Greenland ice sheet surface mass balance projections from IPCC AR4 global models

Laboratoire de climatologie
Université de Liège

Franco, B.[1] ; X. Fettweis[1] ; M. Erpicum[1]

(1) Laboratoire de climatologie, Département de géographie, Université de Liège, Belgium, bruno.franco@ulg.ac.be. (Ph. D., FNRS research fellow)

Abstract

*Results from atmosphere-ocean general circulation models (AOGCM's) for the IPCC 4th Assessment Report are used to investigate surface mass balance (**SMB**) future projections of the Greenland ice sheet (**GrIS**). The most efficient models for the GrIS climate modeling are chosen by comparison between the 1970-1999 outputs (averages and trends) from the Climate of the twentieth Century Experiment (20C3M) and reanalyses (ECMWF, NCEP) as well as observations (ice core measurements). The outputs from these most efficient models are after used to assess changes planned by the IPCC greenhouse gas emissions scenarios (SRES) for the 2070-2099 period. The GrIS SMB projections are estimated from changes in precipitation and temperatures from these AOGCM's outputs. However, large uncertainties remain in these SMB projections based on simplified physics and huge model outputs. High resolution simulations made with regional models (which simulate explicitly the SMB by taking into account the surface feedbacks) forced at their boundaries by a GrIS well-adapted AOGCM could bring more precise brief replies.*

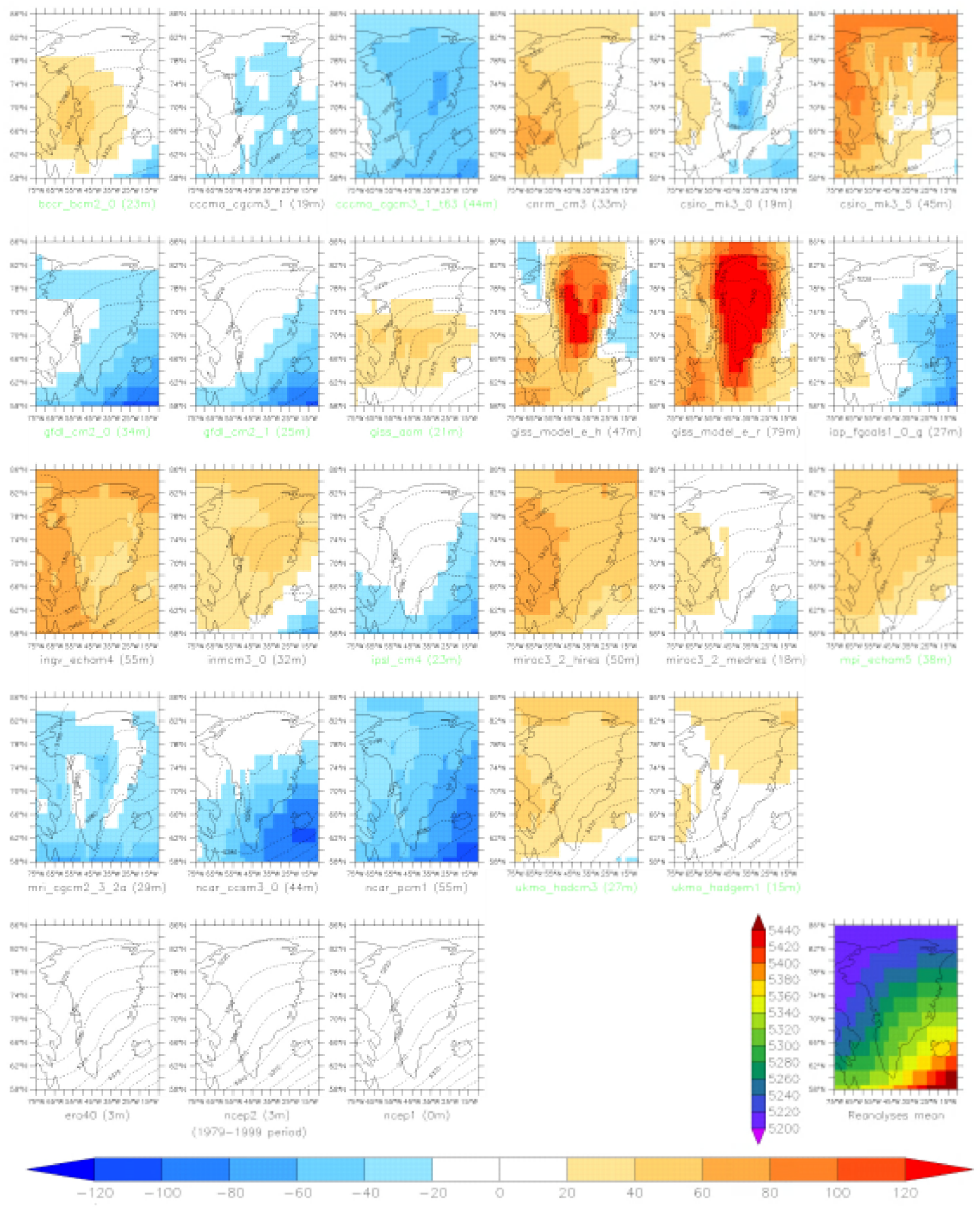

Fig. 1 : Anomalies (in m) between the annual 500hPa geopotential height simulated by the AOGCM's from the 20C3M Experiment outputs, and the annual 500hPa geopotential height from the reanalyses mean, for the 1970-1999 period. In brackets, the average of absolute anomalies compared to the reanalyses mean over the GrIS. The 500hPa geopotential height (in m) is marked in dashed lines. In green, the efficient AOGCM's to the atmospheric circulation modeling.

GrIS modeling by IPCC AR4 AOGCM's outputs

The global models outputs are projected on a common grid 2.5°x2.5° (which corresponds to the NCEP reanalysis grid) in order to assess the AOGCM's abilities to the GrIS modeling for the 1970-1999 period by comparing with reanalyses simulations (ERA-40, NCEP1 and NCEP2) and ice core measurements. The climate components investigated are the following :

- The near surface temperature (3 m height) is a main component of the SMB equation from which is deduced the run-off, acting on the melting conditions (Ohmura, 2001) (not shown).
- The precipitation is the other main component of the SMB equation by adding snow or liquid water to the ice sheet. The winter accumulation also conditions the appearance of the low albedo zones in summer, such as the tundra, and so the bare ice in the ablation zone (Fettweis, 2007) (not shown).
- The atmospheric circulation pattern induced by the 500hPa geopotential height controls the climatic conditions over Greenland, as the near surface temperature and precipitation. This is the essential criterion in the GrIS modeling.

West atmospheric circulation is dominant over Greenland, with a component from the south-west which reaches mainly the western coast in providing heat and moisture from the ocean. The main atmospheric circulation pattern is efficiently simulated by some AOGCM's through the annual mean 500hPa geopotential height (**Fig. 1**), as in the GISS_AOM or GFDL_CM2_0 models. It is a eastward general circulation from the North American continent, which turns toward the north-east over the Baffin Bay before reaching the western coast of Greenland. Finally this oscillation gradually becomes an only eastward circulation, passing over the central GrIS.

The main component of the atmospheric circulation over Greenland is the North Atlantic Oscillation (NAO), which represents the dominant mode of the regional atmospheric variability around Greenland (Rogers, 1997 ; Appenzeller et al., 1998 ; Bromwich et al., 1999). Through east-west rocking motions of the Icelandic Low and the Azores High from year to year, the NAO controls the strength and direction of westerly winds, which are opposed to northerly winds over the Baffin Bay.

The standard deviation of the annual mean 500hPa geopotential height allows to highlight areas strongly affected by the interannual atmospheric circulation changes (**Fig. 2**). A very high variability area lies in the south-west of the GrIS, more precisely located on the Davis Strait and the southern extremity of Greenland. This area is the most affected by the NAO, which enhances or dampens the westerly winds reaching the western coast of Greenland, like the heat and moisture fluxes toward the GrIS. Few AOGCM's are able to simulate the 500hPa geopotential height standard deviation (for example, the IPSL or UKMO_HADGEM1 models) compared to the reanalyses. The other global models show generally too low atmospheric circulation variability (NAO) on the whole Greenland (like the INMCM or MIROC models).

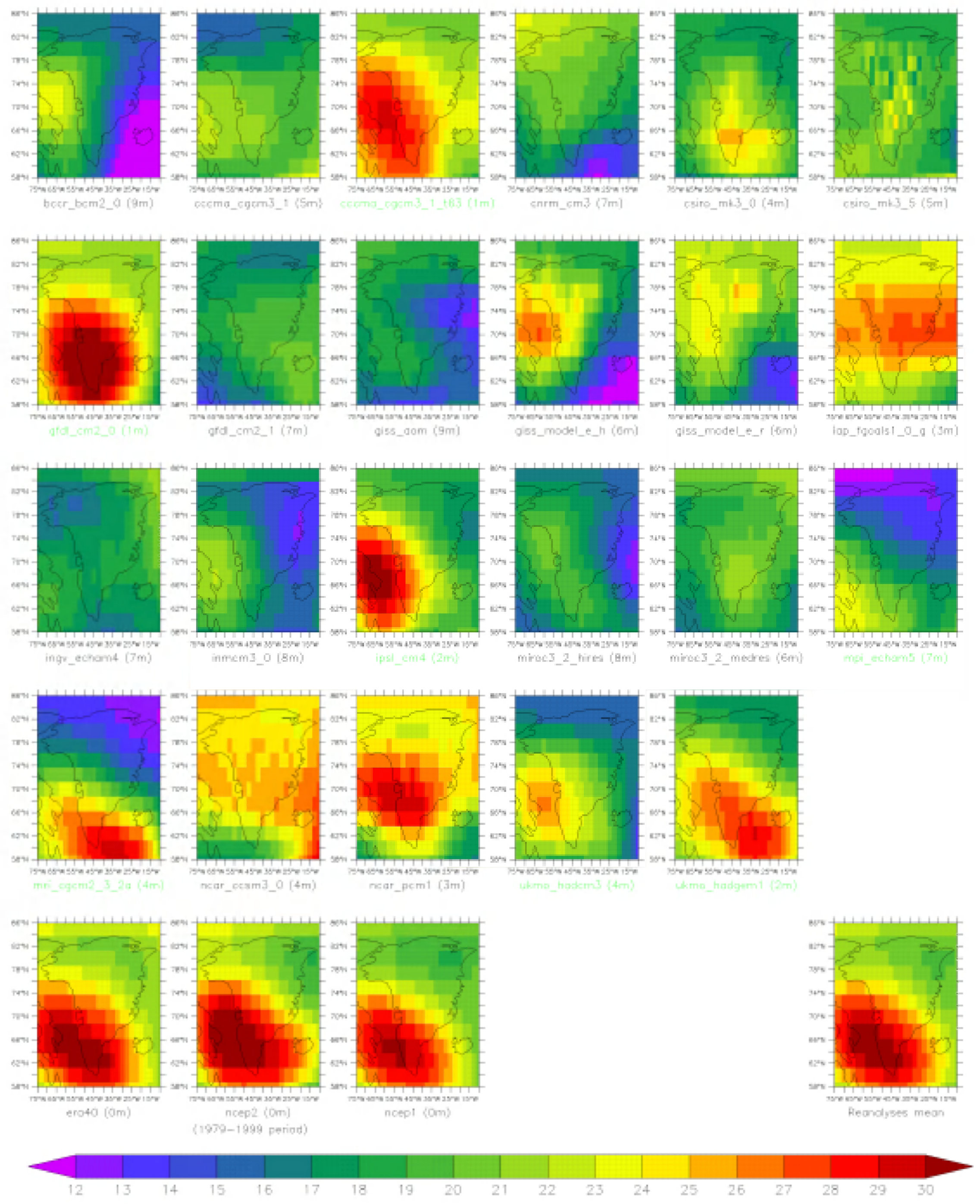

Fig. 2 : Standard deviation (in m) of the annual 500hPa geopotential height simulated by the AOGCM's from the 20C3M Experiment outputs and the reanalyses, for the 1970-1999 period. In brackets, the average of absolute anomalies compared to the reanalyses mean. In green, the efficient AOGCM's to the standard deviation modeling of the 500hPa geopotential height.

AOGCM's future projections from SRES

Some AOGCM's (the MPI_ECHAM5, UKMO_HADCM3 and UKMO_HADGEM1 models) can be used to make future projections on Greenland according to their abilities to modeling the present climate, especially the atmospheric circulation and the NAO variability. These GrIS future simulations for the 2070-2099 period are based on the IPCC greenhouse gas emissions scenarios outputs.

Fig. 3 shows small anomalies of the 500hPa geopotential height compared to the present climate taking place in southern Greenland, but they are growing strongly toward the central GrIS and become the higher along the northern coast. These changes mainly due to a strengthening of the Azores High dampen the west to east circulation (zonal flow), which enhances the Meridional Overturning Circulation (MOC) providing more heat and moisture to the GrIS.

The AOGCM's future projections also simulate increases of the annual mean precipitation over Greenland (**Fig. 3**) induced by the atmospheric circulation changes. These precipitation increases are particularly high on the north-eastern GrIS where they are mainly caused by the strengthened meridional flow, which enhances the subsidence in this region.

Fig. 4 shows a significant increase of the annual mean near surface temperature on the whole Greenland compared to the present climate, especially along the northern coast according to the geopotential height changes and the weakening of sea ice concentration in this region. The projected increases of the summer (June-July-August) mean near surface temperature (which occur in the central GrIS) are dampened by the influence of melting snow and ice. Thus the near surface temperatures are locked near the melting point, given the influence of the sensible heat into melting and evaporation (Steffen, 1995).

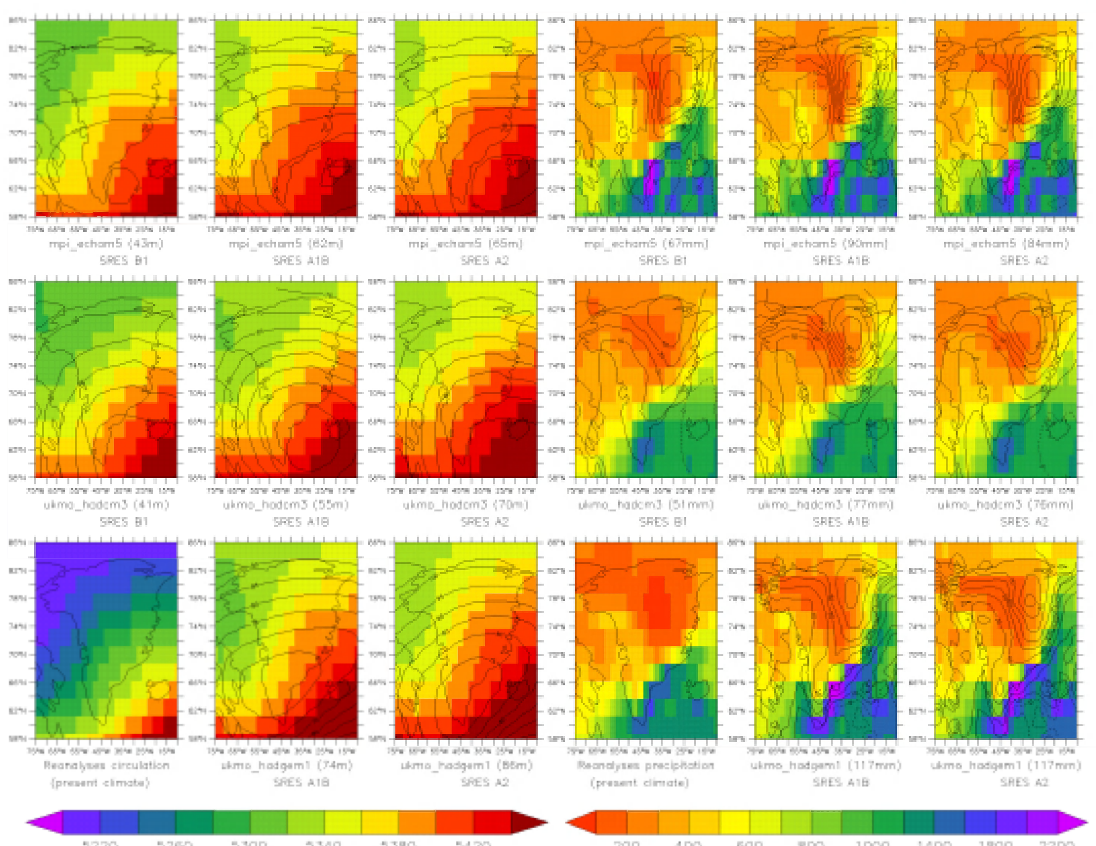

*Fig. 3 : **(a)** Annual 500hPa geopotential height (in m) simulated by the AOGCM's from SRES scenarios for the 2070-2099 period. Anomalies (in m) compared to the AOGCM's 500hPa geopotential height for the present climate are marked in continuous lines (positive anomalies) and in dashed lines (negative anomalies). In brackets, the average of anomalies compared to the 1970-1999 period over the GrIS. **(b)** The same as a), but for the projected precipitation expressed in mm. In brackets, the amount of precipitation anomalies over the GrIS.*

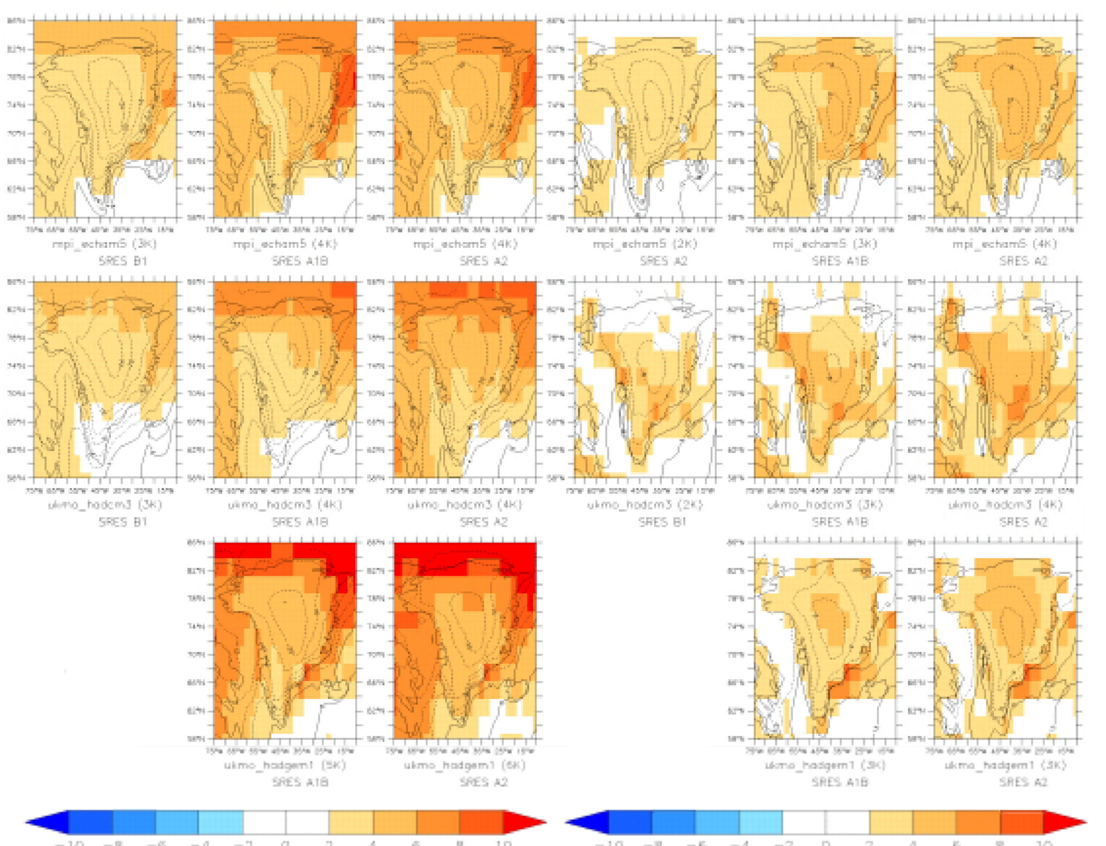

*Fig. 4 : **(a)** AOGCM's anomalies (in °K) of the annual near surface temperature (for the 2070-2099 period) compared to AOGCM's near surface temperature for the present climate. Projected near surface temperatures (in °C) are marked in continuous lines (positive temperatures) and in dashed lines (negative temperatures). In brackets, the average of anomalies compared to the 1970-1999 period over the GrIS. **(b)** The same as a), but for the summer near surface temperature (June-July-August).*

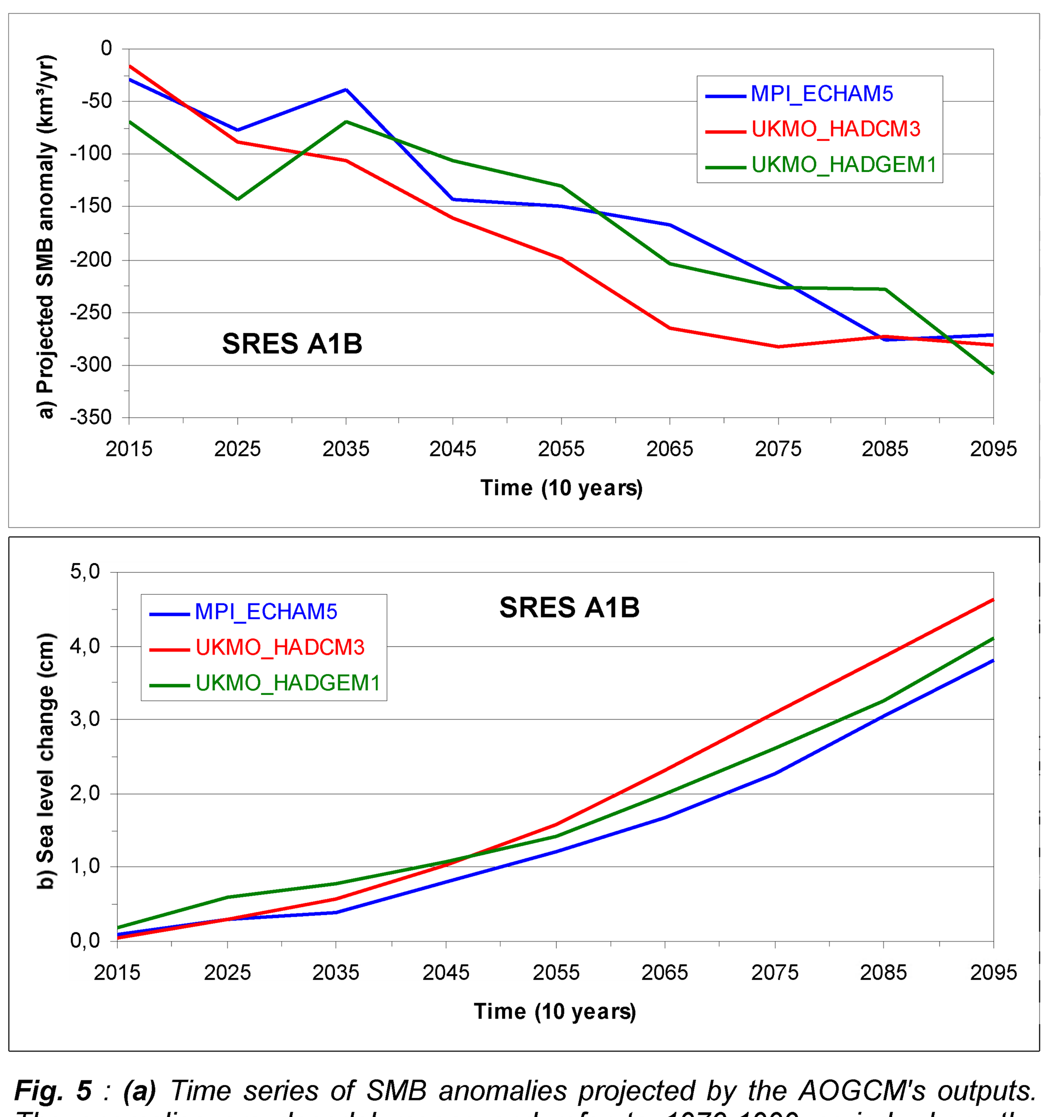

*Fig. 5 : **(a)** Time series of SMB anomalies projected by the AOGCM's outputs. The anomalies are decadal means and refer to 1970-1999 period where the mean SMB rate is estimated to be ~ 350 km³/yr. **(b)** The same as a) but for the projected GrIS SMB changes expressed in equivalent sea-level rise (in cm). The computation was made by using an area of a world ocean of 361 million km².*

GrIS SMB future projections

We provide estimates of the GrIS SMB from 2010 to 2100 based on a multiple regression model (**Equation 1**) by using the selected AOGCM's outputs from the IPCC AR4 SRES scenario A1B. This regression model uses anomalies of GrIS summer temperature and from GrIS annual precipitation, computed on specific regions for the 1970-1999 period to determine parameters *a* and *b*. Then the SMB anomaly estimation is extended to the whole future period (more details in Fettweis, 2008) to assess SMB anomalies projected by AOGCM's time series and estimated sea-level rises (**Fig. 5**).

The GrIS SMB anomalies projected by the AOGCM's outputs from the SRES scenario A1B are about -300 km³/yr for the 2090-2100 decade. These values correspond to the GrIS SMB anomaly simulated by the regional model MAR (who is validated and optimized for Greenland) for 2007, which is the record melting year compared to the present climate (Fettweis, 2007). The projected GrIS SMB anomalies transform to about 4-5 cm of sea-level rise for the end of this century under SRES scenario A1B.

The GrIS SMB anomalies based on summer 500hPa geopotential height and annual precipitation are also extended to the 21st century. However these projected SMB anomalies are not significant because geopotential height reacts more slowly than near surface temperature to climate change.

$$\Delta SMB_{GrIS} \approx a \times \Delta T_{JJA} + b \times \Delta P_{yr}$$

Equation 1 : Relation used to estimate the GrIS SMB anomalies (ΔSMB_{GrIS}) from summer temperature anomalies (ΔT_{JJA}) and from annual precipitation anomalies (ΔP_{yr}), computed on specific regions for the 1970-1999 period. a et b are constant parameters and are determined by solving the multiple regression equation using the simulated GrIS SMB anomaly time series.

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Conclusions

The simulation of the atmospheric circulation pattern and the NAO variability is assumed to be the main criterion to the GrIS modeling. Then the most efficient AOGCM's for the present climate can be used to simulate GrIS SMB anomalies for the 21st century. However large uncertainties remain in these SMB projections. High resolution simulations made with a regional model forced at its boundaries by a well-adapted global model could bring more precise results. This work represents a first step of Ph.D. researches dedicated to the GrIS SMB modeling.