1.22 Greenland precipitation variability in recent years retrieved by an initialization dynamic method and its relation to atmospheric circulation

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1. Introduction

Recent[1] airborne laser-altimetry surveys (Krabill et al. 1999; 2000) show ice sheet elevation decreases over the southern coast of Greenland. In order to determine if the climate processes are responsible for these elevation changes, it is necessary to investigate the Greenland precipitation variations and their relation to the circulation. Precipitation variations over Greenland from 1985-99 have been retrieved by a generalized omega-equation method (Chen et al. 1997; Bromwich et al. 1999; 2001). There is a high degree of correspondence in the interannual variations between the measured net water equivalent accumulation from ice cores and retrieved precipitation, and the results are better than those of P from the ECMWF Reanalysis (ERA-15). It is interesting to know how the modeled precipitation changes are responsible for most of the measured ice sheet elevation changes. For this purpose, the mesoscale spatial distribution of the computed precipitation need further improvement.

The data sets (ECMWF TOGA and ERA-15 from NCAR) used currently are large scale with a 2.5^{o}x2.5^o resolution. An important problem is to use these large-scale analyzed data with the high resolution topography of Greenland to obtain a mesoscale precipitation distribution better than that from the omega-equation method. The initialization not only filters the fast gravity waves but also includes the interactions and feedbacks between the large-scale initial conditions and mesoscale topography in the iterative process. Recently, an application of the equivalent geopotential and geo-streamfunction in sigma-coordinates to the initialization for limited-area models has been developed by Chen et al. (2001) for use over mountainous regions, especially over the steep slopes of mountains and ice sheets. This newly developed initialization method has been used to retrieve the precipitation over Greenland.

2. An initialization dynamic method

Anthes (1990) showed that a mesoscale model with realistic treatment of mesoscale topography, earth surface conditions and physical processes is capable of developing mesoscale phenomena and precipitation from good large-scale initial conditions. Such mesoscale model simulations can also produce high-resolution dynamically consistent data sets. However, from the large-scale initial conditions, the mesoscale systems can be produced by a mesoscale model only after a certain time period of integration. Physically, this means that the mesoscale systems produced by a mesoscale model from the large-scale initial conditions result from a certain time interaction and feedback processes between the large-scale initial conditions and the mesoscale topography, earth surface conditions and physical processes. This above phenomenon is also related to the spin-up problem of a forecast model. This problem may be caused by inaccuracies in the initial specification of divergence, moisture and thermal fields, especially those associated with the relatively small scale precipitation systems. The data initialization for the dynamic variables, diabatic heating and physical processes has been recognized as a means to solve the spin-up problem.

The dynamic method used by Chen et al. (1997) and Bromwich et al. (1999, 2001) is based on the generalized omega-equation. Recently, Colle et al. (1999) verified the 36- and 12-km resolution Penn State/NCAR Mesoscale Model (MM5) precipitation forecasts and NCEP's 10-km resolution Eta Model (Eta-10) forecasts across the Pacific Northwest. It is found that these models tend to generate too much precipitation along the steep windward slopes. Dempsay and Davis (1998) found that the standard horizontal pressure gradient force (PGF) scheme in MM5 can produce significant velocity errors above steep terrain. Recently, Chen and Bromwich (1999) proposed that the horizontal PGF in sigma-coordinates can be computed 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 have been used in the generalized omega-equation method (Chen et al. 1997; Bromwich et al. 1999, 2001). Thus, it can better describe the topographic effects on precipitation. Another advantage is that the omega-equation method is very simple and easy to get a reasonable precipitation description over a long term, for example, 15 years. In comparison to the computer time needed to simulate the same period of precipitation by a limited-area model, only about 5 percent of the computer time is needed for the omega - equation method. However, the ω-equation is only a

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diagnostic relation, it cannot generate correct mesoscale systems from the large-scale initial conditions because it derives precipitation immediately and does not include enough interaction and feedback processes between the large scale initial conditions and mesoscale topography.

The initialization, which is currently used for limited-area models, not only filters the fast gravity waves but also partially includes the interactions and feedbacks between the large-scale initial conditions and mesoscale topography through iterative processes. Due to these iterative processes, some mesoscale features of the wind field, divergence, moisture and thermal fields can be partially produced. Recently, the initialization method (Chen et al. 1996) is further to extended to use the equivalent geopotential and geo-streamfunction in σ-coordinate limited-area models (Chen et al. 2001), and it is very useful for the initialization over mountainous regions, especially by near steep slopes of mountains and ice sheets. The generalized omega-equation is one of the equations in this initialization but it is solved many times in the iterative processes.

3. Greenland precipitation for 1985-1999 retrieved by the initialization dynamic method and its interannual variability

3.1 The mean annual precipitation for 1985-1999

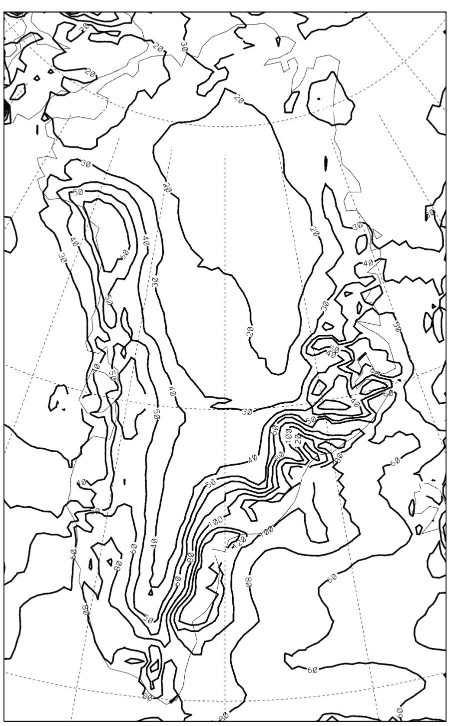


Fig.1. The distribution of the mean annual precipitation for 1985-99 derived by the initialization method

In order to check how the computed precipitation is affected by the initialization method, the distribution of the mean annual precipitation for 1985-99 is shown in Fig. 1. This figure has been compared with that computed from the omega-equation method (Bromwich et al. 2001) and Csatho-PARCA (Program for Arctic Regional Climate Assessment) accumulation map (Csatho et al., 1997). The precipitation near the west coast of southern Greenland shown in Fig. 1 is greatly improved and its value and mesoscale structure are in close agreement with those of the accumulation map. The local precipitation maximum located near (70^{o}N, 47^{o}W) is better simulated by this method, and the overall mesoscale spatial distribution of precipitation is much better than the old omega equation method.

3.2 Comparison of the interannual variability between precipitation and snow accumulation at ice core sites

The locations of the 11 ice core sites near the 2000 m contour of the Greenland Ice Sheet are studied by McConnell et al. [2000]. The precipitation amounts at the grid points retrieved from the initialization dynamic methods are interpolated to the ice core locations. ERA-15 [Gibson et al., 1997] is a 15-year data assimilation product for the period 1979-93, and it provides the values of precipitation P and the difference between the precipitation and evaporation/ sublimation, P - E. Because we only have the ERA-15 data for 1979-93 and ECMWF operational data from TOGA Archive II from NCAR for 1985-99, a common 9-year period 1985-93 is chosen for comparison. The annual mean errors, ε_j , at the site j of the modeled precipitation from various methods and their averaged values, $\underline{\varepsilon_j}$, over all ice cores are shown in Table 1. The average value of the annual mean error, $\underline{\varepsilon_j}$ for the initialization method is 2.76 cm /yr, while that for the P and P-E from ERA-15 is 14.5 and 14.0 cm /yr, respectively.

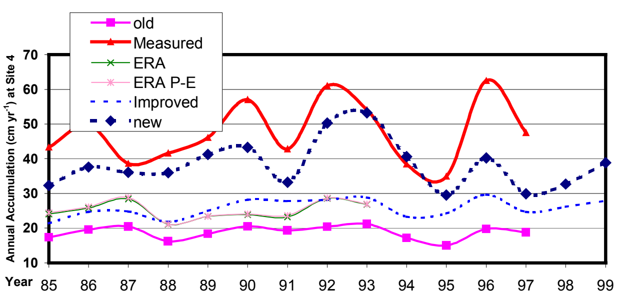
The annual mean observed accumulation, $M_{obs,j}$, and annual mean modeled precipitation, $M_{mod,j}$, at the different site j and the total mean errors ε_M for the different method are given in Table 2. It is easily seen from Table 2 that the total mean error ε_M for the initialization method is 2.1 cm /yr, while that ε_M for the improved ω-equation method , P and P-E from ERA is 3.0, 4.0 and 3.8 cm /yr, respectively. The total mean errors show that the precipitation modeled by the initialization method is better than the P and P-E of ERA-15 at these 11 sites. From Tables 1 and 2 we can conclude that the distribution of precipitation and its interannual variations at the ice core sites retrieved by the initialization method are considerably improved.

Table 1. The yearly mean error, ε_j , of the modeled values, , ε_j , averaged precipitation from various methods at each site and the mean over all sites

Site	Old method	Improved method	P from ERA-15	P-E from ERA-15	New method
1	36.66	13.22	31.11	28.70	3.65
2	25.11	5.40	11.83	11.94	2.78
3	22.75	16.24	22.65	22.21	3.22
4	29.71	23.36	24.17	23.97	2.95
5	4.97	5.81	4.96	4.46	1.04
6	11.66	5.88	5.37	5.15	2.17
7	19.44	7.95	5.85	5.56	2.99
8	15.47	4.37	3.06	2.85	1.92
9	13.30	6.14	3.15	2.93	1.96
10	9.88	9.85	8.02	8.54	4.69
11	3.32	5.17	10.14	9.90	2.98
Mean value	21.36	11.49	14.48	14.02	2.76

Table 2. The annual mean values of the observed accumulation, $M_{obs,j}$, and various modeled precipitation, $M_{mod,j}$, at site j, as well as the mean error over all sites ε_M

Site	Observed	Old method	Improved method	P from ERA-15	P-E from ERA-15	New method
1	69.98	34.28	53.75	98.97	96.45	60.83
2	45.60	21.21	42.73	56.10	56.23	38.82
3	59.72	41.88	48.84	75.92	75.30	57.12
4	48.24	19.25	23.05	25.02	25.26	39.46
5	13.17	8.95	15.25	8.60	9.19	11.98
6	42.63	31.95	41.00	45.41	44.91	42.64
7	42.13	23.58	33.48	39.39	39.68	36.42
8	31.72	16.28	29.43	31.98	31.72	30.20
9	29.42	17.12	29.48	30.38	29.95	35.66
10	34.79	27.62	37.31	29.57	28.70	51.47
11	13.78	10.76	15.85	22.99	22.66	21.74
Mean error		5.71	3.04	3.96	3.77	2.08



.Fig. 2. The annual variation of precipitation at site 4 (new-initialization method)

Site 4 is located at (69.8 ^{0} N, 35.0 ^{o} W), and it is at the margin of a zone of very large precipitation gradient. A slight shift in the model simulation will easily give a different precipitation. If the model cannot simulate the mesoscale features, it is difficult to get a good precipitation result at this site. The annual variation of precipitation at site 4 is shown in Fig.2. The mean values of the retrieved precipitation from the initialization method at this site shown in Table 2 is 39.5 cm/yr, while the mean values of the improved dynamic method ,P and P - E of ERA-15 in Table 2 are 23.1, 25.0 and 25.3 cm /yr, respectively. However, the mean value of the measured time series of the accumulation at site 4 shown in Table 2 is 48.2 cm/yr. The large errors from other dynamic methods has been greatly improved by the initialization method at this site.

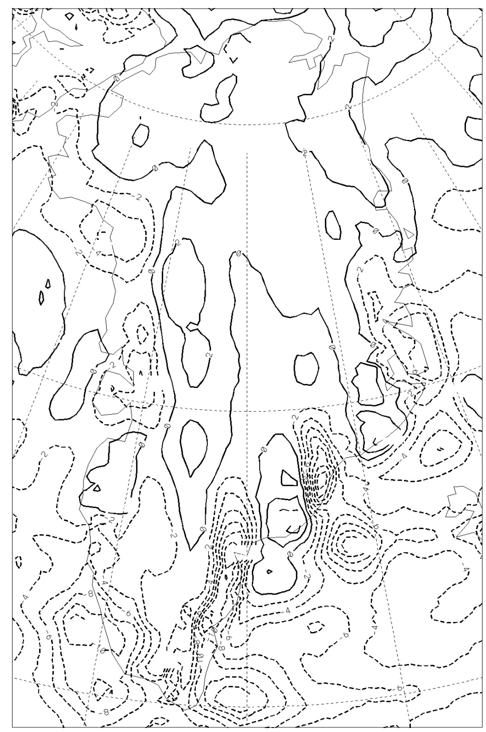


Fig. 3 The distribution of slope of linear regression line of annual precipitation for 1993-1999 (unit: cm/yr in water equivalent).

3.3 Temporal variation rate of the annual precipitation over Greenland in recent years

The distribution of slope of linear regression line of annual precipitation derived from the initialization method for 1993-1999 is shown in Fig. 3. In comparison with the ice sheet elevation change observed from airborne laser-altimetry (Krabill et al. 1999; 2000), the interannual variations of the retrieved precipitation are in agreement with the measured ice sheet elevation change, especially decreases over the southern coastal parts of Greenland. Thus, the Greenland ice sheet elevation change is closely related to the change of the precipitation.

4. The relationship between the Greenland precipitation variability and atmospheric circulation in recent years

It is also found that there are many more cyclones in 1985-1988 than in 1996-1999 over the Labrador Sea and across the southern part of Greenland, which favors more precipitation over Greenland and its southern part. In the multi-year mean sea-level pressure field for the winters of 1985-1988, a mean cyclone is located in the Labrador Sea, while in winters of 1996-1999 it is located to southeast of Greenland in the Atlantic. In the multi-year mean 500 hPa winter circulation of 1985-1988, a mean ridge is located over the west coast of North America and a mean trough is over Newfoundland along the east coast, which favors the development of cyclones over the Labrador Sea. By contrast, in 1996-1999 there are a mean trough over the west coast and a mean ridge over the Labrador Sea, consistent with reduced cyclonic activity near the southern Greenland. The variation of precipitation over Greenland is closely related to changes of cyclonic activity and atmospheric circulation in recent years. Thus, the precipitation changes over Greenland are not a local variation but a result of variation of Northern Hemisphere circulation. The Greenland ice sheet elevation change can only be explained from the large scale climate variability.

5. Conclusion

1. The precipitation is better simulated by the initialization method, and the overall mesoscale spatial distribution of precipitation is much better derived than the other dynamic method.
2. The distribution of precipitation and its interannual variations at the ice core sites retrieved by the initialization method are considerably improved, and the large errors at site 4 from the other dynamic methods has been greatly improved.
3. The Greenland ice sheet elevation change is closely related to the change of the precipitation.

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