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The Effect of a Doubling of Atmospheric CO2 on the Stormtracks in the Climate of a General Circulation Model

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ABSTRACT

We have determined the effect of a doubling of the atmospheric CO2 content on the stormtracks in the climate of a general circulation model. Stormtracks are defined as areas with pronounced geopotential height variability in the 2.25-6 day range. A band-pass filter is designed which filters these periods out of the spectrum. For our analysis we have used the doubled CO2 experiment performed by Wilson and Mitchell (1987). Significant decreases (at a 95 % level of confidence) of the band-pass rms field of the transient part of the 500 hPa height occur over the eastern part of the Pacific stormtrack, over the Atlantic stormtrack off the west-coast of North America and south-east of Africa. Significant increases occur in very high latitudes of the Northern Hemisphere.

1. Introduction

In various climate simulation experiments with general circulation models (GCM's) the climate response to a doubling of the atmospheric CO2 concentration was simulated (e.g. Manabe and Wetherald, 1975; Wilson and Mitchell, 1987). These experiments indicate a reduction of the meridional temperature gradient. Important reasons for this reduction are the enhancement of the warming in high latitudes by the poleward retreat of the highly reflective snowcover, the confinement of the additional heat in high latitudes to the lower part of the troposphere by stable stratification (see Manabe, 1975), the moist adiabatic lapse rate feedback, which tends to produce smaller surface temperature changes in the tropics than in high latitudes, and the large increase in the poleward transport of latent heat due to the increased amount of water vapour in the lower troposphere (see Manabe, 1980). A change of the atmospheric temperature field and accordingly a change of the wind field may change the location and intensity of the jetstream.

Stormtracks, defined by Lau (1976) as area's with pronounced geopotential height variability in the 2.5-6 day period range, tend to coincide closely with regions of strong baroclinicity, which is closely related to the existence of large vertical wind shear (see Blackmon, 1977). Because large vertical wind shear occurs near the jetstream, a change in the location and intensity of the jetstream may have important consequences for properties of stormtracks like location, intensity and frequency of storms.

In this study we determine the effect of a doubling of the atmospheric CO2 content on the stormtracks in the climate of a GCM. We use the doubled CO2 experiment performed by Wilson and Mitchell (1987). The GCM has a resolution of $5^\circ * 7.5^\circ$ latitude/longitude, and 11 sigma-layers which are irregularly spaced, being concentrated near the boundary layer and the tropopause. The GCM contains the seasonal and diurnal solar cycles. The ocean is represented by a 50 m slab in which the heat convergence due to ocean dynamics is prescribed. The control integration simulated 20 years and at the end of year 7 the perturbation run was started with an instantaneous doubling of CO2 amount and ran for 38 years to a new equilibrium. The U.K. Met. Office provided us with the daily fields of the last five winters of both integrations. We use winter data because the observed maxima in the stormtracks are situated in the Northern winter-Hemisphere. We will determine stormtracks at 500 hPa, which level is frequently used in stormtrack-studies (see e.g. Sawyer, 1970; Blackmon, 1976; Lau, 1979).

In calculating band-pass fluctuations (2-6 days) of the geopotential height at 500 hPa we use the filter that is described in the appendix.

In section 2 we firstly show rms fields of the unfiltered and band-pass filtered transient part of the 500 hPa height as observed in the atmosphere. Next we show the fields of these variables in the GCM-control and perturbation climate. Also the difference between the perturbation and control climate of the unfiltered and band-pass filtered fields are shown. The statistical significance of the climate changes are determined with a t-test and a Wilcoxon-test.

2. Results

We confine our results to the unfiltered and band-pass filtered 500 hPa height. Before presenting the fields of the GCM-control and perturbation climate we show plots of the fields as observed in the atmosphere.

(a) Atmospheric observations

Fig. 1 shows some statistical quantities relating to the observed 500 hPa height in winter according to Blackmon (1976). One measure of the intensity of transient disturbances, the total rms of the transient part of the 500 hPa height, is seen in Fig. 1a. In addition to a general increase from south to north up to about 50° N, three maxima are noticed. The band-pass fluctuations, shown in Fig. 1b, have their largest intensity along the major storm tracks off the eastern coast of the two continents.

(b) The GCM-control and perturbation climate

The total and band-pass rms of the transient part of the 500 hPa height in the GCM-control and perturbation climate are shown in Fig. 2 and Fig. 3 respectively. The total rms of the control climate (Fig. 2a) shows, like the observations in Fig. 1a, a general increase in the Northern Hemisphere from south to north. However, the observed and simulated maxima at about 60° N are not located at the same longitudes and the rms values in the observed field are up to 50 % larger than those in the control climate. The band-pass rms in the control climate (Fig. 2b) shows maxima off the eastern coast of the two continents and off the western coast of North America. The latter maximum is not observed in the real atmosphere (Fig. 1b). The amplitudes of the band-pass rms field in the control climate are similar to the observed amplitudes. The rms fields in the perturbation climate, shown in Fig. 3, are similar to those in the control climate. The band-pass rms field in the perturbation climate does not show the maximum off the western coast of North America that is observed in the control climate.

(c) Differences between the GCM-perturbation and control climate

The differences between the perturbation and the control climate of the transient part of the 500 hPa height, unfiltered and band-pass filtered, are shown in Fig. 4. We will concentrate on differences in the band-pass part of the spectrum, shown in Fig. 4b. Generally, in the Northern Hemisphere the CO2 doubling induces an increase of the band-pass rms field north and a decrease south of 45^{o} N. The most pronounced changes occur over the Pacific stormtrack, which intensity increases in its western and decreases in its eastern part. A similar but smaller change occurs over the Atlantic stormtrack. In the Southern Hemisphere, the most important change is the decrease of the maximum south-east of Africa.

To estimate the statistical significance of the simulated CO2-induced climate changes, a two tailed Student's t-test and a two-tailed Wilcoxon-test are performed, both at a 95 % level of confidence. The tests are performed on time series of winter-mean data (one serie of five winters of the control and one serie of five winters of the perturbation climate). A t-test is allowed when the elements of the series are independent, have a Gaussian distribution and when in addition the two series have the same variance (i.e. the same interannual variability). It is not obvious that the second and third condition are fulfilled in our situation. That's why we also use the Wilcoxon-test, which does not require constraints of the probability distributions of the elements of the timeseries. Fig. 5 shows the areas of significant increase and decrease of the total and band-pass rms of the transient part of the 500 hPa height. Fig. 5a and 5c show that according to both tests almost nowhere changes in the total rms field are significant. However, both test show (Fig. 5b and 5d) a significant increase of the band-pass rms in very high latitudes and a significant decrease off the western coast of North America and south-east of Africa. The 'significant areas' according to the Wilcoxon-test are, of course, smaller than those according to the t-test.

3. Conclusions

We have determined the effect of a doubling of the atmospheric CO2 content on the stormtracks in the climate of a GCM. Generally in the Northern Hemisphere the CO2 doubling induces an increase of the band-pass (2.25-6 days) rms field of the transient part of the 500 hPa height north and a decrease south of 45° N. The most pronounced changes occur over the Pacific stormtrack, which intensity significantly decreases (at a 95 % level of confidence) over its eastern part. Also a significant decrease occurs near the center of the Atlantic stormtrack off the eastern coast of North America. In the Southern Hemisphere a significant decrease occurs south-east of Africa.

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APPENDIX : Derivation of the band-pass filter

We determine the winter-mean geopotential height variability in the 2-6 day range, $\left(\overline{\phi^2_{BP}}\right)^{1/2}$, as follows :

$$\left(\overline{\phi^2_{BP}}\right)^{1/2} = \left(\frac{1}{74}\sum_{i=9}^{82}\phi^2_{BP}(i)\right)^{\frac{1}{2}}, \tag{1}$$

where

$$\phi_{BP}(i) = \sum_{j=-8}^{8} c(j)\,\phi(i+j), \tag{2}$$

where $\phi_{BP}(i)$ is the band-pass filtered and $\phi(i)$ the unfiltered geopotential height at 500 hPa at day i and c(j) are the filtercoefficients. Each time series consists of 90 days (DJF) so $\phi_{BP}(i)$ can be determined for i=9 to i=82. Stormtracks are defined as areas with pronounced $\left(\overline{\phi^2_{BP}}\right)^{\frac{1}{2}}$.

The filtercoefficients are estimated as follows. If L(t) is the part of a timeseries x(t) which passes a filter with a transferfunction B(λ) then

$$L(t) = \sum_{j=-\infty}^{\infty} C(j)\,x(t-j). \tag{3}$$

The filtercoefficients are given by

$$c(j) = \mathrm{Re}\left(\frac{1}{2\pi}\int_{-\pi}^{\pi}\exp(i\lambda j)\,B(\lambda)\,d\lambda\right), \tag{4}$$

where λ equals 2π/T and T is period (see e.g. Koopmans, 1974). We use a filter which passes periods between 2.25 and 6 days :

$$\begin{aligned} B(\lambda) &= 1 \quad \text{for} \quad 2\pi/6 < \lambda < 2\pi/2\tfrac{1}{4} \\ &= 0 \quad \text{else.} \end{aligned} \tag{5}$$

Calculation of (4), using (5) gives :

$$c(j) = \frac{1}{\pi j}\left(-\sin\frac{\pi j}{3} + \sin\frac{8\pi j}{9}\right). \tag{6}$$

Following Blackmon (1976) we only use j=-8 to j+8. We don't use the filter that was applied by Blackmon (1976) because his filter was designed to filter timeseries that consist of two values per day, while our timeseries consist of one value per day.

Because a signal with T = ∞ (x = constant) should not pass the band-pass filter, it follows from (1) that

$$\sum_{j=-\infty}^{\infty} c(j) = 0 \ . \qquad (7)$$

In our case, in which only j=-8 to j=8 are used, a constant signal would partially pass the filter when (6) would be applied. To stop a constant signal entirely we modify the c(0)-coefficient such that

$$\sum_{j=-8}^{8} c(j) = 0 . \qquad (8)$$

Applying (6) and (8) we get the filter-coefficients :

c(0) = 0.6216594

c(1) = -0.1667961

c(2) = -0.2401350

c(3) = 0.0918881

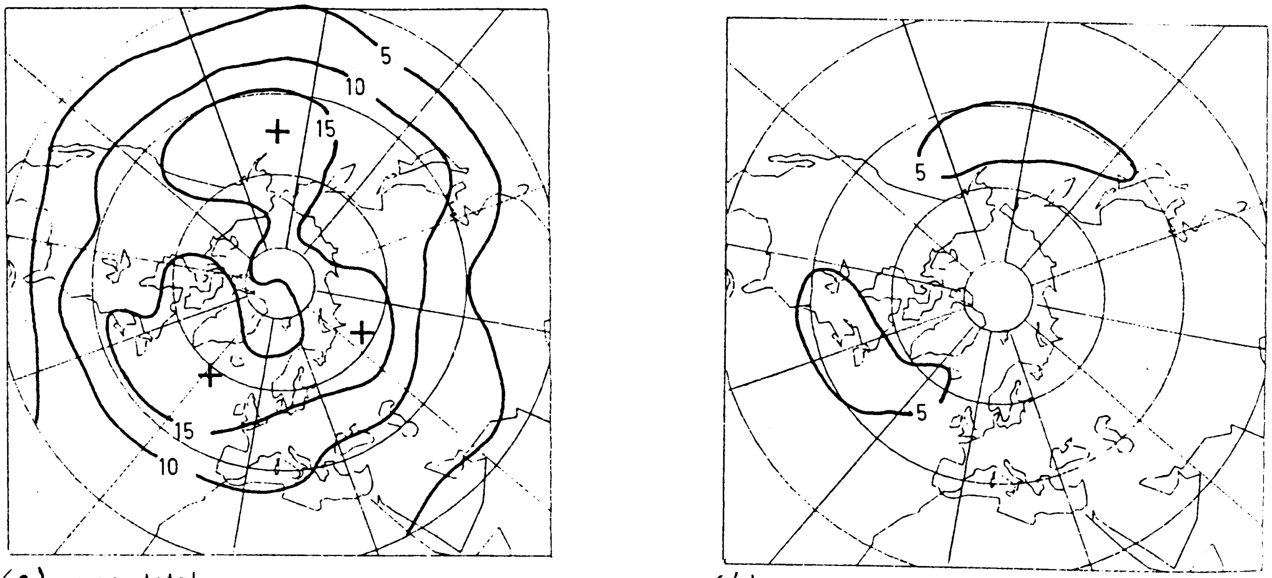
c(4) = -0.0094524

c(5) = 0.1178277

c(6) = -0.0459441

c(7) = -0.0101513

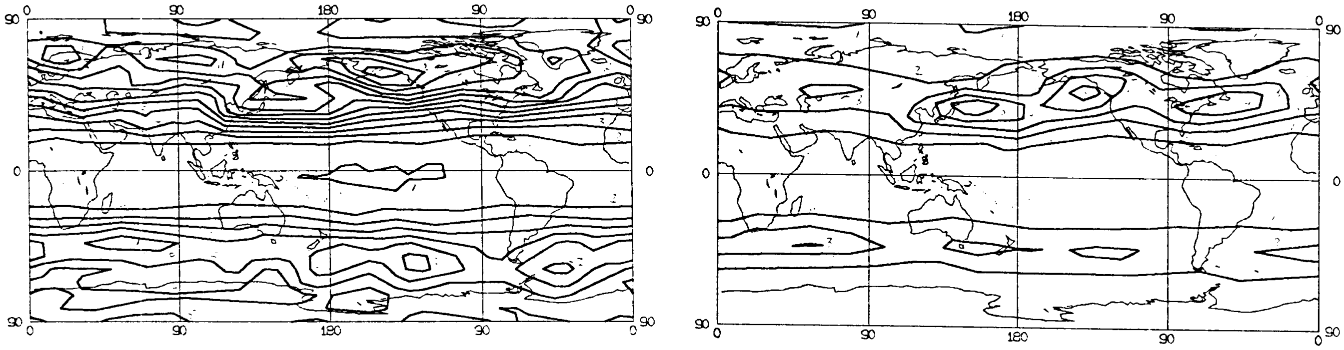
c(8) = -0.0480666



(a) rms total OBSERVED

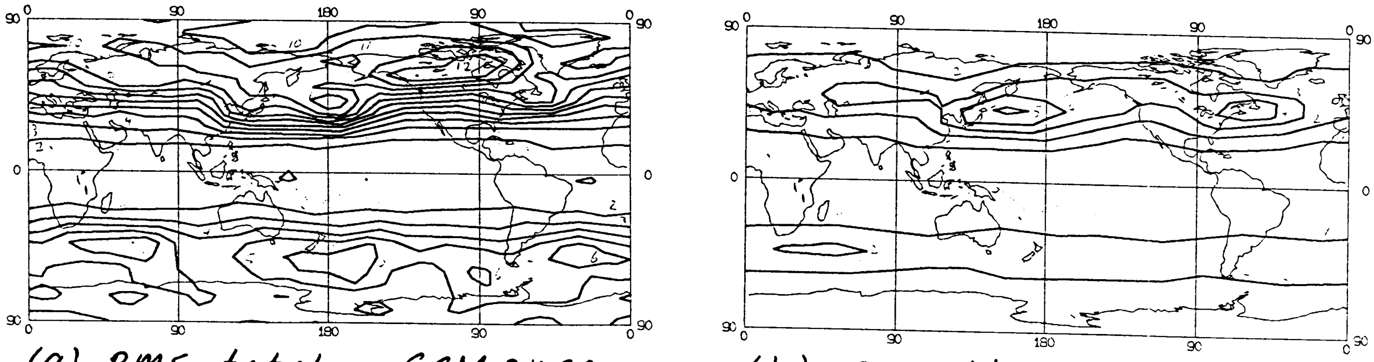
(b) rms, 'band-pass' (2.5 - 6 days) OBSERVED

FIG. 1. rms fields of the transient part of the 500 hPa height in a 10 year sample of observations, redrawn from Blackmon (1976) : (a) unfiltered; (b) band-pass (2.5-6 days) filtered. The contour interval is 5 gpDm.



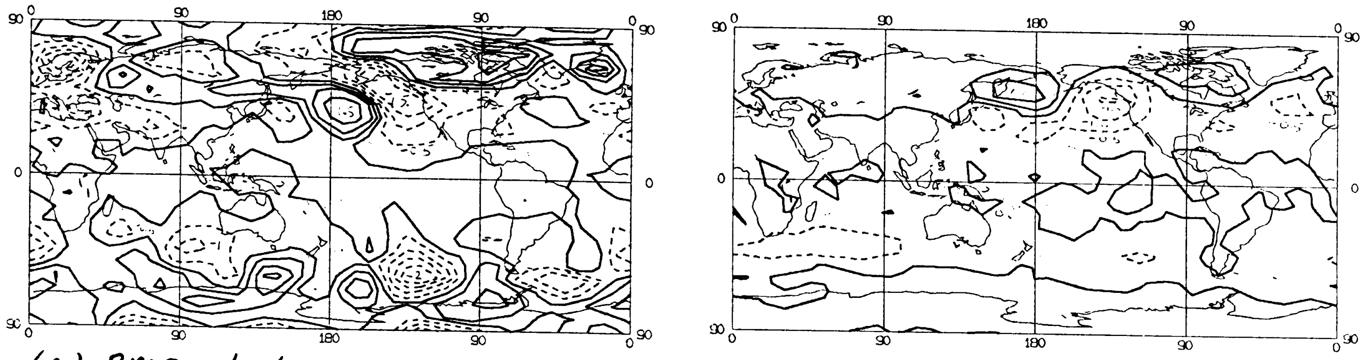
(a) Rms total GCM $1 * CO_2$ (b) Rms 'band-pass'

FIG. 2. rms fields of the transient part of the 500 hPa height in the GCM-control climate : (a) unfiltered; (b) band-pass filtered. The contour interval is 1 gpDm.



(a) Rms total GCM $2*CO_2$ (b) Rms 'band-pass'

FIG. 3. rms fields of the transient part of the 500 hPa height in the GCM-perturbation climate : (a) unfiltered; (b) band-pass filtered. The contour interval is 1 gpDm.



(a) Rms total GCM $2*CO_2 - 1*CO_2$ (b) Rms 'band-pass'

FIG. 4. rms fields of the transient part of the 500 hPa height in the GCM-perturbation climate minus the corresponding fields in the GCM-control climate : (a) unfiltered; (b) band-pass filtered. The contour interval is 0.5 gpDm.

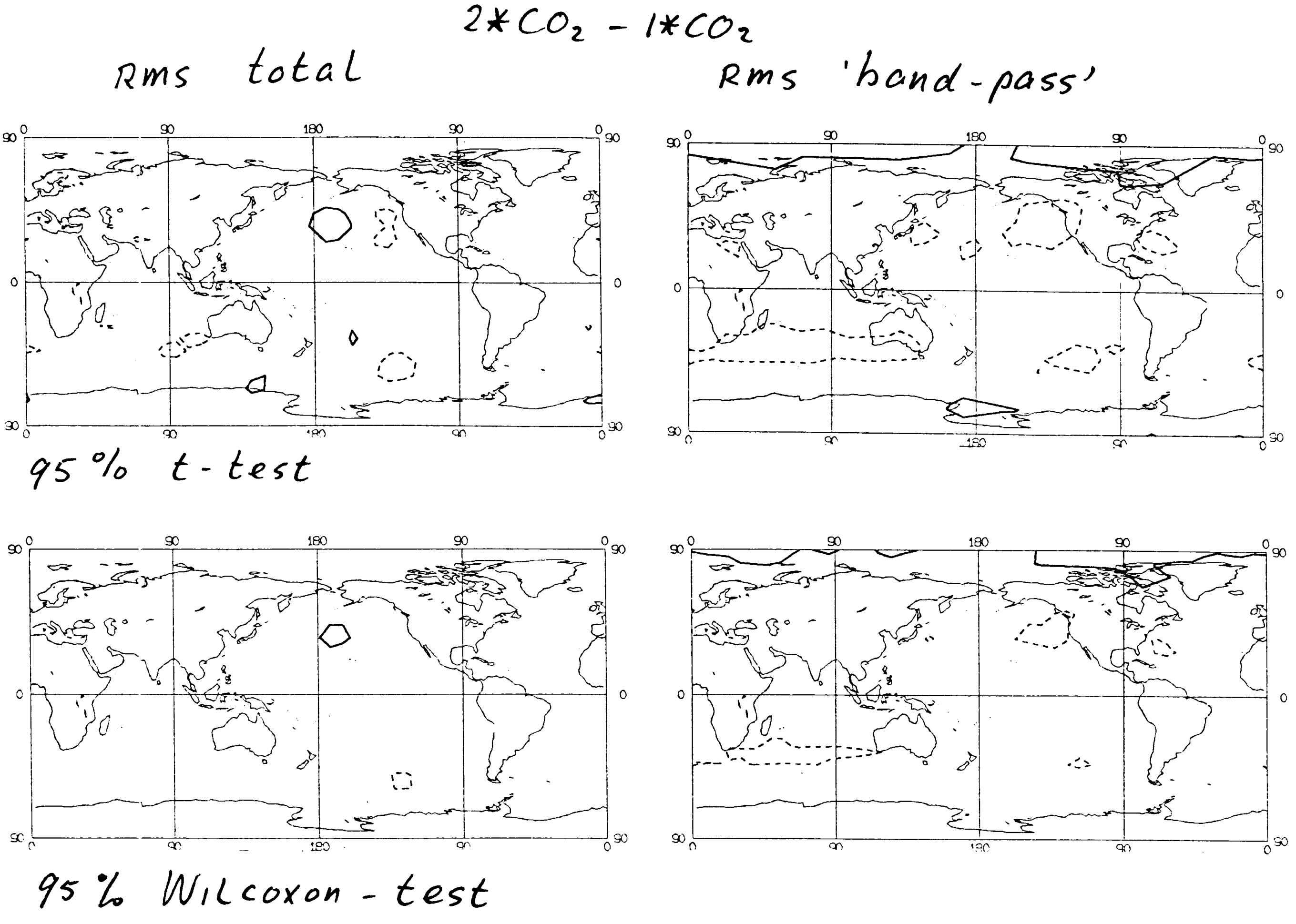


FIG. 5. Statistical significance at a 95 % level of confidence on differences between the perturbation and control climate of rms fields of the transient part of the 500 hPa height. Solid lines encircle areas of significant increase, areas of significant decrease are encircled by dashed lines. Students t-test on (a) the total and (b) the band-pass rms fields; Wilcoxon-test on (c) the total and (d) the band-pass rms fields.