6. Synthesis

6.1 Introduction

This thesis revolved around 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” (EMIC). In our study, melting icebergs influence the climate in three ways:
1) They freshen the surface ocean.
2) They cool the surface ocean.
3) They are driven by the currents and the winds, leading to a dynamic spatio-temporal distribution of the melting fluxes.

In chapter 2 we first studied the sensitivity of the North Atlantic Ocean to small fresh water injections in the Labrador Sea. The coupling of the iceberg module to the climate model was described in detail in chapter 3, including a sensitivity-test of the modern Southern Ocean to various aspects (freshening, cooling, dynamic distribution) of the modelled icebergs. Chapter 4 was a case study of the largest Holocene abrupt climate change, the 8.2 ka event, with a scenario involving icebergs and a data-model comparison by A.Wiersma. In chapter 5 we simulated a glacial Heinrich event, again focussing on the sensitivity of the climatic response to the icebergs characteristics.

6.2 Research questions

The research questions we posed in the introduction (Chapter 1) can be subdivided in three categories: key questions; systematic (methodological) questions; and specific questions.

The key question, from a modeller’s perspective, is whether the iceberg module we implemented has a significant impact on model results. In general terms:

- **Do we need to take dynamic and thermodynamic aspects of iceberg behaviour into account?**

This question can be applied to the behaviour of the climate model:

- **Can icebergs significantly affect the modern (preindustrial) climate?**

And it can be applied to the simulation of specific abrupt climate change events associated with iceberg armadas:

- **Is fresh water hosing a reasonable simplification of iceberg armadas?**

In other words; with an interactive iceberg module, can we improve our simulations of major past climate events and our understanding thereof?

In order to answer these key questions, which will be done at the end of this synthesis (6.6), we have often applied a methodology of sensitivity experiments. In a sensitivity experiment, an aspect of the icebergs is deactivated to evaluate its impact on the results. For example, we compare a hosing approach with fresh meltwater distributed by melting icebergs and with Cool & Fresh icebergs. This approach has lead to the following systematic questions, or recurring issues:

- **The distribution effect:** What is the effect of the dynamic distribution of melt water by moving icebergs as compared to homogeneous or parameterized “hosing” of fresh water fluxes?

- **The cooling effect:** What is the effect of the latent heat of melting (which has been ignored in other studies)?

- **Sea-ice facilitation:** What is the role of sea-ice facilitation in these results? Melting icebergs lead to cooler and fresher surface waters, which facilitates the formation of sea-ice. In turn, sea-ice plays an important role in deep water formation.

These issues occur repeatedly in our discussion below, and they will not be treated as independent ques-
tions. Apart from these recurring issues, every chapter in this thesis had its own focus and angle, its specific questions, which have been formulated in the introduction section and in the chapters themselves. Rather than repeat all the conclusions from the individual chapters we will focus on the results that are relevant for our key questions.

In line with the key questions, in this synthesis we first discuss the sensitivity of the North Atlantic Ocean system to small fresh water flux fluctuations, and then the sensitivity of the Southern Ocean system to the various aspects of (thermo) dynamic icebergs. This allows us to summarize how icebergs can affect the climate. Then we will assess the role of icebergs in two abrupt climate change events (the 8.2 ka event and Heinrich event 1) in order to evaluate to what extent (thermo) dynamic icebergs are necessary for realistic simulations of these events.

### 6.3 Sensitivity of the North Atlantic Ocean to fresh water fluxes in the Labrador Sea (Chapter 2).

The Holocene climate is relatively stable compared to the last glacial. Nevertheless, the North Atlantic area exhibits variability at multicentennial time scales, which correlates with fluctuations in solar activity [Bond et al. 2001; 1999]. However, these fluctuations are so small that an amplifying mechanism is required to explain multicentennial Holocene climate variability driven by solar forcing [Bond’s Hypothesis. [Bond et al. 2001]]. In the introduction we posed the specific question

- **Is there a plausible amplification mechanism to link small cyclical changes in solar activity to (Holocene) D/O cyclicity?**

In chapter 2 we showed that small fluctuations in fresh water flux to the surface of the Labrador Sea can be amplified to a hemispheric scale by triggering mode-transitions in the North Atlantic overturning circulation. Under preindustrial boundary conditions, the North Atlantic deep water production in our model exhibits several modes of operation. In particular, there is a bistable regime characterized by “On” and “Off” modes in Labrador Sea deep water production [Schulz et al. 2007], which is supported by paleoceanographic data [Hillaire-Marcel et al. 2001]. We demonstrated that a small periodic fresh water forcing in the Labrador Sea can trigger state switches between these modes in a quasi-deterministic manner. This suggests that if the solar fluctuations somehow affect the (precipitation + evaporation + meltwater) - balance, state switches in Labrador-Sea deep water production could amplify these fluctuations to a hemispheric scale. The precise way in which solar fluctuations affect this fresh water balance falls beyond the scope of this thesis, but one hypothesis is that solar wind can distort Earth’s magnetic field, thus weakening its shielding effect against cosmogenic nuclei, which in turn tend to facilitate the formation of clouds by producing cloud condensation nuclei [Kirkby 2007]. A more abstract specific question was:

- **Can we demonstrate the stochastic resonance phenomenon in a 3-dimensional climate model?**

The forcing was subthreshold, meaning that it could only trigger these state-switches with the assistance of internal climatic fluctuations or “noise”. We argued that such quasi-deterministic behaviour indicates that the system operates on the interval of resonance, and as such is expected to have a stochastic resonance point, a peak-sensitivity to cyclical forcings of an (as yet unknown) multicentennial time-scale. This underpins the notion of oscillations in North-Atlantic overturning circulation as amplification mechanism behind D/O cyclicity.

This stochastic resonance also implies that the system has a multicentennial memory. The bistala-
ble behaviour of the Labrador Sea convection relies on the feedback from other key areas in the North Atlantic Ocean. A box-model experiment [Prange et al. 2010] illustrates that this behaviour depends on the inflow of polar waters through the East-Greenland current. When Labrador Sea convection is “Off”, fresh surface water will tend to gather, leading to a strong halocline and providing a positive feedback to the non-convection. However, the inflowing East Greenland current will be relatively salty. By eroding the halocline these polar waters can open the door for a switching-“on” of Labrador Sea convection. Likewise, when Labrador Sea convection is active, there is a positive salinity feedback (deep mixing removes the fresh surface layer, which makes convection easier). In this case, the polar inflow is relatively fresh, which destabilizes the convection. Of course, in reality the East Greenland current does not have a constant salinity. For instance, it depends on processes in the Arctic basin, net-prefcipitation, sea-ice dynamics and GIN-seas convection. In other words, our amplification mechanism depends on the three-dimensional configuration of the North Atlantic system.

This implies that under the right circumstances, depending on the history of the three-dimensional system, North Atlantic climate can be governed by a (possibly external) local forcing that is too weak to control it in an indisputable (monostable) manner. More specifically, our maximum forcing of 10 mSv was only one order of magnitude larger than the discharge of Greenland’s largest glacier, and would be a very conservative estimate of melting water from a shrinking Greenland ice-sheet [Gregory and Huybrechts 2006]. We tentatively conclude that if the Greenland ice-sheet shrinks due to global warming, the melting water could have a major (~20%) impact on the AMOC and hence on future North Atlantic climate. Our results indicate that the (local) history of the North Atlantic system plays a role in its sensitivity, implying that we might expect considerable uncertainty in the exact timing of such climate change. It must be noted however that LOVECLIM’s sensitivity of North Atlantic overturning circulation is version dependent (see section 6.7).

We conclude that in principle, depending on the circumstances, the melt water associated with plausible amounts of icebergs might strongly affect the modern and future climate. This provides a partial, mechanistic, answer to one of our key research questions: Can icebergs affect the modern climate? To study this issue we performed a sensitivity experiment with dynamic thermo-dynamic icebergs in the Southern Ocean.

### 6.4 Sensitivity of the Southern Ocean to three aspects of dynamic thermodynamic icebergs (Chapter 3)

Melting icebergs not only freshen their surrounding waters (“freshening-effect”), they also cool them by absorbing heat that is needed to make the phase-transition from ice to water (“cooling-effect”). Furthermore, their drifting property causes a dynamical spatio-temporal distribution of the melting fluxes (“distribution-effect”). To evaluate the climatic role of these three aspects of icebergs we need to do sensitivity experiments in which we switch off respectively the freshening effect, the cooling effect and the distribution effect. We can then assess the character of these effects and estimate their relative importance, assuming that other mechanisms do not dominate our results. Given the demonstrated memory and three-dimensional complexity of the North Atlantic system, such an assumption might not be justified in the North Atlantic. This is a good reason to perform our sensitivity study (Chapter 3) in the Southern Ocean, which appears to be spatially less complex (more symmetrical) than the North Atlantic.

Our coupled model produced a reasonable iceberg distribution in both hemispheres when compared to recent data, bearing in mind that observations are too limited to provide strong quantitative
constraints. Compared to “homogeneously distributed fluxes south of 55°S”, the heat and fresh water fluxes from dynamic icebergs were concentrated closer to shore except for a distinct plume of icebergs floating North-East from the tip of the Antarctic Peninsula. Icebergs also tended to melt north of 55°S near Australia and New-Zealand.

- **Does this more realistic distribution of melt water thru melting iceberg trajectories significantly affect the modelled climate?**

The redistribution of the fluxes by dynamic icebergs had asymmetric consequences. In the Indian and Pacific sector of the Southern Ocean the icebergs facilitated sea ice formation, whereas east of the Antarctic Peninsula the sea ice fraction was larger under homogeneous flux conditions. These asymmetric distribution effects influenced the local deep water formation, with consequences for the overall overturning. The net deep water production was 10% greater when the melting fluxes were distributed by dynamic-thermodynamic icebergs than with homogeneously distributed fluxes, while the net sea-ice area was only 1.4% lower.

- **How important is sea-ice facilitation in the climatic response to the freshening and cooling fluxes from the melting icebergs?**

Since melting icebergs cool and freshen the surface ocean, and fresher water freezes more readily, icebergs can facilitate the formation of sea-ice. Sea-ice facilitation and increased stratification are important feedbacks from the local cooling and freshening by icebergs. On the one hand sea-ice formation leads to brine rejection, which enhances deep convection. On the other hand sea-ice affects both the albedo and the ocean stratification by heat insulation, wind shielding and precipitation buffering, which further amplifies the cooling and freshening of the surface waters.

Both the fresh water and the cooling flux lead to a significant increase in sea ice area of 12% respectively 6%, affecting the highly coupled and interactive air/sea/ice system. Interestingly, the homogeneous fluxes lead to almost the same (1.4% larger) net sea-ice area in the Southern Ocean as the fully coupled icebergs, but the distribution was quite different. This coincided with a 10% weaker deep water production under homogeneous-flux circumstances than with dynamic icebergs. In most areas where the model exhibited strong deep water production, the homogeneous fluxes showed a denser sea-ice cover and shallower convection. This indicates that the distribution of the fluxes is quite important and that net sea-ice area is not the key variable in this complex system. In our more detailed analysis of specific climate change events (Chapters 4 and 5, see below), results imply that the secondary mechanism of sea-ice facilitation must be invoked to explain net convection.

We have seen that with dynamic icebergs the model exhibits a 10% greater net production of Antarctic bottom water (AABW), than with 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. Possibly, this result could have implications for EcBilt-CLIO and climate models in general. Roughly speaking, the tuning of ocean models involves obtaining a plausible deep water formation, stratification and overturning, by tweaking model-parameters. The effective stratification of the Southern Ocean is particularly sensitive to changes in mixing parameters [Goosse et al. 1999]. If the chosen value of these global parameters was based on a Southern Ocean state with a “homogeneous distribution” of “iceberg-melting” fluxes, then that means that the mixing parameters might be set too strong, to compensate for a too-efficient stratification. In turn, this could have implications for the sensitivity and for the glacial state of the model. As such, this provides a confirming answer to the key question can
Icebergs affect the climate in another, model-tuning oriented manner.

6.5 Icebergs vs. hosing; simulating abrupt climate change events that are associated with armadas of icebergs (Chapters 4 and 5)

In chapters 4 and 5 we presented detailed simulations of specific abrupt climate change events associated with iceberg armadas: the Holocene 8.2 ka event, and the glacial Heinrich event 1. In past model studies, these types of events have been simulated rather simplistically with fluxes of fresh water, neglecting the dynamical distribution of melting icebergs and ignoring the latent heat needed to melt the ice. At the beginning of this synthesis chapter we posed the key question

Is fresh water hosing a reasonable simplification of iceberg armadas?

We investigated the potential role of icebergs in the 8.2 ka climate event. In our model, melting icebergs influence the climate directly by locally freshening and cooling the ocean. Amongst other things, we evaluated the effect of a large iceberg discharge originating from the decaying Laurentide ice sheet on ocean circulation, compared to a release of an identical volume of freshwater alone. Our results showed that, on top of the freshwater effect, a large iceberg discharge facilitates sea-ice growth as a result of lower sea-surface temperatures induced by latent heat of melting. This causes an 8% increased sea-ice cover, 5% stronger reduction in North Atlantic Deep Water production and 1°C lower temperature in Greenland.

Heinrich event 1 was simulated using an armada of interactive dynamic-thermodynamic icebergs coupled to the same climate model with Last Glacial Maximum boundary conditions. The cooling effect was explored in a sensitivity experiment. Icebergs that included both the freshening and the cooling effects were 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 a secondary mechanism: facilitation of sea-ice formation, which affects deep-water formation, disturbing the thermohaline circulation. In another sensitivity experiment, the role of the dynamic distribution of melting icebergs was examined by comparison with a classic hosing approach with homogeneous distribution of the melting fluxes in the Ruddiman belt. The early response of the climate system is much stronger in the iceberg experiments than in the hosing experiments. Furthermore, the homogeneous hosing overestimates the freshwater flux in the East, leading to excessive freshening and cooling of the eastern North Atlantic and a delayed recovery of the circulation after the event. So the dynamic-thermodynamic icebergs lead to a faster and spatially different response, with possible consequences for the net melting flux “needed” to disturb the thermohaline circulation. These cooling and distribution effects imply that a realistic simulation of Heinrich events requires that iceberg dynamics and latent heat of melting are taken into account.

6.6 Conclusion

In conclusion, icebergs can significantly affect the modern climate, since: firstly the North Atlantic Ocean meridional overturning circulation in general and the Labrador Sea convection in particular was shown to be sensitive to small fresh water fluxes in the order of 10 times the flux from Greenland’s largest glacier; secondly the Southern ocean deep convection was shown to be sensitive to the dynamic spatial distribution of melting fluxes from icebergs.

The Southern Ocean results also imply that fresh water hosing is not a reasonable simplification of icebergs melting fluxes, unless you are willing
to disregard differences in deep water formation in
the order of 10%, and delays in the order of 50 years,
as is further illustrated in the iceberg-armada experi-
ments. We invoked a secondary mechanism; sea-ice
facilitation, to be able to explain the non-linear and
counter-intuitive efficiency of Cool & Fresh icebergs at
disturbing deep-water formation.

Therefore dynamic and thermodynamic
aspects of iceberg behaviour should be taken into ac-
count.

6.7 Limitations and suggestions for
future research

Our results can be regarded as a starting point for a
wide range of climate modelling, paleoclimate, and/or
climate-proxy (IRD) -research. Here we will briefly dis-
cuss two alternative strategies for future development
and research. In the present version of the coupled
model (LOVECLIM version 1), activation of the dynamic
iceberg module is optional. Given our conclusion
that dynamic and thermodynamic aspects of iceberg
behaviour should be taken into account, there are two
fundamentally different approaches for further devel-
opment of the model; fine-tuning and/or upgrading
of the present iceberg module, or switching to another
type of iceberg-melting-fluxes modelling.

The computational costs of tracking indi-
vidual (or groups of) melting icebergs are quite large;
we estimate that the model run time roughly doubles
when coupled with the dynamic iceberg module.

From this point of view it could prove worthwhile
to develop a statistical iceberg distribution module,
where (groups of) icebergs are not tracked on a sub-
grid scale, but iceberg density per grid cell is modelled
in a more abstract, statistical manner. Other research
groups have made efforts in this direction [Clarke and
La Prairie 2001; Marko 1996; Young et al. 1998; Ebbes-
meyer et al. 1980]. Clarke and La Prairie [2001] have
dubbed this approach “the Heinrich problem” (Figure
6.1), as opposed to “the Titanic problem” of tracking in-

![Image](image-url)
On the role of icebergs in the climate system | Ph.D. Thesis Jongma J. I.

coupled dynamical iceberg tracking model could prove to be quite valuable in evaluating the performance of such a statistical model.

On the other hand there is room for improvement in the iceberg tracking module that we have used, among other things: one might wish to implement more detailed physics behind iceberg dynamics. For example, other modellers have pointed out the relevance or complexity of additional forces (e.g. Effects of iceberg shape and size and entrained water acceleration [Eltahan et al. 1983; Keghouche et al. 2009] and wave action [Hsiung and Aboulazm 1982; Eik 2009]). Here we remind the reader that imprecise knowledge of ocean state and iceberg properties are compensated for by adjusted drag-coefficients (section 1.2.1.3). Another aspect that could be refined is the interaction of the icebergs with sea-ice. Specifically, at present the sea-ice drag-coefficient is not a function of sea-ice thickness, and the dampening effect of sea-ice on wave-radiation force [Keghouche et al. 2009] might also require further research. One might also want to incorporate the specific behaviour and impact of giant icebergs on polynyas (open water) in the sea-ice. Given the intimate relationship between iceberg melt and sea-ice facilitation, deep-water formation by brine rejection in polynyas could be affected by icebergs, and a giant icebergs “wake” could be regarded as a polynya. We also note that the presented maps of melting flux from the icebergs cannot be considered as quantitatively accurate estimates of IRD (ice rafted debris) deposition, since IRD tends to not be homogeneously distributed in the icebergs, and icebergs can roll over. Finally we note that a more plausible iceberg production is now being developed in our research group by coupling to a dynamical ice-sheet module.

There is also room for additional research with regards to the version of LOVECLIM that is being used. For example, the grid-scale potentially affects the sea-ice module regarding polynyas, and from that point of view it could prove worthwhile to investigate our results with a higher resolution version of the climate model. Furthermore, different “versions” of the LOVECLIM model exist, with varying climatic sensitivity to greenhouse gasses and fresh water fluxes, depending on a large set of parameters that are subject to tuning within plausible ranges. Recently this parameter-space has been investigated methodically [Loutre et al. 2011], which might be regarded as a transparent way of tuning the model. They conclude that a relatively sensitive model version performs best, but all versions exhibit systematic bias, such as a too strong ocean heat uptake, and therefore an improvement of the physics would be required to further improve the performance. In this context we repeat (section 6.4) that dynamical thermodynamical icebergs could be expected to affect the vertical mixing parameters of the ocean since homogeneous hosing is more efficient at stratifying the ocean than spatially diverse iceberg melt. Furthermore we note that the above mentioned study highlights the sensitivity of the ocean circulation to heat compared to fresh water fluxes, which apparently underlines our conclusions regarding significance of the melting heat of icebergs. Therefore for the longer term we would suggest that once a plausible interactive iceberg production has been developed, a tuning exercise similar to [Loutre et al. 2011] would be appropriate. Meanwhile our general approach of preferring sensitivity experiments over transient simulations is supported by the fact that Loutre et al. [2011] point out some systematic biases of LOVECLIM.

Of course, this is not an exhaustive list of limitations and possible future research, we would like to emphasize that all our results are to be considered as model- (and -version) dependent and should be confirmed independently in other climate models.