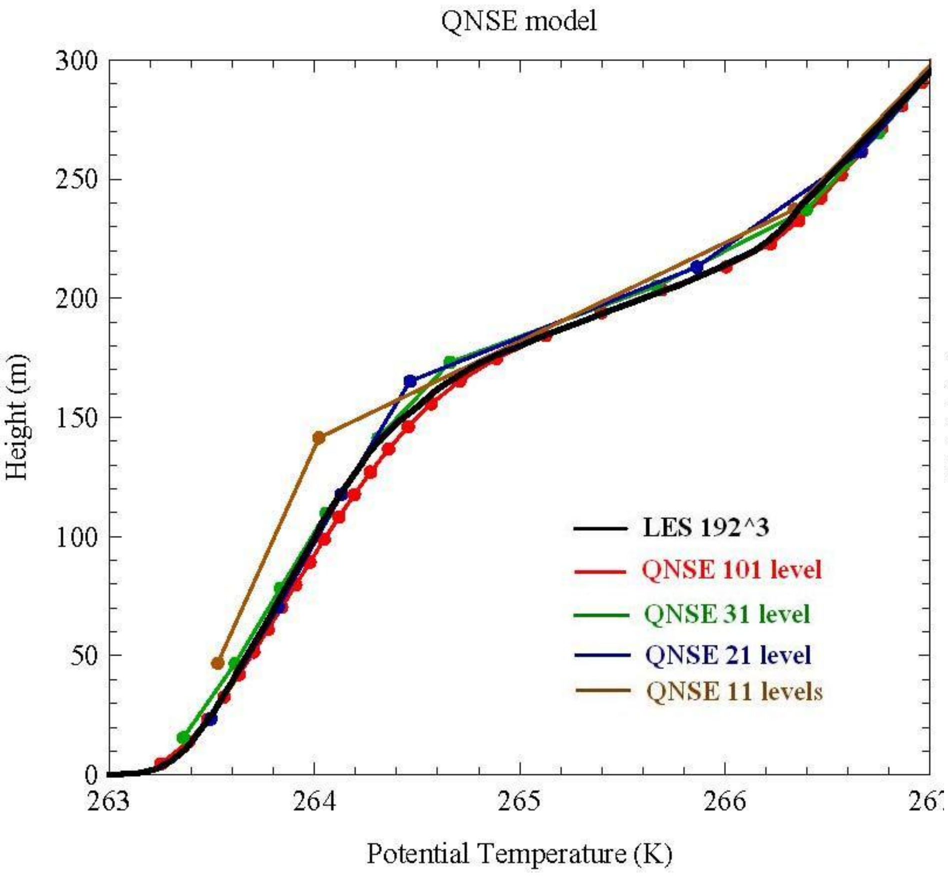
$$C_H = \frac{\kappa^2}{\left(\ln\frac{z}{z_0} + \psi_M(\zeta) - \psi_M(\zeta_{0T})\right)\left(\mathrm{Pr}_0 \ln\frac{z}{z_{0T}} + \psi_H(\zeta) - \psi_H(\zeta_{0T})\right)}$$

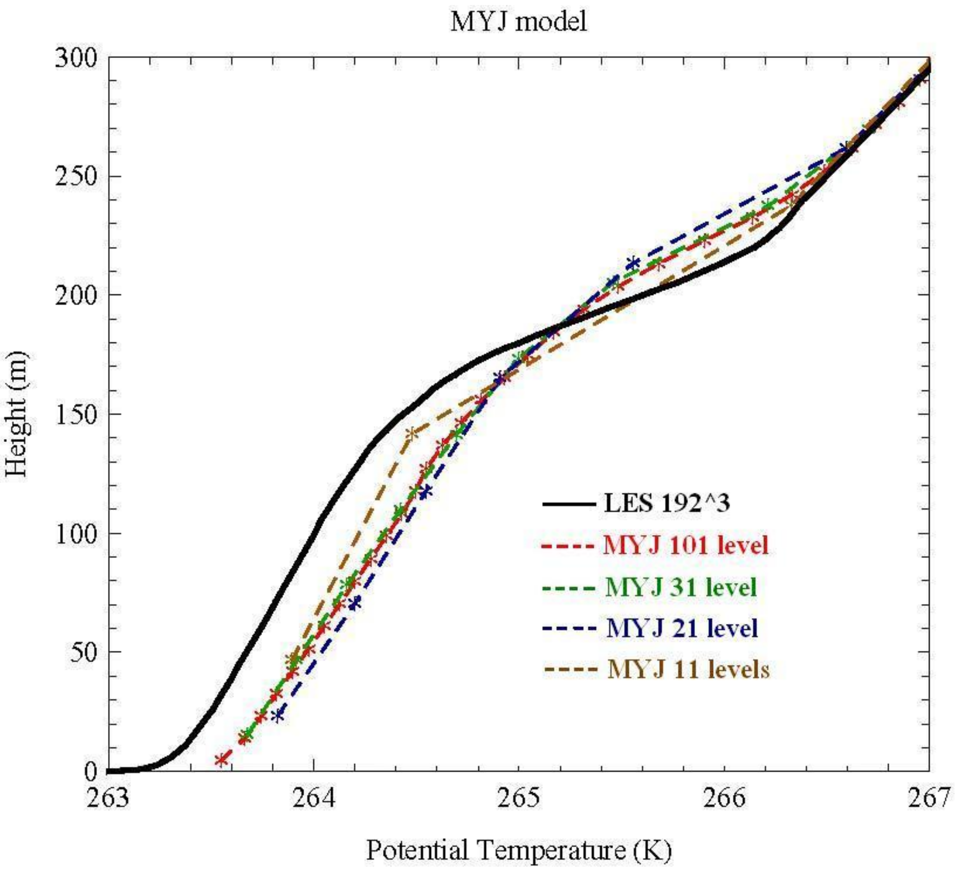
$$\psi_M(\zeta) = 2.25\zeta - 0.2\zeta^2$$

$$\psi_H(\zeta) = 2\,\mathrm{Pr}_0\,\zeta + 0.1\left((\zeta - 0.5)^5 - 0.5^5\right),$$

$$\mathrm{Pr}_0 = 0.71 - \text{turbulent Prandtl number for neutral flow}$$

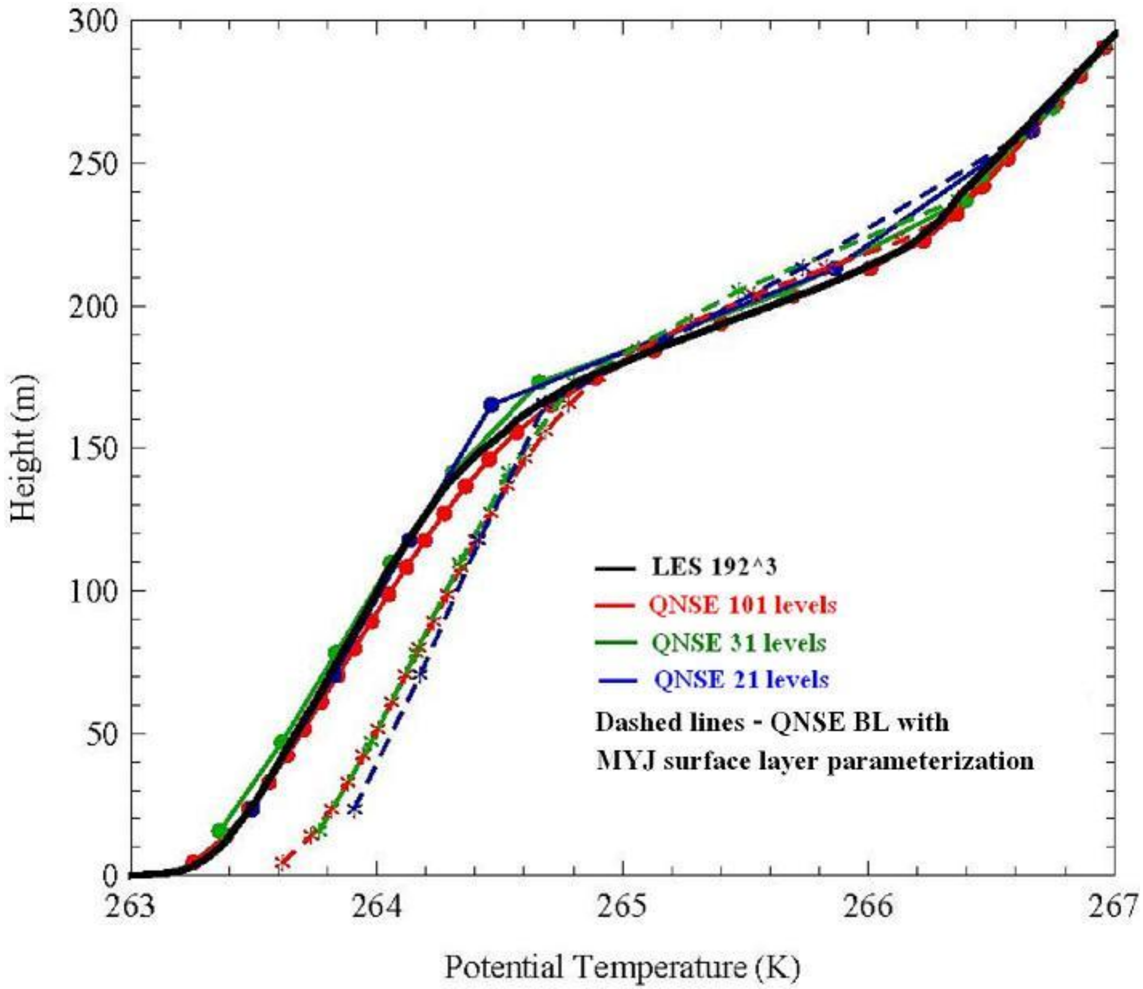
Testing in WRF – BASE temperature profiles





Comparison with LES results (Stroll and Porte-Agel, BLM, 2008)

Effect of surface layer parameterization



QNSE surface scheme eliminates warm temperature bias. With other schemes, increase in resolution may decrease the bias but does not eliminate it.

Testing of the QNSE model

SAF-WRF 9 km Scandinavian domain
(courtesy of Andreas Grantinger, Swedish Armed Forces)

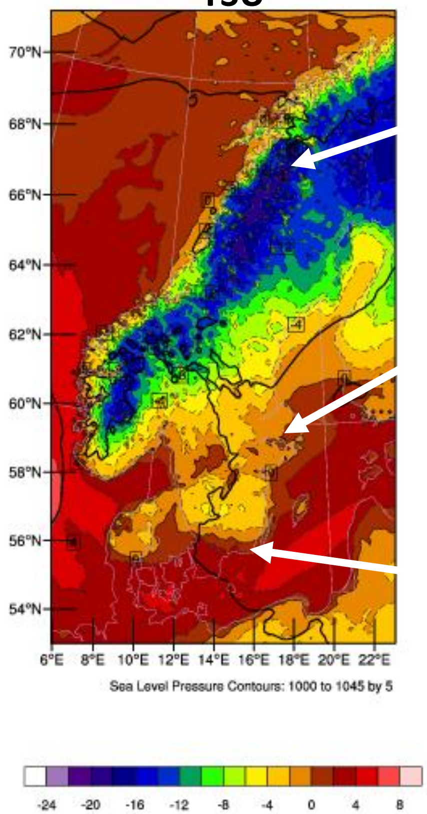
Setup of tests

- WRFv3.0.1 with YSU PBL scheme compared to WRFv3.1beta2 with QNSE PBL scheme
- 00z+48 hrs runs for 090101 – 090131
- Scandinavian domain 9 km, 30 levels
- cold starts
- Model outputs compared to SYNOP observations, all domain and station Kiruna 02044 (N Sweden), Uppsala 02458 (Centre Sweden) and Ronneby 02664 (S Sweden)

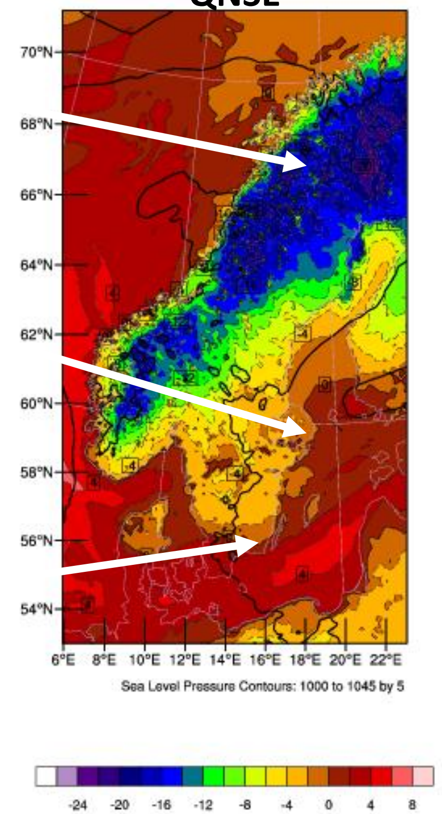
SAF-WRF 9 km Scandinavian domain

Comparison at Kiruna, Uppsala and Ronneby

YSU



QNSE



Kiruna 02044

Uppsala 02548

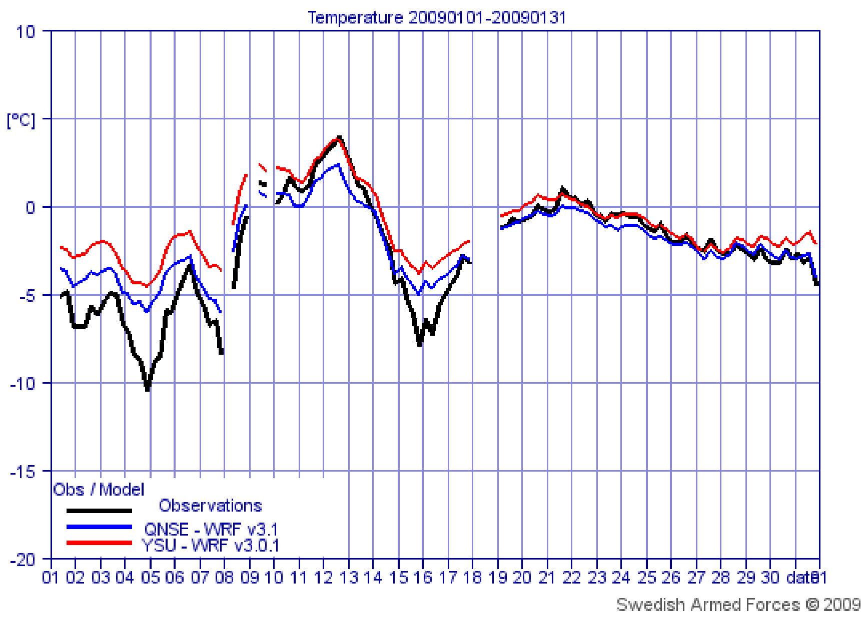
Ronneby 02664

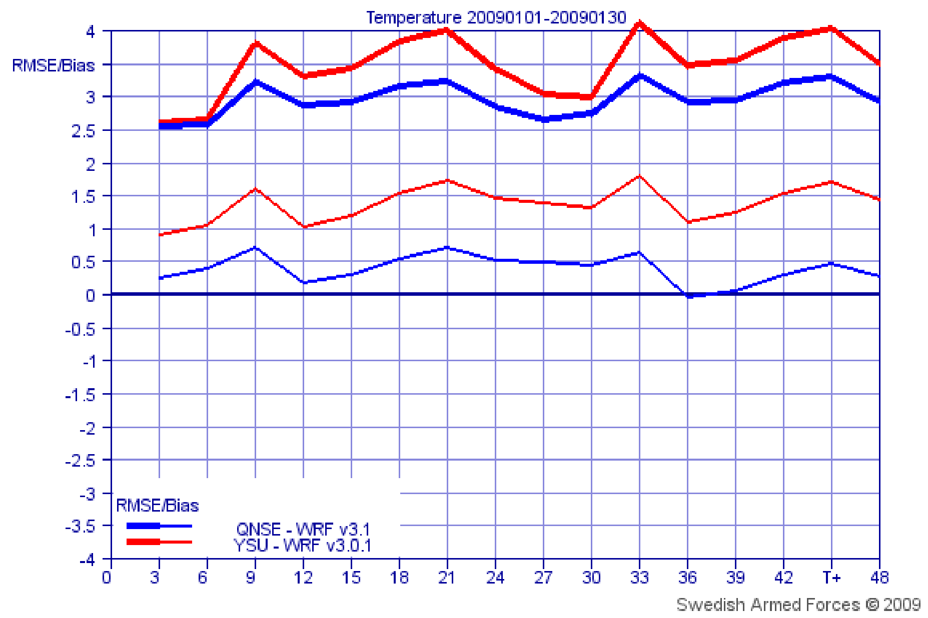
24 hrs forecast of T 2m
valid at 20090115 00z

Andreas Grantinger, Swedish Armed Forces METOCC

SAF-WRF 9 km Scandinavian domain

2 m Temperature: 6 hrs time-average and RMSE/Bias for all domains

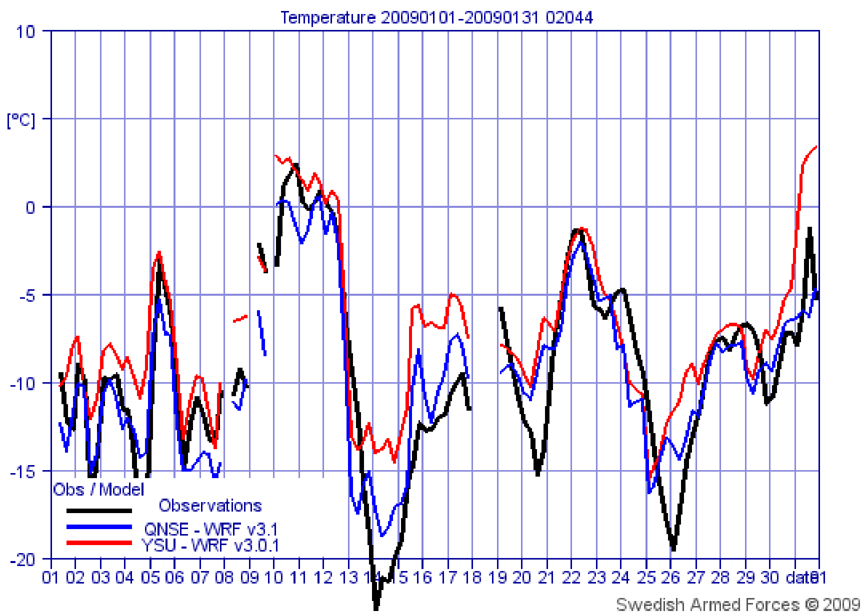


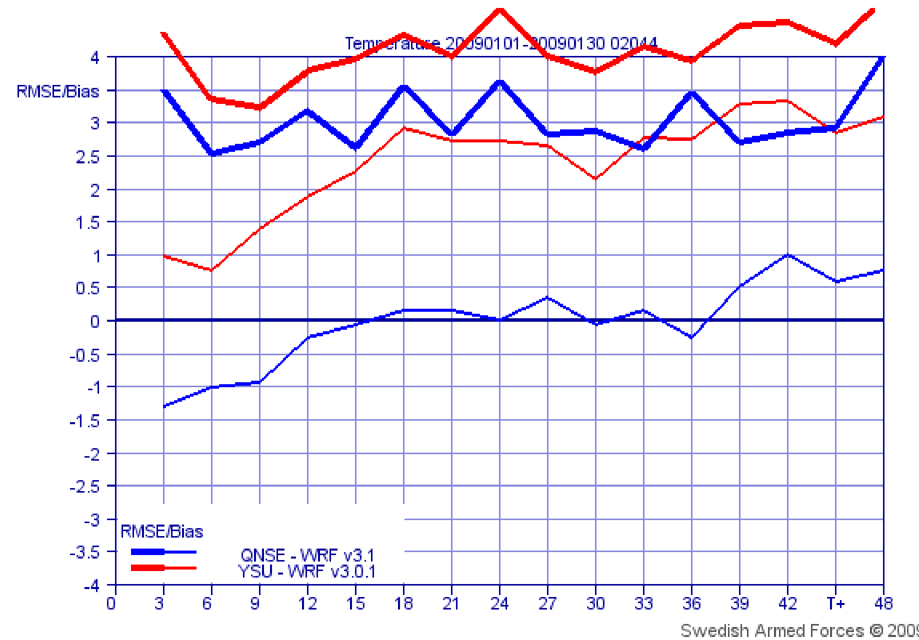


Andreas Grantinger, Swedish Armed Forces METOCC

SAF-WRF 9 km Scandinavian domain

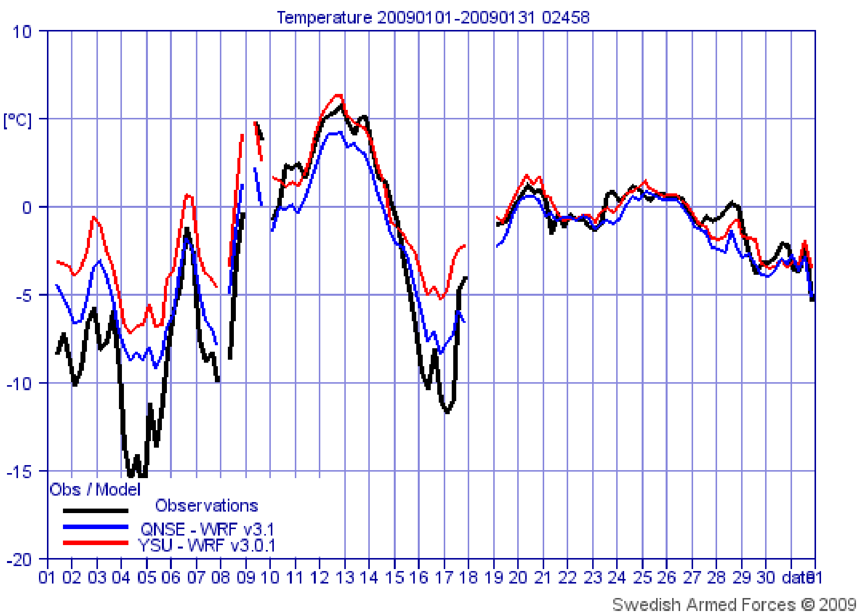
2 m Temperature: 6 hrs time-average and RMSE/Bias for Kiruna 02044

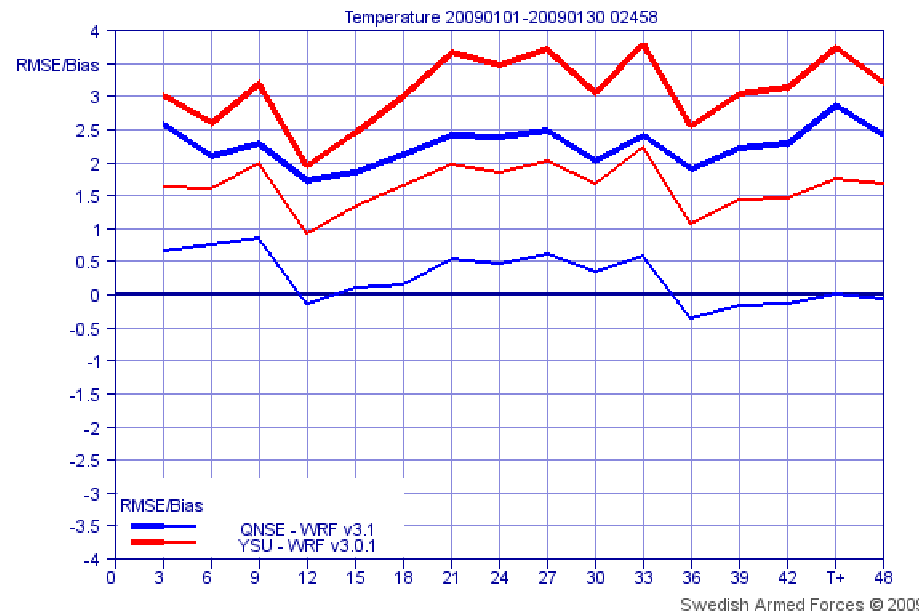




SAF-WRF 9 km Scandinavian domain

2 m Temperature: 6 hrs time-average and RMSE/Bias for Uppsala 02458

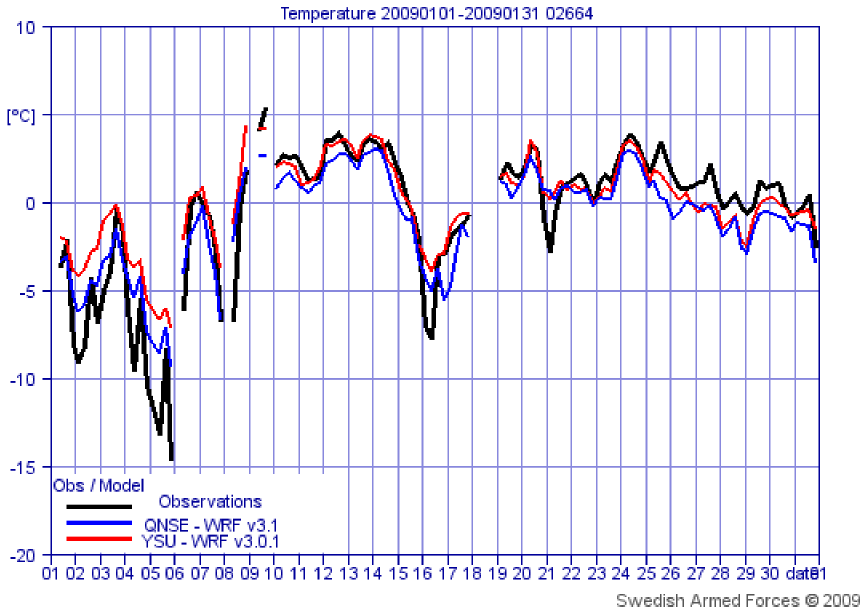


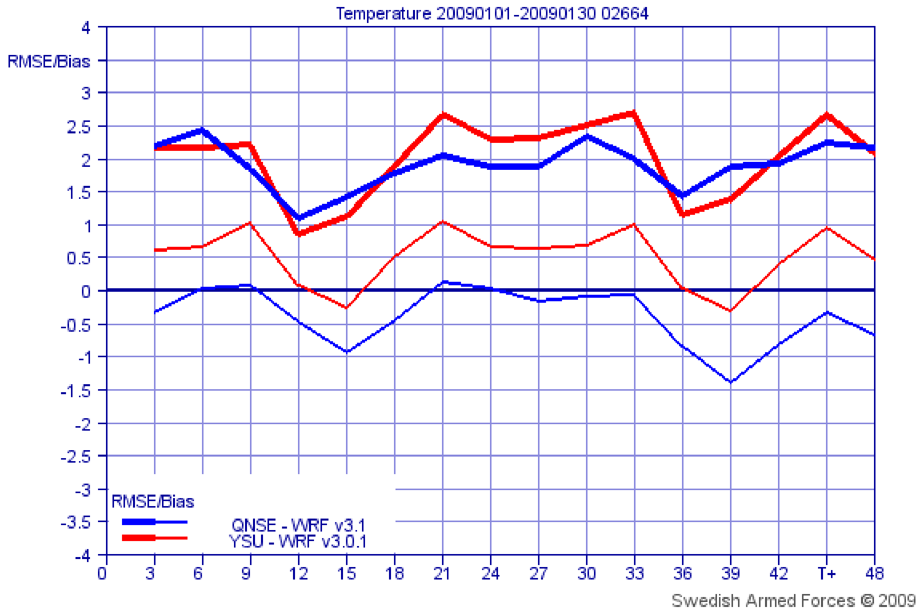


Andreas Grantinger, Swedish Armed Forces METOCC

SAF-WRF 9 km Scandinavian domain

2 m Temperature: 6 hrs time-average and RMSE/Bias for Ronneby 02664





Extension to unstable stratification and shallow convection

- QNSE model performs well in simulations of stably stratified PBLs
- In the unstable case, QNSE in that WRF release was partially reverting back to the MYJ model thus inheriting its problems
- To improve the performance in the unstable case, we merged QNSE with the mass flux model – EDKF or PMMC09 – developed by Julien Pergaud, first at Meteo France and later at NumTech
- The goal is to improve PBL description in unstable cases with shallow convection with or without clouds

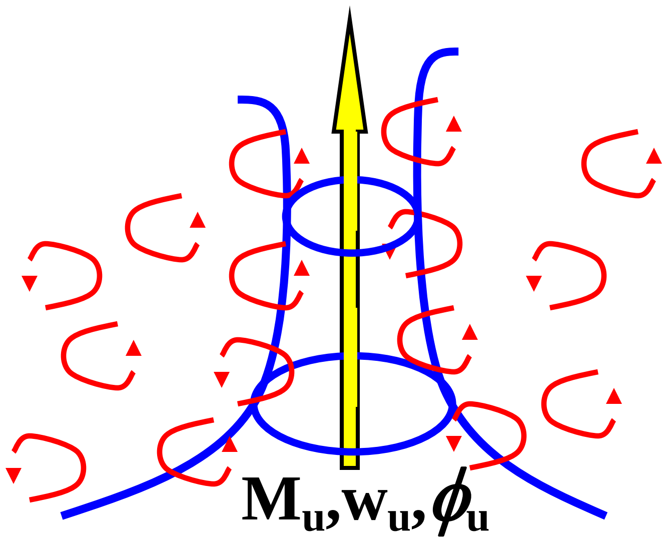
Mass Flux scheme EDKF based on the EDMF concept

- In the unstable case, thermals are responsible for a big part of mixing notably near the inversion and in the counter-gradient part
- A mass flux scheme based on the representation of an updraft is used to compute the part of turbulent fluxes due to thermals
- Different equations are used to diagnose M_u, w_u, ϕ_u (conservative variables r_{tu} or θ_{lu} or wind components)

$$\overline{w'\phi'} \cong -K\frac{\partial\overline{\phi}}{\partial z} + M(\phi_{\rm up} - \overline{\phi}),$$

QNSE **MF**

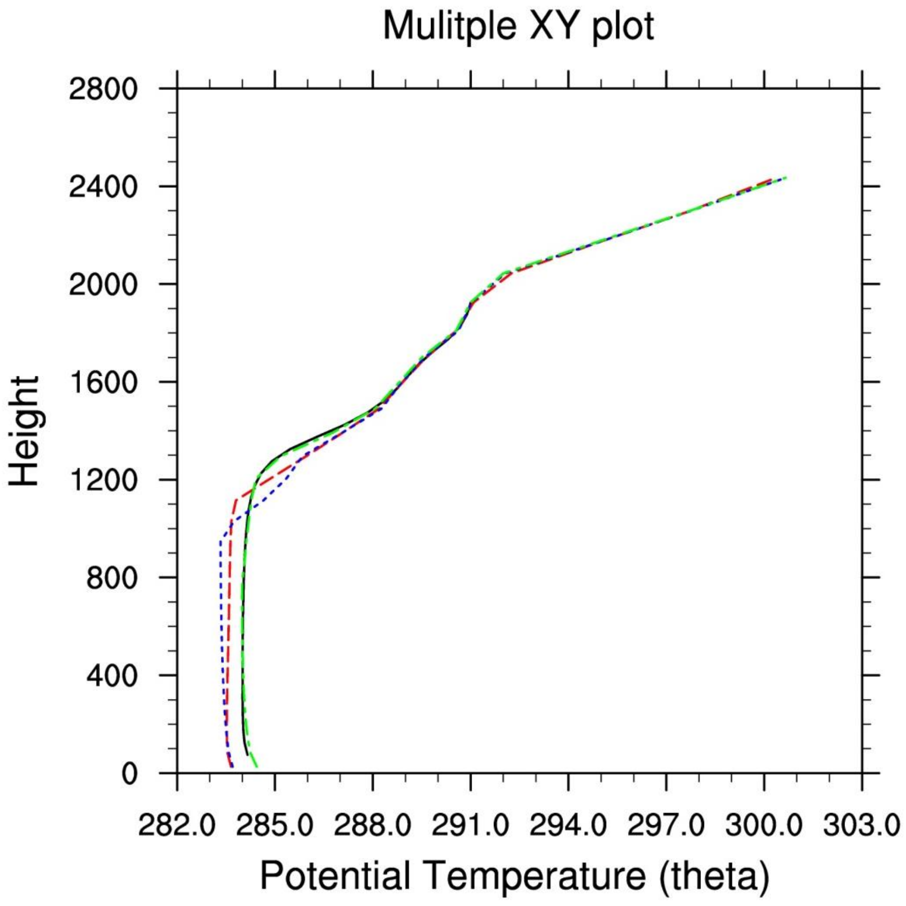
Small Eddies **Thermals**



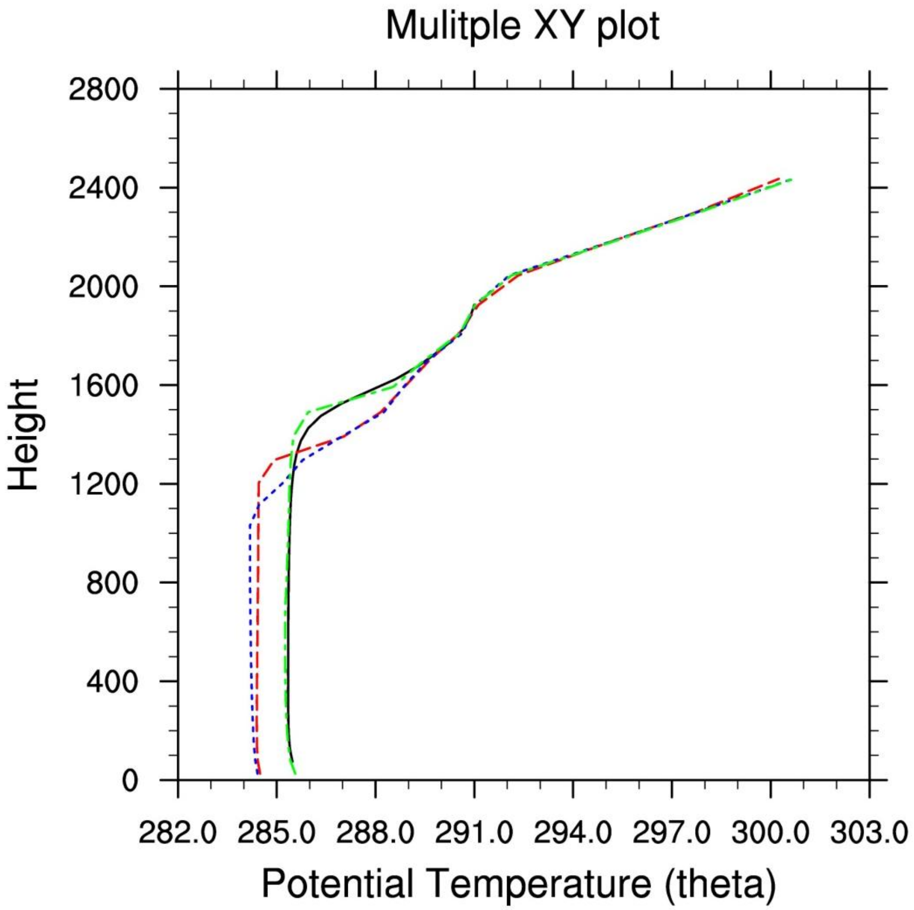
Potential temperature profiles in the convective boundary layer for the WANGARA case

Color coding of various curves: **LES** **YSU** **QNSE** **QNSE+MF**

(LES by Rachel Honnert, Meteo France)

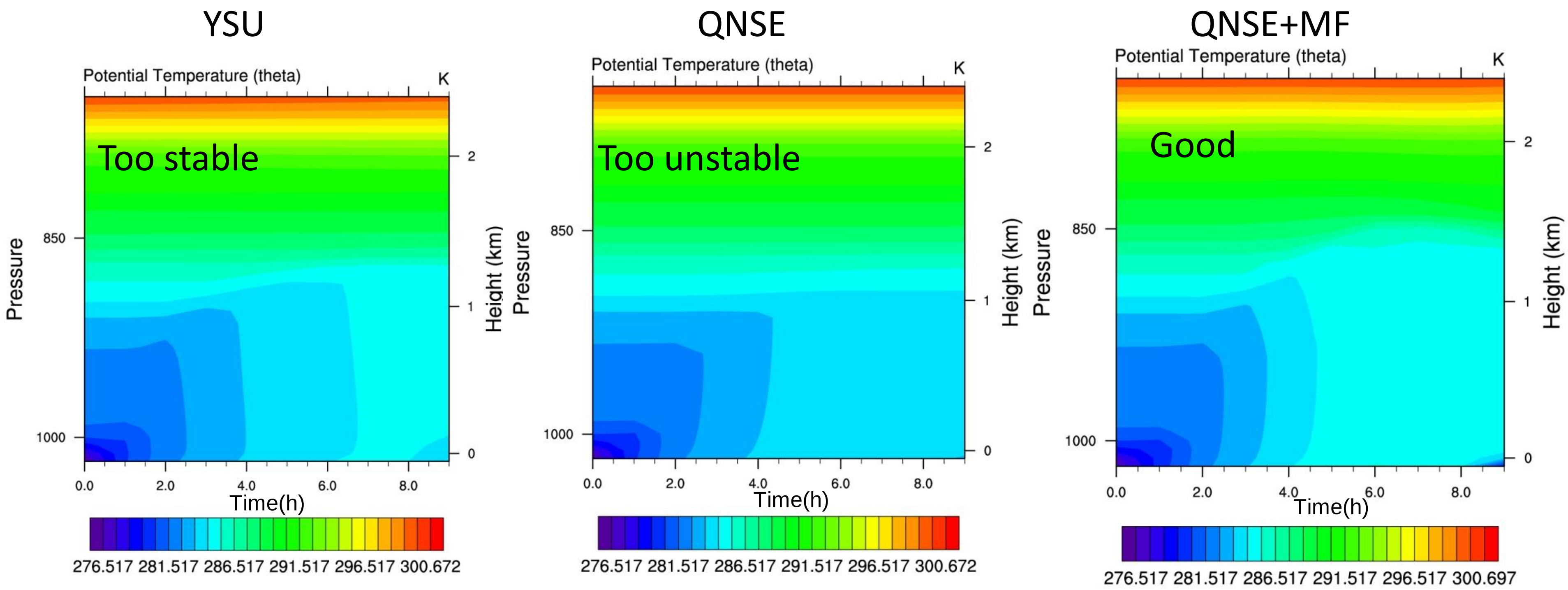


After 4 hour of simulation



After 6 hour of simulation

Evolution of the potential temperature profile for the WANGARA case



- ➢ QNSE+MF is responsible for a better development of convective boundary layer leading to a better representation of theta (and r_t) in the PBL
- ➢The mixing at the inversion realized by MF part improves the results obtained with the QNSE scheme alone
- ➢The results are more realistic than those obtained with YSU

Work in progress:

- Test the QNSE-MF scheme on other ideal 1D cases:
  - ARM case: diurnal cycle of shallow cumulus over land
  - GABLS 3 case: diurnal cycle
  - BOMEX: a quasi stationary case of cumulus cloud over ocean

- After these tests, the scheme will be tested in real conditions on 3D cases

Conclusions

- QNSE model provides improved description of stably stratified PBLs. Its main advantages:
  - accounts for the anisotropy and the effect of the internal waves
  - does not have Ri_{cr}
- QNSE provides good parameterization of the surface layer
- Adding a MF scheme improves performance of QNSE in unstable cases and cases with shallow convection
- The QNSE-EDKF hybrid scheme retains the advantages of each scheme in their specific realms of application. It should provide vastly improved PBL parameterization for WRF and other NWP models.