55 94 81

NASA GRANT # NAG5-6001
FINAL REPORT

Report of Work for the Period: 1 January 2000 to 31 July 2001

Satellite and Model Analysis of the Atmospheric Moisture Budget in High Latitudes

Submitted to :

Dr. Waleed Abdalati
Mail Code YS
NASA Headquarters
Washington DC 20546-0001

By

The Ohio State University Research Foundation
1960 Kenny Road
Columbus OH 43210

David H. Bromwich, Principal Investigator
Qiu-shi Chen, Co-Principal Investigator
Polar Meteorology Group, Byrd Polar Research Center
The Ohio State University, 1090 Carmack Road, Columbus, Oh 43210-1002
Phone: 614-292-6692; Fax: 614-292-4697; Email: bromwich.1@osu.edu

December 28, 2001

A report of work

for the period from January 1 to July 31, 2000

(funded)

and

for the period from August 1, 2000 to July 31, 2001

(no cost extension)

NASA grant NAG5-6001 (OSURF No. 734755)

Satellite and Model Analysis of the Atmospheric Moisture Budget in High Latitudes

High resolution precipitation over Greenland studied by a dynamic method

Principal Investigator: David H. Bromwich

Co-Principal Investigator: Qiu-shi Chen

Polar Meteorology Group, Byrd Polar Research Center

The Ohio State University, 1090 Carmack Road, Columbus OH 43210-1002

December 28, 2001

The report of work for the period from January 1 to July 31, 2000 and extension from August 1, 2000 to July 31, 2001

(1) In order to understand variations of accumulation over Greenland, it is necessary to investigate precipitation and its variations. Observations of precipitation over Greenland are limited and generally inaccurate, but the analyzed wind, geopotential height and moisture fields are available for recent years. The objective of this study is to enhance the dynamic method for retrieving high resolution precipitation over Greenland from the analyzed fields. The dynamic method enhanced in this study is referred to as the improved dynamic method. There are three differences between the original dynamic method used by Chen et al. (1997) and Bromwich et al. (1999) and the improved dynamic method. 1), The topographic effects on precipitation and atmospheric motion are greatly influenced by the computational accuracy of the horizontal pressure gradient force over mountainous regions, especially near steep slopes of mountains and ice sheets. Chen and Bromwich (1999) showed that the horizontal pressure gradient force in sigma-coordinates can be computed more accurately by separating this horizontal vector into its irrotational and rotational parts, which are expressed by the equivalent geopotential and geo-streamfunction, respectively. The equivalent geopotential and geo-streamfunction are implemented in a fully consistent manner in the improved dynamic method. 2), Several of the deficiencies in the precipitation spatial distributions were investigated by Bromwich et al. (1998) based on evaluation of recent Greenland precipitation studies. One of the deficiencies is related to the topographic data employed in assimilation and modeling. The Matrikelstyrelsen and Ekholm (Ekholm, 1996) field is a realistic digital elevation data set synthesized from a variety of observations including satellite radar altimetry. The U.S. Navy 10 arc minute global data set was used by European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis for 1979-1993 (ERA-15), the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis, Chen et al. (1997) and Bromwich et al. (1999), but it is significantly different from the modern data set of Ekholm (1996), particularly in southern Greenland. The corrected Greenland topography based on the modern data set of Ekholm (1996) is used in calculations with the improved dynamic method. 3), The large scale condensation scheme is revised to be suitable for use over Greenland. The improved dynamic method is discussed in detail in the paper entitled "Modeled precipitation variability over the Greenland ice sheet" by Bromwich et al. (2001), which is in press with the *Journal of Geophysical Research.*

(2) In order to check how the computed precipitation is affected by the improved dynamic method, the distribution of the mean annual precipitation for 1985-99 has been derived. Two aspects of the precipitation distribution are refined by the improved dynamic method. The 10 $cm\,yr^{-1}$ contour near Summit Greenland is much closer to that of the measured accumulation than that derived by the original method. A relatively large precipitation area centered near the point ($70^{\circ}N, 49^{\circ}W$) is resolved, but is absent from the original method.

McConnell et al. (2000a) showed that the modeled precipitation from the original method with the topography based on the U.S. Navy 10 arc minute global data set must use scalers to have a high degree of correspondence in the interannual variations between the measured accumulation and retrieved precipitation. However, the retrieved precipitation from the improved method increases at all of the ice core sites, and a good correspondence in the interannual variations between the measured accumulation and retrieved precipitation is obtained without the use of any scalar. The spatial average of multi-year mean error ($\overline{\varepsilon_j}$) is 11.5 $cm\,yr^{-1}$ for the modeled precipitation from the improved method, while that for precipitation (P) predicted by ERA-15 is 14.5 $cm\,yr^{-1}$. The total mean error (ε_M) over all ice cores is 3.0 $cm\,yr^{-1}$ for the improved method, while ε_M for the P from ERA-15 is 4.0 $cm\,yr^{-1}$. These two errors show that the precipitation modeled by the improved method is better than the P from ERA-15. Thus, the distribution of precipitation over the 11 sites retrieved by the improved dynamic method is considerably refined.

(3) The surface elevation change of the Greenland ice sheet is of considerable importance to change of global sea level. The elevation of the ice sheet surface rises and falls over a relatively short period simply because of snow accumulation, firn densification and snow melting rates. Recent advances in airborne laser altimetry and global positioning system (GPS) technology have made possible the large-scale assessment of elevation change characteristics of the entire ice sheet through repeated surveys separated in time. Such repeated surveys in 1993 and 1998 (Krabill et al. 1999) showed that the southeast margin of the Greenland ice sheet has been thinning. The snow accumulation is a net result of precipitation, evaporation/sublimation and drifting snow. In order to understand what is responsible for the changes of the surface elevation and snow accumulation over Greenland, it is necessary to investigate the corresponding change of precipitation.

Aircraft laser-altimeter surveys over northern Greenland in 1994 and 1999 have also been studied by Krabill et al. (2000), and Fig. 1 shows the changes in the surface elevation of Greenland between 1993 and 1999 derived from radar and laser altimetry and estimated coastal melting. It is found that, above 2000 meters elevation, the entire ice sheet is in balance on average but has some regions of local thickening or thinning. Below 2000 m surface elevation, thinning predominates along 70% of the coast, with rates about 1 meter per year close to the coast. At elevations below 1700 m, radar altimeter data become unreliable (Thomas et al. 1999). Krabill et al. (2000) calculated a hypothetical thinning rate at the coast on the basis of the coastal positive degree day (PDD) anomalies, using a melting factor of 9 mm per PDD. From this approach, only melt is considered near coast in the thinning rate.

Above 2000 m surface elevation, most of northern ice sheet lies above the region of summer melting. Because McConnell et al. (2000b) found that altimetry-derived estimates of ice-sheet thickening and thinning from 1978-1988 over southern Greenland above 2000 m are consistent with elevation changes caused by temporal variability in snow accumulation, the effects of melting on the surface elevation change of southern Greenland above 2000 m should also be small. Thus, melting is very small over both northern and southern Greenland above 2000 m. In order to compare the temporal variability of precipitation with that of surface elevation over the entire Greenland above 2000 m, the spatial distribution of the slope of the linear regression line of the annual precipitation from the improved dynamic method for 1993-1999 has been computed, and it covers the same period as that of Fig. 1. A color-coded figure of the slope of the linear regression line of the annual precipitation from 1993-1999 is shown in Fig. 2. In northern Greenland (north of $70^{o} N$) above 2000 m, there are three thickening areas shown in Fig. 1 and they are centered at about $(74^{o} N, 48^{o} W)$, $(76^{o} N, 28^{o} W)$ and $(78^{o} N, 52^{o} W)$, respectively. Except for coastal regions, there is only one thinning area centered at about $(76^{o} N, 44^{o} W)$ shown in Fig. 1. These three thickening and one thinning regions respectively correspond to three positive and one negative areas of precipitation change centered at about the same locations in Fig. 2. It should be pointed out that the unit used in Fig. 2 is cm/year in water equivalent, and a multiplying factor of about 3.3 is necessary to transform the water equivalent values to the thickness of snow (R. Thomas, personal communication, 2001).

In southern Greenland above 2000 m, there is a major thinning area over its western part and south of $66^{o} N$, and there are also three thickening areas located at about $(68^{o} N, 38^{o} W)$, $(67^{o} N, 47^{o} W)$ and $(63^{o} N, 47^{o} W)$ shown in both Figs. 1 and 2, respectively. From the above, it is seen that altimetry-derived estimates of ice-sheet thickening and thinning from 1993-1999 over the entire Greenland above 2000 m are approximately consistent with precipitation change retrieved by the improved dynamic method.

It is obvious that a positive precipitation increase region centered at about $(70^{o} N, 28^{o} W)$ shown

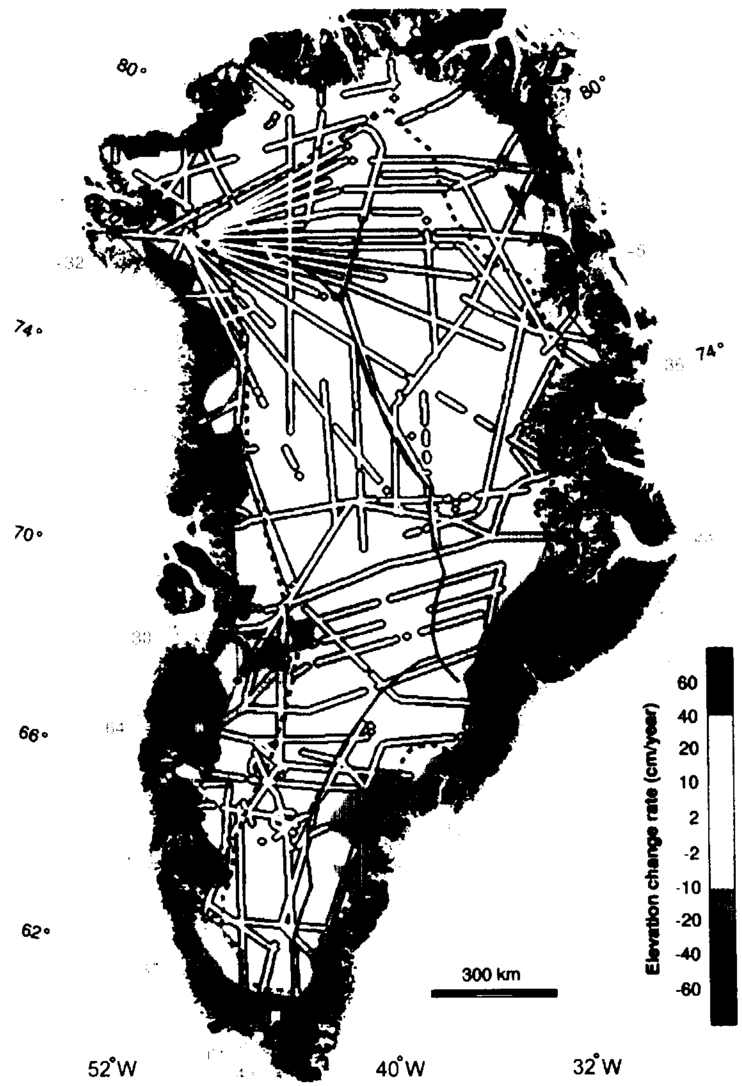

Fig. 1 Greenland ice-surface elevation change (*dh/dt* in unit *cm/year*) for 1993-1999 derived mostly from airborne laser-altimetry (colors with scale at lower right). The black hollow lines show the flight tracks. In the area near the coast (outside the pink boundary), surface elevation change is interpolated between flight-track data and hypothetical values derived from the PDD anomalies. The violet solid and dashed lines are major ice-sheet ridges and the 2000m elevation contour, respectively. From Kraybill et al. (2000).

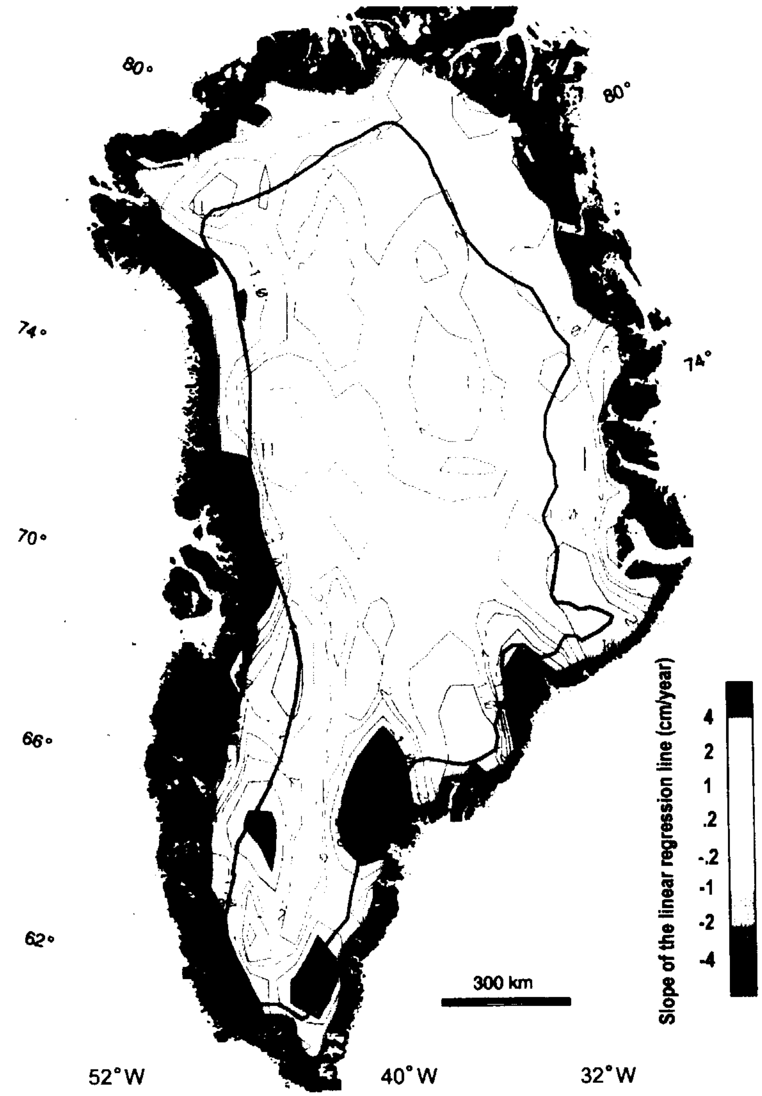

Fig. 2 The distribution of the annual precipitation trend over Greenland except for the coastal region (elevation below 1000m) in unit *cm/year* (in water equivalent, multiply by 3.3 to get snow thickness changes) for 1993-1999 derived from the improved dynamic method (colors with scale at lower right). The red solid line is the 2000m elevation contour.

in Fig. 2 is not matched to thickening in Fig. 1. This may be due to deficiencies in the precipitation retrieval or other causes, for example, the melt is important near the coast.

Krabill et al. (2000) excluded measured surface elevation change in coastal areas; instead, an interpolation was used between the calculated PDD thinning rates due to melting and nearest observed elevation changes to yield thinning rates over the ice-covered coastal regions. Change of surface elevation over the ice sheet is due to not only the effects of melting but also those of firn densification and snow accumulation, in which precipitation predominates. It is not appropriate that only melting is considered in estimating the change of surface elevation of the ice sheet even in the coastal areas. At least, the sum of precipitation and melting must be used. On the other hand, thinning rates exceeding 1 m/year over the coastal areas are probably too large to be caused by these factors. We note that there are many precipitation decrease areas along the coast shown in Fig. 2, especially in southern Greenland, and they likely contribute to the surface elevation thinning in the coastal regions. Thus, both of the precipitation and melting need to be accurately derived in a future study and the thickening and thinning of surface elevation over coastal regions will be estimated from their combined impact.

(4) There are at least two remaining deficiencies in the retrieved annual mean precipitation. One is that the relatively large accumulation with the contour value of 50 $cm\,yr^{-1}$ in the region centered near the point ($70^o\,N, 47^o\,W$) shown in the accumulation map is not well simulated by the improved dynamic method. The second is that the annual mean errors ε_j of the precipitation modeled by the improved dynamic method are pretty large at some sites. The above two deficiencies might be produced by a more fundamental shortcoming that some mesoscale features of the Greenland precipitation are not well simulated.

The accumulation map over Greenland has many mesoscale features, which are produced by the mesoscale characteristics of Greenland topography in this region. The data sets (TOGA Archive from NCAR or ERA data) of the analyzed wind, geopotential height and moisture fields used in this study are large scale with $2.5^o \times 2.5^o$ resolution. These data sets must reflect the coarse resolution of the topography adopted at the forecast center (here ECMWF) from which the analyses originate. The large scale data sets have an important impact on the precipitation results. The problem of how to use the large-scale $2.5^o \times 2.5^o$ resolution analyzed data and mesoscale high resolution topography to obtain a mesoscale high resolution precipitation distribution over Greenland needs further investigation.

References

Bromwich D. H., R. I. Cullather, Q.-S. Chen, and B. M. Csatho, 1998: Evaluation of recent precipitation studies for the Greenland ice sheet. *J. Geophys. Res.*, **130**(D20), 26,007-26,024.

Bromwich, D. H., Q.-S. Chen, Y. Li, and R. I. Cullather, 1999: Precipitation over Greenland and its relation to the North Atlantic Oscillation. *J. Geophys. Res.*, **104**(D18), 22,103 - 22,115.

Bromwich, D. H., Q.-S. Chen, L. Bai and Y. Li, 2001: Modeled precipitation variability over the Greenland ice sheet. *J. Geophys. Res.*, Special Issue on the PARCA (Program for Arctic Regional Climate Assessment) project, (in press).

Chen, Q.-S., D. H. Bromwich and L. Bai, 1997: Precipitation over Greenland retrieved by a dynamic method and its relation to cyclonic activity. *J. Climate*, **10,** 839-870.

Chen, Q.-S., and D. H. Bromwich, 1999: An equivalent isobaric geopotential height and its application to synoptic analysis and to a generalized ω-equation in σ –coordinates. *Mon. Wea. Rev.*, **127**, 145-172.

Ekholm, S., 1996: A full coverage, high-resolution, topographic model of Greenland computed from a variety of digital elevation data. *J. Geophys. Res.*, **101**(B10), 21,961-21,972.

Krabill, W., E. Frederick, S. Manizade, C. Martin, J. Sonntag, R. Swift, R. Thomas, W. Wright, and J. Yungel, 1999: Rapid thinning of parts of the southern Greenland ice sheet. *Science,* **283**, 1522-1524.

Krabill, W., W. Abdalati, E. Frederick, S. Manizade, C. Martin, J. Sonntag, R. Swift, R. Thomas, W. Wright, and J. Yungel, 2000: Greenland ice sheet: High-elevation balance and peripheral thinning, *Science,* **289**, 428-430.

McConnell, J. R., E. Mosley-Thompson, D. H. Bromwich, R. C. Bales, and J. F. Kyne, 2000a: Interannual varations of snow accumulation on the Greenland Ice Sheet (1985-1996): new observations versus model predictions. *J. Geophys. Res.*, **105**(D3), 4,039 - 4,046.

McConnell, J. R., R. J. Arthern, E. Mosley-Thompson, C. N. Davis, R. C. Bales, R. Thomas, J. F. Burkhart, and J. F. Kyne, 2000b: Changes in Greenland ice sheet elevation attributed primarily to snow accumulation variability. *Nature*, **406**, 877-879.

Thomas, R., C. Davis, E. Frederick, S. Manizade, J. Sonntag, W. Krabill, and J. McConnell, 1999: Greenland ice sheet elevation change since 1978 from radar and laser altimetry, *Polar Geogra.*, **23**, 169-184.