Atmospheric Response to a Hypothetical Tibetan Ice Sheet

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ABSTRACT

The atmospheric response to a hypothetical Tibetan ice sheet was tested with the T21 Atmospheric General Circulation Model (AGCM) of the European Centre for Medium-Range Weather Forecasts (ECMWF). The model response is discussed in terms of an "autocycle" hypothesis of the ice ages proposed by Kuhle. According to this hypothesis, ice-albedo feedbacks associated with the growth and retreat of the Tibetan ice sheet are the mechanism that amplifies the variation of solar insolation on astronomical time scales, producing conditions that favor glaciation or deglaciation in North America and Eurasia.

The imposed Tibetan ice sheet forcing did not increase the annual snow balance at the locations of the Laurentide and Eurasian ice sheets. Analysis of the seasonal cycle results indicated that there were small areas of locally significant temperature decreases in July (at the ice sheet locations), but no corresponding precipitation increases in January. The upper-tropospheric response to the elevated Tibetan plateau is not confined to the vicinity of the forcing, but changes in the global energetics of the atmosphere are small (less than 5%) relative to the control.

The results of this experiment do not permit a conclusive decision regarding the validity of Kuhle's autocycle hypothesis. Future modeling studies need to consider ocean-atmosphere-ice sheet feedbacks and to investigate the transient response of the climate system over a complete ice age cycle.

1. Introduction

Marine sediment cores provide evidence for the existence of an ice age cycle of approximately 100 000 years in the climate system (Hays et al. 1976). Spectral analysis of insolation variations over the past 468 000 years, however, indicates direct solar forcing at average periods of 21 000 and 41 000 years but not at 100 000 years (Vernekar 1972). This shows that the ice age cycle in the climate system is probably modulated but not caused by variations of the earth's orbital parameters. As there is negligible direct solar forcing at the 100 000-year period, the strength and periodicity of the ice age cycle must come from within the climate system by amplification through some feedback process (e.g., ice-bedrock interaction).

Kuhle (1987) proposed a so-called "autocycle" hypothesis to explain the ice age cycle by amplification of variations in the solar insolation due to the ice-albedo feedback of a Tibetan ice sheet. From consideration of the main equilibrium lines of present day glaciation, Kuhle inferred that an annual mean temperature decrease of about 3.5°C would be necessary for the initiation of glaciation in Tibet, and a decrease of at least 5°C for triggering glaciation in northern Europe.

The autocycle hypothesis states that at the beginning of an ice age, a temperature decrease of 3°–4°C in the Northern Hemisphere at a corresponding minimum of solar insolation (associated with the 21 000 and/or 41 000 year periods in the precession and obliquity parameters) was sufficient to initiate the glaciation of the Tibetan Plateau. The ice-albedo feedback associated with the growth of the Tibetan ice sheet produced an additional atmospheric temperature decrease of 1°–2°C and initiated glaciation in North America and northern Europe. During the return of solar insolation to interglacial values, the flat lowland ice sheets melted. The ice-albedo feedback associated with their retreat led to further heating of the atmosphere and to the observed rapid deglaciation, beginning in North America and northern Europe and ending in Tibet. Therefore, the Tibetan ice sheet was "the first to come and the last to go," and it should have existed at the last glacial maximum. In terms of Kuhle's autocycle hypothesis, ice-albedo feedbacks associated with the growth and retreat of the Tibetan ice sheet are the mechanism that amplifies the variation of solar insolation, thus explaining the strength but not the periodicity of the observed ice age cycle.

In order to perform a true test of the validity of the autocycle hypothesis, it would be necessary to conduct an experiment with a fully coupled model of the atmosphere, biosphere, ocean, and cryosphere, forcing the model with the transient changes in solar insolation over an entire ice age cycle. At present, such a coupled

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experiment is not feasible because of the prohibitive amount of computing time required. Furthermore, given the present state of climate modeling it would be difficult (if not impossible) to couple the individual components of the climate system and keep them stable in a 100 000-year integration.

Here, we investigate the equilibrium climate response to a hypothetical Tibetan ice sheet (with ice sheet extent and height specified according to Kuhle 1987). Present day boundary conditions are used for prescribing sea surface temperature (SST), albedo, and snow and ice cover in all regions except Tibet. The model used is the T21 Atmospheric General Circulation Model (AGCM) of the European Centre for Medium-Range Weather Forecasts (ECMWF).

The motivation for this uncoupled atmospheric experiment was to test whether Kuhle's hypothetical Tibetan ice sheet could produce conditions that favor initiation of glaciation in Northern Hemisphere high latitudes. The climate response to this forcing can occur via both ice-albedo feedbacks and interactions between atmospheric waves and the altered elevation of the Tibetan Plateau.

We stress that this is a zero-order test of the purely atmospheric response to Tibetan ice sheet forcing. Possible changes in oceanic circulation are not considered. Therefore, this experiment should not be regarded as a complete test of Kuhle's autocycle hypothesis.

2. Evidence for the existence of a Tibetan ice sheet

Evidence for the existence of a Tibetan ice sheet can be obtained from two sources: observations and modeling studies. Both sources of evidence provide controversial information. After examination of Tibetan moraines, Kuhle (1986) concluded that the equilibrium snow line during the last ice age was approximately 1200 m lower than at present. He also used local geomorphological evidence (e.g., glacial erratics) to support his contention that the Tibetan Plateau had a "compact ice cover, (which) attained a thickness of at least 700 to 1200 m" during the last ice age (Kuhle 1987). This conclusion is not in agreement with the results of the CLIMAP group (1981).

Not all observational evidence supports Kuhle's contention of more extensive Tibetan glaciation. Frenzel and Sirocko (1990) examined lake sediments in a central area of the Tibetan Plateau (at an unnamed lake 25 km west of Amdo) and inferred from radiocarbon dating and geomorphological evidence that sediments must have existed at this site throughout the last glacial maximum.

Further evidence in support of Kuhle's hypothesis can be obtained from ice sheet modeling. The buildup of a Tibetan ice sheet was simulated with a three-dimensional ice sheet model with parameterized atmospheric forcing (i.e., no atmospheric circulation) and prescribed snow balance (Kuhle et al. 1989). The annual snow balance (snow fall minus melting) required to build up the Tibetan ice sheet in a realistic time of approximately 10 000 years was 0.1 m liquid-water equivalent. This is 20%–40% of the present annual sum of precipitation in the region of the Tibetan Plateau (Jaeger 1976). Therefore, in this simple experiment, the existence of a Tibetan ice sheet at some time during the last ice age cycle is physically reasonable in terms of mass balance considerations alone.

An experiment with a full atmospheric GCM failed to confirm this result. Lautenschlager and Herterich (1990) performed an equilibrium response experiment with the ECMWF T21 AGCM, using CLIMAP (1981) boundary conditions for the last glacial maximum and a Tibetan ice sheet according to Kuhle (1987). The annual snow balance was negative for the Tibetan ice sheet and was positive for the North American and the Eurasian ice sheets. Therefore, if a Tibetan ice sheet had existed at the last glacial maximum, it would not have been maintained in the model.

Evidence from deep-sea sediment cores in the northern Indian Ocean indicates a reduction of the Indian summer monsoon at the last glacial maximum (e.g., Duplessy 1982). Is the existence of a Tibetan ice sheet necessary in order to achieve such a reduction? The above-described AGCM experiment by Lautenschlager and Herterich (1990) simulated a decrease in the intensity of the Indian summer monsoon consistent with Duplessy's results. However, a comparable reduction of the monsoon has also been observed in other AGCM experiments that do *not* consider glaciation of the Tibetan Plateau (Kutzbach and Guetter 1986; Broccoli and Manabe 1987; Rind 1987). We conclude that the existence of a Tibetan ice sheet is not essential for the reduction of the summer monsoon, and that permanent or at least more persistent snow coverage of the Tibetan Plateau throughout the seasonal cycle seems to be the most important factor.

In summary, unambiguous evidence for the existence of a Tibetan ice sheet at the last glacial maximum could not be obtained, either from observational evidence or from various model simulations.

3. AGCM response to a hypothetical Tibetan ice sheet

Adding an ice sheet effectively raises the Tibetan Plateau. Thus any changes in the atmospheric circulation are not due to ice-albedo feedback alone, but will also involve interactions of atmospheric waves with the plateau (e.g., Gates 1984). Note that previous GCM studies of the effects of mountains on the atmospheric general circulation have generally considered only "mountain" and "no-mountain" cases and have not examined the effect of elevated mountains (e.g., Kasahara and Washington 1969; Manabe and Terpstra 1974). Here we test the atmospheric response to the dynamic and thermodynamic perturbation of a Tibetan ice sheet.

Present day climatic boundary conditions were used for the control integration with the T21 AGCM. In the response experiment, these boundary conditions were altered only at the location of the Tibetan ice sheet, which is represented by 11 model grid points (out of a total of 2048). Following Kuhle (1987), an ice sheet with a mean thickness of 900 m and a maximum (minimum) of 1200 m (500 m) was added to the modern topography. The ice albedo at all 11 grid points was set to 0.8. The control and response experiments were integrated for six annual cycles. The first annual cycle was used for model spinup, and the results presented here are from the final five years.

The suitability of the ECMWF T21 AGCM for this type of experiment has been demonstrated in a number of different investigations. The model's control run performance has been investigated by Santer and Wigley (1990), who concluded that it reproduced many large-scale features of the Northern Hemisphere general circulation with better fidelity than other AGCMs of comparable resolution. The model's simulation of present day and ice age climate has also been examined by Lautenschlager and Herterich (1990). The control run surface climate was broadly consistent with observed data, while the ice age response showed good agreement with geological evidence and was comparable to results obtained from other AGCM ice age simulations. The ability of the model to respond to regional changes in boundary conditions, such as changes in snow cover, has been demonstrated by Barnett et al. (1989).

Results are presented for precipitation and 2-m temperature. For the statistical analysis, zonal and meridional wind at 10-m height are also included.

a. Local response at the glacial ice sheet locations

If Kuhle's autocycle hypothesis is correct, the T21 model response to Tibetan ice sheet forcing should produce atmospheric conditions that favor the initiation of glaciation at the locations of the Northern Hemisphere glacial ice sheets. The regions where the glaciation was expected to start were Labrador for the North American ice sheet and Scandinavia for the Eurasian ice sheet. The regional response was considered in the entire area of the ice sheets to take into account a possible regional displacement of the model response. An increase of the annual snow balance will be indicated by positive precipitation anomalies (more snow) in winter and negative temperature anomalies (less melting) in summer.

We considered the area-weighted averages of the annual mean anomalies of 2-m temperature, precipitation, and snow balance at the location of the Laurentide and Eurasian ice sheets in order to obtain the annual mean atmospheric response to Tibetan ice sheet forcing. There was no annual mean decrease in temperature or increase in precipitation and consequently no increase in the annual snow balance. The proposed annual mean temperature decrease of 1°–2°C due to a Tibetan ice sheet (Kuhle 1987) was not simulated by the model.

We next examined the geographical distributions of the experiment minus control changes in January and July 2-m temperature and precipitation in order to determine whether any seasonal changes were in accord with Kuhle's hypothesis (Figs. 1a–4a). Gridpoint *t*-tests were performed in order to evaluate the univariate significance of these changes (Figs. 1b–4b).

For both 2-m temperature and precipitation, there is a strong local response at the position of the Tibetan ice sheet. In the region of the North American and Eurasian glacial ice sheets a significant surface temperature response was obtained in July only. Surface temperature decreased by up to 2°C in Northern Siberia and by less than 2°C in Canada. There was no locally significant precipitation response at the position of the North American ice sheet. The small precipitation increase in Scandinavia in July was significant, as well as the slight precipitation decrease in northern Siberia in January and July.

In the upper troposphere, the dynamical response to the imposed ice sheet forcing is not a purely local response, as is evident in the 300-mb wind field (not shown). In January, the intensity of the subtropical westerly jet is increased (decreased) by more than 10% downstream (upstream) of the Himalayas. Changes in the 300-mb wind field of similar magnitude are obtained near the location of the major subtropical highs in both hemispheres. In July the subtropical westerly jet is displaced northwards and broadened, and its intensity is decreased upstream of the Tibetan plateau.

In summary, the seasonal results provide conflicting evidence for Kuhle's autocycle hypothesis. The T21 model simulated small regions of significant temperature decrease in July (less melting) at the positions of the Laurentide and Eurasian glacial ice sheets, a result that supports Kuhle's contention that Tibetan ice sheet forcing can generate conditions that favor the initiation of glaciation in the Northern Hemisphere. However, the hypothesized significant precipitation increase in January was not simulated.

b. Global response

The previous section considered the spatial structure and univariate significance of the atmospheric response to the forcing imposed by a Tibetan ice sheet. Here we examine the overall significance of the response and changes in the global energy cycle.

1) GLOBAL SIGNIFICANCE

In order to assess the global significance of control versus experiment differences in means and spatial patterns, we employ the pool-permutation procedure (PPP) introduced by Preisendorfer and Barnett (1983).

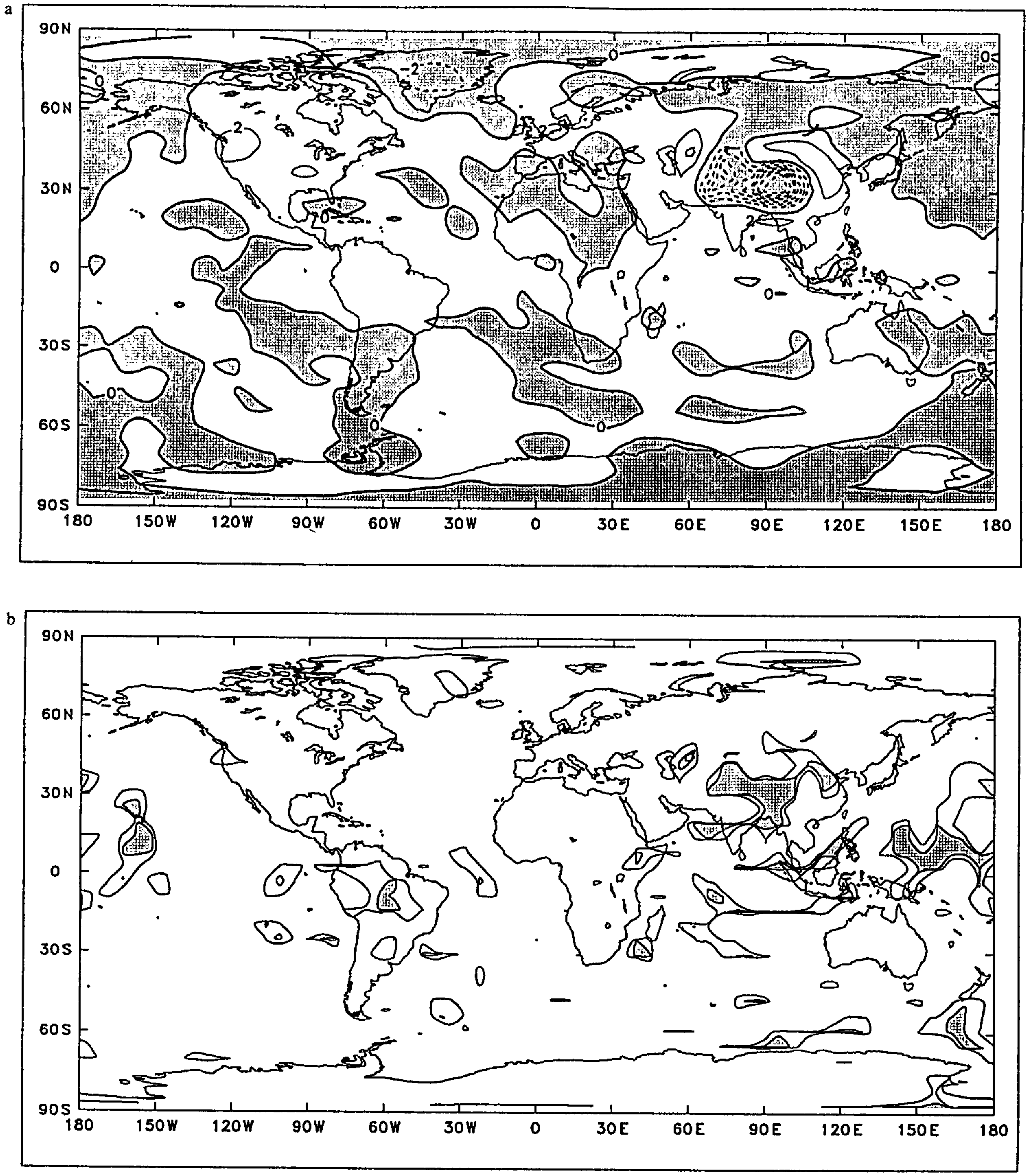

FIG. 1. January response of temperature at 2-m height. a) Anomaly (Tibetan response minus present), contour interval: 2°C, negative anomalies are shaded; b) *t*-statistic, isolines: 5% and 1% significance level, 1% areas are shaded.

The PPP accounts for the effects of multiplicity and spatial autocorrelation and is useful in significance testing situations where the number of time samples is small. For a full description of PPP, refer to Preisendorfer and Barnett (1983) and Wigley and Santer (1990). The test statistics used were the cumulative fraction of locally significant 1% and 5% gridpoint *t*-tests (NT1/NT5) and the time-mean spatial pattern

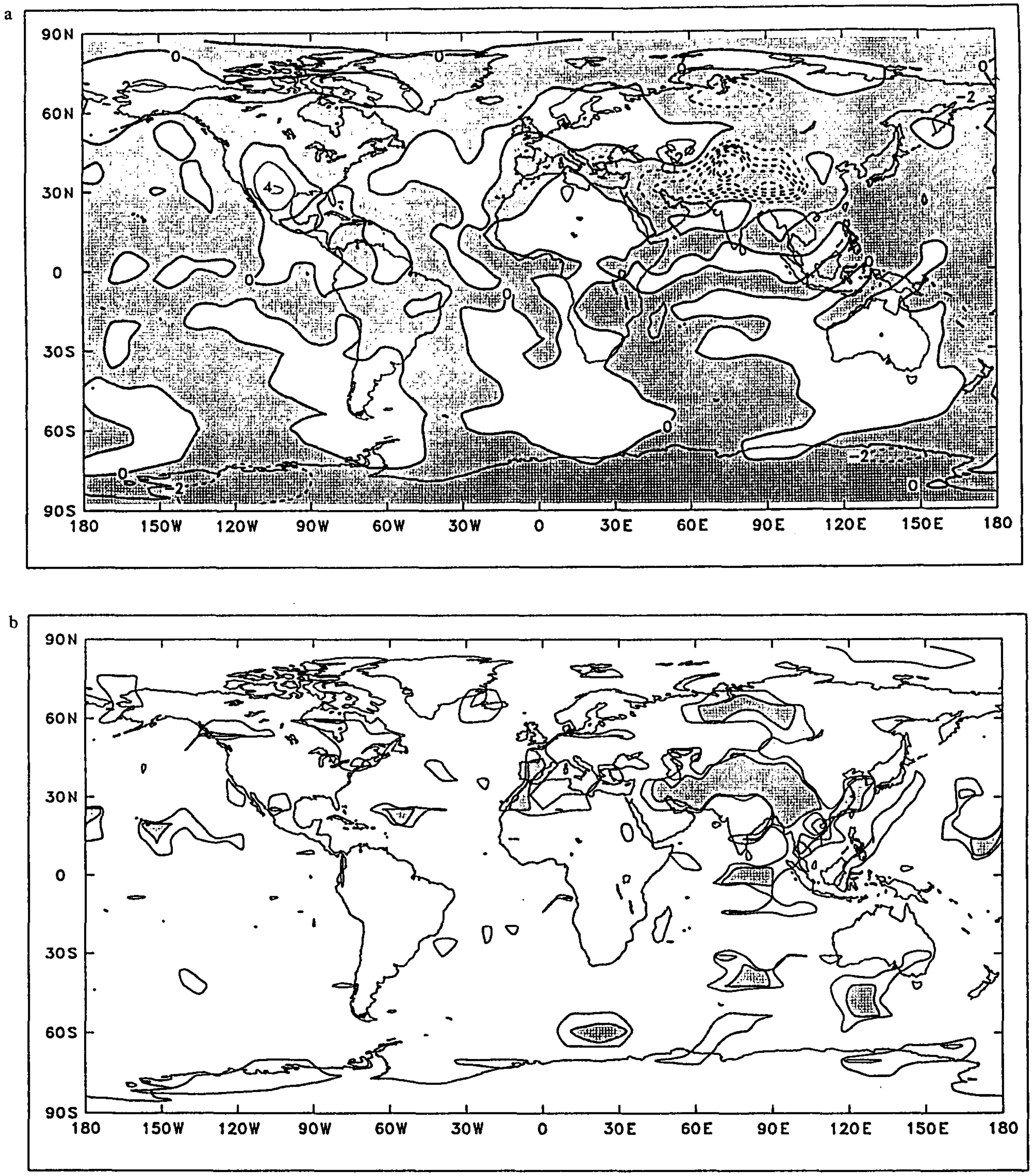

FIG. 2. July response of temperature at 2-m height. a) Anomaly (Tibetan response minus present), contour interval: 2°C, negative anomalies are shaded; b) *t*-statistic, isolines: 5% and 1% significance level, 1% areas are shaded.

correlation, *r* (Santer and Wigley 1990). We stress that the significance test results should be treated cautiously in view of the small number of time samples.

The NT1 and NT5 statistics indicate that the control versus experiment differences in overall means are globally significant at the 1% level during both months and for all variables (see Table 1). For temperature and precipitation, global significance is dictated by the

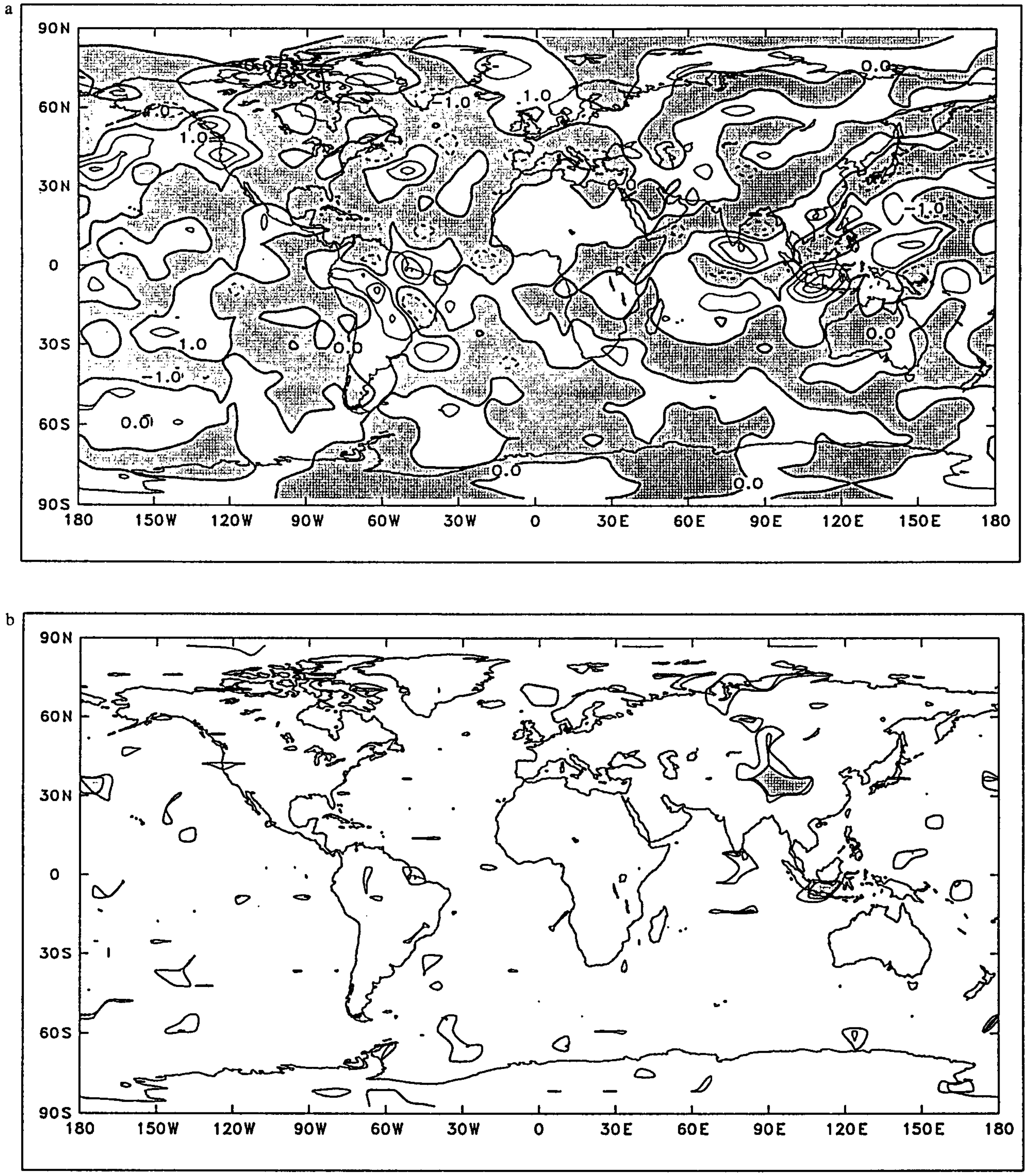

FIG. 3. January response of precipitation. a) Anomaly (Tibetan response minus present), contour interval: 1 mm day,$^{-1}$ negative anomalies are shaded; b) *t*-statistic, isolines: 5% and 1% significance level, 1% areas are shaded.

strong local response at the Tibetan ice sheet position. (see Figs. 1–4). Here NT1 and NT5 both identify the strongest response in the July temperature field (NT1 = 6%; NT5 = 17%).

The actual statistic values for r show close correspondence between the spatial patterns in the control and Tibetan ice-sheet experiment, particularly for temperature ($r = 0.99$ in both January and July). The

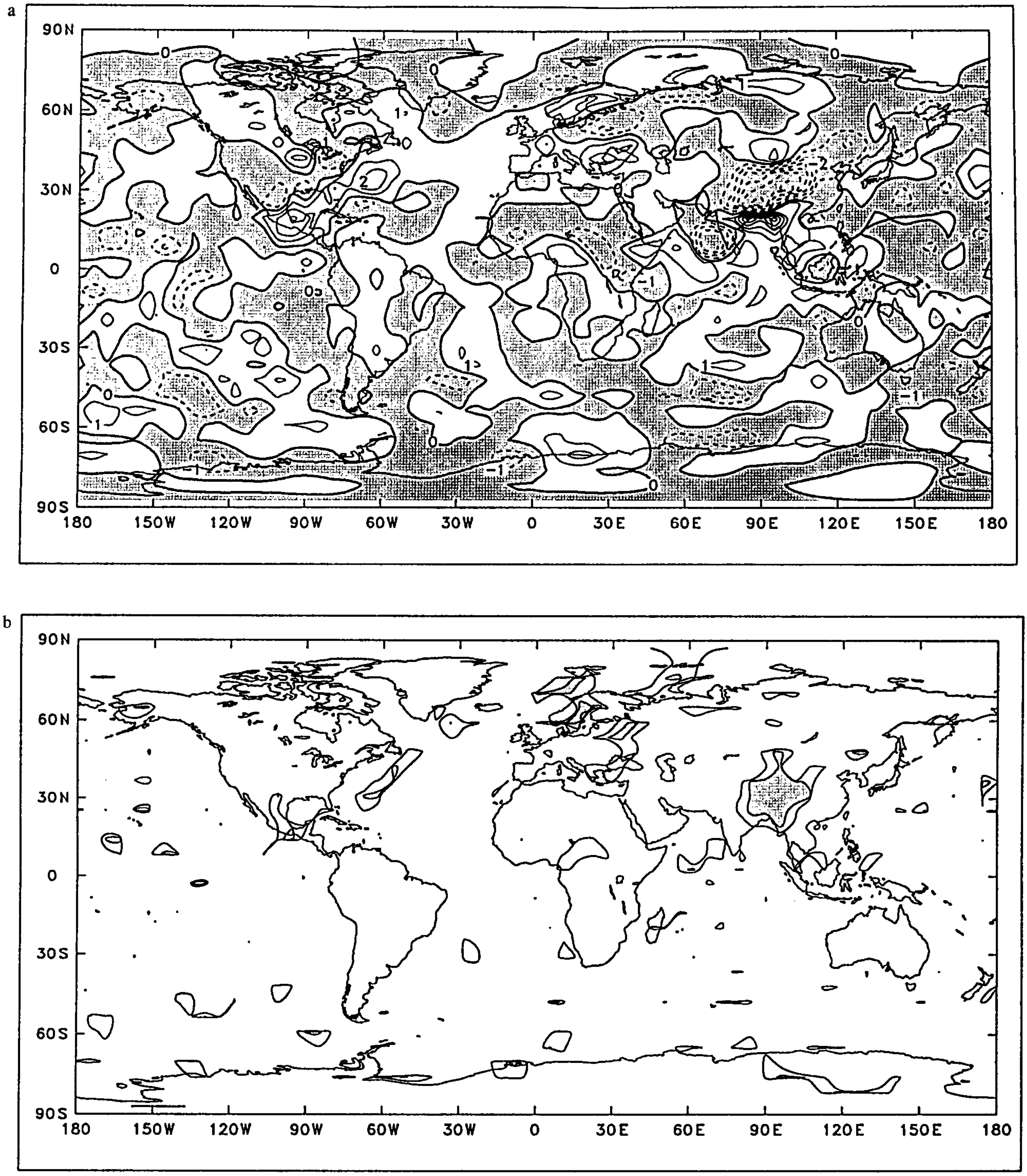

FIG. 4. July response of precipitation. a) Anomaly (Tibetan response minus present), contour interval: 1 mm day,$^{-1}$ negative anomalies are shaded; b) t-statistic, isolines: 5% and 1% significance level, 1% areas are shaded.

high pattern correlations reflect the relatively small changes in the general circulation and the persistence of strong north–south gradients. Despite the high actual statistic values for r, the differences in temperature and precipitation patterns are significant at the 1% level. This is due to the fact that the PPP test for r is too powerful in situations where the patterns tested have low temporal variability and are dominated by strong

TABLE 1. Statistics: *t*-test at the 1% and 5% significance level. Global significance at the 1% level is indicated by *.

	Temperature at 2-m height	Zonal wind at 10-m height	Meridional wind at 10-m height	Precipitation
		Means [percent of grid points]		
January 1%	5*	4*	3	2*
January 5%	15*	11*	9	9*
July 1%	6*	5*	6*	3*
July 5%	17*	15*	15*	10*
		Pattern correlation coefficient		
January	0.99*	0.90	0.92	0.94*
July	0.99*	0.95	0.94	0.88*

gradients. Spatial pattern differences for the 10-m zonal and meridional wind fields are not significant.

2) GLOBAL ENERGETICS

The global energy cycle characterizes the overall atmospheric circulation. The T21 energetics were calculated from daily data taken from the five-year control and Tibetan ice sheet integrations. The calculations were performed in the spectral domain according to Speth et al. (1987). In January and July, all terms of the global energy cycle in the experiment were changed by less than 5% relative to the control run. Most of the changes in the zonally averaged vertical cross sections of the energy contributions were located near the earth's surface at 35°N (the position of the Tibetan ice sheet). The global energy cycle results indicate that the overall energetics of the atmospheric general circulation was only weakly affected by Tibetan ice sheet forcing.

4. Summary

Kuhle's (1987) geomorphological observations during numerous expeditions to the Tibetan plateau, together with results from recent ice sheet modeling studies (Kuhle et al. 1989) provide some empirical and theoretical evidence for the existence of a Tibetan ice sheet at some time during the last ice age cycle. However, the evidence from both empirical sources and modeling studies is controversial (Frenzel and Sirocko 1990; Lautenschlager and Herterich 1990).

In the present study, an experiment was performed to test whether Kuhle's hypothetical Tibetan ice sheet could produce conditions that would favor the initiation of glaciation in Northern Hemisphere high latitudes. The results are ambiguous. The imposed forcing did not increase the annual snow balance at the locations of the Laurentide and Eurasian ice sheets. However, analysis of the seasonal cycle results indicated that there were small, locally significant temperature decreases in July (at the ice sheet locations), but that there was no evidence for a corresponding significant precipitation increase in January.

There was a strong locally significant response to the Tibetan ice sheet forcing in the vicinity of the forcing itself. Control versus experiment differences in January and July 2-m temperature and precipitation rate were globally significant, a result that is dictated by the large local changes. The small sample size available here (five years) means that global significance results should be treated cautiously.

There is some evidence that the upper-tropospheric response to the elevated Tibetan plateau is not confined to the vicinity of the forcing (as seen in the 300-mb wind field). Near the surface, however, differences between the control and experiment spatial patterns for the zonal and meridional wind fields were not globally significant. The changes in the global energetics of the atmosphere are small.

In summary, the results of this experiment do not permit a conclusive decision regarding the question of whether Tibetan ice sheet forcing could have generated conditions that favored the initiation of Northern Hemisphere glaciation during the last ice age cycle. Future modeling studies need to consider ocean–atmosphere–ice sheet feedbacks that were neglected here and to investigate the transient response of the climate system over a complete ice age cycle. Without such studies the existence of the Tibetan ice sheet still remains hypothetical.

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