Calculation of surface fluxes for EULAG

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Wall effects

Limitation of eddy size/transport by

- wall proximity
- stratification

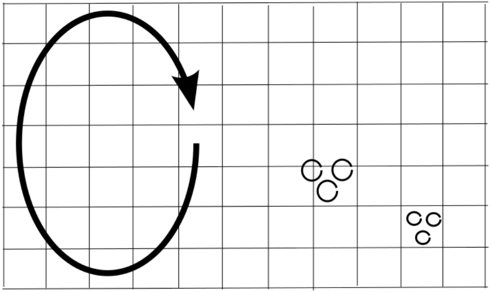
Handling of ground proximity effects

- 1-D models: log-linear vertical spacing distribution (e.g. Taylor & Delage, BLM 1971)
- NWP: bulk parameterization of the surface layer
- EULAG: explicit specification of the heat flux as a boundary condition

Handling of stable stratification effects

- 1-D models & NWP: diverse parameterizations
- EULAG: ??? (a subgrid issue)

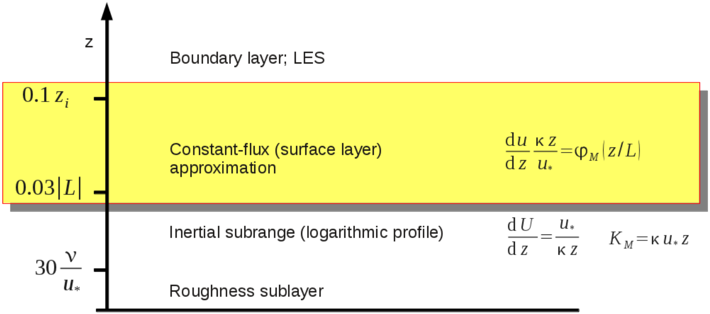
Resolved or subgrid?



Expectations

- consistency of the surface layer parameterization with the subgrid turbulence scheme
- possible adaptation for inclined terrain
- applicable for both the LES & NWP (quasi-hydrostatic) modes (see Cuxart et al, QJRMS 2000)

Surface layer regimes & scales



Bulk transfer coefficients

$$\left|\overline{w'w'}\right| = u_*^2 = C_U^2 u^2 = C_D u^2$$

$$\overline{w'\Theta'} = u_* T_* = C_U C_T u \Delta T = C_H u \Delta T$$

Conventional framework: MOST

$$u(z_2) - u(z_1) = \frac{u_*}{\kappa}\left[\ln\left(\frac{z_2}{z_1}\right) + \Psi_M\left(\frac{z_2}{L}\right) - \Psi_M\left(\frac{z_1}{L}\right)\right]$$

$$T(z_2) - T(z_1) = \frac{T_*}{\kappa_T}\left[\ln\left(\frac{z_2}{z_1}\right) + \Psi_H\left(\frac{z_2}{L}\right) - \Psi_H\left(\frac{z_1}{L}\right)\right]$$

$L = \frac{u_*^2}{\kappa\beta T_*}$ - Monin-Obukhov-length,

$\beta = \frac{g}{\langle T\rangle}$ - buoyancy parameter,

$u_* = \sqrt{\left|\overline{u'w'}\right|}$ - friction velocity,

$T_* - \frac{\overline{w'\Theta'}}{u_*}$ - temperature scale

1-D modeling: importance of choice of the SL-package

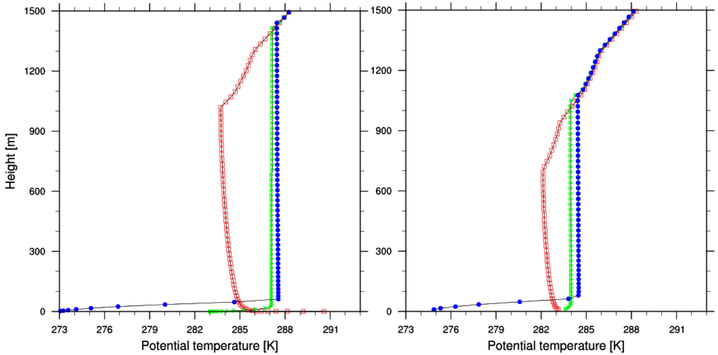


FIGURE: Wangara Day 33 simulation with the Mellor-Yamada Level 2 model: left - with high-resolution finite-differencing, right - with bulk surface-layer parameterization using BWIB (1971) profiles. Potential temperature profiles at 12 LST (red), 18 LST (green), 3 LST (blue)

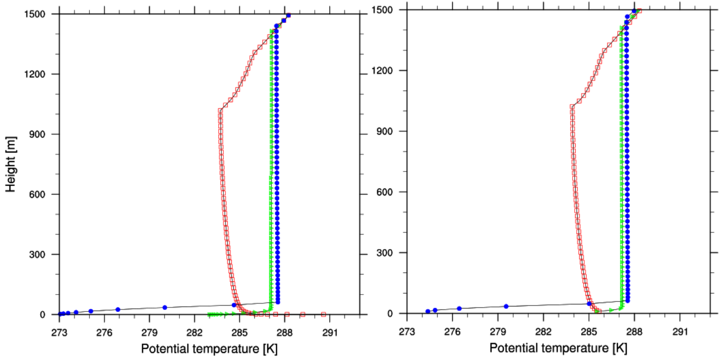


FIGURE: As Figure 1, but with the bulk surface-layer integrals calculated using the Mellor-Yamada Level 2 model (Łobocki, 1993, right pane)

1-D MODELING: CONSISTENCY ISSUE

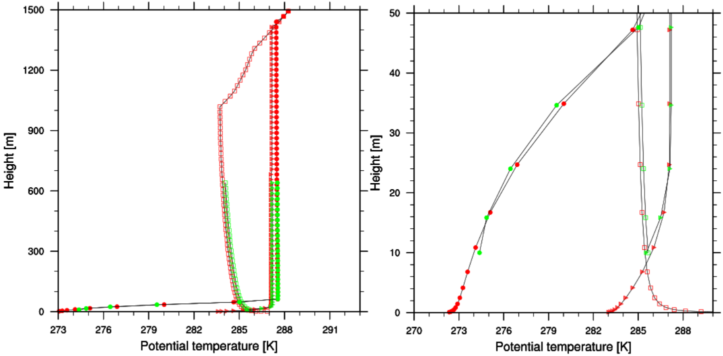


FIGURE: A comparison of the high-resolution finite-difference solution (red) and the integral surface-layer parameterization (green). Right pane focuses on the lowest 50 m.

1-D MODELING: CHOICE OF MODEL CONSTANTS

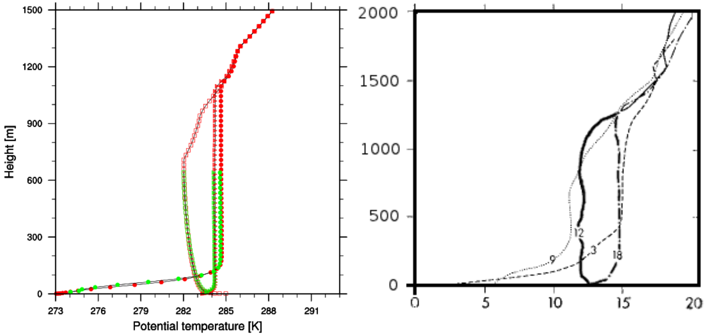


FIGURE: Attempt to change model constants (Łobocki, 1993): a better representation of the nocturnal inversion. Right pane: measurements.

C_U, C_T IN MOST

$$C_U = \frac{\kappa}{\ln\left(\frac{z}{z_0}\right) + \Psi_M\left(\frac{z}{L}\right)}$$

$$C_T = \frac{\kappa_T}{\ln\left(\frac{z}{z_{0t}}\right) + \Psi_H\left(\frac{z}{L}\right)}$$

NOTE:

$$C_U = C_U\left(\ln\left(\frac{z}{z_0}\right), \zeta\right)$$

$$C_T = C_T\left(\ln\left(\frac{z}{z_0}\right), \ln\left(\frac{z_0}{z_{0t}}\right), \zeta\right)$$

Conventional bulk calculations

$$\frac{\Delta z}{L} = \frac{\kappa_T \beta \left(T_2 - T_1\right) \Delta z}{\kappa \left(u_2 - u_1\right)^2} \cdot \frac{\left[\ln\left(\frac{z_2}{z_1}\right) + \Psi_M\left(\frac{z_2}{L}\right) - \Psi_M\left(\frac{z_1}{L}\right)\right]^2}{\ln\left(\frac{z_2}{z_1}\right) + \Psi_H\left(\frac{z_2}{L}\right) - \Psi_H\left(\frac{z_1}{L}\right)}$$

$$z \gg (z_0, z_{0t}), \quad |L| \gg (z_0, z_{0t}) \ :$$

$$\frac{z}{L} = \frac{\beta \left(T - T_0\right) z}{(u)^2} \cdot \frac{\kappa_T}{\kappa} \cdot \frac{\left[\ln\left(\frac{z}{z_0}\right) + \Psi_M\left(\frac{z}{L}\right)\right]^2}{\ln\left(\frac{z}{z_0}\right) + \ln\left(\frac{z_0}{z_{0t}}\right) + \Psi_H\left(\frac{z}{L}\right)}$$

$$\zeta = \mathrm{Ri_B} \cdot \Phi\left(\ln\frac{z}{z_0}, \ln\frac{z_0}{z_{0t}}, \zeta\right)$$

EULAG Lower Boundary Conditions

Momentum:

- no-slip / partial slip (Grubisić & Smolarkiewicz 1999)
- bulk transfer coefficient C_D

Heat:

- specified value

Note:

Taylor (QJRMS 1971) posed a similar problem of determining surface stress from wind speed and surface heat flux.

Algebra

$$\frac{z}{L} = -\frac{\kappa\beta\overline{w'T'}z}{{u_*}^3} = -\underbrace{\frac{\kappa\beta\overline{w'T'}z}{u^3}}_{\text{given}} C_U^{-3}$$

let

$$\chi = -\frac{\kappa\beta\overline{w'T'}z}{u^3}$$

Hence, we must solve

$$\chi = \zeta \cdot C_U^3\left(\ln\left(\frac{z}{z_0}\right), \zeta\right)$$

Solved?

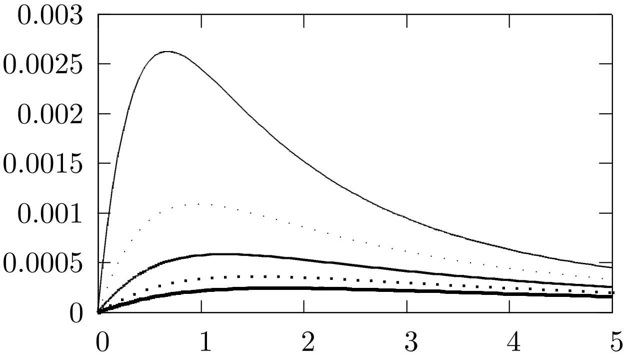


Figure: Function $\chi(\zeta)$ calculated using Mellor-Yamada Level 2 turbulence closure model (Mellor, Yamada, 1982) and integral forms $\Psi_M(\zeta)$ (Łobocki, 1993) for different values of z/z_0.

Questions

Is there a viable physical explanation?

Yes. The issue can be related to existence of a maximum heat flux for a given wind speed under stable stratification. The heat flux is zero under neutral conditions, and if it vanishes at extreme stability, there should be a maximum.

Is it a known phenomenon?

Yes. It was noted by Taylor (QJRMS 1971), and Carson and Richards (BLM 1978). However, very few papers mention it.

Questions

Has it ever been noticed in reality?

It seems so. Malhi (BLM 1995) presents experimental data which seem to support the existence of a maximum.

What is the physical meaning of the two solutions?

Are there corresponding different scenarios in the nature?

- Frequently, we observe either intense and shallow ground-based inversions, or much deeper nocturnal boundary layers with small temperature difference.
- Modelers are familiar with a “runaway cooling” phenomenon.

Questions

Can it be a more general problem?

Is this problem specific to the surface layer and its bulk parameterization? Perhaps it is a more general problem of turbulence (parameterization) in the entire SBL?

Is it important?

- How frequently it happens?
- What are the consequences?

(Subgrid) Turbulence parameterization

Mellor-Yamada Level 2 RSM

$$\frac{\overline{w'^2}}{q^2} = \frac{1}{3} + A_1 \frac{\ell}{q^3}\left(2\overline{u'w'}\frac{\mathrm{d}U}{\mathrm{d}z} + 4\beta\overline{w'\theta'}\right)$$

$$\frac{\overline{u'w'}}{q^2} = 3A_1 \frac{\ell}{q^3}\left[\left(C_1 q^2 - \overline{w'^2}\right)\frac{\mathrm{d}U}{\mathrm{d}z} + \beta\overline{u'\theta'}\right]$$

$$\overline{u'\theta'} = -3A_2 \frac{\ell}{q}\left(\overline{w'\theta'}\frac{\mathrm{d}U}{\mathrm{d}z} + \overline{u'w'}\frac{\mathrm{d}\Theta}{\mathrm{d}z}\right)$$

$$\overline{w'\theta'} = 3A_2 \frac{\ell}{q}\left(\beta\overline{\theta'^2}\frac{\mathrm{d}U}{\mathrm{d}z} - \overline{w'^2}\frac{\mathrm{d}\Theta}{\mathrm{d}z}\right)$$

$$\overline{\theta'^2} = -B_2 \frac{\ell}{q}\overline{w'\theta'}\frac{\mathrm{d}\Theta}{\mathrm{d}z}$$

$$-\overline{u'w'}\frac{\mathrm{d}U}{\mathrm{d}z} + \beta\overline{w'\theta'} = \frac{q^3}{B_1 \ell}$$

(Subgrid) Turbulence parameterization

Mellor-Yamada Level 2 - solutions

$$\overline{u'w'} = -\ell q S_M \frac{\mathrm{d}U}{\mathrm{d}z}$$

$$\overline{w'\theta'} = -\ell q S_H \frac{\mathrm{d}\Theta}{\mathrm{d}z}$$

$$R_F = S_M B_1^{1/3} q_n \frac{\ell}{\kappa z} \zeta$$

$$q_n = \left(\frac{1 - R_F}{S_M B_1^{1/3}} \right)^{1/4} \qquad q_n = B_1^{-1/3} \frac{q}{u_*}$$

$$S_M = S_M(\mathrm{R_F}) = S_M(\zeta) = S_M(\mathrm{Ri})$$

$$S_H = S_H(R_F) = S_H(\zeta) = S_H(\mathrm{Ri})$$

Vertical heat flux

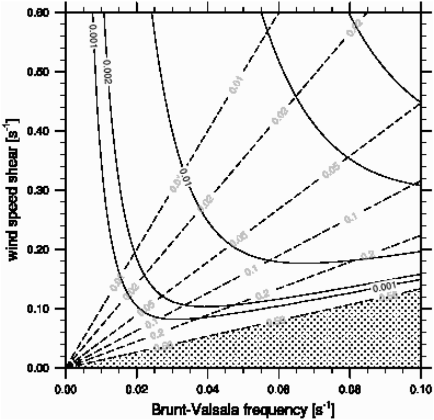


FIGURE: Kinematic vertical heat flux per unit master length scale $\overline{w'\theta'}/\ell$ as calculated from the Mellor-Yamada Level 2 model using constants proposed by Łobocki (1993)

1-D MODELING

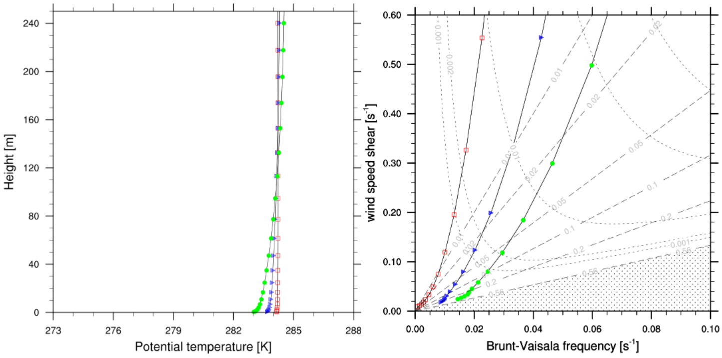


FIGURE: Weak surface cooling scenario. Left: potential temperature profiles at 21 (green), 24 (blue) and 3 (red) LST. Right: hodographs of the solutions in the (N^2, S^2) parameter space. High-resolution finite-difference Mellor-Yamada Level 2 model, modified constants (Łobocki, 1993)

1-D MODELING

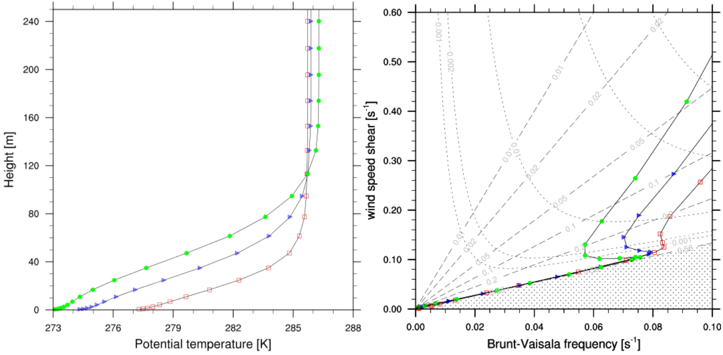


FIGURE: Intense surface cooling scenario. Left: potential temperature profiles at 21 (green), 24 (blue) and 3 (red) LST. Right: hodographs of the solutions in the (N^2, S^2) parameter space. High-resolution finite-difference Mellor-Yamada Level 2 model, modified constants (Łobocki, 1993)

Vertical heat flux

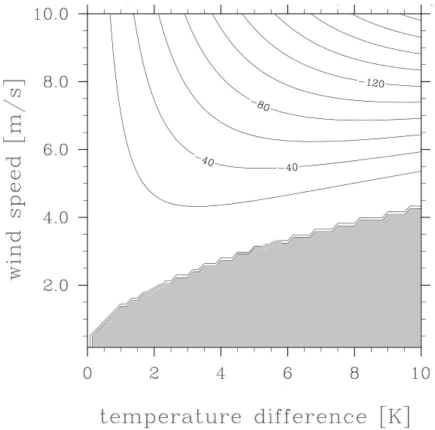


FIGURE: Surface vertical heat flux $\overline{w'\theta'}$ as calculated from the Mellor-Yamada Level 2 model

Conclusions & discussion

Dual solutions:

- do not necessarily arise from the log-linear nondimensional wind profile (as shown by Malhi, 1995)
- are not an endemic feature of the surface layer - they may be reproduced by the turbulence closure model regardless of height.
- are associated with the existence of the critical value of the gradient Richardson number. Existence of such critical value is now disputed (e.g. Galperin et al. (2007), Zilitinkevich and Esau (2007), Mahrt (2010))

Conclusions & discussion

Dual solutions:

- apparently are not related to different cooling scenarios
- apparently are not associated with model instabilities at the surface

Moreover,

- We see that zone where the critical flux Richardson number is maintained, is separated from the ground with a layer, where wind shear is present and subcritical regime is mantained.

So, what's next? - Length scale issue

Prandtl, 1925; Mellor, 1974

$$\ell = \kappa z$$

Deardorff (1980):

$$\ell_N \propto \frac{q}{N} \qquad \frac{1}{\ell} = \frac{1}{\kappa z} + \frac{1}{\ell_N}$$

Generalized von Karman (Laikhtman, 1979; Łobocki, 1992):

$$\ell \propto \Psi \left(\frac{\mathrm{d}\Psi}{\mathrm{d}z} \right)^{-1}$$

$$\Psi = \left(\frac{\mathrm{d}U}{\mathrm{d}z} \right) + \mu\beta \frac{\mathrm{d}\Theta}{\mathrm{d}z}$$

Prandtl length scale

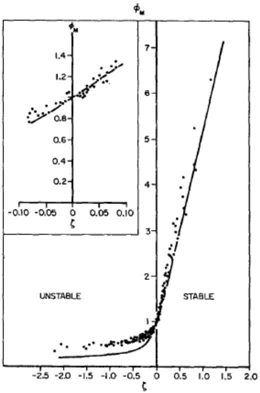


Figure: Nondimensional wind profile obtained by Mellor (1973) using Level 2 model with Prandtl length scale (Good results for a wrong reason?)

TKE budget, local equilibrium, no shear

ℓ independent of time and of TKE

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{q^2}{2}\right) = \beta\overline{w'\theta'} - \frac{q^3}{B_1\ell}$$

Suppose at the extreme stability

$$\overline{w'\theta'} = 0$$

$$\frac{\mathrm{d}E}{\mathrm{d}t} \propto -E^{3/2}$$

$$E(t) \propto t^{-2}$$

TKE budget, local equilibrium, no shear

Deardorff's asymptotic ℓ

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{q^2}{2}\right) = \beta\overline{w'\theta'} - \frac{q^3}{B_1\ell}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{q^2}{2}\right) = -\ell q S_H N^2 - B_1^{-1}q^2N = -q^2 S_H N - B_1^{-1}q^2N$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{q^2}{2}\right) = -(S_H + B_1^{-1})q^2N$$

$$\frac{\mathrm{d}E}{\mathrm{d}t} \propto -E$$

$$E(t) \propto e^{-t}$$

Notes: S_H shall assume a constant value (corresponding to the critical value of R_F)

Asymptotic properties depend on model constants. $q/u_* \rightarrow const.$ possible when $R_F \rightarrow 1$. Realizeability should be checked.