Overview of the GEWEX Atmospheric Boundary Layer Study (GABLS)

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Abstract

In 2001 the steering group of GEWEX (formally known as the Global Energy and Water Cycle Experiment) initiated the GEWEX Atmospheric Boundary Layer Study (GABLS). The objective of GABLS is to improve the representation of the atmospheric boundary layer in regional and large-scale atmospheric models. As such, GABLS provides a platform for model inter-comparison and development to benefit studies of Climate, Weather, Air Quality, Wind Energy and other applications. The focus of GABLS has so far been on stable boundary layers (SBLs) over land and on the representation of the diurnal cycle under clear skies. Three inter-comparison studies have been organised and below a summary of some of the results and achievements is given. Here we primarily focus on the performance of single column versions of several state-of-the-art atmospheric models.

1. Introduction

The atmospheric boundary layer is an important part of any atmospheric model in use for operational weather and climate studies on all scales. As such an overall representation is needed for boundary layer turbulence and near surface processes, as well as for vertical diffusion above the boundary layer. This representation is typically referred as the parameterization of vertical diffusion and turbulent mixing. It appears that models at various research groups and operational centres use rather different methods to represent turbulence and vertical diffusion and the reasons behind this diversity are not that easy to unravel. Most likely, this is due to historical reasons due to the outcome of various tuning exercises and how models have been evaluated with observations in the past. In addition, modellers often have different opinions on the complexity needed to represent atmospheric turbulence and vertical diffusion processes.

Besides of turbulence, boundary layers are characterized by other small-scale processes such as clear air radiation, drainage flow, gravity waves and shear instabilities, fog and dew formation and the occurrence of low-level jets. In addition, the phenomenology of atmospheric boundary layers is quite diverse, e.g. shallow and deep boundary layers with continuous turbulence through most of their depth during daytime over land, and boundary layers with intermittent turbulence or even laminar flow in the very stable cases at night. The small-scale processes influence the vertical and horizontal exchange of heat, momentum and scalars between the surface and the atmosphere as well as the mixing in the atmosphere on a variety of scales. It also appears that the magnitude of the diurnal temperature cycle is typically underestimated over land. These results are to a large extent influenced by the boundary layer scheme in stable conditions, although other atmospheric processes (like clouds and radiation) and land surface processes also play a role (Viterbo et al., 1999).

The overall representation of the small-scale atmospheric processes and the related 'spatial averaging' is highly non-trivial due to the fact that there are many nonlinear processes, and also because the land surface often displays a heterogeneous character on a variety of scales. This normally is a motivation to allow for some enhanced mixing in models as compared with tower observations (e.g., Beljaars and Holtslag, 1991). Another justification for having enhanced mixing is to prevent the models to go into a decoupled mode separating the atmosphere from the cool surface, as decoupling may lead to a run-away cooling close to the ground (e.g., Louis, 1979; Steeneveld et al., 2006). This is an example of the more general phenomena that turbulent mixing in stratified flows has an inherent nonlinear character and may, as such, trigger positive feedbacks (e.g., Mahrt and Vickers, 2006). These positive feedbacks, in turn, may cause unexpected transitions between totally different regimes in the stable boundary layer (e.g., Derbyshire, 1999; Delage, 1997; Van de Wiel et al, 2002; Bintanja et al, 2011).

To understand the basis for the various parameterisations and to make a critical evaluation of the various schemes, model inter-comparison studies are organised within GABLS. As such, single column (SCM) versions of these models are compared with observations and fine-scale (large-eddy) model simulations (LES). The cases are so far based on observations taken in the Arctic, Kansas (USA) and Cabauw (the Netherlands). The first two benchmark cases GABLS1 and GABLS2 were forced with prescribed surface temperatures and simplified geostrophic winds, while the third inter-comparison case for SCM's (GABLS3) had a more complete description of atmospheric and surface forcings and also allowed for land surface feedbacks and radiation impacts (following Holtslag et al, 2007).

Next, we will describe the set-up of the three GABLS benchmark cases in some detail and provide an overview of the main results and achievements.

2. The first GABLS model inter-comparison study (GABLS1)

Given the state-of-the-art, it was decided to first focus on the representation of the stable atmospheric boundary layer in models of various complexity (Holtslag et al, 2003). Stable conditions prevail in the atmospheric boundary layer over the continental land and polar regions during night, and may be sustained during several days in wintertime and in polar regions. It appears that much of the warming predicted by climate models occurs during such stable atmospheric conditions (see for example Figure 9.10, pages 546-548 in Cubasch and Meehl, 2001). Consequently, the representation of the stable atmospheric boundary layer is very relevant for proper modelling of regional and global climates.

Overall, the parameterisation of the SBL is still rather poor, and progress has been slow (e.g. Beljaars and Holtslag, 1991; Holtslag and Boville, 1993; Beljaars and Viterbo, 1998). Unfortunately, regional and global climate models show great sensitivity to the model formulation of mixing in stratified conditions. As an example, Viterbo et al. (1999) studied the vertical mixing in the ECMWF model in stable conditions. From two model runs with the same forcing conditions, but with (slightly) different stability functions in the mixing scheme, they noticed that differences in the mean winter temperatures at a height of 2 meters between the two model runs can be as large as 10K over the continental areas (see also contribution by Anton Beljaars in this volume). King et al. (2001) found similar results between model runs for winter climate over Antarctica. Also over Europe, it was found that significant differences are present between the 2-meter temperatures of a 30-year regional climate simulation with observations for present day winter climate (e.g., Lenderink et al, 2003).

For GABLS1, an idealised case with unsophisticated forcing was set up as a benchmark to review the state of the art and to compare the skills of SCM's (Cuxart et al, 2006) and LES models (Beare et al, 2006). The case studied is based on the results originally presented by Kosovic and Curry (2000). As such, the stable boundary layer is driven by an imposed, uniform geostrophic wind, with a specified surface-cooling rate over (homogeneous) ice. Overall, it turns out that with the same initial conditions and model forcings, the results of the LES models are surprisingly consistent (Beare et al, 2006). As such, the LES outputs can serve as suitable reference for the 1D models. Moreover, the results of the LES models are consistent with field observations and local scaling ideas (Nieuwstadt, 1984), at least for the case studied here.

The results by the 19 participating single-column (SCM) models indicate a large range of results for the mean temperature and wind profiles as well as the heat and momentum flux profiles (Figure 1). The models in use at operational weather forecast and climate centres typically allow for enhanced mixing, while the typical research models show less mixing in more in agreement with the LES results for this case. Because of the enhanced mixing in weather and climate models, these models tend to show too strong surface drag and too deep boundary layers. This results in the erosion of low level jets and the underestimation of the turning of wind with height in the lower atmosphere (Svensson and Holtslag, 2009).

Figure 2a shows the Ekman spirals produced by the various models. Here a selection of those participating models in GABLS1 has been made which showed a consistent behaviour of the momentum flux in the surface layer (for a discussion, see Svensson and Holtslag, 2009). The model results line up with the operational models having the least turning of the wind in the boundary layer, followed by the LES results placed in the middle of the research model results. The lowest 10% (or the surface-layer) part of the solution is indicated in Figure 2 with dotted lines. It is clear that the surface layer is resolved with a variable number of grid levels (dots in the figure). Note also that some turning of the wind occurs within the surface layer in most of the models. The shape of the spirals in Figure 2a depends on how the turbulent stress is parameterized, which varies significantly among the participating models (Cuxart et al, 2006).

As can be seen in Figure 2a, the magnitude of the surface angle (the angle between the near-surface and geostrophic winds) varies substantially among the models (see also Table IV in Cuxart et al, 2006). The averaged LES result has a surface angle of 36 degrees while the operational models vary between 23 and 36 degrees. The surface angle averaged over all research models is 36 degrees, which agrees well with the averaged LES result but the variation is substantial (27 – 46 degrees). It is interesting to note that Van Ulden and Holtslag (1985) found by analysing the Cabauw data an average turning angle of about 35 degrees across the moderately stable boundary layer. This appears to be consistent with the LES (and averaged research) model results of GABLS1.

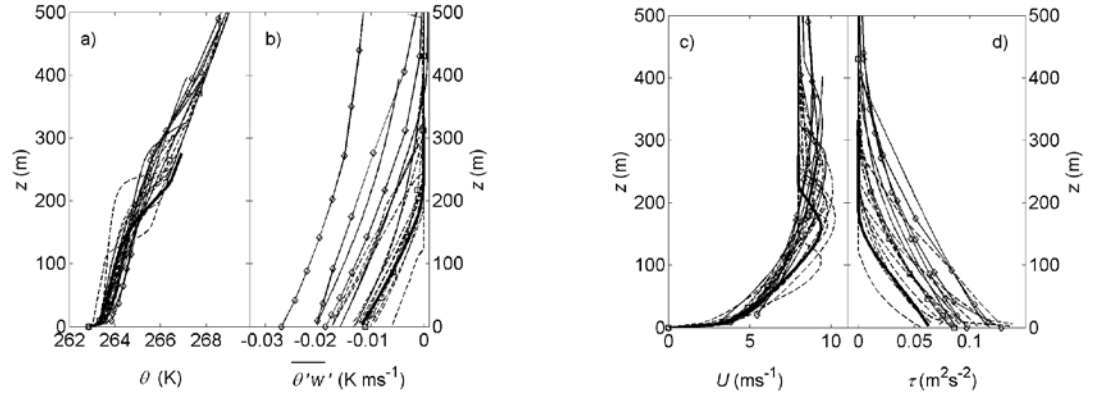

Figure 1. Results of Single-Column models (SCM) in GABLS1 for a) potential temperature, b) turbulent heat flux, c) total horizontal wind speed and d) turbulent momentum flux for operational models (solid lines), research models (dashed lines) and averaged results for LES (thick solid line). Model results are adapted from Beare et al. (2006), Cuxart et al. (2006) and Svensson and Holtslag (2009).

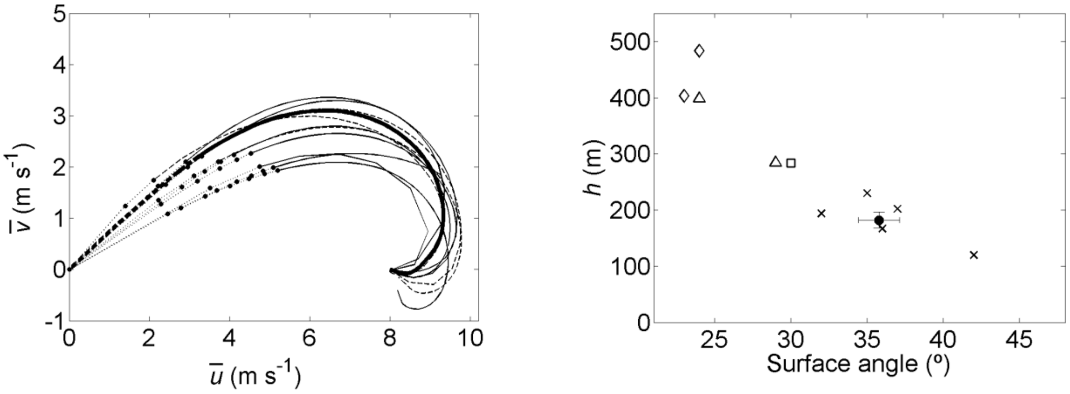

Figure 2. Model results for boundary layer wind turning (adapted from Svensson and Holtslag, 2009):

- *a) Hodographs for selected operational models (solid lines), research models (dashed lines) and averaged results for LES (thick solid line) for GABLS1 (left hand side). The surface-layer part (lowermost 10%) of the boundary layer are shown as dotted lines and here the larger black dots indicate the various model levels, and*
- *b) The angle between the surface wind and the geostrophic wind plotted against the boundary-layer height (m) for a selection of SCMs in GABLS1 (right hand side). The various symbols indicate results by operational models with first-order closure (diamonds), operational models with higher-order closure (triangles), a research model with first-order closure (square),higher -order research models (crosses), and the averaged LES result with standard deviations (filled circle with error bars).*

It turns out that the surface angle is directly related to the depth of the turbulent boundary layer h, and in Figure 2b the calculated boundary-layer height for each model is plotted as a function of the corresponding surface angle. It is seen that deeper (shallower) boundary layers have smaller (larger) surface angles. Svensson and Holtslag (2009) show that the operational models with enhanced mixing and a deeper boundary layer also have a larger integrated cross-isobaric flux, where the difference between the lowest and the highest value is almost a factor of three. And a deeper layer also means less turning of the wind in the boundary layer. However, by decreasing the mixing and surface drag, a direct impact on the atmospheric dynamics (‘Ekman pumping’) is noted (e.g., Beljaars and Viterbo, 1998). Consequently, cyclones may become too active, corresponding to high extremes for wind speed and precipitation (Beare, 2007).

The analysis by Svensson and Holtslag (2009) further indicated that the surface angle is determined by rather subtle details in the turbulence closure formulation near the surface, which in turn influences the height of the stable boundary layer. Thus, it is important not only to examine the total momentum flux, but also its components. In addition, the height to the first model level and the vertical resolution near the surface play a crucial role since the curvature in the momentum profile cannot be resolved properly on a coarse grid.

3. The second GABLS model inter-comparison study (GABLS2)

The GABLS2 benchmark case is based on observation taken in Kansas, USA in the early autumn during the Cooperative Atmosphere-Surface Exchange Study – 1999 (CASES-99; Poulos et al., 2002). Two consecutive clear days from these data with a strong diurnal cycle over relatively dry land were selected for the inter-comparison study following Steeneveld et al. (2006). The latter authors performed a case study with these data and found overall very good agreement with their model set-up that allowed for surface feedback and radiation processes in addition to turbulent mixing.

For the GABLS2 benchmark case the forcing conditions have been simplified to facilitate a more straight-forward comparison between the model closures. As such a prescribed surface temperature and simplified geostrophic wind forcing were used (Svensson et al, 2011). Nineteen models participated in the SCM inter-comparison study, ranging from operational models with first-order closure and a vertical resolution having six grid points within the first 400 m (minimum vertical grid), to higher-order closure models with the same resolution as the LES experiment (6.25 m, the suggested resolution for the single-column models). The model results are displayed in the figures below according to their turbulent closure and height of their first model level below or above 5 m above the surface. The latter was inspired by the outcome of GABLS1 (see above). Also the LES results by Kumar et al (2010) are presented as an additional reference.

It was found that the models produce very different results in all parameters and that they all differ substantially from the observations of CASES99. Striking results are the strong underestimation of the diurnal cycles of 2 m temperature (Figure 3) and of the 10-m wind speed (Figure 4). Given the large variation of model results, one may wonder to what extent the setup of the case has influenced the results. As such the impact of the forcing and boundary conditions on the variability of model results is discussed by Holtslag et al. (2007). It appears that the variety of model results is typically less when the boundary layer schemes are coupled to the land surface. Thus, prescribing the surface temperature

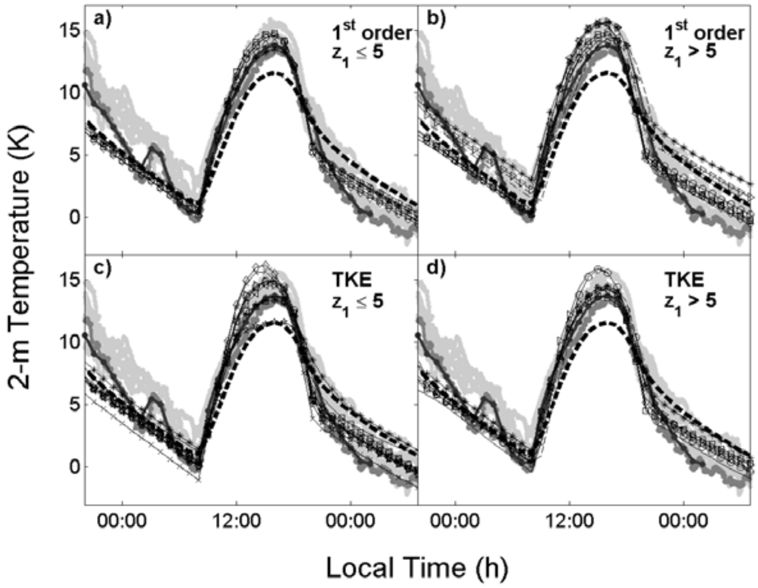

Figure 3. Time series for GABLS2 of observed (grey background values) and modelled (various lines) temperatures (ºC) at 2 m a.g.l. The thick black dashed line reflects the LES result by Kumar et al (2010). The single column model results are presented in four categories based on model closure a) and b) first-order closures; c) and d) TKE-based schemes. Also a distinction is made depending on height of the first model layer below (a and c) or above (b and d) 5 m a.g.l. Figures adapted from Svensson et al (2011).

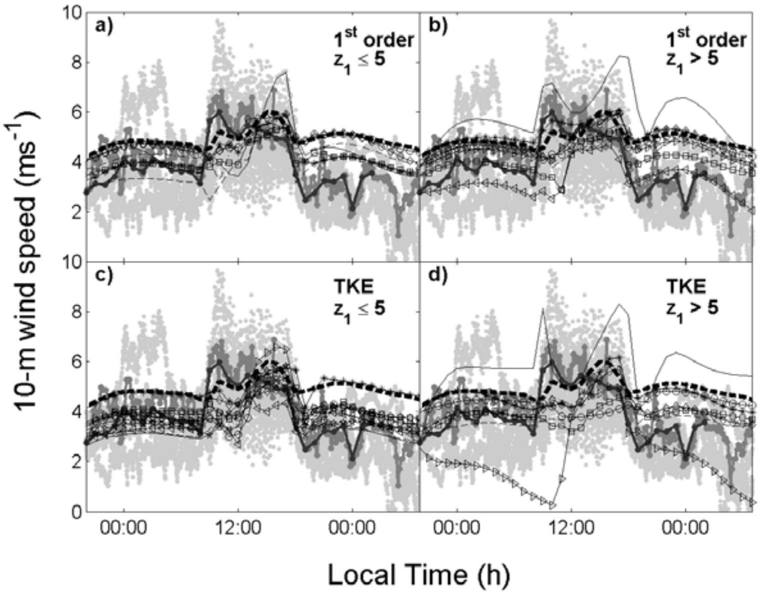

Figure 4. As Figure 3 for observed and modelled wind speeds (m s-1) at 10 m a. g. l. l. Here the light grey dashed line shows the average for the entire CASES-99 campaign. Figures adapted from Svensson et al (2011).

as in GABLS2 seems to be a more critical test for the boundary layer schemes than with evaluations allowing for surface interaction.

The use of the lower boundary condition in the stable boundary layer, has actually for a long time been debated (e.g., Basu et al, 2008) and is further examined for GABLS2 in a LES study were simulations using either prescribed surface temperature or heat flux is used (Kumar et al., 2010). The influence of the constant versus variable geostrophic forcing was also examined. This data provides also useful information as an independent check of the column model outputs. The results from GABLS2 have also inspired researchers to run the case for advancing their own model, and for mesoscale model inter-comparisons (Steeneveld et al., 2008).

It is clear that with GABLS2 we have moved towards more realistic and more difficult cases of atmospheric boundary layers, such as inertial oscillations and Low Level Jets (LLJs). LLJs are of large importance for the dynamics of the stable boundary layer and the transport of atmospheric constituents. Here it is also find that it rather difficult to properly represent the details of decoupling around sunset and the mixing during the morning time transition. A further discussion on the SCM results for GABLS2 is given in Svensson et al (2011).

4. The third GABLS model inter-comparison study (GABLS3)

The previous GABLS benchmark studies and experiences led to the set-up of the third inter-comparison case using data gathered by the Royal Netherlands Meteorological Institute (KNMI) at the Cabauw tower (Baas et al, 2010; Bosveld et al., 2012a). The Cabauw site with its 200 m meteorological tower is situated in a flat environment dominated by grassland and on many nights a low level jet develops due to decoupling and inertial oscillation. In the previous studies it was found that especially the complexity of real world large scale forcing and the lack of interaction with the surface make it difficult to confront the models with observations. Moreover, the transitions at sunset and sunrise are difficult to simulate correctly. Holtslag et al. (2007) showed that the spread in outcome of various SBL parameterizations tends to decrease when they are allowed to interact with the surface instead of using prescribed surface temperature as a lower boundary condition. This suggests that feedbacks with the land surface are very important and need to be taken into account for a proper evaluation with observations.

Thus, the third GABLS case addresses the issues of the large scale forcings, the interaction with the surface, transitions and the direct evaluation of models with observations. The case was derived from the long term dataset of Cabauw. The specific characteristics of the Cabauw site with its flat topography and reasonable homogeneity, make it well-suited to study decoupling around sunset, low-level jet formation and the morning transition. The case covers the 24-h period starting at 12 UTC 1 July 2006. This is an (almost) clear sky period with reasonably constant geostrophic wind over time of typically 7 m s^{-1} resulting in a turbulent stable boundary layer over night with a pronounced temperature drop and a well-developed low level jet at around 200 m height, caused by an inertial oscillation. To make a valid comparison with observations possible, care was taken to prescribe realistic geostrophic forcing and dynamic tendencies to the SCMs. These were estimated from both local observations and hind-casts of several 3D NWP models. The description of the 3rd GABLS SCM case, details of the selection criteria and the composition of the large-scale forcings are documented in Bosveld et al. (2012a).

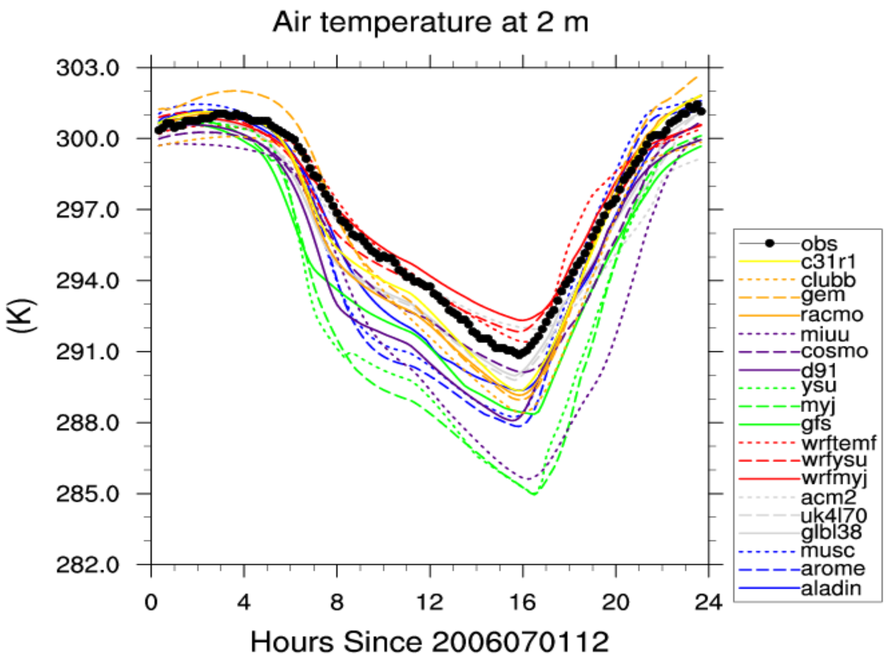

Figure 5. Time series for GABLS3 of observed (black line with dots) and modelled temperatures (various other lines) at 2 meter for the 24 h period starting at noon of July1, 2006 at Cabauw, NL. Figure is adapted from Bosveld et al (2012b).

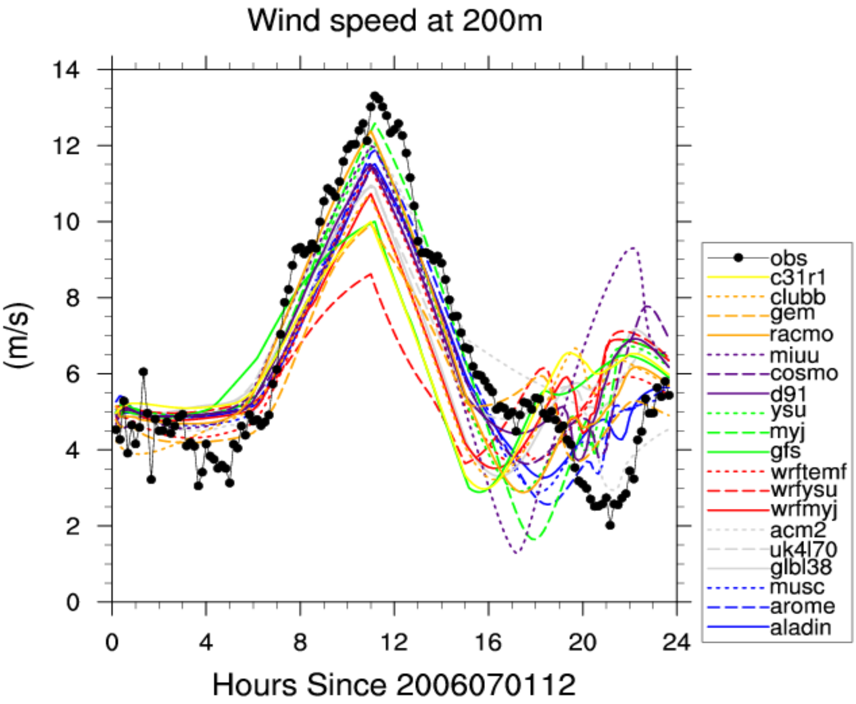

Figure 6. Time series for GABLS3 of observed (black line with dots) and modelled wind speeds at 200 m (various other lines) for the 24 h period starting at noon of July1, 2006 at Cabauw, NL. Figure is adapted from Bosveld et al (2012b).

Nineteen models from eleven institutes participated in the inter-comparison. Twelve of the models participated also in GABLS2. The models varied with respect to application, resolution and parameterization of the fundamental processes. Some of the models were run with varying turbulence schemes, while other aspects of the models stayed the same. The SCMs were run with full physical interaction, e.g. interaction with their own soil vegetation and radiation schemes.

Figure 5 shows time series of the 2 m temperature from the models together with the observations. The general signature of the temperature change is well captured by the models, i.e. an initial fast decrease, followed by a more gradual decrease in the subsequent hours and then from one hour before midnight a bit faster cooling. Seven out of the nineteen models are within 1 K of the observations. The remaining models are up to 5 K colder than observed which seems mostly be related to the coupling of the atmosphere to the surface (see also contribution of Bosveld et al. in this volume).

Winds at the 200 m level are shown in Figure 6. For each model the first level above 200 m was chosen. The 200 m level is interesting because in the observations it is well decoupled from the surface and exhibits a clear inertial oscillation. After decoupling the observed wind accelerates much stronger then the modelled winds. The inertial oscillation is affected by horizontal momentum advection especially after midnight. This is clearly seen for most of the models, which show a sharp decrease in wind speed after midnight, much sharper than would be expected when no advection was present. All models peak at 11 hours after the start of the simulation but all at a lower value than observed. More than half of the models peak within 2 m s^{-1} from the observed values. Around and after sunrise models start to differ from each other and from the observations. At the 80 m level (not shown), which is well within the turbulent layer, a number of models peak at higher wind speed than observed.

In the contributions by Bosveld et al. (2012b) and Basu et al. (2012) and their contributions in these proceedings the overall findings for the Single column and LES models for GABLS3 are presented and discussed in more detail.

5. Summary and prospects

In this contribution an overview is given of the GABLS benchmark studies for stable boundary layers (SBL) and on the representation of the diurnal cycle at clear skies over land. Three inter-comparison studies have been organised with increasing boundary layer stability (see Figure 7). Above a summary of some of the results and achievements is given where we focused on the performance of single column versions of state of the art atmospheric models.

From the GABLS benchmarks it became clear that operational models show too much mixing resulting in too deep boundary layers (GABLS1), too large downward sensible heat fluxes and too weak low level jets (GABLS2 and GABLS3). This also impacts on the diurnal cycle. By carefully selecting a case and prescribing the atmospheric forcings and allowing for land surface interaction, it is possible to guide the models in such a way that a useful comparison with observations is possible (GABLS3).

Inspired by the GABLS benchmark results, modelling groups at ECMWF, the UK Met. Office, Meteo-France, the HIRLAM project and elsewhere have been encouraged to study and improve their representation of the stable boundary layer. It is clear that this issue is still not fully solved and needs further attention. It also appears that changes in the mixing formulation may have strong impacts on the representation of fog and clouds, as well as vertical diffusion in the atmosphere above the boundary layer. Also the GABLS benchmarks are increasingly being used for model development (Buzzi et al, 2011) and for applications like particle dispersion (e.g., Weil, 2010).

Given the GABLS findings, there is still a clear need for a better understanding and a more general description of the atmospheric boundary layer under stably stratified conditions in atmospheric models for weather and climate. This may also benefit wind energy, air quality and earth system studies. However, confronting boundary-layer models with observations remains a difficult task.

In the future we foresee to study boundary layers that have a stronger stratification as recommended by participants of the ECMWF-GABLS workshop. Boundary layers over heterogeneous landscapes (such as in Lindenberg, Germany and Sodankylä, Finland) provide additional complexities and challenges. Also, attention could be paid to further integrate the GABLS activities with modellers at weather forecast and climate centers, for instance by facilitating regional model inter-comparisons such as in ARCMIP (Tjernström et al., 2005) and to acquire and compare short-term forecasts from full GCM models for the study point on interest.

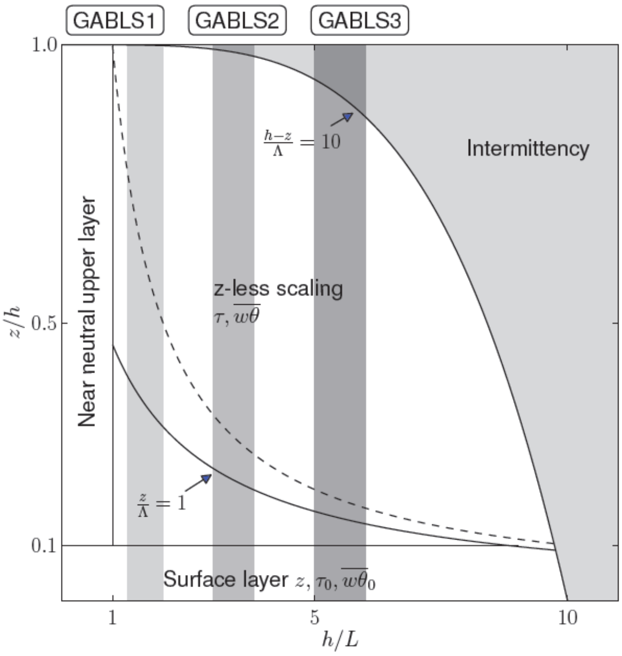

Figure 7 Typical night-time stability conditions in the three GABLS benchmark studies as indicated by grey vertical columns in the stability diagram for the stable boundary layer by Holtslag and Nieuwstadt (1986) and as modified for GABLS by Moene et al (2011).

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