Accumulation in Svalbard glaciers deduced from ice cores with nuclear tests and Chernobyl reference layers

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Mean net annual balance and the related spatio-temporal variations have been determined on the basis of well-dated artificial layers in shallow ice cores (Chernobyl, 1986, and atmospheric thermonuclear tests, mainly in 1961–62 in Novaya Zemlya). Seventy ice cores from 13 Svalbard glaciers have been analysed. On each glacier, in its accumulation area and at the highest elevation, one ice core was recovered down to about 40 m and sampled for radioactivity measurements to determine the 1986 and 1962–63 layer (1954 was the initial date of the nuclear tests). For each glacier, at least five complementary ice cores from the accumulation area were analysed to determine the Chernobyl reference layer. Six ice cores exhibit both the Chernobyl and nuclear tests layers and are of special interest in this study.

This work provides new data on the deposition rates of natural and artificial radioisotopes. Using ice cores samples from the Arctic glaciers, even with superimposed ice accumulation, it is possible to distinguish between the Chernobyl and the nuclear tests fallouts. This work also shows that the mean annual net balance did not significantly change for at least five ice core locations in the Svalbard glaciers for the two periods extending from 1963 to 1986 and from 1986 to the recent date of drilling.

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Introduction

The aim of this study is to predict the sensitivity and the response of Arctic glaciers and ice caps to climate change over the next century, together with the associated implications for global sea level. As predicted by models, global warming due to greenhouse gases from anthropogenic activities will first affect the Arctic glaciers (Fleming et al. 1997).

To use and calibrate energy balance models, field data – including mass balance measurements – are required. The two well-known reference layers from Chernobyl (1986) (Pourchet, Pinglot et al. 1988) and atmospheric nuclear tests (from 1954 to 1974, with a clear maximum in 1962–63) (Holdsworth et al. 1984) can be detected in Arctic glaciers and ice caps, and be used to determine the long term mean annual accumulation rates, and their corresponding spatio-temporal variations (Pinglot, Pourchet, Lefauconnier, Hagen et al. 1994), as well as the total amount of artificial deposition of radioactivity.

Ice core sampling

Seventy shallow ice cores (down to a maximum of 40 m), adding up to ca. 800 m altogether, have been retrieved between 1981 and 1998 from 13 glaciers in Svalbard. The Chernobyl layer has been detected in 35 of these ice cores, generally

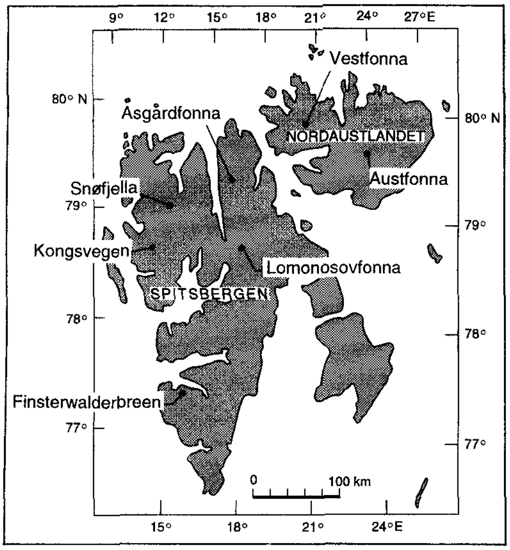

Fig. 1. Svalbard, with locations of the drilling sites.

between the surface and about 15 m deep. The complete sequence of the atmospheric nuclear tests (1954–1974) is available in 9 deeper ice cores (Fig. 1, Table 1). At least 5 ice cores, retrieved from the summits of the glaciers' accumulation areas, exhibit both the Chernobyl (1986) and the nuclear tests layers (1962–63), and can be used to study the temporal variations of the mean annual net balance (Table 1).

Smaller ice cores were drilled close to the equilibrium line (ELA) of the glaciers, to accurately determine the mean altitude of the ELA (Watanabe 1996; Pinglot, Pourchet, Lefauconnier & Creseveur 1997).

Ice cores from Kongsvegen (Kon K and Kon L) and Snøfjella (Sno M and Sno W) were retrieved in 1990 and 1992 (Pinglot, Pourchet, Lefauconnier, Hagen et al. 1994; Goto-Azuma et al. 1995). Two other ice cores were extracted by K. Kamiyama from Japan's National Institute of Polar Research at Nordaustlandet (Vestfonna, 1995, and Austfonna, 1998) (Kamiyama et al. 1998). Another ice core was taken from Åsgårdfonna in 1993 by NIPR (Uchida et al. 1996); its ^{137}Cs profile will be compared to other ^{137}Cs ice core profiles. Several shallow ice cores and a deep ice core were drilled at Lomonosovfonna (Nordenskiöldbreen) in 1997 (Isaksson et al. 1998).

Ice cores from Vestfonna, Austfonna, Åsgårdfonna and Lomonosovfonna were retrieved well above the equilibrium line, at the summits of these dome-shaped ice caps, where the horizontal velocity is very low (less than 1 m per year at Austfonna) (Dowdeswell & Drewry 1989). The thinning of the estimated annual layers at Austfonna is negligible down to about 40 m (Zagorodnov & Arkhipov 1990). Ice cores from Kongsvegen and Snøfjella were also retrieved from their highest altitude (excepted Kon K), well above the equilibrium line. At the top of Kongsvegen, the horizontal velocity is less than 2 m per year and the surface is horizontal. The thinning of the annual layers is therefore also expected to be negligible for the time period from 1963 to the 1992 drilling date. The Sno M ice core from Snøfjella was taken from a location (Sno W ice core) about 500 m away from an ice divide, with a slope of about 5%.

Methods

The ice core samples were melted, weighed,

Table 1. Coordinates and altitude of the ice cores at different glaciers, with ELA. Ref. 1 = Pinglot, Pourchet, Lefauconnier, Hagen et al. 1994; 2 = Goto-Azuma et al. 1995; 3 = Kamiyama et al. 1998; 4 = Gordiyenko et al. 1981; 5 = Uchida et al. 1993.

Glaciers	Ice cores (year)	Coordinates	Alt. (m)	ELA (m)	Ref.
Kongsvegen	Kon K (1990)	78°47′N–13°17′E	639	520	1
	Kon L (1992)	78°46′N–13°27′E	726	520	1
Snøfjella	Snow M (1992)	79°08′N–13°18′E	1170	650	1
	Snow W (1992)	79°08′N–13°17′E	1190	650	2
Vestfonna	Vest 95 (1995)	79°58′N–21°01′E	600	505	3
Austfonna	Aust 98 (1998)	79°48′N–24°00′E	740	505	3
Lomonosovfonna	Ice core (1976)	78°47′N–17°30′E	1000	660	4
	Stake 8 (1997)	78°48′N–17°28′E	1173	660	this
	Stake 10 (1997)	78°52′N–17°25′E	1230	660	work
Åsgårdfonna	Asg 93 (1993)	79°27′N–16°43′E	1140	800	5

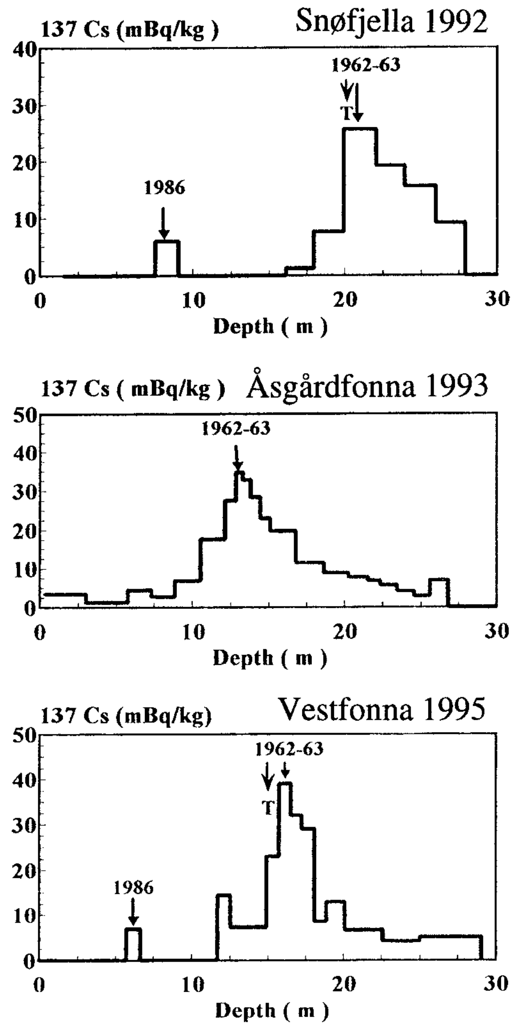

Fig. 2. ^{137}Cs versus depth of three Svalbard ice cores with the 1986 and 1962–63 radioactive layers (at Snøfjella, the 1986 layer was detected at the nearby Sno M ice core, close to Sno W; at Åsgårdfonna the 1986 layer was not detected). The depth of the tritium (T) maximum in 1963 is indicated by an arrow.

acidified, filtered (Delmas & Pourchet 1977) and then assembled for radioactivity analysis (Pinglot & Pourchet 1979; Pinglot, Pourchet, Lefauconnier, Hagen et al. 1994). From the density values of each sample of a given core, snow depths were converted into water equivalent (w.e.) depths, and the last winter snow layer was subtracted for determination of the annual net mass balance. The radioactivity measurements consist mainly of high resolution gamma spectrometry for the determination of ^{137}Cs. All studied ice core samples were analysed in the laboratory in Grenoble, in the low background radioactivity facility.

The radioactivity of the snow and ice of Svalbard glaciers comes from natural and artificial isotopes. The natural radioactivity (mainly ^{210}Pb) is greater than the artificial activity (mainly ^{137}Cs and ^{90}Sr), even in presence of the above described radioactive reference layers. Some enriched ^{210}Pb layers reach an activity of 40 mBq per kg, as much as the 1963 maximum for ^{137}Cs. In such a situation, the determination of these layers cannot be undertaken with the total beta counting technique and high resolution gamma spectrometry must be used instead. Moreover, this spectrometer must be properly shielded against all parasitic ambient radioactivity. An anti-Compton device has been developed to improve the detection limit of the isotopes of interest, namely ^{137}Cs and ^{210}Pb (Pinglot & Pourchet 1994, 1995).

Results

Among the 12 deeper ice cores (down to 40 m) retrieved between 1981 and 1998, nine ice core profiles indicate the complete sequence of ^{137}Cs deposition from the nuclear tests. The mean ^{137}Cs deposition rate for these nine ice cores is about 380 Bq per square meter. As an example, in order to study the deposition processes, the ^{137}Cs profiles (Fig. 2) from three different ice cores are compared. They exhibit a very similar pattern. This indicates that the in-depth catchment of the artificial radioactivity from the atmospheric nuclear tests between 1954 and 1974 occurred in a homogeneous way for these three different glaciers. However, at Åsgårdfonna, a low ^{137}Cs content occurs from the surface (possibly the Chernobyl contribution) down to the depth corresponding to the end of the nuclear tests, in 1974. This could be explained by a post depositional effect. The ELA at Åsgårdfonna is close to 800 m and it is a glacier with superimposed ice feature, and with a low mean annual net mass balance (0.31 m w.e.) (Table 2). The depth at which the ^{137}Cs signal is maximum is considered to be representative of the 1962–63 maximum of radioactivity deposition, after the 1961–62 nuclear tests, mainly performed over the nearby Novaya Zemlya site.

Even for the ice cores retrieved in the

Table 2. Variation of the mean annual net mass balance (with minimum, maximum and average values) over three different periods and ten different ice cores. Both the Chernobyl and the nuclear tests layers are measured in six ice cores.

Glaciers	Ice cores	Periods	Balance (m w.e. per year) Min.	Max.	Ave.
		1963–86	0.46	0.54	0.50
Kongsvegen	Kon K	1986–88	0.45	0.52	0.48
		1963–88	0.45	0.52	0.48
		1965–86	0.54	0.65	0.59
	Kon L	1986–91	0.57	0.67	0.62
		1965–91	0.56	0.64	0.60
	Sno W	1963–86	0.41	0.50	0.455
Snøfjella	Sno M	1986–91	0.54	0.60	0.57
	Sno W	1963–91	0.45	0.51	0.47
		1963–86	0.34	0.40	0.37
Vestfonna	Vest 95	1986–94	0.36	0.46	0.41
		1963–94	0.37	0.39	0.38
		1963–86	0.43	0.52	0.48
Austfonna	Aust 98	1986–97	0.45	0.58	0.52
		1963–97	0.50	0.51	0.50
	1976	1963–76	0.81	0.83	0.82
Lomonosov-	Stake 8	1986–96	0.74	0.76	0.75
fonna	Stake 10	1963–96	0.35	0.37	0.36
Åsgårdfonna	Asg 93	1963–92	0.30	0.33	0.31

accumulation area of glaciers, due to melting and percolation in the summer season the original depth of the 1962–63 maximum may have moved downwards slightly (Koerner 1997). This assumption would lead to higher estimations of mean annual net balances. But as the different ^{137}Cs profiles are of similar shape, this vertical migration is most probably small in comparison to the original deposition depth of the radioactive layers. This is confirmed by the depth of the tritium maximum in 1963 (Goto-Azuma et al. 1995; Kamiyama et al. 1998), in agreement with the ^{137}Cs maximum (see Fig. 2).

Among the 12 ice cores including the nuclear tests (totally or partially), the ^{137}Cs profiles for the Snøfjella and Vestfonna (Nordaustlandet, Svalbard) ice cores (Vestfonna 1995) clearly indicate both the Chernobyl layer (1986) and the atmospheric nuclear tests (maximum in 1962–63) (Fig. 2). However, the Chernobyl layer does not appear in ice core Sno W, but was measured in the nearby ice core Snow M (Fig. 2). The Snøfjella 1992 ^{137}Cs profile (Fig. 2) then contains the complementary results from both ice cores Sno M and Sno W. The same depth for the ^{137}Cs maximum of the nuclear tests deposits was also determined with tritium, and the Lakagigar (Icelandic volcano which erupted in 1783) layer was detected by ECM (Kamiyama et al. 1998).

Four other ice cores also exhibit both radioactive layers. The ^{137}Cs profiles, including Chernobyl and the nuclear tests, for ice cores Kon K, Kon L and Snow M, are described by Pinglot, Pourchet, Lefauconnier, Hagen et al. (1994).

Concerning the ice core from Austfonna in 1998, the first determinations of the radioactive layers came from the direct *in situ* detection of the 1962–63 layer inside the borehole (Pinglot & Pourchet 1995; Pinglot, Pourchet, Lefauconnier & Creseveur 1997), and from the detection of the Chernobyl layer by gamma spectrometry conducted in the laboratory on each run covering samples of drilling chips. The 1962–63 layer and the Chernobyl layer are, respectively, at depths of about 22.7 m and 9.6 m. The accuracy in the position of these layers was improved with more detailed gamma spectrometry done on the ice core samples. The ^{137}Cs from the atmospheric nuclear tests was also present in three previous ice cores conducted by the former USSR at Vestfonna (1981), and Austfonna (1985 and 1987) (Punning et al. 1986; Pinglot, Pourchet, Lefauconnier, Hagen et al. 1994).

Discussion and conclusion

The mean annual net balance can be determined for the six different locations and for the three different time periods: from 1962–63 (or 1965 for Kon L ice core) to 1986; from 1986 to the date of drilling (varying from 1989 to 1998); and from 1962–63 (or 1965) up to this last date (Table 2, Fig. 3). For ice core Kon L, the period only starts in 1965, as the 1963 ^{137}Cs maximum was not reached.

As illustrated in Fig. 3, each mean annual net balance, for a specified ice core location or a specified time span, is included between a minimum and a maximum value. This is due to the length of the samples. Generally, the sampling corresponds to two samples per year. The mass balance was also conducted by stakes and density in pits, at Kongsvegen (Lefauconnier, Hagen, Pinglot et al. 1994). The results agree closely with the determination of the mass balance from the radioactive layers.

The mean annual net balance depends on each location, as described earlier (Pinglot, Pourchet,

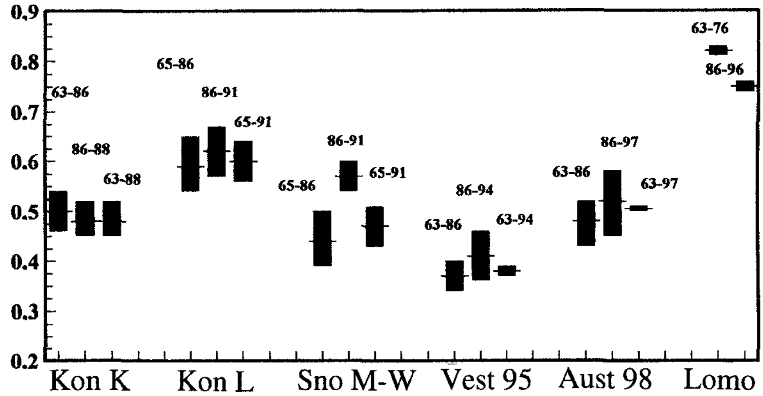

Fig. 3. Spatio-temporal variations in minimum, maximum and average values of the mean annual accumulation indicated by ice cores taken from five Svalbard glaciers. Mean annual mass balance shown as m water equivalent per year.

Lefauconnier, Hagen et al. 1994; Pourchet, Lefauconnier et al. 1995). The estimated ELAs have been studied for all Svalbard glaciers (Hagen et al. 1993). The ELA is only 200 m asl in south-eastern Spitsbergen, but more than 800 m asl in the central-northern area. For Nordaustlandet, the mean annual accumulation since 1963 is smaller at Vestfonna (0.38 m w.e.) compared to Austfonna (0.50 m w.e.), as already demonstrated with the previous ice cores retrieved in 1981, 1985 and 1987 (Pinglot, Pourchet, Lefauconnier, Hagen et al. 1994). This comes most probably from increased melting due to the lower altitude at the summit of Vestfonna compared to Austfonna – 600 m versus 740 m.

Considering the net mass balance values from the ice cores retrieved from the glaciers' accumulation areas and comparing the different time spans – 1962/63–1986 (23/24 years); 1986 to the drilling date (3–12 years) – there is no recent trend in the annual mass balance for five ice core locations. However, the Snow M ice core exhibits a possible 20% increased mean annual net mass balance from 1986 to 1991. But this apparent increase could be due to a thinning effect due to the strain rate in the deeper layers (C. Vincent, pers. comm. 1999).

Several ice cores from Lomonosovfonna (Nordenskiöldbreen), drilled in 1997, were also analysed for ^{137}Cs by gamma spectrometry and provide new mass balance data (Isaksson et al. 1998). The Chernobyl layer was detected in several shallow ice cores. One deep ice core was retrieved at 1000 m elevation in 1976 by a former USSR team (Gordiyenko et al. 1981). The mean annual net mass balance from 1963 to 1976 was 0.82 m w.e. This can be compared to 0.76 m w.e., as determined at ice core "stake 8" (Table 1), at 1173 m elevation, for 1986 to 1996. The net balances for the two time periods show no variations, as for the four other ice cores already studied. A deep ice core, at 1230 m elevation, down to 120 m, was also analysed for ^{137}Cs. Although the complete sequence of the nuclear tests from 1954 to 1974 was determined, the Chernobyl layer could not be detected. This deep ice core was retrieved from the highest dome of Lomonosovfonna. At this location, the surface shows some sastrugis, and the Chernobyl deposit may have been removed due to wind scouring. Three new shallow ice cores were retrieved in 1999 in order to detect the Chernobyl deposits. In this ice core, if the signal from Lakagigar was detected, it would enable comparison of the mean annual net mass balance since 1783 with the 0.36 m w.e. for the time period 1963–1996.

This study indicates no clear change in the mean annual net mass balance over the last 34 years, 1963–1997. This is in accordance with the stable negative net balance of Arctic glaciers since about 1960 (Hagen 1996; Jania & Hagen 1996; Dowdeswell et al. 1997). The total net balance and its temporal variations have also been obtained for other Spitsbergen glaciers of low altitude in the Kongsfjord area, including Brøggerbreen, Lovénbreen, Kongsvegen, as well as Finsterwalderbreen in south Spitsbergen. The Norwegian Polar Institute has been carrying out total mass balance measurements on Brøggerbreen and Lovénbreen since 1967. It was shown that the mean net balance increased from bn = −0.52 to bn = −0.35 m w.e. between 1967 and 1988 for Brøggerbreen (Lefauconnier & Hagen 1990), and from bn = −0.40 to −0.28 m w.e. between 1967 and 1997 for Lovénbreen (Lefauconnier, Hagen, Ørbaek et al. 1999).

For this period, the total net balance trend at Lovénbreen was governed by the winter balance trend, as the summer balance trend was constant. The mean net balance of Arctic glaciers is mostly dependent on the summer temperature, and to a lesser extent on the winter snow accumulation (Fleming et al. 1997).

Shallow ice cores combined with the survey from a stake network in the ablation area of Kongsvegen were used to determine the winter, summer and net balances.The mean net balance of Kongsvegen ($102\,km^2$) was bn = -0.10 m w.e. and bn = 0.11 m w.e. over the periods 1963–1989 and 1986–89, respectively (Lefauconnier, Hagen, Pinglot et al. 1994). The mean net balance of Kronebreen is presently under investigation, while Finsterwalderbreen, which shows a negative balance, is building up slightly in the upper basin (Nuttall et al. 1997).

These results seems to indicate a slight contemporary increase in the mean negative net mass balance for these glaciers of low altitude in the coastal area of Spitsbergen. This increase may be due to a slight decrease in summer temperature by $-0.3\,°C$, and an increase in the winter precipitation by 29%, as recorded at the Ny-Ålesund station (Lefauconnier & Hagen 1990).

However, from the radioactivity measurements, this work clearly shows that the mean annual net balance did not significantly change for at least five ice core locations in the Svalbard glaciers, at the highest altitudes in their accumulation areas, for the two time periods extending from 1963 to 1986 and from 1986 up to the present date of drilling.

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