CHANGES IN EXTRA-TROPICAL STORM TRACKS AND CYCLONE ACTIVITY AS DERIVED FROM TWO GLOBAL REANALYSES AND THE CANADIAN CGCM2 PROJECTIONS OF FUTURE CLIMATE

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ABSTRACT

In this study, a cyclone detection/tracking algorithm was used to identify cyclones from three gridded 6-hourly mean sea level pressure datasets: the ERA-40 and NCEP/NCAR reanalyses for 1958-2001, and the Canadian CGCM2 projections for 1975-94 and 2080-99 under the IS92a forcing scenario. The changes are discussed in terms of storm tracks position, lifespan of cyclone-tracks, and cyclone occurrence frequency and its distribution over its intensity.

The results show that the most substantial changes of cyclone activity are associated with the number and track of strong cyclones (central pressure < 990 hPa), especially in the northern hemisphere. This is true for both the observed and the CGCM2 projected climates.

In the past half century, the changes are characterized by a significant increase in the number of strong winter and spring cyclones over the North Pacific (NP) sector, and strong autumn and winter cyclones in the North Atlantic (NA) sector. In particular, the mean track of strong cyclones in the NA sector has shifted slightly northward in winter. Also, the ERA-40 and NCEP/NCAR reanalyses show generally comparable changes in the storm tracks and cyclone activity.

In the NP sector, CGCM2 projects a clockwise rotation of the NP storm track in winter and a northward shift of the NP storm track with an anti-clockwise rotation of the eastern Asia storm track in spring. In the NA sector, the projected changes are characterized by a significant increase in the number of strong cyclones over northern Eurasia in all seasons except summer (also over the Baffin Bay and Labrador Sea in autumn and winter). In general, changes are often characterized by increases in the number of cyclones in cold seasons but by longer lifespan of cyclone-tracks in the warm seasons. The changes projected for the southern hemisphere are less notable than those for the northern hemisphere and are characterized by significant deductions in the number of strong cyclones in the region between 45°S and 60°S.

1. INTRODUCTION

Originally, storm tracks refer to the preferred regions of storm/cyclone activity and can be defined based on cyclone count statistics (Pettersen 1956, Whitaker and Horn 1984). In this study, we use this original definition, although the use of eddy variance/covariance statistics to define storm tracks is a popular alternative (Blackmon 1976, Chang et al. 2002, Chang and Fu 2003, among others). Also, we distinguish “a cyclone” from “a cyclone-track”. Here, a cyclone refers to a single low pressure center identified at a specific location (grid-point) and time (a terminology commonly used in most of the previous studies); while a cyclone-track consists of a cyclone **and** its track during its life-time (thus identification of a cyclone-track involves both detection of a low pressure center and tracking of its movement during its life-time). A cyclone-track usually lasts more than one time-step and is present at many grid-points nearby one another. A cyclone is a cyclone-track at one single time-step. Therefore, counts of cyclone-tracks are usually much smaller than counts of cyclones.

Extra-tropical cyclone activity plays an important role in the climate system. Cyclones are usually accompanied by adverse weather conditions. A systematic shift in either the geographical location or the intensity of cyclone activity will result in substantial precipitation anomalies among other impacts on regional climates. Since the planetary-scale flow has been found to have a symbiotic link to storm tracks (Cai and Mak 1990), a shift of the storm tracks will be associated with anomalies in the planetary-scale flow.

While there have been many studies using the NCEP/NCAR reanalysis (NRA; Kalnay et al. 1996) data to assess observed changes of extra-tropical storm tracks and cyclone activity (e.g., Fyfe 2003, Chang and Fu 2002, Graham and Diaz 2001, Simmonds and Keay 2000, Lambert 1996), few studies have used the recently completed ERA-40 reanalysis (Simmons and Gibson 2000, Gibson et al. 1996) to do the assessment. Also, most of the previous studies assessed changes in the number of cyclones (typically, total numbers over a hemisphere or a selected region, without revealing the spatial pattern of changes); few of them are about changes in the lifespan of cyclone-tracks or about position-shifts of the storm tracks in this context. The latter aspects of changes and the related spatial patterns have not been well characterized. For example, there has been a debate about how the North Atlantic storm track has changed in the past half century: northward shifted or clockwise rotated or unchanged? Aiming for a more comprehensive assessment of the observed changes, in the first part of the present study, we applied a cyclone finding and tracking algorithm to the 6-hourly mean sea level pressure (MSLP) data from the ERA-40 reanalysis, to characterize the observed changes in terms of the storm tracks position, the lifespan of cyclone-tracks, and cyclone occurrence frequency as a function of its intensity. The results were compared with those derived from the NRA reanalysis using the same algorithm, to see whether or not the two reanalyses agree with each other in representing extratropical storm tracks and cyclone activity, and whether or not the ERA-40 reanalysis shows any difference for regions where the NRA reanalysis has been known to be problematic/erroneous (e.g., East Asia; personal communication with Steven J. Lambert).

Since the extra-tropical storm tracks are large-scale phenomena of the atmospheric circulation, they are generally well simulated by general circulation models (GCMs; Zhang and Wang 1997, Ulbrich and Christoph 1999, Chang et al. 2002) and hence should constitute a suitable feature for assessing the greenhouse-gas (GHG) induced climate change in extra-tropics. There have been several studies assessing changes related to storm tracks and cyclone activities in climates simulated by GCMs (e.g., Ulbrich and Christoph 1999, Sinclair and Watterson 1999, Chang et al. 2002). In particular, based on the daily 1000-mb geopotential heights (Z_{1000}) simulated by the Canadian second generation of GCM (GCM2), Lambert (1995) compared the double CO_2 simulations with a "current-level" CO_2 simulation and showed an increase in the number of intense cyclones ($Z_{1000} < -100$ m), with an overall decrease in the number of cyclones in both winter hemispheres. Fyfe (2003) assessed changes in the decadal mean number of extra-tropical southern hemisphere cyclones derived from daily MSLP data of a 500-yr control simulation and an ensemble of transient climate change simulations (with the IS92a greenhouse-gases and aerosols forcing scenario) using the Canadian first generation of coupled climate model (CGCM1; Flato et al. 2000). He concluded that the number of sub-Antarctic Ocean (40°S-60°S) cyclones will drop by 30% between now and the century's end. Lambert (2004) further examined changes in winter cyclone frequencies and strengths resulting from global warming, using twice-daily MSLP for three ten-year periods (1901-10, 2018-2027, and 2091-2100), as simulated using the Canadian CGCM1 and CGCM2 (second generation) with the IS92a forcing scenario. All the above three studies using Canadian climate model simulations used a simple definition of cyclones, defining a cyclone as the minima of MSLP on daily or twice-daily stereographic grid-points (with a grid-box area of 135,000-145,000 km^2 at 60° latitudes). Changes in the number of cyclones were the focus of these previous studies; little about changes in terms of storm tracks position or the lifespan of cyclone-tracks has been explored. The availability of 6-hourly MSLP data from the CGCM2 simulations (IS92a scenario) for three 20-yr windows (1975-94, 2040-59, 2080-99) makes it possible to take a more comprehensive look at the possible future changes of storm tracks and cyclone activity, in particular, the uncertainties with tracking of cyclones can be greatly diminished. In the second part of the present study, a cyclone finding and tracking algorithm is used to identify and track cyclone systems from 6-hourly MSLP data on an equal-area grid of 62,500 km^2 per grid box (250 x 250 km); changes in the number of cyclones of different intensity categories and in the areal mean lifespan of cyclone-tracks are explored, and shifts in the long-term mean storm tracks position will be illustrated in section 4. The analysis was carried out for each of the four seasons, separately, with the four seasons being defined as January-February-March (JFM), April-May-June (AMJ), July-August-September (JAS), and October-November-December (OND). They are called winter (JFM), spring (AMJ), summer (JAS), and autumn (OND) for the northern hemisphere.

The data sets used in this study and the analysis procedure will be described in section 2. The observed changes as derived from the ERA-40 reanalysis will be described and compared with those of the NRA reanalysis in section 3, and the CGCM2 simulated changes will be discussed in section 4. Finally, some concluding remarks will be given in section 5.

2. DATA AND PROCEDURE

Three global 6-hourly mean sea level pressure (MSLP) datasets were used in this study: the EAR40 reanalysis (Simmons and Gibson 2000, Gibson et al. 1996), the NRA reanalysis (Kalnay et al. 1996), and the Canadian CGCM2 projections of MSLP under the IS92a forcing scenario (i.e, the changes in greenhouse gases forcing corresponds to that observed from 1850 to 1990 and increases at a rate of 1% per year thereafter until year 2100; Flato and Boer 2001). The ERA-40 and NRA datasets that were used in this study cover the period 1958-2001 and were available on a 2.5-by-2.5 lat-long global grid. An ensemble of 3 CGCM2 integrations was available, with individual integrations being initiated from different initial conditions. However, 6-hourly data are available from only one of the 3 integrations for three 20-yr windows: 1975-94, 2040-59, and 2080-99 (12-hourly data are available for the other 2 integrations). The CGCM2 simulated MSLP data are on a global 96 x 48 Gaussian grid. Each of the 3 gridded MSLP datasets was interpolated to a 250 x 250 km version of the NSIDC EASE-grid (the Equal Area SSM/I Earth Grid developed at the National Snow and Ice Data Center; Armstrong and Brodzik 1995) over the Northern (Southern) Hemisphere prior to identification of cyclone centers. Readers are referred to the on-line document ftp://ftp.cdc.noaa.gov/Public/map/storm/README.txt for the rationale for the use of EASE-grid here.

The cyclone identification/tracking algorithm used in this study is the one originally developed by Serreze (1995; see also Serreze et al. 1997) and currently being used by the NOAA-CIRES Climate Diagnostic Center to produce the storm tracks from 6-hourly NCEP reanalysis data (see http://www.cdc.noaa.gov/map/clim/storm.shtml). This is one of the most comprehensive automatic algorithms available. It is similar to the automatic cyclone finding/tracking scheme originally developed by Murray and Simmonds (1991), which has been widely used to analyze southern hemisphere cyclone behavior (e.g., Simmonds and Murray 1999, Simmonds et al. 1999, Simmonds and Keay 2000). Two major components of the algorithm used here are: 1) detection of cyclones from a series of 6-hourly MSLP maps, testing whether a grid point MSLP value is surrounded by grid point values at least a detection-threshold higher than the central point being tested. 2) system tracking, based on a "nearest neighbor" analysis of the positions of systems between time steps with a maximum distance-threshold between candidate pairings, with further checks based on distance moved in the North/South and West directions and pressure tendency. In this study, we used a detection-threshold of 1 hPa and a maximum distance-threshold of 800 km. A distance of 800 km for a cyclone to travel within 6 hours (133 km/hr) seems "too fast", but it allows for "center jumps" to be tracked and is also necessary when one only has data at specific grid-points (cf. ftp://ftp.cdc.noaa.gov/Public/map/storm/README.txt). The latter implies that cyclone movement must be resolved into one of only a finite number of possible distances. Individual 6-hourly movement may appear to be unphysically large, but average speeds over the life of a cyclone should be well represented.

The "detected" cyclones were classified into two intensity categories (strong and weaker) according to whether or not their central pressure value is below 990 hPa. For each season, the long-term mean position of the northern (southern) storm tracks was represented by the mean latitude of all cyclones in the same intensity category within each 5°-longitude band of the 30°-70° North (South) latitude zone. The two-sample t-test for the case of unknown (and maybe unequal) variances (see Section 6.6.5 of von Storch and Zwiers 1999) was used to determined the statistical significance of changes in the cyclone count at each grid-point, or in the areal mean lifespan of cyclone-tracks, from one 20-yr period (e.g., 1975-94) to another (e.g., 2080-99). (For the count data, an empirical logistic transformation was applied prior to the t-test, to achieve better normal approximation.) The analyses were carried out for all cyclones together and separately for each of the two intensity categories. Note that it is possible in the above counting procedure for a quasi-stationary or slow-moving cyclone to be enumerated many times or for a rapid-moving cyclone to traverse a grid-box without being enumerated. However, this was proved not to be a problem because the results are corroborated by investigating changes in counts of cyclone-tracks that are free of the above "problem".

3. OBSERVED CHANGES

In this section, the observed changes in the extra-tropical storm tracks and cyclone activity are discussed using primarily the ERA-40 reanalysis, with a brief comparison with changes derived from the NRA reanalysis. We compare the cyclone climatology for two 20-yr periods (1958-77 and 1982-2001), to characterize the changes observed in the past half century. The following major aspects of the observed changes are discussed below: position of storm tracks, areal mean lifespan of cyclone-tracks, and cyclone occurrence frequency as a function of its intensity.

3.1 Observed changes in the northern hemisphere

Figures 1 and 2 show the 20-yr mean positions of the northern extra-tropical storm tracks for 1958-77 (black curve) and 1982-2001 (green curve), as defined by the mean latitude of all strong/weaker cyclones (within each 5°-longitude band) that are identified from the ERA-40 reanalysis for each of the four seasons. From the first to the last 20-yr period (1958-77 to 1982-2001), the most prominent feature of changes is that the NA storm track has shifted slightly northward in winter (JFM; Fig. 1a). This is corroborated by the results of t-tests, which show that the number of strong cyclones decreased significantly in the mid-latitudes and increased in the northern Atlantic sector (including northern Canada and northern Europe; see blue and red dots in Fig. 1a). Such changes, which are also seen in the NRA reanalysis, are peculiar to winter strong cyclones. In particular, the increase in the number of strong cyclones was accompanied by a decrease in the number of weaker cyclones (central pressure is not less than 990 hPa), showing a distributional shift of cyclone occurrence frequency as a function of its intensity. For example, a shift towards more frequent occurrence of strong cyclones (with less frequent occurrence of weaker cyclones; Fig. 3a) was identified in the high-latitudes of NA (see Box High-lat. NA in Fig. 4a), while a shift towards the opposite direction (i.e., less frequent occurrence of strong cyclones; Fig. 3b) was identified in the high-latitudes of NA (see Box Mid-lat. NA in Fig. 4a). In terms of the total number of winter cyclones identified (both intensity categories together), there was a significant decrease in the region from the subtropical NA to the Mediterranean, and an increase in the high-latitudes of NA (north of 60°N; not shown, but similar to Fig. 2a), which also suggests a slight northward shift of the winter NA storm track.

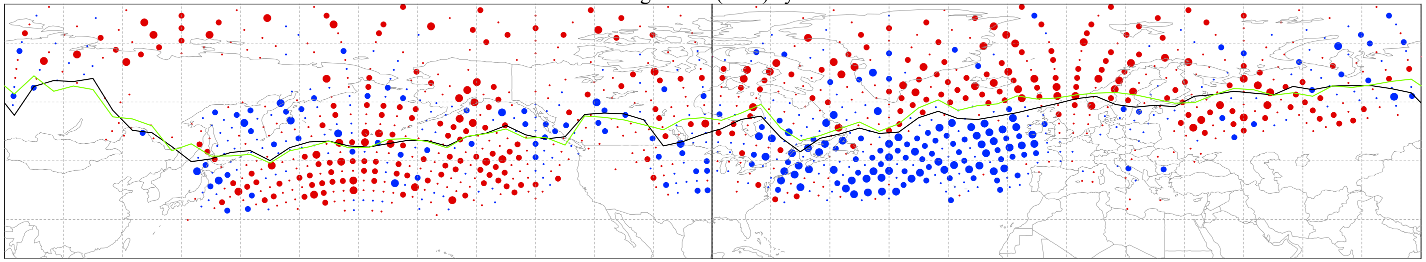
By analyzing cyclone-related 3-hourly sea level pressure changes observed at 99 Canadian stations for the 50-yr period of 1953-2002, Wang et al. (2004b) also show that extreme winter cyclone activity has become more frequent in northern Canada and less frequent in the south, which also indicates a northward shift of the winter storm track in Canada (their pattern of change is similar to that shown in Fig. 1a for Canada). The consistency of the changes identified from the above in-situ data with those from the ERA-40 reanalysis suggests that the changes are most likely real, not just an artifact of the reanalysis procedure or the increasing availability of data (including satellite data) in the recent decades.

Lambert (1996) also reported that there is a noticeable increase in the number of intense winter cyclones in both the NA and NP sectors after 1970, using the operational analyses of the National Meteorological Center (NMC).

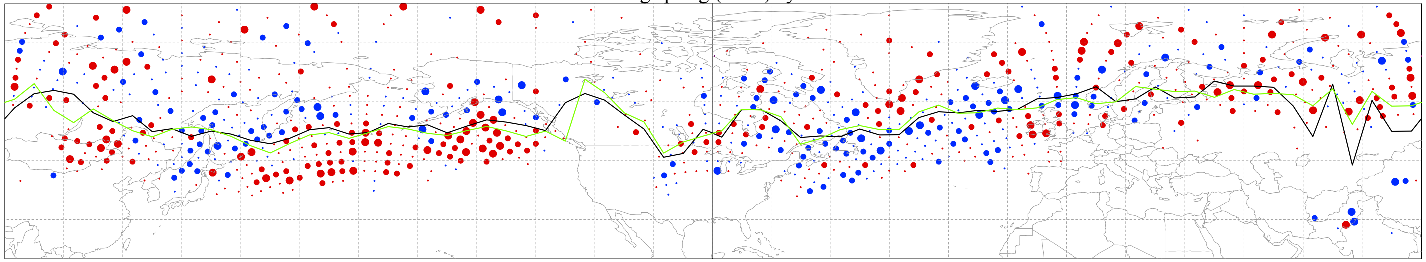
Changes in other seasons are generally not as significant as in winter, showing less organized patterns. As shown in Fig. 2b, the most notable feature of changes in spring is a significant increase in the number of weaker cyclones in the mid-latitudes of NA (centered over the Azores Islands); and changes in autumn (OND) are characterized by increases in the number of strong cyclones almost everywhere across the NA sector, with little shift in the mean position of the storm track (Fig. 1d).

Changes in the number of cyclones are consistent with changes in the number of cyclone-tracks. As listed in Table 1, there have been significant increases in the number of cyclone-tracks traversing the high-latitudes of NA (i.e., Box High-lat NA in Fig. 4a) in autumn through winter (OND-JFM), accompanied with fewer weaker cyclone-tracks in the region. In winter (JFM), more strong cyclone-tracks in the high-latitudes are associated with fewer strong cyclone-tracks in the mid-latitudes (see Box Mid-lat NA in Fig. 4a), which also indicates a northward shift of the strong storm track. For the entire northern extra-tropics, the total number of strong cyclone-tracks has increased in autumn through winter, with a reduction in the total number of weaker cyclone-tracks (see the last column in Table 1). In the warm seasons (AMJ and JAS), the changes are generally weaker. The number of strong cyclone-tracks in the NA sector appears to have decreased slightly in spring (AMJ), with a slight increase in the number of weaker cyclone-tracks. Also, there seems to be a reduction in the number of northern hemisphere summer (JAS) cyclone-tracks.

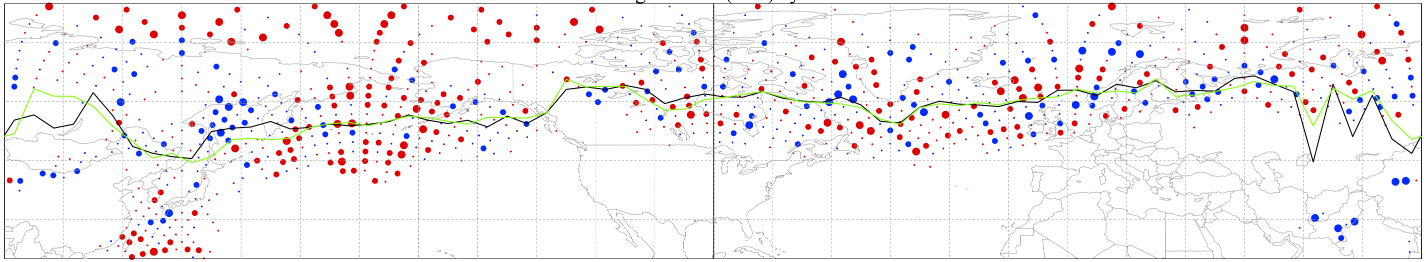
a. Strong winter (JFM) cyclones



b. Strong spring (AMJ) cyclones



c. Strong summer (JAS) cyclones



d. Strong autumn (OND) cyclones

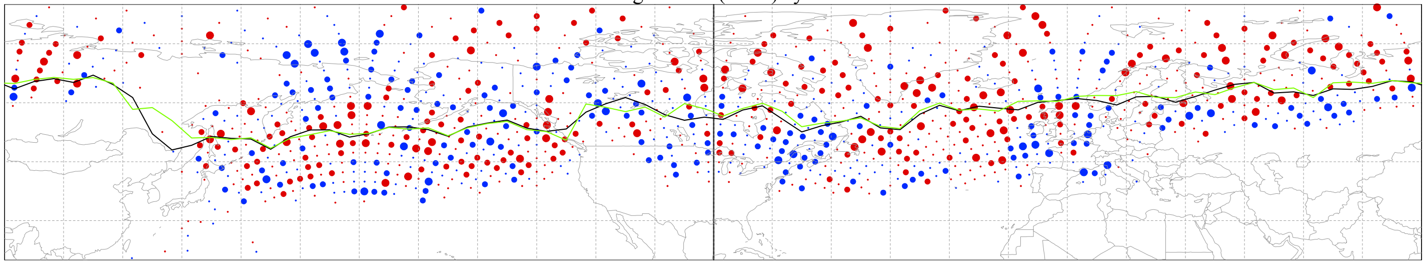
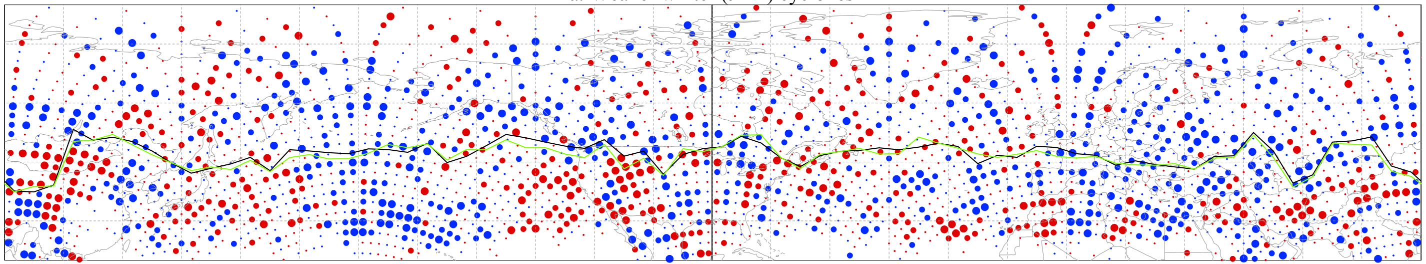
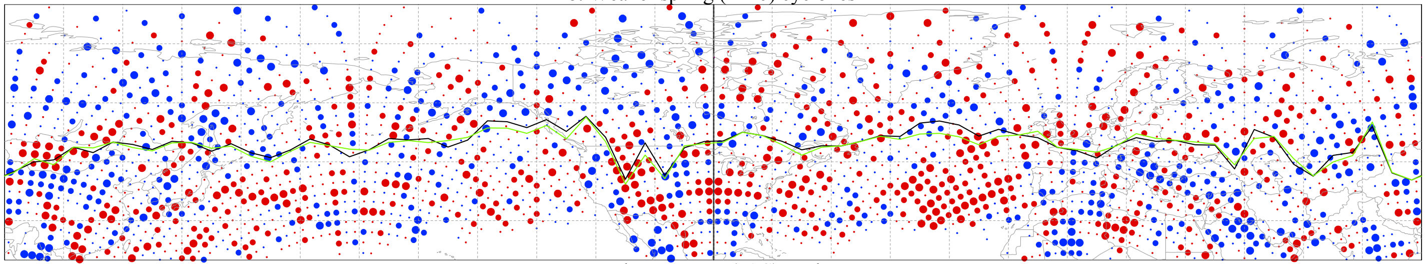


Fig. 1. Mean position of the northern extra-tropical (30°N-70°N) storm tracks for the period 1958-77 (black curve) and the period 1982-2001 (green curve), as defined by the mean latitude of all strong cyclones (central pressure < 990 hPa) identified from the ERA-40 reanalysis within each 5°-longitude band. Red/blue dots indicate increase/decrease in the frequency of strong cyclone at the grid-point from period 1958-77 to period 1982-2001. The large, medium, and small dots indicate that the changes at the grid-point are of at least 95%, 80-95%, and less than 80% level of confidence.

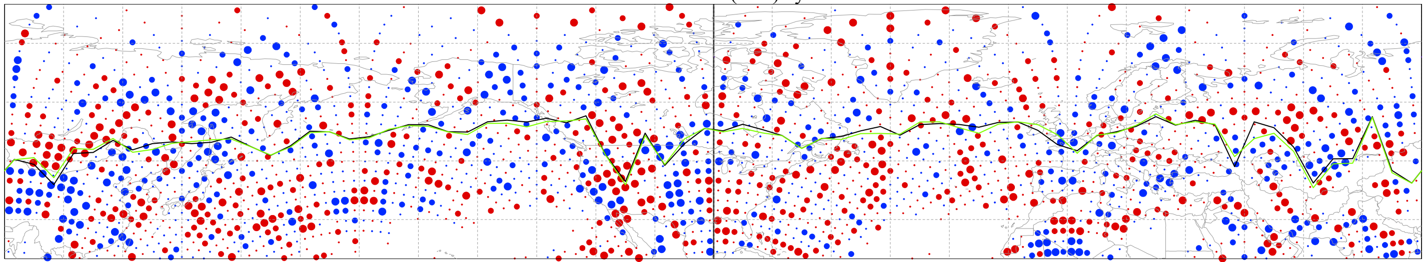
a. Weaker winter (JFM) cyclones



b. Weaker spring (AMJ) cyclones



c. Weaker summer (JAS) cyclones



d. Weaker autumn (OND) cyclones

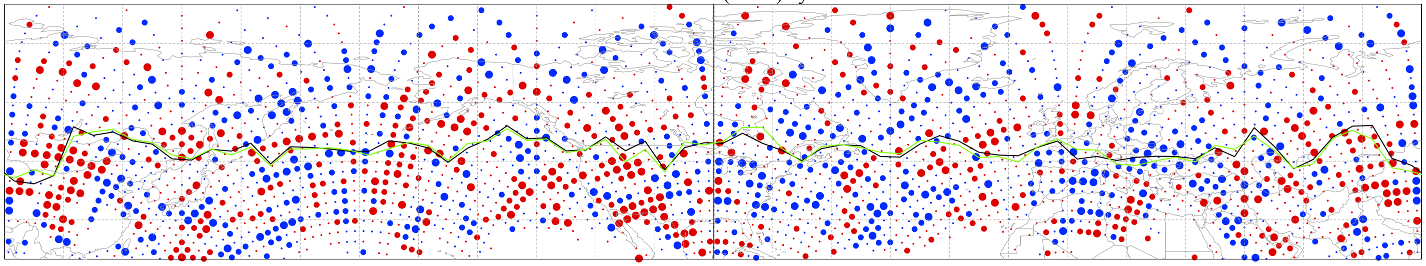


Fig. 2. The same as in Fig. 1 but for changes in the mean track position and in the frequency of all weaker cyclones (central pressure is not less than 990 hPa).

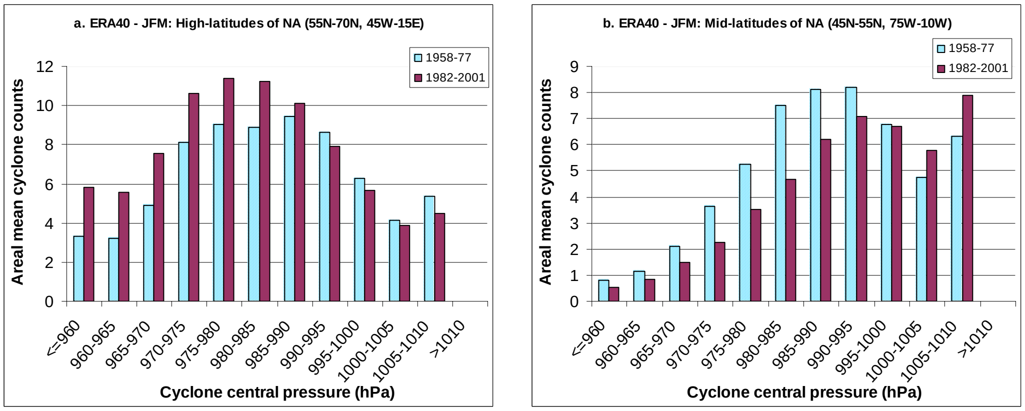


Fig. 3. Areal mean counts of winter cyclones as a function of their central pressure, as derived from 6-hourly MSLP data of the ERA-40 reanalysis for the following two 20-yr periods: 1958-77 and 1982-2001. Note that a cyclone could be enumerated many times here if it "lives" within the analysis area for many 6-hour time-steps. But this does not affect the inference here because a "longer stay" also reflects more frequent presence of low pressure system in the area.

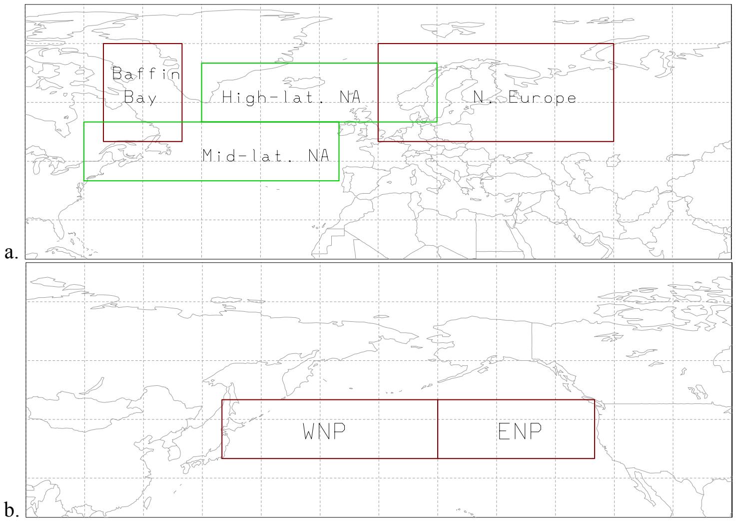


Fig. 4. Selected regions for calculating the total number, the areal mean lifespan of cyclone-tracks.

As shown in Table 2, changes in the areal mean lifespan of cyclone-tracks appear to be the largest in summer (JAS). The lifespan appears to have become longer in this season, especially for the weaker cyclone-tracks in the NA sector. In other seasons, there are little changes in the areal mean lifespan of cyclone-tracks, except that the lifespan of strong autumn cyclone-tracks in the NA seems to have become longer. On a hemispheric average, strong summer cyclone-tracks appear to last longer in recent years, which also appears to be true for the spring season. Note that a notable increase in the lifespan is usually associated with a slight decrease in the number of cyclone-tracks (cf. Tables 1 and 2).

In the North Pacific (NP) sector, as shown in Fig. 1, the observed changes feature significant increases in the number of strong cyclones along the NP storm track area, with a slight southward shift of the spring storm track. In winter, the more frequent strong cyclones were also accompanied by less frequent weaker cyclones, especially in the central NP (around the 180 longitude; see Fig. 2a). Using the NRA 6-hourly MSLP (and winds) data for the winter months (December-March) of 1948/49 to 1997/98, Graham and Diaz (2001) also found evidence of a southward dip and eastward extension of the NP storm track (and increased frequency of deep lows accompanied with decreased minimum central pressure). In particular, they found support for the above changes from analyzing long-term quality-controlled in-situ datasets, including the Comprehensive Ocean-Atmosphere Data Set (COADS; Woodruff et al. 1987), Midway Island (28°N, 177°W) radiosonde observations, and observations from two Ocean Station Vessels (or "weather ships") in the region. Therefore, the above changes are most likely real, not just an artifact of the reanalysis procedure or the increasing availability of data (including satellite data) in recent decades. By analyzing winds at different levels, Graham and Diaz (2001) also showed that the more vigorous cyclone activity in recent years has apparently resulted from increasing upper-tropospheric winds and vertical wind shear over the central NP.

Table 1. Changes in the counts of cyclone-tracks identified in the indicated regions from the ERA-40 reanalysis (1982-2001 minus 1958-77; the numbers in parentheses are the total counts for the two 20-yr periods). Note that a strong cyclone-track is defined as one with central pressure < 990 hPa at least once in its lifetime within the selected region, and that a cyclone-track could be counted twice if its lifespan traverses two consecutive seasons (it gets counted in both seasons; thus, the annual count may be smaller than the sum of the relevant 4 seasonal counts).

		High-lat. NA (55°N-70°N, 45°W-15°E)	Mid-lat. NA (45°N-55°N), 75°W-10°W	Northern Extra-tropics
OND	Strong	50 (732-682)	-6 (494-488)	155 (3116-3271)
	Weaker	-41 (425-466)	2 (702-704)	-55 (20757-20702)
	All	9 (1157-1148)	-4 (1196-1192)	100 (23873-23973)
JFM	Strong	157 (855-698)	-125 (686-561)	160 (3356-3516)
	Weaker	-89 (368-457)	38 (683-721)	-446 (22517-22071)
	All	68 (1223-1155)	-87 (1369-1282)	-286 (25873-25587)
AMJ	Strong	-29 (225-254)	-38 (228-190)	7 (1475-1482)
	Weaker	26 (860-834)	88 (1004-1092)	-1006 (31618-30612)
	All	-3 (1085-1088)	50 (1232-1282)	-996 (33093-32097)
JAS	Strong	-3 (253-256)	20 (105-125)	-37 (1344-1307)
	Weaker	-45 (816-861)	-39 (1014-975)	-545 (31457-30912)
	All	-48 (1069-1117)	-19 (1119-1100)	-582 (32801-32219)
ANN	Strong	175 (2046-1871)	-152 (1506-1354)	258 (9197-9455)
	Weaker	-142 (2450-2592)	88 (3365-3453)	-2065 (105581-103516)
	All	33 (4496-4463)	-64 (4871-4807)	-1807 (114778-112971

Table 2. The same as in Table 1 but for changes in the areal mean lifespan (hr) of cyclone-tracks identified in the indicated regions from the ERA-40 (1982-2001 minus 1958-77).

		High-lat. NA (55°N-70°N, 45°W-15°E)	Mid-lat. NA (45°N-55°N), 75°W-10°W	Northern Extra-tropics
OND	Strong	2.9 (61.8-58.9)	4.2 (62.9-58.7)	1.9 (47.2-45.3)
	All	1.7 (72.0-70.3)	-0.8 (74.7-75.5)	0.5 (29.8-29.3)
JFM	Strong	-1.2 (57.1-58.3)	0.3 (60.6-60.3)	1.6 (46.0-44.4)
	All	1.1 (66.0-64.9)	-2.1 (68.5-70.6)	0.2 (27.1-26.9)
AMJ	Strong	1.7 (51.6-49.9)	0.3 (50.1-49.8)	3.2 (40.1-36.9)
	All	1.7 (69.6-67.9)	3.0 (75.4-72.4)	0.9 (27.4-26.5)
JAS	Strong	2.4 (53.0-50.6)	-0.2 (56.8-57.0)	5.9 (43.7-37.8)
	All	7.8 (77.6-69.8)	7.2 (79.9-72.7)	1.1 (28.3-27.2)
ANN	Strong	1.3 (57.3-56.0)	1.5 (59.4-57.9)	2.5 (44.7-42.2)
	All	3.0 (70.7-67.7)	1.7 (74.0-72.3)	0.6 (27.5-26.9)

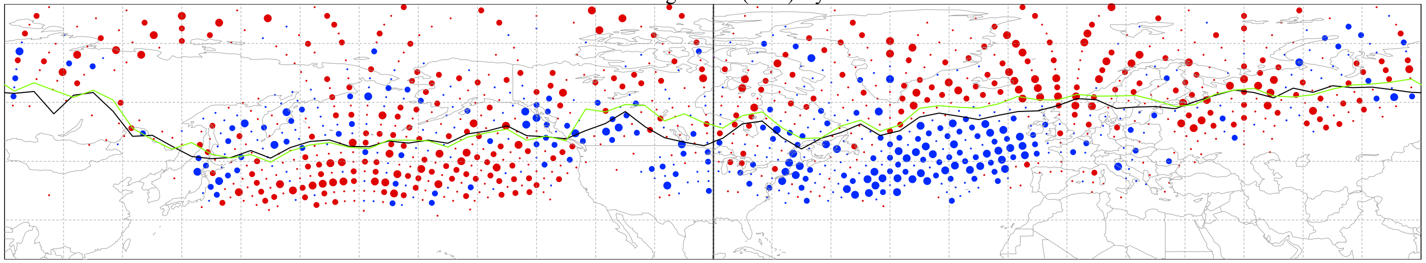
The NP storm track and cyclone activity also shows less significant changes in seasons other than winter. Nevertheless, significant decreases in the number of weaker winter cyclones in western Canada were identified to be accompanied with significant increases in the eastern NP and western United States (see Fig. 2a). In particular, the number of weaker cyclones seems to have increased in western United States in all four seasons (cf. Fig. 2).

Generally, the NRA displays similar mean extra-tropical storm tracks and cyclone activity, especially over the oceans and for oceanic storm tracks (cf. Figs. 5a-b, 1a, and 2c). The most notable difference is seen in East Asia, where the NRA shows much more extensive increase in the number of weaker cyclones in spring and summer (see Fig. 5b for summer; the NRA shows increases in Mongolia only, cf. Fig. 2c). These differences are probably due to an error in the NRA for East Asia (according to Steven J. Lambert; personal communication). In terms of the number of strong cyclones, the NRA shows a slightly more extensive decrease along the storm track in East Asia (eastward of 90°E) in spring and summer, and a slightly more extensive increase in the NA in winter and in southern Greenland in spring (not shown). However, in terms of the 44-yr total cyclone counts, significant differences between the ERA-40 and the NRA are seen in the west coast of North America and in the region from East Asia southwestward to the Mediterranean (see Fig. 5c for winter; similar differences are seen in other three seasons and hence not shown).

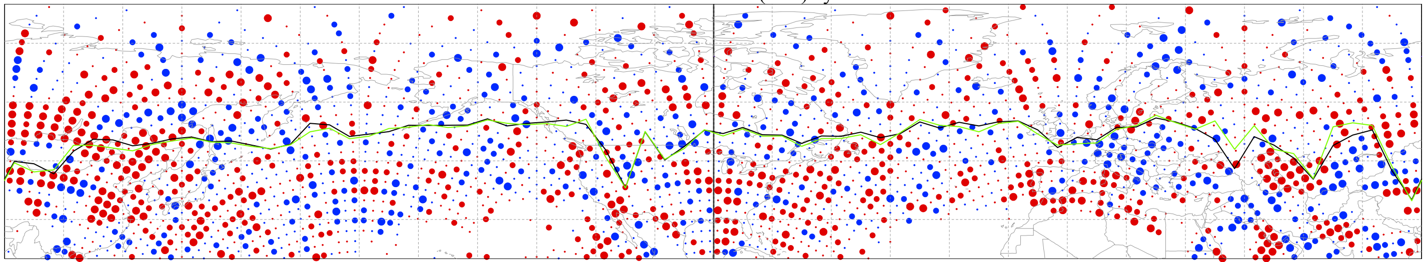
3.2 Observed changes in the southern hemisphere

Simmonds and Keay (2000) did a comprehensive study on variability of extratropical southern hemisphere cyclone behavior by applying a state-of-the-art cyclone finding and tracking scheme (similar to the one used in this study) to the 6-hourly data from the NRA reanalysis for 1958-97. They have shown that the annual and seasonal cyclone densities have undergone reductions at most locations south (poleward) of 40°S and increases to the north (equatorward). Based on circumstantial evidence, as well as corroborating studies with independent data, they also argued that the decline in cyclones north (equator- ward) of 60°S may

a. NRA: Strong winter (JFM) cyclones



b. NRA: Weaker summer (JAS) cyclones



c. 44-yr total number of winter cyclones (ERA40 minus NRA)

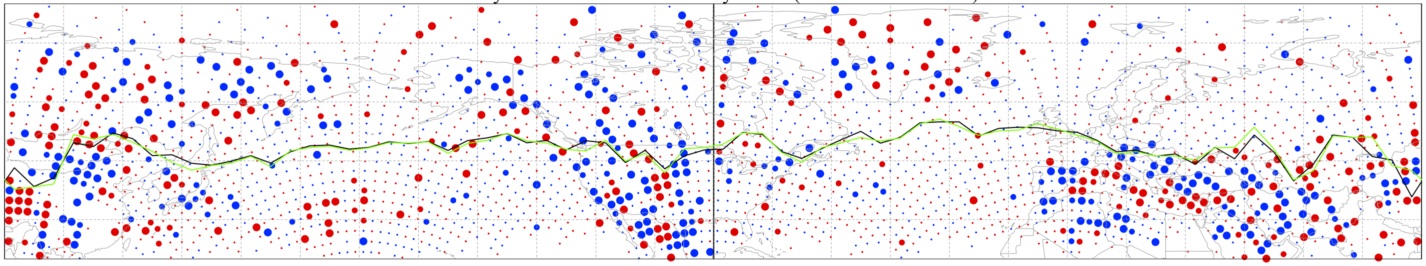
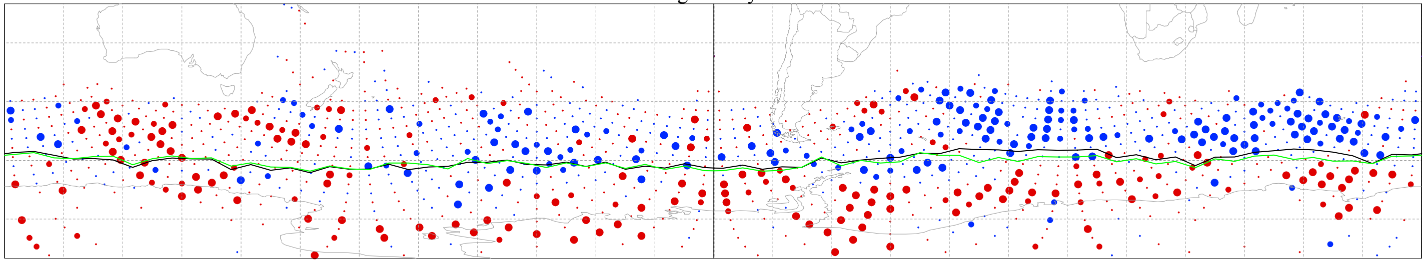
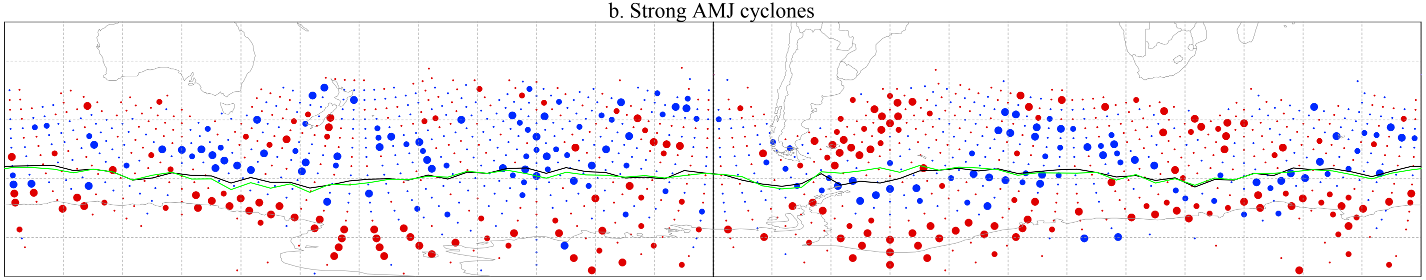


Fig. 5. a, b: The same as in Fig. 1 but for the indicated cyclones derived from the NRA MSLP fields. c: The 44-yr (1958-2001) mean position of the northern extra-tropical winter (JFM) storm tracks (mean latitudes of all cyclones in the 30°N-70°N band) derived from the NRA (black curve) and the ERA-40 (green curve) reanalyses. Red/blue dots indicate positive/negative differences in the number of all cyclones at the grid-cell (ERA-40 minus NRA). The large, medium, and small dots indicate that the differences are of at least 95%, 90-95%, and less than 90% level of confidence.

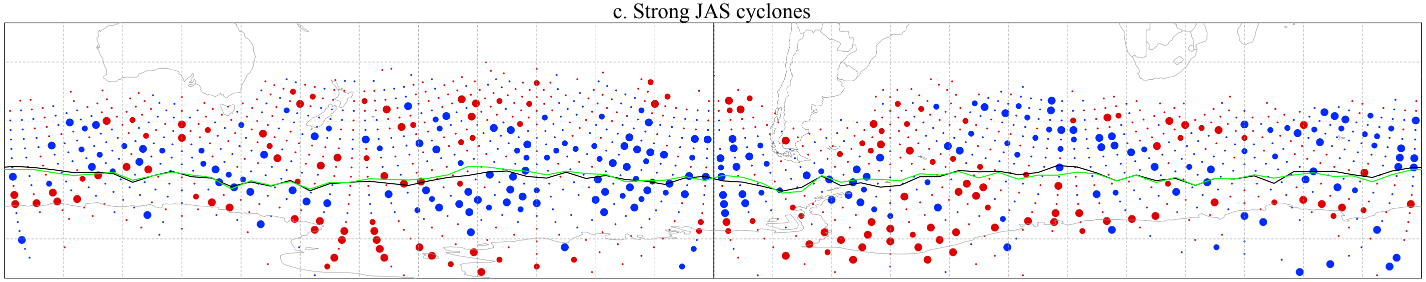
a. Strong JFM cyclones



b. Strong AMJ cyclones



c. Strong JAS cyclones



d. Weaker JAS cyclones

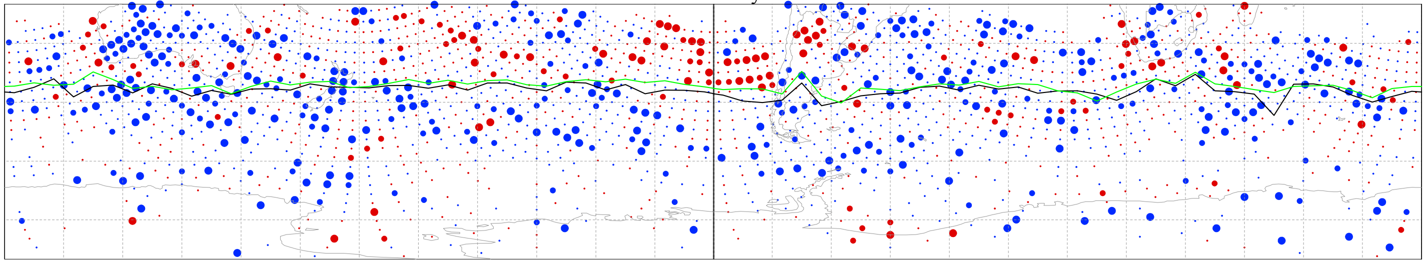


Fig. 6. Tha same as in Fig. 1 but for the mean position of the southern extra-tropical (30°S-70°S) storm tracks and changes in the number of the indicated cyclones at each grid-point.

well be real, not just an artifact of the increasing availability of data (including satellite data) in and around the Antarctic in recent decades.

Our results from analyzing the ERA-40 reanalysis are basically consistent with those of Simmonds and Keay (2000). In terms of the number of strong cyclones, the changes in JFM (Fig. 6a) and OND (not shown) are characterized by increases in the high southern latitudes, with decreases in most areas of the mid-latitudes (except the mid-latitude region south of Australia where strong JFM cyclones have become more frequent; see Fig. 6a). The changes in AMJ and JAS are characterized by decreases in the number of strong cyclones in the mid-latitudes (around 60°S), with increases in the high southern latitudes (Fig. 6b,c). Also, in the South Atlantic (SA) sector, changes in the warm seasons (JFM and OND) are characterized by a slight poleward shift of the storm track, with a decrease in the number of strong cyclones in the area equatorward of the storm track and an increase in the high southern latitudes (Fig. 6a). The number of weaker cyclones appears to have decreased almost everywhere in the southern extra-tropics in all seasons, with the decrease being most notable in and around Australia in JAS (cf. Fig. 6d).

4. POSSIBLE FUTURE CHANGES

Before any discussion about projections of future changes in extra-tropical storm tracks and cyclone activity, it is necessary to check whether or not the climate model adequately represents late 20th century storm tracks and cyclone behaviour. To this end, the CGCM2 simulations were compared with the ERA-40 reanalysis in terms of the 20-yr (1975-94) storm tracks and cyclone climatology. The results suggest that the CGCM2 reasonably well simulates the extra-tropical storm tracks (especially the oceanic storm tracks; cf. Fig. 7), although it simulates remarkably fewer cyclones in most areas of the extra-tropics (especially over the land areas of the mid-latitudes). This is in agreement with our knowledge that the current climate models simulate substantially less variability than that of the observed climate. However, we do not believe this to be an issue in this study for two reasons: i) we compare the mean position of the storm tracks, which are reasonably well simulated, and ii) we are looking at the differences in the number of cyclones or cyclone-tracks between two different 20-yr periods, so that the effect of the model's underestimation of observed climate variability is greatly diminished (also, the remaining effect on the differences, if any, more likely leads to a conservative estimate of the projected changes).

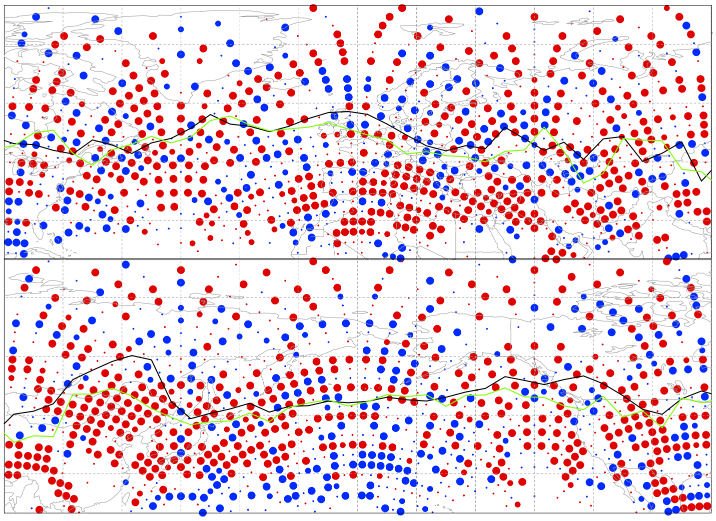


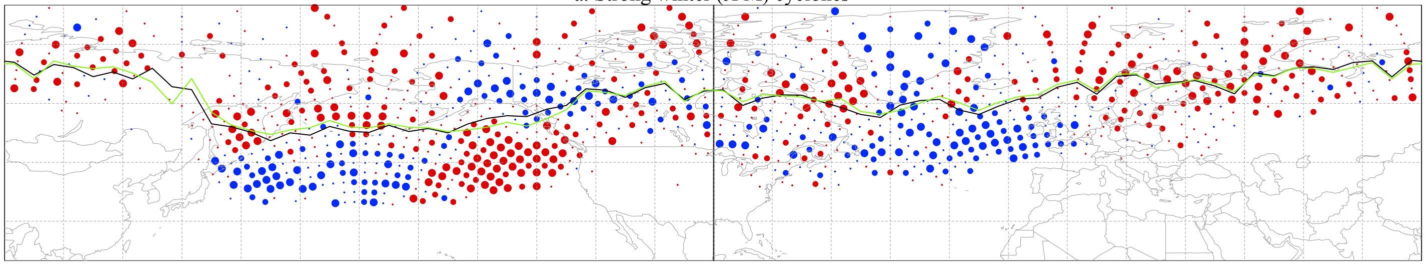
Fig. 7. The same as in Fig. 5c but for the 20-yr (1975-94) mean position of the northern winter storm tracks derived from the ERA-40 reanalysis (green curve) and the CGCM2 simulations (black curve), as well as the differences in the number of all cyclones (ERA-40 minus CGCM2).

In the rest of this section, we compare the CGCM2 simulated cyclone climatology for the 20-yr period of 1975-94 with that for the last two decades of the twenty-first century (2080-99). Similar to the way of characterizing the observed changes, possible future changes are discussed in this section in terms of storm tracks position, lifespan of cyclone-tracks, and cyclone occurrence frequency and its distribution over its intensity.

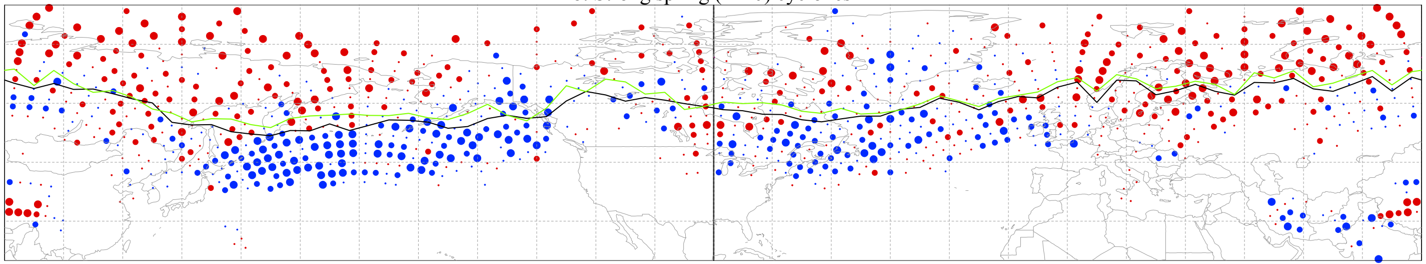
4.1 Possible future changes in the northern hemisphere

In the NA sector, as shown in Figs. 8 and 9, the most striking feature of the projected changes is a significant increase in the number of strong cyclones over northern Europe in all seasons except summer (also over the Baffin Bay and Labrador Sea in autumn and winter), while eastern Canada would probably experience fewer strong cyclones in summer (Fig. 8c). In particular, northern Europe and the Baffin Bay were projected to have increases in the number of strong cyclones with a deduction in the number of weaker cyclones in winter and autumn (cf. panels a, d in Figs. 8 and 9). The distributional shifts of autumn cyclone

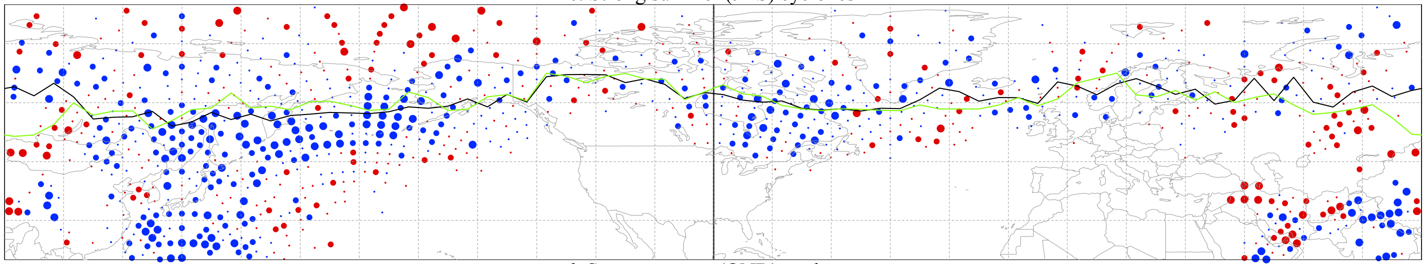
a. Strong winter (JFM) cyclones



b. Strong spring (AMJ) cyclones



c. Strong summer (JAS) cyclones



d. Strong autumn (OND) cyclones

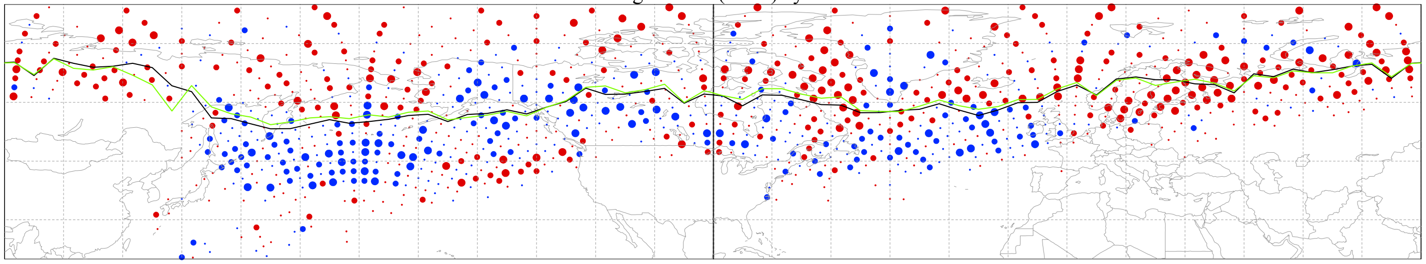
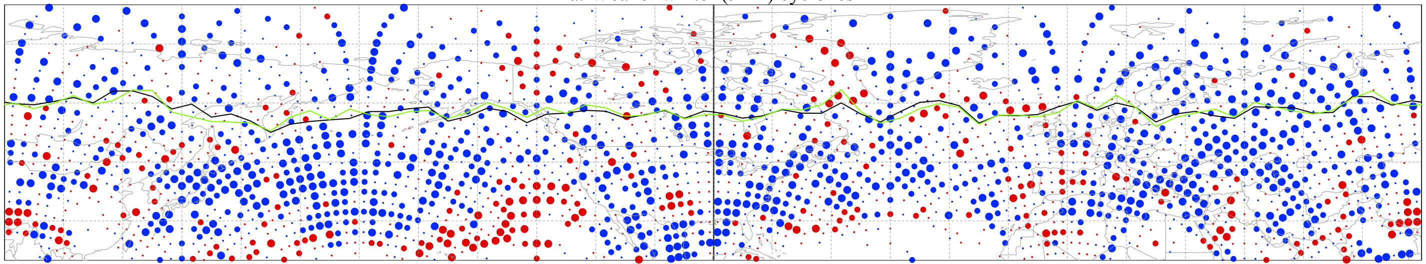
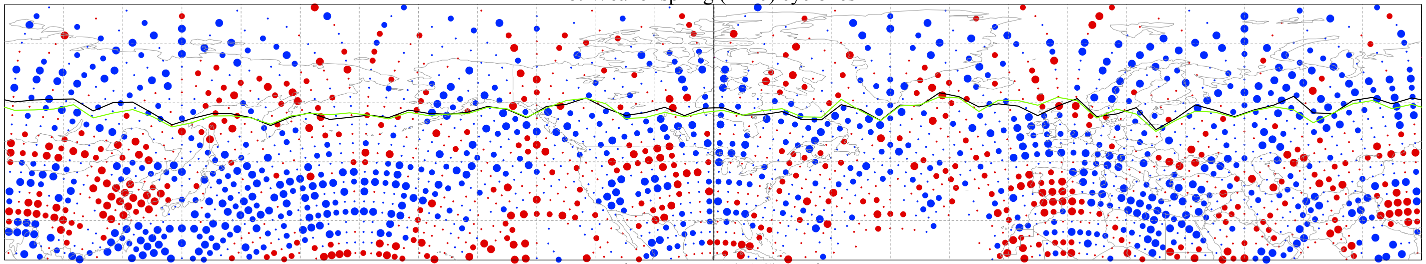


Fig. 8. Mean position of the northern extra-tropical (30°N-70°N) storm tracks for the period 1975-94 (black curve) and the period 2080-99 (green curve), as defined by the mean latitude of all strong cyclones (central pressure < 990 hPa) identified from the CGCM2 simulated 6-hourly MSLP within each 5°-longitude band. Red/blue dots indicate increase/decrease in the frequency of strong cyclone at the grid-point from period 1975-94 to period 2080-99. The large, medium, and small dots indicate that the changes at the grid-point are of at least 95%, 80-95%, and less than 80% level of confidence.

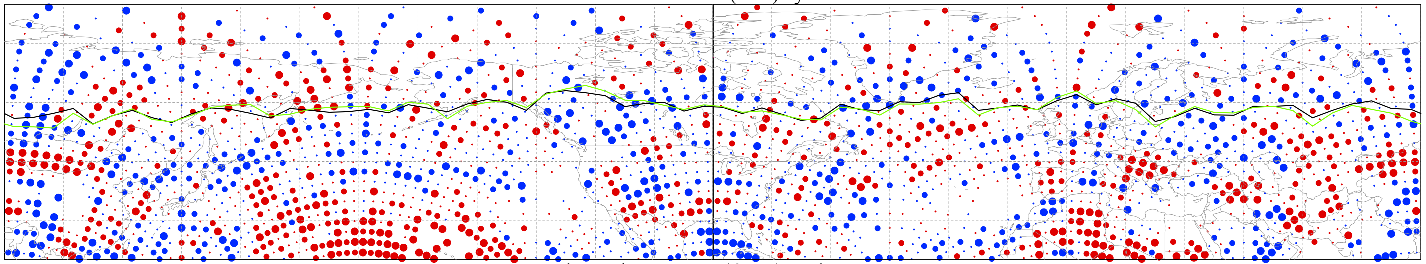
a. Weaker winter (JFM) cyclones



b. Weaker spring (AMJ) cyclones



c. Weaker summer (JAS) cyclones



d. Weaker autumn (OND) cyclones

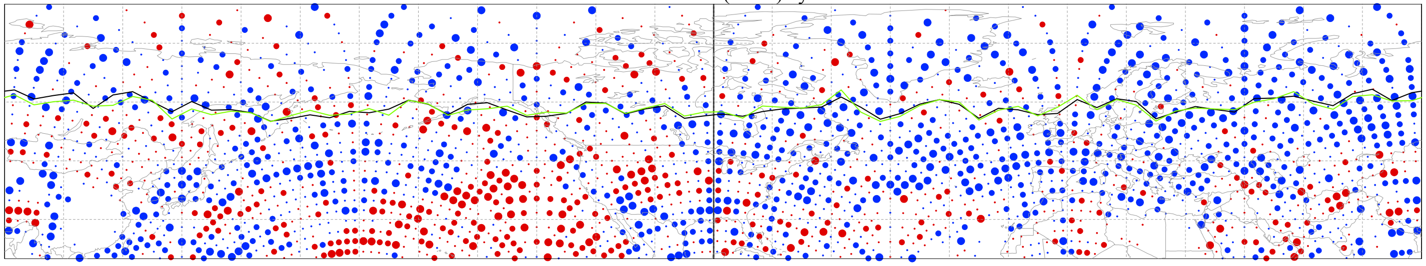


Fig. 9. The same as in Fig. 8 but for changes in the mean track position and in the frequency of all weaker cyclones (central pressure ≥ 990 hPa) identified from the CGCM2 simulations.

counts with relation to their central pressure are shown in Figs. 10a-b. Clearly, the CGCM2 projected warmer climate is associated with more frequent occurrence of strong cyclones and fewer weaker cyclones in northern Europe and the Baffin Bay in winter and autumn. Associated with these changes in storm tracks and cyclone activity is an increased pressure gradient over the northeast Atlantic, stronger westerly winds towards the northern European coast, and significant increases of wave heights in the northeast Atlantic (Wang et al. 2004a, Wang and Swail 2004).

In the NP sector, changes are characterized by a clock-wise rotation of the storm track in winter and a northward shift in spring (Figs. 8a,b), with the East Asia-western NP being projected to experience fewer strong cyclones in summer (Fig. 8c). The clockwise rotation of winter NP storm track is associated with a significant increase in the number of strong cyclones in the mid-latitudes of eastern NP (ENP in Fig. 4b; and a decrease to the east; see Fig. 8a), which would result in significant increases in ocean wave heights (especially extremes) in the region: the average waiting time between extreme wave height events of a fixed size was projected to shorten approximately by half by year 2080 (Wang and Swail 2004). In terms of changes in the climate (long term mean) fields, these winter changes are associated with an intensified and south-eastward expanded Aleutian low (see Fig. 14a in Wang and Swail 2004). The increase in the number of strong cyclones in the mid-latitudes of eastern NP (see ENP in Fig. 4) is again associated with a decrease in the number of weaker cyclones, as shown in Fig. 10c. However, the decrease in the number of cyclones in the mid-latitudes of western NP (see WNP in Fig. 4b) is less notable for intense cyclones (central pressure < 980 hPa) than the other cyclones, without notable changes for the extreme cyclones (central pressure < 970 hPa; Fig. 10d).

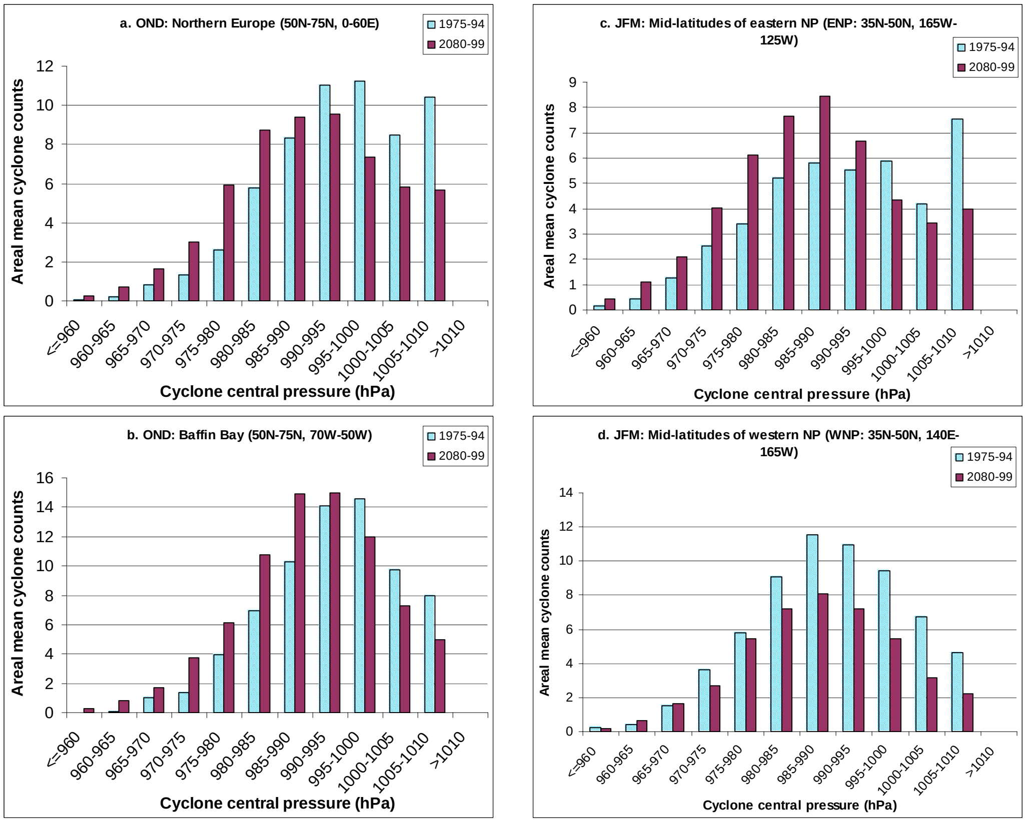


Fig. 10. The same as in Fig. 3 but as derived from 6-hourly MSLP data of the CGCM2 simulations (IS92a scenario) for the following two 20-yr periods: 1975-94 and 2080-99.

The projected changes in the number of cyclones are consistent with the projected changes in the number of cyclone-tracks. As listed in Table 3, the warmer climate as projected using the CGCM2 with the IS92a forcing scenario is associated with more strong (and fewer weaker) cyclone-tracks affecting northern Europe, which is true in all seasons (maybe except summer). The number of strong cyclone-tracks in the Baffin Bay was projected to increase in autumn through winter, but to decrease in summer. In the mid-latitudes of the NP sector, the number of strong cyclone-tracks was projected to decrease in all seasons except winter. In winter, a notable increase in the eastern NP was projected in association with a notable decrease in the western NP (cf. the “JFM Strong” row in Table 3), which has been shown earlier to be a result of a clock-wise rotation of the winter NP storm track. For the entire northern extra-tropics, a decrease in the number of strong cyclone-tracks was projected for summer (JAS), with an increase in other three seasons (the largest increase seen in autumn; cf. the last column in Table 3). Almost all the increases in the number of strong cyclone-tracks are accompanied by decreases in the number of weaker cyclone-tracks, regardless of season or region. Note that the rotation or shift of storm tracks discussed above can hardly be revealed by looking at changes in the total number of cyclones in a hemisphere or in the NA or NP sector (as in many previous studies). For example, the number of winter strong cyclone-tracks was projected to increase by 220 in the northern hemisphere as a whole, but in the meantime it was projected to decrease by 123 in the mid-latitudes of western NP (see the first data row in Table 3).

Table 3. The same as in Table 1 but for changes in the counts of cyclone-tracks identified in the indicated regions from the CGCM2 simulations of MSLP (2080-99 minus 1975-94).

		Northern Europe (50°N-75°N, 0-60°E)	Baffin Bay (50°N-75°N, 70°W-50°W)	Mid-lat. ENP (35°N-50°N, 165°W-125°W)	Mid-lat. WNP (35°N-50°N, 140°E-165°W)	Northern Extra-tropics
OND	Strong	142 (533-391)	94 (350-256)	-39 (310-349)	-123 (336-459)	220 (3073-2853)
	Weaker	-272 (550-822)	-69 (403-472)	-15 (394-409)	-82 (387-469)	-1773 (14971-16744)
	All	-130 (1083-1213)	25 (753-728)	-54 (704-758)	-205 (723-928)	-1558 (18039-19597)
JFM	Strong	98 (551-453)	33 (403-370)	142 (609-467)	-150 (557-707)	84 (3433-3349)
	Weaker	-233 (475-708)	11 (403-392)	-128 (344-472)	-192 (382-574)	-1939 (15057-16996)
	All	-135 (1026-1161)	44 (806-762)	14 (953-939)	-342 (939-1281)	-1855 (18490-20345)
AMJ	Strong	144 (344-200)	-5 (252-257)	-48 (43-91)	-102 (171-273)	29 (2003-1974)
	Weaker	-200 (742-942)	6 (544-538)	-27 (370-397)	-100 (512-612)	-1150 (19849-20999)
	All	-56 (1086-1142)	1 (796-795)	-75 (413-488)	-202 (683-885)	-1121 (21852-22973)
JAS	Strong	6 (82-76)	-32 (120-152)	0 (23-23)	-60 (70-130)	-396 (2414-2810)
	Weaker	-9 (1081-1090)	-27 (580-607)	-18 (230-248)	-69 (629-698)	-91 (18833-18924)
	All	-3 (1163-1166)	-59 (700-759)	-18 (253-271)	-129 (699-828)	-487 (21247-21734)
ANN	Strong	373 (1489-1116)	88 (1118-1030)	58 (984-926)	-441 (1125-1566)	-54 (10774-10828)
	Weaker	-714 (2797-3511)	-79 (1916-1995)	-190 (1324-1514)	-444 (1883-2327)	-4931 (67843-72774)
	All	-341 (4286-4627)	9 (3034-3025)	-132 (2308-2440)	-885 (3008-3893)	-4985 (78617-83602)

In terms of the areal mean lifespan of cyclone-tracks, the largest change was projected for the mid-latitudes of eastern NP (see Box ENP in Fig. 4b) in summer: on average, the cyclone-tracks were projected to last about one day longer, while the lifespan of strong cyclone-tracks was projected to shorten slightly (see the JAS row in Table 4). The second largest changes were projected for the spring strong cyclone-tracks in the ENP region and in the Baffin Bay. The strong cyclone-tracks were projected to last about half a day longer (see the AMJ row in Table 4). The winter cyclone-tracks traversing the Baffin Bay and the autumn cyclone-tracks in the mid-latitudes of NP (both ENP and WNP) were also projected to last about 6-9 hours longer. In general, the lifespan of cyclone-tracks traversing northern European was projected to have little notable changes, the largest changes being about 6-hour shortening in the lifespan of the spring cyclone-tracks and summer strong cyclone tracks. Again, a notable increase in the lifespan was projected to be associated with little change (or a slight decrease) in the number of cyclone-tracks (cf. Tables 3 and 4).

Table 4. The same as in Table 2 but for changes in the areal mean lifespan (hr) of cyclone-tracks identified in the indicated regions from the CGCM2 simulations (2080-99 minus 1975-94).

		Northern Europe (50°N-75°N, 0-60°E)	Baffin Bay (50°N-75°N, 70°W-50°W)	Mid-lat. ENP (35°N-50°N, 165°W-125°W)	Mid-lat. WNP (35°N-50°N, 140°E-165°W)	Northern Extra-tropics
OND	Strong	2.0 (72.0-70.0)	2.9 (82.5-79.6)	8.9 (86.4-77.5)	5.8 (90.0-84.2)	2.0 (58.7-56.7)
	All	-0.7 (85.8-86.5)	4.2 (93.8-89.6)	6.2 (88.5-82.3)	8.6 (105.1-96.5)	0.0 (39.4-39.4)
JFM	Strong	3.6 (67.3-63.7)	9.0 (81.2-72.2)	0.6 (71.9-71.3)	6.6 (76.6-70.0)	3.2 (55.6-52.4)
	All	-4.1 (78.7-82.8)	6.2 (85.3-79.1)	2.0 (79.9-77.9)	-2.0 (77.7-79.7)	-1.5 (34.1-35.6)
AMJ	Strong	0.4 (66.0-65.6)	12.2 (85.2-73.0)	11.7 (72.0-60.3)	5.1 (79.5-74.4)	4.5 (55.9-51.4)
	All	-6.2 (91.3-97.5)	-1.6 (87.2-88.8)	-6.4 (82.0-88.4)	-6.8 (104.8-111.6)	0.0 (41.0-41.0)
JAS	Strong	-5.8 (55.4-61.2)	3.1 (64.3-61.2)	-8.3 (81.4-89.7)	-3.3 (89.2-92.5)	0.8 (41.8-41.0)
	All	2.6 (103.4-100.8)	-3.0 (86.5-89.5)	23.4 (108.2-84.8)	9.3 (112.7-103.4)	0.9 (47.7-46.8)
ANN	Strong	2.2 (67.2-65.0)	7.0 (81.0-74.0)	3.9 (76.7-72.8)	4.5 (81.2-76.7)	3.0 (52.8-49.8)
	All	-2.4 (89.2-91.6)	0.9 (87.0-86.1)	3.4 (85.3-81.9)	2.1 (97.6-95.5)	0.0 (39.7-39.7)

Comparing the double CO_2 simulations using the Canadian climate model with a simulation with current levels of CO_2, Lambert (1995) also showed an increase in the number of intense winter cyclone events, with an overall decrease in the number of winter cyclone events in the northern hemisphere. The coupled German atmosphere-ocean-GCM (ECHAM4 + OPYC3) also simulates increasing upper air storm track activity over the east Atlantic and Western Europe with rising greenhouse gas forcing and a north-eastward shift of the NAO's northern activity center (from a position close to the east coast of Greenland to the Norwegian Sea; Ulbrich and Christoph 1999).

By analyzing an ensemble of 250-yr transient enhanced greenhouse warming simulations using two versions of the Canadian coupled GCM, Lambert (2004) speculated that warmer surface temperatures resulting from enhanced greenhouse warming increase evaporation and thereby increase precipitation and release of latent heat, which contributes to the deepening of cyclones. The increased number of intense events has an increased stabilizing effect on the atmosphere, which is less favorable for the development of mid-latitudes cyclones in general and, hence, fewer cyclones in total (Lambert 2004).

4.2 Possible future changes in the southern hemisphere

The typical patterns of change projected for the southern extra-tropical cyclones are shown in Fig. 11. In all seasons, the projected changes are characterized by decreases in the number of cyclones in most areas, with the most notable decreases being projected for the mid-latitude (45°S-65°S) strong cyclones, especially in JFM (Fig. 11a). Besides, more weaker cyclones were projected to occur in the northeast part of the South Pacific sector in the JFM and AMJ seasons, and also in Australia in JFM and OND (cf. Fig. 11c for JFM) and in Argentina in AMJ (not shown).

Analyzing the decadal mean number of extratropical southern hemisphere cyclones derived from daily MSLP data of a 500-yr control simulation and an ensemble of transient climate change simulations (the IS92a scenario) using the Canadian CGCM1, Fyfe (2003) also concluded that the number of sub-Antarctic Ocean (40°S-60°S) cyclones will drop by 30% between now and the century's end.

5. CONCLUDING REMARKS

By applying a cyclone finding/tracking algorithm to three gridded global 6-hourly MSLP datasets, we have assessed historical and possible future changes in extra-tropical storm tracks and cyclone activity, in terms of storm tracks position, lifespan of cyclone-tracks, cyclone frequency and its change in relation to its intensity. Changes identified from the ERA-40 reanalysis are also briefly compared with those identified from the NRA reanalysis.

The results show that the most notable changes in cyclone activity are associated with the number and track of strong cyclones (central pressure < 990 hPa), which are seen both in the observed climate, as represented by the ERA-40 and NRA reanalyses, and in the CGCM2 projected warmer climate under the IS92a scenario of greenhouse-gases and aerosols forcing. In the past half century, the changes feature a significant increase in the number of strong winter and spring cyclones over the North Pacific (NP) sector, and of strong autumn and winter cyclones in the North Atlantic (NA) sector. In particular, the track of strong cyclones in the NA sector has shifted slightly northward in winter. In the CGCM2 projected warmer climate, a clockwise rotation of the NP storm track in winter, and a northward shift of the NP storm track with an anti-clockwise rotation of the eastern Asia storm track in spring are the most prominent features of the changes projected for the NP sector. In the NA sector, the projected changes are characterized by a significant increase in the number of strong cyclones over northern Eurasia in all seasons except summer (also over the Baffin Bay and Labrador Sea in autumn and winter). Usually, changes are characterized by increases in the number of cyclones in cold seasons but by longer lifespans of cyclone-tracks in the warm seasons.

Changes in the southern extra-tropics are generally weaker than those identified in the northern extra-tropics. This behavior was seen in both the observed and the projected climates. In general, fewer cyclones were projected for the southern extra-tropics, with the most notable deduction in the number of the southern mid-latitude strong cyclones.

The results of this study are basically consistent with the findings of previous studies using different analysis methods and/or different datasets (in-situ data or simulations of different climate models). Also, in terms of storm tracks and cyclone activity, the ERA-40 and NCEP/NCAR reanalyses were found to show generally comparable changes.

ACKNOWLEDGMENTS

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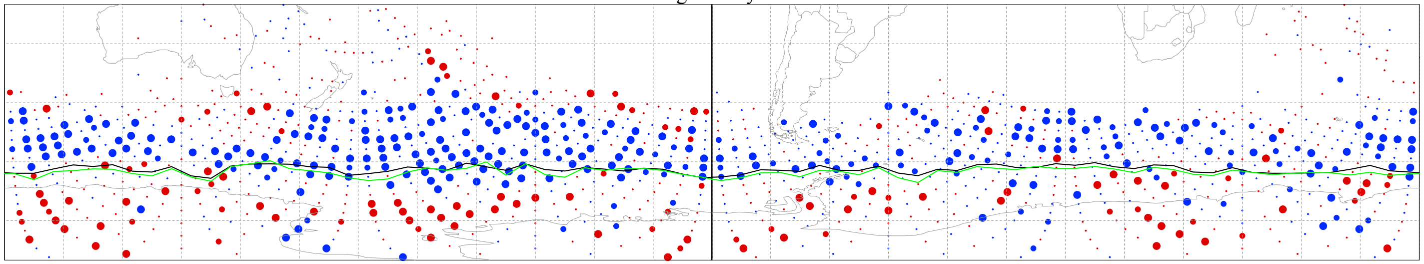
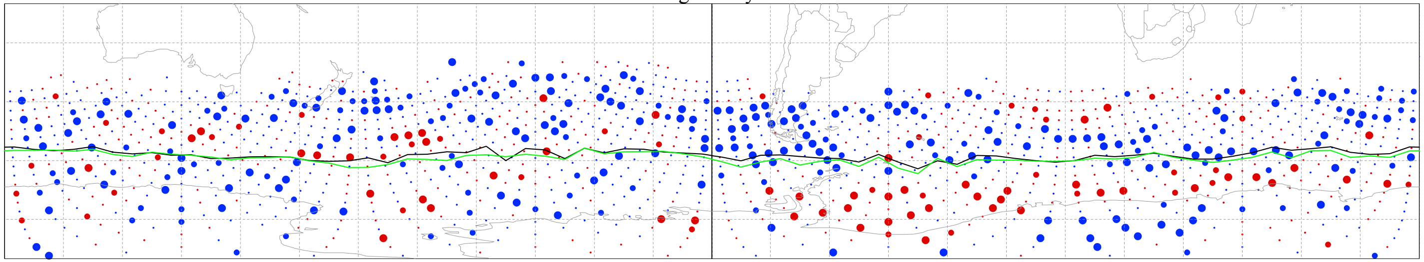
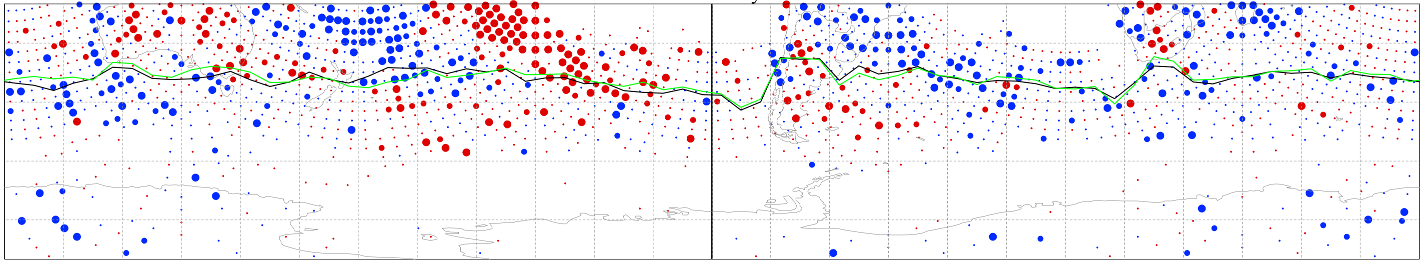
a. Strong JFM cyclones



b. Strong JAS cyclones



c. Weaker JFM cyclones



d. Weaker JAS cyclones

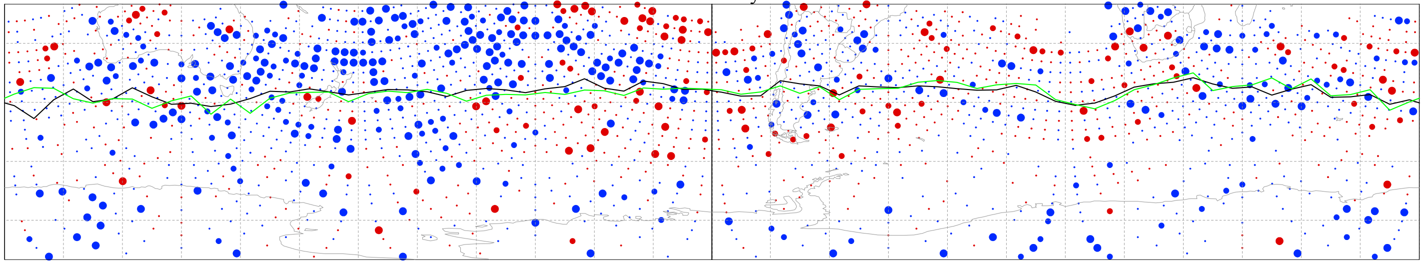


Fig. 11. The same as in Figs. 8 and 9 but for the mean position of the southern extra-tropical (30°S-70°S) storm tracks and changes in the number of the indicated cyclones (identified from the CGCM2 simulations).

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