STABLE ATMOSPHERIC BOUNDARY LAYERS AND DIURNAL CYCLES

Challenges for Weather and Climate Models

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The atmospheric boundary layer impacts strongly the model performance for temperature and wind, yet stable situations, such as in clear, calm conditions at night or over ice, remain problematic.

The atmospheric boundary layer (ABL) is the lower part of the atmosphere that is in continuous interaction with Earth's surface owing to friction and heating or cooling. The ABL is generally turbulent and has a pronounced diurnal cycle of temperature, wind, and related variables—in particular over land and ice. Turbulence in the ABL is three-dimensional and chaotic with time scales typically between fractions of a second and an hour. The corresponding length scales are from a millimeter up to the depth of the boundary layer (or more in the case of convective clouds). The depth of the dry ABL varies both in time and space between tens of meters up to kilometers. Over land it has a strong diurnal variation, while over the sea the depth of the ABL is typically a few hundred meters and rather constant on the time scale of a day.

While turbulence is generally strongest in the ABL, most of the troposphere contains turbulent motions. Strong turbulence is also found at high altitudes in, for example, towering cumulus clouds, which may grow into thunderstorms. In this case, the convection produced by the heat released owing to the condensation of water vapor in the cloud reinforces the turbulence. Strong turbulence may also occur in clear air above the ABL; most of this is produced in layers of strong vertical wind shear known as clear-air turbulence.

Turbulent flows in the atmosphere efficiently transport momentum, heat, and matter. The ABL and its turbulence are also important for the momentum and sensible and latent heat transfers between the surface and the atmosphere. These directly affect the diurnal cycle of the near-surface variables and also strongly impact on the life time of synoptic-scale systems. Appropriate representation of the overall effects by turbulence, either inside or outside the atmospheric boundary layer, is thus an essential part of atmospheric models dealing with the prediction and study of weather, climate, air quality, wind energy, and other environmental factors. Because of the small-scale features of atmospheric turbulence, there will always be important effects on the mean flow from scales smaller than the numerical grid cells of the models used.

To bridge the gap in scales, the equations of motions are averaged over the scales of turbulence, known as ensemble or Reynolds averaging (Reynolds 1895). In this process higher-order terms arise out of the averaged advection terms and this makes the system of equations unclosed. The challenge is to relate the new unknown terms to the forecast variables of the model. This so-called turbulence closure is basically unsolvable on a fundamental level and several approaches have been taken in the past (e.g., Wyngaard 2010).

In its basic form a turbulence closure is based on flux-gradient theory utilizing a proper formulation of an eddy diffusivity. Such a "local" closure is found useful for stably stratified turbulence. For unstable and convective boundary layers, nonlocal mixing effects are also typically required to properly represent the mixing processes (e.g., Holtslag and Moeng 1991). Turbulence closures can be of different order depending on the order of the terms that are parameterized, but in practice few are higher than second order in operational models. A popular version is to combine a prognostic equation for the turbulent kinetic energy (TKE) with a diagnostic equation for the turbulent length scale to derive an eddy diffusivity (e.g., Mellor and Yamada 1974).

While the basic principles underlying the parameterizations are the same, the actual model implementations vary substantially among models developed and used by research groups and by operational centers. This results in large variations for the diurnal cycles of near-surface temperature and wind. The reasons behind this diversity in model formulations and strategies are not that easy to unravel. Most likely, this is for historical reasons owing to the outcome of various tuning exercises and how models have been evaluated with observations in the past (see also discussion by Jakob 2010). In addition, modelers have different standpoints on the complexity needed to represent atmospheric turbulence and vertical diffusion processes (e.g., Delage 1997; Teixeira et al. 2008; Zilitinkevich et al. 2008; Baklanov et al. 2011). An overview of most turbulent mixing and diffusion parameterizations in current use is given by Cuxart et al. (2006).

Figure 1 gives an example of the performance of the leading European Centre for Medium-Range Weather Forecasts (ECMWF) numerical weather prediction model for the 2-m temperature. Here the temperature forecast errors at day and night over Europe are shown as monthly averages during more than 20 years. The results display a rich history with many model changes, including those for the land surface, soil freezing, and vertical mixing. Improvements have been made during the years as indicated by the long-term reduction in biases and standard deviation of the errors. However, at night these measures have increased in recent years. This is due to a change in the vertical diffusion scheme for stratified conditions that was found necessary in the ECMWF model to reduce the dissipation of stratocumulus through erosion of the strong capping inversions (Köhler et al. 2011). This illustrates the difficulty encountered when atmospheric models are improved in one aspect but with unintended implications elsewhere.

Climate models also struggle to represent the correct near-surface parameters and diurnal cycles (e.g., Zhang et al. 2009; Kyselý and Plavcová 2012; Mearns et al. 2012). As an example, Fig. 2 shows errors in 2-m temperature for two versions of the National Center for Atmospheric Research (NCAR) community climate model over land north of 50°N during wintertime. The two model versions share the same dynamical core and resolution as well as land models but have a quite different suite of atmospheric parameterizations. As can be seen in Fig. 2, the 2-m temperature errors are typically positive for the Community Atmosphere Model version 4 (CAM4) and negative for CAM5. They also show large spatial variability over large areas in both models. Furthermore, wind speeds at the lowest model level are rather different in the two versions (not shown). Obviously, not all differences can be attributed to the representation of the boundary layer since cloudiness and land surface factors also play an important role (e.g., Van den Hurk et al. 2011). However, our current understanding

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The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-11-00187.1

In final form 29 March 2013

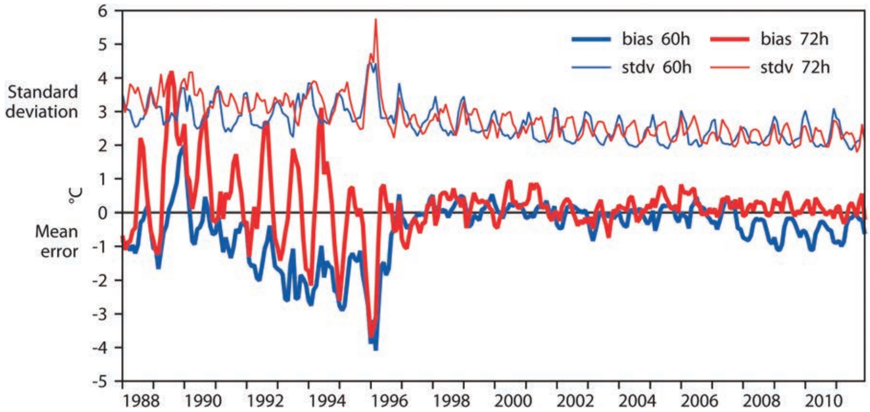

FIG. 1. Long-term history of 2-m temperature errors (°C) of daily 60-h (blue, verifying at 0000 UTC) and 72-h forecasts (red, verifying at 1200 UTC) in the ECMWF model over Europe. Mean errors are given with thick solid lines and standard deviations with thin lines on basis of monthly averages of model errors with respect to about 700 SYNOP stations over Europe.

and capability to model stably stratified conditions is limited and most certainly influences the results (Mahrt 1987; McCabe and Brown 2007). Note also that the descriptions of the ABL are rather different in CAM4 (Holtslag and Boville 1993) and in CAM5 (Bretherton and Park 2009).

The diurnal cycles of near-surface variables in CAM4 and CAM5 have been evaluated using many years of data from flux-tower observations by Lindvall et al. (2013). Figure 3 shows an example from a similar and extended analysis with a large number of the climate models participating in the Coupled Model Intercomparison Project, phase 5 (CMIP5; Taylor et al. 2012). The figure represents models with different complexity, boundary layer parameterizations, and numerical grids and includes the two NCAR models. The diurnal cycles for near-surface wind and temperature in Fig. 3 are shown here in comparison with tower data from the Atmospheric Radiation Measurement Program (ARM) Southern Great Plains main site (Fischer et al. 2007). Notice that the diurnal cycle is given with respect to the mean value. It is seen that wind and temperature vary considerably in the individual models even in this relatively flat and homogenous region. The ensemble model median temperatures in Fig. 3 compare well with the observed diurnal cycles, but with large intermodel variations. Many factors influence these variables, such as soil moisture and clouds in addition to vertical mixing in the ABL. The diurnal cycle in the wind is generally underestimated (see Figs. 3b and 3d) and some models are out of phase, especially during summer.

To understand the basis for the various boundary layer parameterizations and to make a critical evaluation of the various schemes in use, model intercomparison studies have been organized within the Global Energy and Water Exchanges (GEWEX) Atmospheric Boundary Layer Study (GABLS; Holtslag 2003, 2006). Specific cases are chosen for which single-column versions of models (SCMs) are run with the same specifications, and the results are compared with observations and/or finescale (large eddy) simulations (LES). Such a strategy has also been found to be very useful for cloudy boundary layers (e.g., Randall et al. 2003; Neggers et al. 2012). Following the former authors, we note that an "SCM is essentially the column physics of an atmospheric model, considered in isolation from the remainder of the atmospheric model" (p. 456). As such, an SCM can be used to make a direct comparison with observations or LES given prescribed values for advection, specific surface conditions, and other

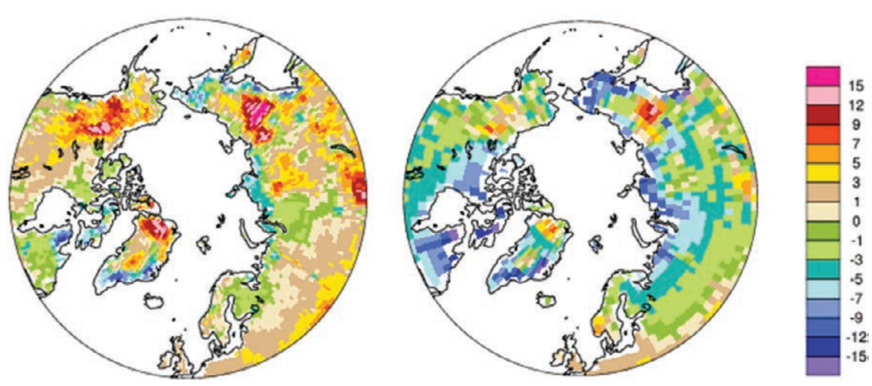

FIG. 2. Wintertime [December–February (DJF)] differences for the 2-m temperature (°C) climatologies of AMIP simulations and observations over land and ice for the Northern Hemisphere (Willmott and Matsuura 2001). The AMIP simulations are for atmosphere only using observed sea surface temperature and sea ice concentration by (left) CAM4 and (right) CAM5. Color range in legend indicates temperature differences between –15° and 15°C.

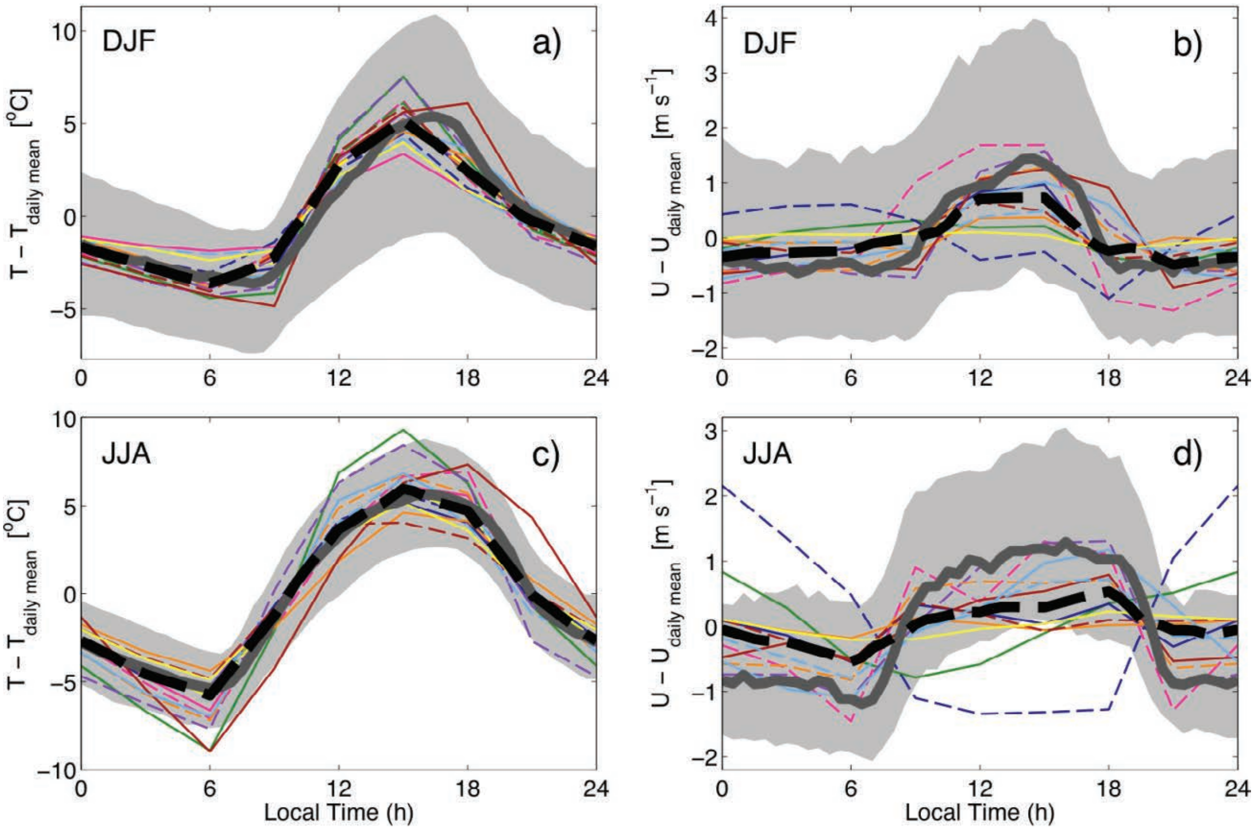

Fig. 3. Observed and modeled diurnal cycles of 2-m temperature (°C) and wind speed (m s^{-1}) with respect to their daily means for the ARM SGP main site (36.6°N, 97.5°W) in (a),(b) winter and (c),(d) summer. The model results are from AMIP simulations (atmosphere-only simulations with observed sea surface temperature and sea ice concentration for the period 1999–2008) by CMIP5 models (colors, 16 models for temperature and 12 for wind speed) including the model median (dashed thick line). Median (solid thick line) and 25th and 75th percentiles (gray area) of observed diurnal cycle minus daily mean for the period 2002–09 are also shown.

factors. The cases studied so far within GABLS are based on observations taken in the Arctic, in Kansas, and at Cabauw (the Netherlands) during clear skies.

Below, we further introduce the subject following the overview by Holtslag et al. (2012), and summarize the GABLS findings in the sections "Stable atmospheric boundary layers" and "Diurnal cycles." Final points are provided in "Summary and prospects."

STABLE ATMOSPHERIC BOUNDARY LAYERS. Stably stratified conditions occur frequently in the ABL over polar regions and over continental land during night and wintertime. Correct representation of the stable boundary layer (SBL) is difficult owing to the weak and sometimes intermittent behavior of turbulence (e.g., Mauritsen and Svensson 2007) and interaction with other small-scale processes (see below). Overall progress in understanding and model formulations has been slow (e.g., Louis 1979; Beljaars and Holtslag 1991; Fernando and Weil 2010; Baklanov et al. 2011). It has also been known for quite some time that numerical weather prediction and climate models show great sensitivity to the model mixing formulations in these conditions.

Viterbo et al. (1999) performed a sensitivity study with the ECMWF model using (slightly) different formulations for describing the impact of increased stability on the damped turbulence for stable conditions (these formulations are known as the stability functions). Even with the same forcing conditions, they noticed large differences in the mean January 2-m temperatures over the Northern Hemispheric continental areas. The sensitivity study was recently repeated with the 2011 version of the ECMWF model. Results for both model experiments are shown in Fig. 4. The sensitivity experiments were for the 1995/96 winter season starting from 1 October 1995 and applying relaxation to the 6-hourly operational analyses above 500 m from the surface. This is an efficient way of doing "deterministic" seasonal integrations without constraining the boundary layer. It appears that the same change in the stability functions has a much larger impact in the 2011 model version than in the 1994 version. In the meantime, many model changes have been made but most likely the different sensitivity is related to the updated soil hydrology scheme (Balsamo et al. 2009) and the new snow scheme (Dutra et al. 2010). In the latter, snow is a much better insulator and therefore the winter temperatures are lower. This illustrates the tight coupling between boundary layer processes and land surface and snow feedbacks, which obviously needs further attention and research (see also Sterk et al 2013).

Besides a tight interaction of atmospheric turbulence with the land surface, stable boundary layers are influenced by other small-scale processes and phenomena such as radiation (divergence), fog and dew formation, drainage flow, gravity waves, and low-level jets. In addition, the morphology of stable boundary layers is quite diverse—for example, shallow and deep boundary layers with continuous turbulence through most of their depth and boundary layers with very weak and/or intermittent turbulence in very stable cases at night (e.g., Mahrt 1985; Van de Wiel et al. 2003, 2007). On the other hand, surface heterogeneities and topography are factors typically enhancing momentum transport over land (e.g., Cuxart and Jiménez 2007; Martinez et al. 2010; McCabe and Brown 2007).

The first GABLS intercomparison case was designed to document and better understand the differences between the various boundary layer schemes in numerical weather and climate models using an idealized case focusing on the representation of turbulence. The case is based on the results from the Arctic originally presented by Kosović and Curry (2000). The stable boundary layer in the SCMs was driven by an imposed, uniform geostrophic wind of 8 m s^{-1}, with a specified surface-cooling rate of 0.25 K h^{-1} and an overlying capping inversion. The same case was run by a range of SCMs and LES models and the main results are presented in Cuxart et al. (2006) and Beare et al. (2006), respectively. Overall, it turns out that with the same initial conditions and model forcings, the results of the LES models are surprisingly consistent when a vertical resolution of 6.25 m was utilized (Beare et al. 2006). Thus, the LES results can serve as a suitable reference for the turbulence representation in the single-column models (since other processes like radiation and land surface schemes are not active in this case).

The results by the participating single-column models (colored lines) indicate a large range in vertical structure for the mean temperature and wind magnitude profiles (Figs. 5a,b) in comparison with the LES results (black lines). In addition, the hodographs are shown in Fig. 5c. In the latter figure, a selection of 10 out of the 19 participating SCMs in GABLS1 was made that showed a consistent behavior between the surface and boundary layer, following the analysis by Svensson and Holtslag (2009). The models not selected for Fig. 5c are shown as dashed lines in Figs. 5a,b and these typically show a larger deviation from the LES reference.

In Figs. 6a,b the turbulent heat and momentum fluxes are given and these show a rather large range owing to the various parameterizations. Overall, the models in use at operational weather forecast and climate centers provide deeper boundary layers and allow for "enhanced mixing" (see also below), resulting in larger fluxes, while the research models show less mixing in more agreement with the LES. Note that the complexity of the turbulent scheme does not seem to matter here; even a relatively basic local diffusivity scheme can do well for this simple case (e.g., Steeneveld et al. 2006a). Because of the

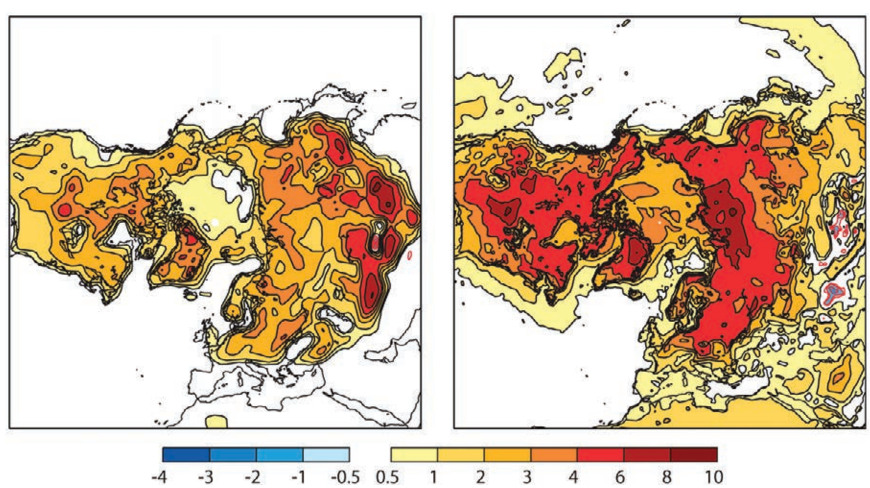

Fig. 4. Difference in 2-m temperature (°C) averaged over January 1996 between simulations with two different stability functions in the ECMWF model (Viterbo et al. 1999; Beljaars 2012). (left) Impact in the 1994 version of the ECMWF model and (right) impact of the same change in the 2011 model version. Color range in legend indicates temperature differences between –4° and 10°C.

enhanced mixing in weather and climate models, these models tend to show too strong surface drag and too deep boundary layers. This typically results in erosion of low-level jets and the underestimation of the turning of wind with height in the lower atmosphere (Svensson and Holtslag 2009). It is clear that this directly leads to errors in any application such as for air quality and wind energy. It also explains why ECMWF has relaxed the mixing in their model to avoid eroding stratocumulus capping inversions (see the above discussion with respect to Fig. 1).

Returning to Fig. 5c for the hodographs, we note a clear lineup such that operational models have the smallest turning of the wind in the boundary layer, followed by the LES results placed in the middle of the research model results. The grid points in the lowest 10% of the SBL (in the surface layer) are indicated with dots to show that even in the surface layer there is a turning of the wind in contrast to what is often assumed. The shape of the spirals depends on how the turbulent stress is parameterized, which varies significantly among the participating models (Cuxart et al. 2006). It can be shown that the angle between the surface wind and the geostrophic wind is directly related to the depth of the turbulent boundary layer such that deeper (shallower) boundary layers have smaller (larger) surface angles (Svensson and Holtslag 2009; Grisogono 2011). The operational models with enhanced mixing and a deeper boundary layer also have a larger integrated cross-isobaric flux, and this directly impacts the larger-scale flow through "Ekman pumping."

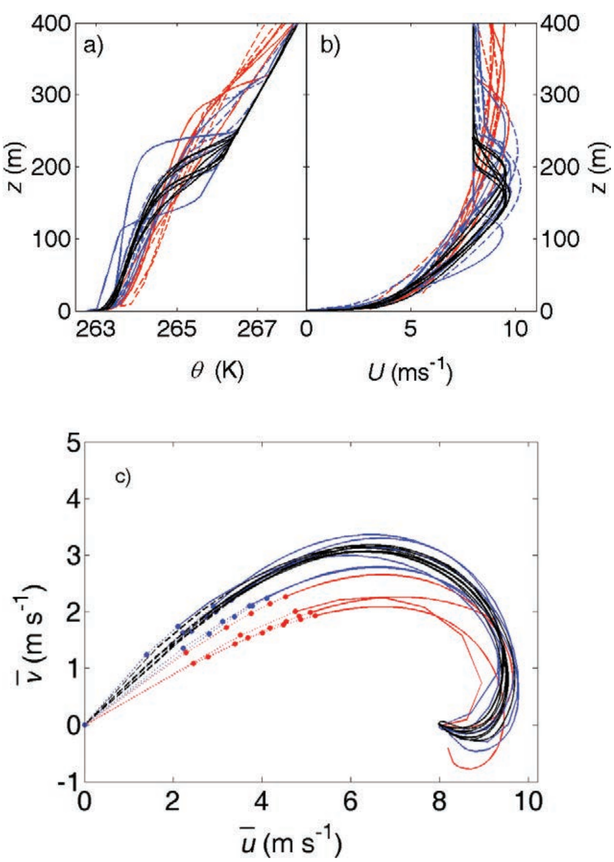

Fig. 5. Results of SCMs in GABLS1 for (a) potential temperature (K), (b) total horizontal wind speed (m s^{-1}), and (c) boundary layer wind turning. Distinction is made for operational models (red lines), research models (blue lines), and results for LES models (solid black lines as indicated for the LES domain). Figures are adapted from Beare et al. (2006), Cuxart et al. (2006), and Svensson and Holtslag (2009). See text for further details.

The boundary layer scheme in any atmospheric model is responsible for surface drag that feeds back to the large-scale flow through the momentum budget and through the ageostrophic flow. In general, boundary layer formulations with enhanced mixing tend to give better performance for the larger-scale flow and as such this has been a motivation to use these. Also, the momentum budget aspect is an important contributor to the sensitivity of large-scale scores of weather forecast models to the formulation of the boundary layer scheme. The mechanism behind this sensitivity is, however, not well understood. It is known that large drag damps weather systems and reduces the "activity" of a model, which tends to be good for operational scores possibly by compensating for other deficiencies. By decreasing the mixing and surface drag, a direct impact on the atmospheric dynamics has been noted (e.g., Beljaars and Viterbo 1998). Consequently, cyclones may become too active (e.g., Beare 2007), resulting in too high extremes for wind speed and precipitation (see also Sinclair et al. 2010).

In GABLS1, the ensemble of results by LES models was used as the reference for the single-column model

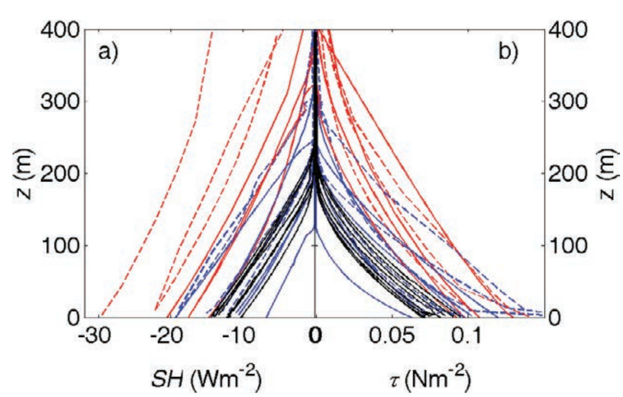

Fig. 6. As in Fig. 5 but for (a) turbulent heat flux (W m^{-2}) and (b) turbulent momentum flux (N m^{-2}).

results (as indicated in Figs. 5 and 6). The GABLS1 case was, however, highly idealized and not directly comparable to observations. Basu et al. (2012) set up an intercomparison of LES models with observations from the Cabauw tower in the Netherlands as a part of the diurnal cycle study within GABLS3 (see next section). The Cabauw site, with its 200-m meteorological tower, is situated in a relatively flat environment dominated by grassland. On many nights a low-level jet develops because of decoupling and inertial oscillation. The GABLS3–LES case involves a total simulation period of 9 hours (0000–0900 UTC 2 July 2006). This period essentially encompasses the development of a moderately/strongly stratified, baroclinic, midlatitude nighttime boundary layer as well as its transition into a daytime convective boundary layer. Here we show some results for the night time hours and we refer to Basu et al. (2012, 2013, unpublished manuscript) and Moene et al. (2011) for additional information.

The initial conditions for the LES runs at 0000 UTC were created by merging the observed 200-m Cabauw tower data, wind profiler data, and a high-resolution sounding from De Bilt. Time–height-dependent geostrophic wind forcing was derived from a network of surface pressure stations combined with the analysis of a mesoscale weather forecasting model. In a similar fashion, time–height-dependent advection terms were also obtained from the Regional Atmospheric Climate Model (RACMO) and Weather Research and Forecasting Model (WRF) forecasts and observed trends at the 200-m level during night time (Baas et al. 2010). For the LES study, observed (extrapolated) near-surface (0.25 m above ground level) potential

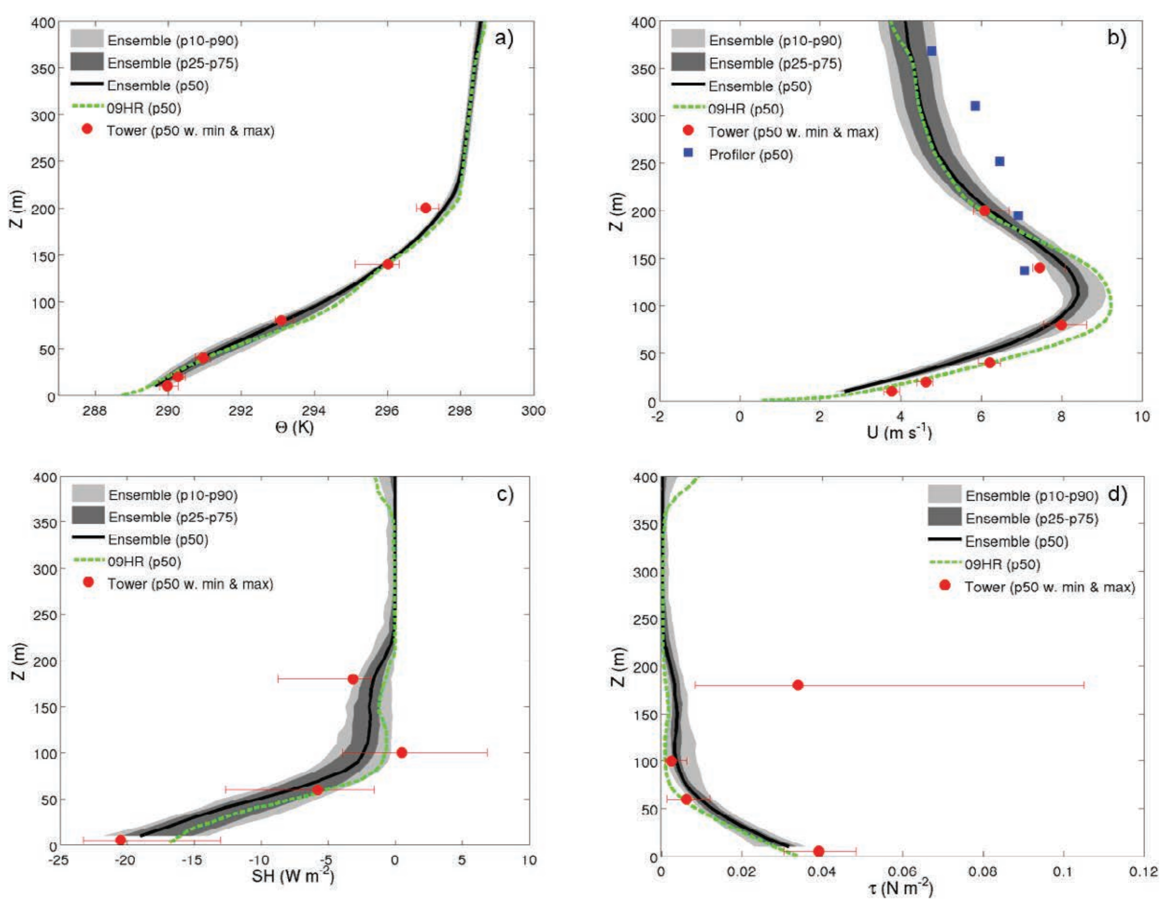

Fig. 7. LES model results (with a vertical resolution of 6.25 m) and observations for the GABLS3 case study corresponding to 0300–0400 UTC 2 Jul 2006. Results are for (a) potential temperature (K), (b) wind speed magnitude (m s^{-1}), (c) sensible heat flux (W m^{-2}), and (d) momentum flux (N m^{-2}). The red dots with whiskers represent median and min–max values of the observations from the Cabauw meteorological tower. Data from a wind profiler are depicted by blue squares. The solid black lines, dark gray shaded areas, and the light gray areas correspond to the medians, 25th–75th percentile ranges, and 10th–90th percentile ranges of the LES ensemble-generated output data, respectively. The simulated profiles from a very-high-resolution LES run (vertical resolution of 1 m) are denoted by the green dashed lines. Results adapted from Basu et al. (2012, 2013, unpublished manuscript).

temperature and specific humidity were prescribed as lower boundary conditions. Thus, the differences among the LES models do not depend on the lower boundary conditions but on differences in numerics and subgrid closures.

Eleven LES groups from different international institutes provided results for the GABLS3–LES case. Figures 7a–d show the results by the LES models for 0300–0400 UTC for wind magnitude, temperature, and their corresponding turbulent fluxes. Overall, the mean wind, temperature, and related turbulent flux profiles are captured very well in the simulations, indicating that LES is a useful reference for SCM intercomparison studies in weak to moderately stably stratified boundary layers, as was anticipated in GABLS1.

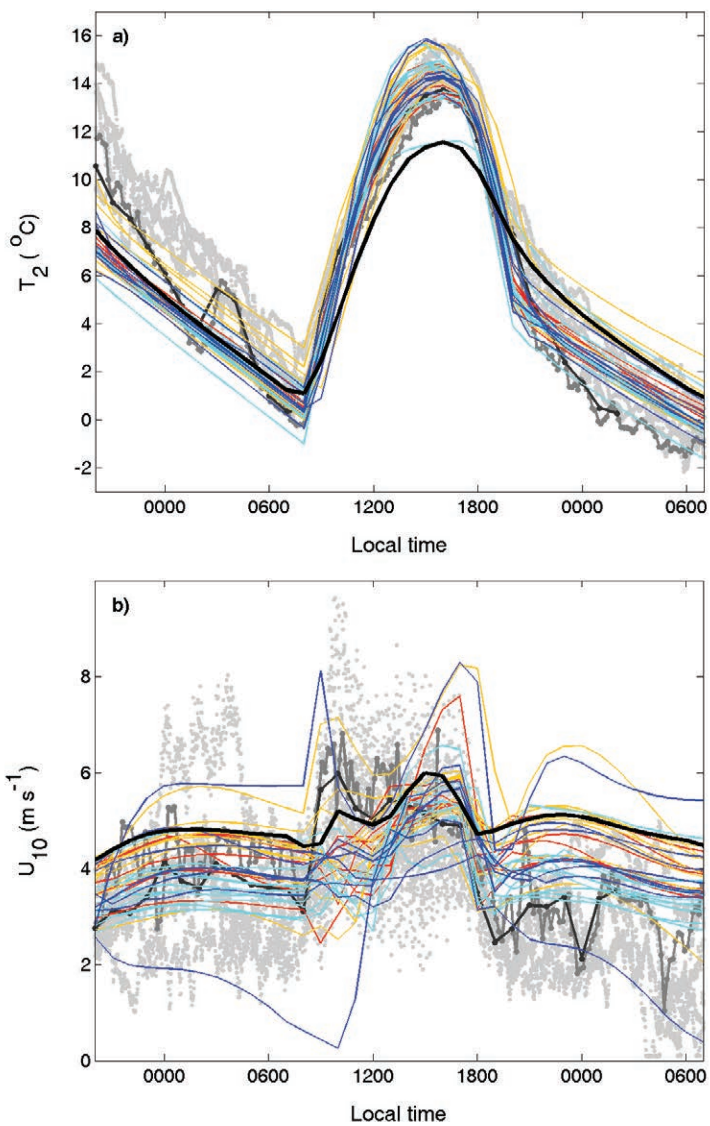

Fig. 8. Time series of observed and GABLS2 model results (various lines) for (a) temperatures (°C) at 2 m AGL and (b) wind speeds (m s^{-1}) at 10 m AGL. The light gray dots are observations from a network spanning a larger area and the two darker gray lines with dots from the central towers at CASES-99. The thick black lines show the LES result by Kumar et al. (2010). The single-column model results are presented in four categories based on model closure and height of the first model level. Red lines represent first-order parameterizations with first grid level below 5 m, yellow lines represent first-order parameterizations with first grid level above 5 m, cyan lines represent TKE parameterizations with first grid level below 5 m, and blue lines reflect TKE parameterizations with first grid level above 5 m. Figure results adapted from Svensson et al. (2011).

DIURNAL CYCLES. As discussed above, operational weather and climate models have difficulty in representing the diurnal cycle of temperature, wind, and related variables (see also Edwards et al. 2011). This has an impact on the modeled temperature trends by climate models, in particular for the minimum temperature (Zhou et al. 2010; Steeneveld et al. 2011a; McNider et al. 2012). Steeneveld et al. (2008b) compared the performance of three state-of-the-art mesoscale models and noted that all three models underestimate the amplitude of the diurnal temperature cycle and the near-surface wind speed. These findings were achieved by comparing the models with observations taken in Kansas in the early autumn during the 1999 Cooperative Atmosphere–Surface Exchange Study (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 intercomparison study, inspired by an earlier single-column study by Steeneveld et al. (2006b).

The CASES-99 dataset was used to set up an intercomparison case for SCMs in GABLS2. The forcing conditions were simplified to facilitate a more straightforward comparison between model closures. As such, a prescribed surface temperature and simplified time-dependent barotropic geostrophic wind forcing was used (Svensson et al. 2011). Nineteen models participated in this SCM intercomparison study, ranging from operational models with first-order closure and a vertical resolution of six grid points within the first 400 m to more advanced models with much higher resolution. The analysis of the model results were performed according to their turbulent closure and the height of their first model level, below or above 5 m above the surface. Results from one experimental LES by Kumar et al. (2010) are also available for this case.

It is found that the models produce very different results in all variables and that they all differ substantially from the observations. Although the surface temperature has been prescribed, a large variation is seen in the diurnal cycle of 2-m temperature with most models overestimating the amplitude while the LES has a smaller amplitude than observed (Fig. 8a). The modeled diurnal cycle of the 10-m wind speed does not resemble the observations in many cases, most models overestimate the wind speed during night, and the speed does not increase enough after the morning transition (Fig. 8b). This is also seen in many of the CMIP5 climate models, especially for wind speed (Fig. 3).

The impact of forcing and boundary conditions on the variability of model results for GABLS2 is discussed by Holtslag et al. (2007). Interestingly, it was found that the variation between various model permutations is less when the boundary layer scheme is coupled to a well-performing land surface scheme. Thus, prescribing the surface temperature as in GABLS2 was, in the end, a more critical test for the boundary layer schemes than when allowing for surface interactions. One may therefore speculate to what extent differences in boundary layer schemes are at least partly a result from tuning them together with other process parameterizations in the different weather and climate models.

The experience from the two first GABLS cases led to the setup of the third SCM intercomparison case using data gathered at the Cabauw tower (Baas et al. 2010). 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 hampered a direct comparison of models with observations. Thus, the GABLS3–SCM case involves a more realistic large-scale forcing and allows for interactions with the land surface and atmospheric radiation.

For the GABLS3–SCM case, the early afternoon of 1 July 2006 was chosen as an initial time. The total simulation of 24 h covers the decoupling around sunset with low-level jet formation and the following morning transition. Note that the LES case of GABLS3 as discussed in "Stable atmospheric boundary layers" encompasses part of the SCM simulation period. The observations show an almost clear sky with a reasonably constant geostrophic wind over time of about 7 m s^{-1}, resulting in a turbulent stable boundary layer overnight with a pronounced temperature drop and a well-developed low-level jet around 200 m. To make a valid comparison with observations possible, care was taken to prescribe realistic geostrophic forcing and dynamic tendencies for the SCMs (Baas et al. 2010). The description of the third GABLS–SCM case, details of the selection criteria, and the composition of the large-scale forcing are documented in Bosveld

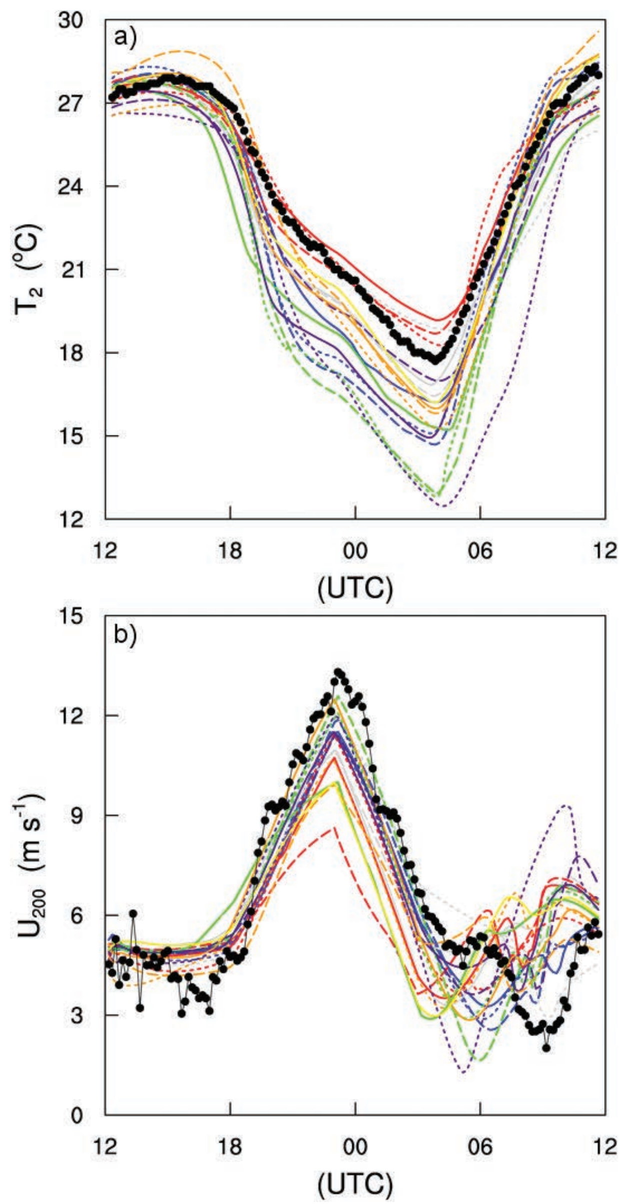

Fig. 9. Time series observed (black line with dots) and GABLS3 model results (various other lines) for (a) temperatures (°C) at 2 m and (b) wind speeds (m s^{-1}) at 200 m. Results are for the 24-h period starting at noon of 1 Jul 2006 at Cabauw, the Netherlands (note that 1200 UTC at Cabauw is 1220 local solar time). Figure adapted from Bosveld et al. (2013b, manuscript submitted to *Bound.-Layer Meteor.*).

et al. (2012, 2013a, manuscript submitted to *Bound.-Layer Meteor.*).

Nineteen models of different complexity from 11 institutes participated in the intercomparison. Twelve of these models also participated in GABLS2. Figure 9a shows time series of the 2-m temperature from the SCMs together with the observations. The general signature of the temperature change is well captured by the models—that is, an initial fast decrease, followed by a more gradual decrease in the subsequent hours, and slightly faster cooling before midnight. Seven out of the 19 models are within 1 K of the observations. The remaining models are up to 5 K colder than observed, which seems mostly related to coupling of the atmosphere to the surface. It appears that variations in thermal land surface coupling among the models explain to a large extent the variations in the minimum 2-m temperature for the GABLS3 case. Variations in turbulent mixing and representation of longwave radiation seem to be of lesser importance for this parameter (Bosveld et al. 2012, 2013a, manuscript submitted to *Bound.-Layer Meteor.*). This issue obviously needs further research.

Winds at the 200-m level are shown in Fig. 9b. For each model, the first level above 200 m was chosen. This height interval is interesting because in the observations it is decoupled from the surface and exhibits a clear inertial oscillation. After the evening decoupling, the observed wind accelerates much faster than the modeled winds, which is related to the timing of the evening transition and the corresponding wind profiles at that time (see also Van de Wiel et al. 2010). The inertial oscillation is also strongly affected by horizontal momentum advection especially after midnight (Baas et al. 2010). All model wind speeds peak 11 h after the start of the simulation at lower values than observed. Around and after sunrise models start to differ even more, both from each other and from the observations. At the 80-m level, which is well within the turbulent layer, a number of models peak at higher wind speed than observed (not shown).

Finally, Fig. 10 shows time series for temperature and wind at a height of 40 m for the LES models in comparison with the observations for the GABLS3 case. The 40-m height was chosen here as a representative level in the middle part of the nighttime stable boundary layer (typically six grid points away from the surface to ensure that the resolved turbulence is not impacted by the surface). Overall, the agreement between the ensemble of model results and the observations is very good for this realistic case, in particular if one compares the outcome with the results of the SCMs for GABLS2. Note again that in both cases the near-surface temperature was prescribed in accordance with the observations. However, coupling of an LES model to an interactive land surface scheme may result in similar discrepancies as seen in Fig. 9 for the SCMs in GABLS3; this calls for further investigation.

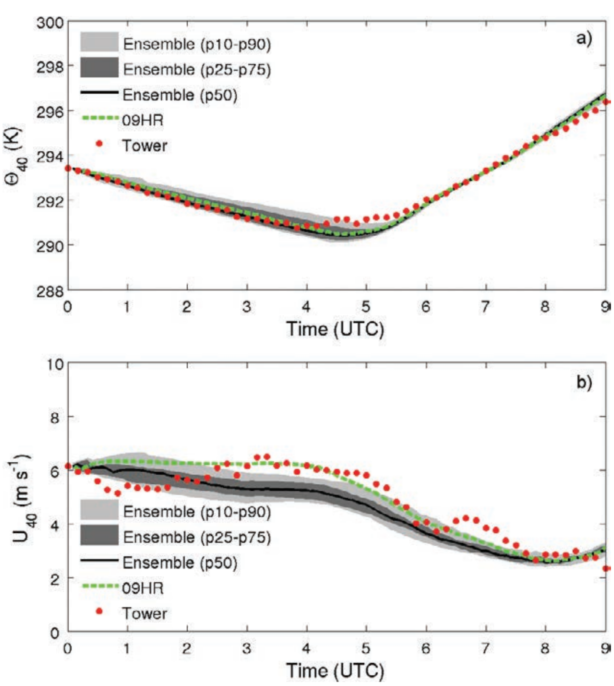

FIG. 10. Time series at a height of 40 m for (a) potential temperature (K) and (b) wind speed magnitude (m s^{-1}) using the LES model results and Cabauw observations for GABLS3 corresponding to 0000–0900 UTC 2 Jul 2006. Symbols and lines as in Fig. 7.

SUMMARY AND PROSPECTS. The representation of the atmospheric boundary layer in state-of-the-art weather forecast and climate models has important practical implications for many users within air quality, wind energy, climate, and Earth system studies. In fact, model output of near-surface weather parameters is increasingly being supplied to users either directly or with some statistical postprocessing. Overall, the diurnal cycles of temperature and wind are strongly influenced by processes in the atmospheric boundary layer, in particular by turbulent diffusion and radiation, but also by the thermal coupling to the underlying surface through vegetation and snow (as illustrated here for the GABLS3 case). This contribution elaborates the state-of-the-art in these areas with particular emphasis on stable boundary layers over land and ice at clear skies.

As discussed in the paper, the performance of weather and climate models is sensitive to the details of the boundary layer formulation. Most large-scale atmospheric models utilize overly diffusive boundary layer schemes in stably stratified conditions with the result that these boundary layers are too thick, have too little wind turning with height, and underestimate the magnitude of the nocturnal jet. Climate projections show large temperature signals at high latitudes where stable boundary layers occur frequently. Findings from investigations with the ECMWF global numerical weather forecast model and analysis of some models participating in the Coupled Model Intercomparison Project phase 5 (CMIP5) are discussed to illustrate the current status and developments.

The performance of NWP and climate models during stably stratified conditions is part of the underpinning for the GEWEX Atmospheric Boundary Layer Study (GABLS) and here findings from the three GABLS model intercomparison studies are presented. Based on these results it is indeed clear that operational models typically have too much mixing in stable conditions. This strongly impacts the diurnal cycles of temperature, wind, and related variables. Enhanced mixing has an impact on the life time of the synoptic systems and thus reduces the "activity" of a model, which improves the operational scores. By decreasing mixing (i.e., reducing the surface drag to more realistic values), a direct impact on the atmospheric dynamics has been noted (e.g., Beljaars and Viterbo 1998; Beljaars et al. 2012a; Sandu et al. 2013).

Another motivation to use enhanced mixing is to prevent models going into an unphysical decoupled mode (i.e., separating the atmosphere from the cool surface). Such a decoupling may lead to a runaway cooling close to the ground (e.g., Louis 1979; Derbyshire 1999; Steeneveld et al. 2006b; Basu et al. 2008). This is one example where the turbulent mixing in stratified flows has an inherent nonlinear character and may trigger unwanted positive feedbacks (e.g., Mahrt and Vickers 2006). Such positive feedbacks, in turn, may cause unexpected transitions between totally different regimes in the stable boundary layer (e.g., McNider et al. 1995; Derbyshire 1999; Delage 1997; Van de Wiel et al. 2007, 2012a,b; Bintanja et al. 2012). The overall representation of the small-scale atmospheric processes and the related "spatial averaging" is highly nontrivial since there are many nonlinear processes involved and because the land surface often displays a heterogeneous character on a variety of scales.

The GABLS cases brought together persons with expertise on LES and observations with academic and operational modeling skills. The cases also inspired new model developments (e.g., Sukoriansky et al. 2005; Mauritsen and Svensson 2007; Buzzi et al. 2011) and are increasingly used for applications like particle dispersion (e.g., Weil 2010). Inspired by the GABLS results, modeling groups at many operational centers—such as ECMWF, the Met Office, Meteo-France, National Centers for Environmental Prediction (NCEP), and elsewhere—have been encouraged to study and improve their representation of the atmospheric boundary layer (e.g., Beare 2007; Brown et al. 2008; Bazile et al. 2012). It is clear that this issue is still not fully solved and needs further attention by the modeling centers and within the academic community (see also Jakob 2010). 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 (Bretherton and Park 2009; Köhler et al. 2011; Steeneveld et al. 2011b; Müller et al. 2010). In the sidebar below, an overview of GABLS achievements is given.

Overall, there is still a clear need for a better understanding and a more general description of the atmospheric boundary layer in atmospheric models for weather and climate, in particular under stably stratified conditions (see also Hong and Dudhia 2012). The ultimate goal is to have a full understanding of the complexity of atmospheric boundary layers as well as a unified treatment of turbulent mixing on the different scales and surface types which occur in

OVERVIEW OF GABLS ACHIEVEMENTS

- GABLS has inspired academia and operational modeling centers to work together on boundary layer issues.
- The GABLS cases are increasingly used for model testing and benchmarking.
- Large-eddy simulation has become a useful tool to study stable boundary layers.
- Research models are able to represent a realistic stable boundary layer structure.
- Weather forecast and climate models generally have too much vertical mixing in stable conditions, resulting in too deep boundary layers, too less turning of wind with height, too large downward sensible heat fluxes, and too weak low-level jets.
- Operational weather forecast models still need enhanced mixing for good forecast scores but have difficulty in representing the diurnal cycles over land.
- Coupling between the atmosphere and the land surface is key for a good representation of the diurnal cycles of temperature, wind, and other variables.

reality. As such, the ongoing challenge for large-scale models is to design an atmospheric model that has the correct level of synoptic activity, good scores for near-surface weather variables, and a realistic boundary layer with correct mean profiles, turbulent fluxes, and vertical extent (e.g., Sandu et al. 2012, 2013). This should also benefit wind energy, air quality, and related Earth system studies.

The conclusions reached so far and reported in this paper are for weakly to moderately stably stratified boundary layers. There are additional challenges to model strongly stratified conditions (e.g., Zilitinkevich et al. 2008; Van de Wiel et al. 2012a,b; Sterk et al. 2013). In the future, we see studying boundary layers that have a stronger stratification and lower geostrophic wind speeds (<5 m s^{-1}) as recommended by participants of the ECMWF–GABLS workshop (Beljaars et al. 2012b). Boundary layers over ice and snow in the Arctic and Antarctic as well as boundary layers over heterogeneous landscapes (e.g., in Lindenberg, Germany, and Sodankylä, Finland) provide additional complexities and challenges. The sidebar above gives an overview of future directions and challenges.

FUTURE DIRECTIONS AND CHALLENGES

- Enhance the activities and interactions between academia and operational modeling centers, and also engage the climate and air-quality communities.
- Study the relation between enhanced mixing in operational models and weather forecast scores, and involve the interaction with other processes.
- Investigate the role of land-surface heterogeneity in the coupling with the atmosphere.
- Develop and evaluate large-eddy simulation models with interactive land surface and radiation processes for the full range of stabilities.
- Advance the understanding of model behavior by creating climatologies of boundary layer relevant parameters (i.e., stability classes, boundary layer depth, and surface fluxes).
- Initiate further work on the understanding and modeling of the diurnal cycles, in particular the morning and evening transitions.
- Develop and test parameterizations for the very stable boundary layer when turbulence is not the dominant driver.

Finally, we recommend to study the ABL in interaction with other atmospheric and Earth surface processes (e.g., Ek and Holtslag 2004; Van Heerwaarden et al. 2009; Sterk et al. 2013), and encourage the setup of such studies within the new GEWEX program on Global Atmospheric System Studies (GASS). Neggers et al. (2012) present an interesting way to enhance process understanding by systematic comparing SCM results with observations in an operational suite. Attention should further be paid to integrate the activities with modelers at weather forecast and climate centers—for instance, by facilitating regional model intercomparisons such as in the Arctic Regional Climate Model Intercomparison Project (ARCMIP) (Tjernström et al. 2005) and to acquire and compare short-term forecasts from full weather forecast and climate models for the study points of interest.

ACKNOWLEDGMENTS. We thank all the contributors to the three GABLS model intercomparisons and the many persons involved in gathering and analyzing the field data. We also thank the participants of the GABLS workshops and meetings during the last decade as well as the hosting organizations (ECMWF, KNMI, NCAR, University of Mallorca, Wageningen University, and Stockholm University) and the various AMS Boundary Layer Symposia for providing a GABLS platform. In addition we thank GEWEX and the Working Group on Numerical Experimentation (WGNE) for their support. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. The paper benefited from discussions at the ECMWF–GABLS workshop in November 2011. Michael Ek, John Edwards, Adrian Lock, and Thorsten Mauritsen are thanked for providing comments on a draft of this paper. SB acknowledges the financial support received from the NationalScience Foundation by way of Grant AGS-1122315.

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