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D.4.1.6. Assessment of non-linear feedbacks and possible abrupt climate change in the atmosphere-land-ocean-cryosphere

David Salas-Melia[1] and Helge Drange[2-3]

[1]CNRM-GAME, Toulouse, France
[2]Nansen Environmental and Remote Sensing Center, Bergen, Norway
[3]Nansen-Zhu International Research Centre, Beijing, China

Abstract

Most atmosphere-ocean general circulation models (GCMs) forced with increasing greenhouse gas concentrations predict enhanced atmospheric moisture transports to the high northern latitudes. Together with melting of Arctic sea ice and glaciers, this implies a gradual freshening of the northern North Atlantic Ocean. The freshening, together with heating of the ocean as a result of global warming, tends to reduce the strength of the Atlantic Meridional Overturning Circulation (AMOC). In this study, we will focus on climate simulations from three global coupled GCMs : BCM, CNRM-CM3 and IPSL-CM4.

1. Introduction

There are increasing observation-based evidences for a large-scale redistribution of the freshwater contents of the World Oceans that is consistent with a spin-up of the hydrological cycle. These include positive salinity trends in the tropics [Curry et al., 2003; Boyer et al, 2005], and freshening trends in both the subpolar Atlantic [Dickson et al., 2002; Curry et al., 2003; Curry and Mauritzen, 2005; Peterson et al., 2006] and the Pacific [Wong et al., 2001] ocean basins. Furthermore, the observations indicate increased atmospheric moisture transports from the Atlantic to the Pacific [Boyer et al., 2005] and also enhanced transports to Siberia, the latter leading to increased river runoff to the Arctic [Peterson et al., 2006]. A spin-up of the hydrological cycle, which is the expected outcome of higher air temperatures and by that enhanced evaporation in the tropics and increased capacity of the atmosphere to keep and transport water, is indeed simulated by most climate models forced with increasing levels of atmospheric greenhouse gases [e.g. Cubasch et al., 2001; Räisänen , 2002, Meehl et al., 2007]. At the high northern latitudes, a combination of warming and dilution of the surface ocean will slow down the formation rate of intermediate and deep water masses, and possibly result in weaker Atlantic meridional overturning circulation and a less efficient oceanic heat conveyor [Cubasch et al., 2001, Stouffer et al., 2006, Meehl et al., 2007].

2. Description of the simulations

BCM – 1% CO2

Six 80 year-long model realizations with the Bergen Climate Model (BCM) [Furevik et al, 2003] have been analyzed. The model experiments follow the protocol of the Coupled Model Intercomparison Project [Meehl et al., 2003; Covey et al., 2003] with a 1% per year increase in atmospheric CO_2, leading to a doubling after 70 years. All other atmospheric gases, aerosols, and external forcing terms are kept constant throughout the integrations. Although highly idealized, the CMIP2 protocol may be taken as a first order approximation to more realistic global warming scenarios.

CNRM-CM3 – A1B stabilization experiments

An A1B stabilization experiment was performed with the third version of the CNRM (Centre National de Recherches Météorologiques) global atmosphere-sea ice-ocean Coupled Model (CNRM-CM3) [Salas-Mélia et al, 2005]. This experiment, requested by CMIP3, is the continuation of an SRES-A1B scenario (about 720 ppm CO2 by 2100) beyond 2100. In the stabilization experiment, denoted as A1BS, all forcing agents are held fixed until 2300.

IPSL-CM4 - A1B scenario
We use the fourth version of the AOGCM developed at the Institut Pierre Simon Laplace, Paris (IPSL-CM4, Marti et al. 2005) to simulate the 1900-2100 period. The part of the experiment covering the twentieth century was performed by using only the anthropogenic forcing (observed greenhouse gases and sulphate aerosol concentrations). For the twenty-first century, we use outputs from the SRES-A1B climate change scenario. A detailed description of those simulations is provided in Dufresne et al. (2005). The results from IPSL-CM4 presented in the following are from Arzel et al. (2008).

3. Results

Fast freshening of the Arctic ocean
The spatial pattern of the simulated freshening in the BCM CMIP2-ensemble is shown in Figure 1a,b. Strongest reductions in vertical averaged salinity occur on the Arctic shelves, in the Hudson Bay, and in the Baltic Sea, where the salinity in several locations drops at a rate of 0.05 or more per decade. These are contrasted by the northern North Atlantic and the Nordic Seas, where the northward transport of more saline Atlantic Water increases the salinity throughout most of the basins. In terms of total fresh water content, the changes are largest in the central Arctic Ocean where the added freshwater is about 2 m per decade.

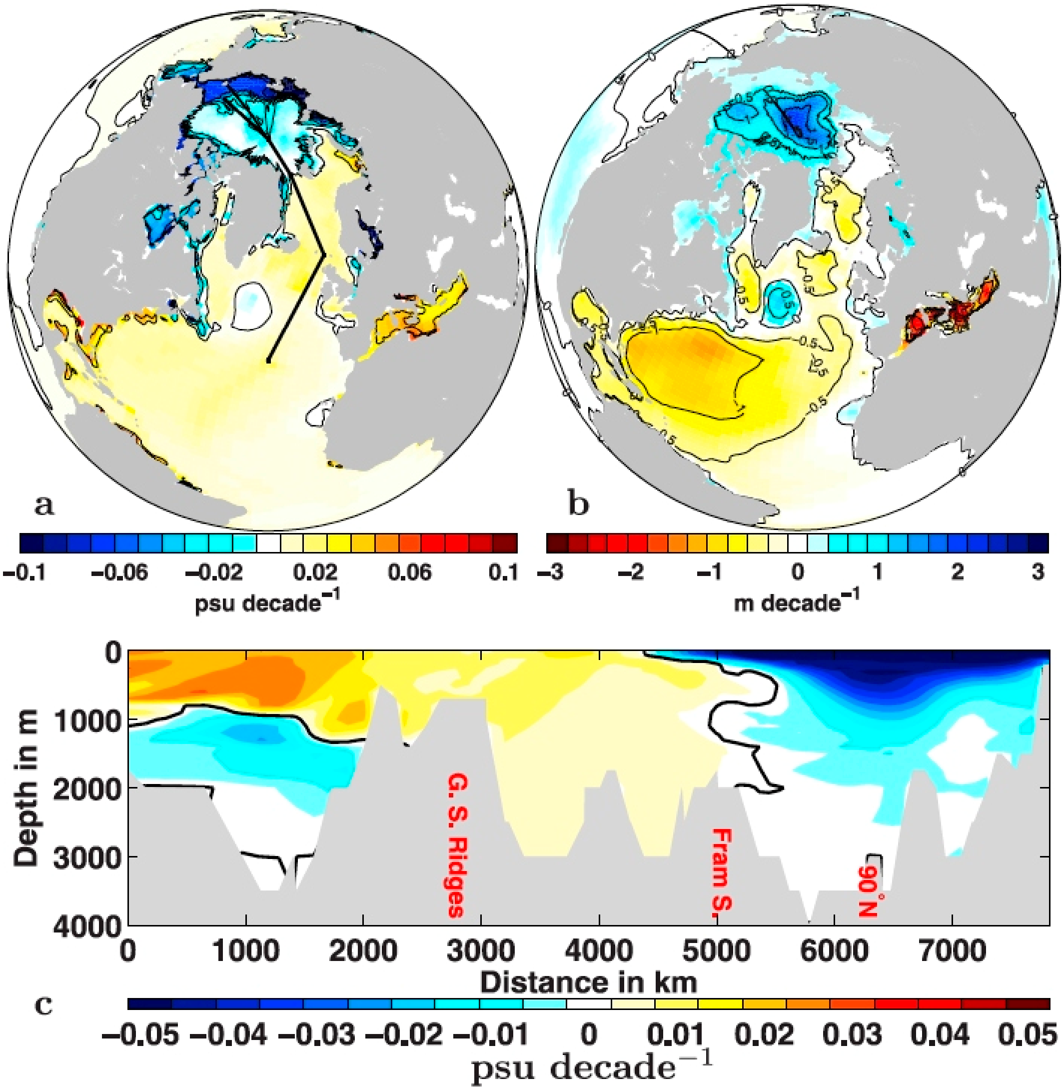

Figure 1. Projected changes by BCM model in a 1% CO2 increase experiment in (a) vertical averaged salinity (psu per decade), (b) freshwater storage (m per decade), and (c) salinity (psu per decade) along the trans-Arctic section from the North Atlantic Ocean towards the Bering Strait. Values are computed as ensemble mean linear trends over the 80 years integration period.

Changes in the vertical freshwater distribution are highlighted with a section running from the North Atlantic through the Nordic Seas and across the Arctic Ocean (Figure 1c). Important features are a significantly fresher Arctic Ocean and slightly more saline Nordic Seas. South of the Greenland-Scotland ridge, the upper 1000 m of the water column becomes more saline while the intermediate and deep waters become fresher. The largest changes are found near the surface, suggesting that the changes originate from surface forcing such as *P-E*, sea-ice processes and continental runoff. In particular, a strong reduction in sea-ice export due to a thinner Arctic ice is simulated in the set of experiments. This reduction in sea-ice export is equivalent to a reduction of the fresh water transport out of the Arctic. This implies reduced production of new ice due to a shorter freezing season, or that most of the ice melts before being transported out of the Arctic. In fact, recent observational studies report a negative thickness trend of the exported sea-ice while the area transport primarily remains controlled by the local wind forcing [Kwok et al., 2004], which also may explain the observed weak decline in the northern North Atlantic freshwater storage after 1990 [Curry and Mauritzen, 2005].

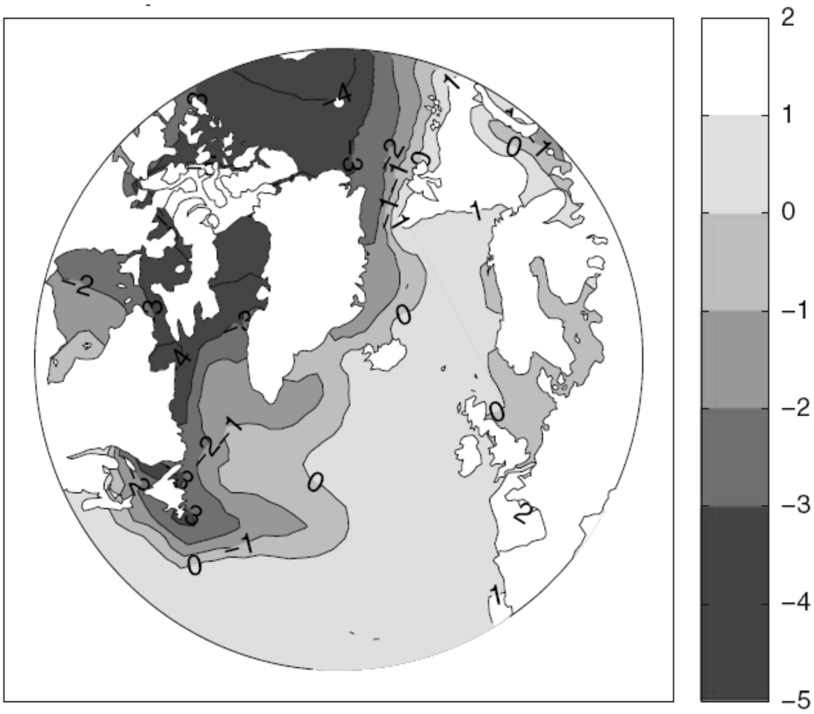

Figure 2. *Projected differences (CNRM-CM3 A1BS minus preindustrial control) for mean winter (December–April) sea surface salinity (psu), years 2100-2299. Contour interval: 1 psu..*

As a response to the increase of greenhouse gases, CNRM-CM3 / A1BS simulates a freshening of the Arctic Ocean (Fig. 2) of up to 4 psu, which is comparable to the value obtained by using IPSL-CM4 for the simulation of the 2081-2100 period. This freshening is however much more pronounced than what the BCM ensemble of experiments projects. Note that both experiments can only be compared in a qualitative way, because the greenhouse forcings are different. The contributions of the different processes in the freshening of the Arctic Ocean were quantified for the CNRM-CM3 / A1BS simulation, in terms of fresh water

budget anomalies (km3/year)to the preindustrial control experiment (see Guemas and Salas-Melia, 2008). It was shown that the main reason for the decrease in arctic surface sea water salinity is the decrease in sea ice formation and export through Fram Strait (+2502 km3). The increase in river runoff (+1113 km3) and fresh water import through Bering Strait (+1044 km3) are two other major contributors. The precipitation minus precipitation change is nearly negligible (+214 km3).
The mechanisms influencing the Arctic freshwater balance in response to anthropogenic greenhouse gas forcing were also investigated in the 20th and 21st century climate simulations run with IPSL-CM4. In these simulations, the Fram Strait outflow, which is an important source of freshwater for the northern North Atlantic, experiences a rapid and strong transition from a weak state toward a relatively strong state during 1990–2010 (see Fig.4).

Abrupt Changes in Atlantic Meridional Overturning Circulation (AMOC)

Most state-of-the art global coupled models simulate a weakening of the Atlantic meridional overturning circulation (MOC) in climate change scenarios but the mechanisms leading to this weakening are still being debated. The analysis of the CNRM-CM3 A1BS scenario experiment shows that global warming leads to a slowdown of North Atlantic deep ocean convection and thermohaline circulation south of Iceland. This slowdown is triggered by an increase in freshwater outflow through Fram Strait, itself related to the freshening of the Arctic Ocean. Sea ice melting in the Barents Sea induces a local amplification of the surface warming, which enhances the cyclonic atmospheric circulation around Spitzberg. This anti-clockwise circulation forces an increase in Fram Strait outflow and a simultaneous increase in ocean transport of warm waters toward the Barents Sea, favouring further sea ice melting and surface warming in the Barents Sea. Additionally, the retreat of sea ice allows more deep water formation north of Iceland and the thermohaline circulation strengthens there. The transport of warm and saline waters toward the Barents Sea is further enhanced, which constitutes a second positive feedback. The whole mechanism is summed up in Fig. 3.

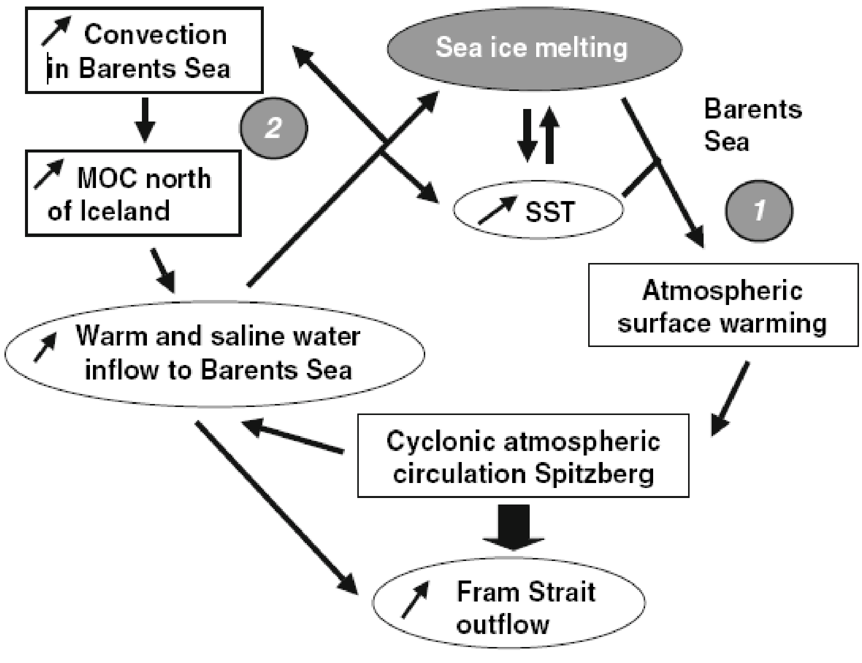

Figure 3. *Summary of the feedback loop mechanism suggested by the analysis of the ENSEMBLES-stream 1 SRES-A1B scenario run with CNRM-CM (Fig. 16 from Guemas and Salas-Mélia, 2008).*

Arzel et al. (2008) propose that this climate shift is triggered by the retreat of sea ice in the Barents Sea during the late twentieth century. In agreement with CNRM-CM simulations, sea ice reduction initiates a positive feedback in the atmosphere-sea ice-ocean system that alters both the atmospheric and oceanic circulations in the Greenland-Iceland-Norwegian (GIN)-Barents Seas sector. Around year 2080, the model simulates a second transition threshold beyond which the Fram Strait outflow is restored toward its original weak value (see Fig.2). The long-term freshening of the GIN Seas is invoked to explain this rapid transition.

It is further found that the mechanism of interannual changes in deep mixing differ fundamentally between the 20th and 21st centuries. This difference is caused by the dominant influence of freshwater over the 21st century. In the GIN Seas, the interannual changes in the liquid freshwater export out of the Arctic Ocean through Fram Strait combined with the interannual changes in the liquid freshwater import from the North Atlantic are shown to have a major influence in driving the interannual variability of the deep convection during the 21st century. South of Iceland, the other region of deep water renewal in the model, changes in freshwater import from the North Atlantic constitute the dominant forcing of deep convection on interannual time scales over the 21st century.
Finally, as a consequence of the long-term warming and freshening of the high latitudes of the North Atlantic Ocean, the model predicts that the convection almost disappears in the GIN Seas and south of Iceland by the end of the twenty-first century. However, this does not lead to a complete shut-down of the AMOC (6 Sv, from a slightly underestimated simulated value of 11 Sv for present climate).

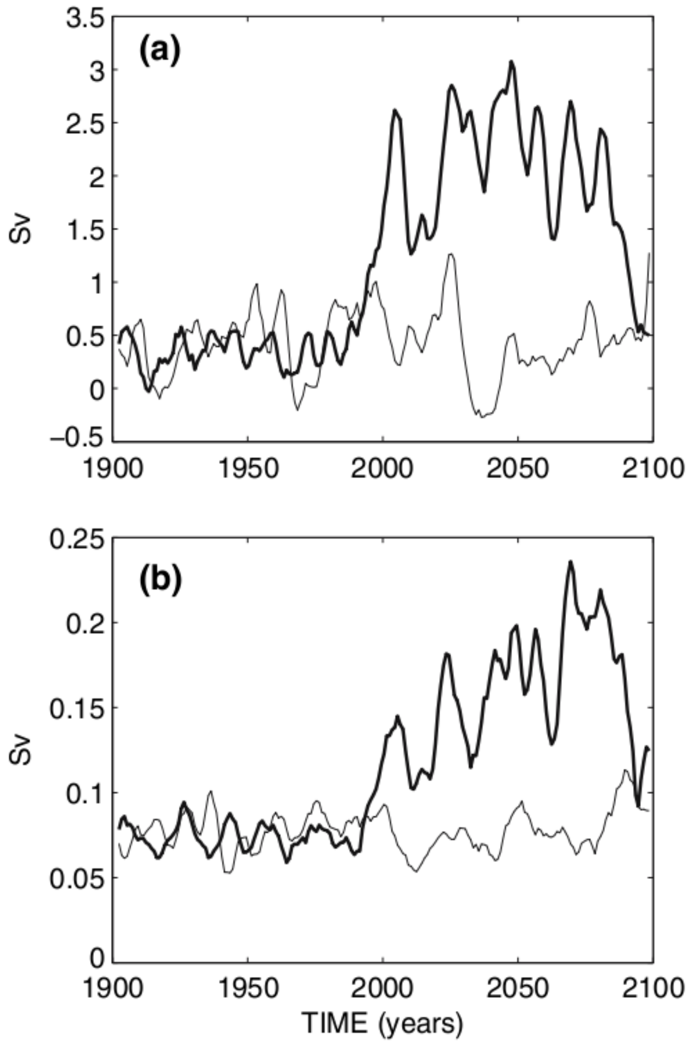

Figure 4. *Timeseries of (a) Fram Strait volume flux and (b) liquid freshwater export at Fram Strait in the pre-industrial experiment (thin line) and in the experiment covering the 20th century and the SRES A1B scenario over the 21st century (thick line) run with IPSL-CM4. A 5-year running mean has been applied (Fig. 6 from Arzel et al., 2008).*

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