SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Permafrost in a changing climate: Formulating the proper lower boundary condition in EC-Earth
Computer Project Account:	spdkhess
Start Year - End Year :	2014 - 2015
Principal Investigator(s)	Dr. Jens Hesselbjerg Christensen
Affiliation/Address:	Danish Meteorological Institute Lyngbyvej 100 2100 CopenhagenØ Denmark
Other Researchers (Name/Affiliation):	Dr. Shuting Yang (DMI) Dr. Peter Langen (DMI) Dr. Martin Stendel (DMI)

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

In climate models a fundamental assumption is often made in the formulation that the lower boundary underlying land surfaces is characterized by a zero flux formulation. As the lowest model level in the soil is often located less than 5 meters below the surface, (and thus also the atmosphere), this is clearly not deep enough to reflect the penetration of transient temperature signals into the deeper layers for cold regions underlain by permafrost (Nicolsky et al. 2007; Christensen et al. 2008). The aim of this project is to investigate the sensitivity of climate response to the zero flux formulation at the lower boundary in the permafrost regions in EC-EARTH.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

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Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

The application procedure is straight forward and transparent. Reporting is somewhat less transparent. It is not clear to what degree various parts of the report is actually used and no-one appreciates to do work for no reason. I would therefore like to suggest that the report scheme is modified to reflect who will make use of the different parts.

Summary of results

(This section should comprise up to 10 pages and can be replaced by a short summary plus an existing scientific report on the project.)

As in all climate models, an approximation of no geothermal heat exchange (i.e., zero flux) everywhere at the lowest boundary in the model land soil is applied in the EC-EARTH model, while a total soil depth is assumed to be 2.89 meters with four discretized layers. It is well known that ground heat flux under the permafrost e.g. in northeast Siberia is very small; however, a study by Lee and Uyeda (1965) it is suggested that the ground heat flow beneath the land permafrost may be between 40 mW/m^2 for the continental shield (i.e., land permafrost) and 60 mW/m^2 for the offshore “canyons” (i.e., subsea permafrost partly filled with sediments), implying the boundary condition underneath permafrost in climate models may be mistaken. On the other hand, Nicolsky et al. (2012) showed that the sensitivity of subsea permafrost to tiny changes in the ground heat flux (in their case from 60 to 70 mW/m^2) has large effect on the stability of permafrost. As the current zero flux condition is equivalent to taking away 40 mW/m^2 at the bottom over extended periods of time, it might be suspected that the warming of permafrost from below is underestimated in the long run. To test the sensitivity of the climate response to heat exchanges beneath the land permafrost, we have therefore replaced the current zero flux boundary condition with a downward relaxation value of 40 mW/m^2 in the model. In this way the heat (energy) from the lowest soil layer in the model is allowed to penetrate into the rigid boundary.

A new set of CMIP5 experiments, evolving the historical period from 1850 to 2005 and following with the two future scenarios of RCP4.5 and RCP8.5 until year 2100, were performed using the above new formulation (hereafter referred to as experiment pmFrost). The experiments are then compared with two sets of the CMIP5 experiments using the standard EC-EARTH (i.e., control runs, hereafter referred to as Ctrl01 and Ctrl02 respectively). Examination of the annual mean surface air temperature (SAT) indicates that the time evolution of the simulated SATs generally

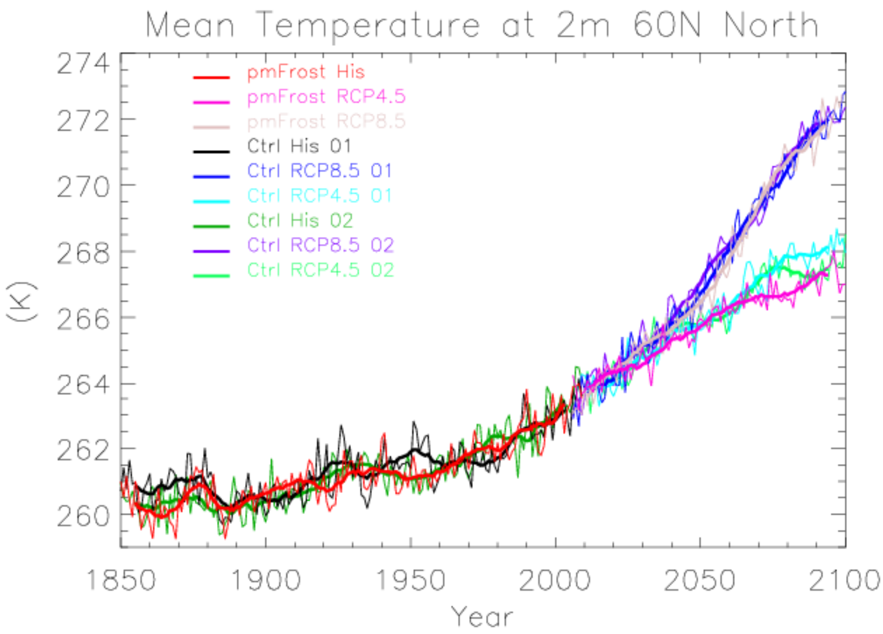

Figure 1. Time evolutions of the annual mean (thin lines) surface air temperature averaged over the area north of 60°N simulated in the CMIP5 experiments using the permafrost-sensible version of the EC-EARTH (pmFrost) and the standard EC-EARTH formulation (Ctrl). The CMIP5 experiments evolve over the historical period from 1850 to 2005 and then follow the future RCP4.5 and RCP8.5 scenarios, respectively, until year 2100. Two Ctrl CMIP5 experiments (labelled as 01 and 02) are shown in the figure. The thick lines indicate the 11-year running mean. Unit: K.

follows similar trajectories in all three sets of experiments, as seen in figure 1 where the average annual mean SAT north of 60°N in all three sets experiments are plotted. Figure 1 also reveals that the boreal SAT in pmFrost could be different from the Ctrl runs from time to time. For instance, in the RCP8.5 scenario, the SAT in pmFrost is somewhat below that in the two Ctrl experiments during the large transition period around 2040 to 2060. In the RCP4.5 scenario, the SAT in pmFrost is more than a half degree lower than that in the Ctrl experiments towards the end of the 21st century. The geographic distribution of the SAT differences in the latter case can be seen in Figure 2, where the Arctic area is about 0.5 – 2.0 K colder almost everywhere in the pmFrost experiment than that in the two Ctrl experiments in this period. It is evident from table 1 that the long-term averaged SAT over 60°N north is at least 0.5 K colder in the pmFrost experiment than that in the control experiments towards the end of the 21st century.

Table 1. 25-year averaged surface temperature over north of 60°N in the permafrost-sensible experiment (pmFrost) and the two control runs (Ctrl01 and Ctrl02, respectively) for the period 2070-2094 in RCP4.5, 2040-2064 and 2070-2094 in RCP8.5 scenario, respectively.

Experiment	RCP4.5 2070-2094	RCP8.5 2040-2064	RCP8.5 2070-2094
pmFrost	266.9	266.9	270.8
Ctrl01	267.7	267.2	270.7
Ctrl02	267.4	267.4	270.9

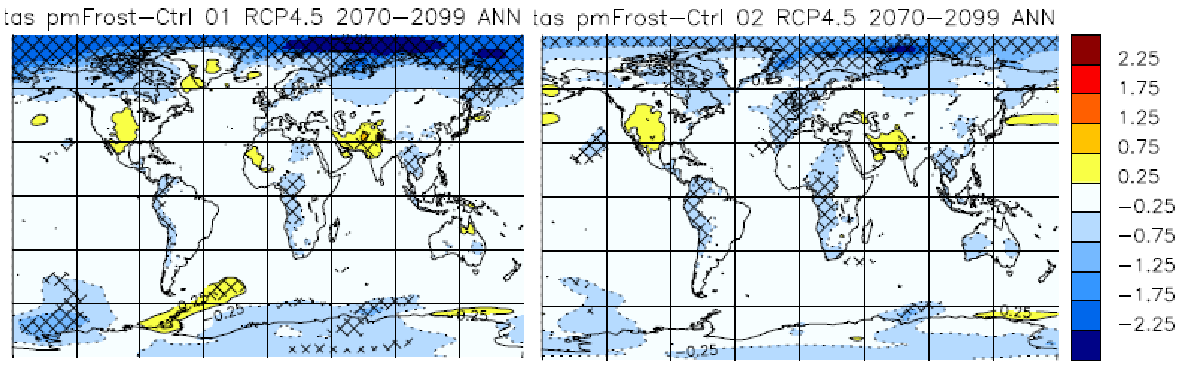

Figure 2. Averaged differences of the annual mean surface temperatures in the period 2070-2099 as simulated in the pmFrost RCP4.5 with respect to the two Ctrl experiments (i.e., Ctrl RCP4.5 01 and Ctrl RCP4.5 02, respectively). The hatched area indicates the significance level exceeding 95%. Unit: K.

As revealed in Figure 1, the large negative differences in the Arctic region in RCP4.5 seen in Figure 2 seem not evident for the warm scenario RCP8.5 during the same period. Figure 3 illustrates the same SAT difference as in Figure 2 but for the simulation of RCP8.5. In contrast to the RCP4.5 simulation, the simulated Arctic SATs in pmFrost under the RCP8.5 scenario are slightly higher than that in two Ctrl experiments, although these positive SAT differences do not exceed the 95% significance level. The 25-year mean SATs for this period indeed show no difference in the RCP8.5 simulations between the pmFrost and the control experiments (Table 1). However, this could be caused from the retreat of Arctic sea ice under the extraordinary warming in the RCP8.5 at the end of the 21st century. To exclude the possible impact of the sea ice, we consider the time period 2040 - 2064 in the RCP8.5 scenario when the mean SAT over 60°N North and the Arctic sea ice coverage simulated in pmFrost is comparable to that for the time period 2070 - 2095 in the RCP4.5. As showed in Figure 4 and in Table 1, the SAT simulated in pmFrost is indeed generally colder in the Arctic area than that in the two control experiments. The time mean differences in average are about 0.3 K (with respect to Ctrl01) to 0.5 K (with respect to Ctrl02), respectively.

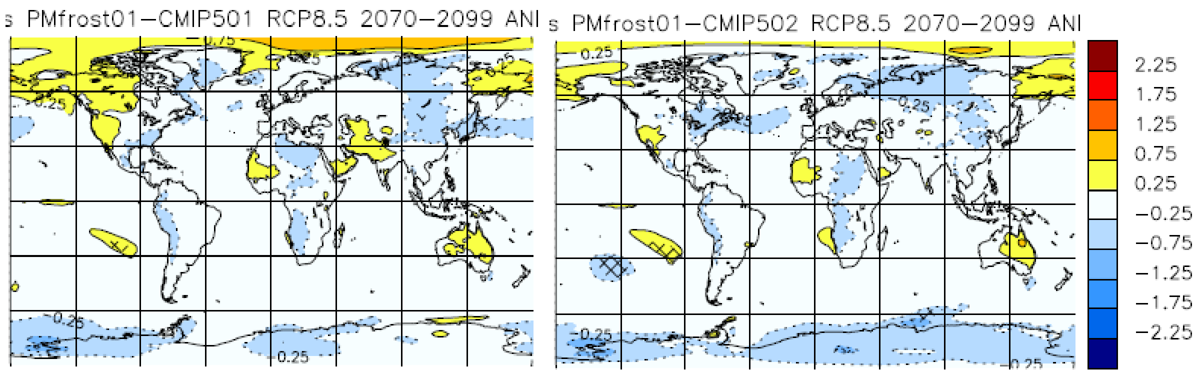

Figure 3. Same as Figure 2 but for RCP8.5 simulations.

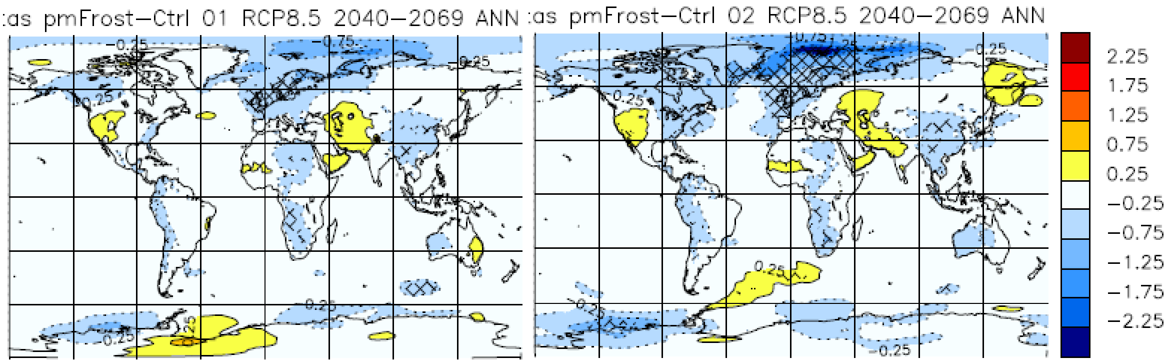

Figure 4. Same as Figure 3 but for time period 2040-2069.

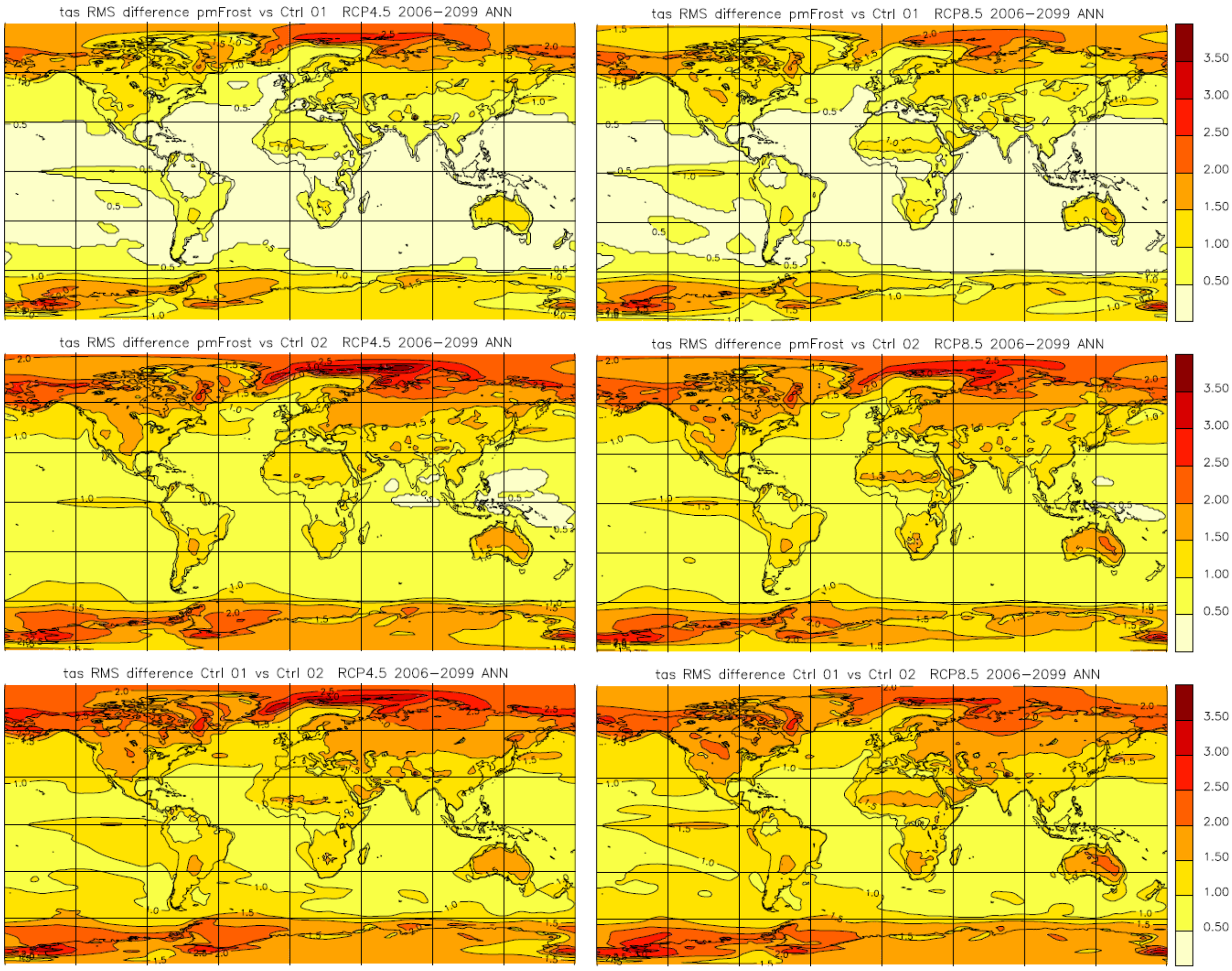

Figure 5. The rms difference between the annual mean SAT simulated in pmFrost and that in Crtl 01 (top), and the Ctrl 02 (middle), and that between Crlt 01 and Ctrl 02 (bottom) for RCM4.5 (left) and RCP8.5 (right), respectively. The SATs were detrended before getting the rms differences. Unit: K.

To further examine whether the colder SAT in the pmFrost experiment shown in Figure 2 is a signal resulting from different treatment in the bottom boundary or due to internal variability, we analysed the root mean square (rms) differences between the detrended SATs in the pmFrost experiment and that in the control runs for the period from 2006 to 2100 in both RCP4.5 and RCP8.5 scenarios, as well as the rms differences between the two control runs for the same period. Figure 5 clearly demonstrates that, if considering the full time period of 21st century, the pattern and the magnitudes of the rms differences between the pmFrost and the control runs, and that between the two control runs are undistinguishable. The current pmFrost experiment does not seem to give significant difference in the warming trend due to increase of the anthropogenic greenhouse gases from that in the control runs.

List of publications/reports from the project with complete references

The results appear to be too insensitive to the perturbation introduced.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

Another experiment in which temperatures in the lowest model level are relaxed to climatology rather than adjusting the flux has been thought of instead, but not been realized due to the used resources. Also a more specific treatment of below surface processes will be looked into by coupling a permafrost module to EC-Earth. This will likely lead to a future SP application.