Summary

It is well known that the enhanced greenhouse effect is the main contributor to the current global warming. However, the sensitivity of the climate system to an increase in greenhouse gas levels in the atmosphere is still very uncertain. The main reason is that the net impact of the numerous positive and negative feedbacks affecting climate is unknown. This thesis focuses on one component of the climate system with potentially important feedbacks: icebergs.

Deep-sea coring has revealed beyond doubt that large “armadas” of icebergs were involved in rapid climate changes in the last ice age. Boulders and other drop-stones that are so large that they must have been ice-rafted form a clear iceberg armada signature in these sediment cores. These ice-rafted sediments are abundant in the so-called Ruddiman belt (40° - 55° N in the north Atlantic Ocean) [Ruddiman 1977], indicating that quasi-periodic episodes of abrupt climate change (such as Heinrich-events) were being accompanied by iceberg armadas.

However, the quantification of the icebergs’ influence on oceanic circulation and the climate system has remained somewhat elusive, mainly because most modelling studies have simplified iceberg discharge by releasing an appropriate amount of meltwater to the Atlantic Ocean in the Ruddiman belt. In such a “fresh water hosing” approach, neither the dynamic distribution of the icebergs by the winds and the seas, nor the cooling effect melting icebergs have on the ocean are correctly represented.

We present further development of the coupled ocean-atmosphere-sea-ice model EcBilt-CLIO (also known as LOVECLIM) by explicit numerical representation of iceberg behaviour. We have coupled a model that predicts the trajectory and melt of icebergs to this “Earth-system Model of Intermediate Complexity”. In our study, melting icebergs influence the climate in three ways:
- Freshening the ocean.
- Cooling the ocean.
- Dynamic spatio-temporal distribution of melting fluxes.

In Chapter 2, we study the potential impact of the first effect (i.e. freshening of the ocean surface) with a model version without the dynamical iceberg module. We show an amplifying mechanism at work in a three-dimensional climate model. Effectively a small periodic freshwater forcing in the Labrador Sea, fluctuating on a favourable centennial scale, is amplified to hemispheric proportion with the assistance of the internal variability of the climate system by triggering quasi-periodic state changes in the deep water circulation. This illustrates that, even in our relatively stable modern (Holocene) climate, abrupt climate change might be triggered by relatively small disturbances in the freshwater budget. In order to better understand rapid climate change we can turn to the era when abrupt state-changes (accompanied by iceberg armadas) in the global climate were quite common: the last ice age, or more generally the Quaternary.

In Chapter 3, coupling of the iceberg module to the climate model is described in detail, including a sensitivity-test of the modern Southern Ocean to various aspects of the modelled icebergs. We find that the cooling and freshening aspects of the iceberg melt affect the formation of sea-ice, which can have strong implications for various climatic variables. We name this effect “sea-ice facilitation”.

With dynamic icebergs the model exhibits a 10% increase in the production of Antarctic Bottom Water, compared to homogeneous fluxes. This greater bottom water production involves stronger open ocean convection. Simply put, the homogeneous flux distribution is more efficient at stratifying the ocean, which inhibits convection. This result could have implications for the tuning of EcBilt-CLIO and climate models in general, which in turn can affect the sensitivity and the glacial state of the model.

In Chapter 4 and 5 the coupled model including the dynamic iceberg component is applied to study cases of abrupt climate events in which icebergs probably played an important role. Chapter 4 is a
study of the largest and most abrupt Holocene climate change, the 8.2 ka event, with a scenario involving icebergs and a data-model comparison. In Chapter 5 we present a simulation study of a glacial Heinrich event, again focussing on the sensitivity of the climatic response to the icebergs’ characteristics.

In EcBilt-CLIO, icebergs that include both the freshening and the cooling effects are much more efficient at weakening North Atlantic Deep Water formation than non-cooling icebergs, while cooling is generally expected to enhance deep water formation. The cause of this intriguing result is the secondary mechanism of sea-ice-facilitation, which affects deep-water formation, disturbing the thermohaline circulation.

Compared to a classic hosing approach, dynamic-thermodynamic icebergs lead to a quicker response of the climate system. Furthermore, homogeneous Ruddiman-belt hosing overestimates the freshwater flux in the northeast Atlantic, leading to excessive freshening and cooling of the eastern North Atlantic and a delay in the recovery of the circulation after the event. So the dynamic-thermodynamic icebergs result in a faster and topographically different response, with consequences for the net melting flux “required” to disturb the thermohaline circulation.

The main contributions of this thesis to scientific progress are:

- The first demonstration of phase synchronisation of oscillations in the large-scale overturning to a weak external forcing in a three-dimensional climate model (Chapter 2).
- The experiments presented in Chapter 3, 4 and 5 imply that fresh water hosing is not a reasonable simplification of icebergs’ melting fluxes, unless one is willing to disregard differences in deep water formation in the order of 10%, and delays in the order of 50 years;
- We invoke a secondary mechanism, which we name sea-ice facilitation, to explain the non-linear and counter-intuitive efficiency of Cool & Fresh icebergs at disturbing deep-water formation.
- Thus dynamic and thermodynamic aspects of iceberg behaviour should be taken into account, when simulating the interaction between ice sheets and the rest of the climate system in general and specifically when simulating Heinrich events.