

GABLS 3 SCM intercomparison and evaluation

What did we learn?

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Abstract

A weakly stable case is selected from the Cabauw long term archive. The case is used for an evaluation and intercomparison of nineteen SCM in the context of the GEWEX Atmospheric Boundary Layer studies. Care was taken to prescribe realistic geostrophic forcing and dynamic tendencies to the SCM's. It is shown that in this way a direct evaluation of SCM runs with observations is feasible. The results are analyzed using a method which allows the interpretation of differences among models in terms of the dominating physical processes in the stable boundary layer, i.e. coupling to the soil, turbulent mixing and long wave radiation. Significant differences among models are found in the representation of these three processes. It is shown that on a single case basis, atmospheric forcings as obtained from a state of the art 3D atmospheric model are not accurate enough to drive the case if a direct comparison with observations is desired. Ensemble and composite approaches are applied on the basis of eight comparable nights, showing that deviations in the forcings between the model and the real-world are diminished to such extent that a very accurate comparison between models and observations becomes feasible. As a by-product, it is shown that systematic dynamical tendencies remain in the composite case, probably related to the presence of the sea.

1. Introduction

The third GABLS single column model (SCM) case was designed on the basis of the long term dataset of the Cabauw Experimental Site for Atmospheric Research (CESAR). The case has been set into perspective of the GABLS program by Holtslag et al., 2012. In order to make a comparison with observations possible, care was taken to prescribe realistic geostrophic forcing and dynamic tendencies to the SCM's. These were estimated from both local observations and hindcasts of several 3D NWP models, among which RACMO, the regional climate model of KNMI. The defined case setup is available at www.knmi.nl/samenw/gabls. The SCM models were run with full physical interaction, e.g. interaction with their own soil/vegetation and radiation schemes. Here, we highlight some critical issues with respect to the case set-up and selection (section 2) and on the model intercomparison and evaluation (Section 3). Finally, we show how the case is extended to an ensemble of comparable cases and discuss the prospect for future evaluation studies (Section 4). Extended manuscripts are in preparation for the case set-up (Bosveld et al., 2012a) and for the intercomparison and evaluation (Bosveld et al., 2012b).

2. Case description

The selected case comprises 24 hours starting at 12 UTC (12:20 local solar time) of July 1st, 2006 and ending at 12 UTC the next day. Figure 1 shows time series of the profiles of the basic meteorological parameters along the 200 m tower. Already 3 hours before sunset (17 UTC), cooling starts near the surface. The rapid decline of turbulence in the mixed-layer, initiates a clear inertial oscillation in the wind. By the end of the night the potential temperature difference between the 2 and 200 m levels in the tower is 9 K. Wind direction at 10 m varies between 80 and 120 degrees.

The complete case set-up involves the initial conditions in the full column including the soil, the characterisation of the surface to allow for a correct interaction of the atmospheric component of the model with the surface scheme, and the geostrophic forcing and dynamical tendencies as function of height and time. Here we highlight a few critical issues.

Surface geostrophic forcing at Cabauw was estimated from surface pressure observations of the Dutch national network. A piecewise linear approximation is used for the case prescription. Figure 2 shows the observed and prescribed course of the surface geostrophic wind in an East-North diagram. Note that the geostrophic wind has three periods with nearly constant components and with rapid changes in between. In the morning, the linear approximation takes a shortcut with consequentially somewhat larger deviations between observations and prescription. For the change of geostrophic wind with height and the vertical movement we resorted to the RACMO-3D simulation. Model derived horizontal dynamical tendencies were found to be inappropriate to drive the case and therefore we resorted to the observations at 200 m in the tower.

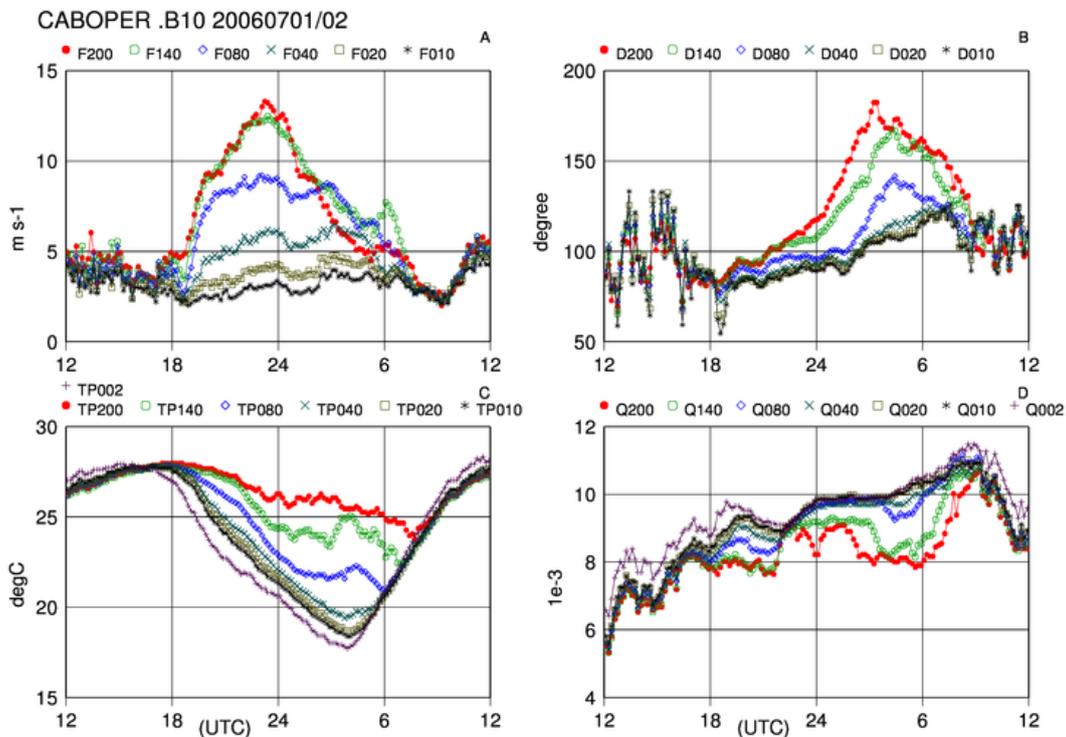


Figure 1. Observed (A) wind speed, (B) wind direction, (C) potential temperature and (D) specific humidity at 6 (7) levels in the Cabauw 200 m tower for the case period.

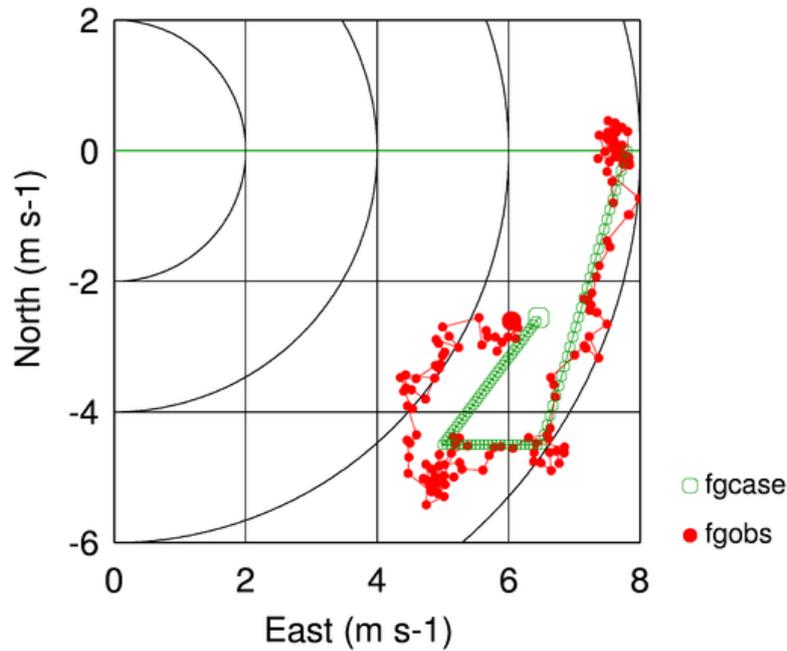


Figure 2. Time trace in the East-North plane of surface geostrophic wind from observations (fgobs) and as prescribed piecewise linearly for the case (fgcase). Time step is 10 minutes.

During night time, when interaction with the surface is relatively small, changes in observed wind at sufficient height may indicate dynamical tendencies at work. Here we attempt to derive dynamical tendencies for this case by looking at the observed rate of change of observations at 200 m height during the night. We apply the prognostic equations for momentum at a height of 200 m, while ignoring the physical processes but retaining the influence of geostrophic wind and the Coriolis acceleration on the momentum budget:

$$\begin{aligned} \frac{\partial u}{\partial t} &= \vec{v} \cdot \vec{\nabla} u + f(v - v_G) \\ \frac{\partial v}{\partial t} &= \vec{v} \cdot \vec{\nabla} v - f(u - u_G) \end{aligned} \quad (1)$$

Here u and v are the zonal and meridional wind components and u_G and v_G are the geostrophic wind components. The first terms on the r.h.s. represent the horizontal dynamical tendencies. We call this the Simplified Prognostic Equations (SPE). The 200 m wind is initialized by the observed values at sunset, after the moment of decoupling, and then the SPE's are integrated forward in time by using the observed surface geostrophic wind. The dynamical tendencies for the GABLS case are estimated by varying the tendencies until a reasonable agreement between observed 200 m wind and SPE simulated wind was obtained.

The result is given in Figure 3, which shows the evolution in time of the observed wind at 200 m together with the observed geostrophic wind. Also shown are results from the integration of the SPE either forced with RACMO-3D tendencies or without momentum tendencies. Here we see that the

effect of advection of momentum is quite complex due to the interaction with the Coriolis force and the changing geostrophic wind. The SPE with RACMO-3D tendencies are not able to give a good representation of the observed 200 m wind. The same is true for the integration without momentum tendencies (NOADV).

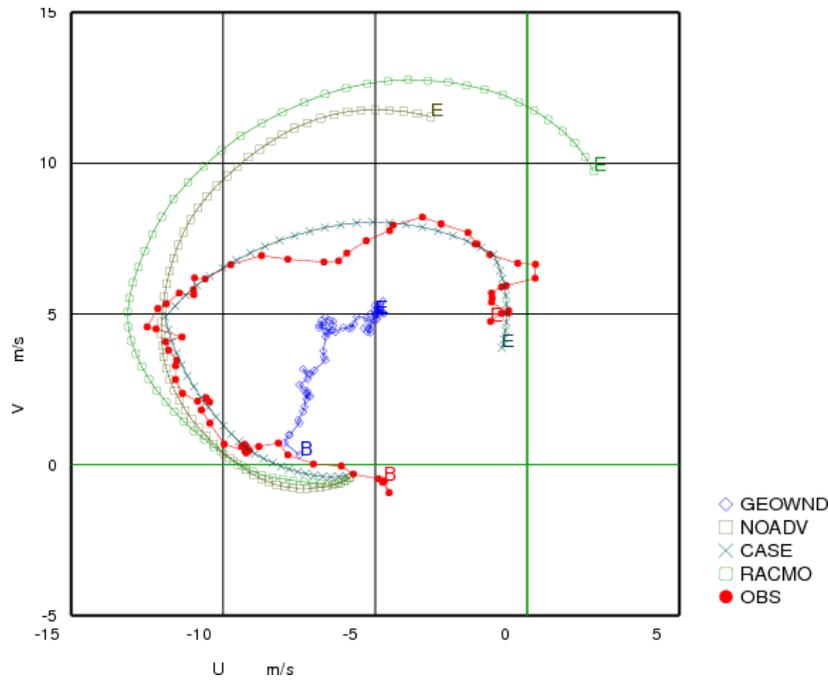


Figure 3. Horizontal wind evolution at 200 m. Observations (OBS) and when RACMO-3D and CASE advection is applied on sunset wind vector. Also shown is evolution when no advection is applied (NOADV) and shown is the geostrophic wind evolution (GEOWND). B indicates begin of time series (sunset) and E indicates end of time series (11 hours later). Time step is 10 minutes. In all simulations the observed geostrophic wind is used.

3. Model evaluation and intercomparison

Nineteen models joined the intercomparison ranging from operational global models with coarse vertical resolution and K-diffusion to research models with TKE-1 and 2nd order closure schemes run at higher vertical resolution. Observations for model evaluation are taken from the continuous observational program of Cabauw. Stable boundary layer height is defined as the height at which the air temperature profile attains its maximum value.

The main physical processes that play a role in the development of nocturnal boundary layers are turbulent mixing, long wave radiation exchange and thermal coupling to the land surface. All these processes are parameterized in the SCM's. All models are driven with the same external forcing. Even for a perfect model differences with reality may occur since the prescribed forcings are based on indirect observations.

Figure 4 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. the fast decrease

during the first hours after sunset, followed by a more gradual decrease in the subsequent hours. Half of the models are within 1 K of the observations. The remaining models are up to 5 K colder than observed. Winds at the 200 m level are also shown in Figure 4. 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 it exhibits a substantial inertial oscillation after the onset of decoupling around sunset.

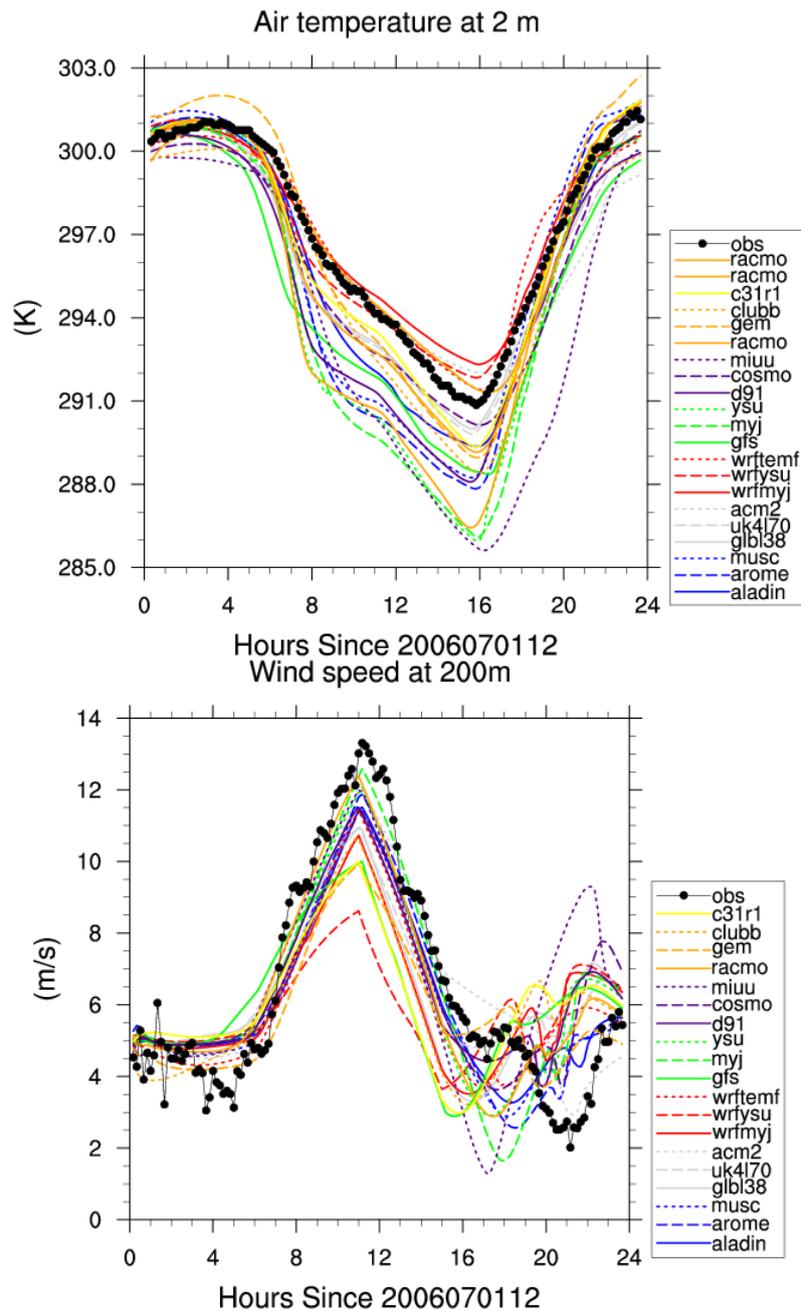


Figure 4. Air temperature at 2 m (top) and wind speed at 200 m for the models together with observations (bottom).

All models peak at 11 hours after the start of the simulation but all of them at a lower value than observed. More than half of the models peak within 2 m/s from the observed values. 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 advection would be absent (c.f. Figure 3).

Having characterized the behaviour of the models and their differences we now will try to explain the differences among models, taking the observations as a guidance. To facilitate this, we make use of a number of sensitivity runs performed with one of the participating models (RACMO). The sensitivity runs were chosen such that the main physical processes in the NBL are affected. Thermal coupling with the land-surface/soil system was changed by varying the thermal conductance between the skin layer and the soil. These runs are labelled coupling. Turbulent mixing in the TKE-1 scheme was changed by varying the parameters that relates turbulent length scale to the properties of the flow. These runs are labelled mixing. Long wave incoming radiation was varied by varying specific humidity in the atmospheric profile. These runs are labelled radiation.

Figure 5 shows the surface soil heat flux after midnight as function of the 2 m air temperature change from 3 hours before till 3 hours after midnight. A line is drawn through the observation and the origin, indicating the expected relation if thermal coupling would be constant.

A considerable spread among models is observed mainly perpendicular to the constant coupling line, indicating that the strength of the land-surface coupling varies considerably amongst the models. The line for coupling sensitivity has the same orientation as the main spread among models. The effect of changing mixing is small.

Longwave incoming and outgoing radiation at the surface are tightly coupled to the temperatures in the SBL and at the surface respectively. Cooling at the surface is determined, among others, by the net long wave radiation flux. Figure 6 shows the 2m temperature after midnight as function of net longwave radiation during the night. A clear correlation is found with strong radiative cooling occurring when temperatures are high. This counter intuitive result, suggests that the most important mechanism here is the impact of surface temperature on the long wave upward radiation. The radiation sensitivity runs show an opposite behaviour with indeed low minimum temperatures at low longwave incoming radiation. The result of the coupling sensitivity runs shows that strong coupling to the soil results in relatively high minimum temperatures and vice versa as already discussed. A simple change of land surface coupling may bring the models closer to the observations but still a discrepancy would remain. This suggests that the models also misrepresent longwave radiation for this case.

To isolate the strong interaction of 2 m temperature and long wave upward radiation from the sensitivity to the other processes, we use in the right panel the iso-thermal net radiation, which is the difference between the incoming long wave radiation and the radiation that the surface would emit if it had the same temperature as the top of the stable boundary layer. We used the observed 200-m temperature as a proxy. We now find an opposite behaviour with high temperatures corresponding to weak iso-thermal cooling. The sensitivity lines suggest that a combination of different representation of coupling and radiation may account for the differences among models.

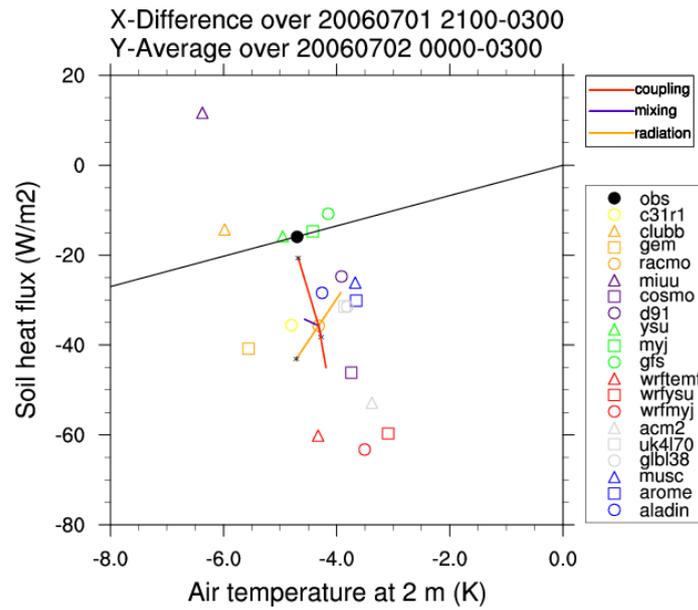


Figure 5. Night time soil heat flux as function of 2m air temperature change over the night. The black line represents points with the same coupling as observed. The three coloured lines connect the different sensitivity runs (see main text). The crosses at the coloured lines represent the points with lowest coupling, mixing and radiation respectively.

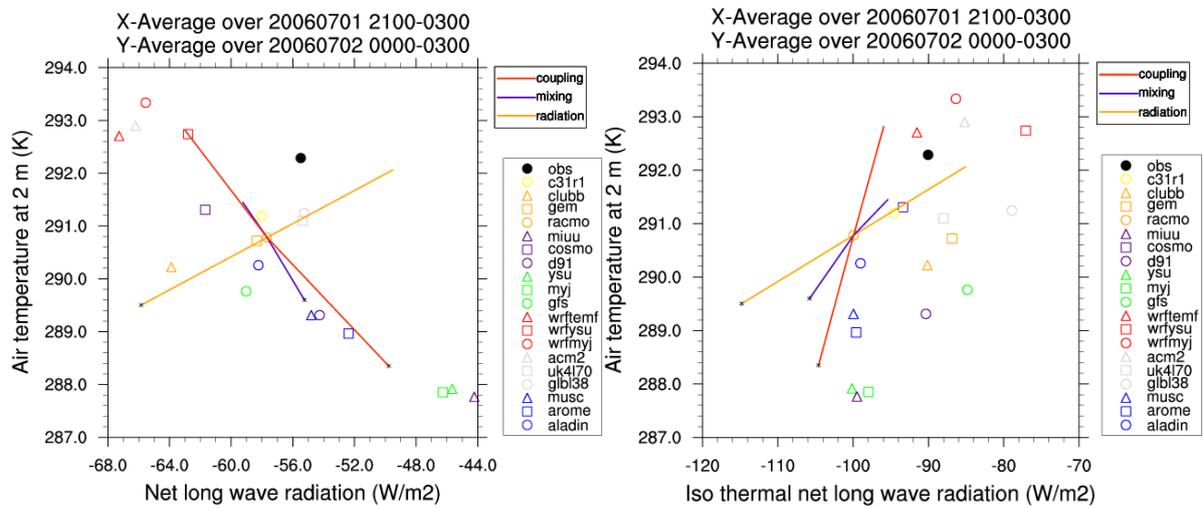


Figure 6. 2 m air temperature after midnight as function of night time net long wave radiation (left). 2 m air temperature after midnight as function of night time iso-thermal net long wave radiation (right). For explanation of lines see Figure 5.

Figure 7 shows mean night time sensible heat flux before midnight as function of boundary-layer height at midnight. Increased downward sensible heat flux is coupled to deeper stable boundary layers, most probably due to more efficient turbulent mixing, as is illuminated by the mixing sensitivity runs. Most of the models are relatively close to the observations.

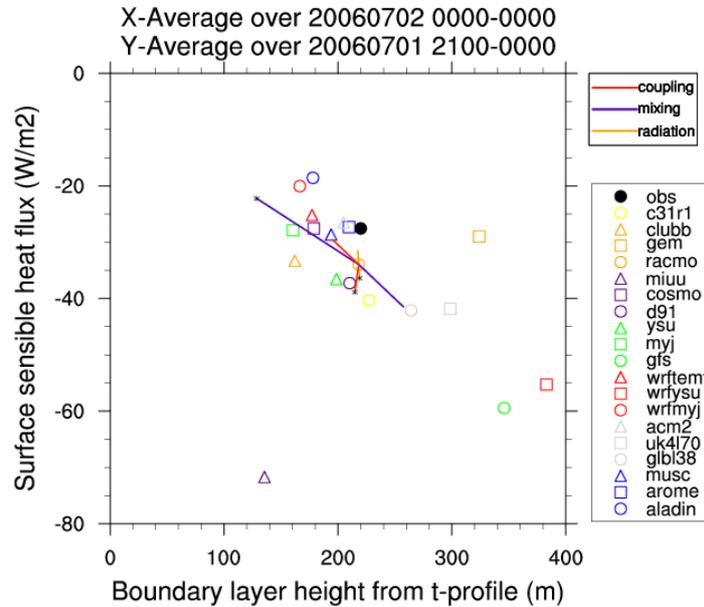


Figure 7. Night time sensible heat flux before midnight as function of boundary layer height at midnight. For definition of boundary layer height see text. For explanation of lines see Figure 5.

4. Ensemble and composite case

The material in this section is extracted from Baas et al., 2010. Currently, attempts are undertaken to test physical aspects of atmospheric models in a continuous mode (Neggers et al., 2012) by prescribing atmospheric forcings for a SCM-case from a 3D NWP model. Here we investigate how this works out for stable conditions. For the GABLS 3rd SCM case we already found that prescribing the atmospheric forcings from the NWP to the SCM didn't lead to a realistic simulation of the nocturnal low-level jet. Figure 8 shows the momentum related forcings as prescribed for the GABLS3-case and as obtained from RACMO2 runs with two different turbulence parameterizations. A simulation with the TKE-1 scheme (3DTKE in Figure 9) and a simulation with the 1st order scheme based on ECMWF Cycle31 (3DC31 in Figure 9).

Figure 9 shows the observed evolution of the 200 m wind compared with the SCM results with the 3 different atmospheric forcings as prescribed by the GABLS3 case and derived from the two flavours of RACMO2. Observed is a significant difference between simulated forcings and the forcing needed to obtain a correct evolution of the 200 m. We speculate that both in reality and in the 3D model meso-scale features are present. In the model these are not deterministically resolved leading to a mismatch between the observations and the simulation. To investigate this further, we turn to an ensemble of comparable cases and investigate to what extent such an ensemble can be simulated correctly. Two roads can be chosen. Firstly, we run the SCM model for each individual case of the ensemble, average

the outcome of the simulations and compare this with the average of the observations. We call this the ensemble approach. Secondly, we start with averaging the atmospheric forcings over the ensemble and then run the model for this composite forcing. We call this the composite approach.

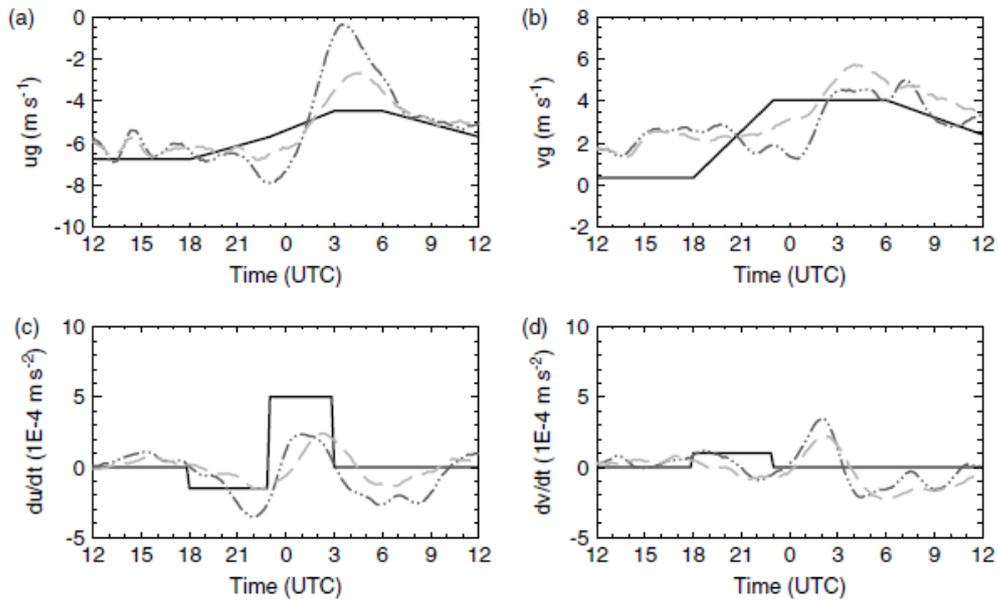


Figure 8. Geostrophic winds and momentum tendencies derived from 3D RACMO2 simulations averaged over the layer between 200 and 500 m. The full line represents the GABLS3 set-up, the dashed-dotted line the simulation with the TKE-1 scheme, and the dashed line the simulation with 1st order scheme based on ECMWF Cycle31.

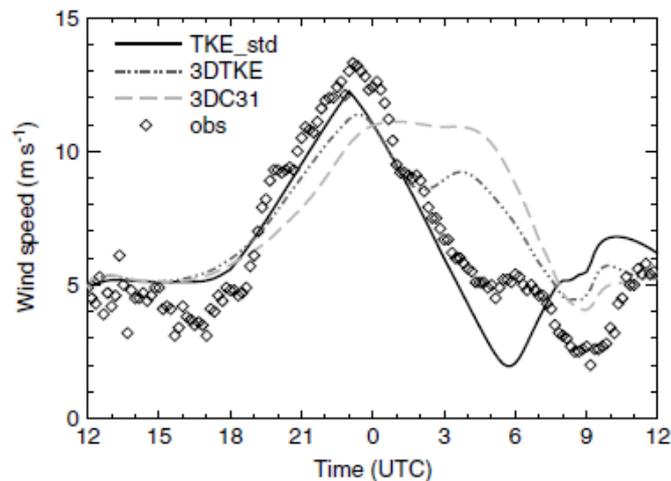


Figure 9. Time series (hours) of the 200 m wind speed for three SCM simulations with different forcings. Tower observations are added for comparison. Solid line is with GABLS3 prescribed forcings.

Seven additional nights were selected from the Cabauw database with similar characteristics as the GABLS3-case. Both the ensemble and the composite approach were applied. The results are shown in Figure 10. The left panel shows the 200 m wind evolution for all eight ensemble members. The figure also compares the average over the ensemble of model runs (solid line) with the average over the ensemble of observations (diamonds). We find that the observed ensemble averaged wind is very well simulated by the ensemble averaged model runs. The right panel of Figure 10 shows the composite result. Also in this case close correspondence with the observations is found. The advantage of the composite approach is that easily sensitivity experiments with different parameterizations can be performed, as illustrated in Figure 10b. Apart from the standard setting of the TKE-scheme (solid line) also a variation is displayed where the parameters that control the length scales for mixing of momentum and heat are varied (dashed line). We see that by using multiple comparable cases a direct evaluation with observations of subtle differences in parameterization comes into reach. More robust results can be achieved when we also include a comparison with other observations available such as wind at lower levels and temperature evolution (not shown here).

A difference in simulated night time winds may occur due to wrong timing of decoupling around sun set or erroneous representation of the wind prior to the transition. To avoid these complications, the simulated wind (with standard TKE parameterization) was relaxed towards the observed wind until the moment of decoupling, i.e. when the observed 200 m wind started to accelerate. The result is shown in Figure 10 (right panel) as the dash-dot line. A better correspondence with observations is found for the first half of the night. After midnight the deviations from the observations become comparable to that of the standard run.

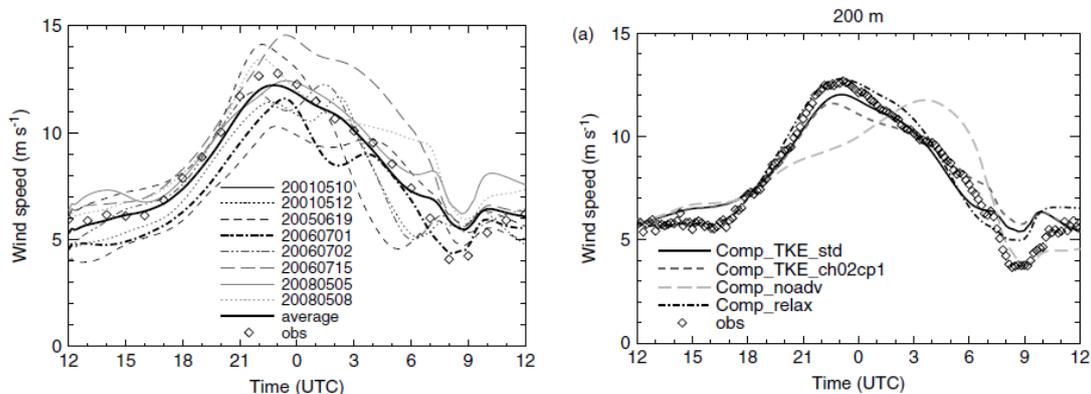


Figure 10. Time series of observed and modelled wind speed at 200 m for (left panel) SCM simulations of eight selected nights using forcings derived from 3D model output. The thin lines represent individual cases (labelled by their respective date, *yyyymmdd*), the simulation that corresponds to the GABLS3 night is indicated by the bold dashed-dotted line. The full line gives the average of the SCM runs, the diamonds give the averaged observations, and (right panel) the composite case with two subtle different flavours of the turbulence scheme, a run without advection and one in which a relaxation is applied.

One may wonder whether the dynamical tendencies approach zero when averaging over such an ensemble. Figure 11 shows that this is not the case. A definite signature remains for these comparable summer time easterly wind cases, which might be related to the influence of the nearby sea to the west. In Figure 10 (right panel) a run without dynamical tendency set to zero (gray dashed) shows that indeed the prescription of the correct composite horizontal tendencies is crucial for a good simulation of the composite case.

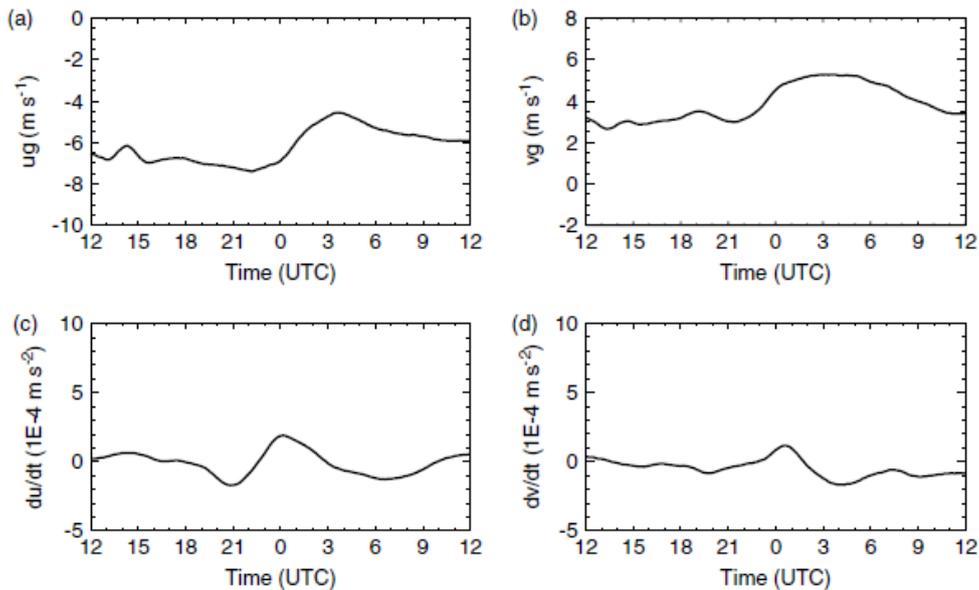


Figure 11. Modelled geostrophic wind and tendencies of momentum averaged over the eight selected cases. Average values between 200 and 500 m are shown.

5. Conclusions

A weakly stable case is selected from the Cabauw long term archive. The case is used for an evaluation and intercomparison of nineteen SCM in the context of the GEWEX Atmospheric Boundary Layer studies. Care was taken to prescribe realistic geostrophic forcing and dynamic tendencies to the SCM's. It is shown that in this way a direct evaluation of SCM runs with observations is feasible. The results are analyzed using a method which allows the interpretation of differences among models in terms of the dominating physical processes in the stable boundary layer, i.e. coupling to the soil, turbulent mixing and long wave radiation. Significant differences among models are found in the representation of these three processes. Some of the differences can be attributed to a misrepresentation of the site characteristics, e.g. coupling to the soil. Other differences are site independent, e.g. mixing and radiation. It is shown that on a single case basis, atmospheric forcings as obtained from a state of the art 3D atmospheric model are not accurate enough to drive the case if a direct comparison with observations is desired. Ensemble and composite approaches are applied on the basis of eight comparable nights, showing that deviations in the forcings between the model and the real-world are diminished to such extent that a very accurate comparison between models and observations becomes feasible. As a by-product, it is shown that systematic dynamical tendencies remain in the composite case, probably related to the presence of the sea.

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