Improved Atmospheric Stable Boundary Layer Formulations for Navy Seasonal Forecasting

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LONG-TERM GOALS

To develop methods, descriptions and parameterizations that will alleviate long-standing problems in large-scale numerical atmospheric models in dealing with statically stable conditions, and to implement these in Navy models.

OBJECTIVES

Most weather forecast models prescribes too much turbulent mixing in stably stratified conditions, which causes problems with the depth of nocturnal or high-latitude winter boundary layers, lack of inertially driven low-level wind maxima and inversion-capped low clouds. The link between the turbulent momentum flux and the associated Ekman pumping and therefore the lifetime of synoptic-scale weather system has so far made impossible a satisfactory solution.

Several detrimental feedbacks are also involved in this problem. There is a negative feedback between stability and the sensible heat flux in the unstable boundary layer (larger instability → more heat flux → more mixing → less instability etc.) and the momentum flux at large instability becomes relatively unimportant compared to buoyancy in producing turbulence. For stable stratification this feedback is positive: larger stability → less heat flux → less mixing → larger stability. Here only increasing wind shear, as stability continues to increase, can break the cycle otherwise leading to a collapse of the boundary layer. The balance between the buoyancy destruction and wind-shear generation of turbulence thus becomes critical to prevent for example model surface temperature to plunge. For this reason the wind-shear generation of turbulence is exaggerated in models to avoid this collapse; this, however, also has detrimental effects.

The objectives of this project are to develop and understanding in three specific areas and to explore if these concepts can be used to alleviate the problem described above. These specific areas are:

1. The "Total Turbulent Energy" (TTE) approach, in which turbulent potential energy is included in a new prognostic variable. This allows kinetic energy to be transformed into potential energy for "storage" and later retransformation. Physically this is essentially the same thing as energy transferring back and forth between classical turbulence small-scale buoyancy waves.

2. Turbulence generation by breaking of small-scale sub-grid topography-generated gravity waves, which may happen in the boundary layer even at seemingly modest terrain variations, due to its inherent-wind turning and thus potential formation of a critical layer.
3. Describing the uncertainty in turbulence flux-gradient relationships, by exploring probabilistic expressions for these.

APPROACH

Originally, the strategy was chosen to explore new formulations in either COAMPS, or in a single column version of the NOGAPS/NAVGEM model, before being implemented in a global context. Both the single-column and global modeling concepts can be either directly implemented in Navy models provided we can have simple access to these. All steps of the development and testing will involve evaluations of model results against filed observations to ensure the correct results for the correct reasons. As test beds we will start using data from the SHEBA and CASES99 experiments. The former has long periods of stable stratification during the Arctic winter while the latter is dominated by nocturnally stable conditions. These two types differ in that while the latter involves a capping near-neutral residual layer, the Arctic case develops a strong and continuous stratification through the whole troposphere; buoyancy waves can travel very far in that environment and still affect the surface.

For the TTS implementation, this has been achived already in WRF and will now be attempted in COAMPS. The TTE will be embedded in an EDMF context and in contrast to WRF we will use couple the formulation for the stably stratified case (the ED part) to a probabilistic mass flux model also developed and used in this project, by Dr Joao Teixeira's group.

For the work on gravity wave breaking we are collaborating with Dr Carmen Nappo who has developed a saturation-critical layer analytic model that takes a terrain data base and wind speed and direction profiles to solve for the momentum deposition necessary to prevent waves from breaking; this is necessary to stay in the linear model concept but the energy deposited should be the same as that would be generated by the breaking waves. This analytic model, that scans for possible propagation directions to find a critical layer will be coupled first to a single column model, then to COAMPS and eventually to a global model.

For the description of uncertainty in the flux-gradient relationship, we collaborate with Dr Larry Mahrt who has significant amounts of data from stable conditions in various settings. Together we will generate a pdf-based relationship between the flux of momentum and the wind speed gradient; for each stability, there will thus be a pdf of such relationships and in the model we will sample that pdf such that over time the ensemble average relationship will be conserved. Since the pdf is very likely skewed, we expect that this will allow a reduction in mean mixing while maintaining the stratification thus alleviating some of the basic problems described above.

WORK COMPLETED

Over the last year we have worked with various aspects of the stable boundary-layer formulations in COAMPS. COAMPS has been our mesoscale model of choice since the early 2000's and has served us well in several coastal boundary layer projects over the years and in fact it plays a major role in a recent PhD-thesis in this group in the fall of 2013.

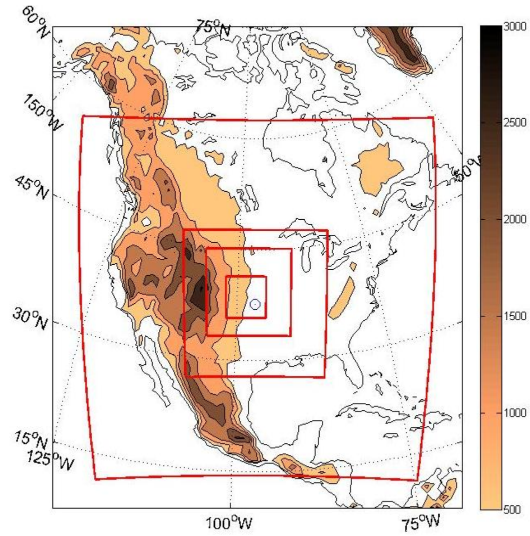

Figure 1 The domain(s) of COAMPS used here showing the outer (parent) domain at 54 km resolution and the three nests at 18, 6 and 2 km resolution, respectively.

We have aimed at setting up simulations for a specific set of days from CASES-99 and to generate a baseline simulation from which we would be able to estimate improvements for new methods. The plan was to then run COAMPS for the entire CASE99 period to facilitate a statistical evaluation; this has not happened yet because of several problems that we have run into. This has been an integrated effort, where we have looked both at the surface layer formulation, in collaboration with Dr Larry Mahrt, and the PBL-mixing scheme. In parallel we have investigated the effects on the same simulation by imposing a hypothetical probabilistic factor into the surface layer scheme as well as tested a so-called "generalized velocity scale" introduced by Dr Mahrt.

Three main problems that has slowed down the progress during this year are:

1) Technical aspects of the code that has made changes in the stability regime difficult
2) Initial conditions not conforming to observations
3) An extremely tight coupling between the surface layer meteorology and the land surface properties

RESULTS

Figure 1 shows the model domain that was used; Figure 2 and Figure 3 illustrates some of the first results, comparing COAMPS wind speed and temperature profiles from the outer and inner domains in Figure 1 at two against a select set of sounding profiles from the field deployment. It is quite clear from Figure 2 that while COAMPS produces reasonable results in the day time, the formation of an inertial low-level jet during the night is much underestimated. The nose of the jet is too high and the wind speed too low; clear signs of too much mixing. The same symptoms are clear from the temperature profiles in Figure 3. Although there is a positive bias the second day, the structure of the daytime well-mixed layer is adequately described, but during the night there is s significant warm bias and the observed strong surface-based inversion is entirely missing in the model simulation

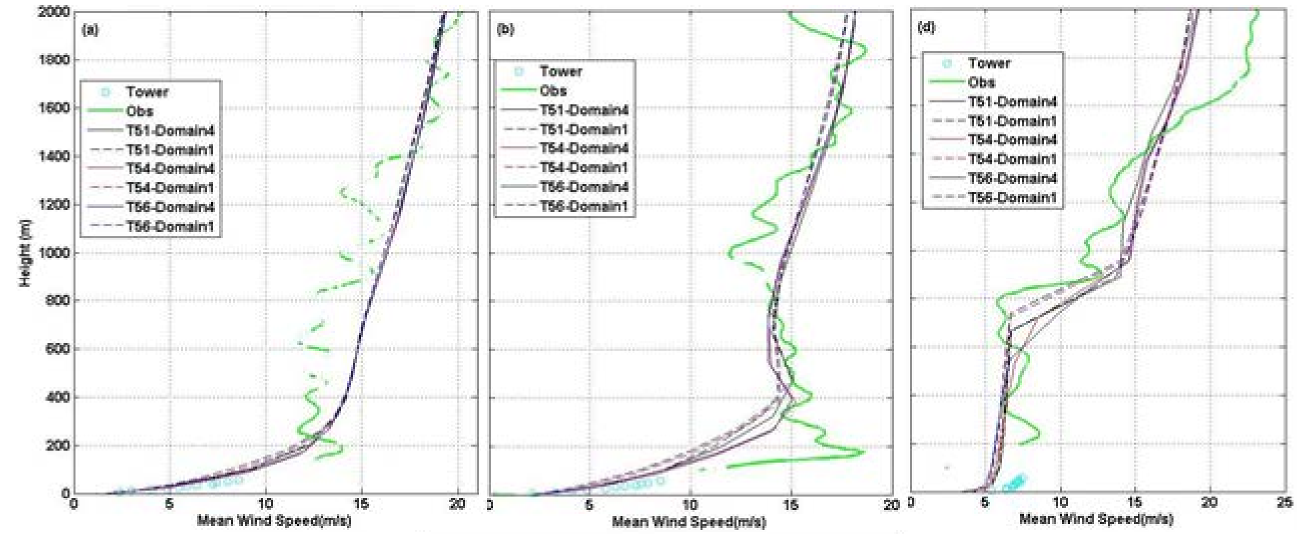

Figure 2. Examples of COAMPS comparison to three soundings for one particular night, 23-24 October, during CASES99. The panels show observed wind speed profiles (ms^{-1}, green) from sounding from 22, 04 and 14 local time, left to right. The simulations are from the outmost (Domain 1) and innermost (Domain 4) domains and shows results from two setups, one with 54 model levels with only one within the CASES 50-m mast and one where the near-surface is enhanced by adding two more layers in the lowest 50 m.

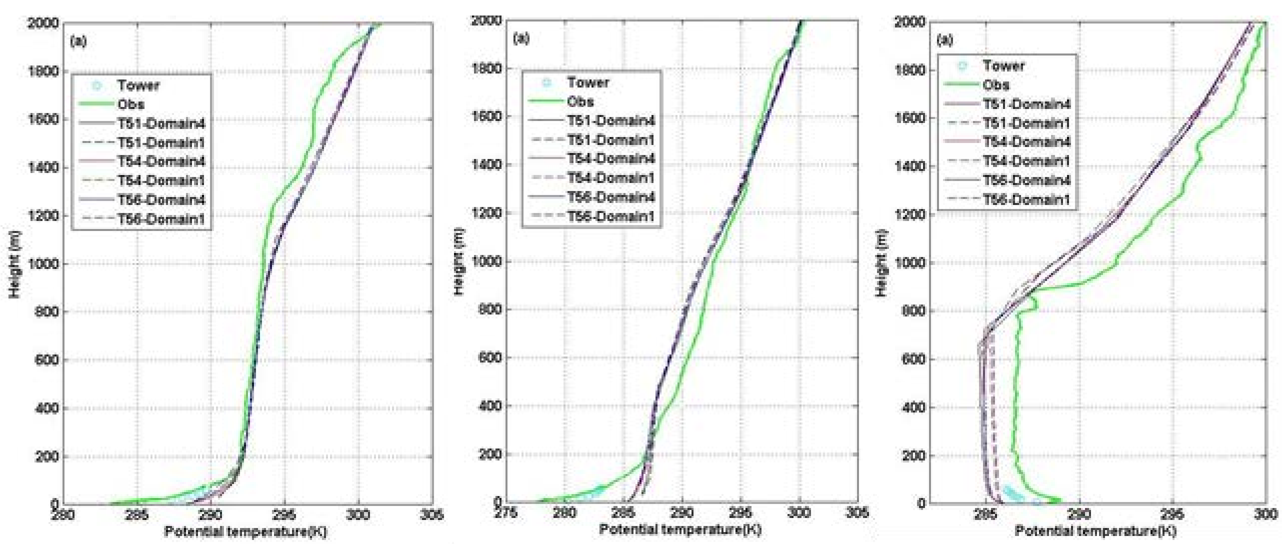

Figure 3. Same as Figure 2 but for potential temperature (K).

When analyzing the time series in Figure 4, it is clear that while daytime temperatures are somewhat low but reasonable, the nighttime temperatures are much too warm, especially the first two nights; the diurnal temperature range is much too small. The wind speed is also reasonable during the day but much too high during the night. At the same time the sensible heat flux is reasonable but the latent heat flux is much too high in the model, by a factor of three to four. The momentum flux (not shown) is also too high, especially at night. Taking this all together, it is difficult to explain the surface energy budget and the temperature from just one process. After extensive testing altering boundary and initial conditions, it is clear that the culprit is the soil model. Excessive ground heat flux in the night keeps the surface temperature from falling and the restoring of the surface soil moisture to the deep soil conditions (set at initial time) prevents the surface soil from drying out. Inspection of the code reveals the restore time scales in the so-called "force-restore" formulation is much to short; even reducing the initial top soil moisture to a small fraction of the values from the analysis does not help; the top soil moisture adjust back to the same high values less than half a day (~10 h); since the deep soil properties are not updated, this means an initially too moist soil cannot dry out in response to the very high latent heat flux and the surface temperature cannot be as low as it should. Even though loosing surface moisture in response to the high daytime surface fluxes, the next day is the same again because the surface moisture is restored during the night.
Our conclusion is that the coupling in the soil model is much too fast and that to the surface atmosphere is much too tight. In essence one can do almost anything to the initial conditions and the same thing will happen anyway. This also means that for example introducing different manipulations of the surface mixing, for example using stochastic methods, altering the stability functions in the surface layer or introducing the generalized velocity scale suggested by Dr Mahrt has no effect at all on the near-surface temperature.

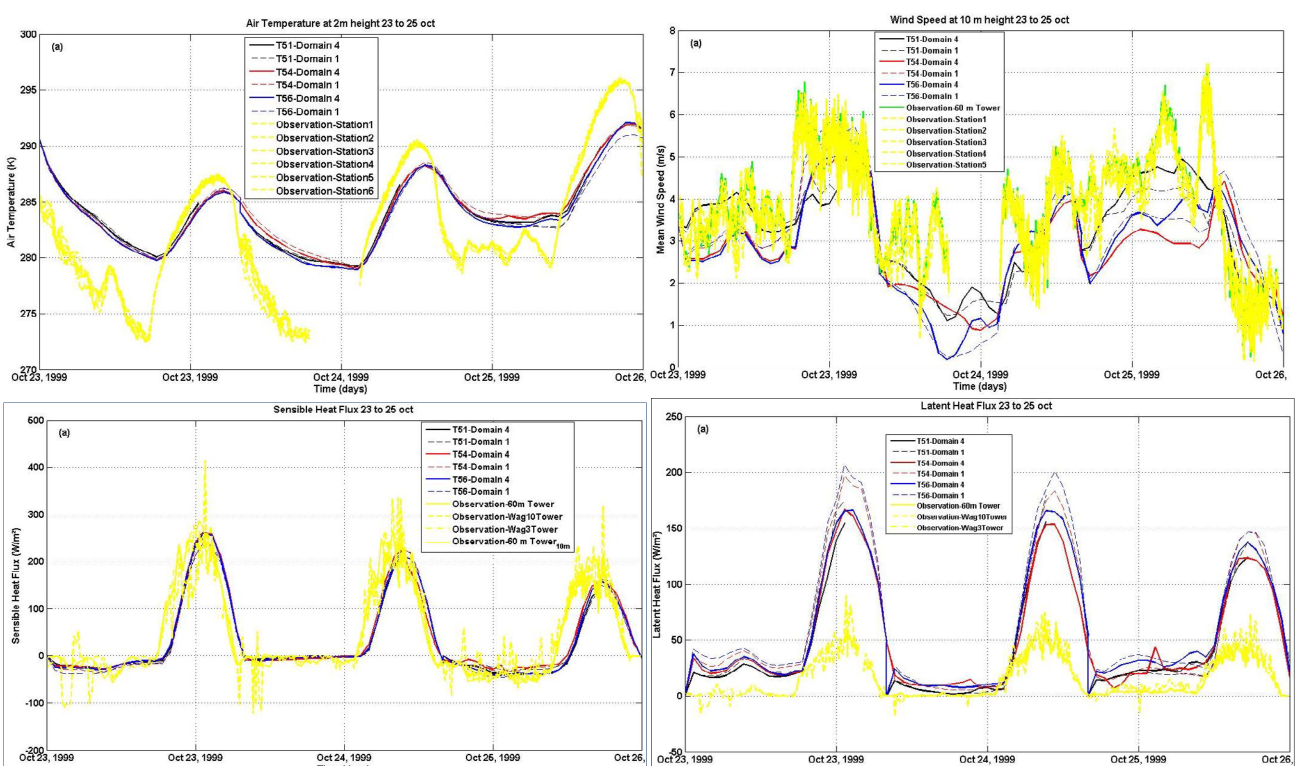

Figure 4. Time series of near-surface variables showing (top left) air temperature (K), (top right) wind speed (ms^{-1}), and of (low left) sensible and (low right) latent heat fluxes (Wm^{-2}).

After extensive experimentation we have generated a run where the surface temperature is starting to behave realistically during the night. This was done by reducing the initial temperatures by 4K and the initial soil moisture from ~ 0.2 to 0.05 gkg^{-1}, while artificially reducing the soil heat flux by a factor 0.6. Further analysis reveals that the important impact of the reduced initial temperature was the effect this had on the initial and therefore constant deep soil temperature; other effects from different initial conditions are “washed away” within one day. Interestingly, while the agreement between the modeled and observed latent het fluxes is dramatically improved, the effects on the sensible heat flux are small (Figure 5). Although the match is still not perfect this could be achieved by further fine-tuning the properties of the soil model, and the indications are clear; COAMPS needs an improved description of the PBL-land surface coupling. A similar conclusion lies behind the strategy in the 3rd GABLS model intercomparison experiment, where all models were required to run soil models, rather than prescribing fluxes or temperatures at the lower boundary as in the 1st and 2nd experiments.

Further testing with stochastic physics shows that this has the expected results. While multiplying the calculated friction velocity in the model by a factor randomly varying between 0.5 and 1.5, but keeping this factor constant for ten-minute periods, shows that even though the time averaged friction velocity is unaltered, the mixing is increased. Right now this pushes the results in COAMPS away from the observations, since there already is excessive mixing in the model. However, this will now allow us to target this excessive mixing and reduce it, without risking that the PBL collapses in very strong conditions.

Most of the work was supposed to be conducted using COAMPS as a test bed. However, for success this required as reasonably realistic reproduction to begin with. Since a less than adequate soil model prohibited COAMPS from generating even very stable conditions at all, this work has been stalled by this problem.

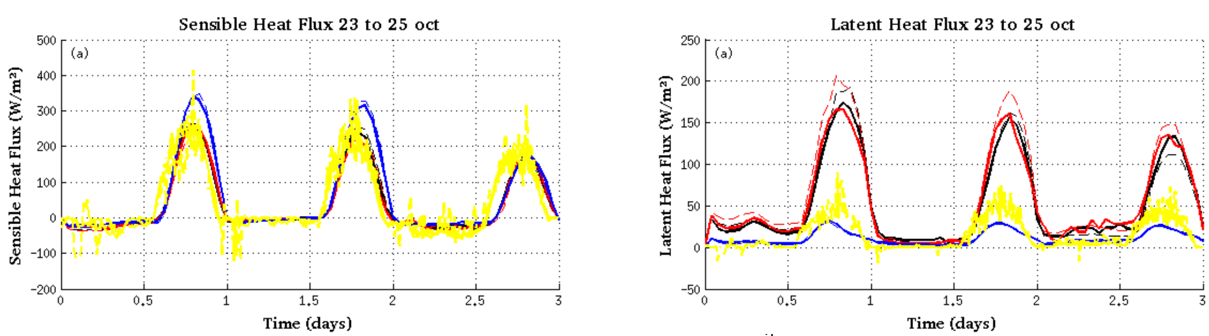

Figure 5. Time series of (left) sensible and (right) latent heat fluxes (Wm^{-2}) in a run where the initial conditions are altered and the soil heat flux is reduced, as discussed in the text (blue) compared to the control run (red and black) and observations (yellow).

Having had a single column model would have provided progress faster; COAMPS does not have such a facility and we were not supplied with a single column version of NAVGEM or NOGAPS, although this was discussed at length at the DRI workshop in 2012. Hence the work to include TTE has not started. The work on breaking gravity waves have also been dormant due to lack of manpower

IMPACT/APPLICATIONS

A better treatment of the stable boundary layer processes is directly directed towards reducing some persistent systematic errors in several of the the near-surface variables while maintaining the forecast quality on the synoptic scales by not adversely affecting the Ekman pumping in the boundary layer.