Implementation of the Quasi-Normal Scale Elimination (QNSE) Model of Stably Stratified Turbulence in WRF

Semion Sukoriansky

(*Ben-Gurion University of the Negev*

Beer-Sheva, Israel)

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Report on WRF-DTC Visit of Semion Sukoriansky – June 2008

Introduction

Quasi-normal scale elimination - QNSE - is a new theory of turbulence with stable and weakly unstable stratification. The theory accommodates the stratification-induced disparity between the transport processes in the horizontal and vertical directions and accounts for the combined effect of turbulence and waves. It predicts various important characteristics of stably stratified flows, such as the dependence of the vertical turbulent Prandtl number on Froude and Richardson numbers, anisotropization of the flow filed, and decay of vertical diffusivity under strong stratification, all in good agreement with computational and observational data. The theory also yields analytical expressions for various 1D and 3D kinetic and potential energy spectra that reflect the effects of waves and anisotropy.

Details of the QNSE theory are given in the papers by Sukoriansky et al. appearing in the Reference section of the report. The main results of the theory are horizontal and vertical turbulent viscosities and diffusivities which can be normalized by eddy viscosity of neutral turbulent flow and than presented as functions of the local gradient Richardson number, Ri, or Froude number, Fr, as shown on Fig. 1.

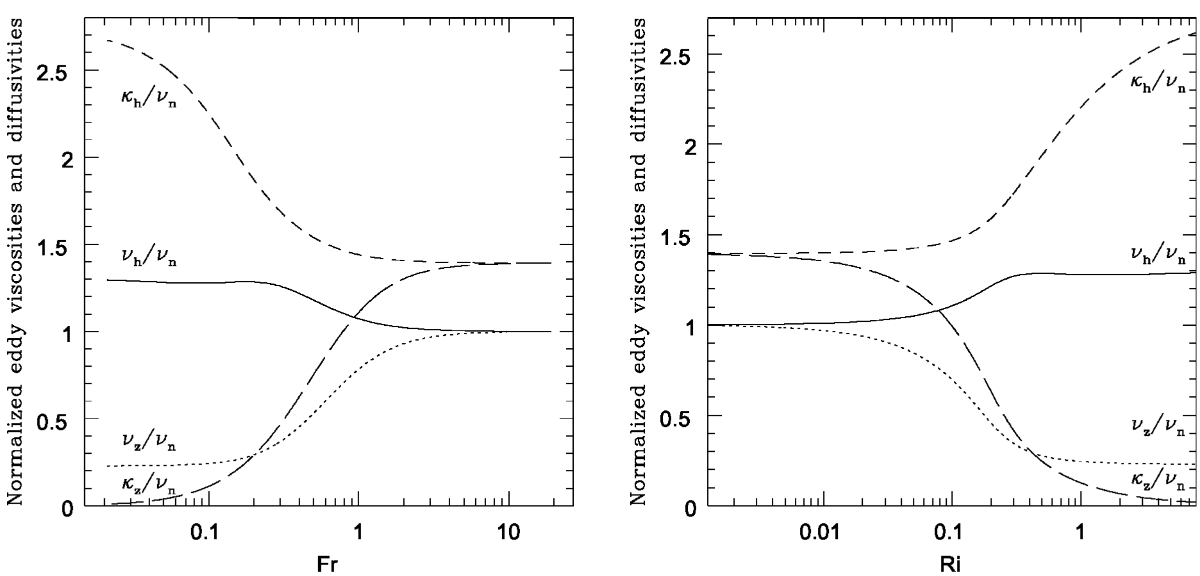

FIG. 1 – Normalized eddy viscosities and diffusivities as functions of the Froude number Fr (left panel) and the gradient Richardson number Ri (right panel).

The results of the theory are suitable for immediate use in practical applications. The QNSE-based TKE-*l* model and surface layer parameterization have been implemented and tested in numerical weather prediction system WRF.

Short description of the QNSE model in the TKE-*l* format.

The implementation of the QNSE-based models is quite straightforward. Firstly, the vertical eddy viscosity (K_M) and eddy diffusivity (K_H) in the model are expressed via stability functions, $\alpha_M = K_M / K_0$ and $\alpha_H = K_H / K_0$; K_0 is eddy viscosity at Ri=0 (neutral flow). Secondly, these expressions are replaced by the QNSE-based approximate expressions for α_M, α_H as functions of local gradient Richardson number Ri:

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

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

In the TKE − *l* format, the equation for the length scale *l* is given by

$$l_B = \frac{kz}{1+\frac{kz}{\lambda}}\,,\;\; l_N = c_N\,\frac{K^{1/2}}{N};\, c_N = 0.75$$

$$\frac{1}{l} = \frac{1}{l_B} + \frac{1}{l_N};\quad \lambda = B\,u_* / f\,,\;\; B = 0.0063$$

where l_B is the Blackadar scale and l_N is the length scale limitation due to stable stratification. Eddy viscosity of neutral flow is evaluated using the Prandtl-Kolmogorov formula:

$$K_0 = C_0\, l\, E^{1/2}, \quad C_0 = 0.55\cdot$$

Here E is turbulence kinetic energy which is computed using prognostic TKE equation:

$$\frac{\partial E}{\partial t} = K_M\left[\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2\right] - \frac{g}{\Theta_0} K_H \frac{\partial \theta}{\partial z} - \varepsilon + \frac{\partial}{\partial z}\left(\alpha_E K_M \frac{\partial E}{\partial z}\right), \quad \alpha_E = 1$$

The energy dissipation ε is given by the Kolmogorov relation:

$$\varepsilon = C_\varepsilon \frac{E^{3/2}}{l}$$

with the constant $C_\varepsilon = C_0^3$.

All these equations have been programmed in the **module_bl_qnsepbl.F** which is called from **module_pbl_driver.F.** Note that the QNSE scheme was used for stable stratification only. In unstable situations, the model reverts to the Mellor-Yamada-Janjich (MYJ) formulation.

QNSE-based surface layer parameterization

The relationship between the surface values of the prognostic variables and their values at the first computational level may significantly impact the quality of simulations. 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 Mellor-Yamada-Janjich formulation. The corresponding expressions are:

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

$$C_H = \frac{\kappa^2}{\left(\ln\frac{z}{z_{0T}} + \psi_M(\zeta) - \psi_M(\zeta_{0T})\right)\left(\Pr_0 \ln\frac{z}{z_{0T}} + \psi_H(\zeta) - \psi_H(\zeta_{0T})\right)}$$

where

$$\psi_M(\zeta) = 2.25\zeta - 0.2\zeta^2$$
$$\psi_H(\zeta) = 2\Pr_0 \zeta + 0.1\left((\zeta - 0.5)^5 - 0.5^5\right),$$

L is the Monin-Obuhov length scale, and $\Pr_0 = 0.71$ is turbulent Prandtl number for fully developed neutral turbulence.

The new surface layer parameterization is coded in the **module_sf_qnsesfc.F** called by **module_surface_driver.F**

Preliminary testing of the QNSE model

To assess the impact of the QNSE model upon the performance of WRF, concurrent simulations with the reference MYJ model were conducted. First test case corresponds to the BASE (Beaufort Arctic Storms Experiment). The goal of BASE was to improve understanding of the Arctic weather systems during the fall season.

Accordingly, BASE was conducted from September 19 through October 29, 1994 in the Beaufort Sea. The data from BASE was successfully simulated in LES by Kosovic and Curry (2000), Stroll and Porte-Agel (BLM, 2008) and others. The boundary layer is driven by an imposed, uniform geostrophic wind with a specified surface cooling rate. The geostrophic wind was imposed at 8 m/s at a latitude of 73^o North (corresponding to f=1.39e-04). The initial potential temperature profile was 265K for $0 < z < 100$ m, increasing at 0.01K/m above. The test case corresponds to the surface cooling rate equal to 0.25 K^0/h. The surface roughness for momentum was 0.1m. The LES simulated the transitional process of the boundary layer adjustment to the surface cooling rate.

The QNSE model has been tested in single-column simulations against the high resolution LES by Stroll and Porte-Agel. Potential temperature profiles after 9 hours of evolution computed with the QNSE and the reference MYJ models are shown on Fig. 2.

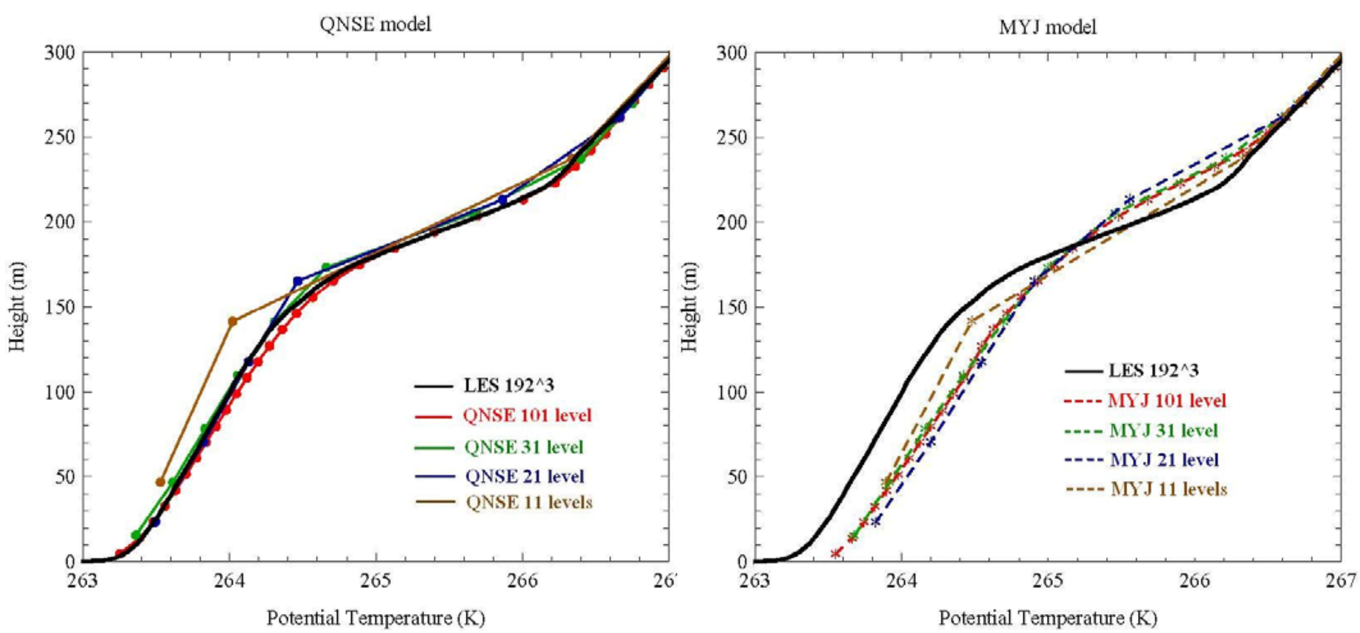

Fig. 2. Comparison of the QNSE and MYJ temperature profiles with LES results

The simulations employed different vertical resolutions - 101, 31, 21 and 11 vertical levels. It is evident from the figure that the QNSE results are close to those from LES for all simulations except for the very coarse resolution of 11 vertical grid points, only 3 of which belong in the boundary layer. On the other hand, the MYJ model replicates correctly neither the shape of the temperature profile, nor the boundary layer height nor the near-surface temperature.

Vertical profiles of horizontal velocity are shown on Fig. 3. Agreement of the QNSE model with the LES results is again very good. The reference model overestimates the height of the velocity maximum and has difficulties with replicating the jet.

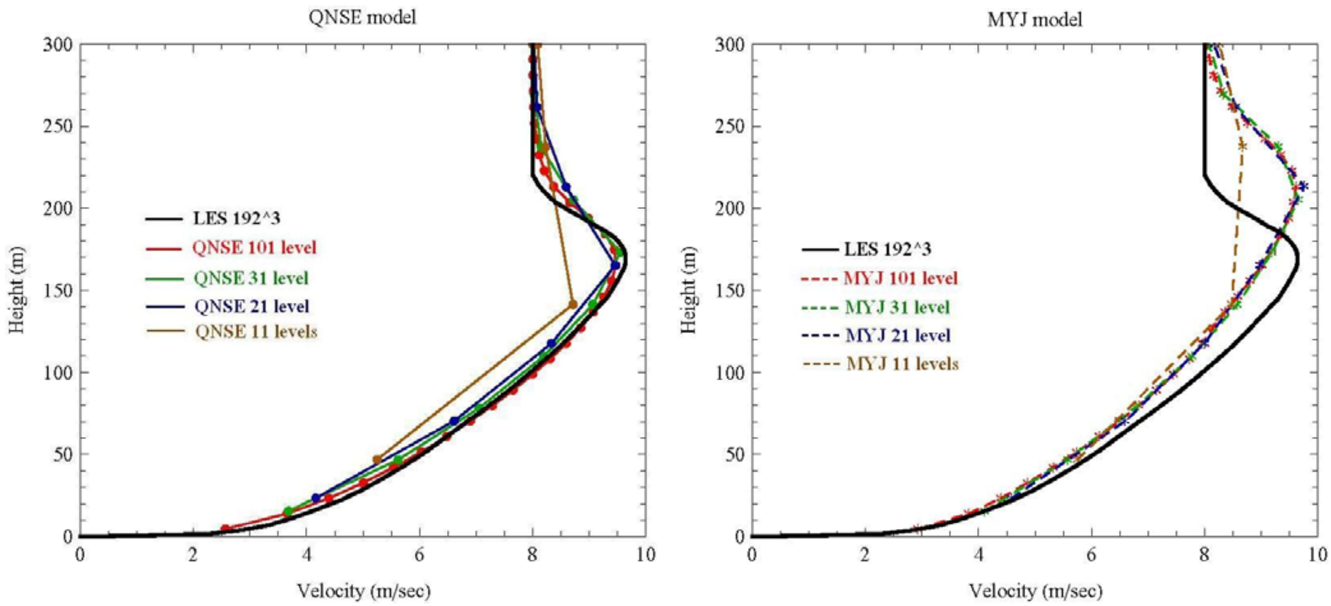

Fig. 3. Comparison of the QNSE and MYJ velocity profiles with LES results

Effect of surface layer parameterization

In order to assess the effect of the QNSE-based surface layer parameterization we run the test case with the QNSE boundary layer model and two concurrent surface layer schemes – QNSE and MYJ. The results are shown on Fig. 4. Significant warm bias of the 2 m temperature appears in simulations with the MYJ surface layer parameterization. The bias is completely eliminated when the QNSE model is employed. This result is particularly important for ABL simulations in Arctic conditions where the bias of the 2 m screen temperature is a recognized problem of the existing models. Additional testing is needed to assess the effect of the new surface layer parameterization, but this preliminary result looks very promising.

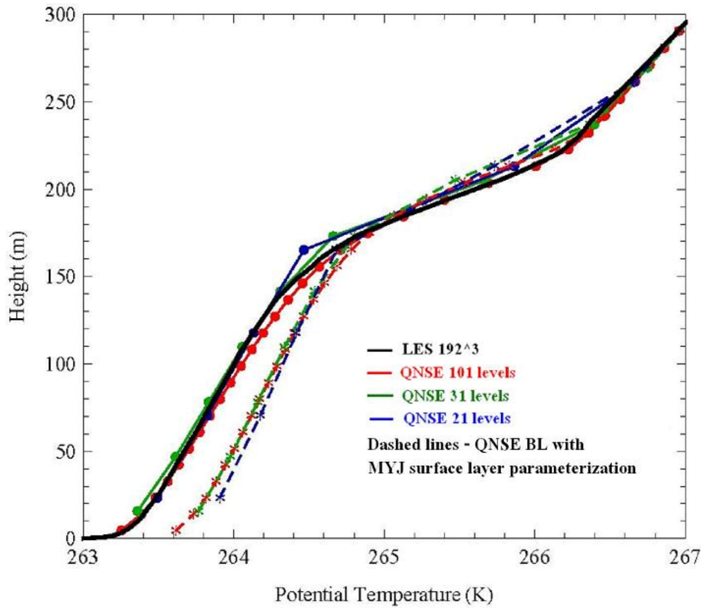

Fig. 4. Comparison of the QNSE and MYJ surface layer schemes

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