CHANGE IN CLIMATE VARIABILITY IN THE 21st CENTURY

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Abstract. As climate changes due to the increase of greenhouse gases, there is the potential for climate variability to change as well. The change in variability of temperature and precipitation in a transient climate simulation, where trace gases are allowed to increase gradually, and in the doubled CO_2 climate is investigated using the GISS general circulation model. The current climate control run is compared with observations and with the climate change simulations for variability on three time-scales: interannual variability, daily variability, and the amplitude of the diurnal cycle. The results show that the modeled variability is often larger than observed, especially in late summer, possibly due to the crude ground hydrology. In the warmer climates, temperature variability and the diurnal cycle amplitude usually decrease, in conjunction with a decrease in the latitudinal temperature gradient and the increased greenhouse inhibition of radiative cooling. Precipitation variability generally changes with the same sign as the mean precipitation itself, usually increasing in the warmer climate. Changes at a particular grid box are often not significant, with the prevailing tendency determined from a broader sampling. Little change is seen in daily persistence. The results are relevant to the continuing assessments of climate change impacts on society, though their use should be tempered by appreciation of the model deficiencies for the current climate.

1. Introduction

The increasing concentration of greenhouse gases in the atmosphere has led to the likelihood of substantial climatic warming in the coming decades. The climate perturbation is usually expressed in terms of the change of the mean value of specific parameters, such as temperature or precipitation. However, in many instances, a change in climate variability would have as great an influence as a change in the mean. This is especially true for biologically-oriented processes, such as tree growth or agriculture, where killing frosts or anomalous heat waves can destroy the crop regardless of the 'mean temperature' for the month or year. Solomon and West (1985) emphasized the lack of suitable projections of changes in climate variability as a limiting factor in evaluating the response of forests to the projected climate change. As implied by this opinion, were variability to change as climate warms, it would likely alter the impact of the greenhouse warming on society.

The United States Environmental Protection Agency (EPA) is currently

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studying the potential affects of climate change on various aspects of society, including agriculture, forestry and water resources (EPA, 1988). The EPA study uses climate change results for the monthly mean temperatue and precipitation as calculated by several different general circulation models (GCMs). However, the study assumes variability will not change from its present magnitude. This was done out of necessity, since no systematic study of possible alterations in variability had been undertaken. The variability change produced by the GCMs was not used directly, since there had also been no study of how realistic their variability was for the current climate simulation. Thus interannual and daily variations were taken from observed data for a thirty year time period, and the models' monthly mean climate change values were simply appended to them. It was recognized that this conservative approach might well underestimate the influence of the projected climate changes, in the sense that many of society's processes are inherently arranged with the current variability in mind. In an attempt to determine whether the GCMs could be used for an estimate of the change in variability, and what change would have resulted, the following study was undertaken.

The GISS GCM was one of the models providing data for the climate change assessments. Results used were from both the GISS doubled CO_2 run with its current climate control, and a transient climate change experiment in which trace gases are increased gradually. To assess how well this model can simulate the observed variability we compare model and observed interannual and daily variations of temperature and precipitation for the four geographic areas of concern in the EPA analysis: southeast United States, the Great Lakes region, the Southern Great Plains, and the West Coast. We also compare how the variability for these time scales is altered in the climate change simulations. We then repeat these comparisons for the diurnal cycle variation of temperature. The results of this study provide a first estimate of how variability changes with climate change.

2. Model and Climate Change Experiments

The model used is the GISS GCM (Hansen *et al.*, 1983) run at the 8° × 10° resolution. The model numerically solves the conservation equations for mass, momentum, energy and moisture. It includes parameterizations for rain and snow generation, cloud cover, short wave and long wave radiation, surface fluxes, etc., and uses two ground layers for surface hydrologic calculations. For climate change experiments, the ocean temperatures are allowed to adjust but ocean heat transports, required to produce current sea surface temperatures, are specified as unchanged. Uncertainties in climate models' cloud cover, ground hydrology, and ocean parameterizations induce uncertainties in model responses to climate change forcing.

The model has been run for both doubled CO_2 experiments (Hansen *et al.*, 1984), and the transient climate change, in which trace gases are allowed to accumulate gradually, and the climate change is calculated for the next 100 yr. This transient experiment has been reported in several different forums (Hansen *et al.*, 1987; 1988), and the results reported here correspond to a trace gas growth scenario in which current trends are continued into the future unchanged. Both climate change experiments will be used in this analysis, depending on the availability of model output for the various time-scales of variability.

3. Mean Values

Temperature and precipitation results will be reported for the four areas of the United States which are the focus of the EPA climate-change effects study. The four grid box regions for the 8° × 10° resolution model are shown in Figure 1, along with the cities that are used for comparison purposes (Table I). We present in Table II(a, b) a comparison of the model and observed temperature and preci-

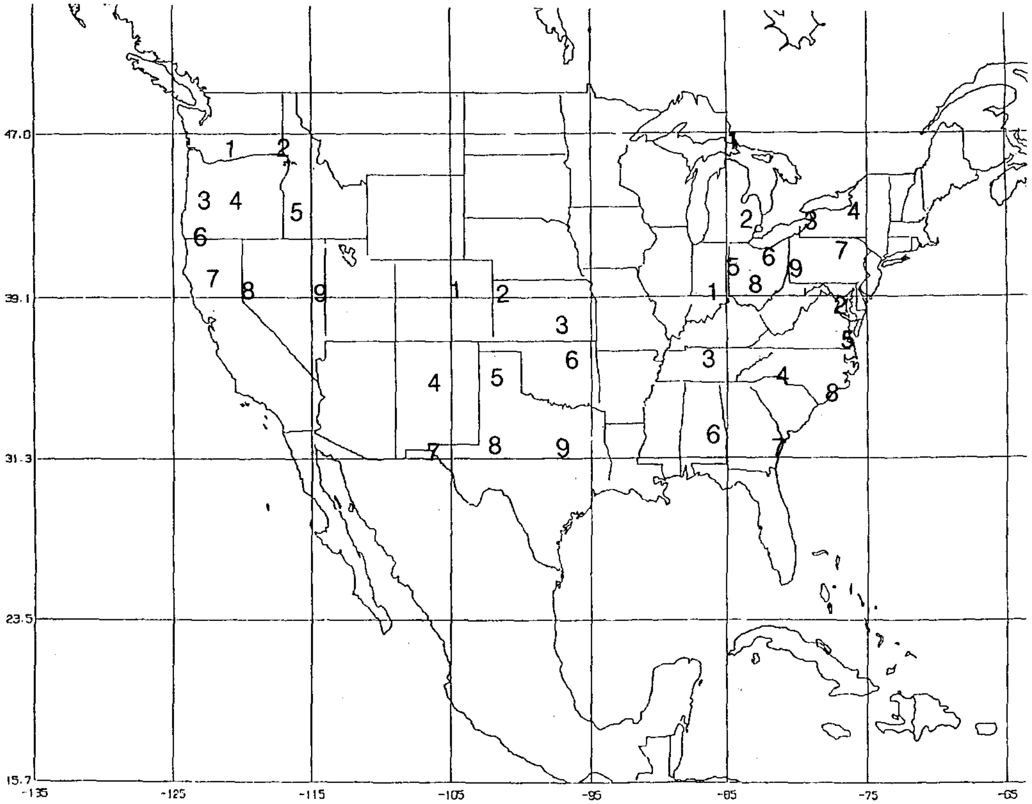

Fig. 1. Location of grid boxes for model results, and cities from which observed data has been used for comparison. The cities corresponding to the numbers are listed in Table I.

TABLE I: Stations used to obtain grid box averages

Southern Great Plains (31–39° N, 95–105° W)		Southeast (31–39° N, 75–85° W)	
1. Denver	6. Tulsa	1. Indianapolis	6. Montgomery
2. Goodland	7. El Paso	2. Washington	7. Savanah
3. Wichita	8. Midland	3. Nashville	8. Wilmington
4. Albuquerque	9. Waco	4. Charlotte	9. Columbus
5. Amarillo		5. Norfolk	
West Coast (39–47° N, 115–125° W)		Great Lakes (39–47° N, 75–85° W)	
1. Yakima	6. Medford	1. Slte St. Marie	6. Cleveland
2. Lewiston	7. Red Bluff	2. Flint	7. Williamsport
3. Eugene	8. Reno	3. Buffalo	8. Columbus
4. Redmond	9. Ely	4. Syracuse	9. Pittsburg
5. Boise		5. Ft. Wayne	

pitation for the four months, with observations obtained by averaging values for the nine cities within or in the proximity of each of the grid boxes. The reason for chosing nine cities will be discussed in Section 4. The model results are averages over 10 model years (ten independent samples) for the control run, doubled CO_2 study, and transient experiment decades.

We evaluate the statistical significance of the differences between the model and observations, and the model and climate change experiments, by using the first moment test variate (Chervin, 1981), which equals the difference in mean values divided by the square root of the sum of the squares of the standard deviations. Standard deviations for observations, current climate, and doubled CO_2 climate are given in Table III. We use the hypothesis that there is no difference between the means, and reject it at the *a priori* selected significance level of 5%, for a two-sided critical region. Cases in which the hypothesis is rejected, and thus values can be determined to be significantly different, are indicated by an asterisk in Table II. Note that even if we cannot prove a significant difference, it does not necessarily indicate that the model is reproducing the current temperatures or precipitation. It may be that we simply do not have enough data to disprove the assumption. Thus in the cases where the differences are not significant, we must simply say we cannot reject the hypothesis (rather than accepting it).

Model monthly mean temperatures (Table IIa) are significantly different from the observed during summer and fall. In these seasons the model is consistently cooler, due most likely to the ground hydrology scheme which keeps too much moisture in the ground in summer (Hansen *et al.*, 1983). As the winter temperatures are more accurately reproduced, the model tends to underestimate the seasonal temperature cycle by 15–20%.

TABLE IIA: Monthly average mean temperatures (°C)

Month	Location	OBS Temp	Current Temp	2010s ΔT	2030s ΔT	~2060 ΔT	$2\times CO_2$ ΔT
January	S.G. Plains	2.32	−0.07	1.87	3.07*	5.39*	5.0*
	Southeast	2.79	4.40	2.10	1.71	4.74*	4.0*
	West Coast	−0.08	−1.23	1.38	3.71*	4.17*	6.0*
	Grt. Lakes	−4.79	−2.72	0.06	1.84	5.16*	6.0*
April	S.G. Plains	14.30	14.08	0.44	4.06*	5.32*	5.0*
	Southeast	14.46	14.36	2.31*	5.07*	5.79*	4.0*+
	West Coast	8.59*	6.85	1.82*	2.43*	5.58*	6.0*
	Grt. Lakes	8.41	7.52	1.45	3.08*	3.52*	5.0*+
July	S.G. Plains	26.80*	20.50	1.19*	1.84*	4.84*	4.0*
	Southeast	25.60*	22.86	1.68*	2.44*	4.57*	3.0*
	West Coast	21.40*	16.84	0.60	3.55*	4.14*	3.0*
	Grt. Lakes	21.69*	18.61	2.06*	2.89*	3.75*	4.0*
October	S.G. Plains	15.55*	12.83	1.52	1.76	6.24*	7.0*
	Southeast	15.49	15.28	1.51	3.01*	4.80*	5.0*
	West Coast	10.84*	8.21	1.72	3.42*	4.96*	5.0*
	Grt. Lakes	10.88*	6.41	2.15*	2.81*	5.89*	4.0*+

TABLE IIB: Monthly average precipitation (mm d^{-1})

Month	Location	OBS Prec	Current Prec	2010s ΔP	2030s ΔP	~2060 ΔP	$2\times CO_2$ ΔP
January	S.G. Plains	0.46*	2.08	−0.07	0.00	1.12*	−0.76+
	Southeast	2.83	2.85	−0.29	−0.96	−0.41	0.27
	West Coast	2.18*	4.03	−0.19	0.08	0.13	0.93
	Grt. Lakes	2.04*	2.98	−0.79	−0.81	−0.43	0.07
April	S.G. Plains	1.31	1.93	1.44	1.36	1.39	−0.47
	Southeast	2.93	2.27	0.77	−0.50	0.25	0.54
	West Coast	0.94*	2.40	−0.16	−0.02	−1.19	0.04+
	Grt. Lakes	2.73	2.08	−0.15	−0.34	0.14	0.25
July	S.G. Plains	1.99*	4.31	−0.43	−0.23	−0.33	1.05
	Southeast	4.07	4.51	−0.21	0.25	0.06	1.60
	West Coast	0.25*	1.54	0.41	0.09	0.73	0.14
	Grt. Lakes	2.82	2.44	0.01	0.70	−0.16	0.61
October	S.G. Plains	1.22	0.57	0.03	0.57	0.27	0.02
	Southeast	2.14	1.87	1.57	−0.39	0.19	−0.06
	West Coast	0.91	1.40	0.59	−0.55	0.39	0.57
	Grt. Lakes	2.16	1.62	0.04	0.04	0.32	−0.25

Model monthly mean precipitation values (Table IIb) are generally realistic for the southeast and Great Lakes grid boxes, while they tend to overestimate the rainfall for the west coast and southern Great Plains. These discrepancies will affect the precipitation distributions discussed below.

Thus as indicated in Table II, in about half the cases the model produces significantly different mean temperature and precipitation values when compared with observations. This properly raises doubts about the validity of model-produced changes in these fields, as well as changes in variability. We return to this question in the discussion section; here we simply note that the model discrepancies must be borne in mind when evaluating the results.

The current climate control run utilized the atmospheric composition of 1958. Also shown in Table II are the model predicted changes for the decades of the 2010s, 2030s, 2056–2065, and the equilibrium doubled CO_2 results. The annual average global mean warming for the 2010s was about 1 °C relative to the control run, for the 2030s about 2 °C, and for 2056–2065 about 4.2 °C. Close to one-half of the temperature changes in the 2010s are significant, while temperature changes in later decades and for the doubled CO_2 climate are usually so.

The doubled CO_2 results are averages for years 26–35 from the experiment, when the atmosphere was 4.2 °C warmer and temperature was no longer changing. In that respect it can be compared with the values for 2056–2065, in which the warming was reached in a transient mode. Cases in which the two temperatures are significantly different are indicated by a plus sign in Table II; several of the cases fall into this category, with the equilibrium doubled CO_2 changes being smaller than that for the decade around 2060. In the cases which lack significant differences, there is no consistent sign of the difference. For the purposes of the following discussion we will look upon the experimental results for the 2060 time period as being similar to those for equilibrium doubled CO_2.

The precipitation changes (Table IIB) are not significant, although the doubled CO_2 or equivalent 2060 changes usually indicate increased rainfall: 23 of the 32 cases shown for these time periods have increased precipitation. From standard binomial probability testing for increase versus decrease, this or higher percentages of increase would occur less than 1% of the time simply by chance. As discussed in more detail (Rind, 1988a) the ten year average changes are generally on the order of one (interannual) standard deviation regardless of the size of area averaging. Such differences would require integrations for many years to establish their significance. We will see this tendency repeated throughout the study: individual results often show little significant change, although a majority of the results show the same sign of the change. Note also that as the doubled CO_2 and 2060 precipitation differences are not significantly different, we again treat the two simulations as being similar.

Given this character of the modeled climate change, we now investigate the model's variability compared to the observed, and indicate how variability changes as the climate warms. The time-scales of variability are investigated in inverse order, starting with the longest accessible scale of year-to-year variability, then daily, and finally the diurnal cycle amplitude.

4. Year-to-Year Variability

How does the modeled year-to-year variability compare with observed variability? We compare the model variability from a 100-year control run for the present climate (Hansen *et al.*, 1988) with the interannual variability obtained from the stations shown in Figure 1/Table I for the 1951–1980 time period. The results of this comparison are given in Table IIIA for the relevant areas. To

TABLE IIIA: Interannual standard deviations of temperature (°C)

Grid box		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
S.G. Plains	OBS	2.0	2.02	1.9	1.4*	1.2	1.2	1.1	0.9	1.3	1.4	1.5	1.5
	CONT	3.1	2.7	2.2	2.5	1.3	1.1	0.9	1.3	1.5	2.1	2.4	2.5
	$2CO_2$	2.1	1.9	1.7	1.2*	0.7*	1.0	1.1	0.9	2.0	1.9	1.5	2.3
	STD	0.7	0.7	0.5	0.5	0.3	0.3	0.4	0.5	0.5	0.4	0.8	0.6
Southeast	OBS	2.3	2.3	2.1	1.2*	1.4	1.0	0.7*	0.8*	1.1	1.4	1.3	1.9
	CONT	3.0	2.3	2.2	2.4	1.9	0.9	1.3	3.1	1.2	2.0	1.4	2.9
	$2CO_2$	2.1	1.9	1.7	1.2*	0.7*	1.0	1.1	0.9*	2.0	1.9	1.5	2.3
	STD	0.3	0.6	0.5	0.4	0.3	0.2	0.3	0.7	0.5	0.5	0.7	0.4
West Coast	OBS	2.1	1.7	1.2	1.4	1.3	1.3	0.9	1.3*	1.5*	1.1*	1.3	1.5
	CONT	2.2	2.4	1.7	1.6	1.2	1.3	1.5	4.2	3.0	2.5	2.1	1.3
	$2CO_2$	1.7	2.1	2.2	1.2	1.5	1.3	1.6	3.5	2.6	2.7	2.4	2.3
	STD	0.7	0.6	0.4	0.4	0.4	0.6	0.5	0.7	0.6	0.5	0.5	0.4
Great Lake	OBS	2.4	2.5	2.0	1.4	1.7	1.1	1.0	1.1	1.3	1.7	1.5	2.2
	CONT	3.0	1.8	1.7	2.3	2.0	1.5	1.3	1.7	1.8	1.8	1.4	2.2
	$2CO_2$	1.5*	1.8	1.8	1.3	1.6	1.0	1.1	1.6	1.4	1.8	1.9	2.5
	STD	0.6	0.7	0.6	0.4	0.4	0.3	0.5	0.7	0.4	0.3	0.5	0.5

TABLE IIIB: Interannual standard deviations of precipitation (mm d^{-1})

Grid Box		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
S.G. Plains	OBS	0.3*	0.3*	0.6*	0.6*	0.7*	0.7	0.8	0.6	0.9*	0.8	0.5*	0.4*
	CONT	1.0	1.2	1.7	1.5	1.4	1.0	1.2	1.0	0.4	0.6	1.2	0.8
	$2CO_2$	0.9	1.5	1.4	1.9	1.4	2.0*	1.9	1.3	1.0*	1.5*	0.8	0.7
	STD	0.4	0.3	0.3	0.6	0.4	0.3	0.3	0.2	0.2	0.3	0.2	0.2
Southeast	OBS	0.7*	0.9	0.8*	0.8	0.7*	0.8	0.9*	0.8*	1.2	0.9	0.8*	0.8
	CONT	1.5	1.5	1.5	1.2	1.9	1.2	1.9	2.0	1.6	1.4	1.7	1.4
	$2CO_2$	1.9	1.7	2.0	2.0	1.9	1.5	1.9	2.0	2.0	1.9	1.9	1.6
	STD	0.3	0.2	0.5	0.4	0.5	0.4	0.3	0.3	0.6	0.4	0.3	0.4
West Coast	OBS	0.8*	0.7	0.5	0.5*	0.5*	0.4*	0.1*	0.3*	0.3	0.6	0.9*	1.1
	CONT	1.6	1.2	0.6	1.5	1.3	1.2	0.9	0.6	0.3	0.9	1.7	1.5
	$2CO_2$	0.9*	1.6	1.5*	1.2	1.5	1.9	0.6	0.8	0.2	1.4	2.0	1.9
	STD	0.3	0.6	0.2	2.0	0.2	0.3	0.1	0.2	0.1	0.2	0.5	0.3
Great Lake	OBS	0.7	0.7	0.7	0.7	0.8	1.0	0.6*	0.8*	0.8	1.0	0.7*	0.7
	CONT	1.0	0.5	1.2	0.8	1.3	1.4	1.2	1.5	1.0	0.8	1.3	1.2
	$2CO_2$	1.1	0.8	1.3	1.5*	1.4	1.0	1.5	1.1	0.7	1.7*	1.0	0.9
	STD	0.2	0.2	0.3	0.3	0.2	0.4	0.3	0.1	0.4	0.2	0.3	0.2

determine significant differences, we evaluate the second-moment test variate, equal to the square root of the *F* statistic, from the ratio of model to observed standard deviations (Chervin, 1981). Following Chervin, we determine the significance at the *a priori* selected 10% significance level using the hypothesis of equal variances. Significant differences are again indicated by an asterisk. For comparison we also show the standard deviation of the 10-year standard deviation, determined by breaking the 100-year run up into 10 equal intervals. Note again the test allows us only to determine whether significant differences exist between the model and observations, and not prove that the model is actually reproducing the current climate values.

Overall the modeled and observed temperature variability are in good agreement, statistically different at the 10% level in only 7 of the 48 cases. However, the model in summer generally overestimates the variability, even if the magnitude of the difference is not significant. The modeled surface air temperatures in summer are sensitive to the ground hydrology parameterization, which is very crude in this and most other climate models. It would appear to allow for greater variability in soil moisture and surface air temperature than occurs in the real world, an effect which is exaggerated by August when the ground can become completely dry in the model due to continual evapotranspiration (the parameterized vegetation does not completely shut off moisture loss before the ground dries out entirely).

The comparison between model and observed interannual variability of rainfall is shown in Table IIIB. In almost half the cases the values are significantly different, with the model variability generally larger than observed; this is especially true in the areas and seasons where mean precipitation amounts were overestimated (e.g., West Coast in summer, Southern Great Plains in winter, Table IIB). With excessive precipitation there is more scope for variability. However, even in other regions, the modeled values are generally too high. The model produces one value for rainfall each time step over the entire grid box; thus either it rains or it does not. In the observations, it can rain at one station and not another, and the result is to smooth the grid box average value and reduce variability. When we reduced the number of stations used for assessing the observed variability from nine to five, precipitation variability increased by some 33%, while temperature variability was relatively unchanged. This indicates the uncertainty that must be attached to the 'observed' interannual precipitation variability for a grid box as a whole. Again, the deviation of the modeled variability from observed will likely affect the confidence that can be placed in the climate change assessments.

What should we expect for changes in the interannual standard deviation of temperature and precipitation as climate warms? If there are physical reasons for expecting changes, then we can establish an *a priori* expectation of sign change. We begin with temperature, and discuss precipitation later in this section.

Climate models have been unanimous in predicting that high latitudes should warm more than lower latitudes (e.g., Schlesinger and Mitchell, 1988). High latitudes have greater static stability, so that low level warming is trapped near the surface, rather than being convected to higher altitudes as occurs in the tropics. Furthermore, snow and ice melting at higher latitudes reduces the surface albedo, allowing more solar radiation to be absorbed, and leading to greater heat ventilation from the oceans during winter.

Because of this latitudinal variation in temperature change, the temperature differential between low and high latitudes is expected to decrease, a result which again holds true in the different climate models (e.g., Rind, 1987). Were the latitudinal temperature differences to be completely eliminated (as is apparently the case for Venus), temperature variability on all time scales would tend toward zero; the variability currently results from the advection of cold and warm pools of air into a region, pools which accumulate at high and low latitudes respectively. All that would be left to provide advective temperature changes would be land/ocean or other longitudinal temperature contrasts. As the equilibrium doubled CO_2 climate reduces the latitudinal temperature contrasts, this should lead to reduced temperature variability in the future.

In addition, the synoptic scale systems of high and low pressure which are responsible for advecting different air masses into a region gain their energy from the latitudinal temperature gradient via the baroclinic process. As this temperature gradient decreases, so should the energy of these systems, as has been seen in doubled CO_2 climate studies (Rind, 1987). Again, this should result in reduced temperature variability.

With these expectations in mind, numerous studies have been made, looking for a trend in variability as climate has warmed over the past century (e.g., Angell and Korshover, 1978; Barnett, 1978; Ratcliffe, *et al.*, 1978; van Loon and Williams, 1978; Diaz and Quayle, 1980). None of these studies has found such a trend, although the warming over this time period, on the order of 0.6 °C (Hansen and Lebedeff, 1987), has not been particularly large when compared with the projected future warming. Does the model show decreased variability as the climate warms?

In Table IIIA we show the monthly standard deviation of temperature for the last ten years of both the current climate control run and the doubled CO_2 run on the $8° \times 10°$ resolution. The significance of the changes at the 10% level are determined as discussed previously. In only six of the cases are the differences significant, although there is a general tendency for the expected reduced variability from January through April in the doubled CO_2 climate (13 of the 15 months which show changes from the four grid boxes have reductions, and all six of the significant changes show reduced variability).

To determine whether the tendency for reduced variability during winter would be evident in a broader sample, a comparison was made for 13 grid boxes over the United States for the months of January through April. In 70% of the approximately 50 cases the control run standard deviations were lower than those for the doubled CO_2 run. However, the grid boxes are not necessarily independent; Hansen and Lebedeff (1987) computed the correlation coefficient of annual mean temperature changes for pairs of randomly selected stations having at least 50 yr of records. They found that for mid latitudes, the correlation dropped off to 0.5 at approximately 1200 km separation, and to 0.1 at 3000 km separation. While those authors used the 1200 km distance as representative of independent data points, to absolutely guarantee that we are dealing with geographically independent regions, we look at grid boxes more than 3000 km apart (i.e., every fourth grid box).

Grid boxes 4000 km apart were chosen at random in the Northern Hemisphere extratropics (20–70° N) during winter, when the high latitude amplification of the temperature change is greatest (Hansen *et al.*, 1984). In 60% of the 150 cases, the standard deviations decreased. Evaluating this result, standard binomial distribution theory shows that such a change, or even greater percentage reductions, would have occurred by chance less than 1% of the time. We show in Figure 2 the change of the standard deviation during January. As evident in the figure, and the fact that only 60% of the cases show a decrease, as well as the sampling for the United States, the reduction does not occur at all grid boxes in all winter months. However, there can be no doubt about the reality of the effect on the largest spatial scales; for the extratropics during

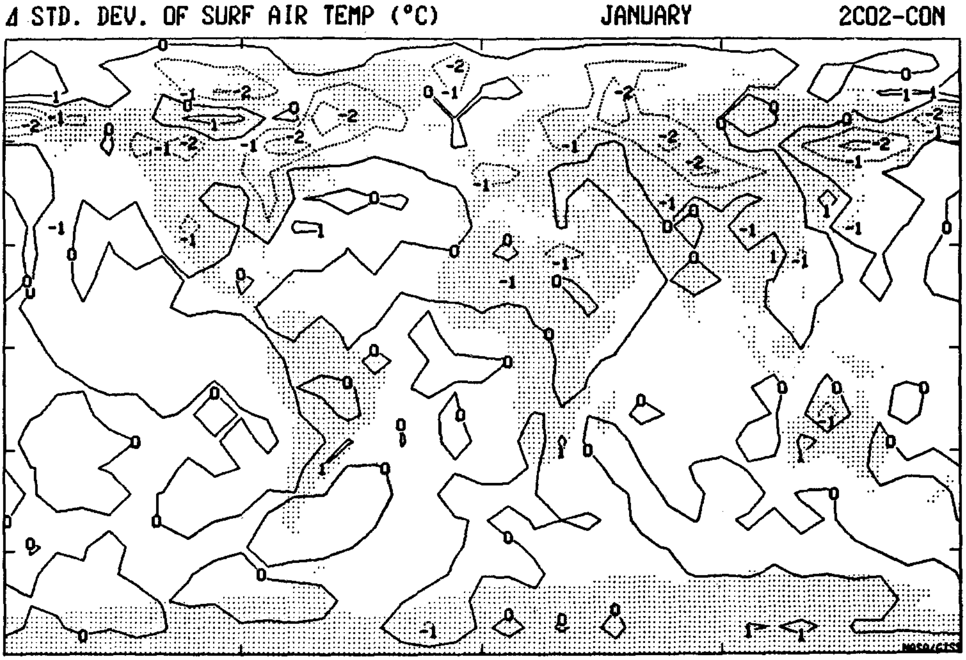

Fig. 2. Latitude-longitude presentation of the change in the interannual standard deviation of surface air temperature in January, doubled CO_2 climate minus control. The tic marks indicate latitudes of 0°, ±30°, and ±60°, and longitudes of 0°and ±90°.

winter, the latitudinal average surface air temperature standard deviation decreases in the doubled CO_2 climate more than 80% of the time. And in the months for which the climate change shows a decrease in the latitudinal temperature gradient (September through May), the interannual variability for the Northern Hemisphere as a whole decreases in every month in the warmer climate.

How should precipitation variability change as climate warms? An indication can be gained by comparing the model's variability relative to the observed with the model's mean values relative to observed. As noted above, where the model severely overestimates precipitation for the mean, it also does so for its variation, as greater magnitude differences between years are possible when rainfall values are greater. As climate warms, there is increased evaporation from the oceans, and an increase in the hydrologic cycle, with global rainfall higher by about 11% (Rind, 1988a, b). With all else the same, this should lead to increased variability, and the annual global average variability does increase in the doubled CO_2 climate by some 3%. Diaz and Quayle (1980) failed to find any significant differences in precipitation variability between warm and cold decades, although the temperature changes were much smaller than is being considered here for doubled CO_2.

The standard deviation of monthly average precipitation in the climate change experiments is given in Table IIIb. The results maintain the character we have seen throughout; on an individual basis, very few of the changes are significantly different (7 of the 48 cases). Overall, however, the expected tendency emerges, as 31 out of the 44 total months in which a change is recorded have increased variability in the doubled CO_2 climate. The tendency was particularly striking in the southeast, in which the variability in the warmer climate did not decrease for any month of the year, including autumn, when the actual mean precipitation values decreased by 0.6 mm day^{-1} (Rind, 1988a).

To look at a broader sample, we need to know the spatial scale for independent precipitation measurements. Rind and Lebedeff (1984) investigated the correlation coefficient between the precipitation trends for stations in the United States, and found that at a distance of 500 km the correlation had already dropped to 0.4. Diaz and Quayle (1980) have clearly shown that the changes in precipitation and precipitation standard deviation between different decades have smaller spatial scales than the corresponding temperature changes. Thus in this case we use 1000 km as the length scale for independent measurements. Referring to the 22 grid boxes over the United States and continguous North America for the 12 months, 65% received precipitation increases in the doubled CO_2 climate (Rind, 1988a). Examination for variability changes indicated that out of the 264 cases, 62% showed increased variability, which would occur by chance (along with even higher percentages) less than 0.1% of the time by chance. When the study is repeated using grid boxes 2000 km apart, increased variability still occurred with a probability which would have occurred by chance less than 1% of the time. On even larger spatial scales, the hemispheric and global standard deviations increased each month. The change in standard deviation is shown in figure 3 for July. Again note that although general increases occur, there are some regions with decreased variability. When this figure is compared with the GISS model change in summertime precipitation in the doubled CO_2 climate (as shown in Schlesinger and Mitchell, 1987) it is evident that the largest changes in interannual variability occur in regions where there are large changes in the mean precipitation itself, and both the mean and variance changes have the same sign. Thus the near equality of percentage of locations which show increases in mean precipitation over the United States, and those which have increased variability, is not fortuitous.

When the change in variability is of the same sign as the change in the mean, it indicates that the change in relative variability is minimized, which may be important in some applications. To examine this issue more closely, the sign of the change of the mean was compared to the sign of the change in interannual variability for the grid boxes and months described above. In 50% of the cases, grid boxes over the United States and adjacent North America had increases in both quantities, while in 23% of the cases there were decreases in both. Thus in 73% of the cases the sign of the change in variability was the same as the sign of the change in the mean. Of the other 27%, 16% had increased mean precipitation but decreased variability.

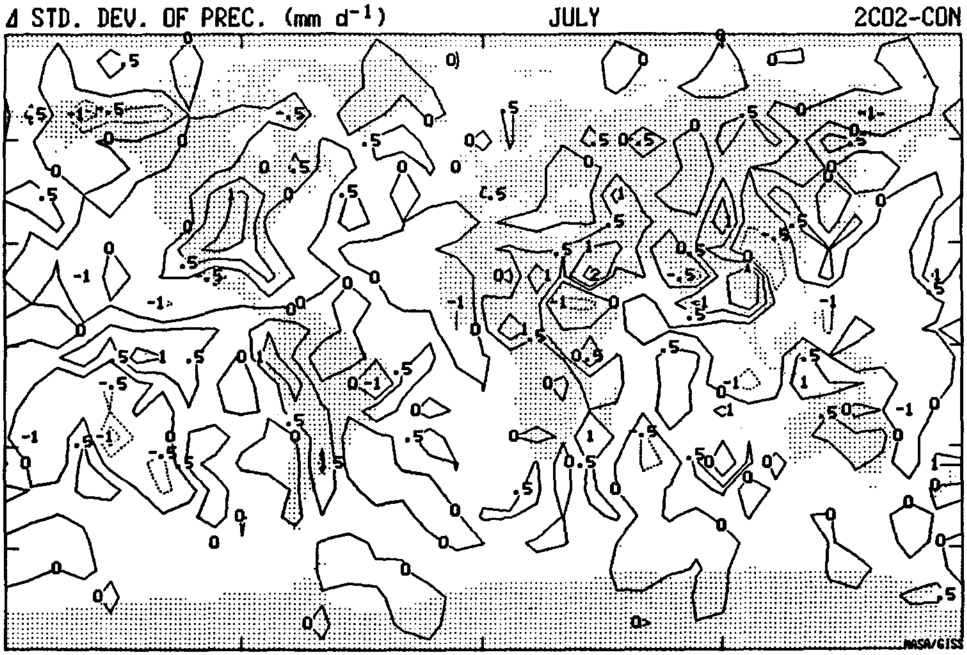

Fig. 3. As in Figure 2 for the change in the interannual standard deviation of precipitation in July, doubled CO_2 climate minus control.

To summarize the results of this section, at individual stations changes in the interannual standard deviation of temperature and precipitation were generally not significant. However, when a larger geographical region is considered, the number of independent grid boxes which show a decrease in interannual temperature variability, and an increase in interannual precipitation variability in the doubled CO_2 climate is significant, with the changes noted 60–70% of the time. As emphasized by this value, as well as the results shown in Table III and Figures 2 and 3, the sign of these changes simply represent tendencies, not uniform results.

5. Daily Variability

In this section our interest is in comparing daily variations in temperature and precipitation, for observations versus the modeled current climate, and for the climate change experiments. For temperature, the daily mean value is compared with the monthly average value and the departure noted; the results are then tabulated for the length of the record, 30 years in observations, ten years for the different model runs. The distribution of these departures can then be compared. While this technique is straightforward for the model values, in which a single temperature represents the entire grid box, the situation is not as clear for the observations.

How many stations are needed to produce a representative result for the area equivalent to the model grid-box? In Figure 4 we compare the distribution of daily temperature departures from the monthly mean for 30 years of April data (1930–1960) when using 3, 5 and 7 stations respectively, for the Southern Great Plains in April. In each case the stations were widely distributed throughout the grid box. While some changes can be noted, the results are rather similar regardless of the number of stations used.

Comparisons were also made between the distributions of observed and modeled precipitation for the same grid boxes and months. Due to the importance of true drought episodes, the frequency of occurrence of absolutely no precipitation was recorded separately from very light precipitation. The distribution of precipitation as a function of number of stations is shown in Figure 5. Here the results are very different. As the station number is increased, the frequency of days with absolutely no rainfall decreases, and the frequency with light rainfall increases. This is not unexpected, since light rainfall occurs with significant spatial variability, and the more stations utilized, the better the chance of recording it. However, it does indicate that the comparison of observed and modeled rainfall distributions will depend on the number of stations utilized.

When the number of stations used was increased to nine, the resulting distribution in the test cases did not differ significantly from the distribution obtained with seven (with significance determined in the manner described below), for

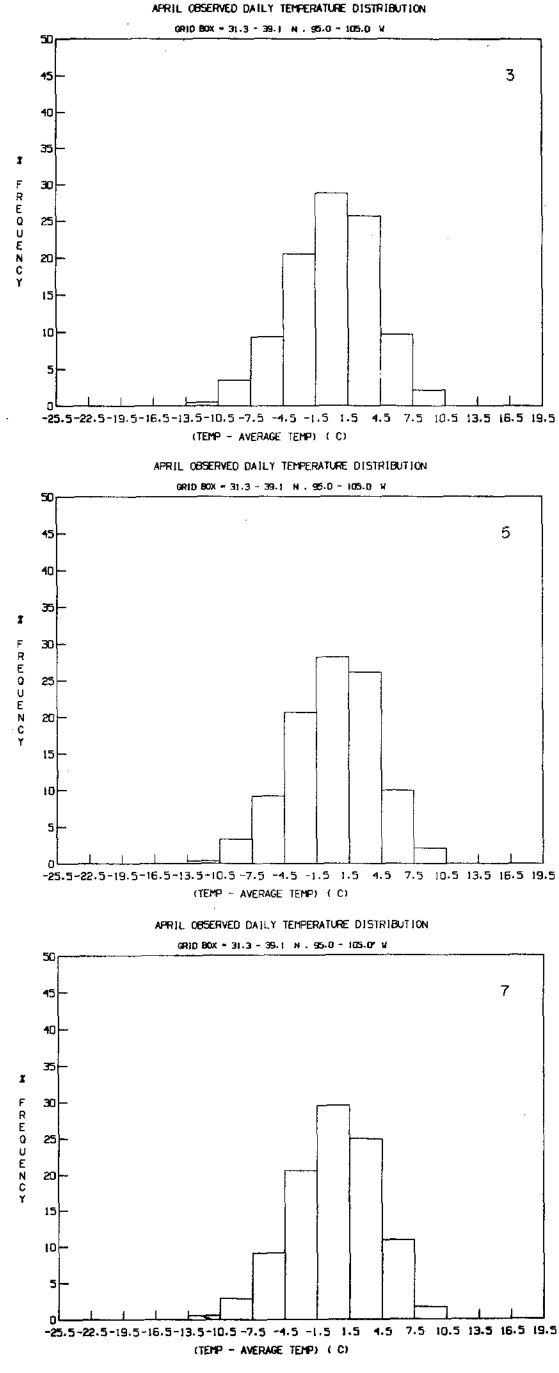

Fig. 4. Distribution of observed daily temperature departures from monthly means for the Southern Great Plains grid box for 30 yr of April data (1930–1960) using three stations (top), five stations (middle), and seven stations (bottom).

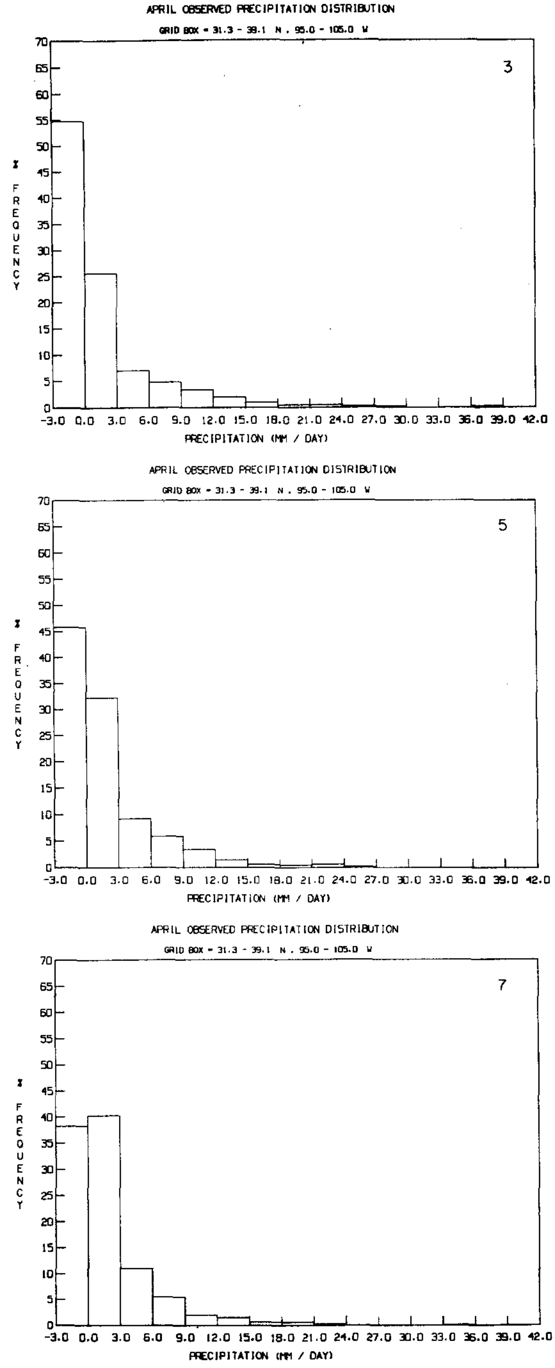

Fig. 5. As in Figure 4 except for daily precipitation intensities.

either temperature (compare Figure 4 with Figure 7, top left) or precipitation. The use of nine stations in each grid box thus appeared to be adequate for the purposes here, although the more uniformly distributed stations used the better the grid box representation would be. The stations are indicated in Figure 1; as is evident we also occasionally chose to use stations which were just outside the grid box, in order to secure a more area-wide representation of the results.

In comparing distributions of this sort, considerable problems are encountered when attempting to evaluate the significance of differences between them. Daily temperature values are unlikely to be independent, as some degree of persistence is prevalent for several days. The daily variance can be defined in terms of autocorrelation coefficients and an uncorrelated contribution. Katz (1984) provided a procedure for investigating the significance of the changes in the uncorrelated contribution. Wilson and Mitchell (1987) employed his technique, and found a significant decrease in the uncorrelated daily variance during winter.

However, our interest is not in the uncorrelated component, it is in the actual daily variation. As climate warms, and the latitudinal temperature gradient decreases, there is the potential for decreases in the mean zonal wind flow, leading to slower movement of synoptic scale systems. This might produce a change in persistence, which would contribute to the change in daily variations, and would be an important component to recognize. The problem in including the correlated changes is that it reduces the number of independent data points being used, a factor which must be considered in the statistical evaluation.

Thus we adopted the following approach. We first calculated the autocorrelation function for the temperature and precipitation data sets for both observations and the different model experiments. An example of the observed and modeled temperature autocorrelation functions for the southeast grid box for April is shown in Figure 6. The area under the curve represents the persistence in the data set, in days. This value was calculated for each autocorrelation function, and is the value used to reduce the number of independent observations in the statistical tests described below.

The results of this analysis are presented in Table IV. Comparing the model with observations, there is a tendency for the model to have greater persistence, especially during the warm season, and more so for precipitation than temperature. The coarse grid used in this model might be expected to retard the movement of synoptic scale systems, increasing the time of persistence; and the simplified ground hydrology could set up stronger positive feedbacks to precipitation changes than exist in the real world. Note also the smaller persistence associated with precipitation; the persistence value of close to one day obtained for these regions for the observations is in agreement with the general independence of precipitation on the preceding day found by Chin and Miller (1980).

What happens as climate changes? As indicated above, the *a priori* assumption is that if warming and reduced latitudinal temperature gradient slows the

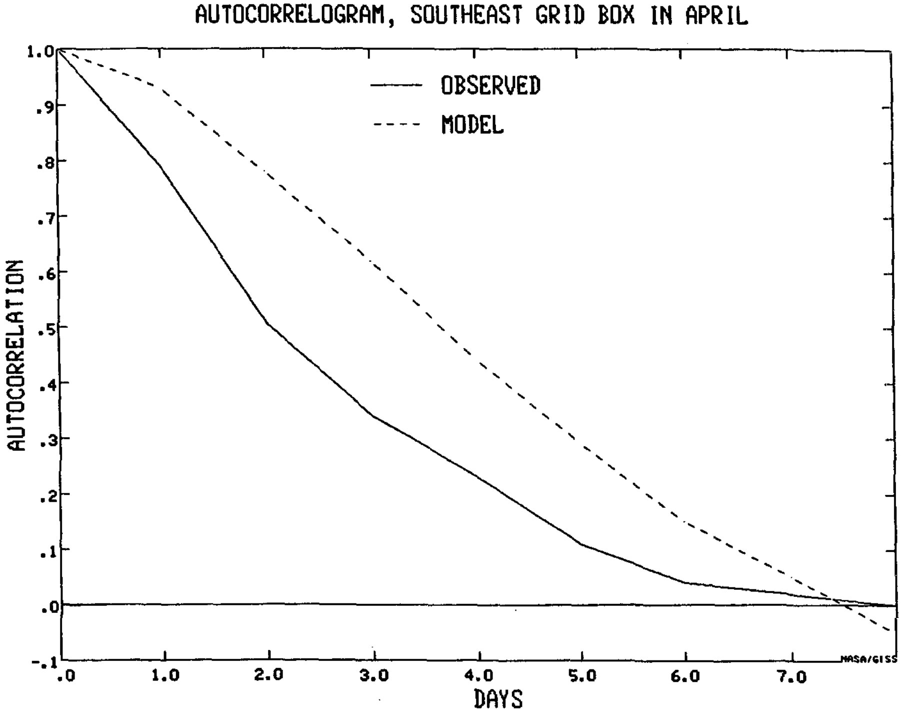

Fig. 6. Autocorrelogram of observed and modeled daily temperatures for the southeast grid box in April.

zonal mean winds, synoptic scale systems might move more slowly, and increase persistence in the future. In fact, while the latitudinal temperature gradient at the surface does decrease, the latitudinal temperature gradient aloft increases, as convection transports heat to the tropical upper troposphere. Thus in the GISS doubled CO_2 experiments the zonal kinetic energy actually increases slightly (Rind, 1987); it is therefore not clear what to expect, and referral to the average persistence times shown in Table IV indicates no obvious trend, for either temperature or precipitation. As noted by Rind (1987) the change in zonal kinetic energy depends strongly on the degree of high latitude temperature change amplification produced in the model, and so may well be model dependent. This implies that changes in persistence may be so as well.

To compare distributions of data, several statistical methods are available. One can bin the data, as in Figures 4 and 5, and use the chi-squared test to evaluate whether the null hypothesis, that the two distributions arise from the same population, can be judged unlikely. The greater the difference in number for each grouping, the more likely the null hypothesis can be rejected. Alternatively, one can generate the distribution function of the continuous data set, and use the Kolmogorov-Smirnov (KS) test to evaluate differences (e.g., Knuth, 1969). In this study, we employ both techniques on the daily temperature and

TABLE IVA: Daily persistence of temperature (days)

Month	Location	OBS	Current	2010s	2030s	~2060
January	S.G. Plains	2.72	2.26	2.10	1.90	2.20
	Southeast	2.17	2.35	2.76	2.25	2.69
	West Coast	2.94	2.46	2.26	2.67	2.27
	Grt. Lakes	2.32	2.25	2.28	2.21	2.47
April	S.G. Plains	2.51	4.22	2.99	2.92	3.08
	Southeast	3.04	4.26	3.63	2.93	3.31
	West Coast	2.38	2.58	3.10	3.20	2.87
	Grt. Lakes	3.06	2.89	2.99	2.62	2.45
July	S.G. Plains	2.36	3.98	2.57	4.36	3.42
	Southeast	2.44	3.63	3.83	3.71	3.10
	West Coast	2.91	3.85	3.91	4.28	4.65
	Grt. Lakes	2.10	2.82	4.07	2.97	3.85
October	S.G. Plains	3.32	3.50	2.82	3.95	3.86
	Southeast	3.00	4.04	3.49	3.79	3.19
	West Coast	3.01	2.54	3.26	2.97	3.14
	Grt. Lakes	2.42	3.60	2.82	3.64	3.79

TABLE IVB: Daily persistence of precipitation (days)

Month	Location	OBS	Current	2010s	2030s	~2060
January	S.G. Plains	1.24	1.78	1.76	1.48	2.34
	Southeast	1.17	1.80	1.96	1.80	1.68
	West Coast	1.76	1.95	2.14	1.77	1.94
	Grt. Lakes	1.14	1.64	1.70	1.51	1.78
April	S.G. Plains	1.24	1.82	2.88	2.81	2.05
	Southeast	1.23	2.32	2.62	2.51	2.17
	West Coast	1.30	2.17	2.38	2.36	1.93
	Grt. Lakes	1.21	2.15	1.99	1.66	1.88
July	S.G. Plains	1.33	2.14	2.09	1.88	1.99
	Southeast	1.16	2.64	2.14	2.78	1.66
	West Coast	1.21	1.63	2.74	2.38	2.11
	Grt. Lakes	1.10	2.32	2.20	2.58	2.49
October	S.G. Plains	1.47	1.86	1.96	1.71	3.28
	Southeast	1.27	2.39	2.22	2.21	2.31
	West Coast	1.66	2.48	1.95	1.92	2.81
	Grt. Lakes	1.30	1.73	2.13	2.08	2.28

precipitation distributions. When we compare the results from the two techniques in the evaluations of significance at the 5% level (i.e., significant versus non-significant), the results were in agreement 84% of the time, with the same value for both temperature and precipitation. This lends confidence to the evaluation of significance; however, it must be mentioned that there are uncertainties in the calculation of the absolute value for the chi-squared test, such as the Yates' approximate correction for using discrete distributions of frequencies (Panofsky and Brier, 1968), and uncertainties associated with significance levels for large data sets with the KS test (Knuth, 1969). It is important to recognize that the characterization of significance is perhaps not as important as the nature of the similarities or differences.

To use the chi-squared statistic when the data set is not completely independent, the chi-squared value must be reduced by the fraction of the data which is correlated (Knute, 1969). For example, in evaluating whether the distributions in Figure 4 are significantly different, the chi-squared value must be divided by 3, the value of persistence shown in Table IV for temperature observations in the southeast grid box in April. When applied to this example, omitting categories in which the numbers are less than five, (as noted by Panofsky and Brier, 1968), the result indicates that the three distributions are not significantly different, even at the 10% level. When correcting for lack of independence in the KS test, the number of observations (30 months $\times$ 30 days month$^{-1} = 900$) is reduced accordingly.

Comparisons were made between thirty years of observations (1951–1980) and ten years of the control run for the transient experiment for the four grid boxes during the months of January, April, July and October. (Here the fact that the degree of dependence in the distributions being compared differs (Table IV) implies that a weighted average correction must be applied.) The results show that the model and observed daily temperature variations about the monthly mean are rarely significantly different, occurring only once in the sample of 16 cases at the 5% level. Shown in Figure 7 are distributions from observations (top) and model (bottom) for the Southern Great Plains (left) and the Great Lakes (right). Although the distributions are not significantly different, it is clear that the model produces days with greater temperature extremes than is observed. (Note that since we are using 30 years of observations and only 10 years of model results, the likelihood of finding extreme values is larger in the observations, contrary to the actual results). This tendency occurs continually, and implies that there are feedback processes in the real atmosphere that limit surface temperature deviations over a grid-box sized area which do not operate with the same magnitude in the model. The difference is not a function of the number of stations used for the observations: the results of Figure 4, for the same month and location, show that even with three stations the extreme temperatures are not recorded.

To determine how the daily temperature variability changes with climate, distributions were produced for the four grid boxes and months from the transient experiment results for the years 2010–2019, 2030–2039, and 2056–2065. As noted above, the first two time periods experienced global mean warming of about 1° and 2 °C respectively, relative to the control run with the 1958 atmospheric composition, and during the last time period the global warming of 4.2 °C was equivalent to the doubled CO_2 equilibrium warming with

TABLE VA: Daily temperature standard deviations (°C)

Month	Location	OBS S.D.	Current S.D.	2010s ΔS.D.	2030s ΔS.D.	~2060 ΔS.D.
January	S.G. Plains	4.81*	8.15	0.61	−1.19*	−0.83*
	Southeast	4.53*	6.90	−0.14	−1.14*	−0.23
	West Coast	3.63*	5.86	−0.61	0.05	−0.16
	Grt. Lakes	4.97	5.79	0.44	−0.33	−0.44
April	S.G. Plains	3.72*	5.77	−0.57	−0.27	−0.80
	Southeast	3.71*	5.50	−0.65	−1.61*	−1.24
	West Coast	2.59*	4.29	0.77*	0.60	0.33
	Grt. Lakes	4.65*	6.15	−0.51	−0.26	−1.39*
July	S.G. Plains	1.74*	2.56	0.54	−0.19	0.18
	Southeast	1.50*	2.34	0.14	−0.22	−0.24
	West Coast	2.40*	3.56	0.03	0.54	0.28
	Grt. Lakes	2.38*	3.02	−0.48	−0.84*	−0.14
October	S.G. Plains	3.79*	5.16	1.16*	0.97	1.35*
	Southeast	3.59*	5.21	−0.54	−0.25	−0.73
	West Coast	3.15*	6.51	−0.55	−0.30	−0.80
	Grt. Lakes	4.09*	5.46	−0.37	0.91	−0.06

the GISS model. Comparison with the control showed that the model distributions did not in general differ from that for today, and there was no obvious progression as climate warmed. The results showed considerable individuality, both from month to month and as a function of location. The distributions for the southeast grid box for April are given in Figure 8; while changes occur, they are neither systematic nor significant.

Although the distributions may not generally differ significantly overall, a change in the occurrence of extreme temperature values could be important. The standard deviation of the values about the monthly mean give greater weight to extreme values, and so these have been calculated for the same cases. The results for observations, the current climate control run, and the climate change experiments are given in Table Va. The asterisk indicates significance at the 10% level, calculated, as before, using the second-moment test variate (Chervin, 1981), correcting the number of independent data points from the persistence values shown in Table IVa. As expected, model values are greater than observed, due to the model's greater extremes.

The interannual variations showed that standard deviations generally decreased, but the changes at individual locations were usually not significant. The decrease was anticipated due to the reduction in latitudinal temperature gradient and eddy energy. The same processes could be expected to reduce daily temperature variations. The changes shown in Table Va are of the same nature; they generally show decreases, but only occasionally are the changes significant. For the winter/early spring months of January and April decreases occur in eighteen of the 24 cases. Were the locations geographically independent, this percentage of decrease would be significant at the 3% level, using binomial probabilities. As the southeast and Great Lakes grid boxes are contiguous, it would be necessary to consider a wider sample to make a firmer assessment.

Precipitation distributions were also tested. Comparison between the model and observations is affected by the fact that the monthly average precipitation may be very diffeent from the observed for the grid box as a whole (Table IIb); similar differences in monthly average temperature were not a factor in the temperature comparison since the daily *departures* from each monthly mean temperature were being recorded. The precipitation difference could not be removed in a unique fashion: if the grid box had twice as much rainfall as observed, should each rainfall occurrence be reduced in intensity by a factor of two, or should the frequency of rainfall be changed? Rather than arbitrarily altering model values, we decided to evaluate the distributions as they were.

As can be seen in Table IIb, for the southeast and Great Lakes grid boxes, the model simulates the observed precipitation reasonably well. For the west coast and southern Great Plains grid boxes the model produces too much rain. Thus it could be expected that these latter two areas would have significantly different rainfall distributions from the model, and such is the case – in three of the four seasons the model and observed precipitation distributions differed at better than the 5% level in those regions. In contrast, the Great Lakes grid box showed significant differences only once. Overall, model and observed values differed slightly more than one-half of the time.

In the majority of cases, the model produced less days of light rain than did the observations. This is illustrated by the distributions for the southeast grid box in October (Figure 9, left). Note that it occurs even though the modeled mean monthly rainfall is only slightly less than observed (Table IIb). As shown in Figure 5, it is just this no rain/light rain distinction that is particularly dependent on the number of stations included in the observations. In the Great Lakes region, extreme rainfall values occur somewhat more frequently in observations in summer and autumn, as exemplified bythe difference between the otherwise very similar distributions in July (Figure 9, right). Extreme values occur more frequently in the model in winter in all four regions. The difference in extreme events is evident in the standard deviations for the model and observations (Table Vb).

To determine the change in distribution as climate warms, similar analyses were made for the decades of the 2010s, 2030s, and 2056–2065. The distributions were significantly different about one-fourth of the time, with no general progression over the decades. Shown in Figure 10 are the distributions for the west coast in April, which has a steady increase in the days with no rain as the climate warms and dries.

Extreme events tended to vary, but an overall tendency does emerge. The assumption made for the interannual standard deviations was that the magni-

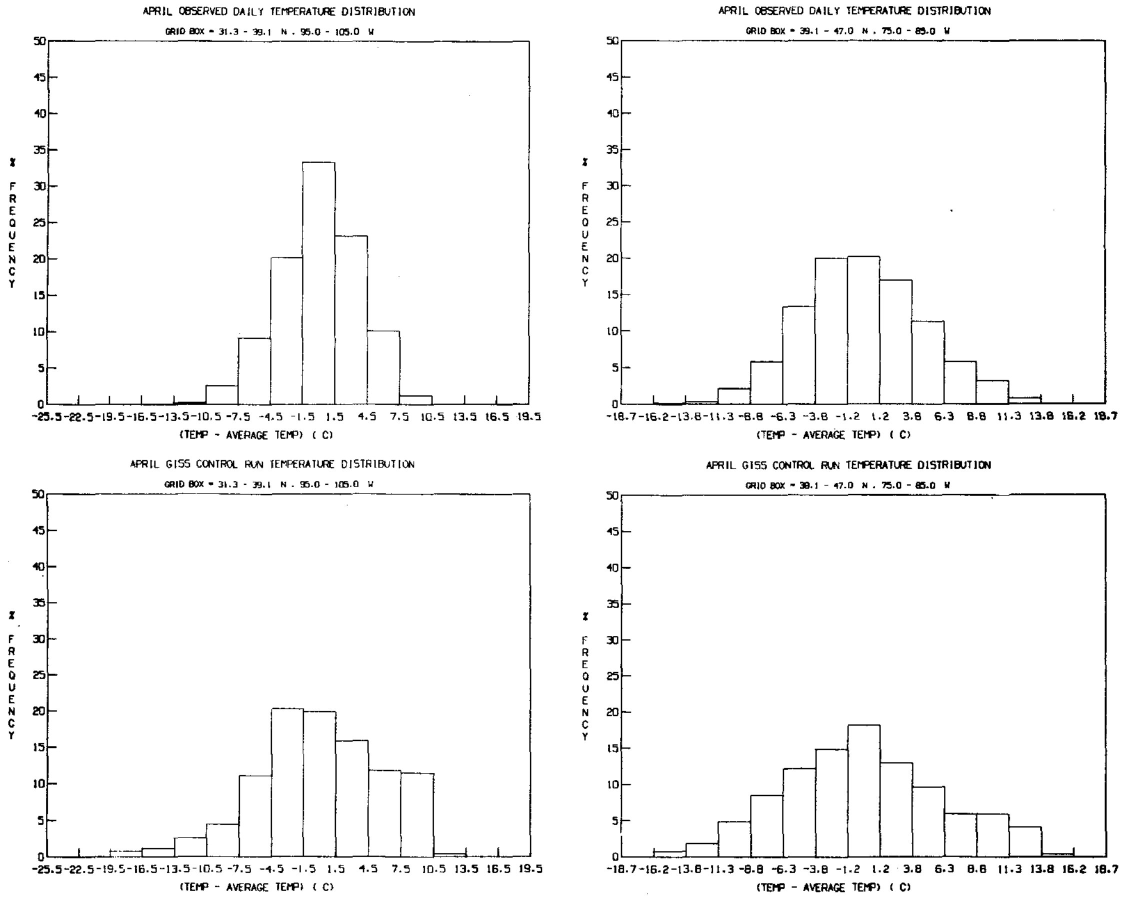

Fig. 7. Observed (top) and model (bottom) daily temperature departure from the monthly mean for the Southern Great Plains in April (left), and the Great Lakes in April (right).

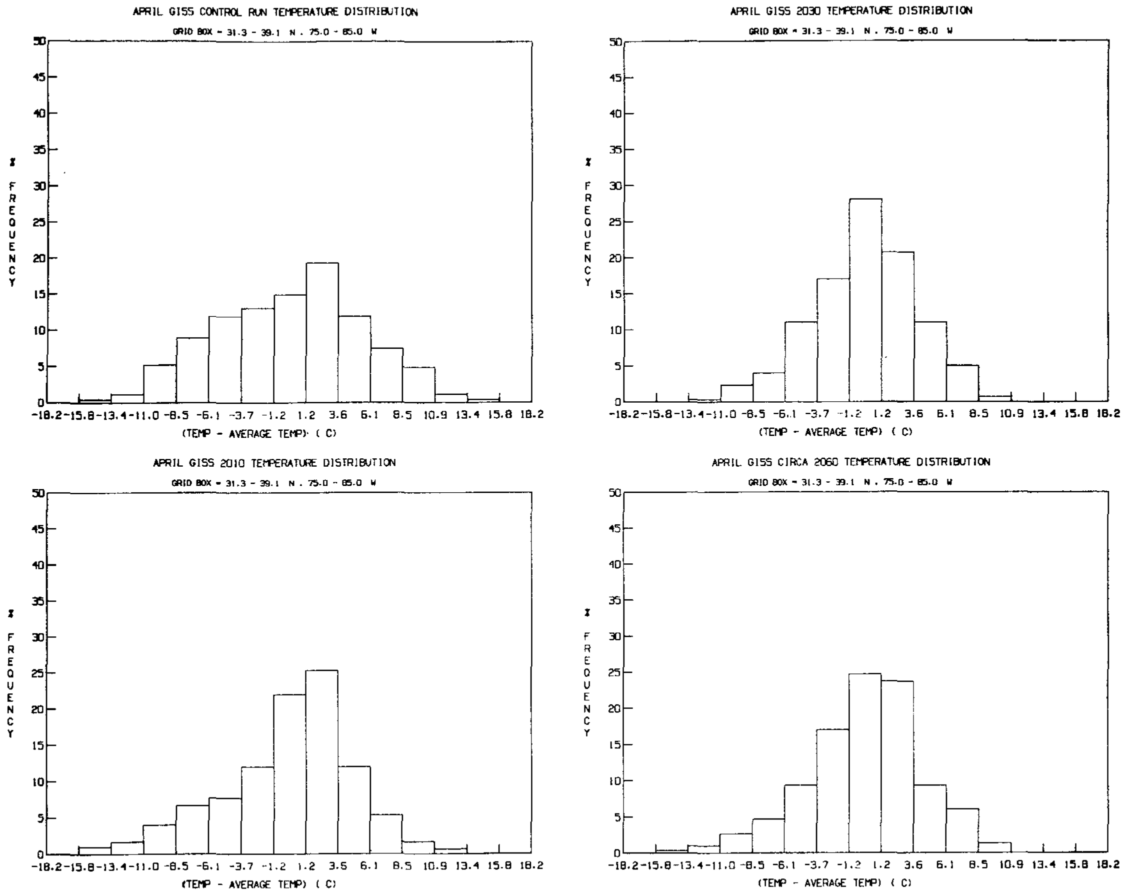

Fig. 8. Distribution of daily temperature departure from the monthly mean for the southeast grid box in April for the current climate (top left), the 2010s (bottom left), the 2030s (top right), and 2056–2065 (bottom right).

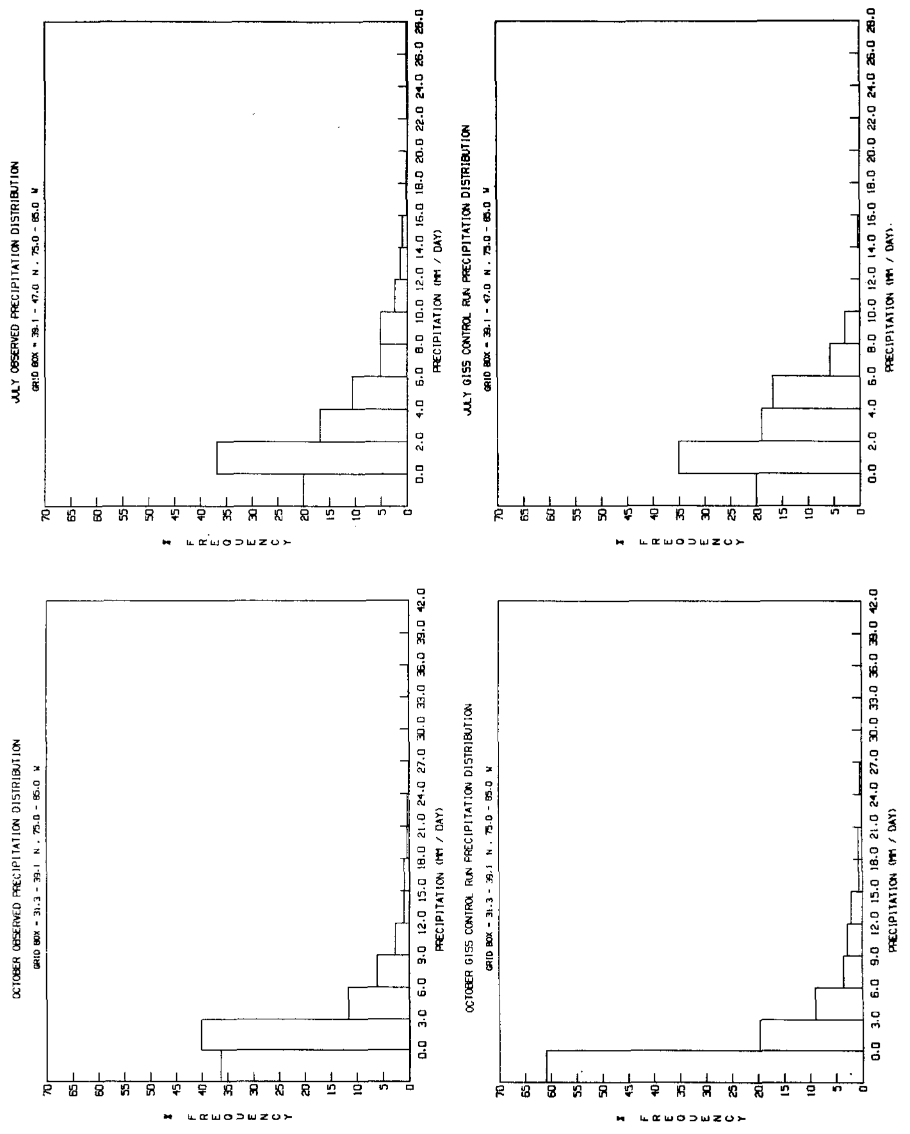

Fig. 9. Observed (top) and model (bottom) daily precipitation intensities for the southeast in October (left) and the Great Lakes in July (right).

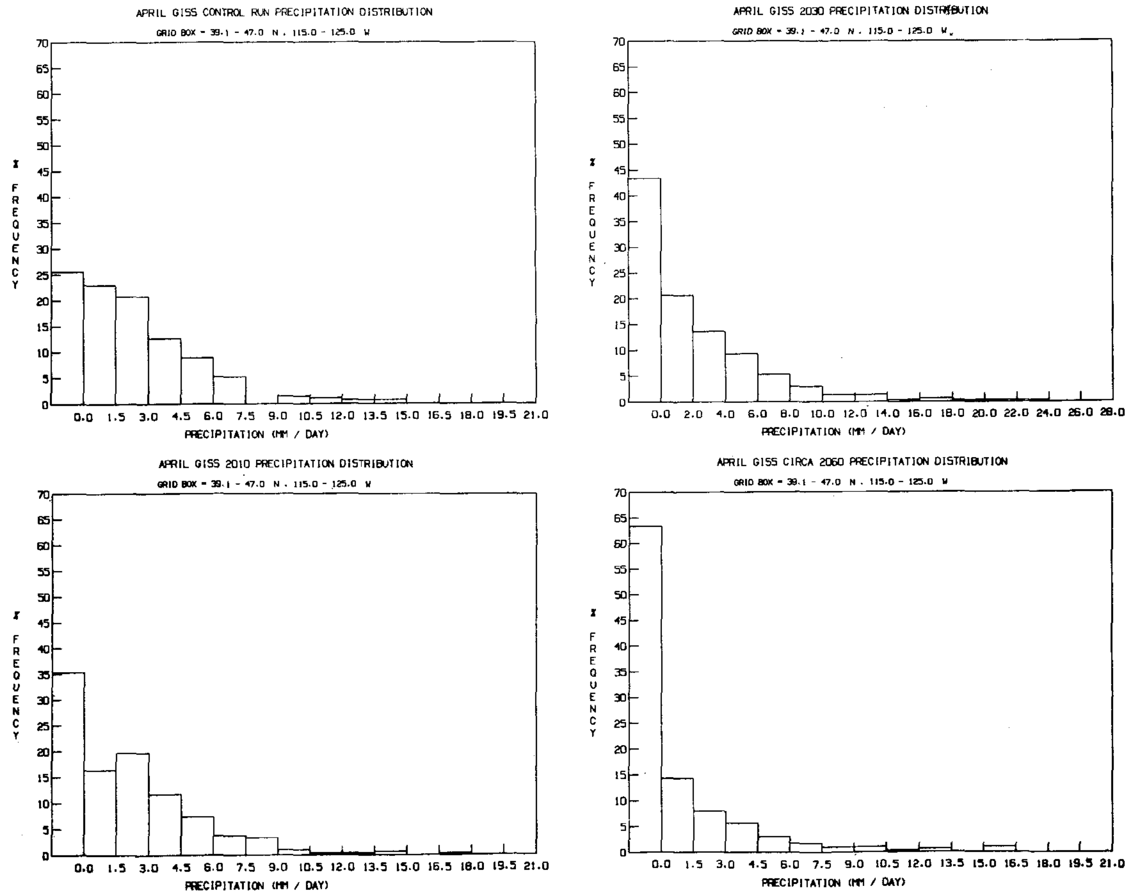

Fig. 10. Daily precipitation intensities for the west coast grid box in April for the current climate (top left), the 2010s (bottom left), the 2030s (top right), and 2056–2065 (bottom right).

TABLE VB: Daily precipitation standard deviations (mm d^{-1})

Month	Location	OBS S.D.	Current S.D.	2010s ΔS.D.	2030s ΔS.D.	~2060 ΔS.D.
January	S.G. Plains	1.08*	2.80	0.05	0.05	1.68*
	Southeast	4.35	4.62	−1.20*	−1.35*	−0.85*
	West Coast	3.23*	4.55	−0.18	0.34	0.13
	Grt. Lakes	2.23*	4.06	−1.07*	−0.94*	−0.50*
April	S.G. Plains	2.51*	3.26	0.94*	1.99*	1.17*
	Southeast	4.35*	3.85	0.95*	−0.15	0.81*
	West Coast	1.41*	2.76	0.07	1.02*	−0.12
	Grt. Lakes	3.85*	3.29	−0.43	−0.31	0.44
July	S.G. Plains	2.79	3.08	−0.10	−0.09	0.36
	Southeast	4.13*	3.31	0.28	0.29	0.11
	West Coast	0.57*	1.53	0.44*	0.24*	0.71*
	Grt. Lakes	3.68*	2.48	−0.06	0.72*	0.35
October	S.G. Plains	2.75*	1.79	0.52*	0.34*	0.00
	Southeast	3.77	3.88	0.72*	−0.15	−0.28
	West Coast	1.86*	2.69	1.20*	−0.63*	1.34*
	Grt. Lakes	3.58*	2.26	0.52*	0.76*	0.95*

tude of variability would increase if precipitation did. As shown in Table Vb, the standard deviations in the climate change experiments were significantly different from the control more than one-half of the time with no general progression over the decades. (Note, however, that the use of the F distribution to evaluate significance in this case is not strictly valid, for the daily precipitation distribution does not have a bell-shaped appearance). A comparison of Tables IIb and Vb indicates that the significant changes in variability coincide in sign with the change in mean precipitation.

In summary, the daily variability of precipitation tended to change with the same sign as the precipitation change itself, e.g., increasing when mean precipitation values did. Precipitation distributions changed significantly about one-fourth of the time, again influenced by mean value changes. Tempeature variability on this time scale tended to decrease, but this cannot be proven statistically with the sample at hand, while temperature distributions showed no obvious change. Nor was there any obvious change in persistence as climate warmed.

6. Variability of the Diurnal Cycle

The GISS general circulation model includes a diurnal cycle, and for certain applications, especially those involving vegetation, variations in the amplitude of the diurnal temperature cycle as climate changed would be an important result. The expectation is that the amplitude should decrease, since additional CO_2 (and water vapor in the warmer climate) would act as greenhouse material in limiting radiative cooling at night, while leaving solar radiational heating during the day unaffected. Karl *et al.* (1984, 1986, 1987) have reported a decrease in the diurnal temperature range, especially during summer.

We first compare the model's annual average diurnal temperature range with observations (US Air Force, 1979) calculated using the cities in Figure 1/Table I in each grid box (in some cases we had to use data which was available only for neighboring stations). In both cases the daily temperature maximum was compared with the daily temperature minimum to determine the diurnal range. The model values average very close to the observed, with a ratio of close to one (model/observed = 1.01 ± 0.27), although there is a tendency for model values to be higher in late summer, when the model ground dries out. The phasing also is appropriate, with temperature peaking during the mid-afternoon.

The change in the diurnal cycle amplitude for each month in the doubled CO_2 climate is shown in Table VI. The prevailing tendency is for the diurnal cycle amplitude to decrease in summer; out of the 12 records for the three months of June–August, decreases were recorded in 10 cases. The magnitudes of the decreases ranged from less than 1% to as much as 27%. There is no doubt about the reality of this effect; for the United States as a whole, during these three months 87% of the grid boxes showed decreases in the diurnal cycle amplitude. Given that the summer, when light winds occur, would be the season most likely to have its temperatures dominated by radiative effects, this result would appear to be in accordance with expectation. However, examination of the results indicates that other factors are operating as well. In the winter, spring and fall seasons, the modeled doubled CO_2 climate features cloud cover decreases at night, which may offset radiative decreases due to different trace gas

TABLE VI: Diurnal temperature range (°C)

Grid box		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
S.G. Plains	OBS	12.1	12.3	13.2	13.0	12.9	13.1	12.6	12.8	12.7	13.2	12.8	12.0
	CONT	10.5	11.2	12.5	15.4	10.4	10.1	9.7	11.2	21.8	19.2	13.6	10.9
	$2CO_2$	10.2	12.3	13.5	16.0	10.2	9.9	10.6	10.9	17.5	19.6	14.0	11.3
Southeast	OBS	9.2	10.0	10.5	11.4	12.4	10.5	10.0	10.1	10.3	11.0	10.6	9.6
	CONT	9.1	10.1	11.1	13.6	9.1	8.7	9.3	10.9	13.6	13.2	11.0	9.3
	$2CO_2$	9.3	9.5	12.4	12.8	8.5	7.9	7.3	8.0	13.6	13.3	10.5	9.7
West Coast	OBS	9.0	10.0	11.3	12.3	13.1	13.5	14.6	13.8	14.3	12.6	10.4	8.7
	CONT	6.6	6.9	8.7	12.1	10.0	10.7	13.1	17.1	19.0	14.8	10.1	7.1
	$2CO_2$	6.5	7.5	8.6	13.2	9.5	10.1	11.5	17.0	20.3	14.4	9.0	8.2
Great Lake	OBS	8.3	8.9	9.5	10.9	11.6	11.6	11.4	11.2	11.2	10.8	8.3	7.6
	CONT	7.4	7.3	8.4	11.4	8.9	9.7	10.5	12.7	14.3	10.1	7.7	6.7
	$2CO_2$	7.0	7.2	9.4	12.7	9.1	9.4	10.2	12.8	15.0	11.9	8.9	7.2

concentrations. In these seasons both increases and decreases in the diurnal cycle amplitude occur, with daytime temperature increases often exceeding those at night. In summer in the model there is little cloud cover change at night, which presumably allows the trace gas radiative effect to become apparent, and the warming is generally greater at night (thus reducing the diurnal temperature amplitude). This example illustrates how simple expectations can be altered by other aspects of the climate system.

7. Discussion

The results show that the year-to-year temperature variability and extremes in the daily temperature variability tended to decrease in the warmer climate during the winter and early spring. The precipitation variability on both time scales tended to increase, to the extent that the mean precipitation itself increased. The diurnal cycle amplitude tended to decrease in summer. In this section we discuss how likely these results are to be true, and briefly comment on their potential consequences.

The primary question that must be addressed is whether the model deficiencies for the current climate invalidate the results for future changes. This question is relevant when assessing the validity of predicted changes in the mean values as well as changes in variability. The comparison of modeled and observed temperatures and precipitation for the four grid boxes and four seasons has indicated the following deficiencies: (1) the model is too cool during summer and fall; (2) the model produces too much rain along the west cost and in the southern Great Plains; (3) the model generally overestimates temperature variability in summer, on both the interannual and daily time scales; (4) the model overestimates the interannual precipitation variability, and has too few days of light rain, as opposed to no rain, each month; and (5) the model persistence is too large, especially during summer and for precipitation. While these errors are not always large or significant, they are often of greater magnitude than the modeled climate change results. Can we believe the results under these circumstances?

A comparison was made of changes produced in the 4° × 5° version of the GISS climate model (when using doubled atmospheric CO_2 and the sea surface temperature changes produced in the equilibrium 8° × 10° experiment, as discussed in Rind, 1987; 1988a, b), with the 8° × 10°. The finer resolution model produces less rain for the western United States, (e.g., 1.4 mm d^{-1} in summer, compared with 2.6 mm d^{-1} in the coarse grid, Rind, 1988a), and smaller interannual variability (0.1 mm d^{-1} for the summer as a whole, compared with 0.5 mm d^{-1} with the coarser grid, Rind, 1988b), both characteristics which are more realistic. In the doubled CO_2 simulations, there are smaller changes in the finer grid run for this region (Rind, 1988b), indicating that the climate change experiment mimics some of the characteristics of the control run. As the changes in precipitation variability are closely tied to the changes in mean precipitation, we might expect that the finer grid model would have reduced variability changes in that region. We could not use this model for the variability study, as it did not generate its own sea surface temperature directly (nor were they allowed to vary from year to year), but the results do imply that model deficiencies can be expected to contaminate climate change estimates, both for mean changes and changes in variability.

What then can be gained from studies made with admittedly imperfect models? Current models can be used to explore potential physical interactions, which they may be able to elucidate, albeit in an imperfect manner. As an example, the models have been used to estimate the global warming due to a doubling of atmospheric carbon dioxide. The magnitudes of warming produced may be inaccurate because of the strong positive feedback that is provided by the cloud cover response in the models, and cloud cover parameterizations are currently very crude. Nevertheless, the models have shown the potential strength of this physical process, and have highlighted the necessity to model clouds more accurately. By running model experiments we hope to learn what mechanisms are of first order importance in climate change. This task requires models which allow for the multiplicity of interactions possible in the complicated, highly nonlinear physical system.

In the studies here, we are concerned with whether variability changes will occur along with the projected climate change. The physical processes that are being examined are (1) does the high latitude temperature change amplification produce significant reductions in interannual and daily temperature variability; (2) does the increased global rainfall produce increased precipitation variability; and (3) does the increased greenhouse capacity of the atmosphere reduce the diurnal temperature range. The results *in toto* verify these physical assumptions but with important caveats as to their generalizability. They thus give us a crude estimate as to the importance of the physical processes, and emphasize what must be done to improve our understanding. For example, to get better estimates of precipitation variability, we must produce better representations of the mean value. While this could have been stated *a priori*, this study, which clearly indicates the relationship of changes in precipitation variability to the mean changes, helps to quantify the issue.

The reduction in the latitudinal temperature gradient during winter is approximately 10% in the GISS doubled CO_2 model, and the eddy energy change is about 5%. The model results indicate that these differences translate into average reductions in temperature variability of the order of 10% (Tables III and V). The reliability of that conclusion is tempered by the tendency of this model to overestimate the variability for the current climate. Especially important in this regard is the need for a more realistic hydrology scheme which could limit late summer water loss and prevent unrealistic temperature changes. An additional uncertainty arises because of the lack of agreement among models as to what the reduction in the latitudinal temperature gradient will really be. The doubled CO_2 climate simulation done at the Geophysical Fluid Dynamics Laboratory produces a reduction in this temperature gradient that is two times as large. The results from this study imply that the decrease in temperature variability in their model might well exceed the values determined here. The use of several different models further serves to clarify areas requiring further research.

would be expected to be most apparent when winds are light, in summer. The model does reproduce this result. However, it also indicates the importance of competing effects, such as altered cloud cover, in occasionally reversing the sign of the change. While we cannot necessarily believe the individual results in this regard, due to uncertainty in cloud and convection schemes, they do highlight the ability of models to provide interactions from other elements of the climate system which can cause the results to deviate from expectations. As models are generated which produce better representations of the current climate, and contain more sophisticated parameterizations for these processes, we should be able to increase our confidence in such projections.

Changes in variability may well be affected by processes that have been omitted in the standard climate change experiments. For example, significant interannual variability is associated with changes in ocean dynamics, such as the El Niño phenomenon. While the GISS model allows sea surface temperatures to change, it does not allow ocean dynamics to change. Were El Niño events to occur with an altered frequency, this would undoubtedly influence interannual variability, at least in specific regions. Ultimately, all variability studies, as well as model projections for mean climate changes, will have to be done with coupled ocean/atmosphere models.

The model does not include hurricanes, which occur on spatial scales ($\sim$100 km) too small to be resolved. Emanuel (1987) estimated that the CO_2 warming of the tropical oceans could increase hurricane intensity by 40–50%, an effect which would add to the hydrologic variability increase produced in the model.

If the results obtained here prove to be valid, what effects are likely as the result of the changes in variability? Decreased temperature variability would appear to be a positive factor in societal planning, limiting the variance around the mean with which we would have to deal. However the variability changes studied here will be superimposed upon a changing mean climate. The impact of changes in the interannual, daily and diurnal cycle temperature variability on society will have to be compared with the potentially rapid rate of change of the mean temperature itself. All these factors will be folded in together in the climate that we experience, so even with reduced interannual temperature variability, the large decadal-scale warming might dominate the perception of temperature instability.

An increased variability of precipitation associated with an increase in mean precipitation might leave the relative variability unchanged. Nevertheless, society would be expected to alter its expectations of the mean conditions, and so increases in variability would still be likely to have a pronounced effect. Droughts, defined as lack of water availability relative to expectation or demand, might be expected to increase, as would floods. In conjunction with the likelihood of increased hurricane intensity, this would stress both ecosystems and civilization's structures. At the time of this writing (the late summer of 1988), we have had a graphic demonstration of such a world: the destructive power of hurricane Gilbert, the devastating floods of Bangladesh, forest fires sweeping the western United States, and the impact of drought in the central Great Plains and the southeast, affecting everything from 30% of the nation's crops to the cooling water and hydroelectric capacity of power plants. Potential changes in precipitation variability need to be factored into the decision-making process.

8. Conclusions

In this study we have looked at how variability on three time-scales, the interannual, daily, and diurnal cycle, may change in the future based on model projections. We concentrate on the areas of the southeast United States, the Southern Great Plains, the west coast and the Great Lakes. Extensive comparisons are made of observations and the model simulations of the current climate.

The primary results of this study are:

(1) The interannual temperature and precipitation variability does not change significantly on the grid box level, but on a broader area, the sign of the change is significant, with temperature variability decreasing and precipitation variability increasing (as mean precipitation increases).

(2) The daily variability in temperature is not significantly different, although there is a tendency for decreases. Precipitation variability on this time scale changes in the same manner as the mean precipitation.

(3) The amplitude of the diurnal temperature range decreases in summer.

These results must be viewed in the context of the comparison between observations and the model's current climate, which shows the model is often too cool and wet, and somewhat too variable. The lack of significance of the changes in variability on the grid box level may well be related to an insufficient length of time of simulation, as the only variable whose variability changed significantly on this scale (daily precipitation) had the largest independent data set to work with. Alternatively, procedures should be developed to take advantage of the predominance of changes of a specific sign, which characterize these results. Finally, the impact of changes in variability on these time scales must be viewed in the context of the projected rapid change of the mean values themselves, to understand their potential consequences for society.

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