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Relative climatic effects of landcover change and elevated carbon dioxide combined with aerosols: A comparison of model results and observations

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Abstract. In this study we examine the possibility that the historical total of human landcover changes have had a comparable effect on climate to that of historical increases in CO_2 and aerosols. We compared results from two coupled climate model simulations which investigated transient climate changes produced by observed historical changes of CO_2 combined with sulfate aerosol forcing with two other climate model simulations that examined the equilibrium climatic effects of currently observed changes in landcover from its natural state. We found that simulated, near-surface temperature anomalies due to transient increases in atmospheric CO_2 combined with aerosols at the level currently observed are of similar amplitude as simulated temperature anomalies due to the direct and remote (nonlocal) equilibrium effects of historical anthropogenic landcover change in all models. Both effects are of comparable amplitude to observed temperature trends in the past 2 decades, the period of largest global surface warming. These results provide evidence for a confounding influence on surface temperatures and may be an indication that the problem of detection of the radiative warming effect of increased CO_2 in the observational record may be more complicated than previously appreciated.

1. Introduction

Several recent observational studies have found evidence for a climate forcing which cannot be attributed solely to solar variability or the internal variability of the climate system [*Wigley et al.*, 1998; *Intergovernmental Panel on Climate Change (IPCC)*, 1996, 2001; *Hansen et al.*, 1998; *Crowley*, 2000; *Santer et al.*, 1996]. The prime candidate for this external forcing is the radiative effect of the buildup of atmospheric CO_2 combined with increased aerosols. In this study we examine the possibility that the historical sum total of human landcover changes have had a comparable effect on climate to that of historical increases in CO_2 and aerosols by reviewing results from several model experiments.

Many modeling studies using idealized, and usually quite large, landcover changes [e.g., *Betts et al.*, 1996, and references within; *Betts*, 1999; *Eltahir*, 1996; *Dirmeyer and Shukla*, 1996; *Zhang et al.*, 1996] and others using more realistic changes [e.g., *Chase et al.*, 1996; *Zhao et al.*, 2001; *Fennessy and Xue*, 1997; *Foley et al.*, 1994; *Bonan*, 1997; *Brovkin et al.*, 1999; *Pielke et al.*, 1999; *Copeland et al.*, 1996; *Wang and Eltahir*, 2000] have shown significant impacts on near-surface atmospheric temperatures. A recent comparison of the effects of a conservative estimate of current changes in landcover [*Pitman and Zhao*, 2000] found that regional effects of landcover change could be of the same magnitude as those due to present levels of CO_2 loading in equilibrium climate experiments with a mixed-layer ocean model. This is a particularly interesting result because the temperature increases due to an instantaneous increase in CO_2 in an equilibrium simulation with a mixed layer ocean are typically substantially larger than the effects of transient increases in CO_2 in a model with a dynamically coupled ocean at any given time during the ramp up [e.g., *Manabe et al.*, 1991; *Washington*, 1992].

Regional observational studies have also identified the influence of landcover change on temperature [*Balling*, 1991; *O'Brien*, 2000]. Regional temperature trends attributable in large part to atmospheric circulation changes have been found in recent global observational studies [*Palecki and Leathers*, 1993; *Hurrell*, 1996] and have been associated by some with increasing greenhouse gasses [*Crowley*, 2000]. Though statistical removal of the well-known urban warming influence on surface temperature observations has been attempted [*Karl and Jones*, 1989], no comparable effort has been mounted to quantify the potential signal due to other types of landcover changes though these affect much larger portions of the globe [*Vitousek et al.*, 1997].

We compared results from several coupled climate model simulations which investigated the transient climate changes produced by current levels of CO_2 combined with aerosol forcing with equilibrium simulations which examined the climatic effects of currently observed changes in landcover from its natural state. We find that simulated, near-surface temperature anomalies due to increased atmospheric CO_2 with aerosols at the level currently observed are of similar amplitude as simulated temperature anomalies due to the direct and remote

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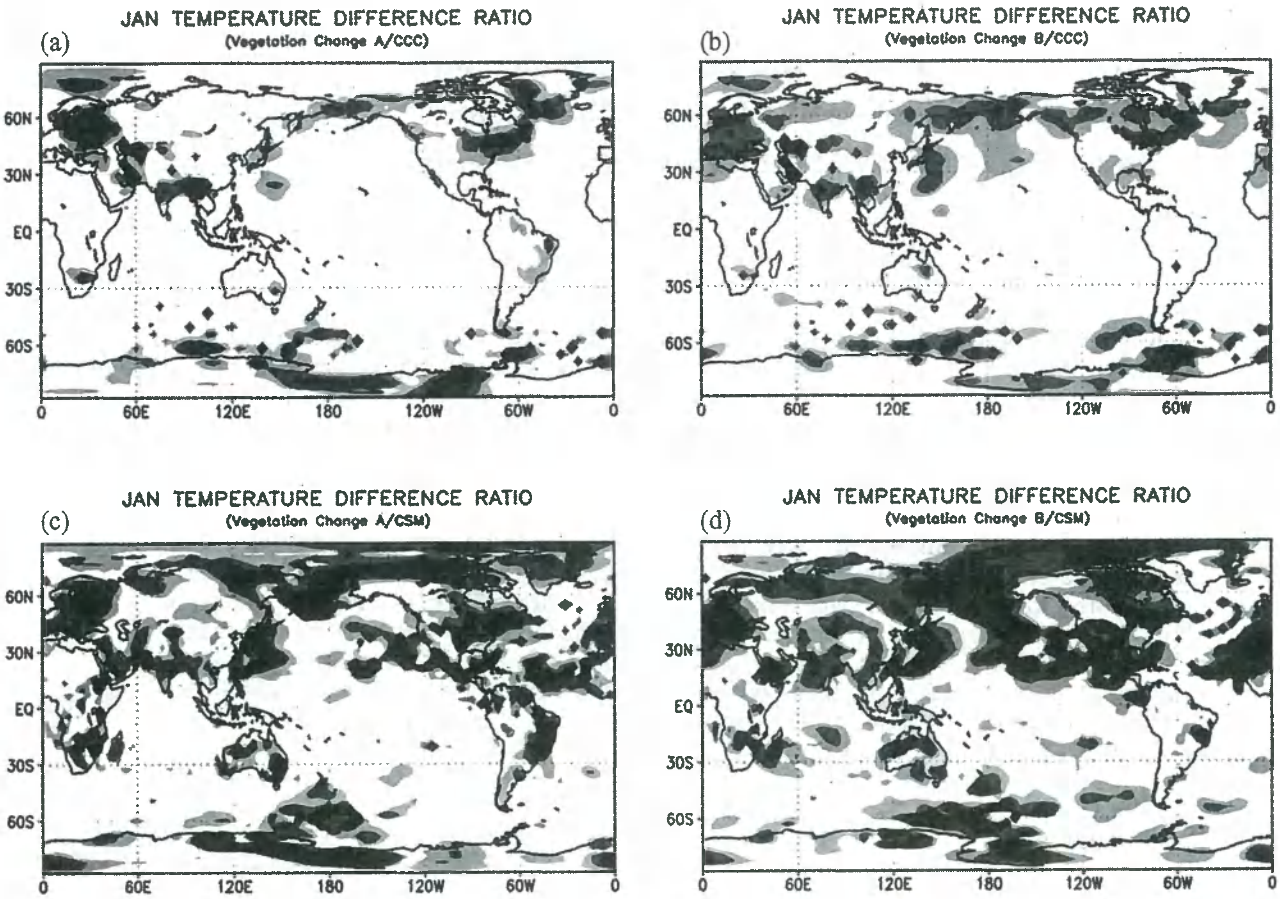

Figure 1. Percentage of the absolute January CO_2/aerosol temperature difference associated with vegetation change (i.e., | vegetation anomaly | / | CO_2 anomaly | ×100). Shading is 50% (lightest), 100%, and 200% (darkest). (a) Vegetation change A/CCCma, (b) vegetation change B/CCCma, (c) vegetation change A/CSM, and (d) vegetation change B/CSM.

effects of historical anthropogenic landcover change (in this context, direct effects are those occurring in regions directly affected by landcover changes; remote effects are those transmitted through the atmosphere to nonlocal regions by circulation changes brought about by landcover changes). Both are of comparable amplitude to observed temperature trends in the past 2 decades, the period of largest global surface warming [e.g., *Karl et al.*, 2000]. This evidence of a confounding influence on surface temperature anomalies may be an indication that the problem of detection of the greenhouse radiative warming fingerprint may be more complicated than previously appreciated.

2. Methods and Data

We used results from a transient CO_2 and sulfate aerosol experiment performed by the National Center for Atmospheric Research (NCAR) with their Climate System Model (CSM). This experiment was driven with observed levels of atmospheric CO_2 and other trace gasses combined with sulfate aerosols representing the period 1870–1998. The NCAR CSM has a fully coupled dynamic ocean and sea-ice model [*Boville and Gent*, 1998]. Fifteen-year averages (consistent with the length of the longest vegetation change experiment) of near-surface temperature were taken from the beginning of the simulation approximating a relatively natural (preindustrial climate). A 15-year average was also taken from the end of the simulations and represents a current climate.

We also used data from a second transient CO_2 and aerosol experiment from the Canadian Center for Climate Modeling and Analysis (CCCma) with their coupled climate model CGCM1 [*Flato et al.*, 2000]. This experiment was forced with observed increases in effective CO_2 and aerosols until the present day when a prescribed increase was used. This simulation ran for a more extensive period (1900–2100) than the CSM simulation. Fifteen-year averages of near-surface temperatures were also taken from the beginning of the simulation and the period ending in 1998.

The two historical landcover change experiments discussed here were performed independently using the NCAR Community Climate Model (CCM3). These model simulations were run with observed, current vegetation as a surface boundary condition and compared against simulations with estimates of vegetation prior to human disturbance (i.e., natural vegetation) as the surface boundary condition. The differences between the surface temperatures simulated under each of these conditions (current-natural vegetation) is therefore an indication of the effect of historical landcover change on climate. The first experiment (vegetation change A) [*Chase et al.*,

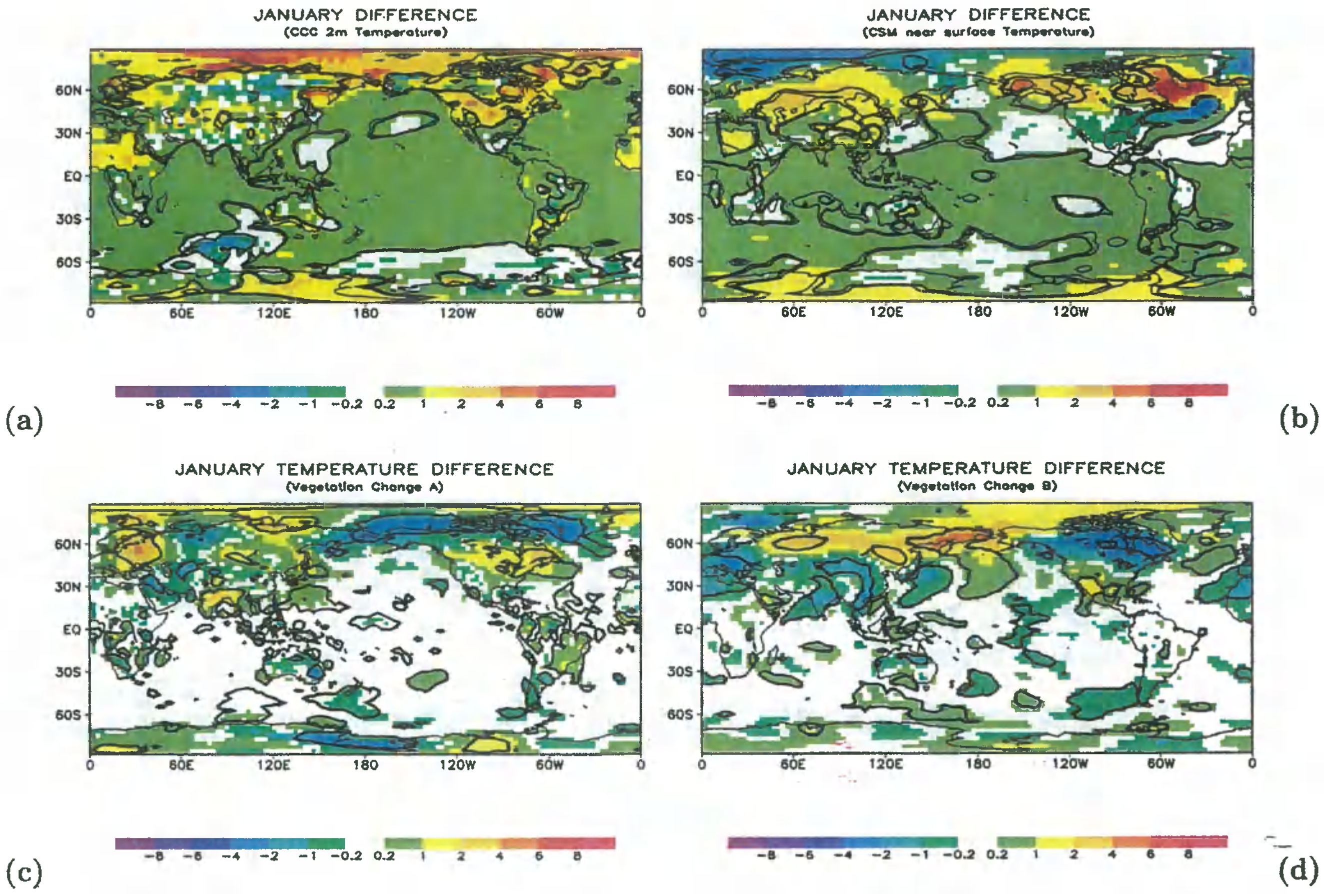

Plate 1. January, near-surface, current-natural temperature differences (°C) with 90% (thick contour) and 95% (thin contour) significance levels contoured. (a) CCCma CO_2/aerosol, (b) CSM CO_2/aerosol, (c) vegetation change experiment A, and (d) vegetation change experiment B.

2000a] was run for 12 years, had noninteracting oceans with a constant sea surface temperature annual cycle, and used the NCAR Land Surface Model (LSM) [*Bonan*, 1996] for land surface calculations. A second experiment (vegetation change B) [*Zhao et al.*, 2001] was run for 17 years and was implemented with a slab ocean model, the Biosphere-Atmosphere Transfer Scheme (BATS) [*Dickinson et al.*, 1993] for surface calculations, and a more conservative land-surface perturbation.

Comparisons of elevated CO_2 experiments have shown that transient simulations where atmospheric models were fully coupled to a dynamic, interacting ocean model had temperature responses relative to equilibrium simulations (with either a static or mixed-layer ocean) which are typically substantially smaller at time of doubled CO_2 [e.g., *Manabe et al.*, 1991; *Dix and Hunt*, 1998; *Gordon and O'Farrell*, 1997; *Washington*, 1992; *Kittel et al.*, 1998]. Modes of variability also varied between these different classes of simulations [*Campbell et al.*, 1995]. Addition of aerosol forcing to climate model simulations further reduced the warming response to CO_2 increases [*IPCC*, 1996, 2001] and invites a comparison to the climatic changes brought about as a result of landcover change. To date, no transient simulations of anthropogenic landcover change with a coupled ocean model have been reported. Because observed changes in landcover appear to affect the strength and positions of global scale circulations [*Chase et al.*, 2000a; *Zhao et al.*, 2001] and to redistribute energy regionally, it is unclear what effect a transient, fully coupled simulation with more degrees of freedom would have on the amplitude and variability of temperature anomalies in these landcover change experiments.

Observed surface temperature trends [*Parker et al.*, 1994] covered the past 2 decades (1978–1998). Missing data were filled by using the first available value from a previous year when possible.

T tests were performed on the observational and CO_2/aerosol records to examine statistical significance. A more powerful Z test [*Katz*, 1982; *Zhao et al.*, 2001] using daily data was performed for the vegetation change scenarios in order to more completely isolate significant signals (i.e., robust climate changes as opposed to natural model variability) due to this less established climate forcing. A comparison of these model results and observations permits an initial assessment of the relative magnitude of the simulated effects due to historical increases in CO_2 combined with aerosols and the effect of historical landcover changes.

3. Model Results

Plate 1 compares the effects of increased CO_2 and landcover change on near-surface temperature in January. Temperature differences are shaded, while contoured regions represent regions of statistically differing means at the 90% (thick contour) and 95% (thin contour) confidence levels. During this month

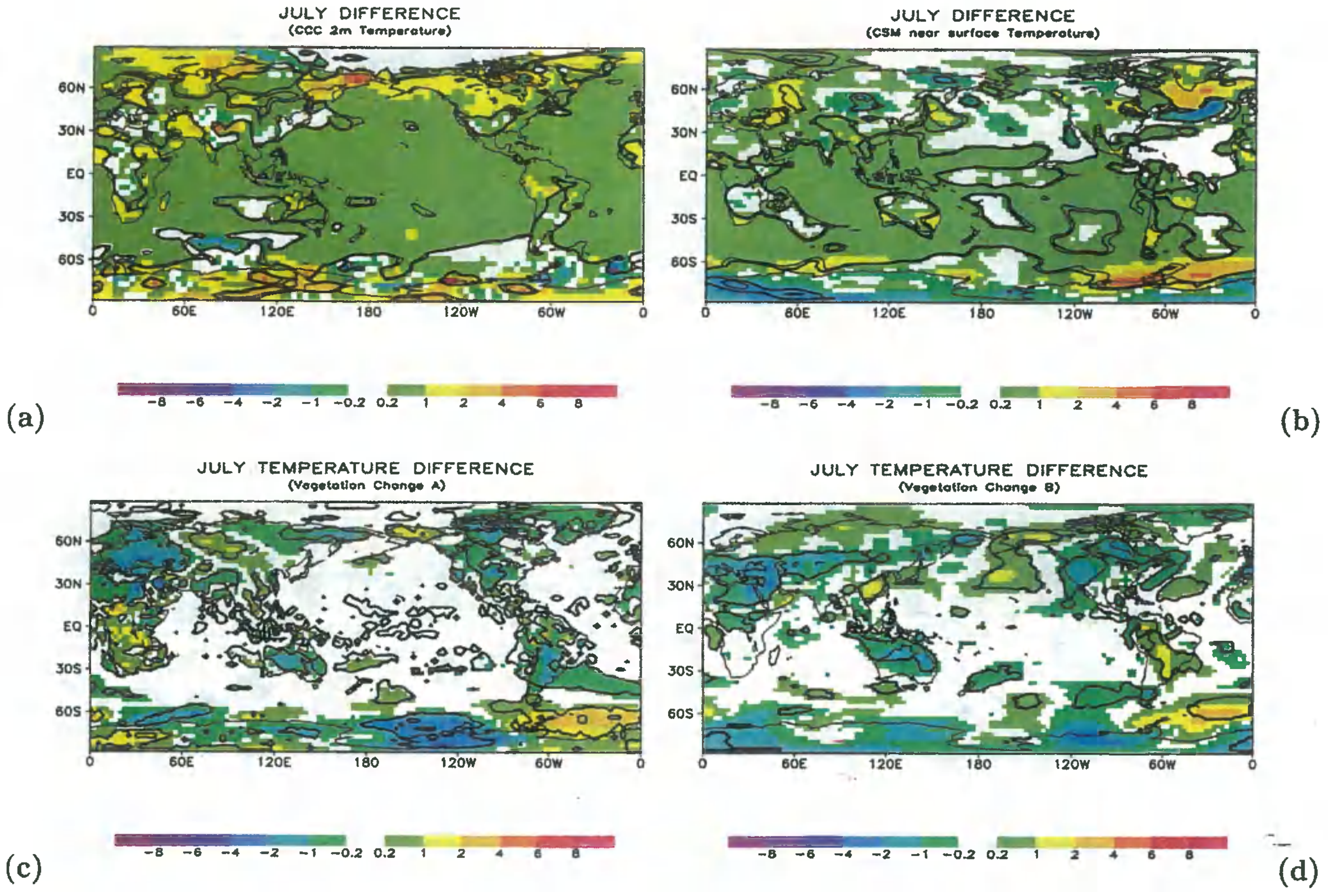

Plate 2. As in Plate 1, but July averages.

both CO_2/aerosol simulations had statistically significant regional climate changes of approximately 1°–3° over large regions of the northern high and midlatitudes. The CCCma model (Plate 1a) had a 1°–4° warming across southern Canada and the northern United States and a 6°–8° warming in the high Arctic. The CSM (Plate 1b) had regions of 2°–4° warming in Alaska, western Canada, and central Asia with an isolated region of warming of 6°–8° in northwestern Canada. The largest temperature anomalies occurred at high northern latitudes in each of these model simulations during this season. Tropical temperature differences are up to 1° in both simulations.

Both landcover experiments (Plates 1c and 1d) simulated regional temperature differences resulting from historical landcover change which were of similar amplitude to those simulated as a result of increased CO_2/aerosols with 1° to 4° differences over much of the higher northern latitudes. Vegetation change experiment A shows a 1°–3° degree warming in the high Arctic. So even in this region of very high temperature

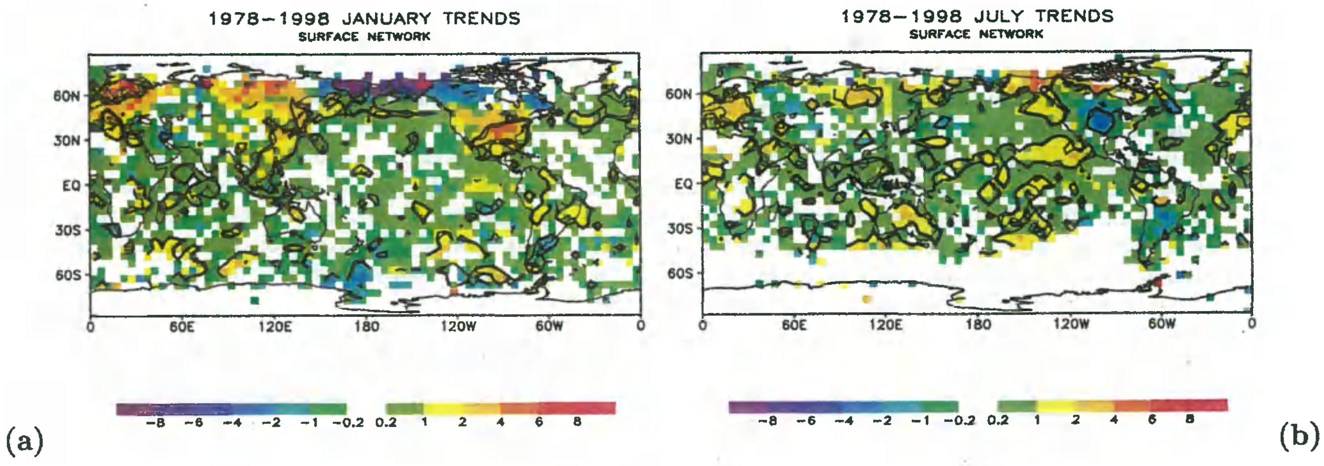

Plate 3. The 1978–1998 observed surface temperature trends in °C/(21 years) with 90 (thick contour) and 95% (thin contour) significance levels contoured. (a) January and (b) July.

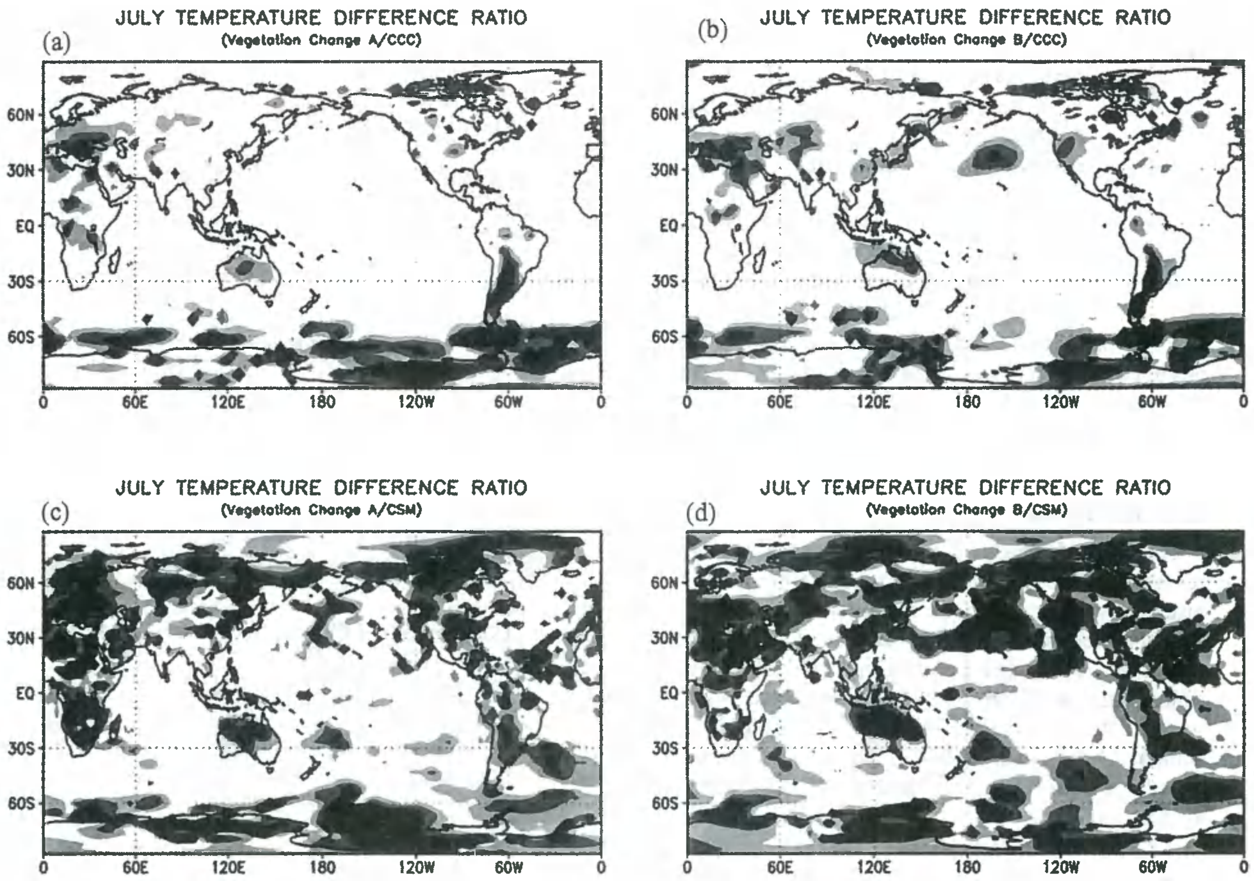

Figure 2. As in Figure 1, but July averages.

anomalies in the CCCma experiment, vegetation change simulates more than 30% of the signal due to greenhouse gasses/aerosols. Both landcover change simulations also show strong and significant temperature anomalies in regions with no direct landcover change forcing. This is an indication that remote teleconnections due to changes in large scale circulations play an important role in the overall effects of historical landcover change.

The ratio of the absolute value of the vegetation change anomalies and the absolute value of the CO_2/aerosol anomalies for January are shown in Figure 1 where shading indicates that the absolute value of the vegetation change anomaly is 50% (light shading), 100%, 200% (darkest shading) that of the corresponding absolute value of the CO_2 anomaly.

Even using the generally more powerful Z test [*Katz*, 1982] on the vegetation change experiments, the statistical significance of the temperature anomalies under CO_2/aerosol forcing is stronger and covers a much wider area than that of the landcover change experiments which is interesting because the size of regional temperature anomalies is comparable in all experiments. This indicates that either the landcover change experiments are generating more variability in general or that differences are occurring preferentially in regions of high variability in the vegetation change experiments.

Plate 2 shows results for July averages. The two CO_2/aerosol experiments (Plates 2a and 2b) have smaller anomalies in this month than in January with between 0°–2° changes over much of the Northern Hemisphere and at high southern latitudes. Tropical differences are usually less than 0.5°. For the vegetation change experiments (Plates 2c and 2d), July anomalies are also smaller than in January, and major differences tend to be limited to land surfaces. Differences of 0°–1° are of the similar magnitude to those generated in the CO_2/aerosol experiments over large regions. The statistical significance is again weaker for the landcover change experiments than for the CO_2/aerosol experiments overall though statistically significant differences tend to be over land areas (where most temperature sensors exist) in contrast to the CO_2/aerosol experiments where the significant differences tend to be over water. Ratios of the anomalies for July are shown in Figure 2 and indicate that the effect of landcover changes in many regions is comparable and can exceed that of CO_2 and aerosols.

4. Comparison With Observations

In this section we compare recently observed climatic changes with the model simulations of section 2. We choose the period starting in 1978 because this period coincides with the steepest rise in temperature in the surface observational record in this century [*Karl et al.*, 2000] and so allows us to compare the magnitude of temperature changes in the model simulations against the largest regional warming trends of this century. Substantial, large-scale landcover changes also occurred during this period [*Leemans*, 1999; *O'Brien*, 2000]. We make no attempt to quantify the relationship between the spatial patterns generated in the model simulations and those in the observations because we believe that any correspondence in regional anomalies would be by chance. Such an analysis would be more appropriate if a large ensemble of each model experiment existed.

In broad terms, the 1978–1998 January temperature changes for the surface observational network (Plate 3) shows recent regional trends of both signs which are of similar magnitude and often occur in similar regions of the globe as those simulated both by increased CO_2/aerosols and by changes in landcover. However, simulations of the effects of CO_2/aerosols show the largest and most significant effects of present-day CO_2 levels to be at precisely the latitudes where the surface observational network has least adequate coverage. In July, observed trends (Plate 3b) are again of similar magnitude to those simulated both in the CO_2/aerosols experiments and in the landcover change experiments.

5. Discussion

The results presented here provide initial evidence from several sources that simulated temperature anomalies due to historically observed CO_2 combined with aerosol forcing and simulated temperature anomalies due to the direct and remote effects of historical, anthropogenic landcover changes are of similar amplitude and may occur in similar regions of the globe so that their effects are not easily spatially isolated. Both are comparable in magnitude to observed trends in the past 2 decades, a period when regional temperature trends should be at their largest.

We emphasize that the effects of historical changes in landcover need further examination with more sophisticated, fully coupled climate system models in order to more completely evaluate the robustness of these results. However, this initial assessment has several implications. First, in order to assess the impact of increases in anthropogenic greenhouse gasses and aerosols on climate, the influence of other factors, including landcover change, must be accounted for in the observational record. Second, disagreements between temperature trends observed at the surface and in the satellite data might be partially explained by changes in landcover which have complex regional effects and might differentially affect surface and tropospheric observations [*National Academy of Sciences*, 2000; *Chase et al.*, 2000b]. Finally, because observed changes in landcover are associated with large scale circulation changes in model simulations, the possibility of an interaction with other natural modes of atmospheric and ocean variability such as the North Atlantic Oscillation (NAO) and Pacific North American (PNA) patterns exists. This interaction might have some role in explaining long-term trends in those modes [*Chase et al.*, 2000a]. Because much of the recent observed warming recorded in the surface observations can be attributed to changes in natural circulation patterns [*Palecki and Leathers*, 1993; *Hurrell*, 1996], this potential interaction is important.

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