Variability of the North Atlantic Cyclone Activity in Winter Analyzed from NCEP–NCAR Reanalysis Data

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ABSTRACT

Principal component analysis is applied to the cyclone density over the North Atlantic in winter analyzed with an objective cyclone identification and tracking algorithm by using the 6-h National Centers for Environmental Prediction reanalysis data from 1958 to 1998. Regressions of the cyclone density, deepening rate, moving speed, and central pressure gradient with the first principal component show that the cyclone activity over the northern North Atlantic exhibits a significant intensifying trend along with a decadal timescale oscillation in winter during the past 40 yr. All these variables vary consistently with larger (smaller) cyclone density corresponding to stronger (weaker) cyclone intensity, faster (slower) moving speed, and stronger (weaker) deepening rate.

Analysis shows that the variations of the cyclone activity over the North Atlantic are closely related to the changes of large-scale baroclinicity at the lower troposphere and the North Atlantic oscillation. The relationships with the change of the North Atlantic SST are also discussed.

1. Introduction

The North Atlantic is one of the most frequent cyclone occurrence regions in the Northern Hemisphere. Cyclones occurred there could have strong impacts on the weather and climate of the eastern United States, eastern Canada, southern Greenland, Iceland, and western Europe. Early studies of the cyclone climatology and the long-term variations over the North America and the North Atlantic regions (Reitan 1974, 1979; Colucci 1976; Zishka and Smith 1980; Hayden 1981; Whittaker and Horn 1981) were performed by identifying the cyclone features on synoptic charts and tracking the features manually. They found that there are clear long-term changes of cyclone frequency in the North America and the North Atlantic regions.

Recent studies of the cyclone activity over the North Atlantic have used objective cyclone identification and tracking algorithms and relatively good quality analysis data. Blender et al. (1997), by using the 5-yr European Centre for Medium-Range Weather Forecasts analysis from 1990 to 1994 with a 6-h interval and T106 horizontal resolution (about $1.125^\circ \times 1.125^\circ$), identified the cyclone-track regimes in the North Atlantic. The Icelandic low cyclone activity has been investigated by Serreze et al. (1997) with the National Meteorological Center sea level pressure fields for the $47 \times 51$ octagonal grid of 28-yr record (1966–93). They found that there is a significant increase of the cyclone counts for the region north of $60^\circ$N as a whole, and generally opposing changes are found for $30^\circ$–$60^\circ$N. On the other hand, a recent increase in the storm intensity over the North Atlantic Ocean is observed by some recent studies. For example, Kushner et al. (1997) have noticed a recent increase in the North Atlantic wave height. Lambert (1996) has found that the intense cyclones over the North Atlantic have increased significantly after the 1970s.

Most of the previous works are concentrated on studying the cyclone frequency. The variations of the other features of cyclone activity, such as cyclone intensity, deepening rate, and moving speed have not been well documented. The purpose of the present paper is to investigate the consistency of the long-term variations of cyclone density with the cyclone intensity, deepening rate, and moving speed, and examine their relationships with large-scale circulation features such as baroclinicity, jet streams, and the North Atlantic oscillation (NAO) index. An objective cyclone identification and
tracking method and the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data make it possible for us to analyze all these features together to give a clearer and more complete picture of the change of cyclone activity in the North Atlantic.

The present paper is organized as follows. In the next section we give a description of the data and method used in the study. In section 3 the spatial pattern and the temporal variations of cyclone activity are examined. The relationships of the change of cyclone activity with the large-scale baroclinicity, the NAO, and the SST over the North Atlantic are discussed in section 4. Finally, in section 5 we will give the summary and conclusions of the present work.

2. Data and a cyclone identification and tracking algorithm

The data used to extract the cyclone activity are the 41-yr NCEP reanalysis data from 1958 to 1998 with a 6-h interval and a spatial resolution of $2.5^\circ \times 2.5^\circ$ in longitude and latitude (Kalnay et al. 1996). For cyclone tracking, the data were interpolated into a $1.125^\circ \times 1.125^\circ$ grid size, a spatial resolution consistent with the T106 AGCM, by using the cubic interpolation. Interpolation of the data into a high resolution is because that, according to Blender and Schubert (2000), the cyclone tracks can be identified much more accurately with high-resolution data (T106) than with relatively low-resolution data (T42). Also, according to the cyclone moving speed in winter estimated by Zhu et al. (1981), in some cases if the cyclone moving is slow, within one time step (6 h) the cyclones cannot move from one grid point to the next (in $2.5^\circ \times 2.5^\circ$ grid size). This means that the grid size of the data is sometimes a little too large compared with the small 6-h time step for cyclone tracking.

An automatic cyclone identification and tracking algorithm is designed to detect, track, and compute the features of cyclone activity from the NCEP reanalysis data. The basics of the algorithm have some similarities to some of the previous studies (Murray and Simmonds 1991; Konig et al. 1993; Sinclair 1994; Serreze et al. 1997; Blender et al. 1997), but have a lot of differences in details. The following is a description of the cyclone identification and tracking algorithm. In the present paper the mean sea level pressure (MSLP) is used to detect the cyclone centers. There are several steps to get the complete dataset of cyclone activity information. The first is the cyclone detecting step. If 1) the MSLP of a grid point is less then its eight surrounding grid point values; 2) the averaged pressure difference between the central grid point and the eight surrounding grid points is larger than a certain value $dP_c$ (0.3 hPa); and 3) meet the geographical tolerance limit, that is, the topographic height at that grid point must be lower than 1500 m, then we call a cyclone center $n$ was found at time step $t$ at the grid point $(i, j)_{nt}$ on position $(\lambda, \varphi)_{nt}$. If it is the first time step, every cyclone center found is considered to be a newly generated cyclone and a cyclone number $c$ will be given to it. Otherwise, a cyclone tracking procedure will be performed to see if this cyclone is a newly generated cyclone or just a cyclone center that came from the already existed cyclone in the previous time step. This is done by checking the cyclone centers detected in the previous time step through the following criteria. If 1) the cyclone center $n'$ in the previous time step $t - 1$ is the one closest to the cyclone center $n$ in the present time step $t$; 2) the distance between these two cyclone centers is less than a certain value $d_{mn}$ (600 km); and 3) the cyclone moving direction meets some tolerance limit that is a function of the 700-hPa steering flow and the geographical location, then we will say that the cyclone center $n$ at time step $t$ comes from the cyclone center $n'$ at time step $t - 1$. So the cyclone center $n$ will share the same cyclone number with the cyclone center $n'$, that is, $c = c'$. If one of the above 2) and 3) is not satisfied, then we call cyclone center $n$ a newly generated cyclone and give it a new cyclone number $c$.

After the cyclone searching, we can obtain the following information for each cyclone center $c$: 1) cyclone center number $n$ (i.e., a number given to each cyclone center of each time step $t$); 2) cyclone number $c(n)$; 3) time step number $t(n)$; 4) time step number within the lifetime of the cyclone $t_l(n)$; 5) location of the cyclone center, that is, longitude and latitude $(\lambda(n), \varphi(n))$ and gridpoint number $(i(n), j(n))$; 6) cyclone central pressure $P_c(n)$; 7) cyclone central pressure gradient $dP_c(n)$ (In the present paper we define that a cyclone has a positive central pressure gradient); and 8) the total lifetime $T_c(n)$ of the cyclone $c$ calculated by counting the time steps lasted by the cyclone centers with the same number $c$. We call the above-mentioned eight items the cyclone information dataset.

Based on the cyclone information dataset, we can calculate the following features of the cyclones in different categories of cyclone intensity (central pressure gradient) or lifetime scale ($\geq 24$ h in the present paper).

1) Cyclone density $f(i, j)$ is calculated by counting the cyclone occurrences at each grid point $(i, j)$ over the whole time period.
2) Cyclone tracks are extracted by reorganizing the longitudes and latitudes of the cyclone centers with the same cyclone number.
3) Cyclone moving velocity of cyclone $c$ at time $t$ within its lifetime at position $(i, j)_{nt}$ along its track is calculated by $V(i, j)_{nt} = |r(i, j)_{nt} - r(i, j)_{nt-1}|/\Delta t$ (here $r(i, j)_{nt}$ denotes the position of the cyclone center of cyclone $c$ at time $t$).
4) Cyclone moving speed is obtained by calculating the magnitude of the cyclone moving velocity, that is to say, $|V(i, j)_{nt}|$.
5) Cyclone deepening rate of cyclone $c$ at time step $t$...
Fig. 1. (a) Cyclone centers and cyclone tracks during 1–10 Jan of 1993 analyzed objectively by using the automatic approach and the NCEP–NCAR reanalysis data, and (b) same as (a) but the cyclone centers and cyclone tracks extracted manually from the weather charts published by Japan Meteorological Agency. The number on the track denotes the two-digit date and time (h) in the format of date.time (here the time is UTC in h). Please note that the time interval of the NCEP–NCAR reanalysis data is 6 h and that of the Japan Meteorological Agency weather charts is 12 h.
within its lifetime at position \((i, j)_{c,t}\) along its track was calculated by \(\Delta P(i, j)_{c,t} = -[P(i, j)_{c,t} - P(i, j)_{c,t-1}]/\Delta t\) [here \(P(i, j)_{c,t}\) denotes the central pressure of the cyclone center of cyclone \(c\) at time \(t\)]. This implies that a deepening cyclone has a positive deepening rate.

If there is more than one cyclone passing through a grid point, then at that point there will be more than one value of cyclone central pressure gradient, velocity, deepening rate, etc. The value at that point will be the average of all the values. At some grid points, there is no cyclone passing through them. At these points the values will be set to missing values.

To test the data and method used in our study, we compared the cyclone centers and cyclone tracks of a 10-day period during 1–10 January of 1993 detected by using the cyclone identification and tracking algorithm of the present paper and the NCEP reanalysis data and that read from the weather charts of the East Asia-Western Pacific region published by the Japan Meteorological Agency (Japan Meteorological Agency 1993; Fig. 1). We can see that generally they agree with each other very well. We assume that the good performance of the cyclone identification and tracking method during this 10-day period is also applicable to other time period and to other regions such as the North Atlantic.

3. Variability of the cyclone activity in the North Atlantic

With the objective cyclone identification and tracking algorithm described in section 2 and the NCEP reanalysis data, a 40-yr cyclone dataset was obtained for wintertime. In the present paper the winter season is defined as the period of December–January–February (DJF). This cyclone dataset includes the cyclone density, cyclone tracks, deepening rate, moving speed, central pressure gradient, and central pressure. To investigate the variability of the cyclone activity in the North Atlantic, principal component analysis was performed for the cyclone density over the North Atlantic in a region of \((45^\circ–80^\circ N, 60^\circ W–0^\circ)\). The first, second, and third principal components (PCs) explain 16.2%, 12.2%, and 7.6% of the total variances, respectively. Since the second and the third PC pattern (not shown) are much weaker and noisier than the first one, so we just discuss the first PC pattern in the present study. The spatial pattern of the first PC mode is illustrated in Fig. 2a by showing the linear regression pattern of the cyclone density over the North Atlantic with the first principal component. Values in Fig. 2a are the regression coefficients multiplied by one standard deviation change of the first PC, that is, the anomalies of cyclone density corresponding to one standard deviation of the first PC. Figures 2b–d show the regression patterns of the cyclone intensity (as indicated by the cyclone central pressure gradient), cyclone deepening rate, and moving speed with the first principal component, respectively. It can be seen that the geographical distributions of the anomalies of cyclone density, intensity, deepening rate, and moving speed are consistent with each other, with the increase of the cyclone density and intensity around the Greenland and Icelandic regions corresponding to the intensification of cyclone deepening rate and moving speed a little downward to the maximum cyclone deepening rate and cyclone moving speed, as shown in the cyclone climatology indicated with bold lines in Figs. 2a–d.

To see the temporal variations of the spatial patterns in Fig. 2, Fig. 3 illustrates the first principal component of the cyclone density. It can be found that except for the interannual variabilities, there is a clear gradually intensifying trend of the first principal mode. Statistical test shows that the intensifying trend exceeds the 95% significance level. Power spectrum analysis of the first principal component shows that there is no significant spectrum peaks in any frequency band, but the spectra tend to be larger at the lower frequencies with periods longer than 7 yr. To see the low-frequency change of the first principal component, a 7-point low-pass filter (the so-called binomial coefficient filter) with the weights of \((1, 6, 15, 20, 15, 6, 1)/64\) (Huang 1990), which can greatly reduce the high-frequency variations less than 7 yr, is applied to the first principal component. Superimposed in Fig. 3 is the low-pass-filtered time series of the first principal component. We can see a clear intensifying trend along with a decadal timescale oscillation.

Considering the gradually intensifying trend in Fig. 3, the anomaly pattern in Fig. 2a means a gradual increase of cyclone density around Greenland and the Icelandic regions and a gradual decrease of cyclone density over the eastern coast of the Atlantic and western Europe during the past 40 yr. It can be found that, consistent with the variations of the cyclone density in Fig. 2a, cyclone deepening rate becomes stronger (Fig. 2c) and the cyclone moving speed becomes faster (Fig. 2d), and, as a result, the intensity of the cyclones (as indicated by the cyclone central pressure gradient) becomes stronger (Fig. 2b) over the northern part of the North Atlantic storm track and the western European region. Since the increasing trend of the first PC in Fig. 3 is 0.031 yr\(^{-1}\), we can expect an increase of about 1.25 during the 40-yr period from 1958/59 to 1997/98, which is about 1.25 times of the standard deviation of the first PC (0.99). Knowing this, we can see that the actual intensification of the cyclone activity is about 1.25 times the value shown in Figs. 2a–d in the 40-yr period. Comparing with the climatological distributions of cyclone density, intensity, deepening rate, and moving speed shown with bold lines in Fig. 2, the anomaly patterns of cyclone activity indicate that the North Atlantic storm track exhibits a significant trend of extending northeastward, or extending toward the end of the storm track.
FIG. 2. Regression patterns of (a) cyclone density [contour interval: 0.4 cyclones (4.5° × 4.5° lat-long season)−1], (b) cyclone central pressure gradient [contour interval: 0.4 hPa (1000 km)−1], (c) cyclone deepening rate [contour interval: 0.03 hPa h−1], and (d) cyclone moving speed (contour interval: 0.4 m s−1) with the first principal component of the cyclone density over the North Atlantic. The values in the figure represent the anomalies corresponding to a unit std dev of the first principal component. Zero lines were omitted and the values larger than a contour interval or smaller than a minus contour interval are shaded. Negative contours are dashed. The bold lines in (a), (b), (c), and (d) indicate the regions of the climatological cyclone density larger than 7.0 cyclones (4.5° × 4.5° lat-long season)−1, central pressure gradient stronger than 16 hPa (1000 km)−1, deepening rate stronger than 0.3 hPa h−1, and moving speed larger than 13 m s−1, respectively.

To see more clearly the temporal variations of the cyclone activity in the North Atlantic, Fig. 4 shows the low-pass-filtered standardized time series of the area mean anomalies of cyclone density (45°–80°N, 80°W–0°), cyclone central pressure gradient (50°–70°N, 60°W–0°), moving speed (40°–60°N, 80°–100°W), and deepening rate (40°–60°N, 80°–100°W), respectively. The regions chosen to calculate the area means are corresponding to the relatively large anomaly regions in Figs. 2a–d. Figure 4 shows that the cyclone density has a clear trend of gradually increasing along with a decadal timescale oscillation. Corresponding to the increasing trend of cyclone density, a clear intensifying trend of the cyclone central pressure gradient (indicating the cyclone intensity), moving speed and deepening rate can be seen from Fig. 4, along with a decadal timescale oscillation. All these four variables vary consistently, with more (less) cyclones corresponding to stronger (weaker) cyclone central pressure gradient, faster (slower) cyclone moving speed, and stronger (weaker) deepening rate. For the unfiltered time series, the increasing trend of the number of cyclones and the intensifying trends of the cyclone central pressure gradient, moving speed and deepening rate are 0.99 cyclone yr−1, 0.03 hPa (1000 km)−1 yr−1, 0.035 m s−1 yr−1, and 0.0028 hPa h−1 yr−1, respectively. All of the trends exceeded the 95% significance level. Recently, Kushnir et al. (1997) have noticed a recent increase of the North Atlantic wave height, also indicating a gradual increase in the storm intensity over the North Atlantic in recent years.
4. Relationships with the large-scale circulation and SST

a. Large-scale baroclinicity and the NAO

Cyclone activity are closely related to the large-scale baroclinicity of the atmosphere. According to Lindzen and Farrell (1980) and Hoskins and Valdes (1990), a suitable measure of the baroclinicity is provided by the Eady growth rate maximum, 

$$ \sigma_{g0} = 0.31 f \frac{\partial |\mathbf{v}|}{\partial z} N^{-1}. $$

Where $f$ is the Coriolis parameter, $N$ the Brunt–Väisälä frequency, $\mathbf{v}$ the horizontal wind, and $z$ the vertical height. This baroclinic parameter has been widely used by a number of researchers (Hall et al. 1994; Zhang and Wang 1997; Carnell et al. 1996) in discussing the change of cyclones due to global warming. As in Hoskins and Valdes (1990), here we use the baroclinicity parameter at the lower troposphere of about 780 hPa.

Figures 5a,b show the linear regression patterns of the large-scale baroclinicity and the 200-hPa zonal winds with the first principal component, respectively. It can be seen that, corresponding to the first principal mode of the cyclone density in Fig. 2a, there is an intensification of the large-scale baroclinicity and the jet streams in the northern part of the North Atlantic. Comparing the anomaly with the climatology shown with bold lines, it is clear that both of the baroclinicity and the jet stream maximums exhibit a northeastward extension, similar to that of the cyclone activity in Fig. 2.

Fig. 5. Regression patterns of (a) Eady growth rate maximum (contour interval: 0.04 day$^{-1}$), and (b) 200-hPa zonal wind (contour interval: 1 m s$^{-1}$) with the first principal component of the cyclone density over the North Atlantic. The values in the figure represent the anomalies corresponding to a unit std dev of the first principal component. Zero lines were omitted and the values larger than a contour interval or smaller than a minus contour interval are shaded. Negative contours are dashed. The bold lines in (a) and (b) indicate the climatological Eady growth rate maximum larger than 0.6 day$^{-1}$ with 0.1 day$^{-1}$ interval, and 200-hPa zonal wind larger than 25 m s$^{-1}$ with 10 m s$^{-1}$ interval, respectively.
This indicates that, the gradual increase of the cyclone density around Greenland, and the intensification of the cyclone deepening rate, moving speed, and central pressure gradient over the northern part of the North Atlantic should be the result of the gradual intensification of the large-scale baroclinicity and the jet streams there.

To see the temporal phase relationship between the large-scale baroclinicity and the cyclone activity, Fig. 6 shows the low-pass-filtered standardized area mean anomalies of the Eady growth rate maximum (40°–60°N, 80°–10°W) and the 200-hPa zonal wind (40°–60°N, 80°–10°W), respectively. Also shown is the low-pass-filtered standardized time series of the first principal component. We can see that the temporal variation of the first principal component is generally in phase with that of the baroclinicity and the 200-hPa jet streams. The baroclinicity and the jet stream over the North Atlantic exhibit very similar intensifying trend and oscillations to that of the cyclone activity. For the unfiltered time series, the intensifying trends of the baroclinicity and the 200-hPa jet stream are 0.0024 d⁻¹ yr⁻¹ and 0.15 m s⁻¹ yr⁻¹, respectively. All of them exceeded the 95% significance level.

In Fig. 5b, the anomaly pattern of the 200-hPa zonal wind corresponding to a unit standard deviation of the first PC of the cyclone density indicates a cyclonic circulation anomaly near the Icelandic region and an anticyclonic circulation anomaly over the central latitudes of the North Atlantic, an anomalous circulation pattern that reflects the NAO pattern (Barnston and Livezey 1987), which is a dominant pattern of the atmospheric circulation variability there. According to Hurrell (1995), a substantial portion of the climate variability over the North Atlantic basin is associated with the NAO. He noticed that there is a trend of the NAO index toward a more positive phase over the past 30 yr and the magnitude of this trend appears to be unprecedented in the observational record. So it is interesting to examine the relationships of the change of cyclone activity with the NAO. In Fig. 6, the low-pass-filtered standardized anomalies of the wintertime (DJF) NAO index (Hurrell 2000) are also shown. We can see that the changes of the cyclone activity over the North Atlantic closely follow the change of the NAO index. The correlation coefficient between the unfiltered 40-yr time series of the first principal component and the NAO index reached 0.77, a value that exceeded the 99% significant level.
However, as pointed out by Hurrell et al. (2000), at present there is no consensus on the mechanisms that are responsible for the observed low-frequency variations in the NAO, including its unprecedented upward trend over the past 30 yr. It seems that SST is one of the most important factors that control the decadal variations and long-term trend of NAO. This was proved by several recent studies, which showed that the observed variations of NAO index can be reproduced very well by AGCMs forced by the observed SST and sea ice (Rodwell et al. 1999; Mehta et al. 2000; Latif et al. 2000). On the other hand, there are studies that showed that the ocean has a strong response to the NAO-like atmospheric forcing (Visbeck et al. 1998; Krahmann et al. 2000; Seager et al. 2000). The ocean, via advective propagation of SST anomalies or through other oceanic dynamics, could introduce delayed feedbacks to the atmosphere (Sutton and Allen 1997; Krahmann et al. 2000), necessary to create decadal oscillations (Latif and Barnett 1996; Sutton and Allen 1997; Grotzner et al. 1998).

As the recent intensifying trend of the NAO, one possibility is that the NAO may be now just in the intensifying phase of its multidecadal oscillation with a period of about 70 yr (Cook et al. 1998). At present it is unclear whether this is a coupled mode of the atmosphere and ocean or just an internal oceanic dynamic oscillation. In a multicentury integration with a coupled model, Delworth et al. (1997) found pronounced oscillations of oceanic temperature and salinity in the Greenland Sea with a timescale of approximately 40–60 yr. Models have shown multidecadal changes in the thermohaline circulation that are forced by the atmosphere (Delworth and Greatbatch 2000; Eden and Jung 2000), but less understanding is available on how these ocean signals feedback to the atmosphere. Another possibility is that the recent trend of the NAO may be interpreted by the anthropogenic forcing. Jones and Osborn (2000) showed that almost all the climate models indicating increasing values of the NAO index when the carbon dioxide level increases in the atmosphere. According to Graf et al. (1998), ozone depletion and global warming can cause anomalously strong stratospheric polar vortex in winter by producing an enhanced stratospheric height gradient through an expansion of the tropical troposphere. Perlwitz and Graf (1995) found that during winter of an anomalously strong stratospheric polar vortex, NAO tends to be in a positive phase with enhanced westerlies across the Atlantic, perhaps associated with changes in vertically propagating planetary waves. This could explain the continuous strengthening of the NAO during winters since the late 1960s.

In this section we have shown that the cyclone activity has close relationships with the NAO. From the recent studies mentioned in the above two paragraphs it seems that the decadal variability and long-term trend of NAO may be strongly influenced by the underlying sea surface temperature. So it is interesting to examine the relationships of the variations of cyclone activity with SST.

b. Sea surface temperature

To investigate how the cyclone activity is related to the underlying sea surface temperature, Fig. 7a shows the linear regressions of the SST anomalies in the North Atlantic with the first principal component of cyclone density. The SST used here is the Global sea-Ice and SST data version 2.3b (Met Office 2000). It can be found that, corresponding to the first principal mode shown in Fig. 2, the SST exhibits a negative anomaly around Greenland, a positive anomaly in the middle North Atlantic and a negative anomaly over the south North Atlantic. This SST anomaly pattern is remarkably similar to the winter seasonal mean change of the land–ocean surface temperature index based on the linear trend of last 30 yr over the North Atlantic, as shown by Hansen et al. 1996 (see their Fig. 4), indicating that the variations of cyclone activity have similar trends with that of the surface temperature. Figure 7b shows the regression pattern of the meridional gradient of SST with the first principal component. Here the meridional gradient of SST is defined as $-\frac{1}{2} \frac{\partial}{\partial \varphi} (\alpha T/\partial \varphi)$, where $\varphi$ is the latitude. The meridional SST gradient also shows a northeastward extension when compared with the climatological distributions indicated by bold lines in the midlatitude North Atlantic, similar to the northeastward extension of the cyclone activity shown in Fig. 2 and the northeastward extension of the baroclinicity and the jet streams shown in Fig. 5, indicating some kind of relationships between the change of the atmosphere and the underlying oceans.

To illustrate the temporal phase relationship of SST
and cyclone activity, Fig. 8 shows the low-pass-filtered standardized anomalies of the meridional SST gradient averaged over a region of (40°–60°N, 80°–10°W) and the first principal component of cyclone density. The reason that we show the meridional SST gradient first other than the SST itself is because that the anomaly patterns of baroclinicity and the 200-hPa jet stream in Fig. 5 are similar to the anomaly pattern of the meridional gradient of SST in Fig. 7b. Figure 8 indicates that the changes of SST gradient always tend to lag behind the changes of cyclone activity. To see the robustness of this kind of phase relationships between the cyclone activity and the meridional SST gradient over the North Atlantic basin, we averaged the SST over three latitude belts within the 80°–10°W longitude band, that is, 50°–70°N, 30°–50°N, and 10°–30°N, which may represent the high latitudes, midlatitudes, and subtropics, respectively. The division of the latitude belts is based on Fig. 7a, which has a tripole SST anomaly structure. Then we use the difference of the SST anomalies averaged over (30°–50°N, 80°–10°W) minus the SST anomalies averaged over (50°–70°N, 80°–10°W) as a measure of the changes in SST gradient around 50°N (midlatitude) and that of the SST anomalies averaged over (30°–50°, 80°–10°W) minus the SST anomalies averaged over (10°–30°N, 80°–10°W) as a measure of the changes in SST gradient around 30°N (subtropics), respectively. From Fig. 8 we can see that, surprisingly, the SST gradient in the midlatitude (around 50°N) and that over the subtropics (around 30°N) have very similar phase and trend and all of them lag behind the PC1 of the cyclone density. In addition to the meridional SST gradient, the SST changes averaged over 50°–70°N, 30°–50°N, and 10°–30°N latitude belts within the 80°–10°W longitude band are illustrated in Fig. 9 along with PC1 of cyclone density. Comparing Fig. 9 with Fig. 8, it is clear that the phase relationships of the PC1 of cyclone density with SST are not as good as that with SST gradient. The reason for this is unknown and further investigation is needed.

To clarify the mechanism that links the decadal timescale variations of cyclone activity and SST is out of the scope of the present work. But the present study does show that a certain kind of relationships exists between the variations of cyclone activity and SST. From the phase lag of meridional SST gradient behind the cyclone activity (Fig. 8) it seems that SST may not be the cause of the change of cyclone activity. However, several recent studies (Rodwell et al. 1999; Mehta et al. 2000; Latif et al. 2000) reproduced the observed variations of NAO index by using AGCMs forced by the observed SST and sea ice, while the NAO could have strong influence on the cyclone activity (as shown in Fig. 6). One possible way to reconcile this contradictory is to think the change of NAO and SST as a decadal timescale coupled mode of the atmosphere and ocean with an oceanic delay, as proposed by several recent studies (Latif and Barnett 1996; Sutton and Allen 1997; Grotzner et al. 1998). The possible mechanism may be that the NAO changes as the atmospheric part of the decadal timescale coupled mode of the atmosphere and ocean, with the atmosphere driving the ocean and the ocean giving delayed feedbacks to the atmosphere. The change of the large-scale NAO circulation pattern then modulates the large-scale baroclinicity and thus gives strong influence on the cyclone activity in the North Atlantic.

There may be other ways that SST can influence on the cyclone activity. The first possibility is that the SST pattern shown in Fig. 7a may result in increased evaporation in the midlatitude North Atlantic. This would contribute to increased development (via increased latent heat release) of cyclones moving from the land to the ocean along the east coast of North America, which would favor increased activity along the Atlantic storm track. However, according to the study of Pavan et al. (1999), the increase of water vapor in the atmosphere has much less effect on cyclone activity than the baroclinicity of the lower troposphere, which is much controlled by large-scale atmospheric circulation patterns such as the NAO.

Another possibility, as pointed out by Bond and Harrison (2000), is that the air temperature of the lower boundary atmosphere tends to have similar spatial distribution as that of the SST. Since the baroclinicity of the lower atmosphere, which has a strong influence on the cyclone activity, is proportional to the temperature gradient, we can expect that the cyclone activity would also have a very good relationship with the SST gradient. However, in this kind of situation we would expect that the cyclone activity vary almost simultaneously with the change of SST gradient. But our results show that the change of SST gradient lags behind the cyclone
activity change by 1 or 2 yr (see Fig. 8). So the direct influence of SST gradient on the cyclone activity in the decadal timescale seems not important in the present case.

5. Summary and conclusions

In the present paper, principal component analysis is applied to the cyclone density over the North Atlantic in winter analyzed with an objective cyclone identification and tracking algorithm by using the 6-h National Centers for Environmental Prediction reanalysis data from 1958 to 1998. Regressions of the cyclone density, deepening rate, moving speed, and central pressure gradient with the first principal component show that the cyclone activity over the northern North Atlantic exhibits a significant intensifying trend along with a decadal timescale oscillation in winter during the past 40 yr. All these variables vary consistently with larger (smaller) cyclone density corresponding to stronger (weaker) cyclone intensity, faster (slower) moving speed and stronger (weaker) deepening rate.

Analysis shows that the variations of the cyclone activity over the North Atlantic are closely related to the changes of large-scale baroclinicity at the lower stratosphere and the NAO. It seems that the relationships of the cyclone activity with the North Atlantic SST is complicated and further investigations are needed to clarify the mechanisms of how SST could influence on the cyclone activity.

Cyclones are important synoptic systems that have strong influences on the everyday weather events and thus are closely linked with climate variability and climate change. It is therefore crucial to understand the nature of the variability of cyclone activity in order to understand the changes of weather and climate events and their extremes. The present work represents a preliminary effort toward this direction.

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