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A SIMPLE PARAMETERIZATION OF ICE LEADS IN A GENERAL CIRCULATION MODEL, AND THE SENSITIVITY OF CLIMATE TO CHANGE IN ANTARCTIC ICE CONCENTRATION

by

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ABSTRACT

We present a simple parameterization of the effect of open leads in a general circulation model of the atmosphere. We consider only the case where the sea ice distribution is prescribed (i.e., not interactive) and the fraction of open water in the ice is also prescribed and set at the same value at all points in the Southern Hemisphere and a different value in the Northern Hemisphere. We approximate the distribution of sea ice over a model "grid box" as a part of the box being covered by solid ice of uniform thickness and the complement of the box consisting of open water at a fixed −1.8°C. Because of the nonlinearity in the flux computations, separate calculations are performed over the solid sea ice and over the open leads. The net fluxes conveyed to the atmosphere over the grid box are determined by performing the appropriate area-weighted average over the two surface types.

We report on an experiment designed to assess the sensitivity of the modelled climate to the imposition of a 50% concentration in the winter Antarctic sea ice. Significant warming of up to 6°C takes place in the vicinity of and above the Antarctic sea ice and is associated with significant changes in the zonal wind structure. Pressure reductions are simulated over the sea ice, being particularly marked in the Weddell Sea region, and an anomalous east–west aligned ridge is simulated at about 60°S. Very large changes in the sensible heat flux (in excess of 200 W m^{-2}) are simulated near the coast of Antarctica.

INTRODUCTION

There are a number of reasons why the study of surface interactions at high latitudes is of considerable importance. Perhaps one of the most timely of these is the need to obtain reliable estimates of the Earth's climate over the next decades and longer in response to the Greenhouse Effect. One of the powerful tools available to us in our quest to understand the workings of the climate system is the General Circulation Model (GCM). In these computer models of the global atmosphere the dynamical and physical processes are represented as well as practicable and if they simulate present-day climate with reasonable veracity we can have some confidence that the models would respond to imposed changes (e.g. the doubling of carbon dioxide) in a way similar to the real atmosphere.

One problem with the use of these models in such sensitivity studies is that the treatment of sea ice has in the past been rather crude. Sea ice plays an important role in climate change and, given the task which GCMs will increasingly be asked to perform in the coming years, it is clear that the sea ice must be handled in a physically realistic manner. Many GCMs prescribe the sea ice as a continuous cover of uniform thickness (usually about 2 m), which has a prescribed albedo and permits a diffusive heat flux related to the difference between the temperature on the bottom and top side of the ice (e.g., Simmonds (1981)). In such models the atmosphere responds to the presence of the ice but the ice is not able to react to atmospheric changes. In the model used in the present study, the structure of which is detailed in Simmonds (1985) and Simmonds and others (1988), the representation of the sea ice is of this type. In this paper we seek to make this representation more realistic without considering the full complexity of a more interactive sea-ice model. The modification we deal with here is to allow consideration of the effects of regions of open water (leads) in the sea-ice zone. It is well known that even rather small regions of open water are able significantly to affect the fluxes of heat across the Earth–atmosphere boundary (e.g. Andreas and Murphy (1986)) and hence the allowance for the effect of leads is potentially quite important. Simmonds and Dix (1986) and Mitchell and Senior (1989) and others have simulated the dramatic effects of the extreme case of the removal of regions of Antarctic winter sea ice. While these experiments are illuminating, they correspond to sea-ice changes not seen in the present climate regime. Below we discuss a model modification in which the distribution of sea ice is still *prescribed* but allows for the specification of the fraction of open water (which we denote as f_w) in the sea-ice zone. We report on an experiment conducted with this modification and compare the behaviour of the atmosphere with that in the "control" (i.e., continuous ice) case. The results of experiments such as this help us determine the climate sensitivity to changes in sea ice and allow an assessment of the likely benefit of expending effort in developing sea-ice models of greater complexity. Ledley (1988) has incorporated a leads parameterization in a simple energy-balance model of climate and found considerable sensitivity to the lead fraction specified.

PARAMETERIZATION OF LEADS

A consistent treatment of the effect of leads in the sea-ice zone must take into account two important modifications that the exposure of open water introduces. These are the impact on the surface fluxes and on the vertical profile of the radiative heating rates. In the following we conceive of each model "grid box" in the sea-ice zone to be broken into a sea-ice part and an open leads part. However, because of the rapid mixing in the atmospheric boundary layer, we are justified in using only one (horizontally averaged) vertical atmospheric profile, which is that computed by the model; we do not consider separate profiles above the sea ice and the leads. In particular this means that the temperature, moisture and wind at the lowest model level (which play a role in determining the various fluxes) apply to the whole grid box (i.e. ice as well as leads). In reality one would expect some difference in atmospheric profiles over the two surface types but we suggest the differences would be rather small.

Surface heat fluxes

An important impact of leads in sea ice is their effect on the surface fluxes of moisture, temperature and

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momentum. The parameterization of these in the model over continuous sea ice and open water is discussed in Simmonds (1985). It suffices to say here that, for a given atmospheric structure, these fluxes are very different over the two domains. Because of the strong nonlinearity in the exchange coefficients of the surface turbulent-heat transfer it is not realistic to "mix" horizontally the surface temperature and albedo and to use the results in a box-average calculation. Instead we must perform separate flux calculations over the sea-ice and open-water parts of the box. The surface temperature over the open water part of the box is assumed to be −1.8 °C while that over the ice is computed from an energy balance, as discussed below. These fluxes are then averaged with the appropriate area weighting and the transports communicated to the lowest level of the model.

Vertical profile of the radiative heating

In the standard model version, the calculation of the vertical profile of the radiative heating rates depends on whether it is performed over sea ice or open water. Over sea ice the requirement of energy balance is used to determine the surface temperature, which in turn affects the heating rate profile. By contrast, over ocean the sea surface temperature (SST) in our model is prescribed. It should also be pointed out that the surface emissivity of sea ice and water will, in general, be different as will the respective albedos. These factors dictate that the surface radiative flux and heating rate profile above sea ice and ocean will be different even though the atmospheric structure above the two may be identical.

However, in our scheme we suppose the leads to be small scale and the vertical profile of the radiative heating rates over the two surface types to be "well mixed". On this assumption we need perform only one radiation calculation for each column and set the surface albedo to the area-weighted average of the sea ice and open water albedo. As mentioned above, to be able to calculate the surface fluxes over the sea-ice parts, we need to determine the surface temperature over this domain. This is done by performing an energy balance. In this we make use of the absorbed solar radiation and downward longwave radiation at the surface already calculated over the entire grid box. This is done to simulate the energy transfer of the radiation absorbed by the water to the sea ice (by mixing) while the water temperature remains fixed at the melting point. This implied horizontal heat transfer is found to be rather small and the energy balance over the sea ice proper is predominantly determined by the outgoing longwave flux and latent and sensible heat fluxes.

ESTIMATES OF ICE CONCENTRATION

The recent compilations of Zwally and others (1983), the Commander, Naval Oceanography Command (1985), Parkinson and others (1987), and Gloersen and Campbell (1988) clearly demonstrate the dependence of sea-ice concentration on season and hemisphere. These various sources estimate the July sea-ice concentration as between 65 and 73% in the Arctic and between 75 and 95% in the Antarctic. Gloersen and Campbell have pointed out the previous analyses may have underestimated the percentage of open water if a significant amount of visual or infrared imagery was used. They reasoned that open water is liable to produce cloud and hence the open water will not have been "seen" by the satellite. The presence of clouds presents no difficulty in the microwave case.

All of the above values represent an average ice concentration over the area specified. Inspection of the various data sources reveals that the concentration does vary and in general becomes higher at higher latitudes, as one would expect. In our parameterization, for simplicity, we do not consider f_w as varying with position but we do prescribe different values in the two hemispheres. On a related matter we specify the ice thickness everywhere as 2 m. We should bear in mind that the winter Antarctic sea ice displays considerable spatial variability in thickness and also that recent analyses suggest mean thicknesses somewhat less than that specified in the model (Budd, 1986). In the present experiment we were particularly interested in the effect of leads in the Antarctic winter ice and our model

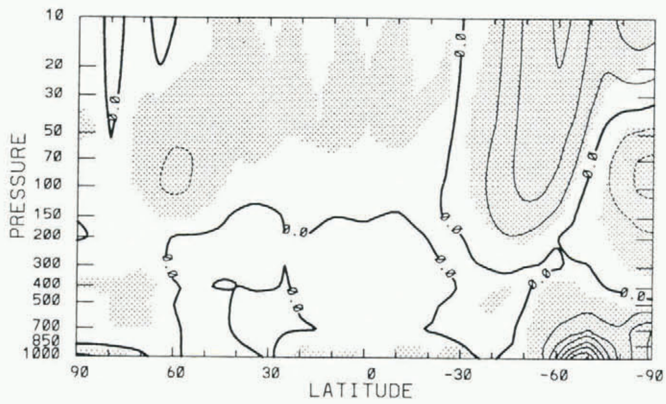

Fig. 1. Difference between the zonal average temperature of the ice leads and control simulations. The contour interval is 1 °C. Negative contours (i.e., cooler in the leads case) are dashed and regions of differences significant at the 95% confidence level are stippled.

was run in "perpetual July" mode. We wish to determine the effect of an Antarctic leads area somewhat greater than observed to allow an assessment of the maximum response that might be expected from the modification to the surface fluxes. At the same time we did not wish to change the leads fraction in the Arctic greatly from the value of zero used in the control experiment. With these considerations in mind we chose values for f_w of 0.05 and 0.50 for the northern and southern hemispheres, respectively.

RESULTS

The "control" experiment of the 21-wave GCM is run with no leads in either hemisphere and its climate is estimated from a 600-day period run with "perpetual July" conditions. The climatology of this control is shown in Simmonds and others (1988). The climate of the anomaly run was estimated from the mean of 300 days of simulation.

The response to the incorporation of leads in the sea ice of the height–latitude structure of the zonally-averaged temperature is shown in Figure 1. In this, and other figures where relevant, stippling has been used to denote regions over which the changes are statistically significant at the 95% confidence level. The statistical significance of the changes was calculated with a t-test, assuming consecutive 30-day means to be independent samples. While this assumption is not exactly valid the bias introduced is quite small; see Simmonds and others (1989).

In the vicinity of the sothern hemisphere ice cover the temperature has increased by up to 6 °C. Significant warming is seen between 50° and 90 °S, up to the 500 hPa level and higher. There is also warming from about 70 °N

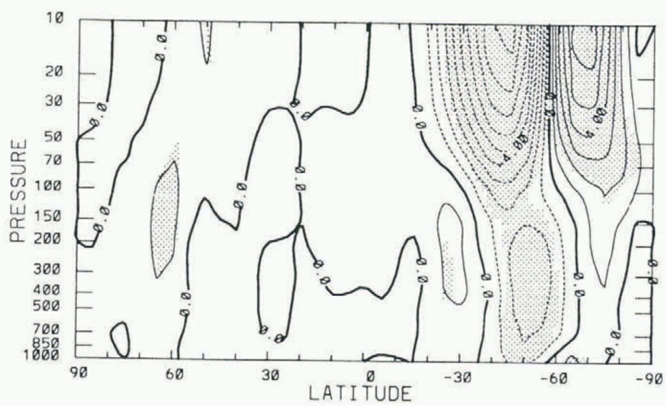

Fig. 2. Difference between the zonal average of the zonal wind of the ice leads and control simulations. The contour interval is 1 m s^{-1}. Negative contours (i.e., weaker westerlies or stronger easterlies in the leads case) are dashed and regions of differences significant at the 95% confidence level are stippled.

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to the North Pole but, as would be expected, its magnitude is small and it is confined to a relatively shallow layer near the surface. In the stratosphere there is a region of cooling centered at about 100 hPa over the South Pole, which is similar to what was observed by Simmonds and Dix (1987) when they removed all Antarctic sea ice. However, there is a region of warming in the stratosphere between about 30° and 65°S. A small region of cooling is simulated in the middle and upper troposphere over the Arctic regions. Cooling is also simulated over much of the stratosphere in the tropics and in the northern hemisphere. We are examining this particular response in more detail but note here that all GCM studies of the greenhouse warming simulate a warmed troposphere and cooler stratosphere, a structure similar to that observed here. This may be the climate response to a broad range of surface heatings.

Figure 2 presents similar information but for the zonal component of the wind. Most of the significant changes occur in the southern extra-tropics and tend to become greater with altitude. This latter behaviour is consistent with the thermal wind equation and the temperature changes depicted in Figure 1. The westerlies are weakened by up to 2 m s^{-1} between 45° and 60°S in the troposphere and by up to 9 m s^{-1} between 30° and 60°S in the stratosphere. Near the surface the zonally-averaged response displays westerly anomalies centered at 65°S and easterly anomalies at 50°S.

To understand the geographic structure of the changes in the surface wind we present in Figure 3 the southern hemisphere mean sea-level pressure change induced in our experiment. Significant areas of pressure reduction occur in the Weddell Sea (in excess of 7 hPa) and near the Ross Sea (4.5 hPa). The mass exported from these regions results in significant increases in mean sea-level pressure over much of Antarctica and at about 60°S in the Pacific and Indian oceans. Further to the north there are regions of pressure reduction, particularly in the Indian Ocean. The pressure change is consistent with the changes in the zonal wind shown above. The westerly anomaly is located between the anomalous ridges and area of pressure reduction further south whereas easterly anomalies are simulated to the north of the ridges.

Of especial interest in this study was the response of the surface fluxes of heat across the ice-leads–atmosphere interface. The greatest changes were seen in the fluxes of sensible heat. In the control experiment the sensible heat flux is everywhere downwards (negative) over southern hemisphere sea ice and large and upwards to the north of the sea-ice edge (not shown). In our experiment with 50% open water, the sensible heat flux is almost everywhere positive over the southern hemisphere sea-ice zone. These points allow us to expect the geographical structure of the sensible heat flux changes induced in the anomaly run (Fig. 4). (The contour of zero change coincides with the ice edge. Note also that the domain of this plot is smaller than those shown previously as the flux changes are small away from the sea-ice zone.) We see changes of typically 80 W m^{-2} over the sea-ice zone, with extreme values near the coast, 178 W m^{-2} near Syowa and 236 W m^{-2} in the western Ross Sea. (As indicated above, these changes are the differences between quite large positive and negative values.) To the north of the sea-ice edge there is a narrow band of sensible heat flux reduction. This behaviour is no doubt due to the fact that as air flows off the continent it picks up more sensible heat over the sea ice with leads than it would over continuous sea ice. Hence such air reaches the ice-free regions warmer and hence is responsible for a downward anomalous sensible heat flux. This argument is consistent with that presented by Simmonds (1981), who considered the effect of the complete removal of Antarctic sea ice.

SUMMARY

We have presented a simple scheme which allows for the parameterization of the effects of open leads in a GCM. In the formulation it is assumed that both the sea-ice distribution and concentration are prescribed rather than predicted. Even though the sea ice is not an interactive variable here, our scheme allows us to assess in a controlled fashion the impact on climate of changing ice concentration.

We have applied this scheme to a July simulation in which the open water fractions in the northern and southern hemispheres were set to 5 and 50%, respectively. The opening of leads led to increases in zonally-averaged tropospheric temperature of up to 6°C at high southern latitudes. The westerlies were significantly weakened between about 40° and 60°S. The surface pressure exhibited significant changes in many regions. Large reductions were simulated in the Weddell Sea and in the western Ross Sea and an anomalous ridge aligned itself approximately along the 60°S latitude belt. In some regions the pressure *increased* when the leads were included (e.g., the region to

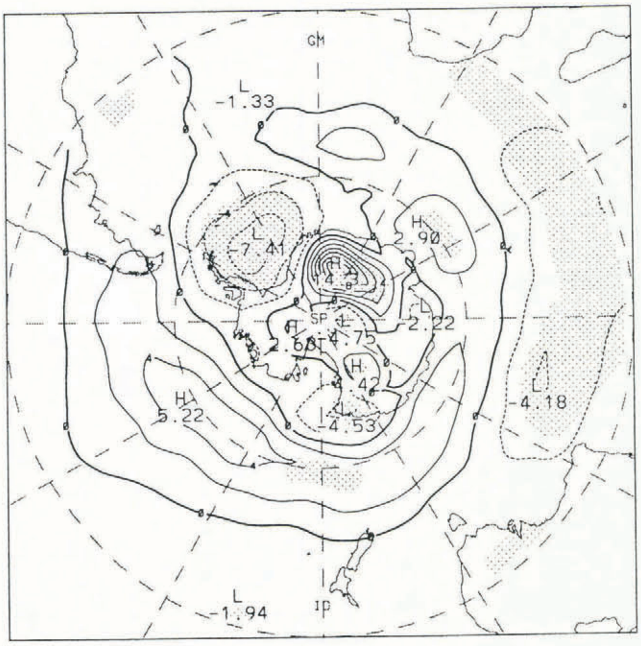

Fig. 3. Difference between the mean sea-level pressure of the ice leads and control simulations. The contour interval is 2 hPa. Negative contours (i.e., lower pressure in the leads case) are dashed and regions of differences significant at the 95% confidence level are stippled.

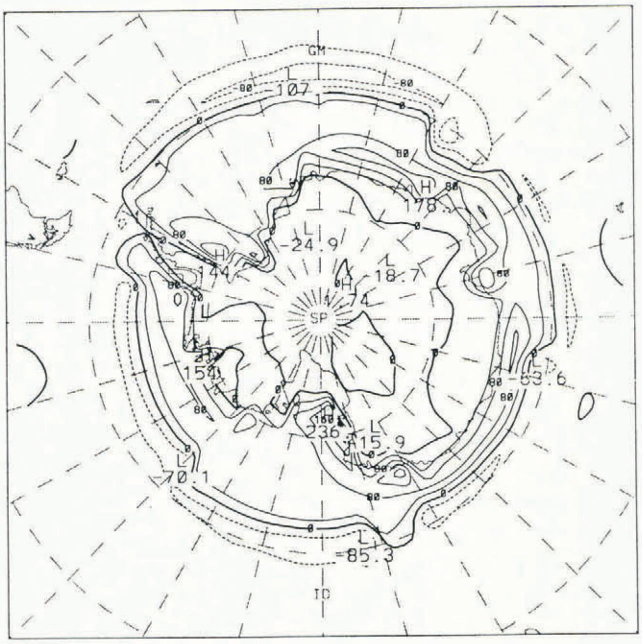

Fig. 4. Difference between the (upward) surface sensible heat flux of the ice leads and control simulations. The contour interval is 40 W m^{-2} and negative contours (i.e., less heat flux in the leads case) are dashed. (Note that the scale is different from Fig. 3.)

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the north of Edward VII Land). The changes in the surface fluxes were greatest for those of sensible heat. Increases in excess of 200 W m^{-2} were simulated over the Antarctic sea ice and reductions of up to 100 W m^{-2} just to the north of the ice edge.

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