ELSEVIER

Global and Planetary Change 12 (1996) 41-51

GLOBAL AND PLANETARY CHANGE

Limits on the areal extent of the Barents Sea ice sheet in Late Weichselian time

Kurt Lambeck

Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200, Australia

Received 1 December 1994; accepted 24 April 1995

Abstract

Observations of Lateglacial and Holocene sea levels from the Barents Sea region provide constraints on the grounded ice sheet during Late Weichselian time. Ice sheets that were restricted primarily to the Svalbard islands and the immediate shallow sea floor are inadequate to explain the observed age–height relations across the region. Instead, the ice sheet extended out to the edge of the shelf and attained a maximum thickness of the order of 3000 m over the central region of the Barents Sea. Ice volumes to the east of Novaya Zemlya have been small compared to the ice over the Barents Sea. The raised shoreline information from western Spitsbergen implies that retreat of ice over this area was initially slow until about 13,000 yr B.P. following which the remaining deglaciation appears to have been rapid.

1. Introduction

The extent of the ice sheet over the Barents Sea during the Last Glacial Maximum and the rates of subsequent decay have remained uncertain and views have ranged from a minimalist model, as exemplified by the arguments of Boulton (1979) of an ice sheet restricted primarily to the Svalbard and other Arctic island groups, to the maximalist model of Denton and Hughes (1981) and Grosswald (1983) with an ice sheet extending over both the Barents and Kara seas that rivals in volume the ice sheet over Fennoscandia. The estimated rates of retreat of this ice sheet also change significantly according to author, with some favouring a retreat that was essentially complete by earliest Holocene time (e.g. Elverhøi et al., 1992) while others, particularly Grosswald (1983), suggest that a substantial ice sheet persisted until as recently as 10,000 years ago. This diversity of views is understandable in the light of the limited information preserved for an ice sheet that may have been largely marine based. More recently, new off-shore sedimentary records have provided constraints on the ice sheet limits and the consensus view now seems to be that a substantial grounded ice sheet covered much of the region of the Barents sea out to the shelf edge (e.g. Solheim et al., 1990; Elverhøi et al., 1993).

It has been recognised at least since the work of Schytt et al. (1968) that an important constraint on the volumes of the past ice sheet is provided by the heights of past shorelines above present sea level. Salvigsen (1981), for example, from observations of height–age relations of shorelines on Kong Karls Land, concluded that a substantial ice sheet covered the region in Late Glacial time. Peltier and Andrews (1976), in their ICE-1 model, introduced a limited ice cover over Svalbard and though they noted some

SSDI 0921-8181(95)00011-9

incompatibility they did not draw conclusions about the possible extent of the ice over the region. Nakada and Lambeck (1988) introduced a more substantial ice sheet over the region, based on the Denton and Hughes (1981) maximum reconstruction, primarily to address the ice balance issue at the time of the Last Glacial Maximum. Tushingham and Peltier (1991) in their ICE-3G global model of the ice sheets indicated a strong preference for ice over Svalbard but noted that their model was not well constrained.

In recent years much more information on the age–height relation of shorelines in Svalbard, Frans Josef Land, and Novaya Zemlya, has become available (e.g. Forman, 1990; Forman et al., 1995; Mangerud et al., 1992a, b) and it has become possible to determine improved constraints on the limits and volumes of the former ice sheet over the region. This was attempted by Lambeck (1995), (referred hereafter to as Paper I) who compared observed shoreline elevations with predicted values based on two alternate ice models and then drew conclusions about modifications required to these a-priori models. It was concluded that the maximum ice sheet reconstruction by Denton and Hughes (1981), with the relatively late melting history advocated by Grosswald (1983), is quite inconsistent with the observed age–height relations for Lateglacial and Holocene shorelines and that plausible ice models will have the following characteristics:

(1) The maximum thickness of the ice is likely to have been at least 1500–2000 m with the centre of the load occurring to the southeast of Kongsoya.

(2) The ice sheet extended out to the edge of the continental shelf, and its maximum thickness over western Svalbard is likely to have exceeded 800 m.

(3) To the north of Svalbard and Frans Josef Land the ice sheet at the time of maximum glaciation extended out to the northern shelf edge.

(4) Retreat of the grounded ice across the southern Barents Sea occurred relatively early such that the region was largely ice free soon after 15,000 yr B.P.

(5) By 12,000 yr B.P. the grounded ice had retreated to the northern islands and had largely reached the present limits by 10,000 yr B.P.

(6) The eastern limit of the ice sheet occurred to the east of Novaya Zemlya but much of the Kara Sea and the western Russian plain was either ice free or covered with only a thin ice sheet.

In this paper predictions for the raised shorelines, based on a starting ice model that incorporates the above characteristics, are compared with observations to examine whether improved constraints on the dimensions of the last ice sheet can be developed. The full glacio-hydro-isostatic theory described in earlier papers (Lambeck, 1993a; Johnston, 1993) is used in these models. Some minimalist models are also explored in order to demonstrate that models in which the ice sheet was mainly restricted to the islands and shallowest waters are excluded by the observations of relative sea level change.

2. The glacio-hydro-isostatic rebound model

The sea-level change that results from the melting of land-based or grounded ice sheets can be schematically written as the sum of the eustatic change, $\Delta\zeta_e$, the crustal rebound associated with the glacial loading and unloading, $\Delta\zeta_i$, and the rebound associated with the changing water load, $\Delta\zeta_w$. Both $\Delta\zeta_i$ and $\Delta\zeta_w$ contain the effects of the changing gravitational field. In the Barents Sea region the sea-level change is dominated by the eustatic and ice load contributions with the latter originating predominantly from the Barents ice and, to a lesser degree, from the Fennoscandian ice. The comparison of the observed sea levels with model-dependent predictions gives an observation equation of the form

$$\Delta\zeta_o(\varphi, t) + \epsilon_o(\varphi, t) = \Delta\zeta_e(t) + \beta^j\left(\Delta\zeta_i^j + \Delta\zeta_w^j\right) \tag{1}$$

where:

$\Delta\zeta_o$ = the observed shoreline elevation (reduced to mean sea level) at location (φ, λ) and time t for a total of S observations,

ϵ_o = estimation of the observation error of each observation,

$\Delta\zeta_e$ = eustatic sea-level function for the totality of the ice sheets,

β^j = scale parameter for the height of the j^{th} ice sheet. In this case all β^j are set to unity except for the one corresponding to the Barents ice sheet.

The eustatic term is assumed to be known from studies of sea level rise in regions away from the ice sheets where the isostatic terms are relatively small. The isostatic terms are functions of the ice sheet history and of the earth's rheological parameters and values for the latter, based on studies of the sea level change in northwestern Europe (Lambeck et al., 1990; Lambeck, 1993b) are used here. The loads include ice sheets over Laurentia, Fennoscandia and Antarctica, as defined before, in addition to the Barents ice sheet discussed below. The procedure for solving the S equations for the unknown scale parameter β of the Barents ice sheet is to predict sea levels for the adopted earth parameters at each observation data point (a height and time) s ($s = 1 \ldots S$). The appropriate ice scale parameter β is then estimated by minimizing the quantity

$$\sigma_k^2 = \frac{1}{S} \sum_{s=1}^{S} \left[\frac{\Delta\zeta_0^{(s)} - \Delta\zeta_{predicted}^{(s)}}{\sigma^{(s)}} \right] \qquad (2)$$

where $\sigma^{(s)}$ is the standard deviation of the s^{th} observation. If the model is complete, the model parameters are accurate, the observation errors have a Gaussian distribution, and the adopted variances are realistic, then the expected value of σ_k^2 is unity. For the well constrained model for the British rebound and sea-level change the optimum silutions give $\sigma_k^2 \sim (1.6)^2$ and a wide range of plausible earth models yield $\sigma_k^2 \leq (2.5)^2$ (Lambeck, 1993a).

3. Observational data

The sea level information used has been discussed in Paper I and includes the important observational evidence for Frans Josef land and Novaya Zemlya collected recently by Forman et al. (1995), and observational evidence from Spitsbergen (Hoppe, 1972; Forman et al., 1987; Forman, 1990; Landvik et al., 1987; Mangerud and Svendsen, 1990, 1992 Salvigsen et al., 1990; Salvigsen and Elgersma, 1991; Salvigsen and Mangerud, 1991), Nordaustlandet (Olsson and Blake, 1962; Salvigsen, 1978; Jonsson, 1983), Edgeoya and Barentssoya (Hoppe, 1972; Gulliksen et al., 1992; Mangerud et al., 1992a, b), Kong Karls Land (Salvigsen, 1981), and Hopen (Hoppe et al., 1969).

4. A minimalist ice model

Despite the substantial rebound observed at some sites, a total of about 150 m at Kongsoya over the past 10,000 years, for example, (raised shorelines occur a little above 100 m here (Salvigsen, 1981), to which the eustatic rise of about 50 m since this time (Nakada and Lambeck, 1988) must be added) it has sometimes been argued that the maximum ice sheet was largely restricted to the Svalbard island group (Boulton et al., 1982). Fig. 1 illustrates such a model in which westernmost Spitsbergen is ice free and the ice sheet remains constant until 12,000 years ago and then melted to its present limits by 9000 yr B.P. The maximum ice thickness was about 2800 m. Melting of the Fennoscandian and other major ice sheets started at 18,000 yr B.P. The Fennoscandian ice sheet model contains ice over Novaya Zemlya but this is largely gone by 12,000 yr B.P. and this model does not give a good representation of the sea level change in this region. Also illustrated in Fig. 1 are the isobases, contours of equal shoreline elevations relative to present sea level. No raised shorelines are predicted to occur until after about 10,000 yr B.P. Prior to this time an area of relative uplift does occur centered over central Svalbard but as the region remains ice covered, conditions for shoreline formation and preservation would not have existed. The maximum elevation of raised shorelines at Kongsoya are predicted to not exceed a few tens of meters compared with an observed value of about 100 m. The predicted values are earth-model dependent but no plausible choice of model parameters can produce such shorelines for the small ice sheet. If the ice limits are maintained then the ice thickness would have to be increased by about 70% of the assumed value, or about 4700 m, and this is inconsistent with any plausible ice sheet profiles. Furthermore, this model predicts an absence of raised shorelines along the length of the west Spitsbergen coast and to produce raised shorelines here requires that the ice margin initially extended much further to the west. (At these sites the isostatic terms for this model are negative and simply increasing the ice thickness will not produce elevated shorelines; see fig. 7 of Paper I for comparison.) Overall, this minimalist model is inconsistent with the observed raised shorelines and

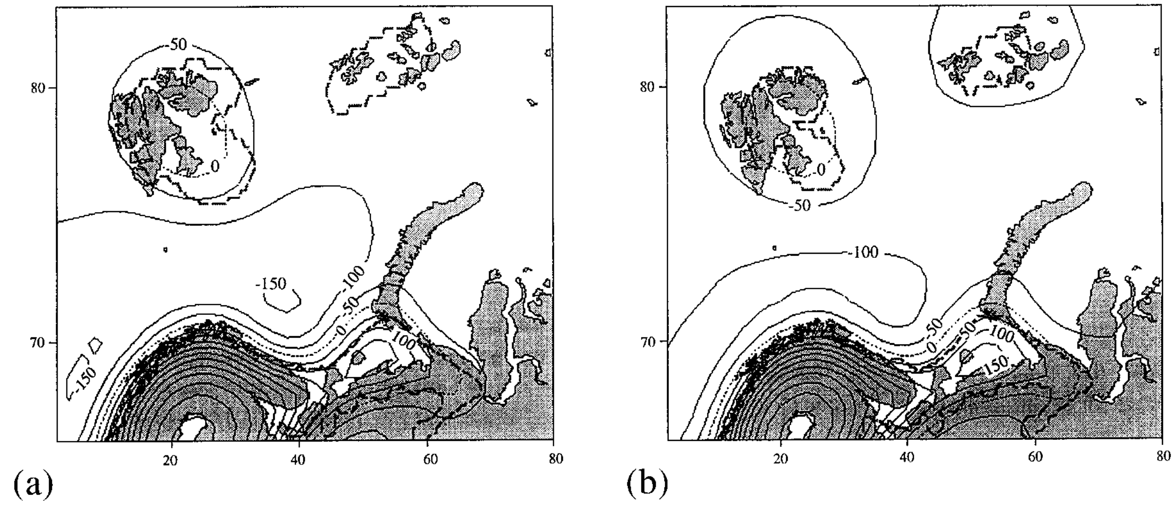


Fig. 1. The minimalist ice model at (a) 12,000 and (b) 10,000 yr B.P. in which the ice sheet is restricted to the Svalbard islands. From 18,000 to 12,000 yr B.P. the ice over Svalbard remains constant although the dimensions of the Scandinavian ice sheet have been significantly reduced in this interval. The ice limits are shown by the thick broken lines. Also shown are the predicted isobases, at 50-m intervals, of the sea level change. The zero isobase is dashed.

the Barents ice sheet must have had considerably larger dimensions than adopted here.

Fig. 2 illustrates the ice sheet and relative sea level isobases for a model in which the northern Barents Sea was covered with an ice sheet that extended from Spitsbergen to Frans Josef Land. The maximum ice thickness in this model occurred to the east of Kongsoya and reached 3200 m. Melting started at 15,000 yr B.P. and ended soon after 10,000 yr B.P. (This model corresponds to the minimum model in Paper I for epochs after 15,000 yr B.P. with ice volume before that being held constant at the

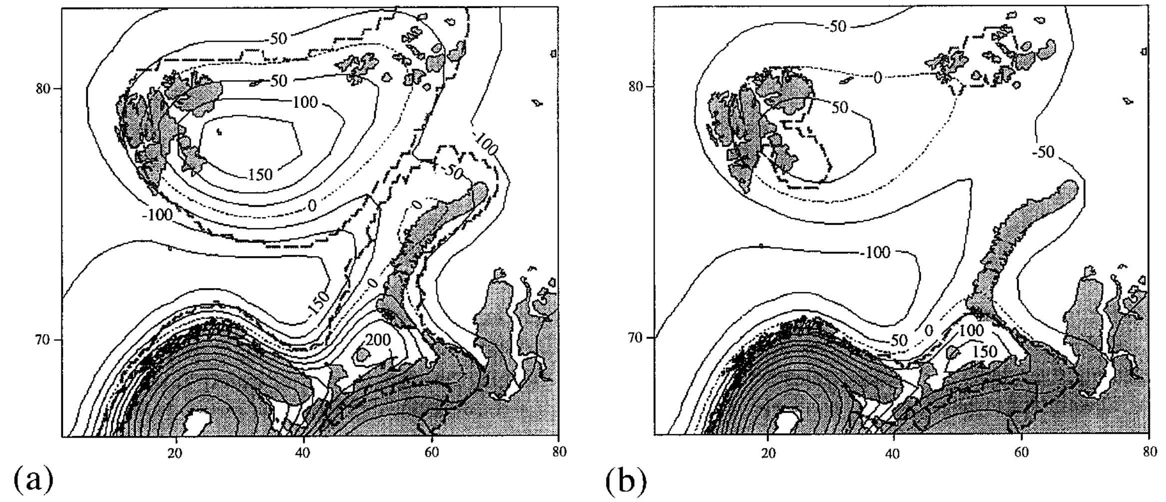


Fig. 2. The same as Fig. 1 for epochs (a) 15,000, and (b) 10,000 yr B.P., but for an ice model over the Barents Sea that started to decay at 15,000 yr B.P.

15,000 year value.) The coast of western Spitsbergen remained ice free throughout. Maximum raised shorelines near 100 m elevation at 10,000–11,000 years are now predicted to occur at Kongsoya although the predictions for southern Edgeoya (e.g. at Halvemaneoya) or Hopen Island are substantially less than the observed values reported by Hoppe (1972) and Hoppe et al. (1969), respectively. Likewise, the predicted shoreline heights for northern Nordaustlandet are close to or just below present sea level at 10,000 yr B.P. compared with observed elevations that approach 50 m (Olsson and Blake, 1962). No raised shorelines are predicted for sites along the west coast of Spitsbergen, nor for the eastern islands of the Frans Josef Land group where Forman et al. (1994) have reported 10,000 year old shorelines at elevations up to about 35 m above present sea level. Raised shorelines are not predicted for Novaya Zemlya at any time with this model. Overall, the comparison of these predictions with observations suggests that while the maximum ice thickness for Lateglacial time is roughly appropriate, the ice sheet limits have to be extended out in all directions in order for the predictions to approach the

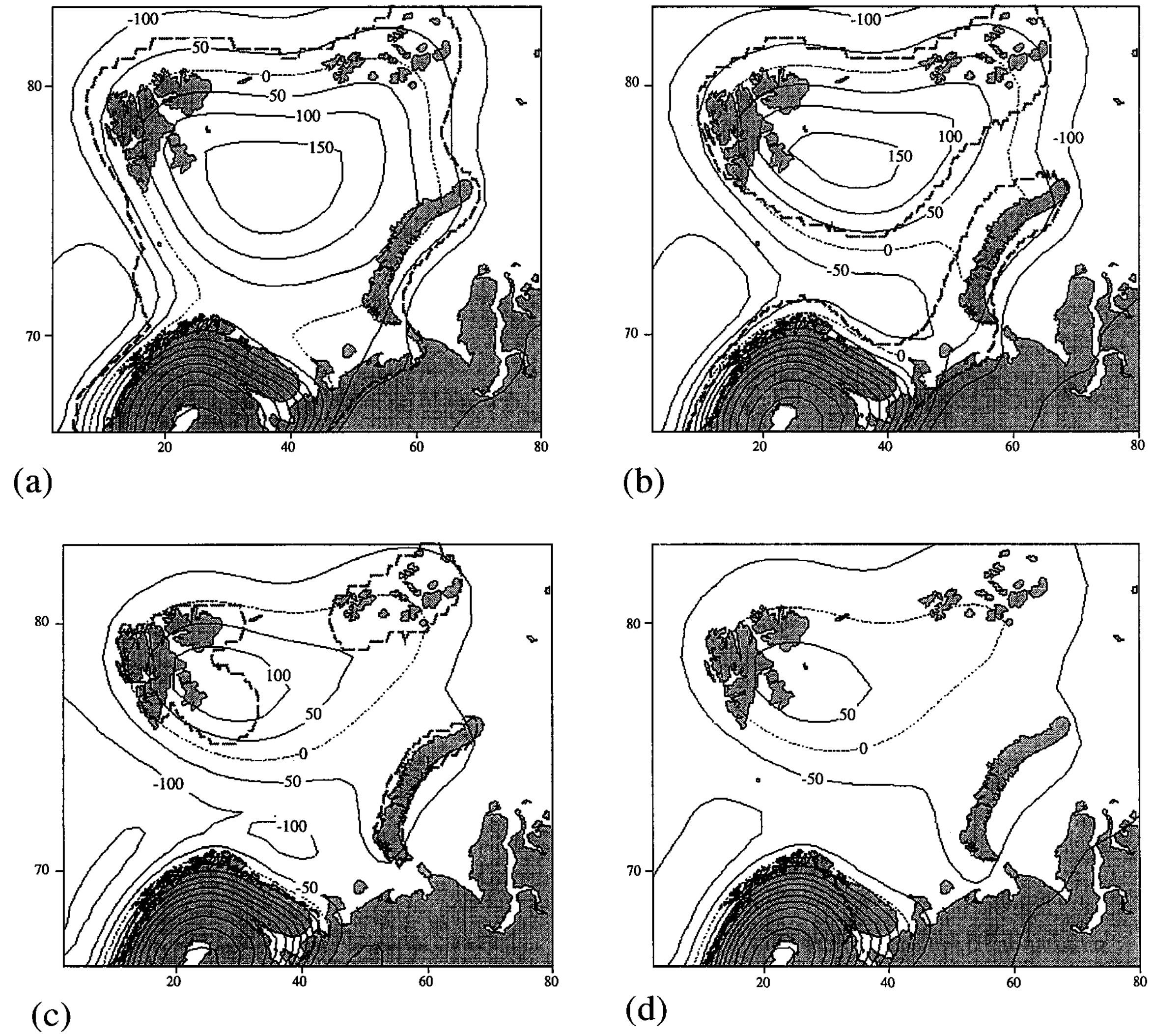
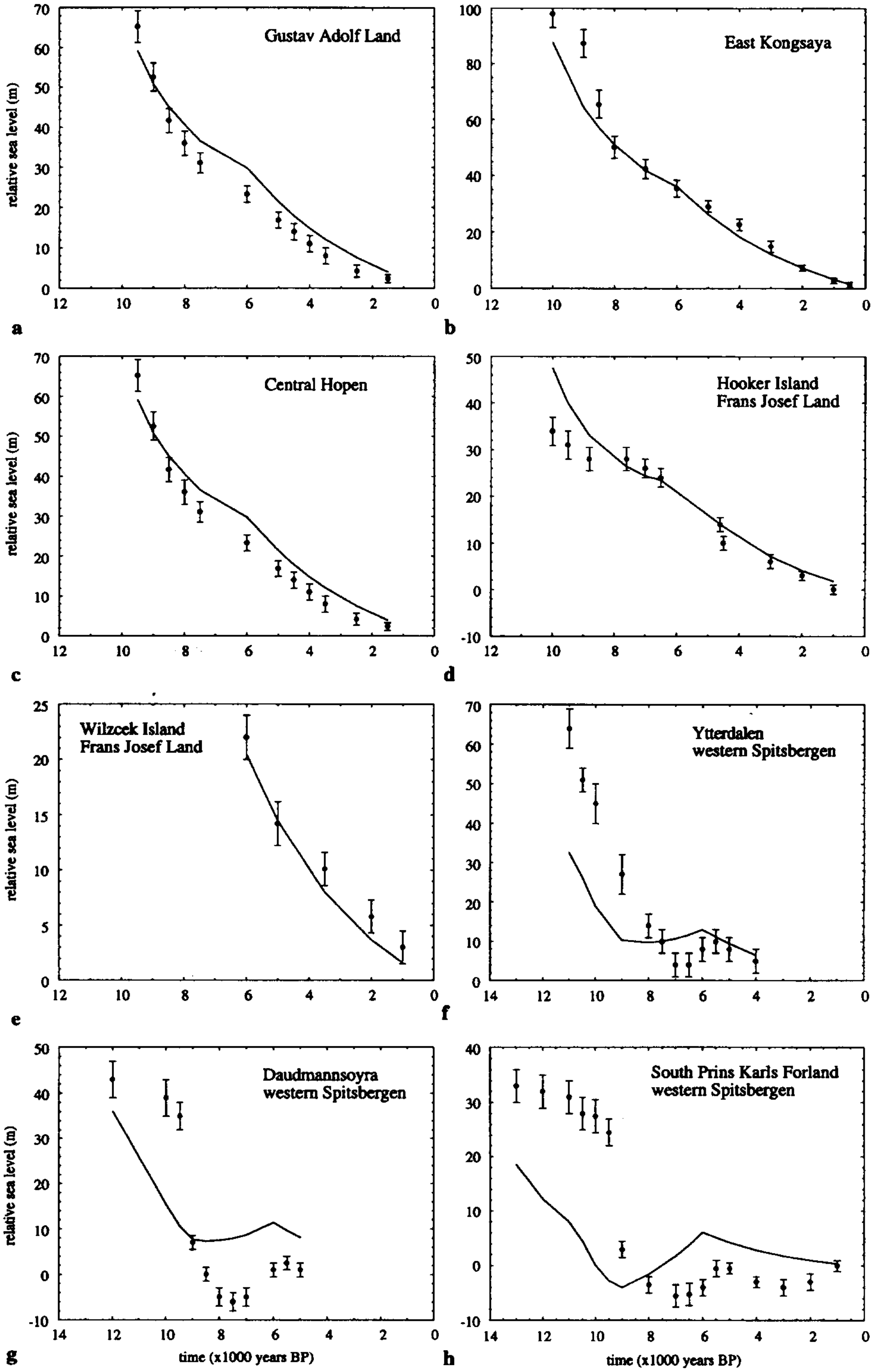


Fig. 3. Same as Fig. 1 but for the model BK-3 at epochs (a) 18,000, (b) 15,000, (c) 12,000 and (d) 10,000 yr B.P.


Gustav Adolf Land
East Kongsaya
Central Hopen
Hooker Island
Frans Josef Land
Wilzcek Island
Frans Josef Land
Ytterdalen
western Spitsbergen
Daudmannsoyra
western Spitsbergen
South Prins Karls Forland
western Spitsbergen
relative sea level (m)
time (x1000 years BP)
a
b
c
d
e
f
g
h
0
10
20
30
40
50
60
70
80
100
-10
5
15
25
14
12
10
8
6
4
2

observed patterns. Ice sheets that were confined largely to the island archipelagos are quite inadequate to explain the raised shorelines of Lateglacial and Holocene age throughout the region.

5. A new ice model for the Barents Sea

The starting model for the Barents ice sheet illustrated in Fig. 3 is based on the minimum model BK_{min} discussed in Paper I but which has been modified to take into consideration the conclusions reached in that paper about limits, rates of retreat, and ice thickness. Thus the ice sheet extends out to the continental margin, as defined at the time of the last glacial maximum, to the west of Spitsbergen. Ice retreat occurs rapidly and early over the southern part of the Barents Sea and no substantial ice occurs over either the Kara Sea or western Siberia, including the Urals. Earlier work with an ice sheet model for Scandinavia that was based on the reconstruction by Andersen (1981) indicated that there would have been a sea connection between the Baltic and White Seas in Lateglacial time, once the ice retreated from the area. In the absence of evidence for a major connection between the two seas this implies that this ice model contained an excessive amount of ice over north-western Russia, between the Urals and the White Sea, including the southeastern part of the Barents Sea. The maximum ice thickness at the time of maximum glaciation occurs over the Barents Sea and reaches 3400 m. This model is referred to here as BK-3.

Predictions of sea levels at all observation sites and times have been made for the revised ice model and for the same earth model considered before (Paper I). The overall agreement of these predictions with observations, as measured by (2), gives $\sigma_k^2 = (4.6)^2$ with $\beta = 1.30$ which represents a significant improvement over the value of $(8.1)^2$ previously found for the minimum model of Paper I. This improvement is almost wholly due to the better agreement for the sites along the western coast of Spitsbergen although the value is still considerably larger than expected and greater than can be attributed to possible uncertainties of the earth model parameters (see, for example, comparable results by Lambeck (1993a) for the Great Britain region).

Agreement between observations and predictions is good for sites in central Svalbard and Kong Karls Land, as is illustrated in Fig. 4, for three localities; Gustav Adolf Land, Kongsaya, and Central Hopen. For the Frans Josef Land sites the agreement is somewhat less satisfactory and the comparisons imply that more ice is required over this region than assumed in the model. (An error in the construction of the ice model, however, resulted in the limit of the ice sheet north of Frans Josef Land not extending all the way to the edge of the shelf as intended and, from the comparison of results for the models in Paper I, this largely explains the discrepancy for the model BK-3 in this region). The comparisons for the Novaya Zemlya sites suggests that a small increase in ice volume in this region is warranted.

Further improvement in the ice sheet appears to be in order. In particular, the model predictions still do not represent well the sea levels observed in Lateglacial times at sites such as Ytterdalen or South Prins Karls Forland (Fig. 4). The predictions for these sites do now lead to Lateglacial shorelines that lie above the present level, unlike the earlier models in which the ice sheet limit did not extend as far beyond the present coastline (see fig. 6 of Paper I). (There are some uncertainties in the observational evidence for the western Spitsbergen sites in that at some locations, (e.g. Daudmannsoya and South Prins Karls Forland) the data for the earliest Holocene suggests a very rapid fall in sea level, whereas a more gradual fall is suggested for other sites such as Ytterdalen and Wedel Jarlsberg Land. It remains unclear whether this difference is real or a consequence of problems with the radiocarbon time scale.)

The new comparisons suggest that the BK-3 model still does not contain enough ice in the western Spitsbergen region in Lateglacial time and this deficiency is largely responsible for the larger than unity

Fig. 4. Predicted and observed sea-levels at three sites in (a–c) central Svalbard; (Gustav Adolf Land (Salvigsen, 1978), East Kongsaya (Salvigsen, 1981), Hopen Island (Hoppe et al., 1969)); (d–e) Frans Josef Land (Hooker and Wilzcek Islands (Forman et al., 1995)); (f–h) western Spitsbergen (Ytterdalen (Landvik et al., 1987), Daudmannsoyra (Forman, 1990) and South Prins Karls Forland (Forman, 1990)).

value for σ_k^2. A regional comparison of predictions and observations for all the western Spitsbergen sites gives $\beta = 1.4$, comparable to the global value of 1.35, and a simple upwards scaling of the ice thickness over the region is inadequate to remove much of the discrepancy noted in Fig. 4. Larger β values give a better match with observations for the Lateglacial time but destroys the agreement for Holocene time. Thus, the comparisons suggest that more ice is required in the region in Lateglacial time, in order to raise the shorelines before about 10,000 yr B.P., followed by early and rapid deglaciation.

6. The anatomy of the relative sea-level change in western Spitsbergen

The sea-level change in the Barents region is the sum of several contributions: the distant ice sheets of Laurentia and Antarctica, the nearby Fennoscandian ice sheet, and the local Barents ice sheet. Fig. 5a illustrates these contributions for one of the western Spitsbergen sites, Ytterdalen, and the results are typical of the predictions for all the other localities near the western edge of the Barents ice sheet (see Fig. 5b for the South Prins Karls Foreland site). The Antarctic contribution is the only one that gives a characteristic far-field signal, following closely its eustatic sea-level component with a small amplitude highstand in mid-Holocene time. The Barents region lies within the intermediate fields of both the Laurentian (including Greenland) and the Fennoscandian ice sheets and the respective sea level contributions are characterised by rising levels up until the present. The spatial variability across the region of both these contribution is small, reaching a total of about 10 m at 13,000 to 15,000 yr B.P. The combined contribution from the three distant ice sheets, Antarctica, Laurentia and Fennoscandinavia at the time of the Last Glacial Maximum reaches about 110 m, less than the eustatic change of about 120 m for the same three ice models. Also illustrated is the contribution from the Barents ice sheet BK-3 which is dominated by the glacial rebound term. This contribution remains approximately constant from 18,000 to 13,000 yr B.P. mainly due to the initially slow change in the model ice sheet over Svalbard and to the delayed

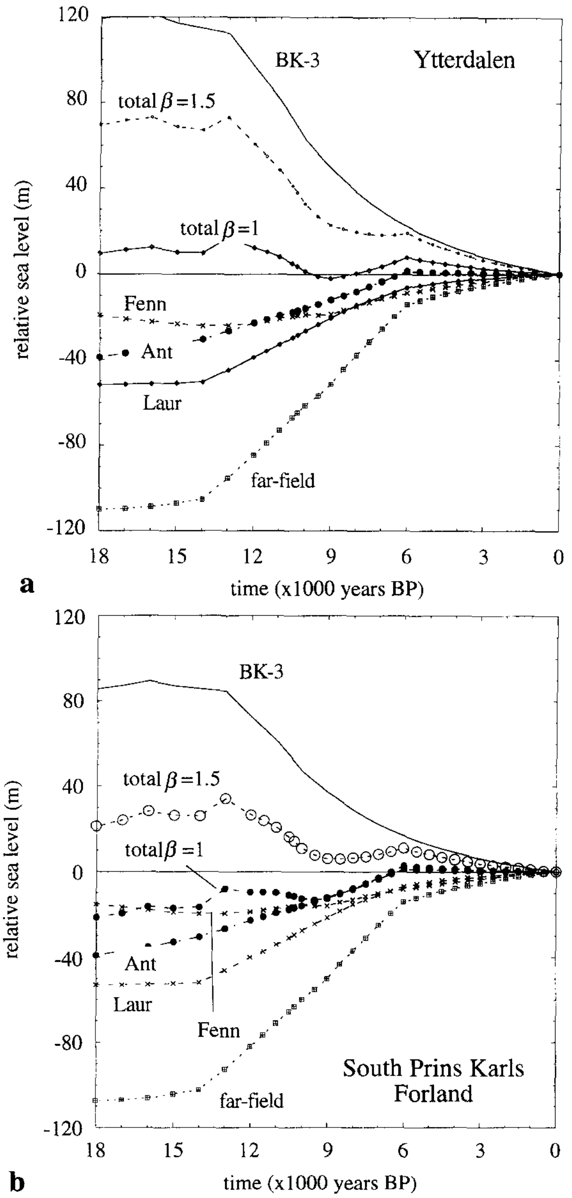


Fig. 5. Predicted components of the sea-level change for the Laurentian (including Greenland) (*Laur*), Antarctic (*Ant*), Fennoscandian (*Fenn*), and Barents (*BK-3*) ice sheets at (a) Ytterdalen and (b) South Prins Karls Forland, both on the south-western coast of Spitsbergen. Also illustrated is the combined contribution (far-field) from the three distant ice sheets (Laur + Ant + Fenn), the total sea level change for these sites (total $\beta = 1$), and the total (Laur + Ant + Fenn + βBK-3) with $\beta = 1.5$.

response of the crust to the changing ice load. The amplitude of this term varies regionally, being greatest at sites such as Erdmannflya that lie within Isfjorden and least at sites in northwestern Svalbard. At the coastal sites such as Ytterdalen the magnitude of the Barents rebound is about equal to the combined contribution from the more distant ice sheets and the total sea level remains close to the present level throughout Lateglacial and Postglacial time. Of note is that the sea-level curve is nearly constant until about 13,000 yr B.P. because of the way in which the various components combine. Fig. 5 also illustrates the total predicted sea levels for a model in which the Barents ice sheet is scaled upwards by a factor of 1.5. Now well raised Lateglacial shorelines are predicted for the coastal sites at elevations that are generally consistent with the observations from Ytterdalen as well as from other nearby sites such as Wedel Jarlsberg Land and Daudmannsoyra. However, the predicted shoreline elevations for epochs after about 9000 yr B.P. are much higher than observed, and inconsistent with the observational evidence.

The discrepancies between observations and predictions at the two sites could be attributed to limitations in either the ice model or the earth model parameters but in this instance, when the ice sheet is poorly constrained from independent field observations, it appears preferable to assume that it is the ice model that is at fault and to use earth model parameters that reproduce well the rebound to the south, even though some lateral variation in mantle structure would not be unexpected between Scandinavia and the tectonically younger Barents Sea province. The discrepancies are therefore interpreted in terms of modifications of the ice load and only if the requisite modifications appear unrealistic will other earth models be considered. The earlier reported results (Paper I) explored a range of plausible earth models and only those characteristics of the inferred ice sheet that were common to all earth models were considered realistic. This approach is also adopted here with the emphasis being on defining the essential characteristics, rather than details, of the ice sheet. Fjeldskaar (pers. comm.) adopted the alternative view and elected to attribute the rapid fall in sea level at about 10,000 yr B.P. to lateral variation in upper mantle structure across the shelf without first exploring the possible limitations of their adopted ice model.

Fig. 6a illustrates the observed sea level curve at

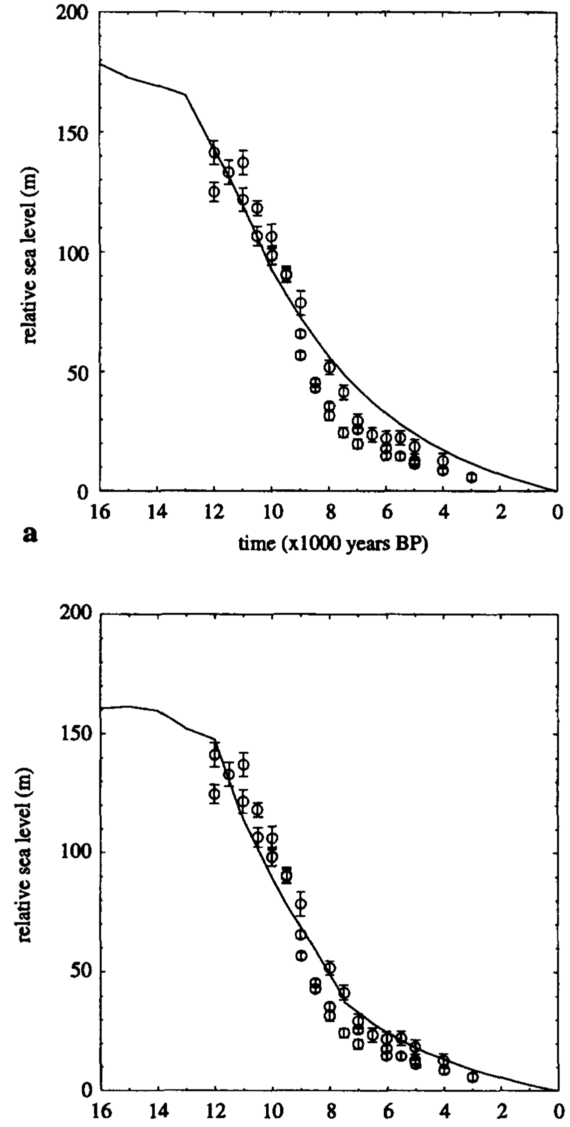


Fig. 6. (a) The observed sea-level change in southwestern Spitsbergen (at Wedel Jarlsberg Land, Ytterdalen and Daudmannsoyra) corrected for the contributions from the distant ice sheets of Laurentia, Antarctica, and Fennoscandia. The error bars correspond to the observational errors only. Also illustrated are the predicted changes for the Barents ice sheet βBK-3 ($\beta = 1.5$) for the average of the three sites. (b) Same as (a) but for the modified ice model BK-3a.

the three southwestern Spitsbergen sites of Ytterdalen, Wedel Jarlsberg Land, and Daudmannsoyra, corrected for the relatively better known contributions from Laurentia, Antarctica and Scandinavia through the isostatic model. This represents the "observed" sea-level change solely due to the Barents ice load and can be compared directly with the average change predicted $(\beta\Delta\zeta)^{BK}$ for the Barents ice sheet at the same West Spitsbergen locations as the observations. This comparison is given in Fig. 6a for the ice model BK-3 with $\beta = 1.5$ (a value greater than the average value of 1.30 estimated for the western Spitsbergen as a whole). Agreement between the observed and predicted estimates is broadly satisfactory although they do not replicate the rapid fall in sea level noted in some of the records for the individual sites at about 9000 yr B.P. What these comparisons suggest is that the initial ice load must have been substantially greater than assumed in the model BK-3, but that the melting of the ice sheet in Late glacial time initially occurred more slowly than assumed in this model and that the final melting occurred very rapidly if the rapid fall in sea level noted before about 9000 yr B.P. is a true reflection of the relative sea level change in the region. Fig. 6b illustrates predictions for an ice model BK-3a which is similar to BK-3 (scaled with $\beta = 1.5$), but with melting lagging BKS-3 by 2000 years until 13,000 yr B.P. and then melting rapidly with all ice gone by 10,000 yr B.P. This model does give a reasonable prediction of the observed sea level changes along this section of the Spitsbergen coast.

7. Conclusion

The height–age observations of the raised shorelines on the Islands in the Barents Sea imply that the region was covered by a large ice sheet that covered much of the Barents sea floor and which extended out to the edge of the continental shelf in the north and west. A substantial ice sheet persisted over Spitsbergen until at least 13,000 yr B.P. at which time melting was rapid with the present ice limits being approximated by about 10,000 yr B.P. Ice sheets that, at their maximum extent, are restricted to Svalbard and the immediate offshore shallow waters are inadequate to reproduce the observations throughout the region.

References

Andersen, B.G., 1981. Late Weichselian ice sheets in Eurasia and Greenland. In: G.H. Denton and T.J. Hughes (Editors), The Last Great Ice Sheets. Wiley, New York, pp. 1–65.

Boulton, G.S., 1979. Glacial history of the Spitsbergen archipelago and the problem of a Barents Shelf ice sheet. Boreas, 8: 31–57.

Boulton, G.S., Baldwin, C.T., Peacock, J.D., McCabe, A.M., Miller, G., Jarvis, J., Horsefield, B., Worsley, P., Eyles, N., Chroston, P.N., Day, T.E., Gibbard, P., Hare, P.E. and Von Brunn, V., 1982. A glacio-isostatic facies model and amino acid stratigraphy for late Quaternary events in Spitsbergen and the Arctic. Nature, 298: 437–441.

Denton, G.H. and Hughes, T.J. (Editors), 1981. The Last Great Ice Sheet. Wiley, New York, 484 pp.

Elverhøi, A., Fjeldskaar, N., Solheim, A., Nyland-Berg, M. and Russwurm, L., 1993. The Barents Sea ice sheet: a model of its growth and decay during the last ice maximum. Quat. Sci. Rev., 12: 863–873.

Elverhøi, A., Solheim, A., Nyland-Berg, M. and Russwurm, L., 1992. Last interglacial–glacial cycle western Barents Sea. In: P. Möller, C. Hjort and O. Ingolfsson (Editors), Weichselian and Holocene glacial and marine history of East Svalbard: Preliminary report on the PONAM fieldwork in 1991. Lund Univ. Dep. Quat. Geol. Lundqua Rep., 35: 17–24.

Forman, S.L., 1990. Post-glacial relative sea-level history of northwestern Spitsbergen, Svalbard. Geol. Soc. Am. Bull., 102: 1580–1590.

Forman, S.L., Lubinsli, D., Miller, G.H., Matishov, G., Snyder, J., Myslivets, V. and Korsun, S., 1995. Post-glacial emergence and distribution of Late Weichselian ice sheet loads in the Northern Barents and Kara Seas, Russia. Geology, 23 (2): 113–116.

Forman, S.L., Mann, D.H. and Miller, G.H., 1987. Late Weichselian and Holocene relative sea-level history of Bröggerhalvöya, Spitsbergen. Quat. Res., 27: 41–50.

Grosswald, M.E., 1983. Ice Sheets of the Continental Shelves. Nauka, Moscow, 215 pp. (in Russian, English summary).

Gulliksen, S., Heinemeier, J., Nielsen, S.H. et al., 1992. 14^{C}-dating of samples collected during the 1991 PONAM expedition to eastern Svalbard. In: P. Möller, C. Hjort and O. Ingolfsson (Editors), Weichselian and Holocene Glacial and Marine History of East Svalbard: Preliminary Report on the PONAM Fieldwork in 1991. Lund Univ. Dep. Quat. Geol. Lundqua Rep., 35: 191–198.

Hoppe, G., 1972. Ice sheets around the Norwegian Sea during the Würm glaciation. In: E. Dahl, A. Strømberg and O.G. Tandberg (Editors), The Norwegian Sea Region, its Hydrography, Glacial and Biological History. Ambio Spec. Rep., 2: 25–29.

Hoppe, G., Schytt, V., Häggblom, A. and Österholm, H., 1969. Studies of the glacial history of Hopen (Hopen Island), Svalbard. Geogr. Ann., 51A: 185–192.

Johnston, P., 1993. The effect of spatially non-uniform water loads on the prediction of sea-level change. Geophys. J. Int., 114: 615–634.

Jonsson, S., 1983. On the Geomorphology and past glaciation of Storöya, Svalbard. Geogr. Ann., 65A: 1–17.

Lambeck, K., 1993a. Glacial rebound of the British Isles. II: A high resolution, high-precision model. Geophys. J. Int., 115: 960–990.

Lambeck, K., 1993b. Glacial rebound and sea-level change: an example of a relationship between mantle and surface processes. Tectonophysics, 223: 15–37.

Lambeck, K., 1995. Constraints on the Late Weichselian ice sheet over the Barents Sea from observations of raised shorelines. Quat. Sci. Rev., 14: 1–16.

Lambeck, K., Johnston, P. and Nakada, M., 1990. Holocene glacial rebound and sea-level change in NW Europe. Geophys. J. Int., 103: 451–468.

Landvik, J.Y., Mangerud, J. and Salvigsen, O., 1987. The Late Weichselian and Holocene shoreline displacement on the west-central coast of Svalbard. Polar Res., 5: 29–44.

Mangerud, J., Bolstad, M., Elgersma, A., Helliksen, D., Landvik, J.Y., Lønne, I., Lycke, A.K., Salvigsen, O., Sandahl, T. and Svendsen, J.I., 1992a. The last glacial maximum on Spitsbergen, Svalbard. Quat. Res., 38: 1–31.

Mangerud, J., Bondevik, S., Ronnert, L. and Salvigsen, O., 1992b. Shore displacement and marine limits on Edgeøya and Barentsøya, eastern Svalbard. In: P. Möller, C. Hjort and O. Ingolfsson (Editors), Weichselian and Holocene Glacial and Marine History of East Svalbard: Preliminary Report on the PONAM Fieldwork in 1991. Lund Univ. Dep. Quat. Geol. Lundqua Rep., 35: 51–60.

Mangerud, J. and Svendsen, J.I., 1990. Deglaciation chronology inferred from marine sediments in a proglacial lake basin, western Spitsbergen, Svalbard. Boreas, 19: 249–272.

Mangerud, J. and Svendsen, J.I., 1992. The last interglacial–glacial period of Spitzbergen, Svalbard. Quat. Sci. Rev., 11: 633–664.

Nakada, M. and Lambeck, K., 1988. The melting history of the Late Pleistocene Antarctic ice sheet. Nature, 333: 36–40.

Olsson, I. and Blake, W., 1962. Problems of radiocarbon dating of raised beaches, based on experiment in Spitsbergen. Nor. Geogr. Tidsskr., 18: 47–64.

Peltier, W.R. and Andrews, J.T., 1976. Glacial-isostatic adjustment—1: the forward problem. Geophys. J. R. Astron. Soc., 46: 605–646.

Salvigsen, O., 1978. Holocene emergence and finds of pumice, whalebones and driftwood at Svartknausflya, Nordaustlandet. Nor. Polarinst. Årbok, 1977: 217–228.

Salvigsen, O., 1981. Radiocarbon dated raised beaches in Kong Karls Land, Svalbard, and their consequences for the glacial history of the Barents Sea area. Geogr. Ann., 63A: 283–291.

Salvigsen, O., Elgersma, A., Hjort, C., Lagerlund, E., Liestøl, O. and Svensson, N.O., 1990. Glacial history and shoreline displacement on Erdmannflya and Bohemanflya, Spitsbergen, Svalbard. Polar Res., 8: 261–273.

Salvigsen, O. and Elgersma, A., 1991. Radiocarbon dated raised beaches in northwestern Wedel Jarlsberg Ladn, Spitsbergen, Svalbard. Wypr. Geogr. Spitsbergen, Lublin, pp. 9–16.

Salvigsen, O. and Mangerud, J., 1991. Holocene shoreline displacement at Agardhbukta, eastern Spitsbergen, Svalbard. Polar Res., 9(1): 1–7.

Schytt, V., Hoppe, G., Blake, W. and Grossman, M.G., 1968. The extent of the Warm glaciation in the European Arctic: A preliminary report about the Stockholm University Svalbard expedition in 1966. In: Int. Soc. Sci. Hydrol. Gen. Assembly, Bern, 1967, pp. 207–216.

Solheim, A., Russwurm, L., Elverhøi, A. and Berg, M.N., 1990. Glacial geomorphic features in the northern Barents Sea: direct evidence for grounded ice and implications for the pattern of deglaciation and late glacial sedimentation. In: J.A. Dowdeswell and J.D. Scourse (Editors), Glacimarine Environments: Processes and Sediments. Geol. Soc. Spl. Paul., 53: 253–268.

Tushingham, A.M. and Peltier, W.R., 1991. ICE-3G: A new global model of Late Pleistocene deglaciation based upon geophysical predictions of postglacial sea-level change. J. Geophys. Res., 96: 4497–4523.