To appear in *Preparing for Climate Change*, Proceedings of the Second North American Conference on Preparing for Climate Change, December 6-8, 1988, Climate Institute, Washington, D.C. 1989.

Regional Greenhouse Climate Effects

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ABSTRACT

We discuss the impact of an increasing greenhouse effect on three aspects of regional climate: droughts, storms and temperature. A continuation of current growth rates of greenhouse gases causes an increase in the frequency and severity of droughts in our climate model simulations, with the greatest impacts in broad regions of the subtropics and middle latitudes. But the greenhouse effect enhances both ends of the hydrologic cycle in the model, i.e., there is an increased frequency of extreme wet situations, as well as increased drought. Model results are shown to imply that increased greenhouse warming will lead to more intense thunderstorms, that is, deeper thunderstorms with greater rainfall. Emanuel has shown that the model results also imply that the greenhouse warming leads to more destructive tropical cyclones. We present updated records of observed temperatures and show that the observations and model results, averaged over the globe and over the United States, are generally consistent. Finally, we quantify recent greenhouse climate forcings, showing, for example, that chlorofluorocarbons have grown to be 25 percent of current increases of the greenhouse effect.

The impacts of simulated climate changes on droughts, storms and temperature provide no evidence that there will be regional "winners" if greenhouse gases continue to increase rapidly.

1. Introduction

We were asked to discuss in this paper regional climate impacts due to an increasing greenhouse effect, with emphasis on North America and the Caribbean. The conventional wisdom is that it is not yet possible to obtain reliable conclusions about regional climate impacts, principally for two reasons. First, the representations of atmospheric and surface processes in current climate models are highly simplified, and the models show a very wide range in their predictions for climate change at any particular region. Second, none of the existing climate models simulates the ocean realistically, and changes in ocean currents could alter regional climate.

These are valid concerns, especially if attention is focused on climate change at some specific time and locale. However, an increasing greenhouse effect undoubtedly implies some broad changes in the nature of regional climate, which it may be possible to investigate with existing modeling capabilities. In section 2 we consider changes of a drought index, defined as the difference between atmospheric supply of moisture and atmospheric demand for moisture. In section 3 we consider the impact of greenhouse warming on atmospheric stability as it affects convective storm intensity on scales from thunderstorms to tropical cyclones. In section 4 we discuss possible impacts of rising temperature itself, and we illustrate global and United States temperature trends. In section 5 we illustrate the magnitude of the 1988 North American and Asian heat waves and discuss the possible relation with the greenhouse effect. In section 6 we quantify recent known greenhouse climate forcings. Finally, in section 7, we summarize our conclusions.

2. Drought

We define a drought index, D, which is a normalized measure of the difference between atmospheric supply of moisture and atmospheric demand for moisture, as follows:

$$D(\text{current month}) = 0.9\ D(\text{previous month}) + d/\sigma$$

$$d = (\text{precipitation} - \text{potential evaporation})_{\text{actual}} - (\text{precipitation} - \text{potential evaporation})_{\text{climatology}}$$

$$\sigma = \text{standard deviation of } d$$

Potential evaporation is the evaporation which occurs if water is available. The ratio d/σ is a dimensionless measure of the precipitation deficit (or excess, if positive) in the current month. The drought index, D, includes a memory of precipitation deficit over preceding months. Note that the drought index continues to yield negative values after evaporation ceases due to lack of available water. It thus provides an indication of stress on vegetation. It is also a relevant measure of reservoir water balance, since there is normally water available for evaporation from a reservoir.

The drought index we have defined is similar to, but simpler than, the Palmer Drought Index[1]. The Palmer Drought Index has many locally defined parameters, which would make it impractical for us to obtain global results. However, we have calculated the Palmer Drought Index for the United States and have verified that the results obtained using it show characteristics of future drought intensification similar to those illustrated below. The factor 0.9 in the definition of D, which implies a time scale for recovery (i.e., a memory) of 9–10 months, is the same as in the Palmer Drought Index. We have tested recovery times as short as 1–3 months, verifying that the results discussed below are qualitatively unchanged.

We have computed the drought index D for some of our computer climate simulations published elsewhere[2]. These simulations were carried out with our global climate model (GCM) which has a global sensitivity 4.2°C for doubled CO_2. Ocean heat transports were assumed to remain the same in the next few decades as estimates for the recent past. Other characteristics and qualifications for these climate simulations have been documented.[2,3]

The drought index obtained for our trace gas scenario A is shown in Figure 1 for June–July–August (Northern Hemisphere summer) of four specific years. The temperature anomalies for the same years, relative to the 100 year control run,[2] are shown for comparison in Figure 2. Scenario A[2] has rapid growth of trace gas emissions, for example, 1.5% per year for CO_2 and 3% per year for CFC's; we describe this scenario as "business as usual", because it may be realistic if there are no controls on trace gas emissions. The color scheme in Figure 1 divides the drought index into categories according to the percent of time that a given drought index occurs in the 100 year control run of the climate model; the control run had 1958 atmospheric composition. The drought index is defined locally, that is, relative to the control run climate at each location. Thus, for example, dry conditions in a rainforest only indicate that it is dry relative to the mean for that location in the control run.

The exact patterns of the drought index and temperature are of course not intended to be forecasts for individual years, because the climate patterns fluctuate almost chaotically on a year to year basis. However, it is meaningful to search for overall trends in the results. In the 1990's there is a tendency for more extensive dry conditions than in the control run. By the 2020's there is no mistaking the great intensification of drought at almost all middle latitude and low latitude land areas. There is also an intensification of wet regions, especially at high latitudes and in the intertropical convergence zone, the latter being the region where the low latitude trade winds of the two hemispheres collide.

A summary of the drought intensification with time is shown in Figure 3 for scenario A, averaged over all land areas except Antarctica. In this figure we define the degrees of dryness intensification which occur 1%, 5% and 16% of the time in the control run as extreme drought, drought, and dry, respectively. Drought conditions, which occur 5% of the time in the control run, have increased to 10% in the 1990's. In scenario A drought conditions continue to increase rapidly, to about 25% in the 2020's and about 45% in the 2050's.

What processes in the model lead to such rapid drought intensification? Of course, the principal factor is the higher surface air temperature, which increases the potential evaporation. More detailed analysis is hampered by the fact that droughts occur in different places in different years and are interspersed with wet periods. Therefore we have sorted model diagnostics according to drought index, which allows us to examine how the drought characteristics change, without concern as to where the droughts occur. We find that the regions with more negative drought index ("dry" regions) tend to warm more than the "wet" regions as the greenhouse warming increases. Several characteristic differences between the dry and wet regions in the control run, specifically reduced rainfall, fewer low clouds and less spring soil moisture in the dry regions, all tend to be further enhanced as the greenhouse warming increases. No doubt low antecedent soil moisture is one factor which helps determine the location of droughts, in part through positive feedbacks such as reduced evaporation and cloud cover. But many other factors, such as atmospheric longwave patterns and ocean temperature distributions, can influence the location and timing of droughts. We emphasize that, even as droughts intensify with a growing greenhouse effect, all of the droughts continue to be "natural", in the sense that their location and timing can be related to antecedent land, atmosphere and ocean conditions.

The qualitative picture which emerges is an intensification of both dry and wet extreme conditions as global temperature increases. A similar result is found for rainfall variability by itself,[4] but the effect is stronger for the drought index because of the effect of warmer temperatures. The fundamental mechanism is increased heating of the surface. In dry regions, where little water is available for evaporation, the increased heating goes mainly into increasing the air temperature, which reduces low-level cloud and thus causes further heating. But over the oceans and land regions which happen to be wet, the added greenhouse heating increases evaporation rates, leading to more intense storms, as discussed below, and to increased rainfall and floods.

Although the increasing drought frequency which we obtain may seem extreme, the changes of the drought index would be even larger if we used the climate parameters obtained by the GFDL

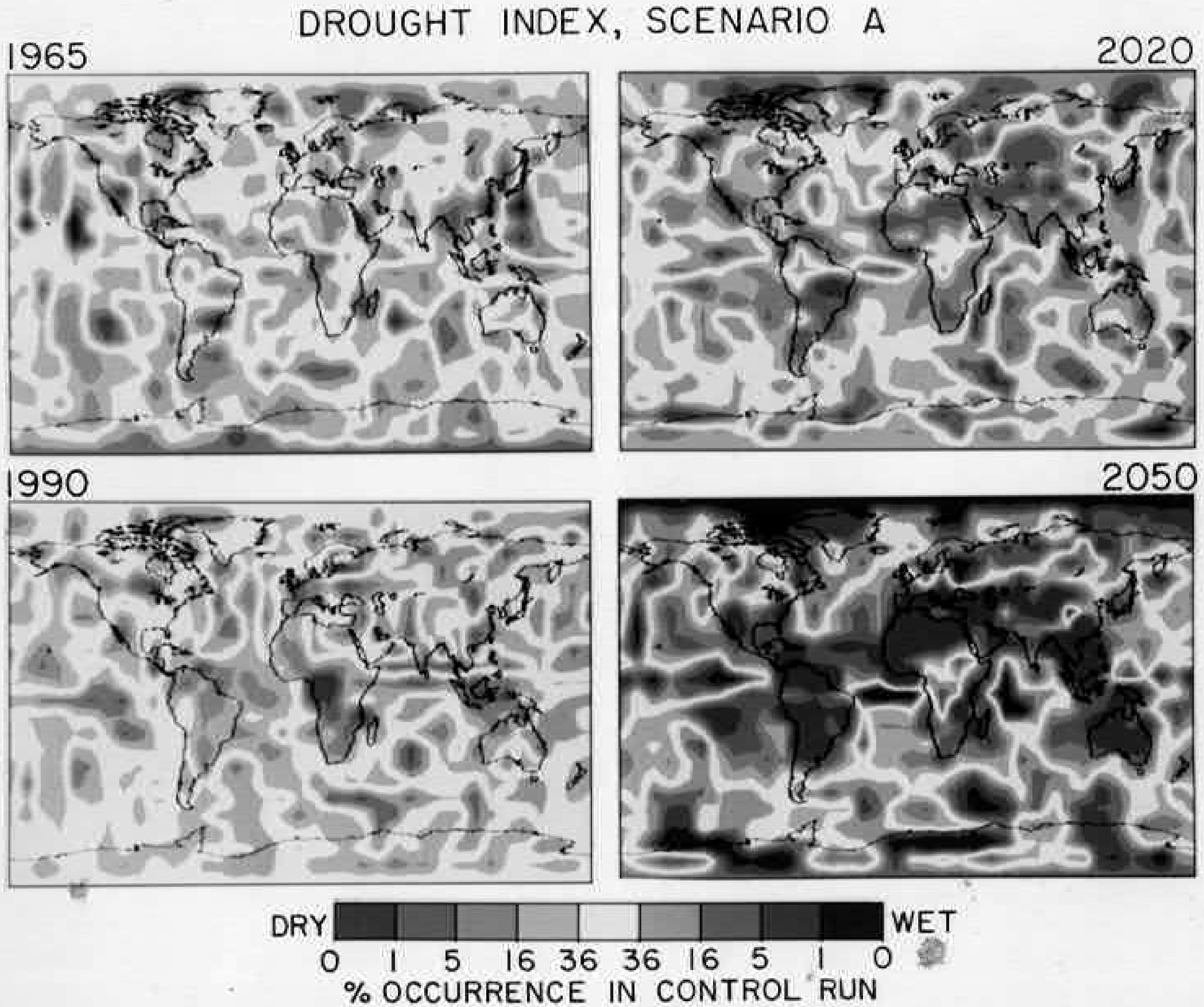


Fig. 1 Drought index for June-July-August in the GISS global climate model simulation for trace gas scenario A. The color scale is set by the frequency of occurrence of a given drought index in the 100 year control run which had 1958 atmospheric composition.

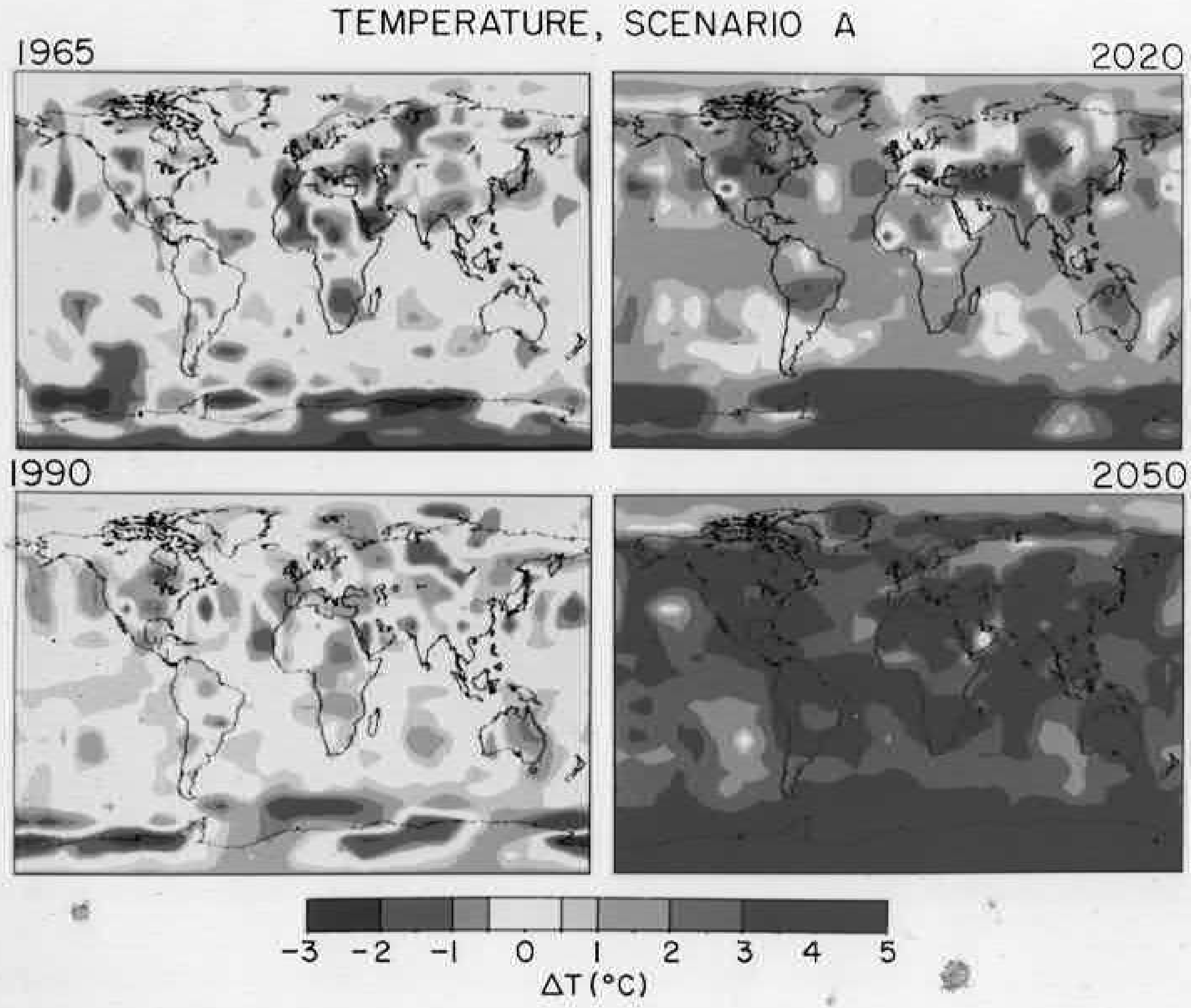


Fig. 2. Temperature change for June-July-August in the GISS global climate model simulation for trace gas scenario A, relative to the 100 year control run which had 1958 atmospheric composition.

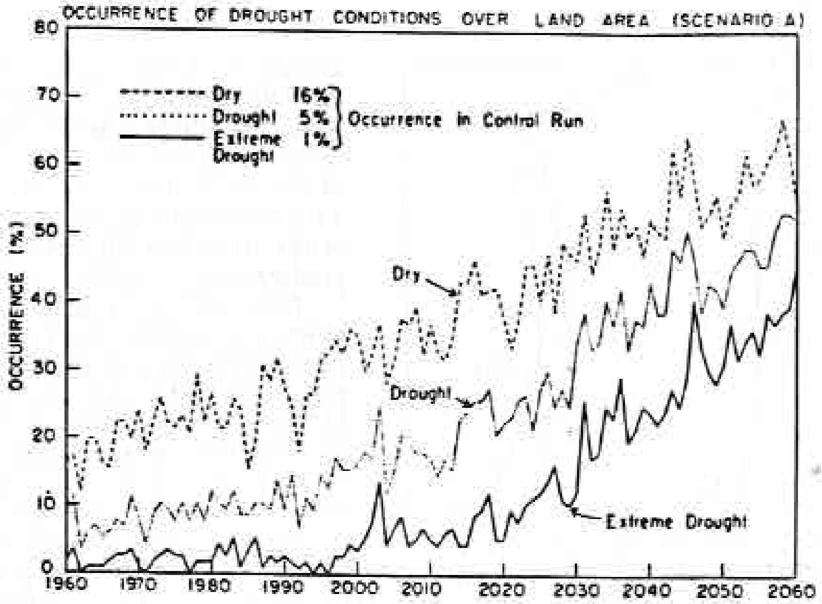


Figure 3. Drought occurrence as a function of time in scenario A. Results are averaged over all gridboxes which are more than 90% land, except that Antarctica is excluded.

(Geophysical Fluid Dynamics Laboratory) model of Manabe and Wetherald[5], because they obtain greater temperature increase and precipitation reduction at middle latitudes than we obtain with our model. The qualitative changes which we obtain in regions of increased drought, e.g., decreased low cloud cover and reduced spring soil moisture, are similar to the results which Manabe and Wetherald obtained for doubled CO_2 in North America and Asia, where their model developed strong drought conditions.

The intensification of both dry and wet extreme conditions is a plausible consequence of the increased surface heating and evaporation. The sense of this result is unlikely to depend upon precise simulation of regional climate patterns or on possible changes in ocean circulation. The magnitude of the effect does depend on regional climate feedbacks, such as decrease of low clouds with increasing drought intensity; this cloud feedback should be analyzed on the basis of global cloud observations. The results may also change somewhat as we improve the realism of the model, for example, by increasing the model's resolution[7,8] and improving the representations of ground hydrology and moist convection, which affect precipitation patterns. But it seems unlikely that such uncertainties will modify the sense of our result, that is, the intensification of both dry and wet extreme conditions.

3. Storms

Storms are generally not resolved by the coarse horizontal resolution of present global climate models. However, models can provide many climate diagnostic parameters which indicate how storm intensity is likely to change with increased greenhouse warming. Some of the specific quantities we have looked at are as follows:

a. Moist static energy

Moist static energy, the sum of sensible heat, latent heat and geopotential energy, is a useful indicator of the likelihood and penetration depth of moist convection. High values of moist static energy near the surface, relative to the air above, and high relative humidity favor deep penetrating convection (e.g., typical thunderstorms). Figure 4 shows the changes in the global mean vertical profile of moist static energy which occur in our transient scenario A and doubled CO_2 simulations. As the greenhouse effect grows, the maximum increase of moist static energy occurs near the surface, because of the higher absolute humidity associated with increased evaporation, and in the upper troposphere, because of the peak in greenhouse warming there. However, the surface moist static energy increase is 2 kJ/kg greater than that at higher altitudes, which represents a 20% enhancement of the lower tropospheric gradient of moist static energy, compared with current climate. Relative humidity changes at low levels are negative but very small in the climate simulations. The implication from these changes is that the warmer climate is prone to deeper, more penetrating convective events. A similar conclusion follows from the results obtained by Wetherald and Manabe[9] in a

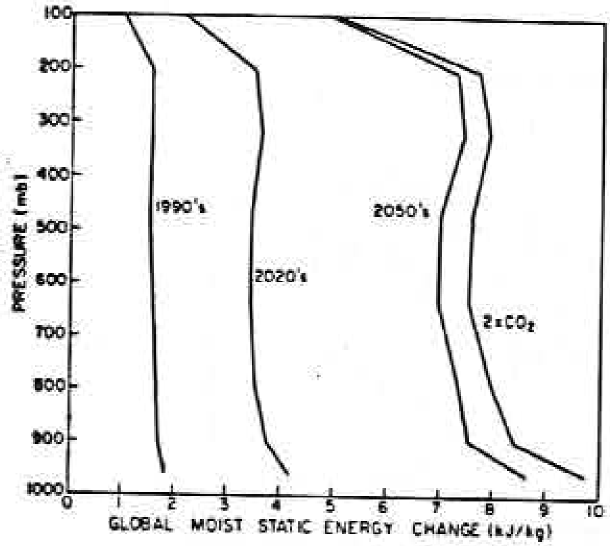


Figure 4. Change of global moist static energy in the doubled CO_2 and transient (scenario A) experiments with the GISS climate model.

GCM with a completely different cumulus parameterization. The tendency of deep convective cloud top heights to increase with increasing sea surface temperature in the tropical Pacific in the current climate[10] is also consistent with this conclusion.

b. Mass flux by moist convection

In our climate simulations the vertical mass exchange due to deep moist convection increases and the mass flux due to shallow convection decreases, consistent with the altered thermodynamic state discussed above. The global average depth of penetration by moist convection increases 20 mb of atmospheric pressure, from $\Delta p = 395$ mb to $\Delta p = 415$ mb, in the doubled CO_2 experiment, and to $\Delta p = 405$ mb by the 2050's in scenario A. The increases are largest near the equator and at middle latitudes. The height of these pressure surfaces increases by several hundred meters as a result of the warming.

c. Precipitation

The increased precipitation in the model, as the climate warms, is almost entirely in the form of moist (penetrating) convection. Changes in large scale (stratiform) rainfall are small, in fact slightly negative, especially at middle latitudes; the latter characteristic is probably a result of reduced synoptic-scale wave activity[11]. Atmospheric heating by moist convection, which is related to precipitation, increases 17% in the doubled CO_2 climate and by 10% by the 2050's in scenario A. These increases are caused by the higher absolute humidity (and latent heat content) of the warmer atmosphere and by the deeper penetration of moist convection, which allows a greater percentage of the latent heat to be released in condensation. Thus thunderstorms are more intense in the model, in the sense that they have higher cloud tops and produce more rainfall for a given mass flux.

Emanuel[6] used a simple Carnot cycle model to estimate the effect of greenhouse warming on the maximum intensity of tropical cyclones, based on the sea surface temperature changes in the doubled CO_2 experiment of the GISS model. Figure 5 shows the resulting minimum sustainable surface pressure which he obtained. With today's climate the minimum sustainable surface pressure is about 880 mb, but this decreases to about 800 mb for the doubled CO_2 climate. The corresponding maximum wind speed increases from about 175 mph to 220 mph. Since the kinetic energy increases with the square of the wind speed, Emanuel estimates that the destructive potential of hurricanes could increase by 40–50% with doubled CO_2.

These quantitative results were obtained for the ocean temperature warmings in the GISS model, which are as large as 4°C. Some other GCMs yield ocean warmings of only 2°C for doubled CO_2, which would imply wind speed increases half as large as those indicated here. Also, note that the maximum potential velocities are obtained in only a small percentage of hurricanes, and that the existing analyses do not permit prediction of the change in storm frequency. Nevertheless, it is obvious that the impact of greenhouse warming on tropical storms would have important implications for the Caribbean, Mexico and parts of the United States coast. And in addition to increased hurricane strength, it seems likely that higher ocean temperatures will lead to an expansion of the region which hurricanes frequent. For example, if the greenhouse warming continues unabated, hurricanes could become common along the entire east coast of the United States in the next century.

The picture that emerges from these diagnostics is an increased intensity of storms which are driven by latent heat of vaporization, both ordinary thunderstorms and mesoscale tropical storms. The basis for this is the increased evaporation and higher temperatures at low levels in the atmosphere, which yield more moist static energy at low levels and greater vertical penetration of moist convection. The magnitudes and detailed spatial and temporal patterns of changes in storms are sensitive to uncertainties in the parameterization of moist convection and other feedback processes in the model. For example, we cannot determine changes in the updraft speed or frequency of storms with the current version of the

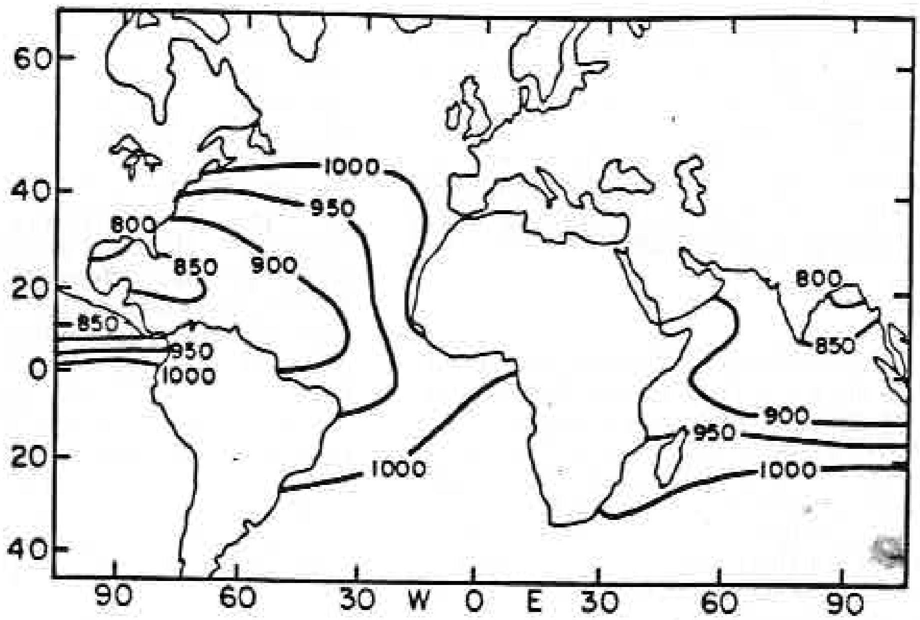


Figure 5. Minimum sustainable surface pressures in August as estimated by Emanuel[6] using sea surface temperatures from the doubled CO_2 experiment with the GISS model.

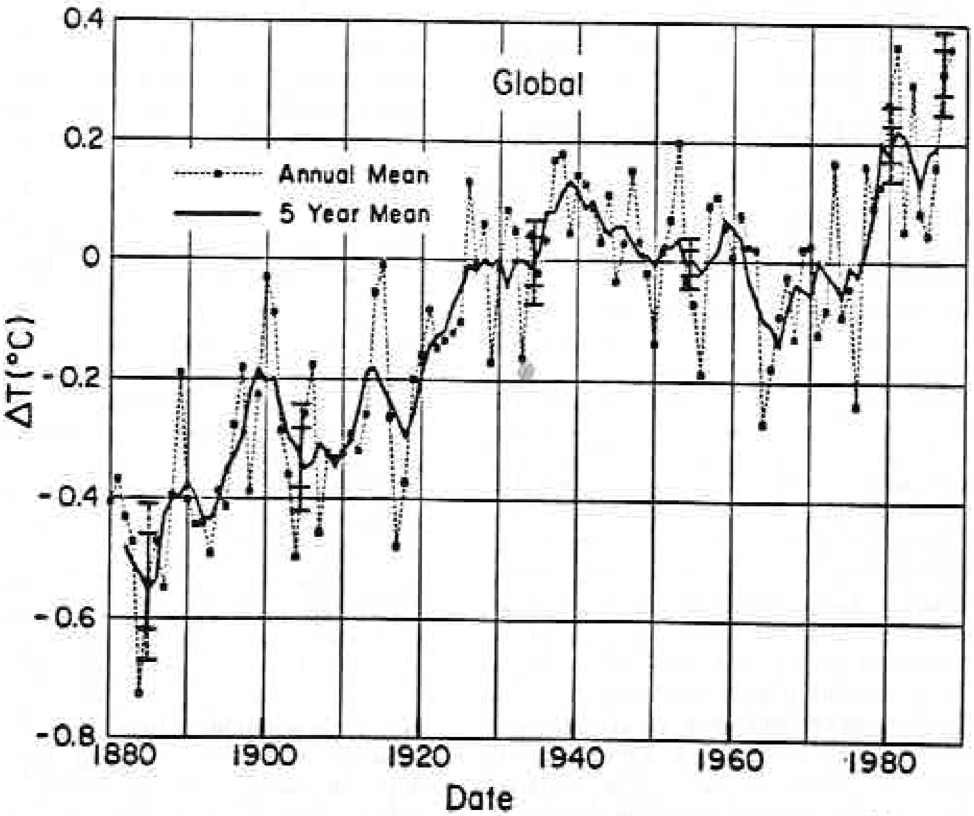


Figure 6. Global surface air temperature change estimated from meteorological station data. Uncertainty bars[13] account only for the incomplete spatial coverage of the stations. The error bar for 1988 is larger than that indicated for 1987, because of poorer station coverage and approximations in the near real time data used for the last several months of the year. Note also that no correction has been made in this figure for urban warming, which is estimated as 0.2°C for the century.

model, nor can we predict the nature of changes in special categories of storms which depend on local wind shear and mingling of different air masses (e.g., squall lines and tornadoes). However, the general nature of those changes we have described is determined largely by the Clausius–Clapeyron equation and is thus a straightforward consequence of fundamental moist thermodynamics.

4. Temperature

We examined elsewhere[2,12] temperature changes forecast by our global climate model for increasing greenhouse gases. In those papers we stressed the importance of a possible increase in the frequency of temperatures above some critical level. For example, we computed the average number of days per year that the simulated temperature exceeds certain limits in specific United States cities. Such quantities have an extremely large year to year variability, so they certainly will not increase smoothly as the world becomes warmer. However, it is meaningful to estimate how the probability of such extreme temperatures may change. For example, our climate model suggests that the probability of a hot summer in most of the United States may increase to 60–70% by the middle 1990's, as compared to 33% in the period 1950–1979 (Figure 6 of reference 2).

The simulated warming in our model is somewhat larger in Canada and smaller in Mexico and the Caribbean, as compared to the United States. But natural climate variability (fluctuations from year to year) also increases with increasing latitude, as illustrated elsewhere[13]. As a result, to a first approximation, the probability of a warm season relative to the local climatology is predicted to increase at a similar rate in these different regions[2].

The impact on the biosphere of increasing temperature will be dramatic at all latitudes, if the results computed for scenario A (rapid growth of trace gases[2]) are realistic. The poleward shift of isotherms by 50 to 75 km per decade in that scenario is faster than most plants and trees are thought to be capable of naturally migrating[14], and thus the warming could cause a decline of many species in North American forests. The productivity of crops which are sensitive to a run of consecutive hot days could suffer also, as indicated by calculations published elsewhere[2,15]. One impact in the Caribbean could be on coral reefs, since many coral populations are unable to survive if water temperatures rise above 30°C[16]. The expected increase in storm intensities, discussed in the section above, would be particularly important in the Caribbean.

Observations of current global temperature change are of special interest, because of the search for a long term warming trend attributable to the greenhouse effect. A preliminary update of the global temperature analysis of Hansen and Lebedeff[13], which uses MCDW (Monthly Climatic Data of the World) data available from NCAR, is shown in Figure 6. The last six months of 1988 are based on NOAA near real time data, adjusted for reporting biases as described elsewhere[17]. The use of these adjusted near real time data for six months affects the global temperature for the full year by at most a few hundredths of a degree. Note that Figure 6 has not been corrected for "urban" effects. As discussed by Hansen and Lebedeff[13] and below, approximately 0.2°C of the global warming in the past century in the MCDW data is estimated to result from urban growth effects.

Figure 6 indicates that 1988, within the error bar of measurement, was the warmest year in the history of instrumental records. Jones *et al.* (private communication) have recently reported that their analysis shows 1988 as the warmest year on record. The annual warmth for the globe in 1988 occurred despite rapid cooling at low latitudes between May and December, which was associated with an unusually strong negative phase of the El Niño cycle[18]. It will be particularly interesting to see whether this cooling of tropical surface air propagates to high latitudes and dominates global temperature trends over coming years. Some scientists have expressed the expectation that this negative El Niño will slow down the greenhouse warming by 30 to 35 years. Global temperature change does have some correlation with El Niños (Figure 3a of reference 17), especially the past two El Niño events, but the correspondence is far from overwhelming. It is a classical confrontation, like the tortoise vs. the hare: how long will it take a "small" global climate forcing to overcome the effects of a large negative El Niño fluctuation? If some recent climate simulations[2] are realistic, it will be at most only a few years before the global temperature records are raised further.

The global temperature record in Figure 6 is the average for all MCDW stations, urban and rural. We illustrated elsewhere[13] that if all stations associated with urban areas of population 100,000 or greater (about one third of the MCDW stations) are eliminated from this record, the global warming is reduced by 0.1°C. Based on studies of how the urban warming varies with population, we estimated that there may be an additional urban effect of about 0.1°C due to smaller cities. Thus we concluded that the warming over the period from the 1880's to the 1980's is reduced from 0.7°C to approximately 0.5°C, if urban effects are removed. Jones *et al.*[19] used an independent labor-intensive procedure to analyze urban effects, comparing nearby stations on a one-by-one basis to try to identify and partially correct for urban bias. After estimation of the remaining urban bias in their data, their result is consistent with ours in indicating a net global warming of approximately 0.5°C in the past century. The 0.5°C global warming is what we and others have used for empirical studies of the greenhouse effect and climate sensitivity[20].

The temperature trend in the United States can be examined in detail, based on comprehensive studies by Karl *et al.*[21,22]. They employ the recently completed Historical Climatology Network (HCN) data for 1219 stations, data which were meticulously scrutinized for biases resulting from such factors as station moves, time of observation changes and instrumental changes. By comparing urban temperature records with those of nearby rural stations, Karl *et al.*[21] obtained empirical relations between population and urban warming. The dependence of urban warming on population which they found is generally consistent with earlier studies, and thus does not modify our estimate of 0.5°C global warming in the past century.

Most of the stations in the Historical Climatology Network are located in sparsely populated regions, over 70% in areas with 1980 population below 10,000. Thus the urban warming which Karl *et al.* found in the raw HCN data was small, amounting to 0.06°C in this century. Here we use the urban-adjusted HCN record, that is, after removal of this urban warming, (1) to estimate the urban warming in the MCDW data for the United States, (2) to examine the United States temperature record for evidence of a trend, and (3) to compare with the results of our global climate model simulations. The HCN record has been updated to include 1985, 1986 and 1987.

Figure 7a compares the urban-adjusted HCN data for the contiguous United States with uncorrected data of Hansen and Lebedeff[13] based on MDCW stations. This comparison suggests that there is an urban warming bias of about 0.13–0.14°C/century in the MCDW data for the United States under the assumption that urban effects are the cause of the difference in the temperature trends. [The linear trend of the urban-adjusted HCN data of Karl *et al.* for the interval 1901–1987 is 0.26°C/century; the Hansen and Lebedeff[13] published data for the contiguous United States have a trend 0.39°C/century; if the Hansen and Lebedeff analysis is repeated using only stations within United States borders, the trend is 0.40°C/century.] Karl and Jones[23] estimated that the urban warming in the Hansen and Lebedeff data for the contiguous United States was close to 0.4°C/century; however, the assumed Hansen and Lebedeff temperature trend (provided by Hansen and Lebedeff) was incorrect, an error having been made in the integration over the contiguous United States. The correct comparison is that shown in Figure 7a. An urban warming of 0.4°C/century also would be inconsistent with the facts that: (1) the Hansen and Lebedeff[13] and Jones *et al.*[24] temperature trends are generally in close agreement (see, e.g., Figure 15 of Hansen and Lebedeff[13]), and (2) both Karl and Jones[23] and Jones *et al.*[24] estimate the urban warming in the Jones *et al.*[24] results to be about 0.1°C or less. These results indicate that urban warming for the United States is not larger than our estimate of 0.2°C for the full globe, despite the fact that per capita energy use in the United States is high and United States cities have experienced large vertical growth, relative to cities in the remainder of the world. Oke[25] and others have shown that, except perhaps for population and energy use, the most important factor in urban warming is the reduction of the skyview factor by vertical growth of the cities. Although indications are that urban effects do not qualitatively modify estimated global temperature trends, it is clearly important to carry out much more comprehensive analyses of the urban effects, as needed to provide optimum estimates of unbiased temperature change.

Figure 7b shows the HCN data for the contiguous United States (48 states) for the period 1901–1987. The linear trend of HCN data is 0.26°C/century. [The change from the trend reported by Karl and Jones[23] (0.16°C/84 years or 0.19°C/century) is due to the addition of data for 1985–87.] If ΔT were a linear function of time and the deviations from the straight line were normally distributed, it could be stated with 90% confidence that the slope of the temperature trend is positive, i.e., that there is a warming trend. But this confidence interval should not be taken literally because of inherent errors in these assumptions.

Figure 7c shows the Climatic Division (CD) data for the contiguous United States for 1901–1987, recently reported by Hanson *et al.*[26] The CD data are from 6,000 stations, including second order and cooperating stations. The small cooling bias on the CD data relative to the HCN data, about 0.1°C, may be a result of incomplete correction for time of observation bias in the CD data, which is known to introduce spurious cooling[21]. In any case, the HCN data, which have undergone elaborate station-by-station scrutiny, are the most reliable record of temperatures in the United States.

Figure 7d shows temperatures for the entire United States (50 states) for the period 1901–1987. This is the area-weighted average of the HCN data for 48 states and MCDW data for Alaska and Hawaii. The Alaska and Hawaii data are based on MCDW records for only stations associated with population centers of less than 5,000. The linear trend for United States temperatures is 0.33°C/century. The mathematical confidence (as defined above) that the slope

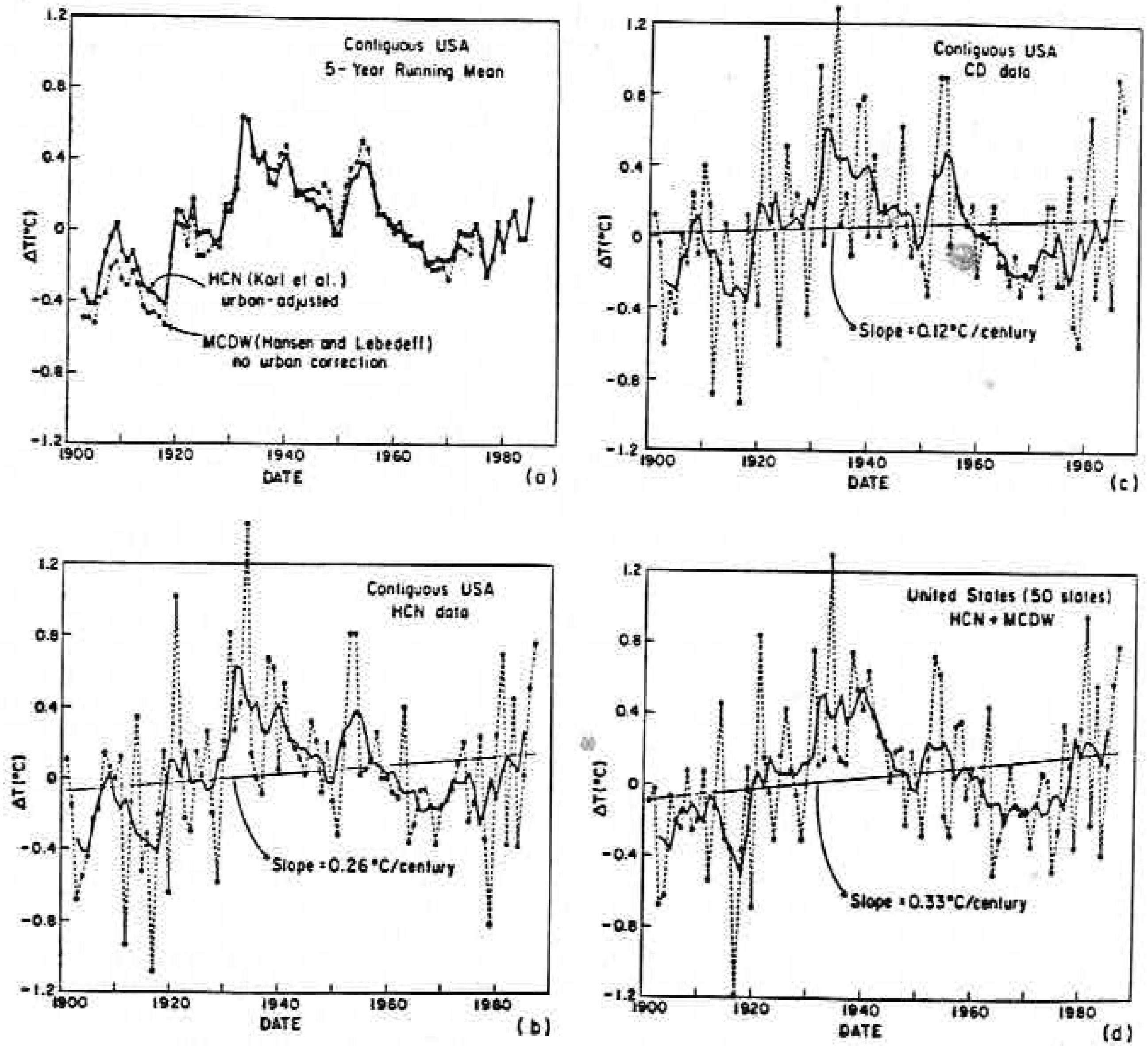


Figure 7. (a) Comparison of urban-adjusted Historical Climatology Network (HCN) temperatures for the contiguous United States and uncorrected Monthly Climatic Data of the World (MCDW) temperatures for the same region; both curves are 5-year running means. (b) Annual urban-adjusted HCN temperatures (Karl *et al.*) for the contiguous United States with linear trend. Data of Karl *et al.*[22] are updated with results for 1985, 1986 and 1987. (c) Annual Climatic Division (CD) temperatures (Hanson *et al.*[26]) for the contiguous United States with linear trend. (d) Temperature for the full United States (50 states). Contiguous United States data are from urban-adjusted HCN record; Alaska and Hawaii are based on MCDW stations associated with population centers of less than 5,000.

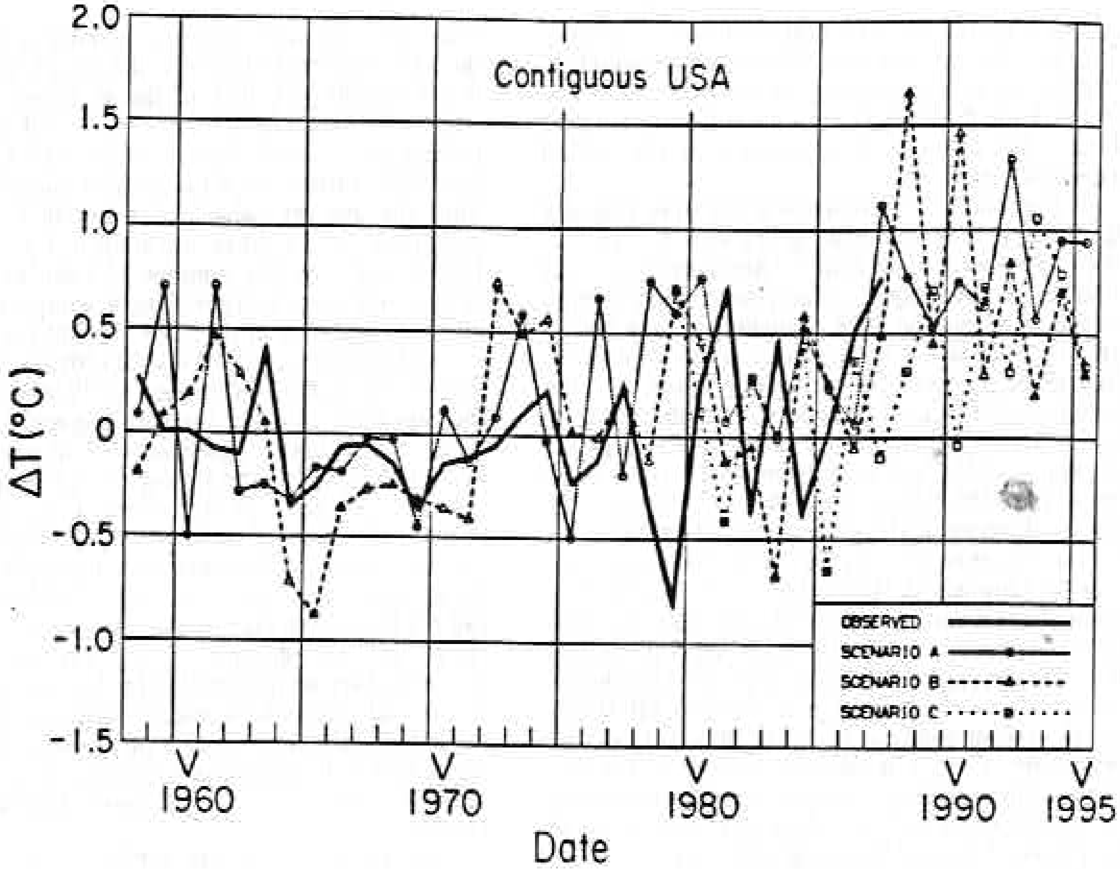


Figure 8. Surface air temperature for the contiguous United States as simulated by a global climate model for three trace gas scenarios,[2] compared with the urban-adjusted HCN (Karl *et al.*) temperature record.

of the temperature trend is positive is 97%.

The contiguous United States is less than 1.5% of the area of the globe. The entire United States is less than 2% of the globe. The natural variability of temperature for such a small area is so great that any long term change must be quite large before it can be definitely identified. That, of course, is why one seeks evidence of a greenhouse warming trend first in the global mean temperature, which has less natural variability.

The temperature trend in the United States is positive, consistent with long-term warming. As expected, the variability is too great to permit United States temperatures to be used as proof of a long term climate change. But, contrary to recent reports in the popular press, the United States temperatures do not provide a basis for questioning the reality of the global warming trend.

Finally, the HCN data is compared in Figure 8 with the surface air temperatures obtained for the United States in the three transient climate simulations with the GISS model[2]. There is warming at the end of the 30 year period in both the model and observations, but it is small compared to the natural variability. The model results indicate a clear tendency toward warming beginning in the late 1980's, but it is too early to determine whether the observations bear this out.

We conclude that there is no basic inconsistency between the model results and the observations of United States temperatures. If the model predictions for the 1990's prove to be realistic, it implies a substantial climate change, to a warmth at least comparable to that of the 1930's. That mean level of warmth remains somewhat smaller than maximum interannual fluctuations, so not every season would be warmer than normal. But it would represent a sufficient "loading" of the climate "dice" to be clearly noticeable.

5. Summer of '88

The summer of 1988 was warm and dry in much of the United States and Asia. The global context of recent temperature anomalies is given by Figures 10 and 11, which, respectively, show the temperature anomalies for the past four years and the four seasons of 1988. In the summer (June–July–August) of 1988 the mean temperature anomaly for the contiguous United States was about +1°C, but it was about +3°C in the hottest region near the United States–Canada border.

Is it possible that greenhouse warming played a significant role in the heat waves and droughts of 1988? Trenberth *et al.* state[27] "Any greenhouse gas effects may have slightly exacerbated these overall conditions during the 1988 drought, but they almost certainly were not a fundamental cause." Manabe, although he has been the principal proponent of the likelihood of increased drought with doubled carbon dioxide, stated[28] that, in view of the fact that global warming of 0.5°C in the past century was so small compared to the 4°C warming in his doubled carbon dioxide experiment, the greenhouse effect had "only a minor role, at most, compared to natural variability".

That rationale is reasonable. The natural variability of precipitation is even greater than the variability of temperature. On the other hand, the results illustrated in Figure 3 suggest that the greenhouse mechanism may be beginning to compete effectively with natural variability at about the present time, i.e., there begins to be a noticeable increase in the frequency of drought in the model. And the increasing greenhouse effect certainly does not have to cause changes which exceed the range of natural variability in order to have important consequences.

It should also be realized that some of the excursions of "natural variability" may be associated with global or large scale climate forcings. The great droughts of the 1930's came at a time of global warmth. That degree of global warmth could have arisen from purely internal fluctuations of the climate system. Our GCM produces similar long term variations in the absence of greenhouse forcing increases.[2] On the other hand, it is also possible that the warmth of the 1930's was related to global forcings, such as the net effect of the near absence of volcanic eruptions in the period 1910–1940, the growth of greenhouse gases in that period, and perhaps other factors such as change of solar irradiance. In any event, the Northern Hemisphere was very warm in the 1930's, and the present Northern Hemisphere temperature seems to be approaching a similar degree of warmth. This is another reason to be concerned about a possible relationship between large scale warming and drought.

We have examined the summer climate changes in our transient scenario A for the period 1986–1995, in comparison with the 100 year control run. For all gridboxes which are more than 90% land between the equator and 55°N (the region where the drought index increases most, see Figure 1) by the period 1986–1995 the mean summer warming is 0.7°C. For the same region and decade the temperature in the driest regions (the 10% of the gridboxes with most negative drought index) has increased about 1°C relative to the driest regions in the control run, to a level 3°C warmer than the control run climatology. Thus the average calculated warming is similar in magnitude to the mean warming in the contiguous United States in the summer of 1988, and the calculated warming in dry regions is comparable to the observed warming in the 1988 drought region.

Although these model results provide no information on the pattern of drought in 1988, they suggest the possibility that the increasing greenhouse effect could already play a significant role in summer heat. We emphasize that the timing and geographical distribution of any specific drought is determined primarily by short-term meteorological fluctuations and antecedent land, ocean and atmospheric conditions. The occurrence or intensity of a single drought can not be used to identify the role of the greenhouse effect in the drought. At the same time, determination of meteorological factors involved in any drought can not be used to disprove the role of the greenhouse effect; such a meteorological analysis provides no information as to whether the greenhouse effect is increasing the frequency and severity of droughts.

We are analyzing the results of our transient climate simulations in greater detail, but there are severe limitations on the information which can be extracted from the model with its present resolution and representation of physical processes. Thus our main effort is now in constructing the next version of the climate model, which will include higher resolution and improved representations of ground hydrology, moist convection and other processes. This should make it possible to do a more thorough analysis of the greenhouse role in summer heat waves and drought.

6. Greenhouse climate forcings

It is possible to make a reasonably accurate comparison of the global radiative forcings due to most of the greenhouse gases that man is presently adding to the earth's atmosphere. Table 1 lists trends of known greenhouse gases during the 1980's and the calculated climate forcing, ΔT_o, due to each gas. ΔT_o is the surface temperature change at equilibrium ($t \rightarrow \infty$) with no climate feedbacks included, computed with a one-dimensional radiative-convective climate model. Uncertainties of decadal trace gas abundance changes are typically less than 10% for the major species. Uncertainties of individual infrared absorption coefficients (Table 1) are larger than that, but averaged over all the greenhouse gases the uncertainty

Table 1. Global mean radiative forcing of the climate system (ΔT_o) due to estimated changes of several trace gases during the 1980's. CFC growth rates are based on UNEP 1989 compilation (a) and on Ramanathan *et al.*[30] estimates (b). Absorption coefficients used to compute ΔT_o were obtained from published laboratory measurements (P), unpublished laboratory measurements (U), and estimates scaled from other published data (E).

	ΔT_o (°C)	Growth Rate (%/year)	Estimated Abundance 1980	1990	Remarks
CCl_2F_2 (F12)	.0143	4.5	297	468	a, P
CCl_3F (F11)	.0067	4.6	173	275	a, P
CCl_2FCClF_2 (F113)	.0042	12.1	15	52	a, P
$CHClF_2$ (F22)	.0032	7.1	58	110	a, U
CF_4 (F14)	.0009	2.5	70	90	b, P
$CClF_2CClF_2$ (F114)	.0004	6.7	4	7	a, P
CCl_4	.0004	1.0	95	105	a, P
$CClF_3$ (F13)	.0004	4.3	7	11	b, E
CF_3CF_2Cl (F115)	.0003	8.5	2	5	a, E
CH_3CCl_3	.0003	4.7	140	225	a, E
CCH_2CCl_2	.0002	3.8	30	44	b, P
CH_2ClCH_2Cl	.0002	2.4	30	38	b, E
C_2F_6 (F116)	.0001	3.2	4	5.5	b, E
$CHCl_3$	.0001	2.2	10	12.5	b, P

in the net climate forcing due to inaccuracies of the absorption coefficient data is probably of the order of 10%.

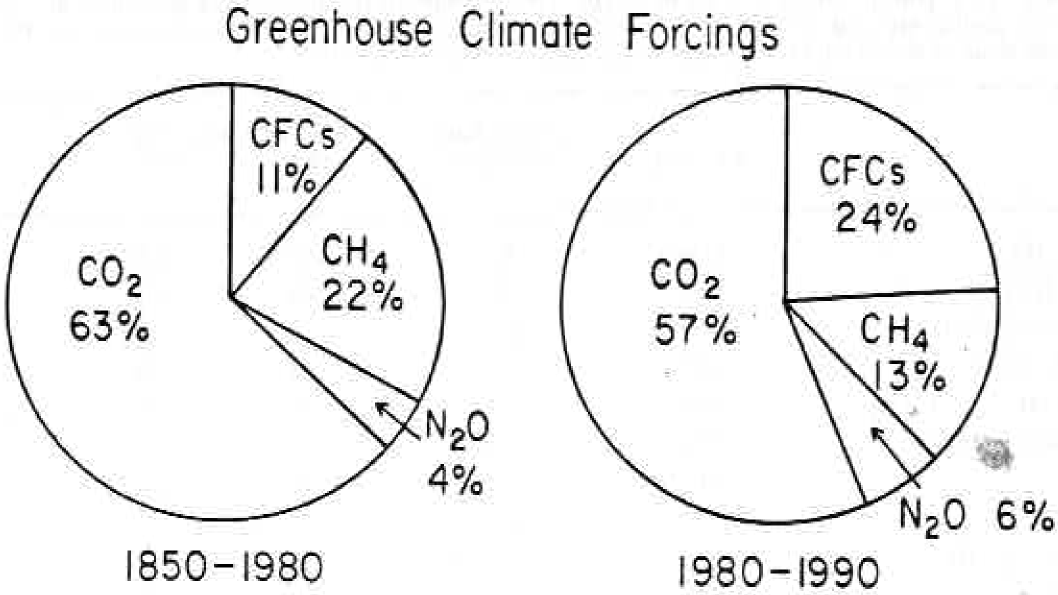
As summarized in Figure 9, CO_2 continues to be the dominant greenhouse gas in the 1980's, accounting for more than half of the net greenhouse effect due to those gases for which measurements are available. However, CFCs now account for one quarter of the current growth of the greenhouse effect. Until constraints were placed on CFC production in the early and middle 1970's, the growth rates of emissions of the principal CFC's were more than 10 percent per year. If CFC growth had continued unchecked, by this time the greenhouse effect of increasing CFCs would probably have exceeded that of CO_2.

There is one potentially important greenhouse gas, ozone, for which present measurements are inadequate to allow reliable greenhouse computations. There is evidence for stratospheric ozone loss and tropospheric ozone increases; both of these changes would lead to surface heating[29]. But ozone molecules in the upper troposphere are the most effective in influencing surface temperature. Very few measurements are available for that altitude range, and those measurements which do exist suggest an ozone decrease and thus a surface cooling,[29] especially at high latitudes. However, the net greenhouse effect of present changes in ozone is impossible to judge reliably without better observations.

7. Summary

Our climate simulations indicate that an increasing greenhouse effect causes an intensification of the extremes of the hydrologic cycle: (1) greater frequency (or areal coverage) and intensity of drought, and (2) more intense wet and stormy conditions. These general conclusions are not per se dependent on the accuracy of the climate model for specific regions, because the analysis avoids the need to predict exactly where the changes occur.

We find no evidence of regional climate "winners" with an increasing greenhouse effect. Droughts increase in the model at essentially all low latitude and middle latitude land areas, where almost all the world's population is located. Although annual precipitation increases at most locations in response to the global warming, the added rainfall occurs in intense (moist convective) events, not as gentle large scale rainfall, implying the likelihood of an increased frequency of flooding. Furthermore, our model results imply that an increased greenhouse effect will lead to



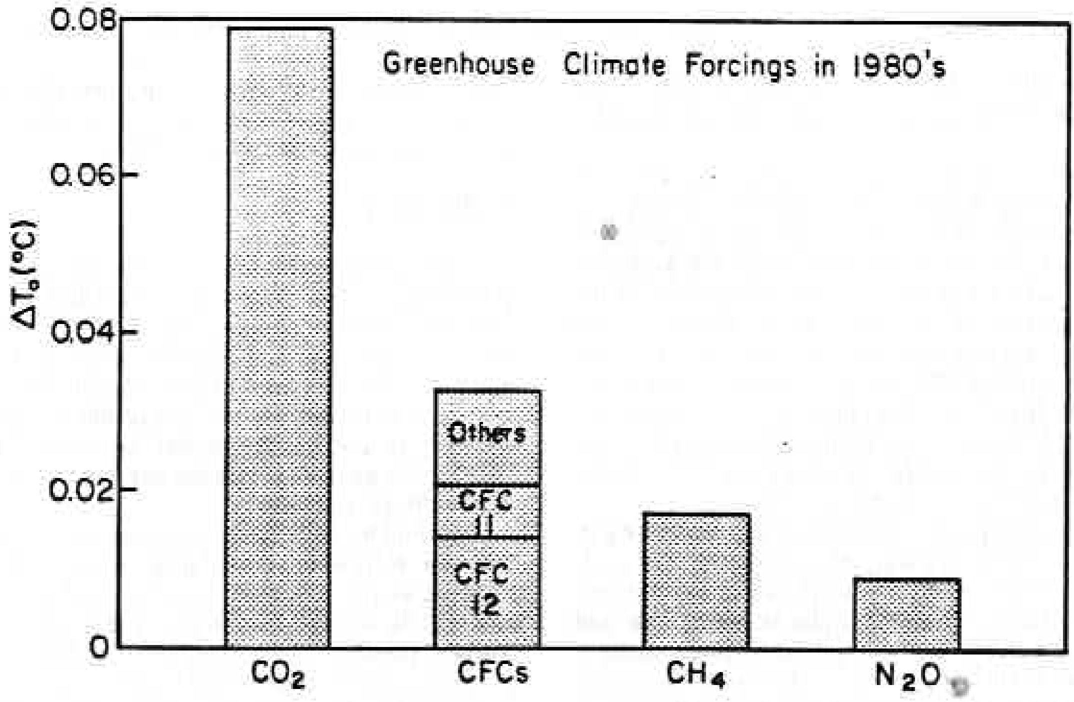


Figure 9. Global mean radiative forcing of the climate system due to estimated changes of trace gases (see Table 1). (a) Relative contributions of greenhouse gases to the total greenhouse climate forcing for two time periods. It is assumed that the 1850 abundances were: CO_2 (285 ppm), CH_4 (0.8 ppm), N_2O (0.285 ppm), CFCs(0). (b) Radiative forcings in the 1980's. The climate system response to this forcing involves many feedback processes, some of which are poorly understood; current global climate models suggest that the global temperature response at equilibrium is about 2–3 times larger than the global radiative forcing.

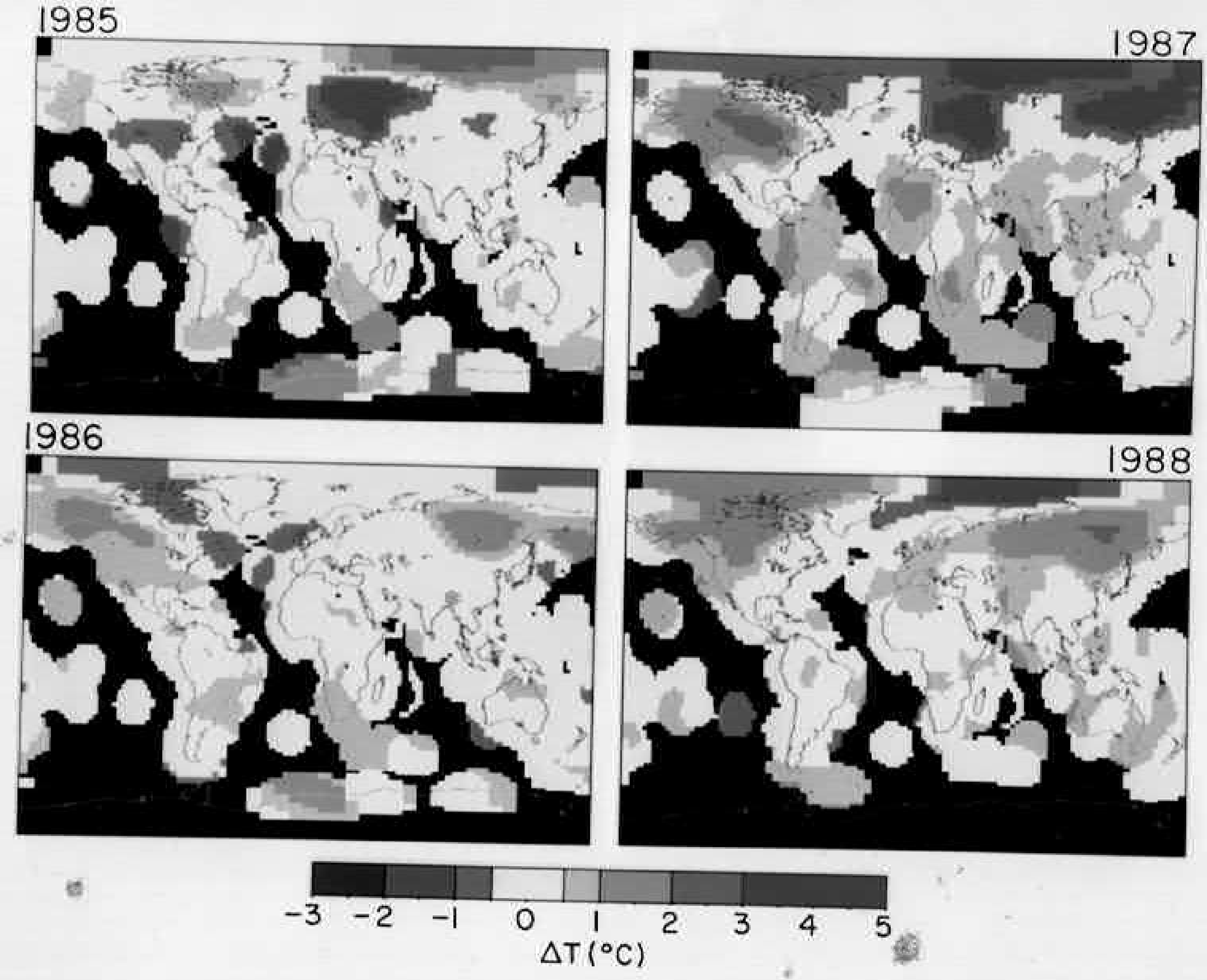


Fig. 10. Annual mean surface air temperature in 1985, 1986, 1987 and 1988. The zero point for each location is the 1951-1980 mean.

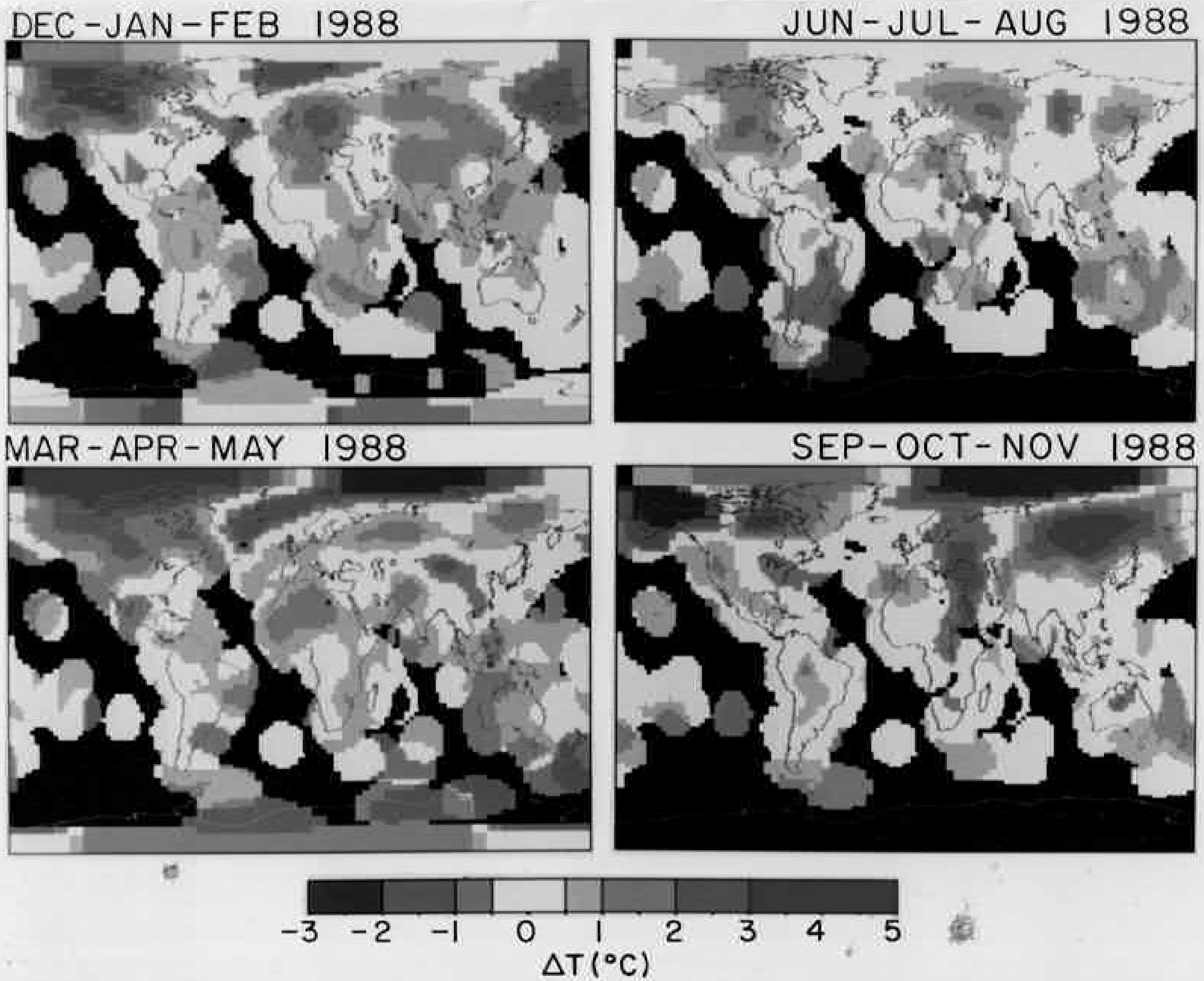


Fig. 11. Seasonal mean surface air temperature for the four seasons from December 1987 through November 1988. The zero point for each period and location is the 1951-1980 mean.

more intense thunderstorms and tropical cyclones. Temperature increases may be considered to be beneficial in some regions, but the predicted rates of temperature change are much greater than those to which the biosphere has adapted in the past. And a principal anticipated impact of higher temperature is a rising sea level, as a result of thermal expansion of the oceans and melting of land ice. None of these major impacts of a rapidly increasing greenhouse effect appears to produce a substantial number of "winners."

The rapid increase of drought intensity in our climate model, which begins at about the present time, is of particular concern. Is it possible that regional droughts could become substantially more frequent, in effect a near-term severe local manifestation of the greenhouse effect, analogous to the Antarctic "hole" of ozone depletion? Recent events provide little guidance. A single drought cannot be used to either prove or disprove a role of greenhouse warming. Concurrent and antecedent meteorological factors, such as jet stream, soil moisture, and ocean temperature distributions, provide "causes" of every specific drought pattern and timing, but they are irrelevant to the issue of whether greenhouse warming increases the frequency and coverage of drought.

Empirical verification of the major effects of greenhouse warming may require observations over 10 or 20 years. Analyses would be aided if global models were improved so as to provide more specific predictions of regional climate effects. As far as droughts are concerned, we can only state at this time that our model suggests that greenhouse warming may have its biggest impacts in certain regions in the subtropics and middle latitudes, such as, in the Northern Hemisphere: United States/Mexico/southern Canada, southern Europe/Mediterranean region, middle latitudes and lower latitudes of Asia, and the African Sahel; and, in the Southern Hemisphere: Australia, the southern quarter of Africa, and parts of Brazil and Argentina. But in analyzing observed drought trends it will be important to account for other anthropogenic effects, such as destruction of vegetation cover in semi-arid regions like the Sahel, which could be as important or more important in disrupting regional climate.

Current climate models are inadequate for detailed, reliable predictions of greenhouse climate impacts in any specific region. Improved investigation of regional climate impacts will depend upon (1) studies based on models with higher spatial resolution, and, especially, more realistic representation of key aspects of the "physics," such as moist convection, clouds, ground hydrology, and vegetation effects, and (2) global observations which permit analysis of key feedback parameters, such as cloud clover, soil moisture levels, vegetation cover, and atmospheric water vapor profiles. Of course, prediction of long range climate change will also require improved knowledge of many global factors[2], principal ones being global climate sensitivity, the rate of heat uptake and transport by the ocean, and future trends of various climate forcings.

But there appears to be little chance that the uncertainties in climate simulations can qualitatively change our principal conclusion, that a growing greenhouse effect will increase the frequency and severity of the extremes of the hydrologic cycle: droughts, on the one hand, and extreme wetness and storms, on the other. If global climate sensitivity proves to be near the lower end of the range which is considered plausible, the magnitude of the simulated effects would be reduced and the time when the impacts clearly exceed natural variability probably would be delayed, but the impacts would not be reduced to negligible proportions. Similarly, although there are major uncertainties about ocean circulation and mixing which could modify regional climate distributions, they would not remove the mechanisms which cause increased hydrologic extremes. The potential for sudden changes in ocean circulation, which cannot be modeled presently, must be recognized, but any such lurches in ocean circulation would only increase regional climate dislocations.

Given our present knowledge of the climate system, and the uncertainties accompanying any climate predictions, we believe that it is appropriate to encourage those steps which would reduce the rate of growth of the greenhouse gases and which would make good policy independent of the climate change issue. Specific examples are: phase out chorofluorocarbons (which have been implicated in the destruction of stratospheric ozone, and which represent 25% of current increases in greenhouse climate forcing), encourage energy efficiency (improving balance of payments and energy independence), and discourage deforestation (preserving natural resources for sustainable use and the habitat of invaluable biological species).

The opinions expressed in this paper are those of the authors, and are not meant to represent policy of NASA or NOAA.

Acknowledgements. We thank Peter Stone and Mark Handel for useful comments on this paper, Patrice Palmer for helping produce the color figures, Jose Mendoza and Lilly DelValle for drafting other figures, and Elizabeth Devine for desktop typesetting. This work has been supported by the NASA Climate Program and EPA grant R812962-01-0.

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