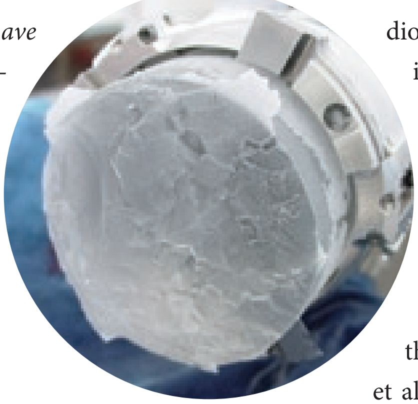
From Polar Ice Cores to Better Climate Models?

***Thomas Stocker**, Professor of Climate and Environmental Physics and Co-Director of the Physics Institute at the University of Bern in Switzerland, spent his 2006 sabbatical at the IPRC. He worked with IPRC research team leader **Axel Timmermann** and postdoctoral fellow **Oliver Timm** on modeling the abrupt climate changes in the past that have resulted from changes in the Atlantic meridional overturning circulation. Understanding processes that have shaped past climates is central to determining what lies ahead for climate change. We asked Professor Stocker to write for the* IPRC Climate *about this work and how it advances our knowledge of Earth's climate system.*

Climate models require accurate forcing data

Numerical models are used to simulate and understand past climate conditions. The forcing conditions in the distant past, such as the concentration of the greenhouse gases or the extent of ice areas, however, were very different from today and must be quantified before experiments with climate models can be performed.

Knowledge of past greenhouse gas composition in the atmosphere is necessary to drive climate models that are to simulate past conditions. This composition can be obtained from polar ice cores. When snow falls on polar ice sheets, it soon forms a porous material, firn, in which air can circulate. The air in the firn becomes trapped under the slow compaction of snowfall, year after year. These bubbles contain tiny samples of ancient air that can be analyzed, and the physical and chemical composition of the atmosphere can be reconstructed by applying various analytical techniques to the ice core samples. Currently, more than 50 components in the ice and in the enclosed gas of a polar ice core are measured (photo below). Such analyses have enabled us at the University of Bern, in partnership with many European colleagues, to trace back climate change in Antarctica to at least 740,000 years ago (EPICA Community Members, *Nature* 2004) and reconstruct the concentrations of carbon dioxide and methane, the two most important greenhouse gases after water vapor.



Within the resolution of the current measurements, our results show that today's levels of CO_2 in the atmosphere are 27% higher than any time during the last 650,000 years (Siegenthaler et al., *Science* 2005). Today's concentrations of CO_2 (annual average in 2006: 382 ppm, as measured on Mauna Loa, Hawai'i, **www.cmdl.noaa.gov/ccgg/trends**) are clearly outside the range of natural fluctuations over the past several 100,000 years (Figure 1). These data provide an indispensable forcing boundary condition for climate models that are used to simulate ice ages and dynamical processes in the distant past.

Above. Drill head with ice core drilled on November 30, 2002, from a depth of 2,874 m at Dome Concordia Station. The ice is about 491,000 years old. The drilling is part of the European Project for Ice Coring in Antarctica (EPICA). This ice core contains a continuous time series of greenhouse gases over the last 650,000 years. The drill head and cutters were designed and constructed by Henry Rufli (University of Bern, Switzerland; *photo courtesy of L. Augustin, LGGE, Grenoble, France*).

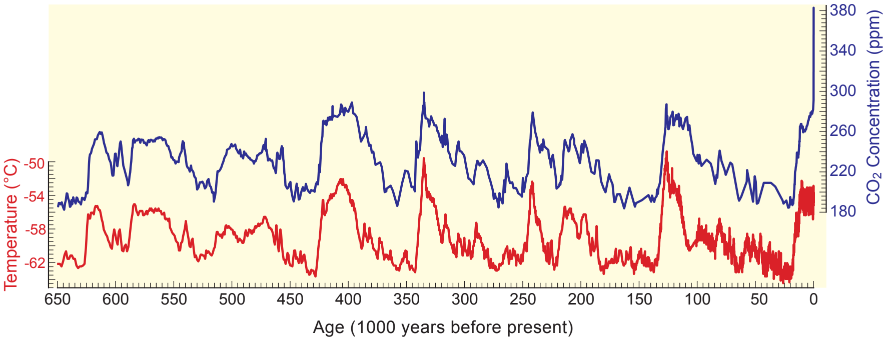


Figure 1. Reconstruction of the atmospheric CO$_2$ concentration of the last 650,000 years (blue curve) based on data from several Antarctic ice cores, combined with the observed increase measured since 1958 on Mauna Loa (Hawai'i). The estimate of temperature in Antarctica (red curve) is derived from measurements of the stable isotopes of the water molecule.

Signals of abrupt climate change

Ice cores from Greenland and Antarctica have radically changed the way we look at climate as a dynamical system on many time scales. More than 10 years ago, two independent international projects, one in the U.S. (GISP2) and one in Europe (GRIP), confirmed earlier reports that a series of abrupt warmings characterized the last ice age. These abrupt swings of climate in Greenland are now commonly known as *Dansgaard/Oeschger* events, and are thought to cause climate change worldwide. A recent, more detailed ice core from North GRIP (NorthGRIP Members, *Nature* 2004) shows 25 of these events during the last ice age. During Dansgaard/Oeschger events temperature in Greenland rises over a few decades by as much as 16°C and then falls over the following millennia (Huber et al., *Earth Plan. Sci. Lett.* 2006). (These short-term events are different from the gradual deglaciation described in the work by Timmermann and his team on p. 3.)

The synchronization of ice core records from Greenland with those from Antarctica by using global time markers, shows that the strong Dansgaard/Oeschger events in the north have a counterpart in Antarctica (Blunier and Brook, *Science* 2001). When Antarctica is warming, Greenland ice cores register very cold temperatures. However, when an abrupt warming occurs in Greenland, the warming in Antarctica stops, and a cooling trend starts. The pattern is very consistent during the entire ice age and is referred to as the bipolar seesaw (Broecker, *Paleoceanogr.* 1998; Stocker, *Science* 1998). This is illustrated in Figure 2, which shows temperature reconstructions from ice cores from Greenland and Antarctica in a typical time window during the last ice age.

Two questions arise from these ice core records: (i) What is the physics behind this north-south connection, and (ii) can current coupled climate models simulate the time and space signature of such dramatic climate events? This is a hard but crucial test for models that are used to assess the likelihood of low-probability but high-impact climate events in response to global warming.

The combination of numerous paleoclimatic reconstructions, climate model simulations, and theory suggests that the Atlantic meridional overturning circulation is a key component in the physics of these abrupt changes (Clark et al., *Nature* 2002; Alley, *Science* 2003). When freshwater is discharged into the North Atlantic Ocean from unstable ice sheets, the meridional overturning circulation is reduced or even stopped. This leads to a decreased meridonal heat flux in the Atlantic Ocean and an associated hemispheric cooling owing to response of the atmospheric circulation.

In fact, climate models are able to capture many aspects of these abrupt changes, such as the rapidity of the events, the amplitude of the cooling in the Northern Hemisphere (Knutti et al., *Nature* 2004), and various other changes reconstructed by paleoclimate archives (LeGrande et al., *Proc. Natl. Acad. Sci.* 2006). They make specific pre-dictions as to what one may find in the paleoclimatic record of variability in the tropical Pacific (Timmermann

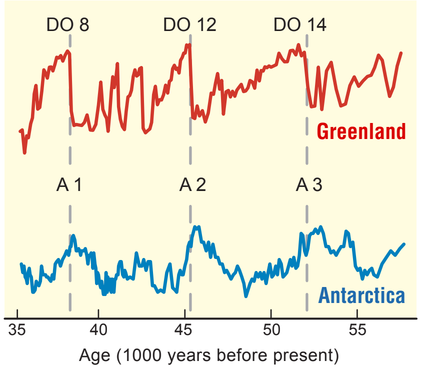


Figure 2. Reconstructions of temperature changes in Greenland (red curve) and Antarctica (blue curve) during a sequence of six Dansgaard/Oeschger events during the last ice age. The curves are put on a common time scale obtained by synchronizing the two ice cores using measured methane variations in both cores. Time is running from right to left (1000 years before present).

et al., *J. Clim.* 2005). While the response of climate models is consistent in the Northern Hemisphere, their signals in the high latitudes of the Southern Hemisphere are ambiguous: one comprehensive model shows cooling, another warming (Stocker, *Science* 2002).

In the current partnership between IPRC (**Axel Timmermann** and **Oliver Timm**) and the University of Bern (**Thomas Stocker** and **Manuel Renold**), established during my sabbatical visit to the IPRC, we set out to better understand this ambiguity. We are analyzing results from a comprehensive coupled climate model that has no flux corrections (NCAR CCSM3-T31). The climate model is perturbed with a strong freshwater flux delivered to the North Atlantic Ocean. Freshwater is injected into the North Atlantic, increasing linearly from 0 Sv (1 Sv = 10^6 m^3/s) to 2 Sv over 100 years, and decreasing to 0 Sv again over the following 100 years. We are considering two cases. In the first case, we applied a globally uniform negative freshwater flux (*i.e.*, saltier water) of the same total magnitude to ensure conservation of mean salinity in the simulation. In the second case, we applied no compensating flux. The model response in the Northern Hemisphere is very similar. The reduction in the meridonal overturning circulation in the Atlantic causes a strong cooling (Figure 3), which is rather uniform but strongest in the northern North Atlantic except for a warm spot in the northwestern part of the subtropical gyre. This is caused by the displacement of this gyre due to changes in the wind stress curl.

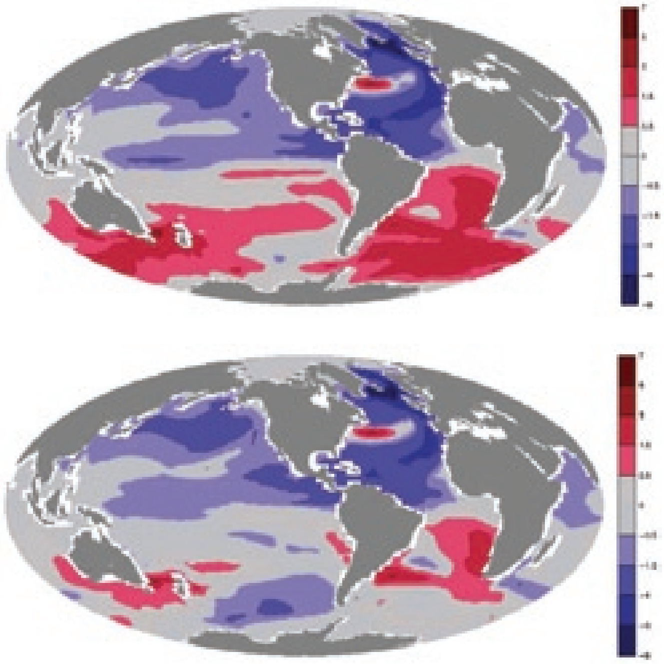


Figure 3. Anomalies of sea surface temperature (°C) in a freshwater experiment using the NCAR CCSM3 model. Freshwater is delivered to the northern North Atlantic increasing to 2 Sv over 100 years and then decreasing again, and globally compensated to ensure salt balance (top panel), or not compensated (bottom panel). Shown are the changes with respect to a control simulation.

The model response in the Southern Hemisphere differs markedly in the two cases. In the experiment with global compensation fluxes, the warming is widespread throughout the entire Southern Hemisphere (top panel); in the uncompensated case, the warming is limited to the South Atlantic and regions south of Australia (bottom panel). Although the compensating freshwater fluxes are comparatively small and uniform, they strongly modify the response beyond the Atlantic Ocean. Particularly in the South Pacific, large spatial differences are found. Thus, while the simulations produce robust results for the Northern Hemisphere (Stouffer, *et al. J. Clim.* 2006), the response of the tropics and the Southern Hemisphere is inconclusive and appears to depend on small changes in how these models are forced. We are now focusing on the dynamical processes responsible for the different response.

Towards models for climate-change impact

Paleoclimate models are indispensable tools to understand the full dynamics of the coupled atmosphere–ocean–land–surface-ice system under altered boundary and forcing conditions. They are also useful for better quantifying changes measured in various paleoclimatic archives such as polar and mid-latitude ice cores, marine sediments, tree rings and speleothems. As models are being improved and their capability is being demonstrated in combination with high-resolution paleoclimate records, future research with these models will be aimed at assessing impacts of climate change on regional scale to continental scale. Of particular interest are extreme weather and climate events and how they might respond to the warming.

As a visitor to the IPRC, I experienced the 46-day rain in February and March 2006, which caused widespread damage in the Hawaiian Islands. What are the odds that such an extreme event occurs again in the next five years, and how will those odds be in the year 2020? Although just one particular example, it stands for the type of questions our science will have to answer in the near future.

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