Atmospheric moisture flux convergence and accumulation on the Greenland Ice Sheet

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Abstract The atmospheric moisture flux convergence over Greenland was investigated based on the analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF). It was found that the spatial distribution of the moisture flux convergence reveals a very close similarity to that of the observed annual accumulation. At the east and south coast, the moisture flux convergence is mainly the result of the transient eddy activity. At the west coast, the time-mean flow and the transient disturbances play comparable importance. Northeast Greenland, which is characterized by very small accumulation rates, receives an excessive contribution from the eddy component, whereas the mean circulation acts to remove some moisture. The present method based on the computation of the moisture flux convergence from objective analyses can be used for estimating seasonal or monthly accumulation rates for the interior of the ice sheet, where measurements are not available with such high resolution.

INTRODUCTION

On the Greenland Ice Sheet, the three main processes contributing to the accumulation are: precipitation, evaporation and snow drift (Ohmura & Reeh, 1991). Although precipitation is the dominant mechanism for the accumulation, there are indications that snow drift may be important in the marginal zones of the ice sheet (Ohmura et al., 1992a). In general, however, the difference between precipitation and evaporation can be considered the first approximation for the accumulation. As stated by the scale analysis of water budget equation for the atmosphere, for time intervals longer than a month the difference between precipitation and evaporation becomes very close to the convergence of the atmospheric water vapour flux. Thus, useful information on the accumulation regime of the Greenland Ice Sheet can be obtained from the computation of the convergence of the atmospheric water vapour flux. This method offers the possibility of assessing the spatial distribution of the accumulation for a much shorter period than a year. This method is also independent of the conventional pit and core analyses, whereby these latter provide the necessary validation.

In this work, the numerical analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF) are used to compute the atmospheric water vapour flux and flux convergence. The average annual distribution is interpreted in terms of the atmospheric circulation. An account of the annual cycle is given. Finally, values of the winter and summer total moisture flux convergence are examined with respect to direct
measurements of the winter total accumulation and summer total precipitation carried out during the ETH Greenland Expedition (Ohmura et al., 1991; Ohmura et al., 1992b).

FUNDAMENTALS, DATA AND METHODS

The equations describing the terrestrial and atmospheric branch of the hydrological cycle can be combined to yield an expression for the accumulation at the ice sheet surface. For sufficiently long periods, and neglecting the mass redistribution through snow drift, this reads:

$$\bar{C} = \bar{P} - \bar{E} = -\nabla_h \cdot \frac{1}{g} \int \bar{v} \bar{q} dp = -\nabla_h \cdot \frac{1}{g} \int (\bar{v} \bar{q} + \bar{v}' \bar{q}') dp$$

(1)

where $C$ is the accumulation, $P$ and $E$ are the precipitation and evaporation at the surface, $\nabla_h$ the horizontal gradient operator, $g$ the acceleration due to gravity, $p_t$ and $p_s$ the pressure at the top and bottom of the atmosphere, respectively, $v$ the horizontal wind vector and $q$ the specific humidity. An overbar denotes a time average. The last equality follows from the partition of the total moisture flux $\bar{v} \bar{q}$ into the component achieved by the mean circulation $\bar{v} \bar{q}$, and the transient eddy component $\bar{v}' \bar{q}'$ (Peixoto & Oort, 1983).

The basic atmospheric fields used to evaluate the water vapour flux convergence are twice-daily, uninitialized analyses of the wind and moisture fields of the ECMWF for the three years from 1989 to 1991. The data cover an area between 50.0 and 87.5°N and 90.0 and 0.0°W. The horizontal resolution is 2.5 by 2.5°. Nine mandatory levels are considered: 1000, 850, 700, 500, 400, 300, 200, 100, and 50 hPa. Time and vertical integrals are computed by the application of the trapezoidal rule. The convergence is calculated for the centre of each grid box by finite differences. Since the moisture flux convergence field is very noisy, an isotropic spatial filter is used to eliminate all features whose typical length scale is less than about 500 km. Finally, the annual cycle of the moisture flux convergence is estimated by fitting a cosine function to the average monthly values.

RESULTS

The annual mean, vertically-integrated moisture flux is presented in Fig. 1. The total field is dominated by the contribution due to the mean circulation. The moisture flux by the time-mean flow can be explained in terms of the geopotential distribution at 700 hPa (approximately the level of vertical mean moisture conditions) and by the spatial distribution of the precipitable water (Fig. 2). As observed in general in mid to high latitudes (Alestalo & Holopainen, 1980), the transient eddy flux is about down the gradient of the precipitable water. It is smaller in magnitude, but to a larger degree irrotational, than the water vapour flux by the mean circulation (Salstein et al., 1980).

The annual total convergence of the vertically integrated water vapour flux, averaged over the three years 1989-1991, is shown in Fig. 3. Over Greenland, the total field presents all the essential features of the climatological accumulation distribution.
Atmospheric moisture flux convergence and accumulation

Fig. 1 Annual mean, vertically integrated water vapour flux. Units are kg m\(^{-1}\) s\(^{-1}\). The scale is shown in the lower right corner. The total flux is shown in the upper panel, the contribution achieved by the mean circulation in the lower left panel, and the transient eddies contribution in the lower right panel.

(Fig. 6 in Ohmura & Reeh, 1991). In southern Greenland, a strong zonal gradient is superimposed on the overall south to north decrease. Along the northwestern slopes there is some evidence for a belt of increased convergence that recalls the belt of higher accumulation seen in the accumulation distribution. In northeastern Greenland, the very small moisture flux convergence is consistent with the observed very low accumulation (Ohmura & Reeh, 1991). Area-averaged, the mean annual total moisture flux convergence for all of Greenland amounts to 315 mm. This figure is quantitatively in good agreement with the observed 310 mm for the annual total accumulation (Ohmura & Reeh, 1991).

The breaking down of the moisture flux convergence field into the component due to the time-mean flow and the component due to transient eddies (Fig. 3) reveals that different mechanisms are responsible for the accumulation in western and eastern
Greenland. In western Greenland, accumulation is significantly enhanced owing to the interplay between the mean circulation and the orography. Along the eastern coast, on the other hand, the bulk of the moisture flux convergence is due to the transient eddy activity. This is not surprising, since this area is characterized by a high degree of baroclinicity and cyclogenesis (Putnins, 1970; Whittacker & Horn, 1984). As far as northeastern Greenland is concerned, the transient disturbances are the only external moisture source for the accumulation. In fact, the moisture flux by the mean circulation is seen to be everywhere divergent. The reason is twofold. On the one hand, advection of moist air from the Baffin Bay area is prevented by the orography (Ohmura & Reeh, 1991). On the other hand, as shown by preliminary investigations by the authors, the katabatic flow is particularly effective in removing moisture from this area.

The annual cycle of the moisture flux convergence is displayed vectorially in Fig. 4. In this representation, the amplitude is proportional to the length of the arrow, whereas the phase is given by the angle between the north and the arrow, measured clockwise. Thus, a vector pointing northward (eastward, southward or westward) indicates a maximum in January (April, July or October, respectively). In general, the peculiarities of the annual cycle depicted in Fig. 4 are consistent with the characteristics of the annual cycle of the measured precipitation (Putnins, 1970). Along the west coast, the moisture flux convergence is the largest in late summer to early autumn. In eastern Greenland, the maximum is observed in late autumn to early winter. In northern Greenland, the maximum convergence occurs in summer, when the sub-synoptic activity in the Polar Basin and in particular along its southern rim is most intense (Reed & Kunkel, 1960; Bradley & Eischeid, 1985).

The annual cycle of the contribution achieved by the mean circulation is particularly pronounced in southeastern Greenland in relation to the Icelandic Low, which is the most striking dynamical feature of the winter circulation in the study area. In western Greenland, the maximum convergence by the mean circulation is observed in autumn, when the dynamic and thermal conditions in the Baffin Bay area are most favourable.

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**Fig. 2** Geographical distribution of the annual mean geopotential height field at 700 hPa (left panel), and of the annual mean precipitable water (right panel). Units are gpm and kg m$^{-2}$, respectively.
Atmospheric moisture flux convergence and accumulation

(Ohmura & Reeh, 1991; Calanca, 1993). In relation to the appearance of the Arctic frontal zone in summer (Reed & Kunkel, 1960), the transient eddy contribution to the moisture flux convergence in the central and northern part of western Greenland does also show a summer/autumn maximum. Moreover, the present analysis reveals that in northeastern Greenland the contributions by the mean circulation and by the transient eddies are not only of opposite sign, but also out of phase. As a consequence, the moisture flux convergence regime in northeastern Greenland is characterized by very small amounts and a weak annual amplitude.

During the ETH Greenland Expedition, winter accumulation and summer precipitation were determined from 1989 to 1991 at the site of the expedition (69°34'N, 49°18'W) (Ohmura et al., 1991 and Ohmura et al., 1992b). In addition, measurements by the Greenland Geological Survey of the winter accumulation along the EGIG profile are available for the same period (H. H. Thomsen, personal communication). It is

![Fig. 3 Average annual total water vapour flux convergence. Units are mm year⁻¹. The total field is shown in the upper panel, the contribution achieved by the mean circulation in the lower left panel, and the transient eddies contribution in the lower right panel.](image-url)
interesting to compare these measurements with corresponding values of the water vapour flux convergence. Figure 5 shows monthly totals of the moisture flux convergence at the site of the ETH Greenland Expedition from January 1989 to December 1991 and the monthly total precipitation for each of the months of the two summer seasons 1990 and 1991. Except for July 1991, there is a good agreement between measurements and calculations. On the other hand, computations of the winter total moisture flux convergence (270 mm for the winter 1989/1990, 340 mm for the winter 1990/1991) seem to systematically underestimate the measured winter accumulation (480 mm for the
Atmospheric moisture flux convergence and accumulation

Fig. 5 Monthly total moisture flux convergence (bars) and measured monthly precipitation (triangles) at the site of the ETH Greenland Expedition (69°34'N, 49°18'W), as well as annual average monthly total moisture flux convergence (dashed line).

winter 1989/1990, 670 mm for the winter 1990/1991, at the ETH Greenland Expedition site; 296 mm for the winter 1989/1990, 490 mm for the winter 1990/1991 at stake T12 of the EGIG profile). This could be due, apart from other factors, to the influence of the snow drift.

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REFERENCES


