Equilibrium Turbulence Analysis: Preliminary Results

Takanobu Yamaguchi and David A. Randall
Department of Atmospheric Science, Colorado State University

Introduction

Large-eddy simulation (LES) has been a useful tool for studies of the planetary boundary layer (PBL). In LESs, however, achieving a literally "steady" state is hard since all horizontal mean profiles (e.g., temperature and moisture) evolve as turbulence evolves with surface forcing and entrainment. Thus, it is difficult to address answers of questions like:

- ***What turbulence structure is expected with the given horizontally-averaged profiles of velocity, temperature and moisture?***
- ***How strongly does the mean state (i.e., given profiles) determine the eddy structure?, etc...***

To study the PBL turbulence under the steady state, a new method called “Equilibrium Turbulence Analysis” (ETA) was developed. We present the preliminary results of a dry PBL simulated with the ETA method.

The ETA method

The ETA method assumes that the eddy structure with the given soundings of velocity, temperature and moisture will be obtained after simulating for a sufficiently long time by always getting the horizontal mean soundings back to the mean state. Turbulence should develop under fixed profiles and forcing.

LESs have been performed with a small domain due to limited computer resources. By collecting samples over a sufficiently long period, the ETA method should provide turbulence statistics of the fixed state equivalent to what would be obtained with a large domain LES.

SAM

Dynamics & Physics

ETA

1. $\psi_{res}\,\Delta t = [\psi_0] - [\psi]$
2. $\psi^{new} = \psi + \psi_{res}\,\Delta t$

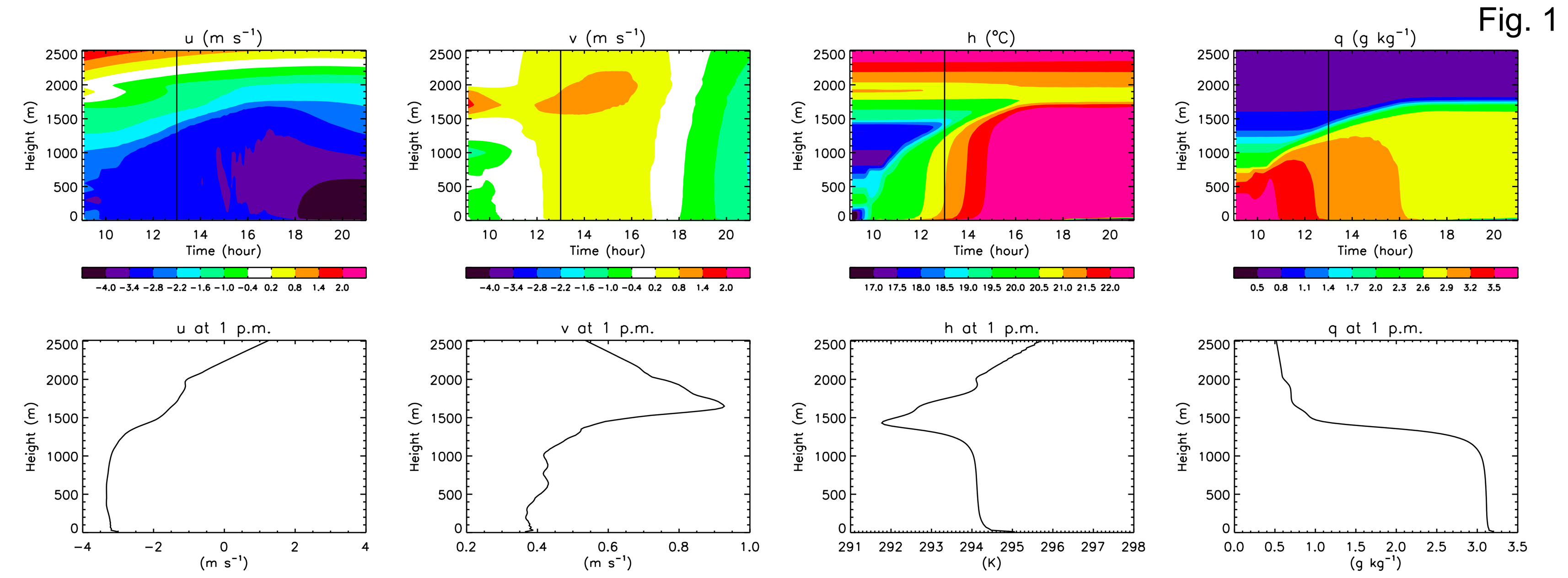
- [ ] denotes horizontal average.
- $[\psi_0]$ is “fixed state,” and ψ_{res} is “rate of restore.”
- $[\psi^{new}] = [\psi] + [\psi_{res}\,\Delta t] = [\psi] + \psi_{res}\,\Delta t = [\psi_0]$
- ψ represents u, v, h, and q.

We fixed mean profiles of horizontal velocities (u, v), moist static energy (h), and water vapor mixing ratio (q). The ETA module was implemented into SAM (System for Atmospheric Modeling, Khairoutdinov and Randall 2003). In SAM, ETA is called at the end of every time step after it has been initialized.

Wangara

As a first SAM-ETA run, we selected the day 33 of Wangara experiment (Clark et al. 1971, Deardorff 1974), which involves a dry PBL over land. Simulation starts at 9 a.m. and finishes at 9 p.m. The horizontal domain width is 10 km and the vertical domain depth is 3 km. The horizontal resolution is 50 m and the vertical resolution is 20 m.

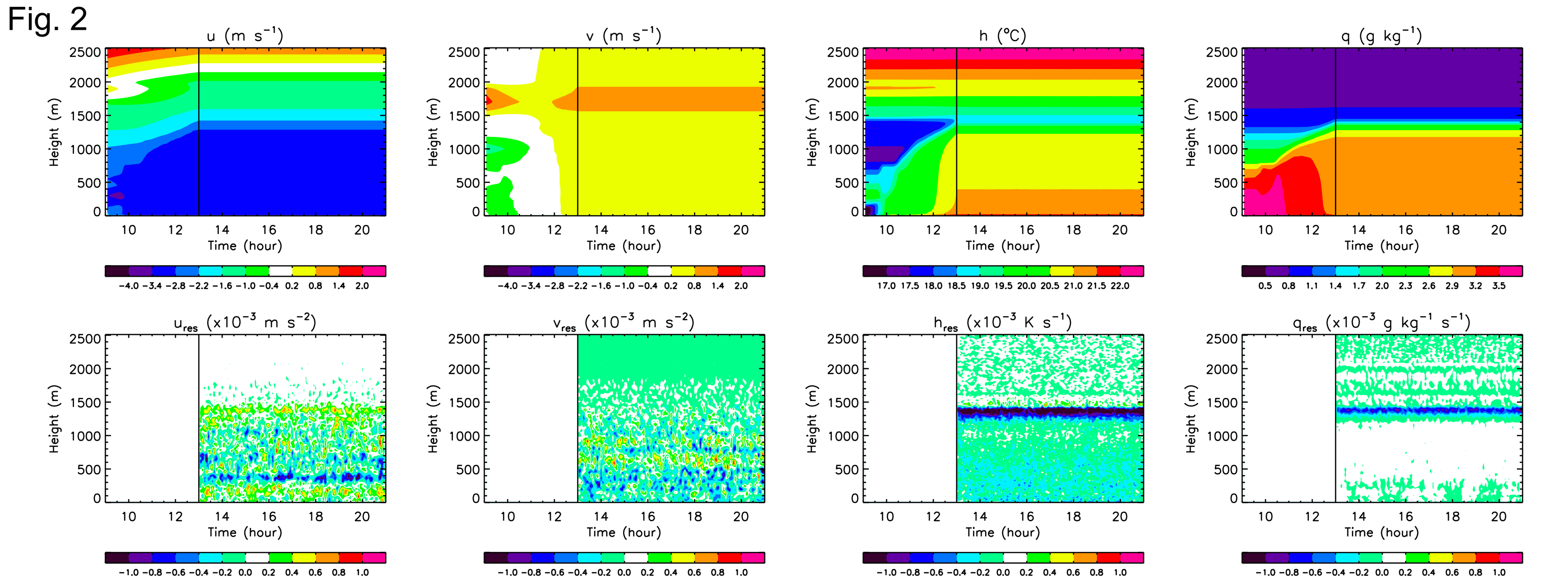
Fig. 1



The upper panels of Fig. 1 show the time evolutions of u, v, h and q from a normal run. For SAM-ETA simulation, ETA is initialized at 1 p.m., and these soundings are shown in the lower panels.

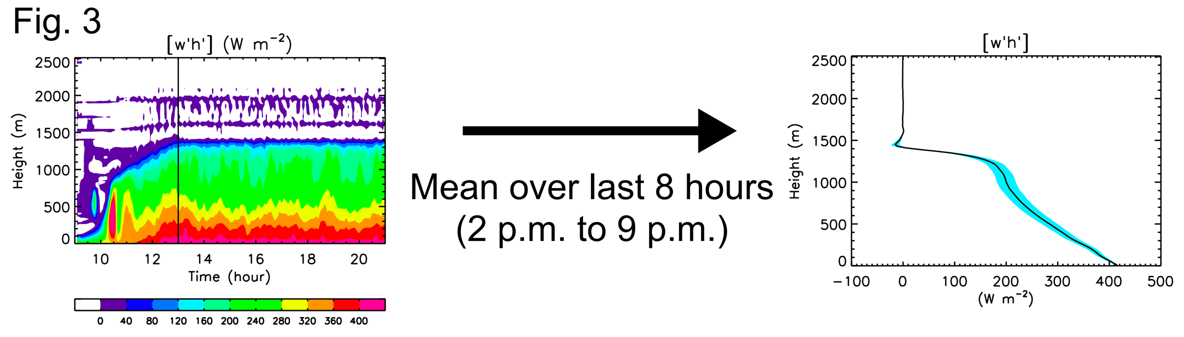
Results

Fig. 2



As shown in the upper panels of Fig. 2, ETA holds soundings of u, v, h and q constant from 1 p.m. Restore rates are very small (lower panels). For h and q, ETA cools and dries in the entrainment zone to counteract constant surface fluxes and entrainment.

Fig. 3



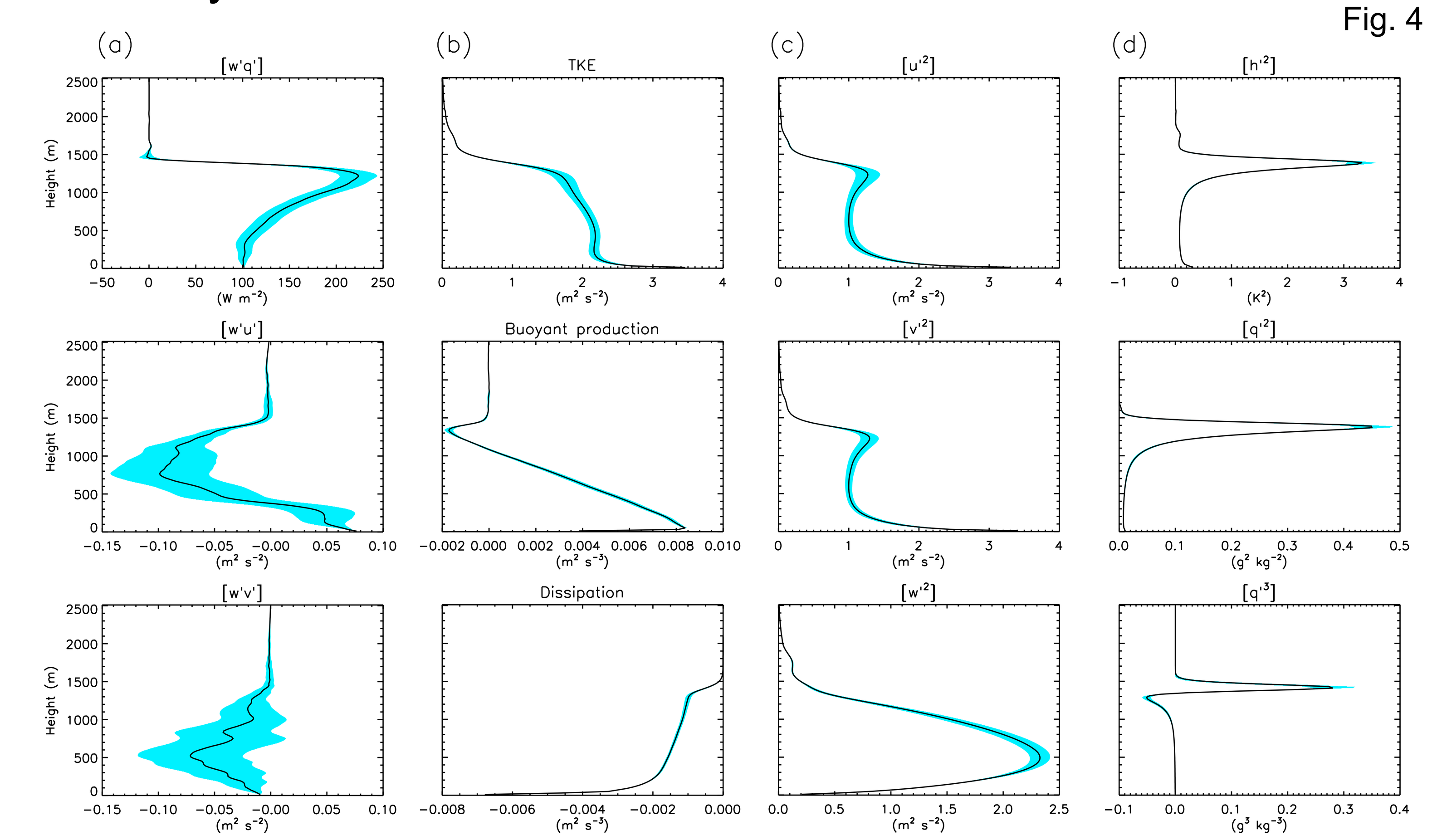
The right plot in Fig. 3 shows the mean profile with shading over the last eight hours. The width of shading for every vertical level is one standard deviation on each side, indicating the variability, i.e., random fluctuations of the turbulence about the equilibrium.

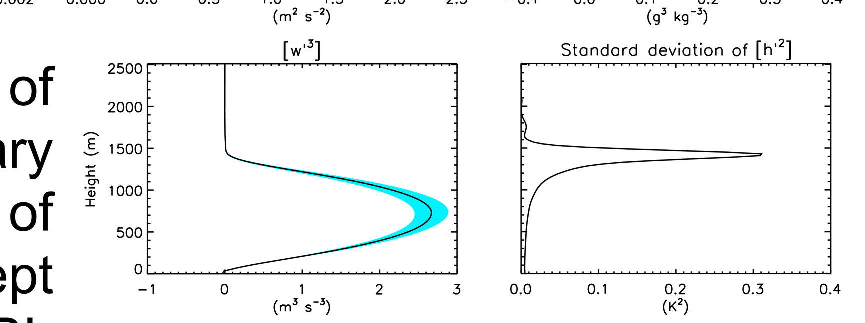
Results (cont.)

Momentum fluxes (Fig. 4a) have large variability in the mixed layer suggesting the weak ability of the mean profile to explain these flux profiles.

On the other hand, the variability of other turbulence variables is roughly 10-20 % of the mean in the mixed layer. The variability of variance and third moment of h and q (Fig. 4d) seem to be very small except in the entrainment zone. However, these standard deviations (e.g., the last plot of Fig. 4d) indicate variability of about 10-15 % of the mean.

Fig. 4





The mean state variables of the dry convective boundary layer explain about 80 % of the turbulent variables, except momentum fluxes. The PBL parameterization should take this variability into account.

Future work

We presented the results of a simple mixed layer SAM-ETA LES for demonstration only. We also plan to study PBL turbulence and PBL parameterization with more complicated cases with the ETA method:

- Finer resolution Wangara,
- Stratocumulus-topped boundary layer (e.g., DYCOMS-II, Stevens et al. 2005),
- Shallow cumulus boundary layer (e.g., BOMEX, Siebesma et al. 2003, RICO), and
- Experiment of the cloud-topped entrainment instability (Randall 1980) with realistic mean soundings.

References

Clark, R. H., A. J. Dyer, R. R. Brook, D. G. Reid, and A. J. Troup, 1971: The Wangara experiment: Boundary layer data. Tech. Pap. No. 19, CSIRO Div. Meteor. Phys., Melbourne, 340 pp.
Deardorff, J. W., 1974: Three-dimensional numerical study of the height and mean structure of a heated planetary boundary layer. Bound.-Layer Meteor., 7, 81-106.
Khairoutdinov, M. F., and D. A. Randall, 2003: Cloud resolving modeling of the ARM summer 1997 IOP: Model formulation, results, uncertainties, and sensitivities. J. Atmos. Sci., 60, 607-625.
Randall, D. A., 1980: Conditional instability of the first kind upside-down. J. Atmos. Sci., 37, 125-130.
Siebesma, A. P., and Coauthors, 2003: A large eddy simulation intercomparison study of shallow cumulus convection. J. Atmos. Sci., 60, 1201-1219.