Evolution of Nordaustlandet ice caps in Svalbard under climate warming

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ABSTRACT Numerical calculations on the basis of a two dimensional dynamic numerical model, taking into account the conditions at ice-land and ice-sea boundaries, and field measurement data are used to construct current temperature and mass balance distributions for three large Nordaustlandet ice caps in Svalbard - Austfonna, Sarfonna, and Vegafonna. With these constructed distributions a simulation became possible of the disintegration of the modern ice sheet under various changes of glacioclimatic conditions due to expected climate warming.

INTRODUCTION

From a glaciological point of view it is most important to understand the reasons for and the mechanisms of glacier changes, primarily connected with climate changes and to obtain quantitative characteristics of the impact of these changes on the regime and dynamics of glaciers. The global climate warming expected in the next century due to intensification of the "greenhouse" effect (Budyko et al., 1989) makes this problem especially actual.

In this work, the impact of climate changes on the evolution of Nordaustlandet ice caps (NIC) in Svalbard is investigated on the basis of a numerical simulation. We used a two dimensional mathematical model of a non-stationary ice sheet with temperature parameterization which takes into account conditions at the land-ice and sea-ice boundaries and is similar to that applied for the modelling of Antarctic ice sheet by Grigoryan et al. (1990). The process of numerical modelling has been very much complicated by the absence of sufficient input information. It is divided into three correlated tasks:
(a) selection of temperatures distribution over glacier depth with the use of radio echo-sounding data on the spread of bottom melting zones;
(b) construction of the distribution of mean multi-year
accumulation and ablation rates; (c) numerical experiments with the model by setting up variants of the change of glacioclimatic conditions (ice temperature and accumulation rate).

FIG.1 Map of present surface elevation and modelled thermal conditions at the bedrock of Nordaustlandet ice caps. 1 - land free of ice; 2 - surface elevation contours marked in meters; 3 - position of snow line by satellite survey data of 1978 (Dowdeswell & Drewry, 1989); 4 - regions with near-bed reflections by airborne radio echo-sounding data of 1984 (Macheret & Vasilenko, 1988); 5 - modelled bottom melting regions; 6 - modelled ice-bottom temperatures; 7- bore hole of 1987.

INPUT DATA
The region of the NIC selected for investigation and its boundary has a complete form: the ice sheet consists of two merged ice caps - Austfonna and Sørfonna and a small ice cap - Vegafonna adjoining them (Fig. 1). The snow line position at the end of ablation season in 1978 in accordance with satellite survey data (Dowdeswell & Drewry, 1989) is shown in Fig. 1. Except several outlet glaciers reaching the sea, northward and westward, the ice sheet ends up on the land. In the east and south, the ice masses come down to the sea in the form of an unbroken ice front 30 to 50 m high.

Ice surface and bedrock elevation data have been obtained from the corresponding maps with contour intervals of 50 m and 100 m, built by data of airborne geophysical investigations of the British-Norwegian...
expedition of 1983 (Dowdeswell et al., 1986). Ice-free land and sea bottom elevations have been determined from the Norwegian topographic maps of 1:500 000 and 1:1 000 000 scales published in 1970 and 1973.

These data were interpolated onto the nodes of a 35x52 point grid with 3 km spacing. The ice viscosity coefficient was chosen to be $10^{-4}$ P, the geothermal flux value $-0.04$ W m$^{-2}$.

Till recently almost nothing has been known about temperature distribution over the ice depth. Few measurements have been made in shallow (up to 18 m) bore holes (Schytt, 1964; Dowdeswell & Drewry, 1989; Zagorodnov et al., 1990). They have shown that ice temperatures $T_b$ at the lower boundary of the active layer vary from $-0.5^\circ $C to $-4.2^\circ$C within the area limited by snow line, and on the outside, i.e. in the ablation zone fall to $-8^\circ$C. Such relatively high ice temperatures in the central region of NIC, where the mean air temperatures are $-10^\circ$ to $-12^\circ$C (Troizky et al., 1975), can be accounted for by the input of heat generated in the process of refreezing of melt water in the snow-firn sequence. Mass balance measurements on NIC were made in 1957 and 1958. Their results were presented by Schytt (1964) in form of an annual accumulation distribution map and the dependence of the annual ablation on the surface elevation typical of the whole ice sheet. It was suggested that there was no surface melting and melt water run-off from accumulation zone at surface elevations over 500 m. We used these data for an initial assignment of the mass balance distribution at the ice sheet surface onto the grid nodes.

**THE RESULTS OF MODELLING AND THEIR DISCUSSION**

**Temperature distribution**

Numerical simulation with the assignment of the surface temperature $T_s^a = -4^\circ$C within snow line and $T_s^b = -8^\circ$C outside it has shown that the bottom ice temperatures reach the melting point all over the ice sheet except in the narrow zone along its southern, western, and eastern edges. These results do not agree with airborne radio echo-sounding data obtained by the expedition of the Institute of Geography, USSR Academy of Sciences in 1984, which show that areas of bottom and possible near-bottom melting have not been so widespread (Macheret & Vasilenko, 1988). In variants with near-surface temperatures of $-8$ to $-10^\circ$C, the areas of bottom melting diminished and satisfactorily coincided with regions where bottom melting had been proposed from airborne radio echo-sounding data (Fig. 1). This fact points out that the rise of near-surface temperatures occurred comparatively late and the ice temperatures should have decreased with depth, keeping "memory" about colder climates.
Deep drilling data of 1987 at the summit of Austfonna (Zagorodnov et al., 1990) confirmed completely the assumption that the ice temperature at the depth of about 170 m falls to -8°C. The 6°C to 8°C temperature rise in upper ice layers is caused by climate warming in the current century leading to intensification of surface melting. A comparison of the measured and calculated ice temperatures at the glacier bottom shows that their difference does not exceed 1-2°C.

Mass balance distribution

Numerical simulation of mass balance distribution based on data by Schytt (1964) (its value is equal to 2.47 km³) shows that for several decades there has been intensive growth of the modelled ice sheet dimensions and its thicknesses. However, satellite surveys of 1969-1981 indicate that the ice-sheet margins are in a near-steady state (Dowdeswell, 1986). For the modelled ice sheet to be in a steady state it is necessary to decrease mass balance approximately 2.5 times. Moreover, the analysis of modelled ice thickness changes shows that the simulated spatial mass balance distribution does not correspond to the real one either.

A detailed analysis of possible reasons for deviations of measured annual accumulation and ablation values from the mean ones shows (Schytt, 1964; Troizky et al., 1975) that the 1957-1958 budget year was not usual because of snowy winter and cold summer. When the ice sheet is steady this mass balance distribution may be constructed in such a way as to achieve correspondence between surface elevations for the modelled steady-state ice sheet and those for the modern NIC (Fig. 2, Table 1, variant 2). The correctness of such selection of the mass balance distribution is confirmed by good correspondence between calculated and measured data:

(a) Calculated null-balance line fully repeats the configuration of snow line, especially in the north of Austfonna (Fig.2). It is closer to the ice sheet edge than snow line because of the presence of super-imposed ice (Dowdeswell & Drewry, 1989).

(b) There is a good agreement between the constructed mass balance values and the data of more recent mass balance measurements in the central part of Austfonna (Sin'kevich & Tarusov, 1989). In both cases the accumulation distributions unlike Schytt’s were uniform, about 50-60 g cm⁻², and only in the narrow zone about 3 km wide in the east of Austfonna measured accumulation values exceed 70 g cm⁻² (calculated ones were 100 g cm⁻²).

(c) The calculated surface velocity increases from 15 m year⁻¹ in the center to 30-40 m year⁻¹ at the ice sheet edge. For comparison, the measured surface velocity values in one of drainage basins are 1-10 m year⁻¹ in the south-east region of Austfonna near ice
Nordaustlandet ice caps in Svalbard and climate warming

Table 1: The integral characteristics of Nordaustlandet ice caps for different variants of glacioclimatic conditions; initial $\tau = 50$ years after the present for variants 1, $\tau = 2000$ years for variants 2, 3 and 4, $\tau = 100$ and 300 years for variants 5, 6 and 7.

<table>
<thead>
<tr>
<th>Initial data and calculation variants</th>
<th>Area (km$^2$)</th>
<th>Average ice thickness (m)</th>
<th>Ice volume (km$^3$)</th>
<th>Mass ice balance (km$^3$/yr)</th>
<th>Iceberg calving on the surface (km$^3$/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial data</td>
<td>7880</td>
<td>319</td>
<td>2511</td>
<td>2.47</td>
<td>-</td>
</tr>
<tr>
<td>Calculation variants:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Mass balance by Schytt (1964)</td>
<td>9331</td>
<td>381</td>
<td>3558</td>
<td>2.47</td>
<td>1.2</td>
</tr>
<tr>
<td>2. Constructed mass balance</td>
<td>7852</td>
<td>342</td>
<td>2685</td>
<td>1.07</td>
<td>0.9</td>
</tr>
<tr>
<td>(see Fig. 2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>3. Increase of $T_s$ by 4°C</td>
<td>7554</td>
<td>318</td>
<td>2400</td>
<td>0.9</td>
<td>0.84</td>
</tr>
<tr>
<td>4. Increase of mass balance by 20%</td>
<td>8725</td>
<td>362</td>
<td>3160</td>
<td>1.3</td>
<td>0.9</td>
</tr>
<tr>
<td>5. Warming by 3°C, increase of accu-</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>mulation rate by 20 cm year$^{-1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>in 100 years</td>
<td>7330</td>
<td>308</td>
<td>2254</td>
<td>-3.2</td>
<td>0.82</td>
</tr>
<tr>
<td>in 300 years</td>
<td>4800</td>
<td>290</td>
<td>1391</td>
<td>-3.6</td>
<td>0.45</td>
</tr>
<tr>
<td>6. Warming by 3°C:</td>
<td>7144</td>
<td>285</td>
<td>2038</td>
<td>-5.4</td>
<td>0.8</td>
</tr>
<tr>
<td>in 100 years</td>
<td>3851</td>
<td>219</td>
<td>844</td>
<td>-5.1</td>
<td>0.2</td>
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<tr>
<td>in 300 years</td>
<td>6744</td>
<td>268</td>
<td>1816</td>
<td>-7.9</td>
<td>0.59</td>
</tr>
<tr>
<td>7. Warming by 5°C, increase of accu-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mulation rate by 45 cm year$^{-1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>in 100 years</td>
<td>2754</td>
<td>183</td>
<td>504</td>
<td>-5.9</td>
<td>0</td>
</tr>
<tr>
<td>in 300 years</td>
<td></td>
<td></td>
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</tbody>
</table>

*At initial moment $\tau$ for variants 1, 2, 3 and 4.

Calculated accumulation values on Vegafonna and Brøsvellbreen exceed by far the values given by Schytt.
Particularly, calculated accumulation rates at the marginal region of Brøsvellbreen are equal to 90-100 g cm$^{-2}$. Such big values can be explained by the fact that this part of the glacier formed after the surge in 1936-1938 when it became 20 km longer (Schytt, 1969), i.e. at present it cannot be in a stable state.

Thus, the constructed mass balance distribution corresponds well to the real balance at the surface of the whole NIC except several areas with complicated dynamics and surface relief.
Surface melting and ablation

The results of calculations with various initial distributions of surface temperature and balance mass have earlier been described in detail by Ignatieva et al. (1990). Here we note only that the same changes of average thickness (about 20-24 m), ice volume, and area occur in variants with a 20% change of balance mass values and a 4°C change of surface temperature. The values of these parameters for the steady-state ice sheet 2000 years ago as compared to the present conditions are presented in the Table 1, variants 3 and 4. Maximal changes have occurred at Brøsvelbreen and at the south-east edge of Austfonna, where glacier bedrock elevations are lower than sea level.

This kind of simulations are useful to study the ice-sheet response to variations of any model parameters but they do not take into account correlation between these parameters that is expected to take place under climate change. To forecast the ice sheet response to possible climate warming, it is necessary at least to consider the accumulation and ablation changes independently, taking into account increase of ablation (melt-water run-off) rates under the change of the ice formation zone and increase of melting and ablation because of a decrease of glacier surface elevations under deglaciation.

The numerical experiments show that values obtained by Schytt (1964) from data of ablation measurements in cold summer of 1957 are smaller by far than the mean multi-year values. Therefore for calculating melting rate we used a modified formula by Khodakov-Krenke (Krenke & Khodakov, 1966; Glaciology..., 1985):

\[ A = 1.33 (T_a + 9.66)^{2.85} \text{ (mm year}^{-1}) \]

where \( T_a \) is average summer air temperature in °C that can be calculated for a given surface elevation using the method described earlier (Glaciology..., 1985). The ratio of ablation rate \( v \) to melting rate \( A \), i.e. the value of coefficient \( K = v / A \) depends on the type of ice formation zones. Its value was changed in numerical calculations depending on air temperature and melting-accumulation ratio from 0.2 for colder zones to 0.8 for warmer ones. Our calculations show that in spite of a rather arbitrary choice of value \( K \), its variations have not changed the general picture of deglaciation but only increased or decreased velocity of the ice sheet retreat. In accordance with earlier estimates (Glaciology..., 1985), we believe that the decrease of surface altitude leads to air temperature rise with the gradient being equal to 0.6°C/100 m.
The ice sheet response to climate warming

Climatologists (Budyko et al., 1989) estimate that the average assumed increase of mean air temperature in
Northern Hemisphere at the beginning of the next century will be about 1-1.5 °C. At the Svalbard latitude, estimates of summer temperature rise are not so precise - from 1 to 5 °C. Penetration values will probably correspond to Holocene optimum conditions and exceed the present ones by 20 cm year⁻¹.

Differing in numeric values, various estimations give a unanimous forecast: in the near future, in subpolar latitudes, climate warming will be accompanied by an increase of penetration. Therefore, the first 30 years were taken for simulations of different variants of mean summer temperature and accumulation rate dynamics. In the remaining time extended to 1300 years, summer temperature and ablation rates changed only depending on the ice sheet surface decrease.

In this model, surface elevation changes due to the increase of winter and ice temperature and, consequently, ice viscosity has not been taken into account because numerical calculations show that these changes are much smaller than the changes due to ablation rise.

The resulting maps show distribution of surface elevation and values of integral parameters of the NIC every 50 years after warming-up. Table 1 shows calculated values of area, ice volume, average ice thickness, mass balance volume, and iceberg calving volume of the NIC 100 and 300 years after the present for some variants of glacioclimatic conditions change. Figure 3 shows variability of the NIC area and volume as function of time. The curves in the plots are labelled with numbers which correspond to the numbers of the following variants of the increase of mean summer temperature by ΔTₐ and accumulation rates by Δυ⁺:

1 a-d: ΔTₐ = 3 °C, Δυ⁺ = 0, 20, 40, 60 cm year⁻¹;
2 a-b: ΔTₐ = 1 °C, Δυ⁺ = 0, 7 cm year⁻¹;
3 a-c: ΔTₐ = 1, 2, 3 °C, Δυ⁺ = 0;
4 a-d: ΔTₐ = 3, 4, 5, 6 °C, Δυ⁺ = 40 cm year⁻¹;
5 a-c: ΔTₐ = 1.5, 3, 4.5 °C, Δυ⁺ = 20 cm year⁻¹.

The simulation has shown that even under small climate warming - for instance by 1-2 °C (variants 2a,b, 3a and 5a), in 400 to 600 years the ice sheet area and volume will decrease by 30-50% mostly because of deglaciation of regions where bedrock elevations are lower than sea level, i.e. in the south-east edge of Austfonna and Brøsvellbreen. Here ice sheet retreats to positive elevations of bedrock relief. Vegafonna will also melt completely, but the north-west margin of Austfonna will
retreat insignificantly - at 3 to 5 km. If the warming is greater than 3°C Sørfonna will melt completely as well. For variants 1a,b,c the ice sheet area and volume will diminish by 50-70%. The temperature rise of over 3°C (variants 4b,c,d and 5c) will lead to a complete disappearance of the ice sheet. With a 4°C warming it will happen in 1000 years and with a 6°C warming in 300 years. Even an essential increase of accumulation will not stop disintegration of the ice sheet. Thus for preservation of Austfonna after a 5°C warming, the increase of accumulation should be over 60 cm year$^{-1}$, and should exceed 110 cm year$^{-1}$ after temperature rise by 6°C.

For example, Fig. 4 shows the sequence of modelled NIC boundaries in the process of degradation from the present state to a small glacier after a 3°C warming and a 20 cm year$^{-1}$ increase of accumulation (variant 1b). In this case the southern and south-eastern regions of Austfonna and Vegafonna will disappear in 300 years, Sørfonna will melt almost completely in 600 years. In 1000 years only a small part of Austfonna with bedrock elevations about 200 m will remain.

FIG. 4 Degradation of the Nordaustlandet ice caps. Degradation of the modelled ice sheet (1 - land free of ice, 2 - summit of caps) under warming-up by 3°C and increasing of accumulation rates by 20 cm year$^{-1}$ is illustrated by boundary position: 3 - at present, and 4 - every 200 years.
For other simulation variants the sequence of ice sheet retreat is similar – from west to east, only the velocity of retreat is different. Deglaciation of Vegafonna and Brøsvellbreen will terminate earlier – in 100-150 years after a 5-6°C warming.

If the warming-up is accompanied by a very high accumulation, like in variant 1d, ice thickness in the central region of NIC will increase a little, although ice front will retreat similar to other variants.

On the basis of the simulation results we have also drawn some conclusions about the modern dynamics of NIC. As noted above, the southern and south-eastern regions of Austfonna and Vegafonna retreated even under insignificant climate changes. For these regions to remain in a stable state, a high accumulation rate of about 70-110 cm year$^{-1}$ is needed. Yet, these values are much greater than the modern ones. Therefore, one can assume that at present only some regions of NIC are in a near-stable state. The ice thickness in other regions as well as in Vegafonna and southern and south-eastern parts of Austfonna decreases and their ice front slowly retreats.

CONCLUSION

Numerical simulations allow to assess the modern mass balance, thermal and regime characteristics of the NIC, as well as their response to different variants of climate changes. A good agreement with experimental data proves that this approach can be used for determining poorly known parameters and forecasting disintegration of the ice sheet due to the warming of climate.

REFERENCES


