Sensitivity of a coupled ice-shelf / ocean system to changed oceanographic boundary conditions

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Introduction

Ice-shelf / ocean interaction processes significantly contribute to the formation and modification of major water masses in the southern polar ocean. As one such process basal melting beneath the Filchner-Ronne Ice Shelf contributes significantly to the ablation of the Antarctic Ice Sheet. The outflow of Ice Shelf Water (ISW) from the ice-shelf cavity, as a result of these melting processes, leads to a preconditioning of waters on the continental shelf and to deep water formation, when ISW mixes with Warm Deep Water (WDW) at the shelf break. On the other hand, heat fluxes across the ice-shelf / ocean interface associated with melting and freezing affect the physical and dynamic properties of the ice shelf, its mass balance and its steady state thickness profile. This has important implications for the stability of the West Antarctic Ice Sheet.

We present first results of numerical model runs with a dynamic three-dimensional ice-shelf model coupled to an ocean model. The coupling of both models provides the possibility to study the reaction of each component to changes at the common interface, the ice-shelf base. After establishing steady state conditions for a prescribed initial ice-shelf and bathymetric geometry in our model, the basal mass balance determines the evolution of the coupled system. We observe particular sensitivity of the model in regions, where high ablation or accretion rates are seen. In order to explore a range of possible developments of the coupled system 'ice-shelf / ocean', we have initially chosen an idealized model geometry, which is, however, comparable to the geometry of the Filchner-Ronne Ice Shelf. A comparable approach, though restricted to ice-shelf dynamics, has been investigated by Lange and MacAyeal (1988) and MacAyeal and Lange (1988).

The Coupled Model System

Investigating the sensitivity of a fully coupled ice-shelf / ocean system to changed boundary conditions, relevant feedback mechanisms and the interactions between both climate components, the ice shelf and the ocean, requires the coupling of numerical models which are able to simulate the high resolution flow field for each component. A schematic diagram of the model design is given in Figure 1.

a) The ice shelf model

To quantify the main parameters describing the dynamic processes of the ice-shelf system, a numerical three-dimensional flow model (Sandhäger, 2000) has been expanded to enable time dependent applications (prognostic model runs). The model is based on the fundamental balance equations of thermo-mechanics, an empirical equation of state for large natural ice bodies (flow law) and material equations for polycrystalline ice (cf. Paterson, 1994). The resulting model equations are solved by employing a finite difference method in combination with specially derived algorithms (e.g. Herterich, 1987, Blatter, 1995). The input parameters include the mass flow over the grounding lines, the mean annual surface temperature, the snow- accumulation rate and the basal mass balance.

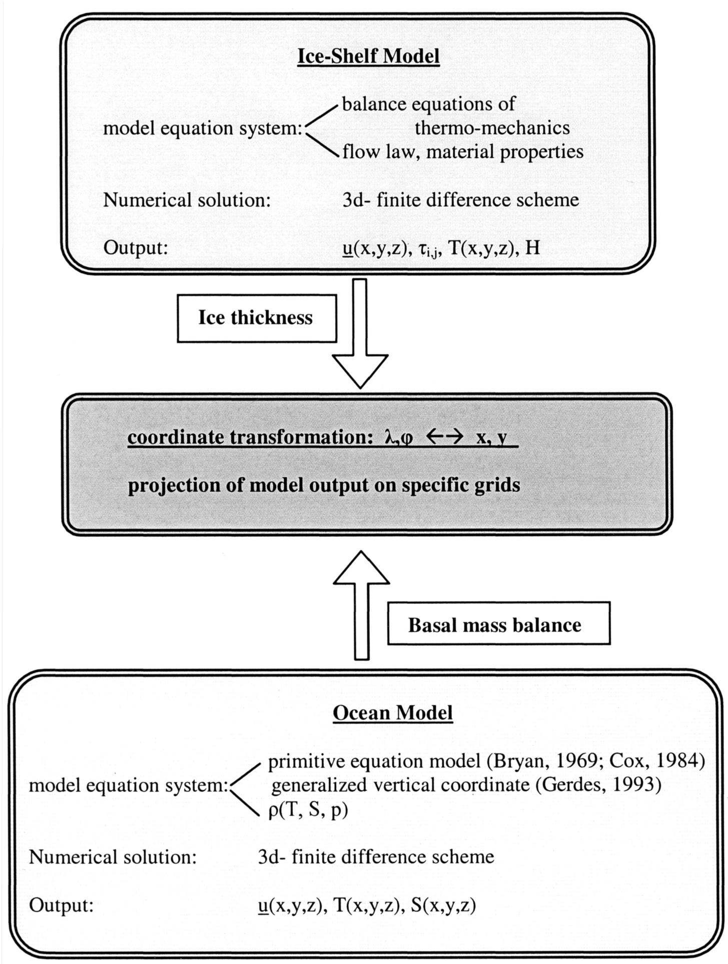

Figure 1: Design of the coupled ice-shelf / ocean model system.

The latter is being derived by the ocean model. Numerical integration yields the flow velocities of the ice masses, the vertical distributions of stress and temperature as well as the ice thickness at each grid point.

b) The ocean model

The ocean model is a version of a three-dimensional general circulation model (Bryan, 1969; Cox, 1984) modified to use generalised vertical coordinates (Gerdes, 1993). It enables the simulation of interactions between an ice-shelf cavity and the adjacent deep ocean (Grosfeld et al., 1997). The model is forced by an idealised cyclonic wind field with zonally, westward winds along the ice front and a simple thermodynamic sea-ice model in the open ocean. In the ice-shelf cavity buoyancy forcing occurs by ice-ocean interactions due to melting and freezing processes at the inclined ice-shelf base, as well as buoyancy fluxes over the open boundary beneath the ice-shelf front. The model is initialised with constant temperatures. A weak density stratification is implemented through increasing salinities from top to bottom. The model starts from an ocean at rest and is integrated until a quasi steady state is reached.

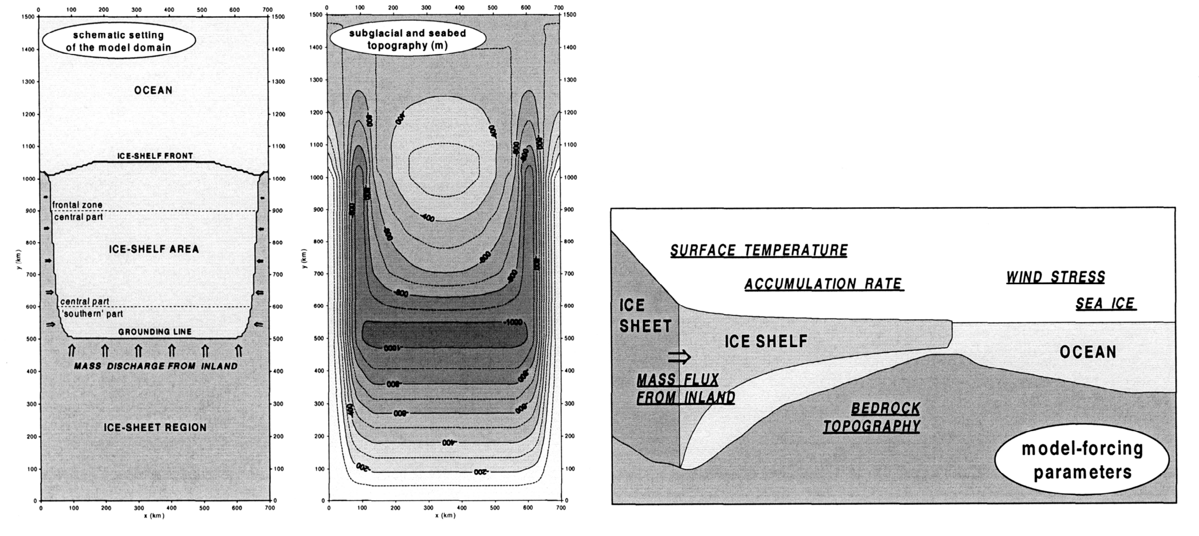

Figure 2: Design of the model domain, and principle forcing parameters for the model study. The coupling between both models is provided by the basal mass exchange parameter, the melting and freezing rate at the ice-shelf base. Special control regions like frontal zone, the central part and the `southern' part of the ice shelf are indicate on the left diagram.

c) The interface of the coupled models

The interaction of ice shelf and ocean occurs at their common interface, the ice-shelf base. Melting or freezing processes at the ice-shelf base which are caused by the oceanic heat flux lead to ice-thickness changes and influence the dynamic regime of the ice shelf. On the other hand the ice-thickness distribution determines the geometry of the sub-ice shelf cavity. Consequently, changes in the ice-shelf draft influence the ocean circulation in two aspects, i) the barotropic flow is steered along f/H_W contours (with f the Coriolis parameter, and H_W the water-column thickness) and hence is sensitive to the ice-shelf thickness and ii) the freshwater flux itself associated with basal melting or freezing depends on the draft of the ice-shelf base. The melting and freezing rates and the ice thickness are therefore exchange parameters between both models in a module that handles the interpolation and transformation on the specific model grids. While the ocean model is discretised in spherical coordinates the ice model is solved on a Cartesian stencil.

Model Set-up and Coupling Procedure

The initial ice-shelf geometry (Figure 2) results from a simple approximation for 1D ice-shelf flow (e.g. Oerlemans and Van der Veen, 1984) and is expanded onto a 2D plane. This geometry was integrated for about 1000 years to derive a stationary flow field for the 3D-domain. The surface-accumulation rate is given by an idealised function which is sensitive to the geographic position (e.g. latitude) and to surface elevation, respectively. The inland-ice discharge into the ice-shelf region has been set to constant values over the whole integration time (see arrows in Figure 2, left). The distribution of the basal melting and freezing rate was provided by the initial model run from the ocean model.

The ocean model has been run with a given bathymetry containing an ice-shelf cavity with two distinct troughs to the west and to the east. In the centre of the domain a shallow water region of -50 m depth is chosen to simulate the existence of an area for possible ice shelf grounding in the coupled model run. The ocean model was integrated for about five years to reach a stable

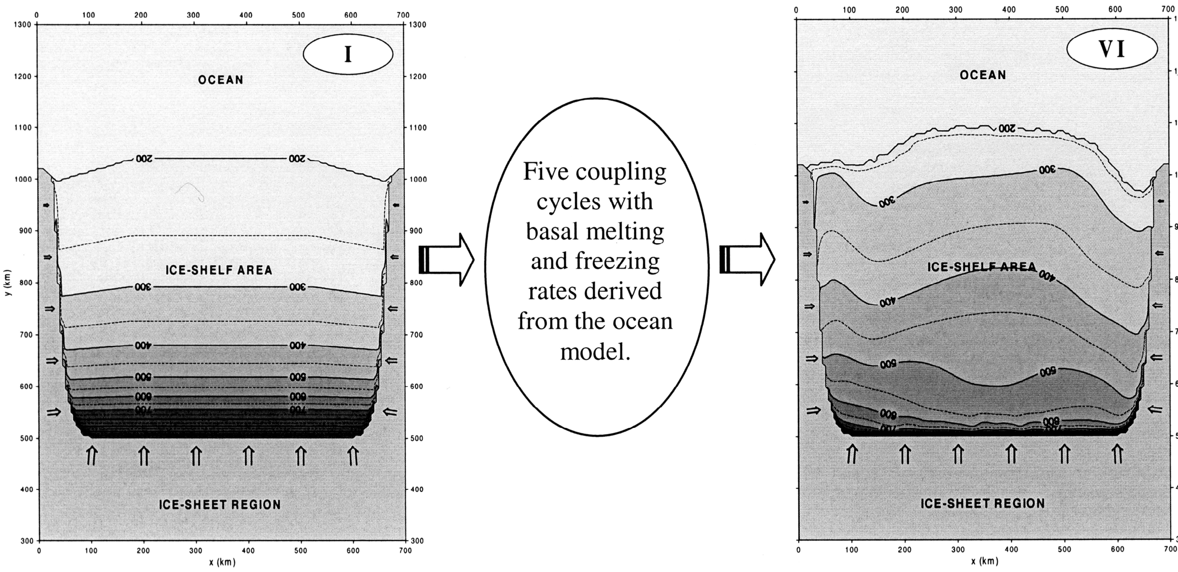

Figure 3: Ice shelf thickness for the initial model geometry (I) and at the end of the coupled model run after five coupling cycles (VI). Because the initial geometry is derived from an analytical estimation for 1D- ice shelf flow the zonal thickness distribution is constant. At the end of the simulation after 250 yrs of integration the ice thickness near the grounding line has strongly decreased and increased in the central and frontal zone.

flow pattern. After five years of integration the calculated melting and freezing patterns are exchanged with the ice-shelf model. In the following, a new restart is performed for each consecutive year, with a new ice-thickness distribution calculated by the dynamic ice-shelf model.

First Results

To investigate the sensitivity of the coupled ice-shelf / ocean model to altered boundary conditions a principal equilibrium state for both model components has to be determined first. To reach this state each set of input data was used for a - 50 years model run for the ice-shelf model and for about one year for the ocean model. This procedure addresses the different relaxation time scales for ice dynamics on the one hand and the ocean circulation on the other hand. Since both models are prognostic ones results could only be determined for a quasi steady state, because longer integration times would automatically lead to an imbalance; e.g. the inland-ice mass flux cannot compensate for increased basal melting near the grounding line. The reaction is a local decrease in the ice thickness near the grounding line which can only be compensated by the ocean model through freezing instead of melting. Consequently, a steady state of the coupled model system is sensitive to changes and integration of the coupled system should only be performed along a quasi equilibrium.

Figure 3 shows the ice-shelf thickness at the beginning and the end of five coupling cycles. While the initial configuration depicts a regular thickness distribution from south to north, according to the simple 1D-approximation for ice-shelf flow in a confined bay, the model results after 250 years show the dynamic reaction of the ice shelf to changed basal melting and freezing patterns derived from the ocean model. High melting rates especially in the southeastern region near the grounding line lead to a rapid thinning of the ice shelf. This corresponds

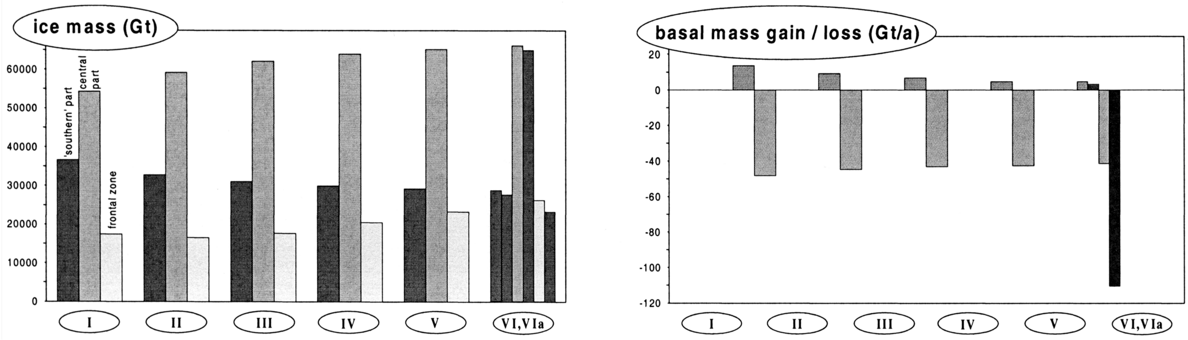

Figure 4: Calculated ice mass (left) and basal mass balances (right) from the different model components. The ice-shelf area is divided into three main areas, the southern part, the central part, and the frontal part (compare Figure 2, left). While the ice mass in the southern part of the ice domain decreases steadily due to the dynamic reaction of strain thinning and basal melting, the central part gains mass. The frontal zone loses ice through melting and calving first, which later is overcompensated through mass flow from the south to the north. The basal mass balance calculated from the ocean model depicts a steady decrease of basal mass loss. This results from continuous adjustment of the oceanic current system to the changed ice-shelf draft.

to the inflow area for ocean currents where relatively warm water masses enter the cavity. Strong melting associated with the formation of cold Ice Shelf Water lead to the deposition of marine ice in shallower areas along the west coast and in the central ice-shelf area. This distribution is compatible to measurements from the Filchner-Ronne Ice Shelf where major marine ice bodies were found in similar regions (Oerter et al., 1992, Thyssen et al., 1992). Basal accumulation of marine ice leads to thickening in the corresponding areas and to an asymmetric distribution of the ice-shelf thickness. The temporal development of the total ice mass in three control regions of the ice shelf and the corresponding time series for the basal mass balance derived from ocean modelling is shown in Figure 4.

While the ice-shelf mass in the southern part of the ice shelf decreases continuously due to melting near the grounding line and through dynamic redistribution of ice, the central part of the ice shelf gains mass throughout the whole simulation. This is caused by flow from south to north and through accretion of marine ice at the ice-shelf base. The behaviour of the frontal zone shows a more different behaviour. At first, the ice front retreats instead of melting processes. After this initial phase, mass flow from south leads to an advance of the ice front and thus to an increase in the total ice mass in the defined area. From an oceanographic point of view the basal mass balance of the ice shelf as determined by melting and freezing processes continuously attunes to the given ice-shelf draft. The basal melting rates decrease from initially -54.4 Gt/a to -46.7 Gt/a, the basal freezing rates change from 15.4 Gt/a to 5.4 Gt.a. The total mass loss of the ice shelf is nearly constant for the whole simulation at about -40.9 ± 1.4 Gt/a.

To investigate the sensitivity of the coupled ice-shelf / ocean system to altered oceanographic conditions we changed the ocean temperature according to a "worst case scenario" with an increase in the ocean temperatures of 0.5° C over all model levels in the open ocean part of the model domain. This scenario is chosen to demonstrate the reaction of the ice-shelf / ocean system to climate warming. This 'ocean-warming run' was integrated for another five years. While the ocean-current system does not change significantly, the warmed water masses penetrate into the deep cavity. In the region of the grounding line enhanced melting occurs and affects the general pattern of melting and freezing beneath the ice shelf. The total basal melting rate increases to -115.8 Gt/a which indicates the strong influence of warmer ocean water on the ice-shelf system. The reaction of the ice shelf is comprised by a strong reduction in ice thickness in the main inflow region of ocean.

Conclusions

We have presented first results of a coupled three-dimensional numerical ice-shelf model and an ocean model aimed to investigate the sensitivity of the coupled system to changing oceanic boundary conditions. The coupling of the models occurs at the ice-shelf base where basal melting and freezing processes influencing both regimes, the ocean currents which depend on the bathymetry and freshwater fluxes in the ice-shelf cavity, and the ice thickness of the ice shelf. The simulation for an idealised geometry, comparable to the Filchner-Ronne Ice Shelf, leads to a stable glacial system where the basal mass balance determines the ice-shelf geometry (all other boundary conditions remain constant). Ice mass and basal balance rate attain typical values for real ice-shelf / ocean systems (e.g. Gerdes et al, 1999 derived about 36-45 Gt/a for the Filchner-Ronne Ice Shelf). A model run for increased ocean temperatures indicates that the coupled system reacts sensitively to changes in the ocean environment. Increased basal melting in the inflow region of ocean currents leads to an erosion of glacial ice and a decrease of the areal coverage of the ice shelf on decadal time scales.

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