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REVIEW

Environmental effects of increased atmospheric carbon dioxide

Willie Soon[1,*], Sallie L. Baliunas[1], Arthur B. Robinson[2], Zachary W. Robinson[2]

[1]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138, USA
[2]Oregon Institute of Science and Medicine, 2251 Dick George Road, Cave Junction, Oregon 97523, USA

ABSTRACT: A review of the literature concerning the environmental consequences of increased levels of atmospheric carbon dioxide leads to the conclusion that increases during the 20th century have produced no deleterious effects upon global climate or temperature. Increased carbon dioxide has, however, markedly increased plant growth rates as inferred from numerous laboratory and field experiments. There is no clear evidence, nor unique attribution, of the global effects of anthropogenic CO_2 on climate. Meaningful integrated assessments of the environmental impacts of anthropogenic CO_2 are not yet possible because model estimates of global and regional climate changes on interannual, decadal and centennial time scales remain highly uncertain.

KEY WORDS: Global warming · Carbon dioxide · Atmospheric and biological effects

1. INTRODUCTION

Increases in minor greenhouse gases (GHGs) are hypothesized to cause large increases in surface and lower atmospheric temperatures on the basis of computer climate modeling, a branch of science still in its infancy despite recent substantial strides in knowledge. Their potential climatological impacts have been studied using a variety of computer simulations, from simple 1-dimensional models to complex 3-dimensional, coupled ocean-atmosphere general circulation models (GCMs). The credibility of the calculations rests on the validity of the models. The only way to evaluate the models is to compare their predictions of current and past conditions to available climate information and look for consistencies or inconsistencies with relevant, observed climate parameters, which ideally should be accurately measured. Although the models intrinsically have heuristic power, that fact does not guarantee accurate retrodiction and prediction. Hence, it is important to test the hypothesis that a significantly increased atmospheric CO_2 causes significant global climatic warming and associated impacts.

We study 2 aspects of the consequences, realized and potential, of increased and increasing atmospheric CO_2.[1] One is the climatic response to increases in atmospheric CO_2 concentration; the other is the response of plants to increases in the air's CO_2 content. We review aspects of observed climatic parameters and compare them to retrodictions of the climate models. Our purpose is to assess the credibility of the models by comparing model outcomes to real-world observations. The parameter selection we use is hardly exhaustive, and focuses on parameters that highlight the weaknesses of the models, from which progress might be made. In particular, we chose global and regional surface and lower tropospheric temperatures, regional storms (i.e. Atlantic hurricanes, as a representation of the ocean-atmosphere interaction) and sea level change (because it is coupled to temperature changes through sea-ice interaction). We also discuss early attempts to integrate the highly complex climatic

*E-mail: wsoon@cfa.harvard.edu

[1]For the purposes of discussion in this paper, we will use carbon dioxide as a surrogate for itself and the other minor GHGs that have been associated with the global warming hypothesis. Greenhouse warming models usually assume that the input of all the minor GHGs produces an effect roughly twice that of CO_2 alone

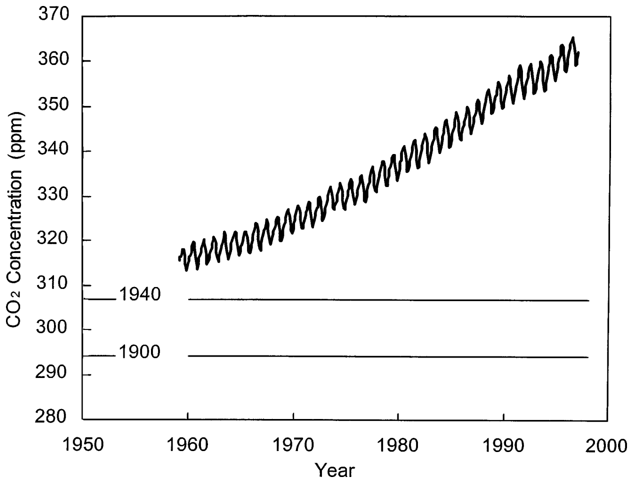

Fig. 1. Atmospheric CO_2 concentration in parts per million by volume (ppm) at Mauna Loa, Hawaii (Keeling & Whorf 1997). The approximate global levels of atmospheric CO_2 in 1900 and 1940 are also displayed (Idso 1989)

feedbacks associated with the biosphere into general circulation models (e.g. Henderson-Sellers et al. 1996).

The second main consequence of increased atmospheric CO_2 that we discuss is the hypothesis that plant growth is enhanced under high CO_2 concentrations, i.e. that elevated atmospheric CO_2 concentrations increase plant growth rates, biomass and yield. This hypothesis is tested against experimental laboratory and field results; again, rather than be exhaustive, we show a few specific examples of vegetation responses to increased atmospheric CO_2.

2. ATMOSPHERIC CARBON DIOXIDE

The concentration of CO_2 in Earth's atmosphere has increased during the past century, as shown in Fig. 1 (Keeling & Whorf 1997). Solid horizontal lines show the levels that prevailed in 1900 and 1940 (Idso 1989). The magnitude of this atmospheric increase during the 1980s was about 3 gigatons of carbon (Gt C) per year. Total annual human CO_2 emissions—primarily from the use of coal, oil, natural gas and the production of cement—estimated for 1996 are 6.52 Gt C (Marland et al. 1999).

To put these values in perspective, it is estimated that the atmosphere contains 750 Gt C; the surface ocean contains 1000 Gt C; vegetation, soils, and detritus contain 2200 Gt C; and the intermediate and deep oceans contain 38000 Gt C. Each year, the surface ocean and atmosphere exchange an estimated 90 Gt C; vegetation and the atmosphere, 60 Gt C; the marine biota and the surface ocean, 50 Gt C; and the surface ocean and the intermediate and deep oceans, 100 Gt C (Schimel 1995).

So great are the magnitudes of these reservoirs, the rates of exchange between them, and the uncertainties with which these numbers are estimated, that the source of the recent rise in atmospheric CO_2 has not been determined with certainty (e.g. Houghton et al. 1998, Keeling et al. 1998, Peng et al. 1998, Segalstad 1998). Atmospheric concentrations of CO_2 are reported to have varied widely over geologic time, with peaks, according to some estimates, some 20-fold higher than at present and troughs at approximately 18th century levels (Berner 1997).

There is, however, a widely believed hypothesis that the 3 Gt C yr^{-1} rise in atmospheric CO_2 is the result of the release of CO_2 from human activities. This hypothesis is reasonable, since the magnitudes of human release and atmospheric rise are comparable, and the atmospheric rise has occurred contemporaneously with the increase in production of CO_2 from human activities since the Industrial Revolution. Atmospheric CO_2 levels have increased substantially during the past century, and are expected to continue to do so.

However, the factors that influence the atmospheric CO_2 concentration are not fully understood. For example, the current increase in CO_2 follows a 300 yr warming trend, during which surface and atmospheric temperatures have been recovering from the global chill of the Little Ice Age (see below). The observed increases in the atmospheric concentration of CO_2 are of a magnitude that can, for example, be explained by oceans giving off gases naturally as temperatures rise (Dettinger & Ghil 1998, Segalstad 1998). Indeed, changes in atmospheric CO_2 have shown a tendency to follow rather than lead global temperature changes (Kuo et al. 1990, Priem 1997, Dettinger & Ghil 1998, Fischer et al. 1999, Indermühle et al. 1999). Those studies emphasize the need to understand changes in terrestrial biomass and sea surface temperature, 2 important drivers of change in atmospheric CO_2 concentration. Thus, understanding the carbon budget is a prerequisite for estimating future atmospheric CO_2 concentration scenarios.

3. ATMOSPHERIC AND SURFACE TEMPERATURES

What effect is the ongoing rise in the air's CO_2 content having upon global temperature? In order to answer this question, one must consider the available temperature information and its qualifications. The temperature of the Earth varies naturally over a wide range, but available temperature records are spatially and temporally limited. Records going back longer than 350 yr are reconstructed from proxies. A recent reconstruction of northern hemisphere temperature from several sites yields a record going back 1000 yr

(Mann et al. 1999). That reconstruction is based primarily on tree ring width and density, which are primarily indicators of summer temperature. The record has varied over a range of no more than 1°C in the hemispheric average. There are important limitations to the interpretation of the proxy temperature. For example, Briffa et al. (1998) find tree width and density have become less sensitive to recent changes in temperature (see their Fig. 6) over the last few decades.

Going back further means having less global information. Fig. 2, for example, summarizes sea surface temperature reconstructed from oxygen isotopes in the shells of *Globigerinoides ruber* in sedimentary deposits in the Sargasso Sea during the past 3000 yr (Keigwin 1996). Sea surface temperatures at this location have varied over a range of about 3.6°C during the past 3000 yr.

Both Mann et al.'s (1999) more widely sampled and Keigwin's (1996) local reconstructions display a long-term cooling trend that ends late in the 19th century. Two noticeable features in the Keigwin record are the Little Ice Age about 300 yr ago and the Medieval Climate Optimum about 1000 yr ago. During the Medieval Climate Optimum, temperatures were warm enough to allow the colonization of Greenland. The colonies were abandoned after the onset of colder temperatures, however, and for the past 300 yr, world temperatures have been gradually recovering (Lamb 1982, Grove 1996). According to Grove (1996), the glacial record maintains significant and coherent cooling over all continents, in agreement with the Bradley & Jones (1993) reconstruction for the Northern Hemisphere. Thus, the evidence is that the Little Ice Age was at least a hemispheric-scale, if not global-scale, event. On the matter of the Medieval Climate Optimum, several lines of evidence point to warm temperatures roughly around 1000 yr BP (before present). The evidence includes montane glaciers, glacial moraines, tree ring and width growth, shell sediments and historical documentation, indicating fairly widespread, although not strongly synchronized, warmth. For example, in China and Japan the warming ended by 900 yr BP, while in Europe and North America the warming continued for 2 or 3 more centuries (Lamb 1982, Grove & Switsur 1994, Hughes & Diaz 1994, Keigwin 1996, Grove 1996). The decreasing trend in reconstructed temperature of the northern hemisphere (Mann et al. 1999) is consistent with the erosion in climate on hemispheric scales, from 1000 yr BP through the Little Ice Age.

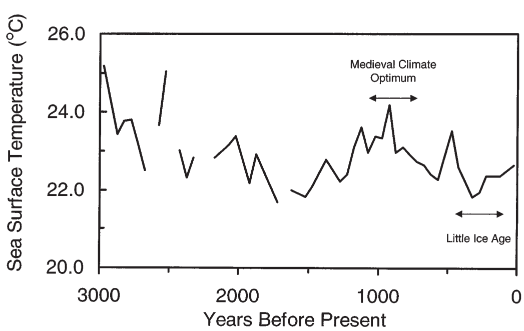

Fig. 2. Surface temperatures in the Sargasso Sea (with a time resolution of about 50 yr) over approximately 3000 yr (ending in 1975), as determined by oxygen isotope ratios of marine organism *(Globigerinoides ruber)* remains in sediment at the bottom of the sea (Keigwin 1996). The Little Ice Age and Medieval Climate Optimum are indicated

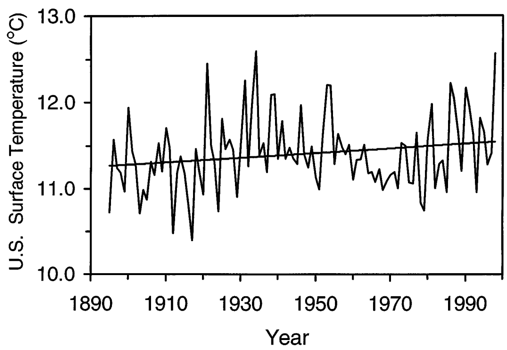

Fig. 3. Annual mean surface temperatures in the continental United States between 1895 and 1998, as compiled by the National Climate Data Center (Brown & Heim 1998). The trend line for the entire data set with slope of +0.027°C decade^{-1} is indicated

In more recent times, instrumental records have become available. One long surface record with good quality control and coverage of a significant land area is that of the continental United States. Fig. 3 shows the annual average temperature of the United States as compiled by the National Climate Data Center (Brown & Heim 1998). The upward temperature fluctuation between 1900 and 1940 is natural and likely a recovery from the Little Ice Age. The United States temperatures show a non-significant increasing trend of +0.027°C decade^{-1}.[2]

[2]In several places in this review, we report linear least-squares calculated trend lines for measurement compilations of temperatures, storm activity, and sea levels. Variability analyses for these compilations are reported in the referenced literature. Quantitative error estimations for the trend values are beyond the scope of this review. Systematic errors such as temporal or spatial limitations of the data and non-random fluctuations in underlying natural phenomena introduce substantial complications and uncertainty into such estimations. The calculated trend values are, however, helpful in understanding the graphically displayed observational results—which have been reproduced in the figures at resolutions that provide readily apparent representations of variability

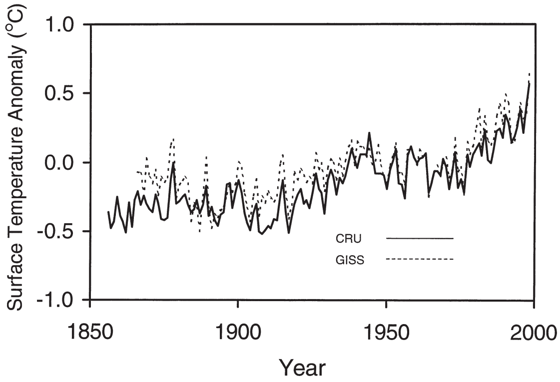

Fig. 4. Annual mean global surface temperature anomalies for land and sea-surface (solid), as reconstructed by CRU (Parker et al. 1994, CRU 1999), and for land only (dashed), as estimated by NASA-GISS (Hansen & Lebedeff 1987, 1988, Hansen et al. 1996). An adjustment has been made for urban warming effects in both the CRU and GISS reconstructions

Surface temperature records compiled from world-wide stations by NASA-GISS (Goddard Institute for Space Studies; Hansen & Lebedeff 1987, 1988, Hansen et al. 1996) and the Climate Research Unit (CRU) at the University of East Anglia, UK (Parker et al. 1994, CRU 1999) are shown in Fig. 4. The overall rise of about 0.5 to 0.6°C during the 20th century is often cited in support of greenhouse global warming (e.g. Schneider 1994). However, since approximately 80% of the CO_2 rise during the 20th century (see Fig. 1) occurred *after* the initial major rise in temperature, the CO_2 increase cannot have caused the bulk of the past century's temperature increase. In addition, it has been pointed out that reported increases in global and northern hemisphere surface temperatures since the 1970s have occurred mostly during cold seasons. The winter warming may be interpreted as natural dynamical variability owing to anomalous atmospheric circulation. The cause of circulation anomalies in the 1970s is a strong positive bias in the distinctive cold-ocean warm-land (COWL) pattern seen in the spatial distribution of the surface temperature records (Wallace et al. 1995, 1996). Could the increase in well-mixed CO_2 gas in the atmosphere produce the observed regional changes in the COWL pattern? Results from GCMs are inconclusive; Broccoli et al. (1998) suggest that separating the COWL pattern from the hypothesized anthropogenic CO_2 fingerprint is not straightforward (see further discussion below). Because a COWL pattern arises primarily from the differential thermal inertia contrast between the land and the sea, such an internal spatial pattern may be caused by any number of external warming influences (see also Corti et al. 1999).

Before interpreting other climate change patterns, the limitations of observed spatial and temporal trends should be examined. In terms of spatial coverage, the surface records are limited because they are not truly global (e.g. Robeson 1995). The 0.5 to 0.6°C century^{-1} temperature trend for the last 100 yr has been determined with uncertainties estimated to be smaller than the magnitude of the increase (Karl et al. 1994), despite the incomplete surface coverage. But serious uncertainty in uneven temporal sampling exists and it can come from 2 sources. One is the unknown time of day of observation, e.g. in cases where only monthly data have been given (Madden et al. 1993). A second source of temporal sampling error is gaps in records (Stooksbury et al. 1999), which in turn can bias spatial coverage through the rejection of a location whose period of measurement is incomplete. For example, in the 100 yr period 1897 to 1996, Michaels et al. (1998) found that imposing the validity requirement that data within 5° × 5° gridded spatial cells should have no more than 10 yr (10% of the period) of measurements missing produced a 'global' sample covering only 18.4% of the earth. This is not an optimal spatial coverage for determining a global mean. Jones et al. (1997) have attempted to address the influence of incomplete spatial sampling on the uncertainty in estimating global mean surface temperature by using several GCMs.

A further uncertainty in surface temperature measurements is the urban heat island bias. Fig. 5 shows the size of the urban heat island effect in measurements from surface stations in California. The results from all counties and selected sites in Fig. 5 should be compared with the results from the East Park station, considered the best situated rural station in the state (Goodridge pers. comm. 1998), which has a calculated temperature trend between 1940 and 1996 of –0.055°C decade^{-1}. The urban heat bias has also been observed elsewhere (Balling 1992, Böhm 1998). Gallo et al. (1999) caution that the designations of surface temperature stations as urban, suburban, or rural need to be reassessed periodically because the current methodology can introduce bias in global and regional trends of surface temperatures.

The systematic error of the urban heat island effect has been extensively studied and debated, and remains controversial. For example, a recent analysis of rural and urban stations found no significant difference introduced into the calculated global trend by the urban stations until 1990 or so (Peterson et al. 1999). After 1990, the urban stations contributed a warming bias to the global average which is not seen in the rural stations. Peterson et al. (1999) note that rural station coverage has fallen from over 20% of the earth's area in the 1970s to 7% in 1998, which may explain the recent difference in trends between urban and rural temperatures, and also may introduce uncertainty in the global average.

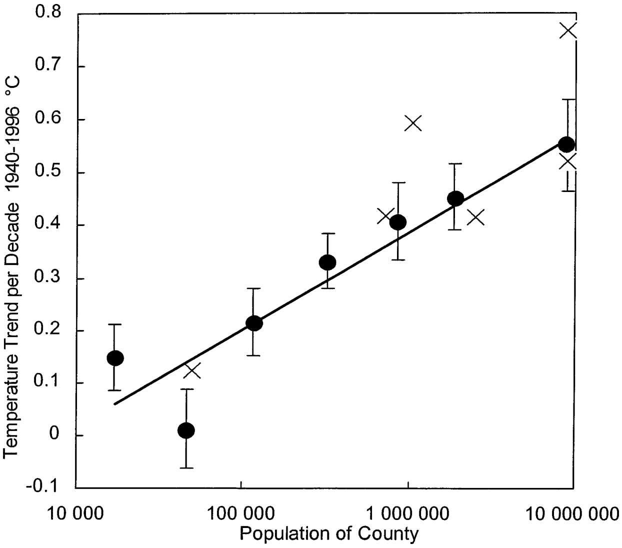

Fig. 5. Surface temperature trends for the period 1940 to 1996 from 107 measuring stations in 49 California counties (Christy & Goodridge 1995, Goodridge 1996). After averaging the means of the trends in each county, counties of similar population were combined and plotted as filled circles along with the standard errors of their means. The 6 measuring stations in Los Angeles County were used to calculate the standard error of that county, which is plotted alone at the county population of 8.9 million. The urban heat island effect on surface measurements is evident. The straight line is a least-squares fit to the filled circles. (×) The 6 unadjusted station records selected by NASA-GISS for use in their estimate of global temperatures as shown in Fig. 4

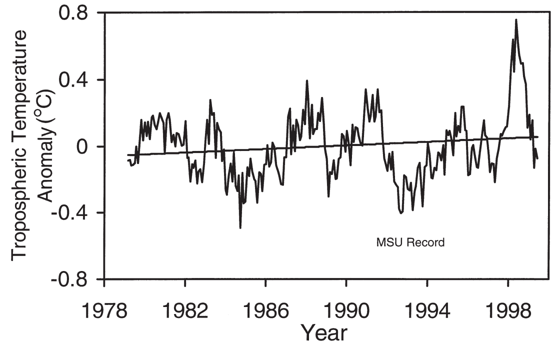

Fig. 6. Satellite Microwave Sounding Unit (MSU) measurements of global lower tropospheric temperatures between 82° N and 82° S from 1979 to May 1999 (Spencer & Christy 1990, Christy et al. 1998). Temperatures are monthly averages and the linear trend for 1979 to May 1999 is shown. The slope of this line is +0.054°C decade^{-1}

With the advent of the rapid growth rate in atmospheric CO_2 concentration, attention has focused on the measurement of temperature trends of the last several decades. The uncertainties on decadal time scales in the surface record may be roughly comparable to the magnitude of the trend expected (Karl et al. 1994). However, tropospheric records can also be considered. Although the tropospheric measurements differ from the surface measurements, and are also relatively short, they are important in examining the effect of increases in the atmospheric concentration of CO_2. In the troposphere, GHG-induced temperature changes are expected to be at least as large as at the surface (e.g. Houghton et al. 1996).

We consider 2 tropospheric records—from satellite and balloon platforms. Since 1979, essentially global lower-tropospheric temperature measurements have been made by means of Microwave Sounding Units (MSUs) on orbiting satellites (Spencer et al. 1990). Fig. 6. shows the average global tropospheric satellite measurements (Spencer & Christy 1990, Christy et al. 1998). The tropospheric record can be extended back to 1958 with radiosonde data (Fig. 7, Angell 1997, pers. com. 1999 [data of Angell 1997 updated to February 1999]). The globally gridded radiosonde data on tropospheric temperature (Parker et al. 1997) are also consistent with the satellite and Angell radiosonde tropospheric temperatures, although the interannual variance is slightly smaller in the Parker et al. (1997) data (not shown here). The agreement of the independent sets of data between 1979 and 1998 verifies their precision. Further agreement between balloon and satellite records has been shown rigorously by extensive analysis (Spencer & Christy 1992, Christy 1995). An analysis of the satellite record (Wentz & Schabel 1998) had pointed out a potential error in the calculated trend in the MSU measurements of the tropospheric temperature. The authors claimed that decay of the orbits of the individual satellites contributed to the records and made spurious trends in the data. However, the estimated uncertainty was exaggerated. The effect of orbital decay, when properly computed, and an additional effect, that of drift in the satellite orbit, have now

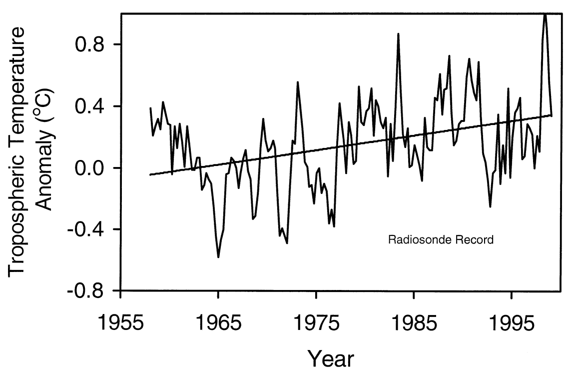

Fig. 7. Radiosonde balloon station measurements of lower tropospheric temperatures at 63 stations between 90° N and 90° S from 1958 to February 1999 (Angell 1997, pers. comm. 1999 [data of Angell 1997 updated to February 1999]). Temperatures are 3 mo averages and the linear trend for 1958 to February 1999 is shown. The slope is +0.095°C decade^{-1}

been applied to the MSU data (Christy et al. 1998). Those corrected data are the ones plotted in Fig. 6.

Tropospheric temperatures have shown a global trend of +0.054°C decade^{-1} (MSU, 1979 to May 1999) or +0.018°C decade^{-1} (radiosonde, 1979 to February 1999). Going back further, the trend in the tropospheric temperatures measured by radiosonde is +0.095°C decade^{-1} (1958 to February 1999). The physical significance of the tropospheric trends is difficult to assess. These periods are relatively short intervals over which to give interpretation to a trend because of large interannual variability (e.g. caused by the effects of ENSO and volcanic eruptions). But Christy & McNider (1994, and updates in Christy 1997) had shown that even after the crude removal of the ENSO and volcanic effects, the adjusted MSU tropospheric global temperature 20 yr trend can only be marginally consistent with the projected warming rates of 0.08 to 0.30°C decade^{-1} by GCM simulations that included effects owing to CO_2 (only) and tropospheric sulfate aerosol (direct effect only) over the last 20 yr (Houghton et al. 1996, p. 438).

The tropospheric temperature trends can be compared to the trend in the CRU surface temperature records of +0.11°C decade^{-1} (1958 to 1998) and +0.19°C decade^{-1} (1979 to 1998). The surface trends are apparently significant, but are not consistent with the tropospheric trends. No clear resolution of this important discrepancy is at hand. However, in addition to uncertainties in the surface measurements, there are physical reasons for differences expected in the surface and tropospheric temperature trends as, for example, for the equatorial oceans (Trenberth et al. 1992, Christy 1995). (See discussion on the complications of attributing causes to recent climate change, below.) New attempts, post-Houghton et al. (1996), like Bengtsson et al. (1999) have further highlighted the inconsistency between the differing observed surface-troposphere trends and the simulated GCM trends which try to include forcing factors like anthropogenic GHGs, tropospheric sulfate aerosols (both the direct and indirect effects), stratospheric aerosols from Mount Pinatubo, and tropospheric and stratospheric ozones.

Another useful record is that of stratospheric temperatures, which have been measured by MSUs since 1979, and by balloon, although with less area and altitude coverage than for the satellite record, since 1958. The lower stratosphere (about 100 mb) has shown a significant cooling trend of about 0.6 to 0.7°C decade^{-1} since 1979 (see e.g. Angell 1997, Parker et al. 1997, Simmons et al. 1999). Qualitatively, the cooling trend is apparently consistent with the expectation of cooling caused by increased radiative emission as a consequence of increased stratospheric CO_2 concentration. However, determination of the potential CO_2 component of stratospheric cooling is ambiguous because the effects of volcanic aerosols, changes in stratospheric ozone and changes in solar ultraviolet forcing are also significant. These 3 effects can change with time and cannot be removed with precision. The frustration associated with the attribution of causes connected to lower stratospheric cooling, as well as variations of the surface and tropospheric temperatures, is discussed further below.

4. MODELLED EFFECTS OF INCREASED ATMOSPHERIC CO_2

Incoming broadband solar radiation is, on average, approximately balanced by the outgoing thermal radiation of the earth. The major GHG, H_2O (in vapor forms), and minor GHGs like CO_2, CH_4 and N_2O act to regulate this radiational balance by absorbing and re-emitting large portions of the outgoing infrared terrestrial radiation. Introduction of additional CO_2 into the atmosphere can be considered as an effective increase in radiative energy input to the Earth because of the increasing infrared opacity of the atmosphere. The heat is redistributed, both vertically and horizontally, by various physical processes, including advection, convection, and diffusion, in the atmosphere and ocean system.

When CO_2 increases the infrared opacity of the atmosphere, how does the atmosphere respond? The radiative contribution of doubling atmospheric CO_2 alone is not large, but the total response depends on many feedback mechanisms. This is the key issue. The computed response differs among the models because many of the physical processes are only rudimentarily understood and are variously parameterized. The essence of such a problem of climate models is documented in a study which showed that differences in the inter-model atmospheric responses on interannual time scales, e.g. to a common sea surface temperature forcing, are somewhat greater than ensemble responses obtained from intrinsic variability for a single model (e.g. Boyle 1998). The climate is a coupled, nonlinear dynamical system. The computer climate models have substantial uncertainties (Mason 1995). Without experimental validation of the models, the calculation of the climate response to increased anthropogenic atmospheric CO_2 is not reliable. Also needed is a reliable calculation of the natural variability of the climate.

We discuss 6 important areas in climate modeling. First, nearly all models have substantial flux errors for which artificial flux adjustments are introduced. Systematic surface-ocean heat flux errors of up to 100 W m^{-2} are locally introduced into the calculations

(Glecker et al. 1995, Murphy 1995, Glecker & Weare 1997). One important consequence of such flux adjustments is to damp low-frequency variability in the simulation of a climate state through excessive overstabilization (Palmer 1999). Another critical consequence of the artificial flux tuning is to introduce systematic biases in the model's estimates for important parameters of the climate system, such as annual mean and annual cycle amplitude of the equator-to-pole temperature gradient and the ocean-land surface temperature contrast (Jain et al. 1999). Several coupled ocean-atmosphere models attempt to avoid flux adjustments. However, those models still show substantial climate drift and bias (Cai & Gordon 1999, Yu & Mechoso 1999).

In addition, results from the cooperative CAGEX[3] and GEBA[4] experiments, as well as the latest ARESE[5] experiments (e.g. Wild et al. 1995, Charlock & Alberta 1996, Valero et al. 1997a, Zender et al. 1997), show that there is atmospheric absorption unaccounted for by the present atmospheric radiation codes generally used in GCMs. Those observations suggest that the missing energy flux, when averaged over the whole globe, amounts to 25 W m^{-2} (Cess et al. 1995, Li et al. 1997) or 17 to 20 W m^{-2} (M. H. Zhang et al. 1998) or 10 to 20 W m^{-2} (Wild et al. 1998). The missing energy flux, interpreted as excess cloud absorption, occurs in both visible (224 to 680 nm) and near-infrared (680 to 3300 nm) wavelengths, while an excess absorption around 500 nm (with 10 nm bandwidth) can be ruled out (Valero et al. 1997b, Cess et al. 1999). The flux uncertainties are large compared to the expected forcing from doubling CO_2, ~4 W m^{-2} globally.

A second important factor in climate modeling is the understanding of water vapor feedback. The underlying process starts with increasing temperature that increases atmospheric water vapor concentration. The models assume that the water vapor is then distributed, especially to the middle and upper troposphere, in such a way as to globally increase water vapor content. Consequently, the enhanced water vapor would amplify the warming caused by increased CO_2 alone. This is the dominant gain in the models for amplifying the effect of CO_2 increases. This mechanism has been studied theoretically and observationally. Some evidence supports a positive water vapor feedback (Liao & Rind 1997, Soden 1997, Inamdar & Ramanathan 1998). However, the model parameterization of the mechanism has been criticized (Renno et al. 1994, Spencer & Braswell 1997). For example, the interannual variations of water vapor and temperature in the tropical troposphere have been shown to be too strongly coupled in a GCM when compared to observed relationships (Sun & Held 1996). A comparison of observed decadal mean tropospheric precipitable water over North America, the Pacific basin and the globe with results from 28 GCMs revealed that simulated values are less moist than the real atmosphere for all 3 areas (Gaffen et al. 1997). Tropospheric moisture and convective transport processes are both spatially and temporally scale-specific (Hu & Liu 1998, Yang & Tung 1998). Without adequate observations, it is difficult to determine the correct parameterization of the CO_2-induced water vapor feedback effect. Limited observations of precipitable water have been obtained in the tropics (30° N to 30° S) and yield an indication of widespread drying of the upper troposphere between 1979 and 1995 (Schroeder & McGuirk 1998a; see also the exchange between Ross & Gaffen 1998 and Schroeder & McGuirk 1998b).

A third factor limiting model performance is uncertainty related to cloud forcing. Necessary observations of cloud properties are incomplete, although current intensive programs are progressing (Rossow & Cairns 1995, Hahn et al. 1996, Weare 1999, Wylie & Menzel 1999). In general, GCMs overpredict the coverage (cloudiness) of high clouds by a factor as large as 2 to 5 (Weare & AMIP Modeling Groups 1996). For low clouds, models present a global average coverage that is 10 to 20% less than observed. Spatially, the modeled cloud distribution is also incorrect (Weare & AMIP Modeling Groups 1996, Cess et al. 1997). The magnitude of such systematic errors in cloud parameterization is not negligible. Additional physical processes like the detrainment temperature-cirrus cloud feedback (Chou & Neelin 1999) and the impact of clouds on the spectral distribution of incident irradiance (Siegel et al. 1999) should also be included. Therefore, the parameterization of radiative, latent and convective effects of cloud forcing needs further improvements (Fowler & Randall 1999, Rotstayn 1999, Senior 1999, Yao & Del Genio 1999).

A fourth critical area of uncertainty concerns the parameterization of the ocean-atmosphere interaction. The physics of the air-sea interaction is actively being studied, especially over the tropical oceans, with *in situ* and satellite observations of heat, momentum and freshwater fluxes. Observations of such parameters should improve our understanding of air-sea coupling (e.g. Godfrey et al. 1998).

[3]CAGEX – CERES/ARM/GEWEX — NASA's Clouds and the Earth's Radiation Energy System (CERES); Department of Energy's Atmospheric Radiation Measurement (ARM); World Climate Research Program's Global Energy and Water Cycle Experiment (GEWEX)

[4]World Climate Research Program's Global Energy Balance Archive (GEBA)

[5]Departments of Energy and Defense and NASA's Atmospheric Radiation Measurements Enhanced Shortwave Experiment (ARESE)

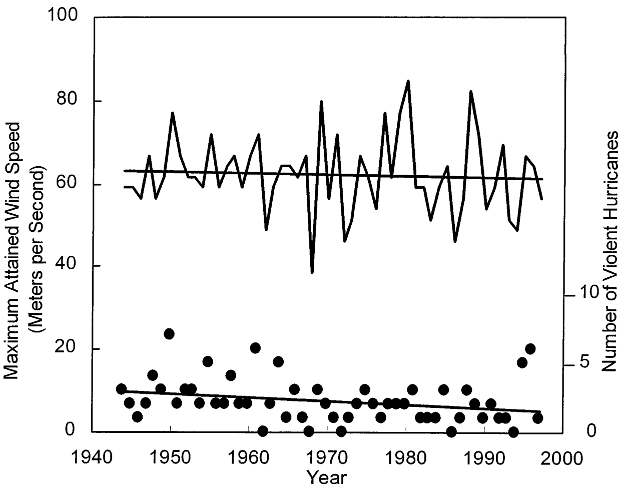

Fig. 8. Annual numbers of violent Atlantic Ocean hurricanes (bottom of panel) and their maximum attained wind speeds (top of panel) (Landsea et al. 1996). Slopes of the trend lines are –0.25 hurricanes decade^{-1} and –0.33 m s^{-1} maximum attained wind speed per decade

As just one example of current model inadequencies in this area, we consider hurricanes and storms. Modeling storms is complex, one reason being that storms occur on spatially fine-scale fronts, below the resolution of most models (e.g. Hendersen-Sellers et al. 1998). One model result for roughly doubling atmospheric CO_2 concentration calls for hurricane wind speeds to increase 3 to 7 m s^{-1} and for central surface pressures to drop by 7 to 20 mb over the Western Pacific (Knutson et al. 1998). Another model predicts increases in precipitation extremes almost everywhere under the scenario of doubled atmospheric CO_2 concentration (Zwiers & Kharin 1998). Both studies admit to significant imprecision arising from uncertainties in the air-sea interaction and other model deficiencies like inadequate spatial resolution.

In testing these various predictions, storm assessment is possible in regions of the Atlantic where data go back 100 yr or so. Fig. 8 shows the number of severe tropical Atlantic hurricanes per year and also the maximum wind intensities of those hurricanes (Landsea et al. 1996). Both of these parameters have been decreasing with time. Another study that focused on a subset of tropical Atlantic hurricanes, US Gulf land-falling hurricanes, also showed no sign of increasing hurricane frequency or intensity over the period 1886 to 1995 (Bove et al. 1998). Likewise, in regions of the northern Atlantic, there is interdecadal variation in the storm index but no century-scale increasing or decreasing trend in storm roughness in the interval 1881 to 1995 (WASA Group 1998).

A fifth important process for models to simulate is sea-ice-snow feedback (Randall et al. 1998). GCM results underpredict the variance of sea-ice thickness in the Arctic on decadal to century time scales (Battisti et al. 1997). J. Zhang et al. (1998) emphasized the importance of including realistic surface fluxes and modeling of convective overturning and vertical advection in both the Arctic and adjacent oceans, in order to reduce the over-warm intermediate layers in the Arctic Ocean and excessive heat influx into the Fram Strait predicted by models. An analysis of results from 27 GCMs reveals that most of the models display less than half the interannual variance of snow extent; furthermore, the models underestimate snow extent in some areas and overestimate it in others (Frei & Robinson 1998). A related consequence of sea-ice-snow feedback is sea level change, the measurements of which can be used to assess the gross state of the model results and the model's parameterization of the sea-ice-snow feedback. Fig. 9 shows satellite measurements of global sea level variations between 1993 and 1996 (Nerem et al. 1997). The reported current global rate of rise amounts to about +2 mm yr^{-1} (Douglas 1995, Nerem et al. 1997). The trends in rise and fall of sea level in various regions have a wide range of about 100 mm yr^{-1}, with most of the globe showing downward trends except near the eastern equatorial Pacific (Douglas 1995, Nerem et al. 1997, Leuliette & Wahr 1999). Historical records show no acceleration in sea level rise in the 20th century (Douglas 1992). Such observations seem inconsistent with even the modest

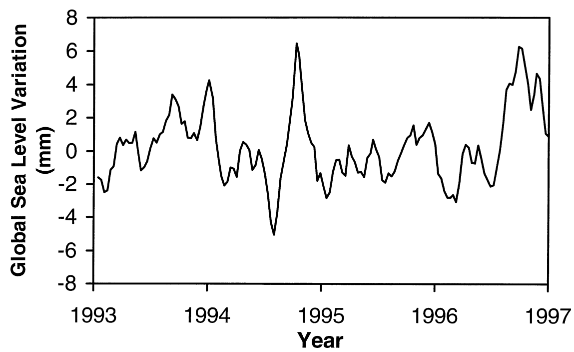

Fig. 9. Global sea level variations from the Topex/Poseidon (T/P) satellite altimeters for 1993 to 1996 (as in Fig. 1 of Nerem et al. 1997; the curve is smoothed by a 60 d boxcar filter and plotted for each 10 d cycle of the T/P altimetry). No trend is calculated here, but according to Nerem et al. (1997) the plotted T/P instrumental time series gives a 'secular' rate of change of about –0.2 mm yr^{-1}, after the removal of annual and semi-annual variations (Nerem et al. 1997, p. 1332; see e.g. Leuliette & Wahr 1999 for updates on the analysis of spatial and temporal variability of T/P sea surface height data). However, it has been reported that 50 yr tide gauge measurements give +1.8 mm yr^{-1} (Douglas 1995). A correction of +2.3 mm yr^{-1} was added to the satellite data, based on comparison to selected tide gauges, to obtain a value of about +2.1 mm yr^{-1} (Nerem et al. 1997)

model predictions of 20th century sea level rise by oceanic thermal expansion. Predictions of CO_2-induced sea level rise will likely remain uncertain for some time, because most of the factors affecting sea level change, including not only the sea-ice feedback but also vertical land motion, are not well understood and are difficult to model (Douglas 1995, Gornitz 1995, Peltier 1996, Conrad & Hager 1997).

A sixth important set of processes to be considered in climate modeling has to do with biosphere-atmosphere-ocean feedback (Idso 1989). These processes are difficult to incorporate in models, yet progress is being made (e.g. Henderson-Sellers et al. 1996, Varejao-Silva et al. 1998). A small positive feedback effect on global temperature sensitivity has been found in a GCM that includes some effects of plant photosynthesis and soil thermodynamics (Cox et al. 1999). For latitudes above 45° N, Levis et al. (1999) have found substantial spring and summer warming and winter cooling effects (primarily through alteration of surface albedo) when vegetation feedbacks are incorporated into a GCM under a doubled CO_2 scenario. Soil moisture changes appreciably when biospheric processes are included, and including them should reduce systematic errors in the simulation of regional climate. The most important aspect of biospheric feedback is perhaps its relevance to the carbon budget of the climate system. Understanding this feedback holds the promise of an internally consistent description of the relationship of CO_2 to climate change.

5. EFFECTS OF INCREASED CO_2 ON PLANTS

Plant life provides a sink for atmospheric CO_2. Using current knowledge about the increased growth rates of plants and assuming a doubling of CO_2 release as compared to current emissions, it has been estimated that atmospheric CO_2 levels will rise by about 300 ppm before leveling off (Idso 1991a,b). At that level, CO_2 absorption by increased terrestrial biomass may be able to absorb about 10 Gt C yr^{-1}.

Figs. 10 to 13 show examples of experimentally measured increases in the growth of plants. These examples are representative of a very large amount of research literature on this subject (Kimball 1983, Cure & Acock 1986, Mortensen 1987, Drake & Leadley 1991, Lawlor & Mitchell 1991, Gifford 1992, Poorter 1993). Since plant response to CO_2 fertilization is nearly linear with respect to CO_2 concentration over a range of a few hundred ppm, as seen, for example, in Figs. 10 & 13, it is convenient to normalize experimental measurements at different levels of CO_2 enrichment. This has been done in Fig. 14a,b in order to illustrate some CO_2 growth enhancements calculated for the atmospheric increase of about 80 ppm that has already taken place, and that expected from a projected total increase of 320 ppm.

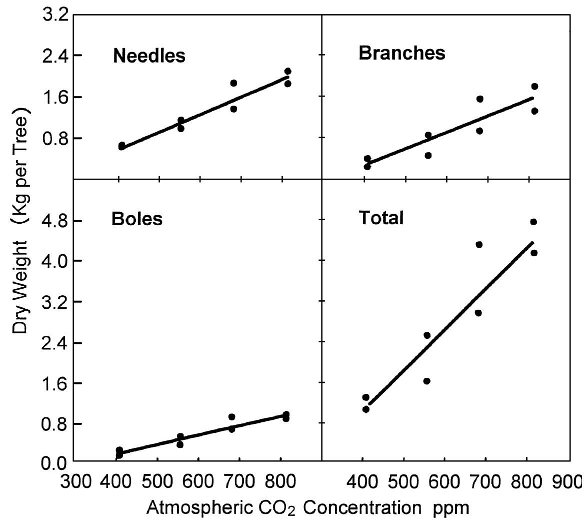

Fig. 10. Young eldarica pine trees were grown for 23 mo under 4 CO_2 concentrations and then cut down and weighed. Each point represents an individual tree (Idso & Kimball 1994). Weights of tree parts are as indicated

Fig. 10 summarizes the increased growth rates of young pine seedlings at 4 CO_2 levels. Again, the response is remarkable, with an increase of 300 ppm more than tripling the rate of growth (Idso & Kimball 1994). Fig. 11 shows the effect of CO_2 fertilization on sour orange trees (Idso & Kimball 1991, 1997). During the early years of growth, the bark, limbs, and fine roots of sour orange trees growing in an atmosphere with 700 ppm of CO_2 exhibited rates of growth more than 170% greater than those at 400 ppm. As the trees matured, this CO_2-induced enhancement dropped to about 100%. Meanwhile, orange production was 127% higher for the 700 ppm trees.

Trees respond to CO_2 fertilization more strongly than do most other plants, but all plants respond to some extent. Fig. 12 shows the response of wheat grown under wet conditions and when the wheat was stressed by lack of water. These were open-field experiments. Wheat was grown in the usual way, but the atmospheric CO_2 concentrations of circular sections of the fields were increased by means of arrays of computer-controlled equipment that released CO_2 into the air to hold the levels as specified.

While the results illustrated in Figs. 10 to 12 are remarkable, they are typical of those reported in a very large number of studies of the effects of CO_2 concentration upon the growth rates of plants. Fig. 13 summarizes 279 similar experiments in which plants of various types were raised under CO_2-enhanced conditions. Plants under stress from less-than-ideal conditions—a

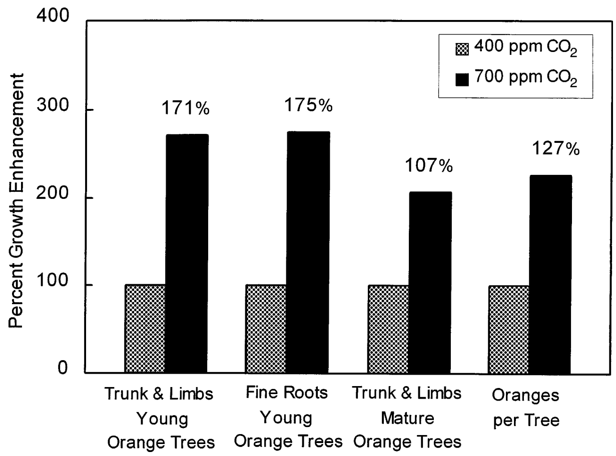

Fig. 11. Relative trunk and limb volumes and fine root biomass of young sour orange trees and trunk and limb volumes and numbers of oranges produced per mature sour orange tree per year at 400 and 700 ppm CO_2 (Idso & Kimball 1991, Idso & Kimball 1997). The 400 ppm values were normalized to 100. The trees were planted in 1987 as 1 yr old seedlings. Young trunk and limb volumes and fine root biomass were measured in 1990. Mature trunk and limb volumes are averages for 1991 to 1996. Orange numbers are averages for 1993 to 1997

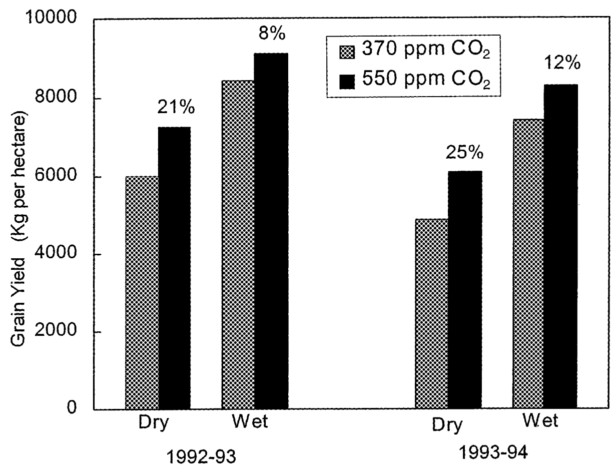

Fig. 12. Grain yields from wheat grown under well-watered and poorly watered conditions at 370 and 550 ppm CO_2 in open-field experiments (Kimball et al. 1995, Pinter et al. 1996). Average CO_2-induced increases for the 2 years were 10% for wet and 23% for dry conditions

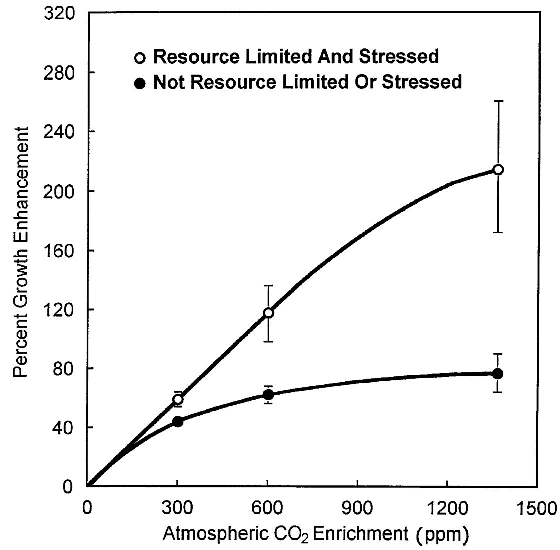

Fig. 13. Summary data from 279 published experiments in which plants of all types were grown under paired stressed and unstressed conditions (Idso & Idso 1994). There were 208, 50, and 21 sets of data at 300, 600, and an average of about 1350 ppm CO_2, respectively. The plant mixture in the 279 studies was slightly biased toward plant types that respond less to CO_2 fertilization than does the actual global mixture and therefore underestimates the expected global response. CO_2 enrichment also allows plants to grow in drier regions, further increasing the expected global response

common occurrence in nature—respond more to CO_2 fertilization. The selections of species shown in Fig. 13 were biased toward plants that respond less to CO_2 fertilization than does the mixture actually covering the Earth, so Fig. 13 underestimates the effects of global CO_2 enhancement.

Fig. 14a,b summarize the wheat, orange tree, and young pine tree enhancements shown in Figs. 12, 11 & 10 with 2 idealized atmospheric CO_2 increases—that which has occurred since 1800 and is believed to be the result of the Industrial Revolution, and that which is projected for the next 2 centuries.

6. DISCUSSION

Calculations of the climatic impacts of increases in atmospheric CO_2 concentration are not robust. Major components of the climate system are not satisfactorily represented in the models. The reason is a lack of good understanding of climate dynamics, both on theoretical and observational grounds. The models give a range of outcomes. Typically, the aggregate of various GCMs is listed as a 1.5 to 4.5°C global temperature rise for an approximate doubling of the atmospheric CO_2 concentration (Houghton et al. 1996). The confluence of the models' outcomes and their range of changes are not to be taken as a mean and standard deviation, either statistically or physically. Given the substantial uncertanties associated with the modeling enterprise and its many parameterizations, the outcomes of the models, which are subject to large systematic errors, cannot be averaged and represented as a consensual result.

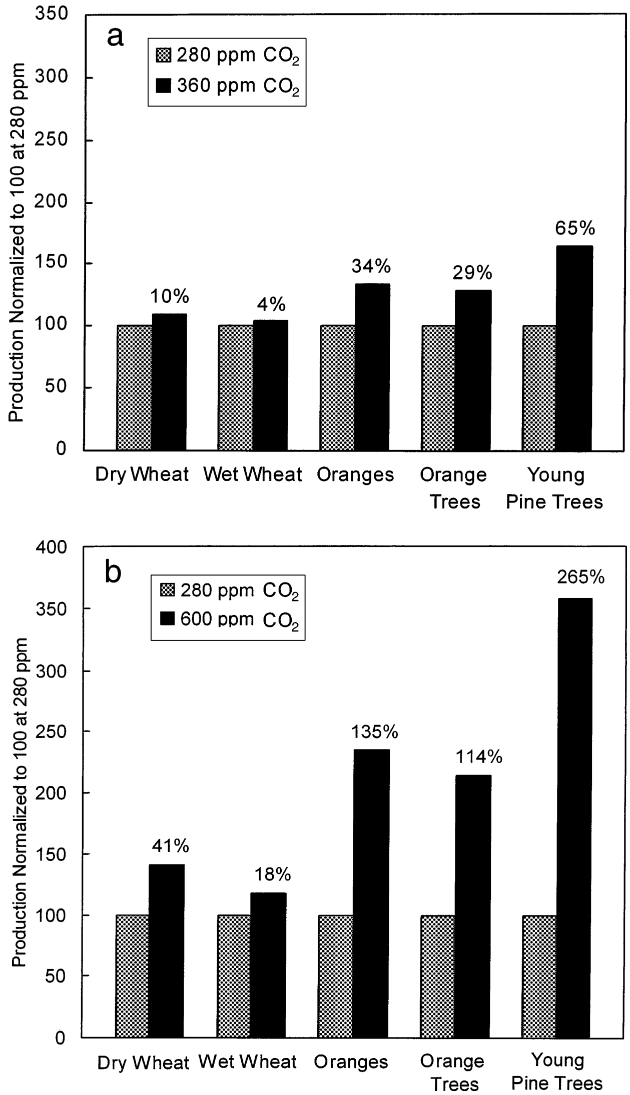

Fig. 14. (a) Calculated growth rate enhancement of wheat, young orange trees, and very young pine trees already taking place as a result of atmospheric enrichment by CO_2 during the past 2 centuries. These values apply to pine trees during their first 2 yr of growth and orange trees during their 4th through 10th years of growth. As is shown in Fig. 11, the effect of increased CO_2 gradually diminishes with tree age, so these values should not be interpreted as applicable over the entire tree lifespan. There are no longer-running controlled CO_2 tree experiments. (b) Calculated growth rate enhancement of wheat, young orange trees, and very young pine trees expected to take place as a result of atmospheric enrichment by CO_2 to a level of 600 ppm

There are independent semi-empirical approaches that give results lying outside the consensual range of temperature change output by the models. For example, analysis of the climate response to perturbations by volcanic eruptions suggests a climate sensitivity of 0.3 to 0.5°C for a doubling of atmospheric CO_2 (Lindzen 1997). In addition, consideration of a variety of biological and other negative feedbacks in the climate system yields a climate sensitivity of roughly 0.4°C for a doubling of the air's CO_2 content (Idso 1998).

Taking a different approach, Forest et al. (1999) defined a probability of expected outcomes by performing a large number of sensitivity runs (i.e. by varying cloud feedback and rate of heat uptake by the deep ocean). The key statistical statement from their modelling effort is that there is a 95% probability that the expected global surface temperature increase from a doubling of the atmosphere's CO_2 concentration would range from 0.5 to 3.3°C. It may or may not be fortuitous that the semi-empirical estimates by Lindzen (1997) and Idso (1998) fall within the acceptable range of global temperature change as deduced from the statistical work of Forest et al. (1999). The result that emerges is that current climate model estimates of global temperature changes owing to increased atmospheric CO_2 concentration remain highly uncertain.

6.1. Attribution of causes of recent climatic change

Anthropogenic global climate impacts occur against a background of natural variability. There are several limitations that impede the detection of anthropogenic effects of increased atmospheric CO_2. One is the inadequacy of climate records, which are, in general, too short to capture the full range of natural variability. For example, in the case of the interpretation of the observations of the North Atlantic oscillation, time series analysis reveals a white spectrum, with little evidence of a long-term trend that might be expected from an anthropogenic signal (Wunsch 1999). Another difficulty in assessing model results for anthropogenic effects is illustrated by the fact that models underpredict the variance of natural climate change on decade to century time scales (Barnett et al. 1996, Stott & Tett 1998), or incorrectly predict the variance (Polyak & North 1997 [see also North 1997, Polyak 1997], Barnett 1999) on the time scale over which the anthropogenic effect of increased CO_2 would be expected to arise. One reason why models underpredict natural climate change is that not all causes of natural variability have been included or have been properly parameterized in the models. A few of the suspected climate forcings that are still poorly handled in the models are volcanic eruptions (e.g. Kondratyev 1996), stratospheric ozone variations (e.g. Haigh 1999), sulfate aerosol changes (e.g. Hansen et al. 1997), and solar particle and radiative variations. The practical issue of attribution requires that such uncertainties be resolved. The radiative impact of increased atmospheric CO_2 is often treated as an anomalous and unique climatic response.

For example, it has been claimed that anthropogenic effects are contained in recent and relatively short tropospheric temperature records (Santer et al. 1996a,b). However, this claim was shown to be unsupportable in a longer record (Michaels & Knappenberger 1996, Weber 1996). In addition, the spatial limitations of such a record complicate the application of statistical methods used to infer correlations (Barnett et al. 1996, Legates & Davis 1997).

The most recent comparisons of model results and observations fail to reveal a unique and significant change caused by GHG increases, sulfate aerosol changes and tropospheric as well as stratospheric ozone variations (e.g. Graf et al. 1998, Bengtsson et al. 1999). These results are consistent with analyses of northern hemisphere circulation patterns (Corti et al. 1999, Palmer 1999), in which the spatial patterns of anthropogenically forced climate change are indistinguishable from those of natural variability. Interpreting climate change under the perspective of such nonlinear dynamics imposes a strong requirement that a GCM must simulate accurately natural circulation regimes and their associated variability. This particular caveat is relevant because the global radiative forcing of a few watts per square meter as expected from combined anthropogenic GHGs is very small compared to the energy budgets of various natural components of the climate system, as well as flux errors in model parameterizations of physical processes.

6.2. Observational outlook

Modeling climate change is a useful approach for studying the attribution of effects of increased atmospheric CO_2. However, validation of the models is essential to placing confidence in this approach. In this regard, improved observations, both in precision, accuracy, and global coverage, are important requirements. A new system of experiments, characterized by an accuracy of 0.1 K in thermal brightness temperature and 1 cm^{-1} in spectral resolution, has been proposed (Goody et al. 1998). The aim of such a system is to provide for the early detection of a relatively weak global anthropogenic signal, as well as to improve models in critical aspects.

7. CONCLUSIONS

At present, the unique attribution of climate change caused by radiative forcing of increased atmospheric CO_2 is not possible, given the limitations of models and observed climate parameters. The use of unverified models in making future projections of incomplete (or unknown) climate forcing scenarios shifts focus from the problem of model validation. In turn, that may lead to the inconsistency of working with a CO_2 global warming hypothesis that is not falsifiable. Further, impact assessments, like sea level rise or altered frequencies and intensities of storms, are premature. In addition, there is no clear evidence of the model-expected anthropogenic CO_2 global effect on climate, either in surface temperature records of the last 100 yr, or in tropospheric temperature records obtained from balloon radiosondes over the last 40 yr, or in tropospheric temperature records obtained from MSU satellite experiments over the last 20 yr. There is, however, substantial evidence for a host of beneficial effects of increased atmospheric CO_2 on plant growth and development.

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