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Atmospheric stability in CFD &NDASH; Representation of the diurnal cycle in the atmospheric boundary layer

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Atmospheric Stability in CFD
the diurnal cycle in the atmospheric boundary layer

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Abstract

For wind resource assessment, the wind industry is increasingly relying on Computational Fluid Dynamics (CFD) models that focus primarily on modeling the airflow in a neutrally stratified surface layer. So far, physical processes that are specific to the atmospheric boundary layer (ABL), for example the Coriolis force, buoyancy forces and heat transport, are mostly ignored in state-of-the-art CFD models. In order to decrease the uncertainty of wind resource assessment, especially in complex terrain, the effect of thermal stratification on the ABL should be included in such models.

The present work examines the influence of stability on the whole ABL using the modified in-house CFD code (DTU Wind Energy) EllipSys3D. Typical diurnal cycles are simulated and compared against previous simulations and measurements from the GABLS II model intercomparison [6].

Objectives

- To modify the existing EllipSys3D CFD to get a more appropriate description of the wind flow in the ABL during non-neutral conditions
- To validate the model against previous simulations and measurements
- To analyze the influence of diurnal temperature variations on the ABL
- To set the starting point for non-neutral simulations over complex terrain

Stable stratification

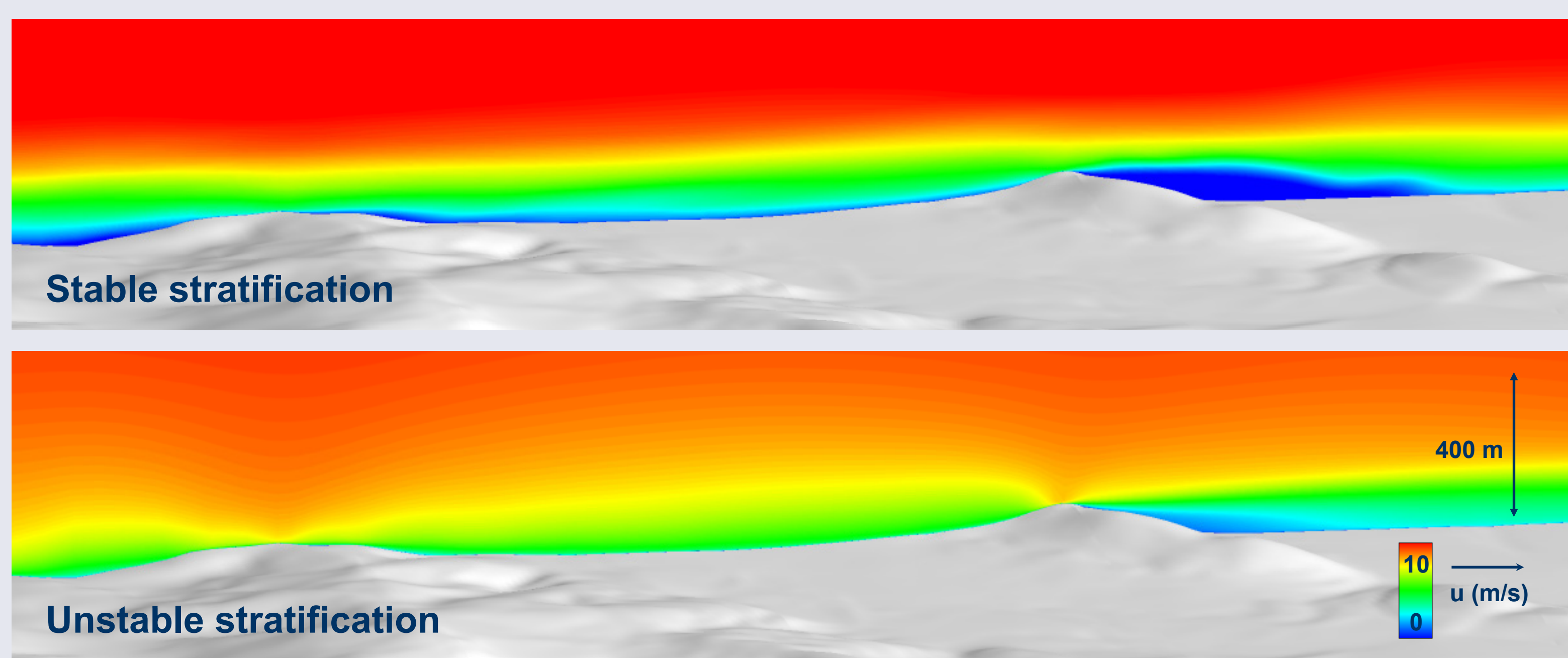Unstable stratification

400 m

u (m/s)

Figure 1: non-neutral simulation over complex terrain: horizontal wind speed for (a) stable and (b) unstable conditions over the Benakanahalli site in India. For details about the Benakanahalli measurement campaign see poster ID 107.

Methods

The present study considers the simulation of the diurnal cycle in the ABL. The focus is on flow over flat terrain (horizontally homogeneous flow), subjected to temporally varying surface temperatures. To model the ABL more appropriately the effect of the Coriolis forcing and buoyancy are included in the CFD code EllipSys3D. Therefore an equation for the energy in terms of the potential temperature is solved in addition to the RANS equations. To close the given set of equations a modified version of the k-ε turbulence model is used: in contrast to the standard formulation we use a limiter on the resulting length-scale [1,2], and additional buoyancy terms [3,4]. Also ambient floor values for the turbulence variables are imposed in order to avoid numerical issues due to turbulence values close to zero [5]. With these modifications the model is capable of representing non-neutral conditions, and the two modified transport equations for the turbulent kinetic energy k and the dissipation ε read:

$$\frac{\delta k}{\delta t} + U_j \frac{\delta k}{\delta x_j} - \frac{\delta}{\delta x_i}\left(\frac{K}{\sigma_k}\frac{\delta k}{\delta x_i}\right) = P - \varepsilon \qquad (1)$$

$$\frac{\delta \varepsilon}{\delta t} + U_j \frac{\delta \varepsilon}{\delta x_j} - \frac{\delta}{\delta x_i}\left(\frac{K}{\sigma_\varepsilon}\frac{\delta k}{\delta x_i}\right) = \frac{\varepsilon}{k}(C_{\varepsilon 1}P - C_{\varepsilon 2}\varepsilon) \qquad (2)$$

$$C_{\varepsilon 1}^* = \left[C_{\varepsilon 1} + (C_{\varepsilon 2} - C_{\varepsilon 1})\frac{l}{l_{max}}\right] \qquad (3)$$

where B is the production (or removal) of turbulent kinetic energy by buoyancy forces, and depends upon the local temperature gradient. The coefficient $C_{\varepsilon 1}$ in (2) is replaced by (3) in order to limit the mixing length [1,2]. All other coefficients are chosen according to [3,4].

Results

Surface winds, temperature stratifications and TKE values resulting from a non-neutrally stratified ABL flow are compared against modelled and observed data from the GABLS II experiment from Kansas, USA [6], shown in figure 2. The development of the ABL throughout the day is driven by a prescribed surface temperature that is varied with time and a constant geostrophic wind (figure 2a,b). Details concerning model set-up and forcing are given in [6].
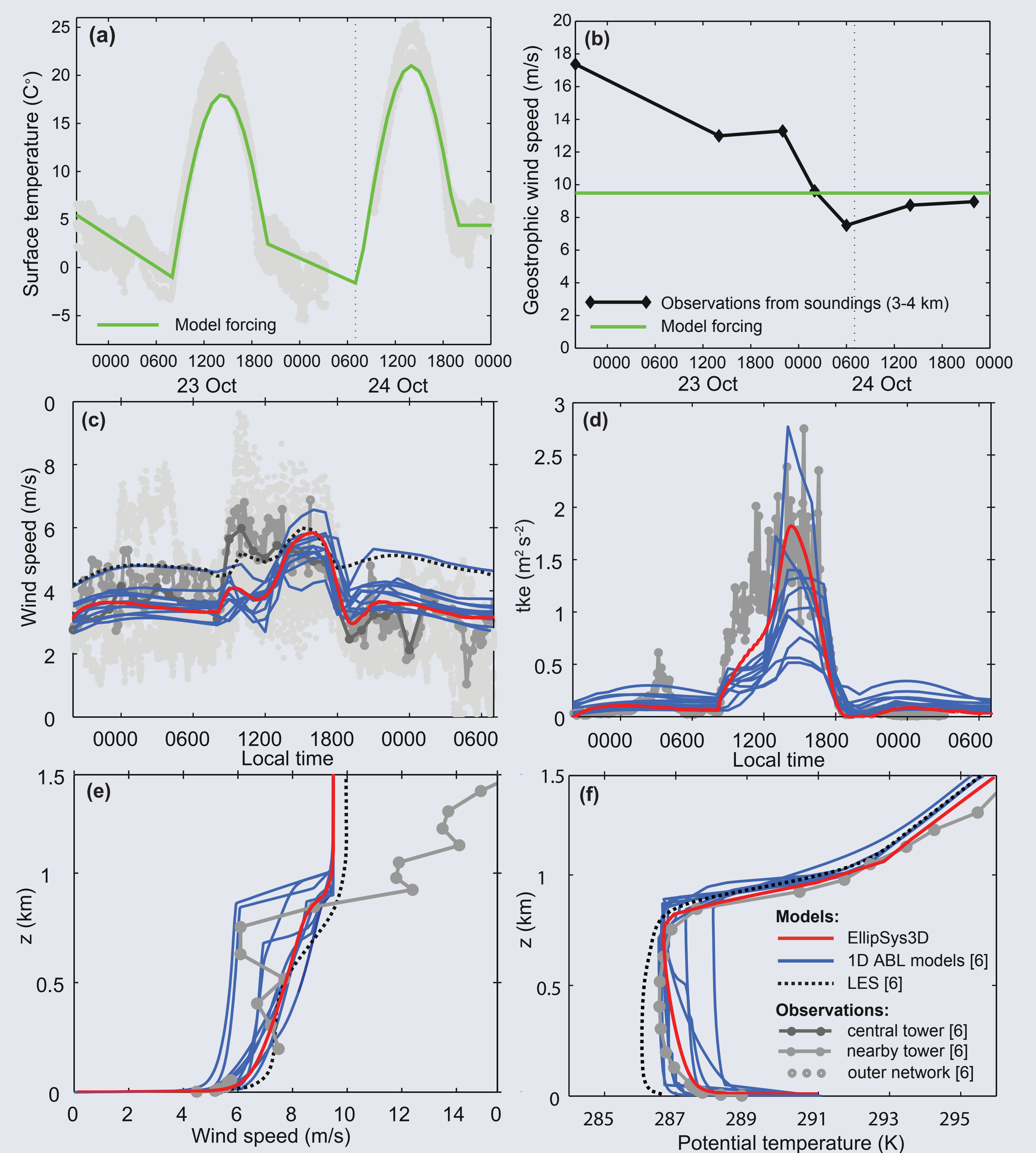

Figure 2: (a) surface temperature (b) geostrophic wind (c) time series of wind speed at 10m a.g.l. (d) time series of turbulent kinetic energy at 55m a.g.l. (e) vertical profiles of wind speed at 1400, 23 October (f) vertical profiles of potential temperature at 1400, 23 October.

The above modifications of the 3D version of EllipSys enable us to apply the developed model for flows over complex terrain. Figure 1 shows the horizontal wind speed for non-neutral conditions over the Benakanahalli site in India.

Conclusions

The general features of the typical diurnal cycle and its representation by the model are presented. Furthermore the sensitivity of the numerical results on the forcing and the initial conditions are examined. The chosen methodology to implement stability effects into the CFD code EllipSys3D represents a promising approach and is a first step to extend the application of the model to stratified flow over complex terrain.
The developed model is able to reproduce the general flow pattern of a non-neutral ABL flow subjected to a diurnally varying surface temperature.

The present simulations and the measurements from [6] show rather good agreement from late afternoon until early morning. During the morning transition, however, the growth of the convective ABL and the turbulence level are too weak, which is also visible in the underestimated low-level wind speed. None of the models intercompared in [6] was able to capture the morning transition. Modelling the diurnal cycle presents a big challenge, and the present model shows the biggest deviations after the morning transition, and the best agreement during late afternoon and early evening.

Comparison against observations raises the issue of initial and boundary conditions of numerical experiments, because perfect test cases do not occur in reality. The modelled results are sensitive to the initial temperature profile. Also large scale atmospheric variations influence measured statistics, as for example apparent in the non-constant geostrophic wind during the GABLS test case (see figure 2b). The simulated wind field is influenced significantly by the choice of the geostrophic wind as the model's forcing.

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