Possible Change of Extratropical Cyclone Activity due to Enhanced Greenhouse Gases and Sulfate Aerosols—Study with a High-Resolution AGCM

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ABSTRACT
To investigate the possible impacts of enhanced greenhouse gases and sulfate aerosols on extratropical cyclone activity, two 20-yr time-slice experiments—the control run and the global warming run—are performed with a high-resolution AGCM (T106) of the Japan Meteorological Agency. In the control run, the atmosphere is forced by the observed SST and sea ice of 1979–98 and present-day CO2 and sulfate aerosol concentrations. In the global warming run, the atmosphere is forced by the observed SST and sea ice of 1979–98 plus the monthly mean anomalies of SST and sea ice at about the year 2050 obtained from a transient climate change experiment with the Geophysical Fluid Dynamics Laboratory (GFDL) coupled ocean–atmosphere model with a low resolution of R15. The equivalent amounts of CO2 and sulfate aerosol concentrations at about the year 2050 as used in the GFDL R15 model are prescribed.

First, the performance of the high-resolution AGCM (T106) in reproducing the extratropical cyclone activity of both hemispheres in the control run is examined—by comparing the cyclone activities simulated in the AGCM and those analyzed from the NCEP–NCAR reanalysis data of the same period from 1979 to 1998. An objective cyclone identification and tracking algorithm is used to analyze the cyclone activity. The results show that the model can reproduce the cyclone activity reasonably well.

Second, the possible change in cyclone activity due to enhanced greenhouse gases and sulfate aerosols is examined. The main results are summarized as follows. 1) The total cyclone density (number of cyclones in a 4.5° × 4.5° area per season) tends to decrease significantly in the midlatitudes of both of the Northern and Southern Hemispheres during the December–January–February (DJF) and June–July–August (JJA) seasons. The decrease of cyclone density in the midlatitudes of both of the Northern and Southern Hemispheres in the DJF season is about 7%. In the JJA season, the decreases of cyclone density in the Northern and Southern Hemispheres’ midlatitudes are about 3% and 10%, respectively. 2) Although weak and medium-strength cyclones decrease, the density of strong cyclones increases by more than 20% in the Northern Hemisphere in JJA and in the Southern Hemisphere in both DJF and JJA. 3) The density of strong cyclones in the Northern Hemisphere summer (JJA) increases over the eastern coasts of Asia and North America. In the Southern Hemisphere, the density of strong cyclones increases over the circumpolar regions around Antarctica in both summer (DJF) and winter (JJA) seasons. The density of strong cyclones also increases over the southeastern coasts of South Africa and South America.

Finally, the possible reasons for the change in cyclone activity due to enhanced greenhouse gases and sulfate aerosols are examined. It is shown that the changes in the extratropical cyclone activity are closely linked to the changes in the baroclinicity in the lower troposphere, which are mainly related to the changes in the horizontal and vertical temperature distributions in the atmosphere due to enhanced greenhouse gases and sulfate aerosols. It is shown that, in the Northern Hemisphere midlatitudes, the decrease of baroclinicity is mainly caused by the decrease of meridional temperature gradient, while in the Southern Hemisphere midlatitudes, the decrease of baroclinicity is mainly caused by the increase of static stability caused by the enhanced greenhouse gases and sulfate aerosols.

1. Introduction
With the increasing ability of supercomputers, we are now able to run GCMs with higher resolutions, which, to some extent, can resolve the smaller spatial-scale weather systems, such as typhoons and extratropical cyclones. Weather systems have more direct impact on our everyday lives than the time-mean atmospheric circulations. The weather and climate events and their extremes in the extratropics have close links with cyclone activity (Trenberth and Owen 1999; Karl et al. 1999a,b). Most of the precipitation events in the midlatitudes are...
associated with extratropical cyclones. Therefore, scientists now are becoming more and more interested in how global warming can influence weather systems. In this study we investigate the possible impacts of global warming on extratropical cyclone activity.

Recently a number of researchers have studied the possible influences of enhanced greenhouse gases on cyclone activity (Table 1). König et al. (1993) designed an objective identification scheme of cyclones in GCM simulations and studied the possible impact of enhanced greenhouse gases on cyclone activity. Lambert (1995) examined the effects of enhanced greenhouse warming on winter cyclone frequency and intensity as simulated in the Canadian Centre for Climate Modelling and Analysis (CCC) AGCM II. By using the 10-yr Northern Hemisphere winter data of National Center for Atmospheric Research (NCAR) community climate model version 1 (CCM1) 100-yr equilibrium simulations, Zhang and Wang (1997) analyzed the model-simulated northern winter cyclone and anticyclone activity under a greenhouse warming scenario. Beersma et al. (1997) and Schubert et al. (1998) analyzed extratropical storms in the North Atlantic region as simulated in the control and 2 × CO₂ time-slice experiments with the European Centre for Medium-Range Weather Forecasts–Hamburg University model version 3 (ECHAM3) GCM in the resolution of T106 and T42, respectively. Very recently, Sinclair and Watterson (1999) studied the impacts of global warming on cyclone activity by using the model output data from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) climate model. Knippertz et al. (2000) studied changes in cyclones over the North Atlantic in a transient greenhouse gas (GHG) experiment with ECHAM4/Ocean Isopycnic Model (OPYC) coupled model. On the other hand, Carnell and Senior (1998) investigated the changes in midlatitude variability due to increasing greenhouse gases and sulfate aerosols and Hall et al. (1994) examined the storm tracks in the Met Office (UKMO) GCM with doubled carbon dioxide. As summarized in Table 1, these previous studies appear to indicate a tendency for decrease of total cyclone numbers and an increase of strong cyclones as an impact of global warming.

However, as shown in Table 1, the resolutions of the climate models used by most of the above-mentioned studies are relatively low, which may not be able to resolve the synoptic systems, such as cyclones, very well, as indicated in the study of Blender and Schubert (2000). Beersma et al. (1997) used a high-resolution model but their integration period is only 5 yr, and they studied only North Atlantic winter cyclone activity. Carnell et al. (1996) and Sinclair and Watterson (1999) have proposed a longer observational record to provide more robust statistics of present-day storms combined with high-resolution runs of state-of-the-art GCMs using more realistic climate scenarios to answer the question of how the midlatitude storms will change with global warming.

The aim of the present paper is to investigate the possible impacts of enhanced greenhouse gases and sulfate aerosols on the extratropical cyclone activity in both hemispheres with a high-resolution model and relatively longer integration. For this purpose, two 20-yr time-slice experiments, the control run and the global warming run, are performed by using the high-resolution AGCM (T106) of the Japan Meteorological Agency. It should be noted that the length of integration (20 yr) may not be long enough considering the decadal-scale variation of cyclone activity.

The present paper is organized as follows. In the next section we give a description of the model and experimental design. In section 3 we describe the objective cyclone identification and tracking algorithm used in the present study and how to apply this method to the model output data and the (National Centers for Environmental Prediction) NCEP–NCAR reanalysis data. The performance of the model in reproducing the extratropical cyclone activity is given in section 4. Possible impacts of enhanced greenhouse gases and sulfate aerosols on cyclone activity are examined in section 5. In section 6 we give some possible mechanisms of the change of extratropical cyclone activity associated with enhanced greenhouse gases and sulfate aerosols. Finally, in section 7 we give a summary of the paper.

2. Model and the time-slice experiments

The atmospheric general circulation model (AGCM) used in the present study is the Japan Meteorological Agency (JMA) forecast model (GSM8911), a global spectral model with a high horizontal resolution of T106 (about 1.125° × 1.125° in latitude and longitude) and 21 vertical levels. Full physics are included in the model and they are described in JMA (1993) and Sugi et al. (1989).

To investigate the possible impacts of enhanced greenhouse gases and sulfate aerosols on the extratropical cyclone activity, two 20-yr time-slice experiments are performed with the model. The first is the control run (CTL), which represents the present climate. In the control run, the atmosphere is forced by the observed SST and sea ice of 1979–98. The present-day CO₂ and sulfate aerosol concentrations are prescribed. Another is the global warming run, which corresponds to the future climate around the year of 2050. In the global warming run (GWR), the atmosphere has been forced by the observed SST and sea ice of 1979–98 plus the monthly mean anomalies of SST and sea ice around the year of 2050. The SST and sea ice anomalies were obtained from a transient climate change experiment with the Geophysical Fluid Dynamics Laboratory (GFDL) coupled ocean–atmosphere model with a low resolution of R15 (Haywood et al. 1997). CO₂ and sulfate aerosol concentrations equivalent to those used in the GFDL R15 model at the year of about 2050 are prescribed. In the time-slice experiments, the model output data were
written at 6-hr intervals in order to study the high-frequency weather systems such as cyclones.

3. Cyclone identification and tracking algorithm

An automatic cyclone identification and tracking algorithm identical to that used in Geng and Sugi (2001) is used in the present paper. The algorithm can calculate the cyclone density (number of cyclones in a 4.5° × 4.5° latitude–longitude area per season), cyclone tracks, speed of movement, deepening rate, intensity, and central pressure. The only difference is that in this paper we count only the relatively fast-moving cyclones when we calculate the cyclone density. This was done by defining cyclone speed as the distance between the cyclone’s first position and the last position during its lifetime divided by the cyclone life time. If the actual speed of a cyclone during its lifetime is larger than 15 km h⁻¹, then it is counted. Otherwise, it is not counted. By doing this, most of the quasi-stationary heat lows, which we are not interested in, are removed from the calculation of the cyclone density. However, there are still some unrealistic maximums of cyclone density over the tropical mountain regions, but these are mainly short-lived and weak cyclones. Since in this paper we study the extratropical cyclone activity, these unrealistic features would not influence our conclusions.

The cyclone identification and tracking algorithm is applied to the two 20-yr 6-hourly model output datasets with a horizontal resolution of 1.125° × 1.125°. The simulated cyclone activity in CTL is then compared with that analyzed from the 6-hourly NCEP–NCAR reanalysis data of the same period from 1979 to 1998 in order to see the model’s ability in simulating the cyclone activity. In the calculation, the NCEP–NCAR reanalysis data was interpolated from the 2.5° × 2.5° grid spacing to the same horizontal resolution as that of the T106 AGCM data by using cubic interpolation.

4. Performance of the model in simulating the extratropical cyclone activity

Figure 1 shows the tracks of cyclones with lifetime ≥3 days in the December–January–February (DJF) season of 1979/80~1997/98, analyzed from the NCEP–NCAR reanalysis data and that simulated in the T106 model. It is clear that the model can reproduce the genesis and movement of cyclones reasonably well. Three major storm tracks are simulated in the Northern Hemisphere: the Mediterranean–European region, the east Asia–North Pacific region, and the North America–North Atlantic region. There are also three major storm tracks in the Southern Hemisphere, which usually begin from the southeastern coasts of the three continents and then extend southeastward toward the circumpolar region around the Antarctic. For the June–July–August (JJA) season the simulation of the Southern Hemisphere cyclone tracks is very good, while for the Northern Hemisphere the simulated cyclone tracks are much more dense than that of the observed (not shown).

The upper four panels of Fig. 2 illustrate the cyclone density analyzed from the NCEP–NCAR reanalysis data and simulated in the T106 model. In the DJF season (Figs. 2a,b) the simulated extratropical cyclone density is very similar to the observed. The model reproduced most of the observed features of the cyclone density distribution. Corresponding to the cyclone tracks, we can see high cyclone density in the Mediterranean–European region, east Asia–North Pacific region, and the North America–North Atlantic region in the Northern Hemisphere. In the Southern Hemisphere, high cyclone density can be found starting from the southern parts of the three continents and extending southeastward toward the oceanic regions around the Antarctic continent. On the other hand, in the JJA season (Figs. 2e,f), the simulation of the cyclone density in the Southern Hemisphere is reasonable, while the simulated cyclone density in the Northern Hemisphere is much larger than the observed one. But, generally, the cyclone density maximum regions are well simulated by the model. The relatively large cyclone density in the northern summer simulated in the model is probably due to the fact that the simulated baroclinicity is stronger than the observed, which may be caused by the systematic error of the model (see section 6).

From the previous discussions, we can see that the...
Table 1. (Extended)

<table>
<thead>
<tr>
<th>Season</th>
<th>Impact of global warming</th>
<th>Total cyclone</th>
<th>Strong cyclone</th>
<th>Position shift</th>
</tr>
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<tbody>
<tr>
<td>Four seasons</td>
<td>Decrease</td>
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<td>Winter</td>
<td>Intensify</td>
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<td>Northward</td>
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<tr>
<td>Winter</td>
<td>Decrease</td>
<td>Increase</td>
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</tr>
<tr>
<td>Winter</td>
<td>Decrease</td>
<td>Increase</td>
<td></td>
<td>Northeastward</td>
</tr>
<tr>
<td>Winter</td>
<td>Decrease</td>
<td>Increase</td>
<td></td>
<td>Poleward and eastward</td>
</tr>
<tr>
<td>Annual Winter</td>
<td>Decrease</td>
<td>Increase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter Summer</td>
<td>Decrease</td>
<td>Increase</td>
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</tbody>
</table>

high-resolution model used in the present paper has a reasonable performance in simulating the climatology of the cyclone activity. In the next section we will go a step further to examine the possible changes of the extratropical cyclone activity due to enhanced greenhouse gases and sulfate aerosols.

5. Cyclone activity changes due to enhanced greenhouse gases and sulfate aerosols

Figures 2c,g show the change of cyclone density due to enhanced greenhouse gases and sulfate aerosols for the DJF and JJA seasons, respectively. The general feature is that cyclone density decreases in the midlatitudes of both hemispheres along the major storm track regions (Figs. 2b,f). In the DJF season of the Northern Hemisphere, cyclone density decreases over the Mediterranean region, northeast Asia–western Pacific and the Gulf of Alaska, south and eastern coast of North America, middle of the North Atlantic, and around Greenland. It increases from the Sea of Okhotsk to the Bering Strait, and around 50°–60°N in the North Atlantic. In the Southern Hemisphere, cyclone density decreases along the three major storm track regions (see Fig. 2b) and the entire latitude belt around 60°S, but increases around the edge of Antarctica. We examined the statistical significance of the changes by the $t$ test, and found that most of the major changes are statistically significant at the 90% confidence level. For the $t$ test, the cyclone count in each season is assumed to be independent of the other seasons and the sample size is 20 (number of years of integration).

For the JJA season, in the Northern Hemisphere cyclones decrease in the major storm track regions such as the region from northeast Asia to the northern North Pacific, and the midlatitude North Atlantic. However, over midlatitude North America and east Russia clear increase of cyclones can be observed. In the Southern Hemisphere cyclones decrease along the vast areas of the midlatitude belt from 30°–60°S and increase along the edge of Antarctica.

To see how cyclones in different strength categories change due to global warming, we divided the cyclones into five categories according to the intensity of cyclones (Table 2). They are denoted by C1, C2, C3, C4, and C5 with the central pressure gradient of 0–10, 10–20, 20–30, 30–40, and $\geq$40 hPa (1000 km)$^{-1}$, respectively. Table 2a shows the cyclone density averaged over the midlatitude region in DJF season. It can be seen that the Northern Hemisphere winter cyclone density in all intensity categories decreases. The total cyclone density decreases about 7%. For the Southern Hemisphere summer, the density of weak- and medium-strength cyclones decreases while the density of strong cyclones (C4, C5) increases substantially due to global warming. The total cyclone density decreases about 7%, similar to that of the Northern Hemisphere.

Table 2b shows the cyclone density for the different strength categories averaged over the midlatitude regions for the JJA season. It can be seen that in the Northern Hemisphere summer, the cyclone density of categories 2 and 3 decreases significantly, while the density for strong cyclones (C4, C5) increases significantly. The total cyclones decrease about 2.7%. For the Southern Hemisphere winter, the density for weak- and medium-strength cyclones decreases while the density for strong cyclones increases due to enhanced greenhouse
gases and sulfate aerosols. The total decrease of cyclone density is about 10%, much larger than that of the Northern Hemisphere.

From Table 2 we can see that, although in most cases the cyclone density for weak and medium strength decreases significantly with enhanced greenhouse gases and sulfate aerosols, the density of strong cyclones increases substantially. Although the number of strong cyclones is small, the extreme weather associated with them often cause disasters in our society. Therefore, it
is interesting to see where these strong cyclones occur and in what regions their numbers will increase or decrease due to global warming. Figure 3 shows the distributions of the density of strong cyclones for the DJF and JJA seasons of the Northern and Southern Hemisphere, and the density changes of strong cyclones due to enhanced greenhouse gases and sulfate aerosols. In the Northern Hemisphere winter (Figs. 3a–c), strong cyclones are located in the two major storm track regions of the northern North Pacific and northern North Atlantic. Associated with enhanced greenhouse gases and sulfate aerosols, the strong cyclones shift northward in the northern North Pacific region and shift southeastward in the northern North Atlantic region (Fig. 3c).

Knippertz et al. (2000) has shown increasing frequencies of strong cyclones but a northward shift of the strong cyclone activity in the North Atlantic associated with greenhouse warming. As shown in Table 2a, the total number of strong cyclones decreases with enhanced greenhouse gases and sulfate aerosols in the northern winter. However, in the Northern Hemisphere summer (Figs. 3g–i), strong cyclones are usually located over the northeastern coast of Asia and North America. Associated with enhanced greenhouse gases and sulfate aerosols, we can see little change in the position of strong cyclones but a clear increase over the northeastern coast of Asia and North America (Fig. 3i).

In the Southern Hemisphere, strong cyclones are seen over the circumpolar ocean. The density increases in both the summer (DJF; Figs. 3d–f) and winter (JJA; Figs. 3j–l) season. The density increase of strong cyclones occurs mainly over the circumpolar region around Antarctica. However, similar to the summer season of the Northern Hemisphere, the density of strong cyclones increases substantially over the southeastern coast of South Africa and South America in the southern summer. The density increase of strong cyclones accompanied with the density decrease of weak and medium-strength cyclones was also observed by some other studies, such as Lambert (1995) and Sinclair and Waterson (1999). However, they did not give detailed geographical distributions of strong cyclones as we do in the present paper.

6. Possible mechanisms of the change of cyclone activity

a. Baroclinicity and cyclone activity

Extratropical cyclones owe their existence primarily to the baroclinicity of the atmosphere. In this section we examine how the change of cyclone activity is related to the change of large-scale baroclinicity due to enhanced greenhouse gases and sulfate aerosols. According to Lindzen and Farrell (1980) and Hoskins and Valdes (1990), a suitable measure of baroclinicity is provided by the Eady growth-rate maximum,

$$\sigma_{m1} = 0.31 |f| \bar{\frac{\partial |V|}{\partial z}} N^{-1}$$

where $f$ is the Coriolis parameter, $N$ the Brunt–Väisälä frequency, $V$ the horizontal wind and $z$ the vertical height. It represents the growth rate of the most rapidly growing disturbances. This baroclinic parameter has been widely used by a number of researchers (Hall et al. 1994; Zhang and Wang 1997; Carnell and Senior 1998) in discussing the change of cyclone activity due to global warming. As in Hoskins and Valdes (1990), here we use the baroclinicity parameter at the lower troposphere of about 780 hPa. In the upper four panels of Fig. 2, contours of baroclinicity parameters are plotted. Cyclone density maxima tend to be located downstream (eastward and poleward) of baroclinicity maxima.
Fig. 3. Density of strong cyclones in DJF of Northern Hemisphere (a) control run (CTL), (b) global warming run (GWR), and (c) GWR-CTL. (d), (e) and (f) Same as (a), (b), and (c) but for the Southern Hemisphere. (g)–(l) Same as (a)–(f) but for JJA. Strong cyclones in the Southern Hemisphere JJA season are defined as those with central pressure gradients larger than 40 hPa (1000 km)$^{-1}$; in all other cases the central pressure gradients is larger than 30 hPa (1000 km)$^{-1}$. 
Figures 2d,h shows the changes of baroclinicity (the Eady growth-rate maximum) at about 780 hPa due to enhanced greenhouse gases and sulfate aerosols for the DJF and JJA season. Statistical significance test (t test) shows that most of the large changes of baroclinicity are statistically significant at the 90% level. From Fig. 2d, we see in the Northern Hemisphere winter, the large baroclinicity zone over the North Pacific shifts northward (poleward), while that over the North Atlantic shifts southward (equatorward). In the Southern Hemisphere summer, the large baroclinicity zones shift southward (poleward).

Comparing Figs. 2d,h with Figs. 2c,g, we can see that the baroclinicity usually weakens at the upstream (westward and equatorward) of the regions of decrease or increase in baroclinicity. This is probably because the weakening of baroclinicity in the upstream will not only reduce cyclogenesis, but also weaken the cyclone development, and thus there will be fewer cyclones moving into the downstream regions, that is, usually from the middle to the end of the storm tracks. We note that in some regions the correspondence between the changes in baroclinicity and cyclone density is not so good. This point will be discussed later in section 6c.

In the Northern Hemisphere DJF, the baroclinicity weakens over northeast Asia to the whole midlatitude North Pacific region, over Canada to the northern North Atlantic around Greenland, and over the south flank of the Mediterranean Sea; but it increases in the midlatitude North Atlantic. The changes of the cyclone density in the Northern Hemisphere winter in Fig. 2c correspond with these changes of baroclinicity in Fig. 2d. The regions of decrease or increase in cyclone density tend to be located downstream (poleward and eastward) of the regions of decrease or increase in baroclinicity.

In the Southern Hemisphere DJF, the baroclinicity decreases over the midlatitude belt from about 30°S to 55°S but increases poleward over the circumpolar region. This can explain the decrease of cyclone density in the three major storm tracks in the Southern Hemisphere summer (DJF) and the increase of the cyclone density along the edge of Antarctica.

On the other hand, in the Northern Hemisphere JJA season (Fig. 2h), baroclinicity decreases over the region from the midlatitude east Asian continent to the midlatitude North Pacific, northern North America, and most parts of the North Atlantic. This may be responsible for the decrease of cyclone density over east Asia and the North Pacific region, while the increase of baroclinicity over midlatitude North America may be responsible for the increase of the cyclone density over midlatitude North America as shown in Fig. 2g.

In the Southern Hemisphere JJA season, baroclinicity decreases over most parts of the latitude belt from around 30°S to about 50°S, which may be responsible for the decrease of cyclone density over the midlatitude belt due to enhanced greenhouse gases and sulfate aerosols. The increase of the baroclinicity over the circum-polar regions may be responsible for the increase of the cyclone density along the edge of Antarctica.

b. Baroclinicity change due to global warming

From previous discussions we can see that the change of cyclone activity is closely related to the change of baroclinicity at the lower troposphere. However, we still do not know why the baroclinicity has such changes associated with enhanced greenhouse gases and sulfate aerosols. As can be seen from Eq. (1), there are two factors that contribute to the change of baroclinicity. One is the vertical wind shear and another one is the Brunt–Väisälä frequency, which is an indicator of the static stability of the atmosphere. Both the change of vertical wind shear and the change of Brunt–Väisälä frequency are linked to the change in the temperature structure in the atmosphere due to enhanced greenhouse gases and sulfate aerosols. The vertical wind shear is proportional to the horizontal temperature gradient in the form of

$$\frac{\partial V}{\partial z} \approx \frac{g}{fT} \mathbf{k} \times \nabla T. \quad (2)$$

Here, $T$ is the air temperature. On the other hand, the Brunt–Väisälä frequency is related to the vertical temperature distributions as

$$N = \left(\frac{g}{\theta \frac{d\theta}{dz}}\right)^{1/2}. \quad (3)$$

Here, $\theta = T(p_o/p)^{\gamma}$ is the potential temperature, and $p$ and $p_o$ are pressure and reference pressure, respectively.

To see the change in temperature distribution due to enhanced greenhouse gas and sulfate aerosols, and how the change of baroclinicity depends on the change in temperature distribution, Figs. 4a–d show the latitude–height cross section of the change in temperature, vertical wind shear, Brunt–Väisälä frequency, and the baroclinicity, respectively, for the DJF season. From Fig. 4a it can be seen that the equatorward meridional temperature gradient in the Northern Hemisphere in the middle and lower troposphere except for the polar region generally decreases with enhanced greenhouse gases and sulfate aerosols. This is because when global warming happens the high latitudes usually warm more than the lower latitudes due to the positive feedback of sea ice and snow cover in winter. In contrast with the Northern Hemisphere, the increase of air temperature in the circumpolar ocean region of the Southern Hemisphere are very small because of the vertical mixing of heat over a deep water column (Manabe et al. 1991, 1992; Manabe 1998). As a result, the equatorward meridional temperature gradient in the Southern Hemisphere midlatitude lower troposphere increases with global warming.

From Eq. (2), the change of vertical wind shear is
Fig. 4. Changes due to enhanced greenhouse gases and sulfate aerosols of zonal-mean (a) temperature (contour interval: 0.25°C), (b) vertical wind shear (contour interval: 0.02 × 10^{-2} m s^{-1} hPa^{-1}), (c) Brunt-Väisälä frequency (contour interval: 0.1 × 10^{-3} s^{-1}), (d) baroclinicity (contour interval: 0.02 day^{-1}). White lines indicate the climatology of baroclinicity with contour interval of 0.2 day^{-1}. Panels (a)–(d) are for DJF and (e)–(h) are for JJA.
directly linked with the change of equatorward meridional temperature gradient, which will influence the change of baroclinicity. In the Northern Hemisphere extratropics, as shown in Fig. 4b, the change of the vertical wind shear (mainly contributed by the zonal wind change) corresponds to the change of the meridional temperature gradient. The vertical wind shear change in the midlatitude Southern Hemisphere also generally corresponds to the meridional temperature gradient change. Below 700 hPa, the temperature gradient in the Southern Hemisphere midlatitudes generally increases. Therefore, the vertical wind shear generally increases below 700 hPa.

Comparing Figs. 4b and 4d, we can see a good agreement between the change of the vertical wind shear and the change of baroclinicity in the Northern Hemisphere. This suggests that the decrease of the baroclinicity in the Northern Hemisphere midlatitudes can be mainly explained by the change of vertical wind shear associated with the change in meridional temperature gradient due to global warming. However, in the Southern Hemisphere, the meridional temperature gradient in the midlatitudes strengthens at the lower troposphere and thus the vertical wind shear increases associated with enhanced greenhouse gases and sulfate aerosols. On the other hand, the baroclinicity change in Fig. 4d is negative over much of the midlatitude Southern Hemisphere throughout the troposphere. This means that the meridional temperature gradient change or the vertical wind shear change alone cannot explain the baroclinicity change over the Southern Hemisphere midlatitudes. From Eqs. (1) and (3) we can see that in addition to the vertical wind shear, the static stability is also a factor that influences the change of baroclinicity. Figure 4c shows the change of the Brunt–Väisälä frequency due to enhanced greenhouse gases and sulfate aerosols. The general feature is that the static stability in the middle and lower troposphere increases almost everywhere. This is because, from Fig. 4a, the upper troposphere and the tropical tropopause warm more than the troposphere anywhere else. This phenomenon is largely a consequence of the fact that the lapse of temperature along a moist adiabat is less in a warmer atmosphere (Knutson and Manabe 1995; Bengtsson et al. 1996). The general increase of static stability is enhanced over the circumpolar ocean region of the Southern Hemisphere due to the relatively less warming there. The static stability increases substantially over a vast region from 30° to 75°S. From Eq. (1), the increase of static stability tends to weaken the baroclinicity from midlatitudes to about 75°S. This means that the decrease of the baroclinicity in the Southern Hemisphere midlatitudes are closely related to the increase of static stability there due to the relatively less warming over the Southern Hemisphere extratropical oceans. It should be noted that the relatively less warming over the Southern Hemisphere extratropical ocean is not specific to the GFDL model experiment result used in the present study but rather commonly found in many GCM experiments (Houghton et al. 2001).

The stability mechanism can be supported by looking at the cyclogenesis in a number of places over the world. For example, over east Asia in winter (DJF), the meridional temperature gradient is very large. However, we could not see frequent cyclogenesis there. The reason, as indicated by Chen et al. (1991), is mainly because of the high static stability due to the cold continent in winter, which is unfavorable for cyclone formation and development. Another example is the maximum cyclogenesis over the Great Lakes of North America due to the relatively warmer water bodies in winter, which cause the less static stability that is favorable for cyclone development (Reitan 1974).

Figures 4e–h illustrate the latitude–height cross section of the changes in temperature, vertical wind shear, static stability, baroclinicity, and the transient kinetic energy for the JJA season, respectively. The temperature change in JJA is somewhat similar to that in DJF. Again, the decrease of baroclinicity in the Northern Hemisphere midlatitudes can be explained mainly by the decrease of vertical wind shear associated with the equatorward meridional temperature gradient decrease due to the enhanced greenhouse gases and sulfate aerosols. This can be seen by comparing the change in baroclinicity in Fig. 4h, and the vertical wind shear in Fig. 4f. In contrast with that of the Northern Hemisphere, the strengthening of the equatorward meridional temperature gradient and the increase of the vertical wind shear in most parts of the Southern Hemisphere midlatitudes as shown in Fig. 4f can not explain the decrease of the baroclinicity there in Fig. 4h. The weakening of the baroclinicity in the midlatitude Southern Hemisphere can be mainly explained by the increase of the static stability in the midlatitude region due to the relatively little warming over the extratropical ocean regions (Fig. 4g).

c. Discussion

In the previous section, we have examined the possible reasons of the change in cyclone activity associated with enhanced greenhouse gases and sulfate aerosols. We found that the cyclone density changes are generally related to the change of large-scale baroclinicity in the lower troposphere. The change of large-scale baroclinicity is linked to the change in the horizontal and vertical distributions of air temperature associated with the enhanced greenhouse gases and sulfate aerosols. However, the mechanisms for the Northern Hemisphere and Southern Hemisphere are quite different. In the Northern Hemisphere midlatitudes, the weakening of baroclinicity can be mainly explained by the decrease of meridional temperature gradient associated with enhanced greenhouse gases and sulfate aerosols. In the Southern Hemisphere midlatitudes, the weakening of baroclinicity is mainly due to the increase of the static stability associated with the relatively small warming
in the circumpolar ocean region due to enhanced greenhouse gases and sulfate aerosols. This explains why the baroclinicity in the Southern Hemisphere will decrease with enhanced greenhouse gases, the reasons have not been well explained. For example, Lambert (1995) did not give a clear explanation in his paper. In the study of Sinclair and Watterson (1999) they pointed out that the decrease of cyclone activity in the Southern Hemisphere midlatitudes is because of the weakening of baroclinicity. However, they did not point out why the baroclinicity decreases in the Southern Hemisphere midlatitudes in an environment where the equatorward meridional temperature gradient generally increases in the midlatitudes with global warming.

In the previous discussion, we have shown the relationship between the change in zonal mean baroclinicity and the change in zonal mean temperature field (Fig. 4). We note, however, a significant zonal asymmetry in the baroclinicity change (Figs. 2d,h). In DJF, the zonal mean baroclinicity decreases in latitudinal belts at around 30° and 60°N (Fig. 4d). From Fig. 2d, we can see that the baroclinicity decreases in the Pacific and increases in the Atlantic at around 30°N, while it increases in the Pacific but decreases in the Atlantic at around 60°N. This difference in the baroclinicity change over the Pacific and the Atlantic may be explained by the difference in SST change due to the increased carbon dioxide and sulfate aerosols over the two regions. The region of large meridional gradient of SST anomaly in the Atlantic is located more northward than in the Pacific (Haywood et al. 1997).

We have seen that geographical distribution of cyclone activity change generally well corresponds to that of baroclinicity change. However, there are some regions where this correspondence is not so good. For example, in DJF we see a negative change in cyclone density from the United States to the central Atlantic, where we see a distinct positive change in baroclinicity. We have also noted that the strong cyclone density increases in JJA in the Northern Hemisphere, and in DJF and JJA in the Southern Hemisphere (Table 2), although total cyclone density and baroclinicity decrease due to global warming. In JJA over east Asia, baroclinicity and total cyclone density decrease (Figs. 2g,h) but strong cyclone density increases (Fig. 3i). Baroclinicity and total cyclone density also decrease over the central Atlantic, but the density of strong cyclones shows a significant increase over the offshore of the United States. Thus, the change in the baroclinicity alone may not explain all the changes in cyclone activity due to global warming, and some other mechanism may be needed to explain them. Regarding the mechanism that is responsible for the increase of strong cyclones, there is speculation that the increase of water vapor in the atmosphere associated with global warming may be the reason (Lambert 1995; Sinclair and Watterson 1999). They suggest that the high levels of humidity present with global warming will increase the latent heat release of some cyclones and therefore contribute to the development of these cyclones. To add supporting evidence for this mechanism, further work is needed in the future with models of various complexities.

In section 6a we have noted a poleward shift of a large baroclinicity zone in the Southern Hemisphere summer. Kushner et al. (2001) reported a poleward shift of the westerly jet in the Southern Hemisphere summer in response to greenhouse warming. They further pointed out an upward shift of transient-eddy activity associated with the increase in troposphere depth due to greenhouse warming. In the present study, we can see the upward shift of baroclinicity due to the baroclinicity increase in the upper troposphere associated with the equatorward meridional temperature increase (Figs. 4d,h).

7. Conclusions

To investigate the possible impacts of enhanced greenhouse gases and sulfate aerosols on the extratropical cyclone activity, two 20-yr time-slice experiments, the control run and the global warming run, are performed with a high-resolution AGCM (T106) of the Japan Meteorological Agency. In the control run, the atmosphere is forced by the observed SST, sea ice of 1979–98, and the present-day CO₂ and sulfate aerosol concentrations. In the global warming run, the atmosphere is forced by the observed SST and sea ice of 1979–98 plus the monthly mean anomalies of SST and sea ice obtained from a transient climate change experiment with the GFDL coupled ocean–atmosphere model with a low resolution of R15. The amounts of CO₂ and sulfate aerosol concentrations equivalent to those used in the GFDL R15 model at about the year 2050 are prescribed.

First, the performance of the high-resolution AGCM (T106) in reproducing the extratropical cyclone activity of both hemispheres in the control run is examined by comparing the cyclone activities simulated in the AGCM and that analyzed from the NCEP–NCAR reanalysis data of the same period from 1979 to 1998 with an objective cyclone identification and tracking algorithm. The results show that the model can reproduce the cyclone activity reasonably well.

Second, the possible change in cyclone activity due to enhanced greenhouse gases and sulfate aerosols is examined. The main results are summarized as follows: 1) The total cyclone density tends to decrease significantly in the midlatitudes of both of the Northern and Southern Hemispheres during the DJF and JJA seasons. The decrease of cyclone density in the midlatitude of both of the Northern and Southern Hemispheres in DJF season is about 7%. In JJA season, the decreases of
cyclone density in the Northern and Southern Hemispheres midlatitudes are about 3% and 10%, respectively. 2) Although the density of weak- and medium-strength cyclones decreases, the density of strong cyclones increases more than 20% in the Northern Hemisphere in JJA and in the Southern Hemisphere in both DJF and JJA. 3) The density of strong cyclones in the Northern Hemisphere summer (JJA) increases over the eastern coasts of Asia and North America. In the Southern Hemisphere, the density of strong cyclones increase over the circumpolar regions around Antarctica in both summer (DJF) and winter (JJA) seasons. The density of strong cyclones also increases over the southeastern coasts of Africa and South America.

Finally, possible reasons for the change in cyclone activity due to enhanced greenhouse gases and sulfate aerosols are examined. It is shown that the changes in extratropical cyclone activity are closely linked to the changes in baroclinicity in the lower troposphere, which are mainly related to the changes in horizontal and vertical temperature distributions in the atmosphere due to enhanced greenhouse gases and sulfate aerosols. It is shown that, in the Northern Hemisphere midlatitudes, the decrease of baroclinicity is mainly caused by the decrease of meridional temperature gradient, while in the Southern Hemisphere midlatitudes, the decrease of baroclinicity is mainly caused by the increase of static stability due to the enhanced greenhouse gases and sulfate aerosols.

The present paper is different from the previous studies in the following aspects: 1) The model used in this study is a high-resolution model and the integration period is longer. Since the experiments are specially designed for the study of high-frequency weather systems, the model output data are stored in a short time interval of 6 h. This means that the model output data used in the present study not only have a high spatial resolution, but also have a high temporal resolution. 2) We have noticed that, different from that of the Northern Hemisphere, the substantial decrease of cyclones in the Southern Hemisphere is mainly caused by the increase of static stability over the midlatitude regions due to the relatively less warming in the circumpolar ocean regions associated with enhanced greenhouse gases and sulfate aerosols. To our knowledge, this has not been pointed out by previous studies. 3) Since strong cyclones usually cause disasters to our socioeconomic, we examined the geographical distributions of the change of strong cyclones due to enhanced greenhouse gases and sulfate aerosols. This gives us some identification of where strong cyclones may increase or decrease over the world. This has not been fully discussed by previous studies.

In the present study, we have shown that the changes in extratropical cyclone activity associated with the increase in greenhouse and sulfate aerosols are closely related to the change in baroclinicity. However, the baroclinicity change alone cannot explain all the changes in cyclone activity. Some other mechanisms need to be considered. The increase in the atmospheric moisture due to global warming may be an important factor that influences the changes in cyclone activities, as pointed out by Hall et al. (1994), Lambert (1995), Zhang and Wang (1997), Sinclair and Watterson (1999), and Carnell et al. (1996). The result of the present study indicates that the frequency of extratropical cyclones may decrease due to global warming, while the number of strong cyclones may increase. We note that there are considerable differences among the studies concerning the possible future behavior of extratropical cyclones. There are some uncertainties in the results of present study due to model physics, boundary conditions, and natural variability of the atmosphere, although we made a relatively long integration with a high-resolution model compared with previous studies. To reduce the uncertainty, we would propose a longer integration using a model with high resolution and improved physical processes.

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