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Arctic and Antarctic precipitation simulations produced by the NCAR community climate models

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ABSTRACT. Precipitation predictions from global-climate models (GCMs) for the ice-covered Arctic Ocean and the ice sheets of Antarctica are among the most important aspects of the inferred response of the polar areas to climate change. It is generally recognized that the atmospheric hydrologic cycle, which includes precipitation as a key part, is one of the components of the climate system that GCMs do not handle particularly well.

The present-day atmospheric-moisture budget poleward of 70° latitude in both hemispheres, as represented by two versions of the NCAR (U.S. National Center for Atmospheric Research) community climate model (CCM1 and CCM2), is compared with observational analyses. The quantities examined on the seasonal and annual time-scales are precipitation, evaporation/sublimation and atmospheric poleward moisture transport. The results are discussed in terms of the physiographic and climatic characteristics of both polar regions and how the particular models handle moisture transport: CCM1 uses the positive-moisture fixer and CCM2 the semi-Lagrangian transport. A particularly important test both for models and for observations is the degree to which the independently determined moisture-budget quantities actually balance. Deficiencies of both observations and models are discussed.

INTRODUCTION AND METHODOLOGY

Two generations of the NCAR (U.S. National Center for Atmospheric Research) community climate model (CCM versions 1 and 2) are widely used global-climate models. However, comparatively little effort has been devoted to evaluating the models' simulations of the present climate in polar regions. Not only are the polar regions the major energy sinks in the global atmospheric circulation but they also play a crucial role in climate change. Recently, Tzeng and others (1993, 1994), Bromwich and others (1994) and Tzeng and Bromwich (1994) have analyzed the simulated climate of the Arctic and Antarctica by CCM1 and CCM2 in terms of atmospheric circulation, storm tracks, moisture and energy budgets, cloud coverage, radiation fluxes, etc. In this summary paper, we will focus on the hydrologic cycle, i.e. moisture budget of the simulated atmosphere in the polar regions by CCM1 and CCM2, with horizontal resolutions of R15 and T42 (about 7.5° × 4.5° and 2.8° × 2.8° in longitude and latitude), respectively. There are 12 and 18 σ levels in the vertical for CCM1 and CCM2, respectively. One of the important differences between the two versions of the model, which is directly related to moisture budgets, is the method used to predict moisture contents. CCM1 uses the spectral-transform method to predict the moisture with a positive-moisture fixer to correct negative values of moist-ure content in arid areas due to the spectral truncation in the model. CCM2 uses a shape-preserving semi-Lagrangian transport for all positive-definite quantities (including water vapor, cloud water, etc.) to alleviate the negative values created by spectral truncation (Williamson and Rasch, 1994).

The moisture budget is calculated from the temporally and spatially averaged moisture-balance equation (Peixoto and Oort, 1983). The equation has the form,

$$\frac{1}{a\cos\phi}\frac{\partial\langle\bar{Q}_\phi\rangle\cos\phi}{\partial\phi} = \langle\bar{E}-\bar{P}\rangle + R\,,$$

where ϕ is the latitude, the angled brackets denote a zonal average, and the overbar a time average, Q_ϕ is the vertically averaged moisture transport (flux) in the meridional direction, E and P are evaporation and precipitation, respectively, and R is a residual term which represents the lack of balance in the moisture equation over long time averages. For the polar caps, the flux-convergence term of the equation can be rewritten using Gauss's theorem:

$$[FQ] \equiv -\left[\frac{1}{a\cos\phi}\frac{\partial\bar{Q}_\phi\cos\phi}{\partial\phi}\right] = \frac{1}{A}\oint_\lambda \bar{Q}_\phi \mathrm{d}\lambda\,,$$

where A is the surface area of the polar cap and the square brackets denote an area average of the polar cap.

ARCTIC MOISTURE BUDGET

The mean annual precipitation rate $[P]$ averaged from 70° N to the North Pole is 29.4 cm a^{-1} from a new analysis

(Walsh and others, 1994; hereafter referred to as W94), which is about twice that of Peixoto and Oort's (1992; hereafter referred to as PO92) observations (Table 1). The simulated precipitation in CCM1 is 51.9 cm a^{-1}, which is about 1.9 and 3.2 times more precipitation than observed by W94 and PO92, respectively. The simulated evaporation rate $[E]$ (13.8 cm a^{-1}) approximates the observed. However, the CCM1's net annual precipitation $[P-E]$ is 2.3 and 6.6 times larger than that of the observations of W94 and PO92, respectively. In addition, CCM1 transports 10.5×10^{15} kg a^{-1} of moisture across 70° N (or 67.8 cm a^{-1} water equivalent), but the observed (W94) is 2.6×10^{15} kg a^{-1} (or 16.3 cm a^{-1} w.e.). At least four times more moisture is transported into the North Polar ice cap by CCM1 than is observed.

However, the CCM1's annual cycle of precipitable

Table 1. Annual values of the Arctic areally averaged (70° N to NP) precipitation ($[P]$), and evaporation ($[E]$) rates, and of the moisture-flux convergence poleward of 70° N ($[FQ]$) from the NCAR CCM1 and CCM2 and observations. Unit is cm a^{-1}

	$[P]$	$[E]$	$[P-E]$	$[FQ]$	R
			Observations		
Ma90				15.8	
PO92	16.1	10.3	5.8	11.6	−5.8
W94	29.4	13.1	16.3	16.3	0.0
			Models		
CCM1	51.9	13.8	38.1	67.8	−29.7
CCM2	37.2	15.5	21.7	17.7	4.0

Moisture-budget residual $(R) = [P-E] - [FQ]$.
Ma90: Masuda (1990). For 1979 annual mean.
PO92: Peixoto and Oort (1992). Climatological average.
W94: Walsh and others (1994). $[P]$ from Gorshkov (1983) atlas; $[FQ]$ from a new analysis of radiosonde data, 1973–90; $[E]$ derived as a residual from the atmospheric-moisture budget.

water (W) is consistent with the observations in terms of both amplitude and phase. The annual average of W is 5.4 kg m^{-2} in CCM1 and 6.0 kg m^{-2} in PO92 (not shown). The maximum of W is in mid-summer (July–August) and the minimum in mid-winter (January–February) in both CCM1 and PO92. Therefore, the excessive precipitation rate in CCM1 ($[P]$, 51.9 vs 29.4 cm a^{-1}) is due to the excessive moisture transported into this region ($[FQ]$, 67.8 vs 16.3 cm a^{-1}). However, CCM1's moisture flux into the Arctic basin ($[FQ]$, 67.8 cm a^{-1}) is much larger than its net annual precipitation ($[P-E]$, 38.1 cm a^{-1}). Obviously, this excessive moisture (−29.7 cm a^{-1}) must be transported out of this region, which is done in an artificial manner by the positive-moisture-fixer scheme in order to remedy negative moisture values spuriously produced by the spectral-transform method (Rasch and Williamson, 1990). On the other hand, the causes of the excessive simulated poleward moisture transport by the advection term ($[FQ]$, 67.8 vs 16.3 cm a^{-1}) are attributed to the meridional-wind component (v) at 70° N. The bias in the simulated v is clearly attributable to the mass-field (sea-level-pressure) simulation (Bromwich and others, 1994), which is caused by the low horizontal R15 spectral-truncation error that distorts the representation of Greenland topography in the model. We conclude that the errors in the moisture budget of CCM1 are due to the positive-moisture-fixer scheme and the low horizontal resolution.

Using the semi-Lagrangian transport scheme to predict water vapor instead of the spectral-transform method with positive-moisture fixer, CCM2 definitely can more realistically simulate the various moisture components (Table 1). The moisture-budget equation is now almost balanced but with a positive residual, and the moisture transport into the Arctic basin is reasonably well simulated. There is substantial uncertainty in the observed value of $[P-E]$ (Peixoto and Oort, 1992; Walsh and others, 1994; Serreze and others, in press), with Walsh and others' result being much closer to those modeled by CCM2. The primary cause of the $[P-E]$ discrepancy is the very different observed values of $[P]$ which need to be rationalized. Even so, the precipitation simulated by CCM2 appears to be high, most likely resulting from the deficiencies in the simulated atmospheric circulation of this region (Bromwich and others, 1994; Tzeng and Bromwich, 1994).

The annual variations of precipitation, evaporation and $[P-E]$ over the Arctic basin are shown in Figure 1 along with the new observations from Walsh and others (1994). It is evident that CCM2 greatly overestimates the precipitation (circles) from late winter to summer, and

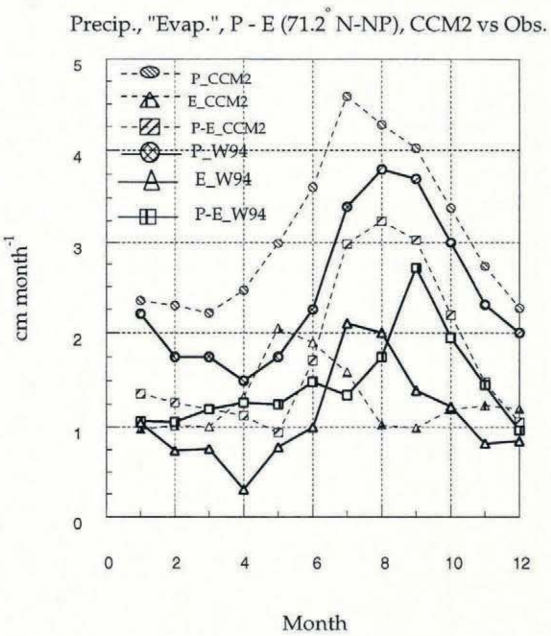

Fig. 1. The areally averaged (Arctic) annual variations of precipitation, surface evaporation, and $(P-E)$ from CCM2 and the observations (from Walsh and others, 1994). Unit is cm month^{-1}. The circle represents precipitation, the triangle evaporation, and the square $P-E$; observations are thick solid lines and CCM2 results are dotted.

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the simulated maximum of $[P]$ comes 1 month earlier than the observed maximum in August. Though the annual average evaporation of CCM2 is close to the observations, the annual variation of CCM2 evaporation (triangles) is shifted 2 months earlier than the observed. These result in large biases of simulated $[P - E]$ (squares) during summer, almost 30% larger than the observations. The observations illustrate that the maxima of evaporation, precipitation and $[P - E]$ occur in July, August and September, respectively. The CCM2 captures this order quite well but is phase-shifted. For the summer months of July and August, $[E]$ exceeds $[P - E]$ (approximately equivalent to moisture-flux convergence) in the observations, implying that surface evaporation is the source of more moisture than the net import of water vapor from outside of the North Polar ice cap. By comparison to the moisture budget over the Arctic Ocean, which is dominated by convergence of moisture fluxes year-round, Walsh and others (1994) pointed out that the hydrologic budget of the entire polar cap (70° N to NP) is influenced significantly by the ice-free parts of the North Atlantic sub-polar seas and by the snow-free (during summer) land areas. Evaporation in the CCM2 also becomes the dominant source from April to June over the Arctic basin, which however, is 2 months ahead of the observed. The cause of these phase shifts in the simulated moisture budget will be investigated in the near future.

ANTARCTIC MOISTURE BUDGET

The accumulation of snowfall on the Antarctic continent is one of the major factors determining the response of the ice sheet to climatic change. The amount of annual snow accumulation simulated over Antarctica and along the coastline by CCM1 and CCM2 is shown in Figure 2. The simulation in CCM2 is close to the observations. In particular, a very arid climate over the continental interior (less than $5\,\mathrm{cm\,a^{-1}}$) is modeled. Also, the accumulation minima (less than $15\,\mathrm{cm\,a^{-1}}$) over the Ross and Filchner–Ronne Ice Shelves are to some extent captured by the model (Tzeng and others, 1994). Although these two accumulation minima are also shown in the CCM1–R15 simulation, the cause of these features is different from that in the CCM2–T42. Tzeng and others (1993) indicated that these accumulation minima and the maximum center around the South Pole in CCM1–R15 are mainly caused by the spectral truncation error in such a low- (R15) resolution model. T42 resolution of CCM1, however, does not seriously suffer from this type of error.

The moisture-budget analyses of CCM1 and CCM2 for the Antarctic are given in Table 2. The simulated precipitation by CCM1 is 3.4 times larger than the observations given by PO92. The large bias of $[P - E]$ (about 3.5 times larger than the observed from Giovinetto and others (1992)) is attributable to the precipitation. Although the poleward moisture transport across 70° S in CCM1 is much closer to the observations than those across 70° N, there is a huge residual in CCM1 ($37.7\,\mathrm{cm\,a^{-1}}$) which is apparently artificially "transported" into Antarctica from outside by the moisture-

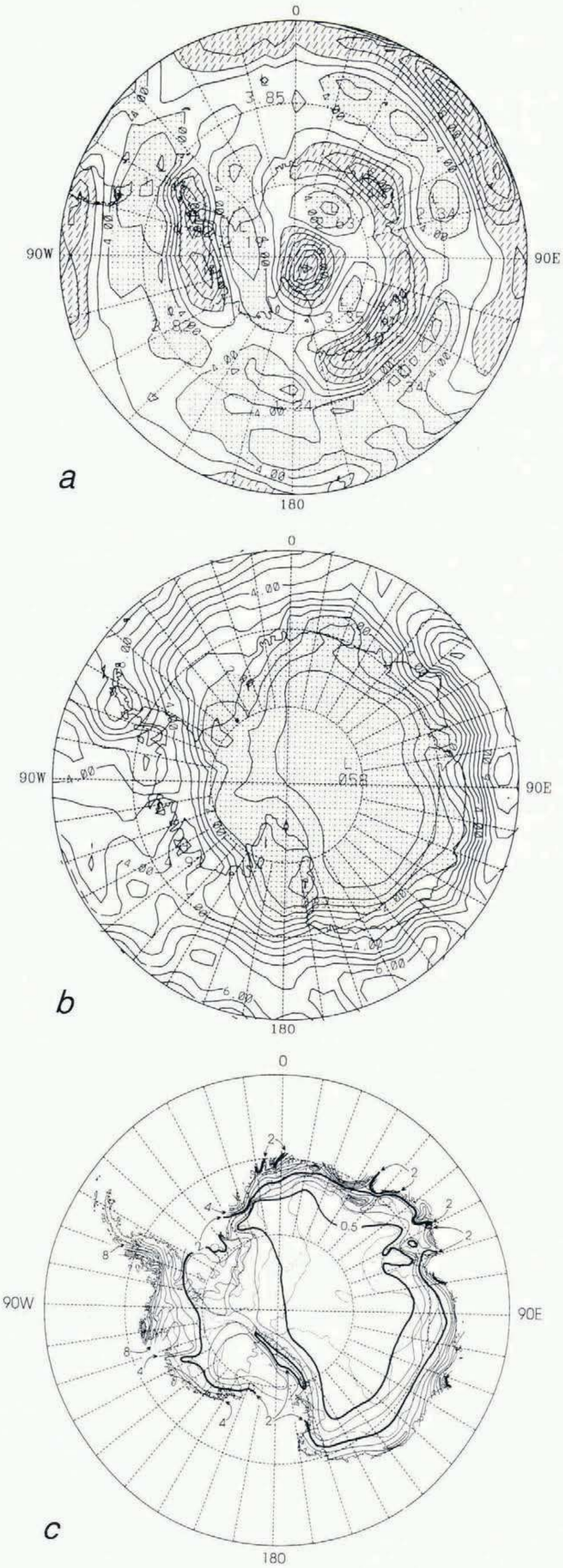

Fig. 2. The annual snowfall accumulation ($P - E$) in $100\,\mathrm{mm\,a^{-1}}$ from (a) CCM1, (b) CCM2, and (c) the observations (after Bromwich, 1988). (a) Contour interval is 1.0; values less than 4.0 are stippled and greater than 6.0 are hatched. (b) C.I. is 0.5; values less than 2.0 are stippled. (c) C.I. is variable; 0.5 and 2.0 contours are bolded.

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Table 2. Annual values of the Antarctic areally averaged (70° S to SP) precipitation ([P]), and evaporation ([E]) rates, and of the moisture-flux convergence poleward of 70° S ([FQ]) from the NCAR CCM1 and CCM2 and observations. Unit is cm a^{-1}

	$[P]$	$[E]$	$[P-E]$	$[FQ]$	R
			Observations		
GBW92			18.4 ± 3.7		
Y92				16.2 ± 1.9	
PO92	19.0	4.3	14.7	11.6	3.1
			Models		
CCM1	64.2	4.2	60.0	22.3	37.7
CCM2	21.6	6.3	15.3	12.0	3.3

Moisture-budget residual $(R) = [P-E] - [FQ]$.
GBW92: Giovinetto and others (1992). Climatological average from surface observations.
Y92: Yamazaki (1992). Climatological average from NMC analyses for 1986–90.
PO92: Peixoto and Oort (1992). Climatological average.

fixer scheme due to the extremely dry and cold conditions over the Antarctic continent on a year-round basis. Therefore, it is clear that CCM1 is not appropriate for climate-change studies that rely on snowfall accumulation (Tzeng and others, 1993). By contrast, the moisture-budget analysis of CCM2 is significantly improved over Antarctica. Although the simulated precipitation ([P]) and evaporation ([E]) rates are slightly greater than PO92's climatological values, the simulated net precipitation ([$P-E$]) (15.3 cm a^{-1}) is slightly better than PO92's result (14.7 cm a^{-1}) in comparison to the latest observational estimate (18.4 ± 3.7 cm a^{-1}) by Giovinetto and others (1992). The CCM2 moisture-transport convergence poleward of 70° S is very close to the observed value quoted by PO92 but significantly smaller than Yamazaki's (1992) diagnosis which matches Giovinetto and others' (1992) surface-based [$P-E$]. The residual of the CCM2 budget equation is quite small (3.3 cm a^{-1}) and approximates that of Peixoto and Oort (1992). The improvement of the moisture budget in CCM2 is attributed to the use of the semi-Lagrangian transport scheme instead of CCM1's positive-moisture-fixer scheme (Tzeng and others, 1994). Definitely, the semi-Lagrangian scheme is very good at reproducing the moisture transport into the polar cap.

Though the total snowfall ([P]) and its accumulation ([$P-E$]) over Antarctica are wrong in the CCM1, the annual cycle of the simulated precipitation rate over the continent is consistent with the observations (Fig. 3). Like observations from surface stations, the maximum of [P] appears during winter while the minimum of [P] occurs during summer in the simulation by CCM1. In addition, CCM1 even captures the semi-annual variation in precipitation rate as some observations show. Figure 4

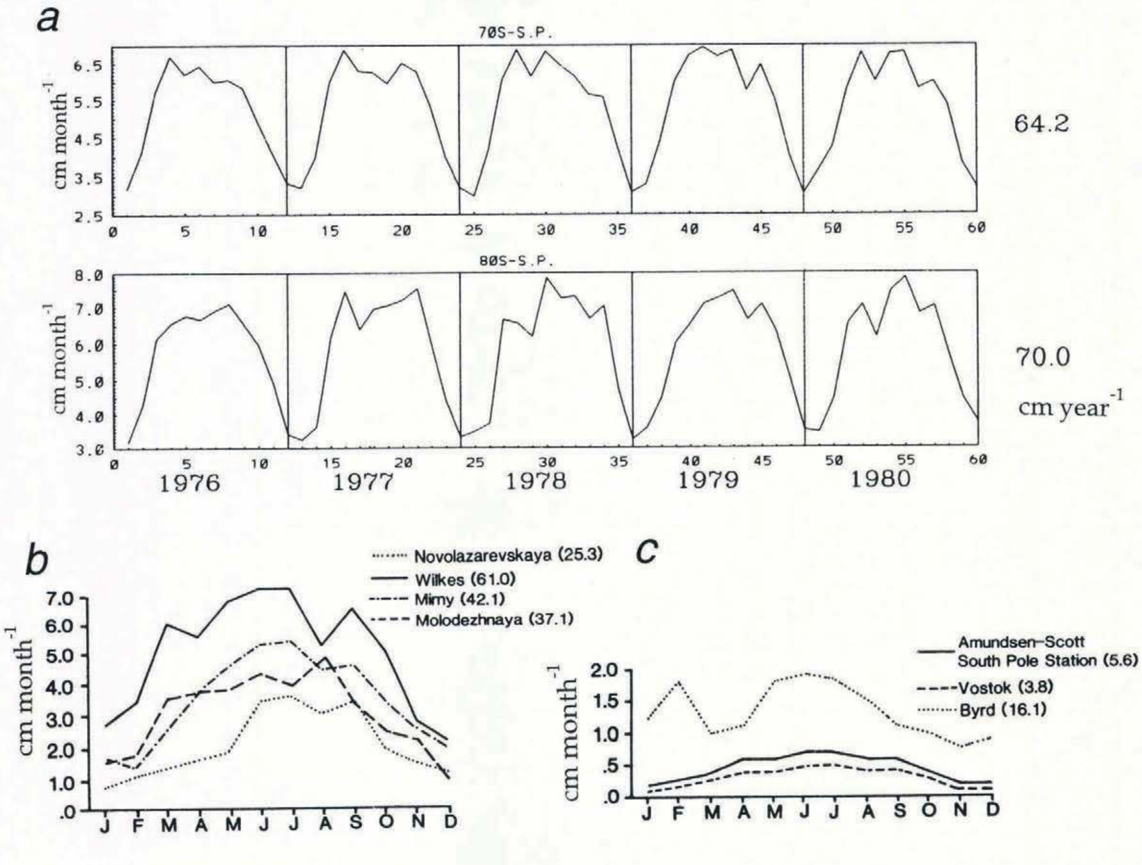

Fig. 3. The areally averaged annual variations of precipitation from CCM1. (a) The annual average is given at the edge of each panel. Observed precipitation rate at stations (b) along the coast of East Antarctica and (c) in the interior of the continent (from Bromwich, 1988); the number in parentheses after each station is the annual average in cm a^{-1}.

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displays the annual variations of precipitation, evaporation and net precipitation $[P-E]$, for the region poleward of 70° S in CCM2 along with the observational estimate of $[P-E]$ by Yamazaki (1992). The simulated snow-accumulation rate ($[P-E]$) is a low 0.6 cm month^{-1} in early summer and reaches maxima in fall (1.8 cm month^{-1}) and late winter (1.6 cm month^{-1}), which is in good agreement with the observations. It seems that this weak semi-annual oscillation is well represented in CCM2 for area-averaged $[P-E]$ over Antarctica in terms of magnitude and phase apart from a variable 1 month phase shift (Tzeng and others, 1994).

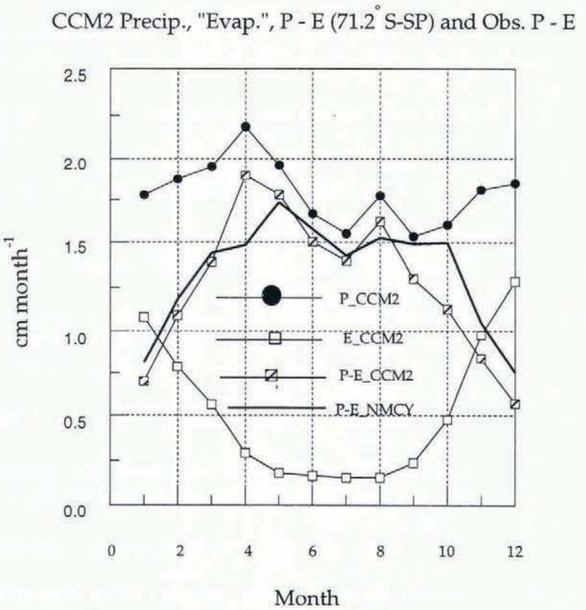

Fig. 4. The areally averaged (Antarctica) annual variations of precipitation, surface evaporation, and (P−E) from CCM2 and the observations [FQ] (from Yamazaki, 1992). Unit is cm month^{-1}. The circle represents precipitation, the square evaporation, and the hatched square P−E; observations of [FQ] are shown by the thick solid line.

CONCLUSIONS

We have examined two generations of the National Center for Atmospheric Research's community climate model (CCM1 and CCM2) for the simulated hydrologic cycle over the polar regions. The moisture-budget analyses reveal that the different levels of bias in simulations are associated with the specific type of moisture scheme, horizontal resolution and other shortcomings in the general circulations of the models.

The moisture budgets over the Arctic and Antarctica are shown again side by side in Table 3 along with the observed analyses to compare clearly the features of the two poles. It is clear that CCM1 and CCM2 estimate evaporation rate quite well in both polar regions. There are large discrepancies in $[P-E]$ in CCM1, however, which are attributable to the huge errors in simulated precipitation $[P]$. CCM1 also significantly over-simulates the moisture-flux convergence across 70° N (S) so that the residual of the moisture budget is on the order of the net precipitation ($[P-E]$) over the Arctic and Antarctica. These errors are primarily due to the simulated meridional-wind component, because the model fails to simulate adequately the large-scale waves and distorts the respresentation of topography by the truncation error in such a low horizontal spectral resolution. Nevertheless, CCM1's precipitable water over the North and South Polar caps approximates the observations. This indicates that the simulated moisture excess (R) in the Arctic (moisture deficiency in the Antarctic) has to be "transported" out of (into) the polar region artificially by the positive-moisture fixer of CCM1.

These opposite impacts of the positive-moisture fixer in the Arctic and Antarctica are most likely attributable to the differences in land–sea configuration and topography. Antarctica (poleward of 70° S) is essentially an ice-covered mountain surrounded by ocean with an average elevation of 2500 m and with very low moisture contents (zonal mean precipitable water at 80° S is only 1.5 kg m^{-2} in the annual average; from Peixoto and Oort, 1983). Due to the large horizontal gradient of moisture over this area, negative values of moisture

Table 3. Annual values of the areally averaged (70°–P) precipitation ($[P]$), and evaporation ($[E]$) rates, and of the moisture-flux convergence poleward of 70° ($[FQ]$), from the NCAR CCM1 and CCM2 and observations. Unit is cm a^{-1}. The values for Antarctica are given in parentheses next to the Arctic values

	$[P]$	$[E]$	$[P-E]$	$[FQ]$	R
			Observations		
W94(PO92)	29.4 (19.0)	13.1 (4.3)	16.3 (14.7)	16.3 (11.6)	0.0 (3.1)
			Models		
CCM1	51.9 (64.2)	13.8 (4.2)	38.1 (60.0)	67.8 (22.3)	–29.7 (37.7)
CCM2	37.2 (21.6)	15.5 (6.3)	21.7(15.3)	17.7 (12.0)	4.0 (3.3)

Moisture-budget residual $(R) = [P-E] - [FQ]$.
PO92: Peixoto and Oort (1992). Climatological average.
W94: Walsh and others (1994). $[P]$ from Gorshkov (1983) atlas; $[FQ]$ from a new analysis of radiosonde data 1973–90; $[E]$ derived as a residual from the atmospheric-moisture budget.

generated by the spectral-transform method inside Antarctica have to be continually corrected artificially by the positive-moisture fixer. Meanwhile, the bias in simulated moisture fluxes across 70° S is relatively small. On the other hand, the Arctic basin primarily consists of sea ice and sea surrounded by major continents with relatively high moisture contents (zonal mean precipitable water at 80° N is 4.9 kg m^{-2} in the annual average, which is more than three times larger than that over Antarctica). Rasch and Williamson (1990) showed that the maximum error due to the artificial positive-moisture-fixer scheme is over high latitudes of the Eurasian continent during winter and that the impact of the moisture fixer in these regions is nearly as large as the largest term in the moisture-balance equation and larger than any other term. Furthermore, Bromwich and others (1994) found that CCM1 over-simulates the storm activity over the continents and underestimates the storm activity over the oceans in the middle and high latitudes during the non-summer months, which is related to the positive-moisture fixer. The model inputs too much moisture into the continents in the lower troposphere, which in turn increases the latent-heat release over these regions and hence intensifies the cyclone activity. In order to conserve the model's total moisture content the specific humidity over the oceans (including the Arctic basin) has to be transported to the continents artificially by the local and global moisture correction.

In contrast to its earlier version, the moisture-budget analyses of CCM2 are significantly improved over the polar regions, especially for Antarctica. Although finer horizontal resolution can alleviate the error introduced by spectral truncation, the implementation of the semi-Lagrangian moisture transport is the more fundamental improvement for the much-improved simulation of the hydrologic cycle by CCM2. All components of the moisture-budget equation over Antarctica are very close to the observed from Peixoto and Oort (1992). However, the precipitation rate simulated by CCM2 over the Arctic appears to be 21% higher than new observations (Walsh and others, 1994), which partly results from biases in large-scale flow pattern and storm track over the north Pacific Ocean that distorts the moisture transport into the Arctic basin. Furthermore, the annual cycle of the moisture budget over the North Polar ice cap is generally shifted 1 or 2 months ahead of the observations.

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