Impact of climate change on the frequency of Northern Hemisphere summer cyclones

Chang Lang¹ and Darryn W. Waugh¹

Received 31 March 2010; revised 18 November 2010; accepted 29 November 2010; published 18 February 2011.

¹Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, Maryland, USA.

Copyright 2011 by the American Geophysical Union.

1048-0227/11/2010JD014300

1 There is considerable interest in how midlatitude cyclones and weather systems may change as Earth’s climate changes. As a consequence, there have been a large number of studies examining model projections of the frequency, position, and strength of cyclones in future warmer climates. These studies generally show a decrease in the number of extratropical storms averaged over the hemisphere (which has been linked to coincident decreases in the equator-to-pole temperature gradients and baroclinicity), but increases in regions on the poleward side of the climatological storm tracks [e.g., Yin, 2005; Lambert and Fyfe, 2006; Bengtsson et al., 2006; Pinto et al., 2007; Löptien et al., 2008; Ulbrich et al., 2008, 2009]. There is general agreement that the above studies have focused on the winter season and only limited attention has been paid to the summer season. A few studies have examined trends in midlatitude summer cyclones in individual models [Geng and Sugi, 2003; Bengtsson et al., 2006; Löptien et al., 2008; Orsolini and Sortberg, 2009]. These have shown decreasing trends over the North Pacific and North Atlantic, with an equatorward shift over the North Pacific and a poleward shift over the North Atlantic. There are, however, discrepancies between these studies, with Geng and Sugi [2003] and Orsolini and Sortberg [2009] showing an increase over eastern Russia but Bengtsson et al. [2006] and Löptien et al. [2008] showing the opposite trend for the same region. [2] Understanding the characteristics and trends in summer cyclones is important not only for understanding midlatitude weather systems and extreme events, but it is also important for understanding the Arctic hydrological cycle and radiation budget [e.g., Orsolini and Sortberg, 2009]. Furthermore, summer cyclones also have potential importance for air quality. The surface concentrations of ozone and aerosols, and as a result surface air quality, depend on a range of meteorological factors, including temperature, humidity, precipitation, and the rate of ventilation of the boundary layer, which are closely connected with cyclones [e.g., Jacobs and Winner, 2009]. A decreasing cyclone frequency will likely increase the frequency and duration of stagnation events that are linked with ozone pollution episodes [e.g., Leibensperger et al., 2008]. [3] In this study we examine the robustness of trends in Northern Hemisphere (NH) summer cyclones in the World Climate Research Programme’s Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel data set that was used in the Fourth Assessment (AR4) of the Intergovernmental Panel on Climate Change (IPCC) [IPCC, 2007]. We use the same approach as Lambert and Fyfe [2006, hereafter LF06], who examined trends in winter cyclones in the same multimodel data set. [4] In section 2 we describe the data and methods used in our analysis. The main results, and their discussion in light of previous studies, are presented in section 3. Concluding remarks are in section 4.

2. Data and Methods

We consider here output from 16 models in the CMIP3 multimodel data set (https://esg.llnl.gov:8443/index.jsp); see Table 1. There are many differences among these models, including dynamic cores, physical parameterizations, and resolution. For example, the horizontal resolution of these...
models varies from $1.125\degree \times 1.125\degree$ to $5\degree \times 4\degree$ longitude by latitude (Table 1).

[7] For each model we have analyzed simulations of the twentieth century (20C3M) and three of the scenarios for future concentrations of greenhouse gases (GHGs) from the Special Report of Emission Scenarios (SRES) [Nakicenovic et al., 2000]: SRES B1, A1B, and A2. These represent low, medium, and high emission scenarios, respectively. We focus here on the 20C3M and A1B simulations, but the cyclone trends and distributions for the B1 and A2 simulations are similar to those for A1B. Model output is available for 1960–2000 for the 20C3M simulation and for 2046–2065, 2081–2100, 2181–2200, and 2281–2300 for the A1B simulations. Multiple simulations of different scenarios are available from some models, but for our analysis we consider only a single simulation for each model. The impact of this choice is examined in section 3.

[8] The CMIP3 data are available only as daily averages. This limits the possible analysis of cyclones that can be done with this data set. Here we use the simple algorithm described by LF06 to characterize the cyclones in the models. In this algorithm surface cyclones are identified by locating the local minimum in the daily-average mean sea level pressure (MSLP). We do not calculate the lifetime or track the movement of the identified cyclones, and in the remainder of this paper surface “cyclone” will refer to a minimum in daily-average MSLP. Possible implications of the use of this simple scheme are discussed below.

[9] As the model output is in different grids and resolutions, the output is transformed, in accordance with LF06, to a common grid. The data are first transformed to a Gaussian grid with T40 ($120 \times 60$) resolution or with T32 ($96 \times 48$) resolution if the original grid does not have enough resolution. The MSLP fields are then interpolated to a northern polar stereographic grid with a grid spacing of 381 km at $60\degree N$, and analysis is then performed on these data. The MSLP was smaller than each of four neighboring grid points, on the polar stereographic grid. We restrict our analysis to NH extratropical cyclones, and we analyze the MSLP field between $30\degree N$ and $90\degree N$. Grid points with topography higher than 1000 m are excluded from the cyclone analysis because of the potential influence of sea level pressure field extrapolation [e.g., Wang et al., 2006], and no upper threshold was applied to filter the shallow cyclones.

[11] The number of cyclones simulated within the 20 or 40 year periods described above are calculated for each grid point. The frequencies are calculated for both the summer (June, July, and August) and winter (December, January, and February) periods. The frequency of occurrence is then expressed as the number of cyclone events count per 20 years (the usual length of consecutive model output). In addition to analyzing the frequencies for each model, we consider the multimodel mean cyclone frequencies (i.e., the mean frequency of the 16 models). The statistical significance of the multimodel mean trends is calculated using the standard $t$ test.

[12] We compare the characteristics of the cyclones in the 20C3M with those in the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) [Kalnay et al., 1996] and ERA40 reanalyses [Uppala et al., 2005]. Cyclones in the reanalysis data are calculated from daily-averaged MSLP in exactly the same manner as the CMIP3 models. The cyclone identification scheme described above is conceptually straightforward, and it can easily be applied to the multimodel data set. However, there are some disadvantages of the scheme and its application to daily-averaged fields. The advantages and disadvantages of this scheme are discussed in detail by Lambert et al. [2002]. One disadvantage is that the scheme identifies thermal lows and minima resulting from extrapolation under high terrain. Also, the use of unfiltered daily-averaged data results in a bias toward large-scale features and slower moving systems [e.g., Hoskins and Hodges, 2002], which may mean that the trends in the cyclone counts are influenced by trends in the background flow. There is also no information on some important characteristics of the cyclones, such as lifetime and size. As a result, we do not know how many of the identified systems are ephemeral and last for just 1 day, and hence may not be counted in schemes that require systems to last a certain lifetime.

[14] To characterize the radius, depth, genesis, lifetime, or tracks of storms requires one of several more sophisticated algorithms that track the movement of storms and/or diagnose additional characteristics of the systems. These schemes have

<table>
<thead>
<tr>
<th>Model</th>
<th>Grid</th>
<th>Country</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCCR-BCM2.0</td>
<td>Gaussian 128 × 64</td>
<td>Norway</td>
<td>Déqué and Piedelievre [1995]</td>
</tr>
<tr>
<td>CGCM3.1</td>
<td>Gaussian 96 × 48</td>
<td>Canada</td>
<td>Flato and Boer [2001]</td>
</tr>
<tr>
<td>CNRM-CM3</td>
<td>Gaussian 128 × 64</td>
<td>France</td>
<td>Salas-Mélia [2002]</td>
</tr>
<tr>
<td>CSIRO-Mk3.5</td>
<td>Gaussian 192 × 96</td>
<td>Australia</td>
<td>Gordon et al. [2002]</td>
</tr>
<tr>
<td>GFDL-CM2.1</td>
<td>Latitude/longitude 144 × 90</td>
<td>USA</td>
<td>Deval et al. [2006]</td>
</tr>
<tr>
<td>GISS-AOM</td>
<td>Latitude/longitude 90 × 60</td>
<td>USA</td>
<td>Russell et al. [1995]</td>
</tr>
<tr>
<td>GISS-ER</td>
<td>Latitude/longitude 72 × 46</td>
<td>USA</td>
<td>Schmidt et al. [2006]</td>
</tr>
<tr>
<td>FGOALS-g1.0</td>
<td>Gaussian 128 × 60</td>
<td>China</td>
<td>Yu et al. [2004]</td>
</tr>
<tr>
<td>INGV-SXG</td>
<td>Gaussian 320 × 160</td>
<td>Italy</td>
<td>Gualdi et al. [2008]</td>
</tr>
<tr>
<td>INM-CM3.0</td>
<td>Latitude/longitude 72 × 45</td>
<td>Russia</td>
<td>Dansky and Volodin [2002]</td>
</tr>
<tr>
<td>IPSL-M4</td>
<td>Latitude/longitude 96 × 72</td>
<td>France</td>
<td>Hourdin et al. [2006]</td>
</tr>
<tr>
<td>MIROC3.2(med)</td>
<td>Gaussian 128 × 64</td>
<td>Japan</td>
<td><a href="http://www.ccsr.u-tokyo.ac.jp/kyosei/hasumi/MIROC.tech-repo.pdf">http://www.ccsr.u-tokyo.ac.jp/kyosei/hasumi/MIROC.tech-repo.pdf</a></td>
</tr>
<tr>
<td>ECHO-G</td>
<td>Gaussian 96 × 48</td>
<td>Germany/Korea</td>
<td>Legutke and Voss [1999]</td>
</tr>
<tr>
<td>ECHAM5/MPI-OM</td>
<td>Gaussian 192 × 96</td>
<td>Germany</td>
<td>Jungclaus et al. [2005]</td>
</tr>
<tr>
<td>MRI-CGCM2.3.2</td>
<td>Gaussian 128 × 64</td>
<td>Japan</td>
<td>Yukimoto et al. [2001]</td>
</tr>
<tr>
<td>CCSR3.2</td>
<td>Gaussian 256 × 128</td>
<td>USA</td>
<td>Kiehl et al. [1998]</td>
</tr>
</tbody>
</table>
been widely applied to both observational data sets and in individual models [e.g., Bengtsson et al., 2006; Wang et al., 2006; Wernli and Schwierz, 2006; Lim and Simmonds, 2007; Löptien et al., 2008; Raible et al., 2008; Simmons and Keay, 2009]. They have been used to characterize the radius, depth, genesis, lifetime, and tracks of storms in both observational data sets and individual models. However, in these applications the data were available at higher temporal resolution (typically 6 hourly data) than the daily-average data available for the CMIP3 models. Previous studies have shown that tracking algorithms require data with higher time resolution than daily averages to be accurate [e.g., Blender and Schubert, 2000]. Furthermore, given the smoothing because of the daily averaging of the MSLP, diagnostics of additional characteristics, such as radius [e.g., Simmonds and Keay, 2009], are also not likely to be accurate. In other words, no significant improvements can be expected using a more sophisticated scheme applied to daily-averaged fields. Therefore, we use the simple LF06 scheme for this study.

[15] Given the above issues, we assess the impact of using this scheme by comparing below our results with previous studies using different schemes. Although some differences are found, there is in general good agreement, and differences with other schemes are of a similar magnitude to differences between any two schemes. This general agreement suggests that the simple scheme we use produces reasonable results.

3. Results

3.1. Current Climate

[16] Before examining trends in the frequency of cyclones, we examine the mean cyclone frequencies for 1960–2000 in the 20C3M simulations. We examine first the frequency of cyclones and then their spatial distribution.

[17] As shown in Figure 1a, there is an extremely large variation in the number of cyclones simulated by the different models, for both winter and summer cyclones: The 20 year cyclone center counts in a model varies between around 20,000 and 40,000 for the winter season, while this number varies between around 25,000 and 50,000 for the summer season. The mean numbers per 20 years averaged over all models (multimodel mean) are 27,589 and 38,807, for winter and summer cyclones, respectively. A more even winter and summer distribution could be expected if we applied an upper threshold for cyclone identification which would more effectively remove the summer shallow heat low. The majority of the models underestimate the number of cyclones, and the multimodel mean values are slightly lower than the cyclone numbers in the NCEP/NCAR and ERA40 reanalyses (Figure 1a).

[18] The large spread in number of winter cyclones among the models was reported by LF06. Ulbrich et al. [2008] also documented a large spread of storm tracks within the IPCC models. Furthermore, several studies have compared individual models with the reanalyses, and they show varying degrees of agreement with the reanalyses but a general underestimate of the number of cyclones in the models [e.g., Pinto et al., 2007; Raible et al., 2008; Löptien et al., 2008]. The exact cause of the large spread in the number of cyclones among the models is not known. One possible reason could be the different horizontal resolutions in the models (see Table 1). However, there is not a strong relationship between number of cyclones and model resolution (see Figure 1b).

[19] Although there is a large range in cyclone frequencies, all models show higher cyclone frequencies in summer than in winter, and the multimodel mean frequencies of summer cyclones is 41% larger than that of winter cyclones (varying from 17% to 78% for individual models). We also find this seasonal difference in cyclone frequency in the reanalyses. However, previous studies using other algorithms to diagnose cyclone center frequency for meteorological reanalyses are not consistent in this regard: Raible et al. [2008] and Löptien et al. [2008] show more summer cyclones, but this is not...
shown by Wernli and Schwierz [2006]. These differences among results from different schemes could be related to seasonal differences in the strengths and lifetimes of cyclones and different methods to identify cyclones. There is also a general tendency for models with a greater number of winter cyclones to also have a larger number of summer cyclones; i.e., models producing larger numbers of cyclones do so in both the winter and summer.

[20] There is also a difference in the strengths or intensities of the cyclones between the winter and summer. This is illustrated in Figure 2a, which shows the multimodel mean probability distribution functions (PDFs) of the central pressure of winter and summer cyclones. (This was formed by taking the mean of the PDFs for each individual model.) This clearly shows that there are more winter cyclones with low central pressure (e.g., less than 970 hPa) than in the summer. The seasonal difference is expected as there is higher baroclinicity along the polar front region during winter (related to the stronger meridional temperature and pressure gradients). Figure 2a also shows that there is larger variability between models in the summer than in the winter (thin solid curves). As in Figure 1, there is reasonable agreement between the multimodel mean and reanalysis data (dashed curves in Figure 2a). This seasonal variation in intensity of cyclones has been found in previous studies using different algorithms [e.g., Wang et al., 2006; Bengtsson et al., 2006; Löptien et al., 2008].

[21] The central pressure is just one of many measures of the intensity of cyclones. Several different measures have been used in previous studies, including minimum in relative vorticity [Bengtsson et al., 2006], horizontal gradient in geopotential height [Raible et al., 2007] or pressure [Geng and Sugi, 2003], and the Laplacian of MSLP [Murray and Simmonds, 1991]. To assess the sensitivity to the measure used to define intense cyclones, we repeat the calculations using the central horizontal pressure gradient as the measure of intensity. This measure is not as susceptible to changes in background pressure as the central pressure, yields a better measure of the wind speed associated with the cyclones, and is straightforward to calculate (we use the average of gradient for the four neighboring grid boxes to define the pressure gradient at a given grid box). Figure 2b shows that there is also a clear seasonal difference in this measure, with more winter cyclones with large pressure gradients (e.g., larger than 1.5 hPa/100 km) than in the summer. There is also good agreement between the multimodel mean PDF and that from reanalysis data.

[22] We now consider the spatial distribution of the cyclones. In both winter and summer, cyclones are not uniformly distributed throughout the extratropics. Figure 3 presents maps of the multimodel mean cyclone frequency for 1960–2000 for (Figure 3a) winter and (Figure 3b) summer, together with (Figures 3c and 3d) the corresponding maps from the NCEP reanalyses. In both seasons there are areas of high frequency over the northern Atlantic and Pacific oceans; however, there are differences in detail. The highest frequency of winter cyclones appears over the high latitude Pacific and Atlantic oceans (Figure 3a), whereas in summer the regions with more frequent cyclones shift to over continental regions, including northern Russia and Alaska (Figure 3b). The spatial variations in the multimodel mean cyclone frequencies are similar to those from meteorological reanalysis (see Figures 3c and 3d). Furthermore, the distributions and seasonal differences shown in Figure 3 are similar to previous studies that have used some of the more sophisticated identification schemes discussed in section 2; e.g., compare Figure 10 from Bengtsson et al. [2006], Figure 4 from Wernli and Schwierz [2006], Figure 2 from Raible et al. [2008], and Figure 2 from Löptien et al. [2008]. This gives us confidence that the simple scheme used is identifying the key aspects of the cyclone distribution. However, we notice that there are some differences. Like Löptien et al. [2008], we find that the summer oceanic cyclones over the North Pacific are weaker than continental cyclones over eastern Russia and Alaska, whereas Bengtsson et al. [2006] and Wernli and Schwierz [2006] find the opposite.

[23] The distribution of intense cyclones has a spatial structure similar to that of all cyclones in the winter (Figures 4a and 4c). However, there are differences in the distributions of all summer cyclones and intense summer
cyclones. In the summer continental cyclones have much higher intensity than oceanic cyclones except over east Asia, and summer intense cyclones are frequently located over Alaska, the northeast Atlantic, and east Asia (Figures 4b and 4d). The large-scale structure is similar whether central pressure or horizontal pressure gradients are used to define the intense cyclones, but there are some differences in detail; e.g., summer cyclones with high horizontal gradients occur primarily over the North Atlantic, whereas low-pressure cyclones are also commonly found over the Pacific and east Asia. For both measures the multimodel mean is similar to that from reanalyses (not shown). A spatial distribution of intense cyclones similar to that shown here is reported by Geng and Sugi [2003].

In sum, the above analysis shows that there is a wide spread in the number of winter and summer cyclones simulated in the CMIP3 models. However, the multimodel mean frequencies and distributions are in reasonable agreement with those from reanalyses and from previous studies.

3.2. Future Trends

[25] We now consider trends in the cyclone frequencies. We focus on differences in cyclone frequency in the A1B scenario (2000–2300) and in the 20C3M simulations (1960–2000), but similar results are found for the other scenarios considered. The results for winter cyclones are the same as those from LF06, and they are briefly discussed here to enable summer trends to be compared with winter trends.

3.2.1. Cyclone Frequencies

[26] As reported by LF06, a consistent result across models is a decrease in the frequency of hemispheric-averaged (30°N–90°N) winter cyclones in future climates with higher GHGs (see Figure 5a). All models show a decrease in the winter cyclone frequency for the A1B scenario, although there is a large variation in the magnitude of the decrease; e.g., within the 21st century the decrease varies from 2% to 12%. The multimodel mean trend is 7% over 100 years, which is significant at greater than 99% confidence level ($p = 10^{-8}$).
The winter cyclone frequency also decreases for the B1 scenario (5%) and A2 scenario (9%), with larger rates of decrease for scenarios with higher emission levels (see also LF06 and Pinto et al. [2007]).

The change of frequency in summer cyclones is very different from that in winter. There is no consistency in the sign of the trend for summer cyclone frequency between models, with the trend over the 21st century for individual models varying from a decrease of around 7% to an increase of around 8% (see Figure 5b). As a consequence, there is essentially no trend for the multimodel mean (trend of 0.3% over 100 years, which is not statistically significant ($p = 0.76$)). This applies for all GHG scenarios considered (not shown).

In the above, we have considered only a single simulation for each model (for given GHG scenarios). The large variation in the simulated trends may not be due to differences between the models but rather the variability between different simulations with the same model. To examine this, we repeat the analysis with the ensemble of simulations from a single model. The triangles in Figures 5a and 5b show the trends from the ensemble of simulations by the CGM3.1 model (these trends were calculated using all combinations of the five 20C3M simulations and three A1B simulations from the CGM3.1 model). There is some variation in the trends from CGM3.1 depending on the simulation used for current or future climate, but the spread is much smaller than that between the different models. For example, the standard deviation of the 21st century trend from the CGM3.1 ensemble is around 0.8%, whereas the standard deviation for single simulation from all models is around 3.6%. This suggests that the variation in trends among different models is not primarily due to the selection of only a single simulation for each model.

### 3.2.2. Intense Cyclone Trends

It is interesting to consider not only trends in the total number of cyclones but also trends in the number of intense cyclones. As in most previous studies, cyclones are identified

**Figure 4.** As in Figure 3, except for multimodel mean frequency of cyclones with (a, b) low central pressure (less than 970 hPa for winter or 990 hPa for summer) or (c, d) high horizontal pressure gradients (greater than 1.5 hPa/100 km).
here as intense when some measure of their strength (e.g., central pressure or pressure gradient) exceeds a threshold value [e.g., LF06; Pinto et al., 2007; Löptien et al., 2008]. The trend in the number of so-defined intense cyclones is calculated for each model, as is the mean of the trends from all models. As above for total cyclone numbers, the significance of this multimodel trend is evaluated using the standard t test.

**Figure 5.** Temporal variation of Northern Hemisphere (NH) cyclone frequency, expressed as percent departure from 1961–2000 frequency, for (a, b) all cyclones, (c, d) cyclones with central pressure less than 970 hPa for winter and 990 hPa for summer, and (e, f) cyclones with horizontal pressure gradients greater than 1.5 hPa/100 km, for the A1B scenario. Figures 5a, 5c, and 5e show the winter case, while Figures 5b, 5d, and 5f show the summer case. The multimodel mean frequencies are shown as black thick lines. Red triangles in Figures 5a and 5b show trends for multiple runs from the CGCM3.1 model.
There are some questions about the reliability of this relatively simple approach to identify extreme values, and more robust results may be obtained using more complex extreme value statistics. These extreme value statistics have very recently been applied to study intense North Atlantic cyclones in simulations from single models [e.g., Della‐Marta and Pinto, 2009; Sienz et al., 2010]. However, we leave the application of this new approach to the CMIP3 multimodel data set, and comparison with the approach used here, to a future study.

LF06 showed that while the models project a decrease in the total number of winter cyclones they predict an increase in the number of cyclones with low central pressure (pressure < 970 hPa). This result is reproduced in Figure 5c. There is also an increase in number of summer low‐pressure cyclones for the multimodel mean and for nearly all individual models (see Figure 5d). (Here a higher threshold of 990 hPa was used to identify low‐pressure cyclones during the summer, as the summer cyclone pressure is seldom lower than 970 hPa.) Thus while there is not consistency in total number of summer cyclones, there is consistency in the number of summer low‐pressure cyclones.

However, the use of a central pressure below a fixed threshold to identify changes in intense cyclones assumes that there is no change in the background pressure field. Examination of the background pressure field in the simulations shows that this assumption is not valid for the A1B simulations as there are temporal changes in large‐scale pressure distributions (see Figure 6). In general, the background pressure decreases in the regions where there is an increasing trend in low‐pressure cyclones (e.g., there is a 2 hPa decrease in the winter background pressure over the Gulf of Alaska and the number of low‐pressure cyclones increases 40%), with a similar relationship between regions where the background pressure increases and the number of low‐pressure cyclones decreases. This means that the trends in low‐pressure cyclones could be mainly reflecting this change in background pressure.

As discussed above, the horizontal gradient of the central pressure [e.g., Geng and Sugi, 2003] is an alternative measure of the intensity of cyclones that is not as susceptible to changes in background pressure. Figures 5e and 5f show the change in number of intense winter and summer cyclones, respectively, using central pressure gradients greater than 1.5 hPa/100 km to define intense cyclones. The trends in this measure are very different from those for cyclones with central pressure below a fixed threshold. Using the pressure gradient diagnostic, nearly all models show a decrease in intense winter cyclones, and the multimodel mean trend of 10% over the century is statistically significant (p = 10⁻⁵). However, there is a larger variation among the models of intense summer cyclones, with only a small positive trend (1% over the century) for the multimodel mean, which is not statistically significant (p = 0.68).

Hence, there is a statistically significant decrease in the hemispheric‐averaged frequency of both the total number of cyclones and the number of intense cyclones (defined using pressure gradients) during winter, but there are only weak, and not statistically significant, trends in the total number of summer cyclones and the number of intense summer cyclones.

### 3.2.3. Spatial Distributions

Although there is no consistency in trends of the hemispheric‐averaged frequency of summer cyclones, it is possible that there are consistent trends for particular regions. Therefore, we examine the model trends for individual locations. Figure 7 presents maps of the difference in frequency between 2081–2100 of the A1B scenario and 1961–2000 for (Figure 7a) all winter, (Figure 7b) all summer, (Figure 7c) intense winter, and (Figure 7d) intense summer cyclones.

There is a seasonal difference in the spatial distribution of the trends in cyclone frequency. There are only weak spatial variations in the change in winter cyclone frequency, with a decrease in frequency at middle latitudes (mainly over the low to middle latitude central North Pacific, south of...
Greenland, the Mediterranean, and south of Canada) (see Figure 7a). In contrast, there are large spatial variations in the difference map for summer midlatitude cyclones (Figure 7b). The trends in multimodel mean summer cyclone frequency varies with both longitude and latitude, but the frequency increases within 30°N–45°N (particularly over the Iberian Peninsula) and decreases within 45°N–60°N (particularly over the British Isles). Comparing the maps in Figures 3b and 7b, it appears that that the decrease at high midlatitudes is mainly caused by a northward shift in regions with cyclones over the Pacific and North Atlantic, and a north-east shift over Europe. Löptien et al. [2008] and Bengtsson et al. [2006] presented the same argument for changes over the North Atlantic, but they argue that the decrease of North Pacific cyclones is caused by a southward shift. The increase in low midlatitudes appears to be associated with the increase in number of low-pressure systems (including heat lows) over the continents.

The spatial distribution of the multimodel trends in intense cyclones also differs between winter and summer (see Figures 7c and 7d). During winter there is a decrease in number of intense cyclones at virtually every location, with the largest decrease occurring over the North Atlantic and Arctic oceans. In contrast, the sign of trends in summer intense cyclones varies with location. Generally, there are decreases in middle latitudes and increases at high latitudes, but in all cases the trends are small.

As the cyclone frequency varies greatly among the different models, it is possible that the spatial distributions in Figure 7 are due to contributions from only a few models with large cyclone frequencies. To examine the variations in more detail we now consider changes in summer cyclone frequencies in different subregions.

As shown in Figure 7b, the multimodel mean frequency tends to increase between 30°N and 45°N and to decrease between 45°N and 60°N. Figures 8a and 8b show the
trends from individual models for these two latitude bins. In both regions there are reasonably robust changes across all the models. For 30°N–45°N there is a statistically significant increase of 6.7% in the 21st century ($p = 0.011$) in the multimodel cyclone frequency, although five models show a decreasing trend. For 45°N–60°N there is a similar agreement among the models, except that the cyclone frequency decreases (the multimodel mean decrease is 4.0% ($p = 0.019$)).

The above shows reasonably consistent projected changes among the models for averages over “low” or “high” midlatitudes. It is interesting to see if such a consistency also holds for individual grid boxes. To explore this issue, we consider three grid boxes that are examples of locations where there is a significant positive trend (grid point “G1” at 40.0°N, 96.0°W), a significant negative trend (“G2” at 50.6°N, 69.7°W), and an insignificant trend in the multimodel cyclone frequency (“G3” at 41.7°N, 80.0°W), respectively (see boxes in Figure 7b). Figures 8c–8e show the changes in each model for these three grid boxes.

At G1 (in the midwestern United States), there is an increase in the multimodel mean summer cyclone frequency between 1960–2000 and 2081–2100 (Figure 8c), and the majority of individual models also show an increasing trend in G1. However, there is a wide spread in magnitude of the
trend among the models, with the change varying between around $-30\%$ to around $60\%$. Thus, even though there is a significant increase in the multimodel trends, there is not necessarily a robust result between models. There is also a significant decrease of cyclone frequency for region G2 (southeastern Canada), but five of the models show virtually no change or an increase in frequency from 1960–2000 to 2081–2100 (Figure 8d). At G3, there is no trend in multimodel mean, with a mean decrease of 1% but a 12.3% standard deviation among models (Figure 8e).

The above examples show that there are some regions where the sign of the trend is consistent across the vast majority of models and there are statistical significant trends for the multimodel analysis. However, even in these regions there is still a large spread in the magnitude of the trend from individual models and, hence, a large uncertainty in the trends from a single model.

The above result showing no (or weak) trends in summer cyclones in NH appears at odds with several previous studies that indicate a change in cyclone frequency and “storm track” [e.g., LF06; Bengtsson et al., 2009; Ulbrich et al., 2009, and references therein]. However, as discussed in section 1, these previous studies have focused primarily on changes in winter cyclones. One exception is the study of Yin [2005], who examined changes in storm tracks in the CMIP3 models, for both winter and summer seasons. Consistent with our analysis, Yin [2005] showed a much weaker change with less consistency among models for the NH summer. Furthermore, the GFDL-CM2.1 and CCSM3 models are near the outliers in our analysis (Figure 5) and in Figure 3 of Yin [2005]. A few other studies have examined summer trends in individual models [Geng and Sugi, 2003; Bengtsson et al., 2006; Orsolini and Sortberg, 2009], and consistent with our analysis, there is limited agreement in the trends from the different models.

The exact reason for the lack of consistency in the sign of summer trends among the models (as opposed to consistency in winter trends) is not known. However, this could just be the result of the smaller summer than winter trends, and not an indication of models performing better or more consistently in the winter.

4. Conclusions

We have examined the trends in Northern Hemisphere midlatitude cyclones, identified as local minima in daily-average MSLP, within a collection of climate models that participated in the IPCC AR4 [IPCC, 2007]. Although all models simulate a reduction in the number of NH winter cyclones for all future scenarios (LF06), such a robust result does not hold for changes in summer cyclones. The simulated trends in summer cyclones are generally smaller than those in winter cyclones, and there is much less consistency among model projections. For example, the change in the hemisphere average frequency of summer cyclones over the 21st century for the A1B scenario varies between $-7\%$ and $+8\%$ for different models, compared with $-2\%$ to $+12\%$ for winter cyclones. When smaller regions are considered, there are some regions where the sign of the trend is consistent across the vast majority of models and there are statistically significant trends in the multimodel mean. However, even in these regions there is still a large spread in the magnitude of the trend from individual models, and, hence, a large uncertainty in the trends from a single model.

It is important to note that in this study we have identified cyclones by applying a very simple scheme to daily-averaged fields. The choice of the simple scheme is linked to the fact that only daily averages are available (i.e., little is to be gained by using more sophisticated schemes), but it does mean that there are potential biases in our cyclone statistics. In particular, there is likely a bias toward large-scale features and slower moving systems, and the climatology may include thermal lows or short-lived systems that are not included in other identification schemes. However, we find overall good agreement with other studies that use more sophisticated schemes and/or more frequent data.

The general lack of consistency between summer trends in the models indicates that care will be required when interpreting changes in summer weather systems in simulations from a single climate model. This has potentially important implications for studies of the impact of climate change on air quality, where a single global model is generally used (either for the complete analysis or to constrain a mesoscale air quality model). In this regard, an important follow-up study will be to examine the simulated changes in diagnostics that are more closely tied to ventilation of the boundary layer or occurrence of stagnation events. This may require more frequent data than are available for the CMIP3 models.

Acknowledgments. We thank three anonymous reviewers, John Fyfe, Eric Leibensperger, Daniel Jacobs, and Lorraine Mickey for helpful advice and comments on an earlier version of this paper. This research was supported by the National Science Foundation through grant ATM-0905863. We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI), and the WCRP’s Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multimodel data set. Support of this data set is provided by the Office of Science, U.S. Department of Energy.

References

Geng, Q., and M. Sugi (2003), Possible change of extratropical cyclone activity due to enhanced greenhouse gases and sulfate aerosols—Study with a high-resolution AGCM, J. Clim., 16, 2262–2274.


