9.2 **THE THIRD GABLS SCM INTERCOMPARISON AND EVALUATION CASE**

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1. INTRODUCTION

The GEWEX Atmospheric Boundary-Layer Study (GABLS) focuses on the representation of stable boundary layers in atmospheric models (Holtslag, 2006). Correct representation of the stable boundary layer in models is of importance for applications ranging from weather forecast, climate studies, atmospheric transport, agriculture, wind engineering, aviation and public transport. One of the main goals of GABLS is to provide a worldwide platform for the atmospheric boundary layer research community through the organization of model intercomparisons. Here we focus on single column models (SCM's), which can be both research models and SCM's derived from operational weather and climate models. Two SCM intercomparison case studies have been performed so far in the context of GABLS. One highly idealized case over snow with prescribed surface temperature (Cuxart et al., 2006) and a second case based on observations taken during the CASES 99 stable boundary layer experiment also with prescribed surface temperature (Svensson and Holtslag, 2007).

In these previous studies it was found that especially the complexity of real world boundary conditions and the lack of interaction with the surface in the model runs make it difficult to confront the models with observations. Holtslag et al. (2007) showed that SCM's tend to represent stable boundary layers better when they are allowed to interact with the surface.

A third GABLS SCM case was derived from the long term dataset of Cabauw. The specific characteristics of the Cabauw site e.g. its flat topography and reasonable homogeneity (van Ulden and Wieringa, 1995; Beljaars and Bosveld, 1997) makes it well suited to study decoupling around sunset, low level jet formation and the morning time transition (Angevine et al. 2001). A reasonable ideal case was found in the Cabauw long observational dataset. It consists of the period July 1st 2006 12 UTC to July 2nd 2006 12 UTC. This is an (almost) clear sky period with reasonable constant geostrophic wind over time of typically 7 m/s 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 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 hind casts of several 3D NWP models. The case setup is defined at www.knmi.nl/samenw/gabls. The modelers were then asked to run their SCM models with full physical interaction, e.g. interaction with their own soil/vegetation and radiation schemes.

In section 2 the models and the observations used for the evaluation are documented. Section 3 focus on a characterization of the differences among models and between models and observations. In section 4 we try to explain the differences found. This is not straightforward due to the strong interactions between turbulent mixing, radiation and the soil/vegetation system. We pursuit this by running one of the models with various parameter settings and compare the variation found in the sensitivity runs with the variation among models.

2. MODELS AND OBSERVATIONS

The important physical phenomena that characterize the nocturnal boundary layer are time of transition around sunset, growth rate of the stable turbulent boundary layer, development of the vertical profiles of wind and temperature and the morning transition. 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. Differences with reality may

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occur since the prescribed forcings are based on indirect observations.

In Table 1 (see end of the manuscript) the nineteen models that joined the intercomparison are listed together with their characteristics. The models range from operational global models with course vertical resolution and K-diffusion to models with TKE- and 2nd order closure schemes and run at higher vertical resolution.

Observations are taken from the continuous observational program of Cabauw. These include profiles of wind speed, wind direction, temperature and humidity from the 200 m tower. A Windprofiler provides wind speed and wind direction above the tower. Incoming long wave and short wave radiative fluxes are from the Cabauw Baseline Surface Radiation Network (BSRN) site. Upward radiative fluxes and sensible and latent eddy correlation heat flux observations are taken from the Cabauw land surface field site. Soil heat flux observations are derived from soil heat flux plates and temperature sensors in the soil extrapolated to the surface to correct for storage in the upper soil layers. Stable boundary layer height is defined as the height at which the air temperature profile attains its maximum value.

3 RESULTS

3.1 *Initial conditions and day time simulation*

In the first hours after the start of the simulation there is already a substantial difference in short wave incoming radiation among models in the range from 780–910 W/m^2. Differences in long wave incoming radiation are much smaller and range from 345–375 W/m2. Modelers were asked to adapt soil water content to arrive at a Bowen ratio of 0.33 at initialization. Still Bowen ratio varies from 0.25-0.40 among models in the first few hours of the simulation. For some models the initialization of the soil thermal profile did lead to an imbalance with the surface energy fluxes. In those cases heat flux into the soil is in general too high and a significant adjustment can be observed in the first few hours of the simulation. All this result in a range of sensible heat flux from 80-140 W/m2. Sensible heat flux is one of the main drivers for the convective boundary layer growth. Boundary layer height in the first few hours varies between 1800–2200 m among models which is nicely around the 2000 m which is prescribed at initialization and diverge deliberately from the observed value of 1500m (see Baas et al., 2008a).

3.2 *Evening and morning transitions*

Due to the high transpiration rates sensible heat flux is significantly suppressed, resulting in an observed transition time from unstable to stable stratification 3 hours before sunset. The times of transition from unstable to stable stratification show a spread of more then one hour among models. Most models simulate an earlier transition then observed. Figure 1 shows the sensible heat flux during the time of transition. The moment of transition and possible decoupling of the boundary layer from the surface may have important impact on the development of the wind during the night.

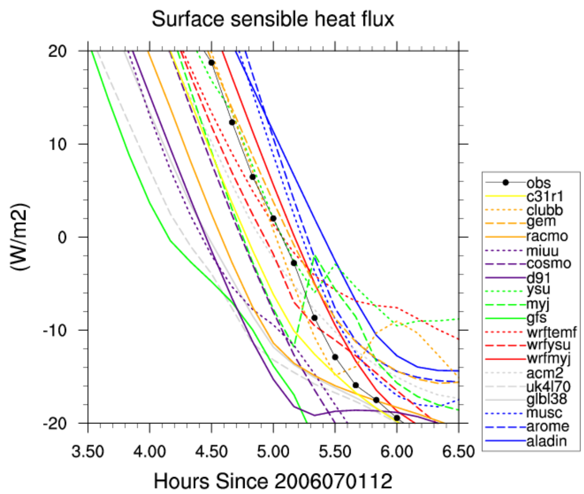

Figure 1. Sensible heat flux in the afternoon at sun set transition.

The observed time of morning transition from stable to unstable stratification (not shown here) is 1.5 hours after sunrise. Models show a 2 hours spread centered around the observed value.

3.3 *State and structure of the stable boundary layer*

Figure 2 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, e.g. a 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 then observed.

Winds at the 200 m level are shown in Figure 3. 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.

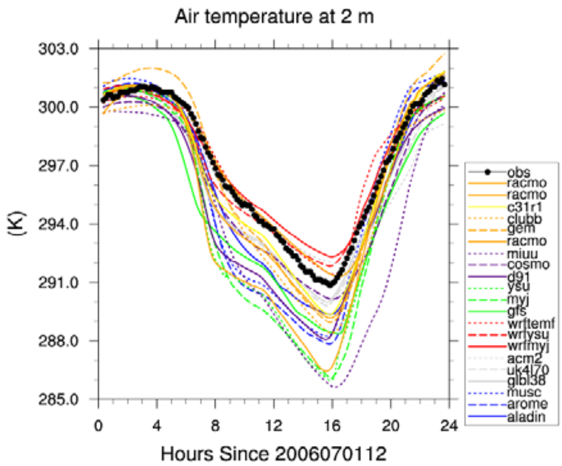

Figure 2. Air temperature at 2 m for the models together with observations.

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 then would be expected when no advection was present. All models peek at 11 hours after the start of the simulation but all of them at a lower value then observed. More then half of the models peek within 2 m/s from the observed values.

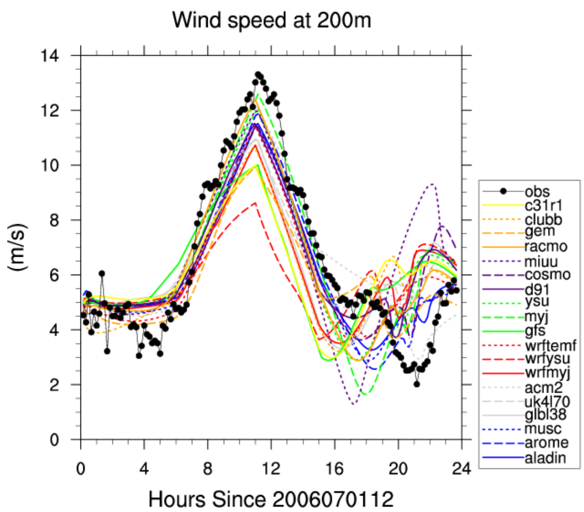

Figure 3*.* Wind speed at 200 m for the models together with observations.

Around and after sun rise models start to differ from each other and from the observations. At the 80 m level (not shown here) well within the turbulent layer, a number of models peek at higher wind speed then observed.

Figure 4 shows the development of the stable boundary layer height, here defined as the height at which air temperature attains its maximum value. 2/3rd of the models do a reasonable job compared to the observations. Most of the remaining models overestimate stable boundary layer height.

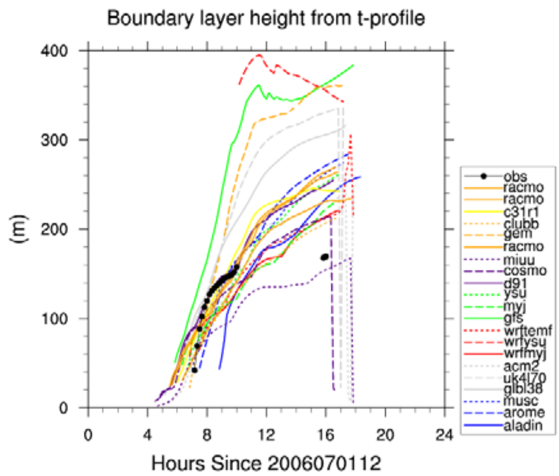

Figure 4*.* Stable boundary layer height, based on air temperature maximum, as function of time.

4. ANALYSIS

Having characterized the behavior 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 will make use of observations and use 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 (Λ) between the skin layer and the soil (Λ = 0.5 -> 5 -> 50 W/m2/K). These runs are named *coupling*. Turbulent mixing in the TKE-l scheme was changed by varying the parameters that relates turbulent length scale to the properties of the flow [c_h , c_p], ([c_h,c_p] = [0.1,0.0] -> [0.2,1.0] -> [0.4,1.0]), (Baas et al, 2008b). These runs are named *mixing*. Long wave incoming radiation was reduced 15 W/m^2 by performing a run with lower specific humidity in the atmospheric profile. A run with higher specific humidity could not be used because undesired cloud formation occurred. A high incoming long wave radiation run was simulated by adding to each analyzed model parameter of the undisturbed run the difference between the undisturbed run and the low humidity run. These runs are named *radiation*.

4.1 *Exchange with land surface*

Most of the models have larger night time soil heat fluxes then observed. Values ranging up to 60 W/m2. Larger soil heat fluxes may arise from a larger variation of the surface temperature and it may arise from a better thermal coupling of the atmosphere with the vegetation soil system. 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.

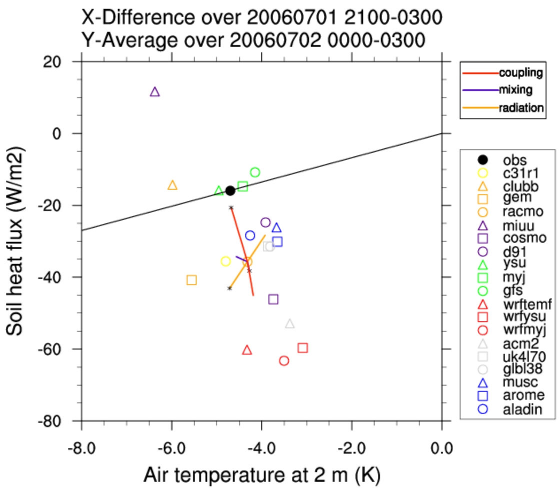

Figure 5. Night time soil heat flux as function of 2m air temperature change over the night. The black line represents points with the same coupling as observed. The three colored lines connect the different sensitivity runs (see main text). The crosses at the colored lines represent the points with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

A considerable spread among models is observed mainly perpendicular to the constant coupling line. The line for *coupling* sensitivity has the same orientation as the main spread among models. The effect of changing *mixing* is small. This is confirmed by looking at groups of models which have the same surface modules and different turbulent mixing schemes. Members in the groups (wrftemf,wrfysu,wrfmyj), (uk4l70,glbl38), (musc,arome, aladin) and (c31r1,racmo) show approximately the same sensitivity. From this it is clear that differences in thermal coupling play a significant role in the differences in surface soil heat flux and in night time temperature drop among models.

It is found that the models with a skin layer cluster in the region between observations and the reference run of RACMO. The group of models without skin layer show a much larger variation in the diagram. The observations suggest that most models overestimate the coupling to the surface.

Not surprisingly figure 6 shows that night time soil heat flux has a significant impact on the minimum 2m temperature. The same models that show strong coupling give higher temperature minima and visa versa.

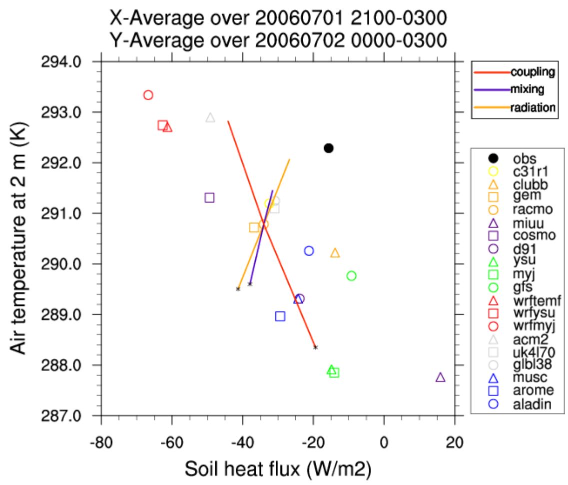

Figure 6. 2m air temperature after midnight as function of averaged night time soil heat flux. For explanation of lines see Figure 5.

4.2 *Radiation*

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 7 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 is perhaps a bit counter intuitive but the 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 behavior 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 visa versa as already discussed.

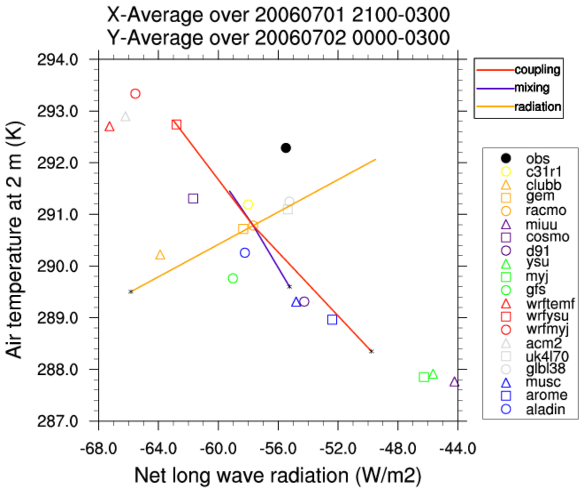

Figure 7. 2 m air temperature after midnight as function of night time net long wave radiation. For explanation of lines see Figure 5.

A simple change of land surface coupling will not bring the models closure to the observations here. This suggests that the models also miss represent longwave radiation.

The discussion on figure 7 shows that net long wave radiation is a so-called internal variable of the SBL since it depends strongly on the evolution of the SBL itself. Iso-thermal net long wave radiation is an external variable. In this variable long wave upward radiation is replaced by the black body radiation at a reference level (here chosen as 200m) above the SBL. Figure 8, where iso-thermal net longwave radiation is on the x-axis, shows that we have now a more intuitive relation between radiative forcing and 2m temperature. It is the variations in long wave incoming radiation that dominates variations in the iso-thermal net long wave radiation. In this case the sensitivity runs suggests that a change in coupling may bring some of the models closure to the observations. This point to a problem in the representation of long wave upward radiation, although compensating effects related to the temperature difference between the surface and the 200 m level, at which the iso thermal radiation is calculated, may also play a role.

We can go one step further and define iso-thermal available energy as the iso-thermal net radiation minus the soil heat flux. This then can loosely be interpreted as an external measure of the thermal energy extracted from the SBL.

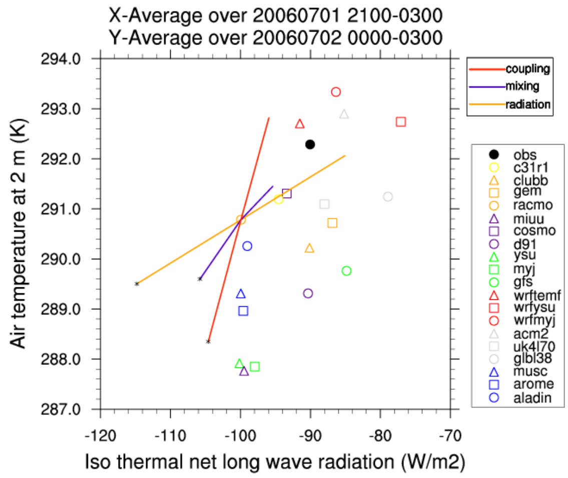

Figure 8. 2 m air temperature after midnight as function of night time iso-thermal net long wave radiation. For explanation of lines see Figure 5.

Figure 9, where now iso-thermal available energy is on the x-axis, shows a nice organization of the model points. The largest negative energies corresponding to the lowest model temperatures. The correlation is even better then in figure 6. The sensitivity lines of *coupling* and *radiation* are parallel and along the spread of the model points. Thus iso-thermal available energy seems to be a nice predictor for the resulting 2m minimum temperature in a model.

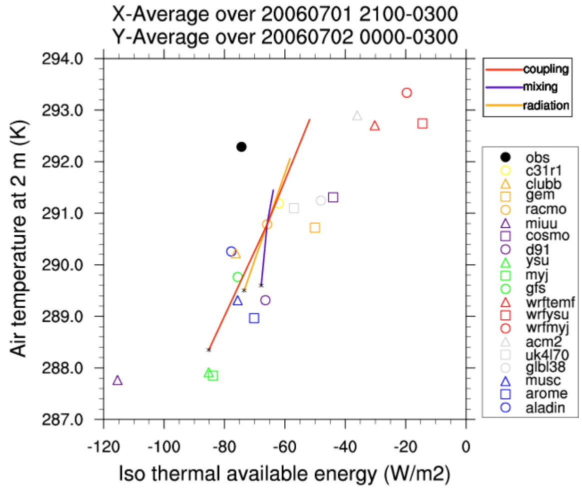

Figure 9. Main 2m air temperature after midnight as function of isothermal available energy. For explanation of lines see Figure 5.

The sensitivity runs do not show an easy way to get the models closure to the observations in this case.

4.3 *Turbulent mixing*

Figure 10 shows mean night time sensible heat fluxes before midnight as function of boundary layer height at midnight. Note that the observed boundary layer height is an extrapolated value based on figure 4. Increased downward sensible heat flux is coupled to higher 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.

Given the correlation between sensible heat flux and boundary layer height it is to be expected that the rate of change of temperature in SBL is not very sensitive to this mixing efficiency since at high downward sensible heat fluxes the heat is extracted from a thicker turbulent layer. This is confirmed by the small *mixing* line in figure 5.

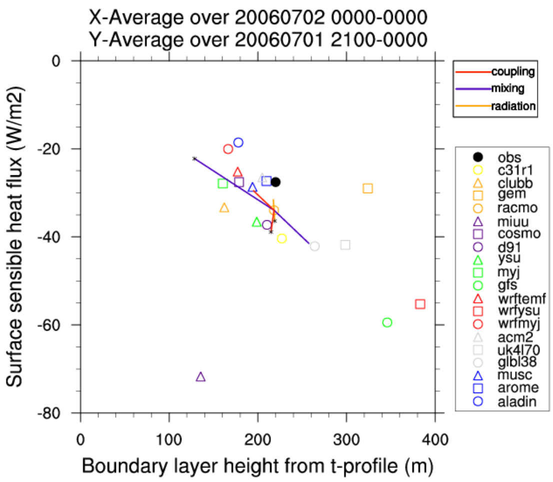

Figure 10. Nigh time sensible heat flux before midnight as function of boundary layer height at midnight. For definition of boundary layer height see text. For explanation of lines see Figure 5.

5 DISCUSSION AND CONCLUSIONS

The Cabauw site with its flat and homogeneous terrain and its long observational record has enabled the selection of a relatively ideal case. By carefully prescribing the forcings on the vertical column as they change in time the models are able to reproduce the gross features of the stable boundary layer like: onset of decoupling, signature of surface temperature over time and evolution of the inertial oscillation. Differences between models occur in details which can now be studied in depth by comparing with observations.

Significant variations among models are found in minimum 2m air temperature, wind maximum at 200 m and in boundary layer height. Using sensitivity runs performed with one of the models this variations can be coupled to differences in parameterization of thermal coupling to the soil, longwave radiation exchange and turbulent mixing. The main conclusions are: 1) Models with strong thermal coupling to the soil gives large surface soil heat flux and high minimum air temperature at 2m. 2) A strong influence is found of surface temperature on net long wave cooling. 3) Spread in iso-thermal available energy seems to be a good predictor for the spread in 2m temperature among models. 4) Sensible heat flux and boundary layer height are well correlated among models. The sensitivity runs show that this spread is caused by a spread in turbulent mixing.

The miss representation of thermal coupling of the SBL to the soil/vegetation system seems to be the most important factor explaining differences between models and observations. Representation of long wave radiation and turbulent mixing are of secondary importance.

Here we have focused mainly on the thermal aspects of the SBL. In future work focus will be on the representation of wind and the representation of the transition periods. This new analysis may well shift our view on the relative importance of the miss representation of various processes.

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Name	***Institute***	***PI***	***Nlev***	***BL.Scheme***	***Skin***
ALADIN	Meteo France	Bazile	41	TKE-l	No
AROME	Meteo France	Bazile	41	TKE-l	No
GLBL38	Met Office	Edwards	38	K (long tail)	Yes
UK4L70	Met Office	Edwards	70	K (short tail)	Yes
D91	WUR	Steeneveld	91	K	Yes
GEM	Env. Canada	Mailhot	89	TKE-l	No
ACM2	NOAA	Pleim	155	K+non-local	No
WRF YSU	NOAA	Angevine	61	K	No
WRF MYJ	NOAA	Angevine	61	TKE-l	No
WRFTEMF	NOAA	Angevine	61	Total E-l	No
COSMO	DWD	Helmert	41	K	No
GFS	NCEP	Freedman	57	K	Yes
WRF MYJ	NCEP	Freedman	57	TKE-l	Yes
WRF YSU	NCEP	Freedman	57	K	Yes
MIUU	MISU	Svensson	65	2nd order	No
MUSC	KNMI	De Bruijn	41	TKE-l	No
RACMO	KNMI	Baas	80	TKE-l	Yes
C31R1	ECMWF	Beljaars	80	K	Yes
CLUBB	UWM	Fasching	250	Higher order	No

Table1. The participating models with their characteristics.