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A CO_2-climate sensitivity study with a mathematical model of the global climate

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An increase in the CO_2-content of the atmosphere resulting from man's activity could have a significant effect on the climate in the near future[1]. We describe here some new results from a study of the response of a mathematical model of the climate to an increase in the CO_2-content of the air.

The mathematical model consists of (1) a general circulation model of the atmosphere and (2) a simple mixed layer ocean model with uniform thickness. The atmospheric model predicts the changes of the vertical component of vorticity, divergence, temperature, moisture and surface pressure based on the equations of motion, the thermodynamical equation, and the continuity equations of moisture and mass. The horizontal distributions of these variables are represented by a limited number of spherical harmonics (maximum zonal wavenumber retained is 15)[2,3]. However, the vertical distributions are specified at nine unequally spaced finite difference levels. The model has a global computational domain and realistic geography.

For the computation of solar and terrestrial radiation, the distributions of ozone and cloud cover are prescribed beforehand and the concentration of carbon dioxide is set differently for each experiment, whereas the distribution of water vapour is determined from the prognostic system of water vapour.

Condensation of water vapour is predicted whenever supersaturation is indicated in the computation of the continuity equation of water vapour[4]. Snowfall is predicted when air temperature near the Earth's surface falls below the freezing temperature[5]. Otherwise, rainfall is predicted.

The temperature of continental surface is determined so that it satisfies the requirement of the heat balance[5]. The changes of soil moisture and snow depths are obtained from the budget-computations of water and snow, respectively[5].

The ocean model is a static isothermal water layer of uniform thickness with provision for a sea ice layer. The thickness of 68 m is chosen to ensure that the heat storage associated with the annual cycle of observed sea surface temperature is correctly modelled. Ocean temperature change is computed based on the budget among surface heat fluxes. In the presence of sea ice, the temperature of underlying water is at the freezing point and the heat flux through ice is balanced by the latent heat of freezing and melting at the bottom of the ice. This process, together with the melting at the ice top, sublimation and snowfall, determines the change of ice thickness[6]. The albedo of sea ice and continental snow is assumed to vary between 60 and 70% depending on latitudes. Smaller values are assigned for thin sea ice or thin snow or melting sea ice.

To evaluate the climatic effect from an atmospheric CO_2 increase, we perform two time integrations of the model assuming the normal seasonal insolation cycle and starting from an isothermal, dry and motionless atmosphere with isothermal ocean. The atmospheric CO_2 concentration is set at 300 p.p.m. and 1,200 p.p.m. by volume, respectively (hereafter, these experiments are referred to as $1\times CO_2$ and $4\times CO_2$ experiments). Both cases settle down to a stable climatic condition in about a decade of model time (see Fig. 1). The standard experiment successfully reproduces the observed basic characteristics of geographical and seasonal temperature variation, encouraging the assertion of realism for the model sensitivity to CO_2 changes. The seasonal variations of the model climate

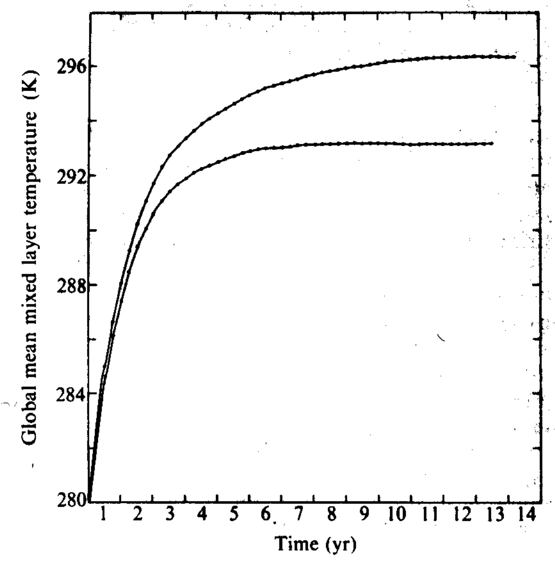

Fig. 1 Time variation of the global mean mixed layer temperature. Lower and upper lines are obtained from the $1\times CO_2$ and $4\times CO_2$ experiment, respectively. The seasonal variation is removed through the application of the running mean procedure over the period of 12 months.

discussed below represent mean annual cycles over the last 3-yr periods of both time integrations.

Figure 2*a* shows the seasonal variation of the difference of zonal mean surface air temperature between the $4\times CO_2$ and $1\times CO_2$ atmospheres. In low latitudes, the warming due to the quadrupling of CO_2 content in air is relatively small and depends little on season, whereas in high latitudes, it is generally larger and varies markedly with season particularly in the Northern Hemisphere. Over the Arctic Ocean and its neighbourhood, the warming is at a maximum in early winter and is small in summer. This implies that the range of seasonal variation of surface air temperature in these regions reduces significantly in response to the quadrupling of CO_2 content of air. From the seasonal variations of zonal mean sea ice thickness shown in Fig. 3, it is observed that the sea ice from the $4\times CO_2$ experiment is everywhere less than the sea ice from the $1\times CO_2$ experiment. Therefore it is reasonable to suggest that the $1\times CO_2$ atmosphere is insulated by thicker sea ice from the influence offrlying seawater and has a more continental climate with a larger seasonal variation of temperature than the $4\times CO_2$ atmosphere. Although the poleward retreat of highly reflective snowcover and sea ice is mainly responsible for the relatively large warming in high latitudes, the change of the thermal insulation effect of sea ice strongly influences the seasonal variation of the warming over the Arctic region.

An analysis of the heat balance over the Arctic Ocean indicates that, in early winter, the flux of sensible heat from the Earth's surface to the atmosphere is much larger in the $4\times CO_2$ case than the $1\times CO_2$ case because of the difference in the magnitude of upward conductive heat flux through sea ice. As the stable stratification in the surface layer of the model atmosphere prevents the sensible heat flux from penetrating into the middle troposphere in high latitudes, the aforementioned difference in sensible heat flux results in the large warming of surface air during early winter. As previously stated, the magnitude of the warming in the summer is much less than the warming in the winter. Because sea ice is thin or absent during summer, the surface albedo reduces significantly and net incoming solar radiation increases from the $1\times CO_2$ to the $4\times CO_2$ case. However, the additional solar radiation is used either for melting upper surface of sea ice or warming the ice-free mixed layer which has a large heat capacity. Thus, the summer warming of the surface air turns out to be relatively small. However, the additional solar energy, which is absorbed during summer in the $4\times CO_2$ case, delays the appearance of sea ice or reduces its thickness. This increases the conductive heat flux through ice in early winter when the air–sea temperature difference becomes large, thereby enhancing the warming of the surface atmospheric layer in early winter.

The seasonal variation of the difference in the surface air temperature between the two experiments over the model continents is significantly different from the variation over the model oceans. According to Fig. 2*b*, which shows the latitude–time distribution of the difference in zonal mean surface air temperature over continents, the CO_2-warming in high latitudes is at a maximum in early winter, being influenced by the large warming over the Arctic Ocean discussed above. However, Fig. 2*b* also indicates a secondary centre of relatively large warming around 65°N in April. This results from a large reduction in surface albedo in spring when the insolation acquires a near-maximum intensity. The reduction of snow cover area from the $1\times CO_2$ to the $4\times CO_2$ experiment is responsible for this albedo difference.

This study shows two interacting mechanisms, each acting to produce its own sensitivity maximum. The maximum warming of the early winter over the Arctic Ocean and its neighbourhood is caused by the change in sea ice thickness, and the relatively large warming over the continents in spring is produced by snow albedo feedback. Therefore, it seems reasonable that simpler climate models with the albedo feedback mechanism but without the thermal insulation effect of sea ice would have the largest sensitivity in the early summer[7,8]. Using his simple model, Sellers[9] found an early winter maximum sensitivity at ~80°N. This winter maximum, however, apparently results from different mechanisms.

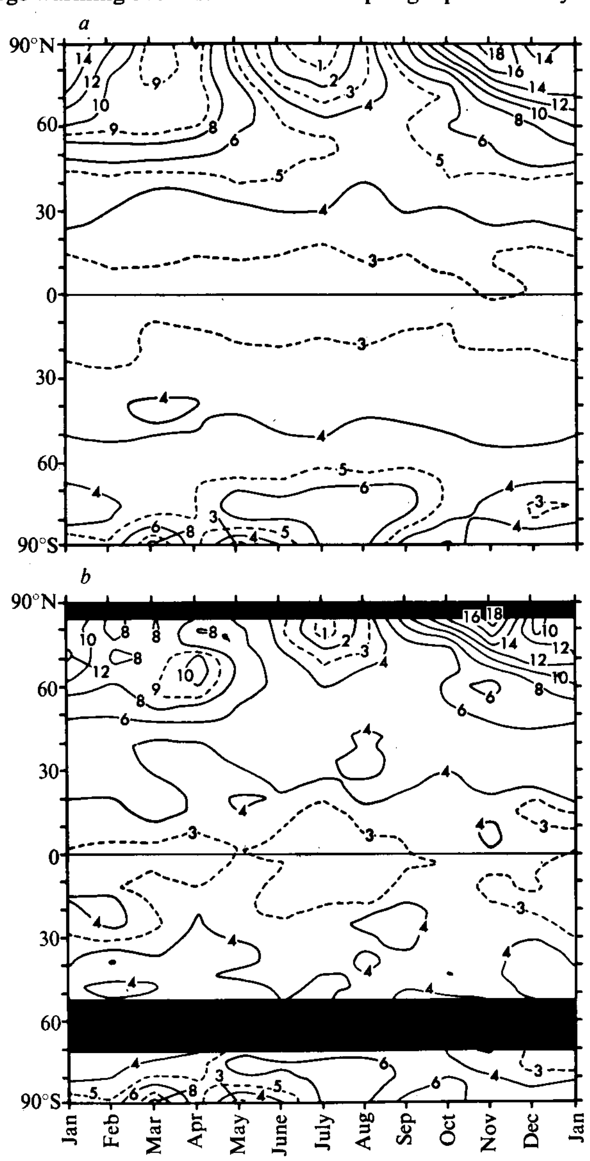

Fig. 2 Latitude–time distributions of the difference in zonal mean surface air temperature between the $4\times CO_2$ and $1\times CO_2$ atmospheres. *a*, Oceans and continents; *b*, continents only. (Positive value indicates warming caused by the quadrupling of CO_2-content of air.)

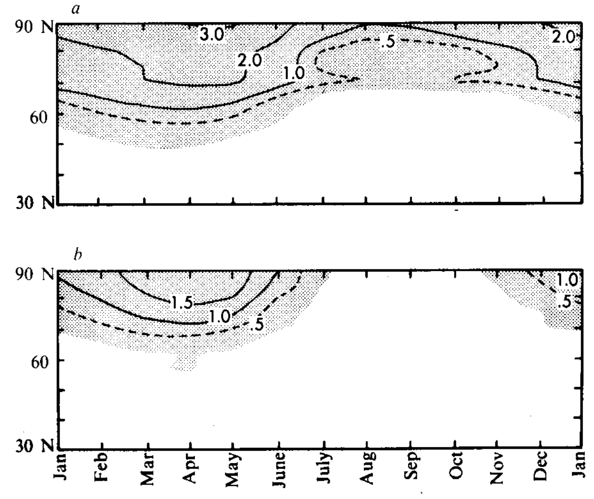

Fig. 3 Latitude–time distributions of zonal mean thickness of sea ice in metres for the Northern Hemisphere oceans. *a*, $1\times CO_2$ experiment; *b*, $4\times CO_2$ experiment. The shading indicates the areas where sea ice thickness is more than 0.1 m.

Table 1 summarises the area mean changes of the annual mean surface air temperature of the model atmosphere which occurs in response to the quadrupling of CO_2 content in air. According to Table 1, the global mean warming of the model atmosphere is ~4°C. This result suggests that the warming caused by the doubling of CO_2-content would be ~2°C. This is significantly less than the warming which is estimated by the general circulation model of Manabe and Wetherald[10] with idealised geography and without seasonal variation of insolation. Table 1 also reveals that the area mean warming of the Northern Hemisphere is significantly larger than that of the Southern Hemisphere. This interhemispheric difference results partly from the smallness of the snow albedo-feedback effect over the Antarctic ice sheet where surface albedo differs little between the $1\times CO_2$ and $4\times CO_2$-experiments.

Table 1 The surface air temperature difference between the $4\times CO_2$ and $1\times CO_2$ atmosphere in °C

	Northern Hemisphere	Southern Hemisphere	Global domain
Difference	4.5	3.6	4.1

Positive value indicates warming caused by the quadrupling of CO_2-content of air.

In view of the assumption of fixed cloudiness and various simplifications contained in the sea ice modelling, the quantitative aspect of the present results should be received with caution. However, this study suggests that the warming of the atmosphere in response to an increase in CO_2-content of the air will have significant seasonal and interhemispheric asymmetries.

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