RC1 (John King)

General

Numerical Weather Prediction (NWP) models, atmospheric reanalyses and Earth System Models (ESMs) are being used increasingly to study the weather and climate of the polar regions. However, the land surface and surface exchange schemes used in such models have generally been optimised for performance in mid-latitudes and, while they may include a representation of snowpack processes, the snow models used may not correctly represent processes at work in the cold, dry and persistent snowpacks of the polar regions. This interesting and well-written paper reports an intercomparison of stand-alone snowpack models using forcing and validation data from Dome C, Antarctica, a location which is representative of the high Antarctic plateau. The intercomparison, carried out as part of the GEWEX GABLS project, included snow models that are components of a number of leading ESMs and NWP models and the results will be of value to users of those models, particularly those using these models in the polar regions. The paper is (mostly) written very clearly and presents useful results. I recommend that it should be published in The Cryosphere after attention has been given to the points listed below.

Major points

1. Section 2.2: I found this section quite difficult to follow. In particular, I found the different ways in which the various runs are referred to - "reference simulation", "XP0", "XP1", "_new" – rather confusing. Please try to adopt a clear and consistent terminology. Are the parameters shown in table 3 those that were used in the "reference simulation" (XP0)? I was also quite confused about how XP1 differed from XP0 – are the changes only applicable to single-layer models? As this section is describes a central part of the methodology of the study it needs to be rewritten to improve its clarity. It might help to add additional tables to highlight the differences between the XP0 and XP1 runs. You don't say anything in this section about how the models were initialised (presumably using observed snow temperatures?) or whether any spin-up was undertaken to avoid initial transients.

   Thank you for this very useful remark. It is true after reading again the manuscript that it was more than unclear. Section 2.2 was modified substantially in order to make it clear. In a few words, XP0 stands for the simulations with model's default values for surface parameters, some models have performed calibration. Then XP1 corresponds to XP0 with imposed parameters for albedo, emissivity, roughness length, density and the thermal coefficient of snow. Some multi-layer model also ran XP1 (but they did not impose density nor thermal coefficient of snow). New tables were added to clarify the differences between XP0, calibrated XP0 and XP1. As now indicated in Section 2.2, models were initialized from the observed snow temperature profile and no spin-up was done.

   Here is the new content of section 2.2:

The models were run offline, i.e. guided by the atmospheric forcing measured at Dome C, for a total simulation time of 15 days. Snow temperature was initialized from in situ

measurements. First, each group had to provide the results obtained with the default settings of the surface parameters of their model. The models were run offline, i.e. guided by the atmospheric forcing measured at Dome C, for a total simulation time of 15 days. This set of simulations is called XP0, it includes one simulation for each of the 10 models and the name of an experiment is made up of the name of the model suffixed by "_xp0". From the simulations in the XP0 set, each participant could propose additional simulations. Only CHTESSEL and CLM4 performed calibration simulations, aiming at minimizing the root mean square error on the surface temperature. CLM4 calibrated the surface albedo and CHTESSEL calibrated the snowpack thickness and from this calibration then calibrated the dynamic and thermal roughness lengths. The names of the corresponding experiments are CLM4_cal1, CHTESSEL_cal1 and CHTESSEL_cal2 respectively. In addition, a rerun was proposed in order to better represent the diurnal cycle and to reduce the dispersion of the surface temperature results, but also to see if this dispersion was reduced or not in the coupled single-column simulations (this last point is not addressed in this study).

Snow albedo depends on zenith angle, but also on grain size and cloud cover. At Dome C, because the sky is generally clear, the effect of solar zenith angle is prominent compared to the typical diurnal cycle. Warren (1982) showed that the albedo of snow was maximum when the sun was low while its effect was less when the sun was at the zenith, it then enabled the surface to warm, or at least cool less by radiative effect. Most models do not consider the variation of albedo with the zenith angle, a fixed average value is proposed in the experimental protocol, corresponding to the average value of the ratio between the incident and reflected radiation measured at Dome C, over the period considered. Concerning the thermal emission of snow, the value of 0.98 is within the range of values commonly used for this type of medium. For the dynamic and thermal roughness lengths, values of 1 mm and 0.1 mm were chosen respectively. The dynamic roughness length is close to that established by Vignon et al. (2017a) who studied the effect of sastrugi on flow and momentum fluxes and proposed using a thermal roughness length that is one order of magnitude smaller than the dynamic roughness length. This ratio of 10 is classically used in many models calculating fluxes at the surface-atmosphere interface. Snow density at the surface can range from 20 kg m^{-3} for fresh snow to 500 kg m^{-3} for old, wet snow. Measurements at Dome C during the summer of 2014-2015 (Fréville, 2015) show that the snow density profile varies between 250 kg m^{-3} and 310 kg m^{-3} between the surface and 20 cm depth (Gallet et al., 2011).

Therefore, all participants were asked to run a new simulation with an albedo of 0.81, an emissivity of 0.98 (which corresponds to the average emissivity of the hemisphere (Armstrong and Brun 2008)), dynamic and thermal roughness lengths of 0.001 m and 0.0001 m, respectively, and for single-layer schemes, to impose a snow density of 300 kg m^{-3}, as well as the snow thermal coefficient c_s=3. 166 ×10^{-5} (K m^2 J^{-1}). This coefficient is directly involved in the temperature evolution equation along the vertical:

$$C_{snow} \times \frac{\partial T(z,t)}{\partial t} = \frac{\partial}{\partial z}\left(\lambda(z)\frac{\partial T(z,t)}{\partial z}\right) \qquad (1)$$

$$c_s = (h_{snow} \times C_{snow})^{-1} \qquad (2)$$

Where $\lambda(z)$ is the heat conductivity of snow, h_{snow} the snow depth (m) and C_{snow} the volumetric heat capacity of the snow (J K^{-1} m^{-3}).

Moreover,

$$C_{snow} = c_i \times \frac{\rho_{snow}}{\rho_i} \tag{3}$$

where c_i and ρ_i are the heat capacity and density of the ice respectively. Combining equations (2) and (3) gives finally equation (4):

$$c_s = \rho_i \times (h_{snow} \times \rho_{snow} \times c_i)^{-1} \tag{4}$$

Taking a thickness of $h_{snow} = 5$ cm, densities of snow and ice of 300 kg m^{-3} and 900 kg m^{-3} respectively, and the heat capacity of ice $c_i = 1.895 \times 10^6$ J K^{-1} m^{-3} we obtain according to equation (4) the value of c_s. This rerun is named XP1 and the name of the simulations that refer to it consists of the name of the model suffixed by "_xp1".

Not all models were able to perform this new experiment, either due to lack of time or because the results came from an operational model that did not allow for adjustment of certain parameters or variables in the schemes. Although not all of them participated, it is interesting to study the impact of the changes induced by the XP1 configuration on the simulations of the XP0 ensemble, considering, when they exist, the calibrations. We therefore calculated the daytime and nighttime biases, as well as the difference in RMSD between XP1 and XP0 (or the simulation calibrated from a simulation of the XP0 ensemble), and evaluated the impact on the model error.

2. Section 3.4: The measured values of Qh and Qle on figures 9 & 10 indicate a Bowen ratio, Qh/Qle of O(1), which seems remarkably low at such low temperatures (see discussion in King et al, 2006, doi:10.1029/2005JD006130). Measuring Qle at such low humidities is very challenging and I suspect that there are very large uncertainties in the measurements.

   This is completely true and it was part of the discussion section, a comment was added in section 3.4 to emphasize the fact that the Bowen ratio is very small and probably a result of large uncertainties in the measurements of both Qh and Qle, particularly an overestimation of Qle, and also made a reference to the mentioned paper.

   Text added in section 3.4:

Figure 9 and 10 are scatter plots that compare Q_h and Q_{le}, the hourly sensible and latent heat flux, respectively, simulated by the different models to the observations. We see at first that the measured latent heat flux is abnormally high. Indeed, as shown by King et al. (2006), this flux can only be of the order of a few W/m2 at Dome C, and that the closure of the energy balance has a high uncertainty. Thus, the reconstruction of heat fluxes from Eddy-Covariance measurements is likely to be subject to error and comparisons made here should be taken with caution.

3. Section 3.4, fig. 11: Looking at this figure, it is apparent that most of the models specify Ch as a universal function of Ri, but GDPS4 and CLM4 seem not to do so. What other factors are used in the calculation of Ch in these models? Would the curves for the different models collapse onto a universal curve if, instead of plotting Ch, you plotted Ch/Ch(Ri=0) – i.e. the ratio of Ch to its value under neutral stratification (which should only depend on the roughness lengths)? It would also be interesting to plot Ch calculated from the Dome C observations on this figure. From my own experience, I would expect to see a lot of scatter if you plotted points for each

30 minute observation, but if you averaged these together in bins of Ri you might get a useful set of points for comparison with the models.

Good remark, most models use Louis model to calculate Ch as a function of Ri. There are 3 exceptions here GDPS4, CLM4 and NOAH (NOAH is not in fig11 since Ri was not provided), for which the calculation of Ch is iterative and based on Monin Obukhov's theory. I have proposed a new figure to replace fig11, where GDPS4, CLM4 and NOAH are removed since their Ch does not depend on Ri. Then I followed your advice to normalize by the Ch at neutrality. This is the figure 11a I have now included in the manuscript, to show that the curves do not collapse into a single universal one, and which highlights the fact that most models have tuned their stability function from the universal one. I have calculated Ch from the observations and tried to compute the bulk Ri from the observation as well. ChObs is very small as compared to the modeled values. There is a large uncertainty in the calculation of Ri (z0_obs, z0h_obs, …) therefore I have not included it. But I have proposed another plot (Fig. 11b) which is the time evolution of Ch (in that way all models can be plotted) in the time window where I have observations (2.5 days) in order to show how different modeled Ch are from estimated ChObs.

The description of Figure 11 results has been modified:

Equation (6) also involves C_h which depends on the dynamic and thermal roughness lengths as well as the stability of the air characterized by the gradient Richardson number R_i, except for the GDPS, CLM4, and NOAH models, for which the calculation of C_h is iterative and based on Monin Obukhov's theory. Figure 11a shows how C_h normalized by its value at neutrality (i.e. when R_i=0) varies as a function of R_i for all models that provided values. that the curves do not collapse into a single universal one, and which highlights the fact that most models have tuned their stability function from the universal one. We note a strong dispersion in the representation of the normalized exchange coefficient with, depending on the model, values twice as large, for instance in the case of convection when R_i is equals to -3. On the other hand, the values are very low for the stable atmosphere cases, i.e. when R_i is positive, which is in good agreement with weaker turbulent exchanges or even almost zero in these conditions. To highlight the disparities in the Ch coefficient, the temporal evolution of Ch has been plotted in Figure 11b for all models, as well as the value of this coefficient calculated from the observations. Figure 11b shows that C_h is simulated rather well for low turbulence conditions (low C_h) but is overestimated for the GDPS4, CLM4 and NOAH models. On the other hand, when the turbulence increases (December 13), these models simulate C_h quite well. However, the variability of the simulated C_h is then much greater.

4. Section 4, concluding remarks. This study has focussed largely on snow models that are used within global models and have not been specifically optimised for polar conditions. It might be worth mentioning here work that has been done on developing polar-optimised snow/firn models for use within regional climate/NWP models, such as Polar WRF (Hines and Bromwich, 2008, 10.1175/2007MWR2112.1), MAR (e.g. Agosta et al, 2019, 10.5194/tc-13-281-2019) and RACMO2 (e.g. van Wessem et al, 2018, 10.5194/tc-12-1479-2018).

I agree that this is missing and I have added a comment to correct that:

This study has largely focused on snow models that are used within global models and have not been specifically optimized for polar conditions. However, it is important to note that work has been done to develop snow/firn models optimized for polar conditions for use in regional NWP and climate models, such as Polar WRF (Hines and Bromwich, 2008), MAR (Agosta et al., 2019), and RACMO2 (van Wessem et al., 2018).

Minor points and typographical corrections

Line 40: "firn", not "firns"

done

Line 146: "UK Met Office"

done

Table 1: Maybe add a column indicating which NWP/ESM/reanalysis models use the snow model that is being tested. I assume that "LMDZ" refers to the snow submodel used within the LMDZ global atmosphere model – doesn't the submodel have its own name?

Table 1 was removed (see RC2 comments)

Lines 171-174: Maybe include a table that gives the snow layer depths, densities, etc.?

This information has been added to the end of the new section 2.2 and a table was added:

For the multilayer models, the snow density and temperature profiles were initialized from observations. Note that the single-layer models use a fixed density close to 300 kg m^{-3} which corresponds to a depth of about 10 cm in the initial profile, and their initial temperature was also provided from in situ measurements. Table 1 describes the vertical discretization and gives the initial temperature and snow density profiles. The LMDZ model is a special case. Indeed, it is a ground thermal model with the thermal inertia of snow that is used and not really a snow scheme, which is why there is no snow density as such.

Line 211: "…enabled us…" instead of "…allowed…"?

done

Figure 1: Pressure seems to have been recorded with only 1 hPa resolution? "Direct solar radiation…" in the caption should (I think) be "downward solar radiation"."Direct" would usually mean direct solar beam only, i.e. not including the diffuse component.

Looking at the pressure time series, it has not always been recorded with a 1hPa resolution but most of time it is the case. The manuscript was not changed.

Direct solar radiation is replaced by downward solar radiation.

Table 3: Caption could be made a bit more informative. [...,...] indicates the range of a parameter that is calculated within the model. Presumably single values are where a fixed value is specified? Explain why several values depart from the control run values listed in section 2.2.

The caption was modified as follows:

Range of variation of model surface parameters for XP0. The values in square brackets indicate the values taken by a parameter when it is calculated by the model while the single values are fixed during the simulation.

Section 2.2 was rewritten and it is now explained that parameters are from the default model's configuration (cf answer to comment number 3)

Line 286: Change "Fig. 4 shows the evolution of the broadband albedos that vary over time. Indeed, the four models presented consider the variation of the albedo…" to "Fig. 4 shows the modeled broadband albedos in the four models that model the albedo…"

done

Line 321: Change "radiation" to "energy".

done

Lines 389-390: "…that varies from simple to double" Please clarify

The text is changed into: that varies from 0.4 K (CHTESSEL) to 1 K (JULES).

Lines 390-392: "It should be noted that the single layer models (D95, CHTESSEL, EBA) have sometimes better results than the more sophisticated models which have to represent more physical processes, such as the evolution of albedo with time, the increase of snow density by compaction, among others." Maybe you could make this clearer on figure 8 by using a different shape of symbol for the multi-layer models?

Figure 8 was modified to distinguish between single-layer models and multilayer ones. Caption has been updated accordingly.

Line 442: "…gradient Richardson number…". Model parametrisations are usually based on a bulk Richardson number, calculated from the temperature difference between the lowest model level and the surface and the wind speed at the lowest model level. Include an equation that defines how the Richardson number is calculated.

The following text was added:

The bulk Richardson number is expressed as:

$$R_i = \frac{g}{\langle T \rangle} \frac{\Delta\theta \; \Delta z}{(\Delta U)^2} \tag{7}$$

Where g is the acceleration of gravity, $\langle T \rangle$ the average virtual temperature, $\Delta\theta$ and ΔU the gradients of virtual potential temperature and wind speed of the considered layer of thickness Δz. The very low humidity of the air allows to assimilate the average virtual temperature and the virtual potential temperature to the average temperature and the average potential temperature.