Response of Storm Tracks to Bimodal Kuroshio Path States South of Japan

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ABSTRACT

A large meridional shift of the sea surface temperature front occurs off the south coast of Japan associated with transitions between the large-meander and straight paths of the Kuroshio. Most extratropical cyclones generated in winter near the Kuroshio in the East China Sea pass through the region where the Kuroshio takes either the meander or the straight path. To examine whether such cyclones change their tracks and intensities according to the two states of the path, a new dataset of winter cyclone tracks derived from surface weather charts from the period 1969/70–2008/09 was produced. The composite analysis of cyclone tracks with respect to the meander and straight path states reveals the following: the cyclone track axis for the meander path state is located away from the south coast of Japan with a dispersive tendency, while that for the straight path state is attached to the south coast with a long extending feature. A difference in track between these two states also occurs to the east of Japan over the North Pacific. In addition, this behavior of the cyclone track is shown to be independent of the wintertime atmospheric circulation anomalies around Japan. The development rate of cyclones is 41% faster for the straight path state than the meander path state. Snowfall in Tokyo caused by south-coast cyclones is more frequent for the meander than the straight path state because the former state can act to decrease air temperature in Tokyo.

1. Introduction

Western boundary currents (WBCs) such as the Kuroshio and Gulf Stream bring enormous amounts of heat from lower latitudes to midlatitudes, where the WBCs influence the atmosphere via air–sea heat fluxes (see a recent review by Kelly et al. 2010). The Kuroshio and Gulf Stream induce a series of time-mean atmospheric responses (e.g., Nonaka and Xie 2003; Minobe et al. 2008, 2010; Tokinaga et al. 2009) and also have a substantial impact on synoptic-scale extratropical cyclones. Frequent cyclogenesis and deepening of extratropical cyclones, including rapidly developing bomb cyclones, occur over the Kuroshio flowing in the East China Sea and south of Japan, the Kuroshio Extension east of Japan (Gyakum et al. 1989; Chen et al. 1991, 1992; Yoshida and Asuma 2004; Adachi and Kimura 2007), and the Gulf Stream in the North Atlantic (Colucci 1976; Sanders and Gyakum 1980; Gyakum et al. 1989; Businger et al. 2005). The mechanisms by which the WBCs influence extratropical cyclones may be low-level baroclinicity and/or diabatic heating associated with sensible and latent air–sea heat fluxes (Hoskins and Valdes 1990; Nakamura et al. 2008), which would be consistent with numerical experiments (Kuo et al. 1991; Reed et al. 1993; Xie et al. 2002; Businger et al. 2005; Taguchi et al. 2009; Kuwano-Yoshida et al. 2010).

An interesting question is whether interannual-to-decadal variations of WBCs play an important role in modifying extratropical cyclones. Joyce et al. (2009) reported that surface storm tracks follow the decadal meridional shift of the Gulf Stream. It should be noted, however, that changes of the surface storm track defined by strong surface winds do not necessary mean that tracks of individual extratropical cyclones shown in weather charts vary substantially. Strong surface winds near the WBCs may be partly due to downward momentum mixing (Wallace et al. 1989; Sampe and Xie

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2007; Booth et al. 2010), which is effective over a region with sea surface temperatures (SSTs) warmer than air temperatures and thus closely associated with the WBCs. For the North Pacific, Nonaka and Xie (2003) and Xu et al. (2010) demonstrated that the two states of the Kuroshio's path to the south of Japan (i.e., large-meander and straight paths) substantially influence local winds, clouds, and precipitation. These studies did not examine whether the meander path state modifies extratropical cyclones. In particular, it is interesting to examine the possible influence of the state of the Kuroshio's path on so-called south-coast cyclones that advance eastward along the south coast of Japan passing through the region where meander and straight paths occur in winter. South-coast cyclones are important for Japanese society because they bring snow or rain to mainland Japan including Tokyo, the Japanese capital with a population of more than 13 million (e.g., Takano 2002). The purpose of the present paper is to investigate whether variations between the meander and straight path states affect the south-coast cyclones in the winter season (from November to March).

2. Data and methods

a. Kuroshio axis position dataset

The Marine Information Research Center, Japan Hydrographic Association, provides a digital dataset containing the position of the Kuroshio path south of Japan since 1955. In this study, data from the period 1969–2007 were used. There are 24 snapshot patterns of the Kuroshio path collected semimonthly for each year from 1969 to 1999 and more than 44 snapshots for each year from 2000 to 2007 because the observation frequency was increased. Snapshots for the period 2000–07 are therefore extracted at fortnightly intervals to create a dataset with a common time interval. We define large-meander and straight paths based on the southernmost position of the Kuroshio's path between 136° and 141°E: if the southernmost position is located to the south of 32°N (north of 33°N), the path is classified as a large-meander (straight) path; the path between 32° and 33°N is, however, classified into the neutral state.

The number of large-meander and straight paths from November to March in the period 1969/70–2006/07 is 138 and 95, respectively (Figs. 1a,b). The trajectories of the paths for each of the two states are almost the same west of 130°E but greatly different off the south coast of Japan and slightly different east of 140°E. It is well known that each state is maintained over long periods spanning several months to a few years, and the epochs in which one state is predominant over the other vary on a decadal time scale (e.g., Kawabe 1995; Qiu and Miao 2000). Figure 1c indicates this behavior as follows: after the straight path state in the early 1970s, the meander path state dominated for 16 yr from 1975 to 1990 and then the straight path state became predominant in the following ~10 yr, but the long-lived meander path appeared again in 1999 and 2004. For a large-meander path state, a cool water pool appears between the Japanese coast and the meandering Kuroshio, whereas such cool water does not occur for a straight path state (Figs. 1d,e). SST shown here was taken from the Advanced Very High Resolution Radiometer (AVHRR) Pathfinder L3 monthly nighttime SST version 5 [National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL)] with a high resolution of 0.044° × 0.044°.

b. Cyclone track dataset

The surface weather charts for the Asia and western North Pacific region are produced by the Japan Meteorological Agency (JMA). In this study, we used these charts in winters (November–March) for the period 1969/70–2008/09. The time interval of the data is 12 h to December 1995 and 6 h from January 1996. The position of the cyclone center, marked by a cross on the chart, was read with the precision of 0.25° in longitude and latitude, along with the sea level pressure at the cyclone's center, which is denoted on the chart. We tracked the cyclones that originated from or passed through the area delimited by 120°–130°E and 24°–35°N and recorded their positions over the domain bounded by 120°–150°E and 24°–50°N. This dataset includes tracks of 802 cyclones (Fig. 2a). Most of cyclones appearing in this area progress to the sea area south of Honshu Island, but a relatively small number of cyclones migrate to the Japan Sea. This is consistent with the two preferred cyclone tracks around Japan (e.g., Adachi and Kimura 2007). These cyclones include some cyclones that move too far from the south coast of Japan to be called south-coast cyclones. Also, cyclones that have different genesis locations (e.g., the Asian continent or around the Kuroshio in the East China Sea) may be in different life stages when they arrive in the region of the bimodal Kuroshio paths. Therefore, in order to analyze the south-coast cyclones that have similar genesis locations, we extract the cyclones that originate from the Kuroshio region in the East China Sea and progress to the north of 30°N (Fig. 2b). Furthermore, we limit our analysis to cyclones that have central pressures less than 1000 hPa when they progress past 150°E, because these relatively strong cyclones may have more important impacts on society than weak

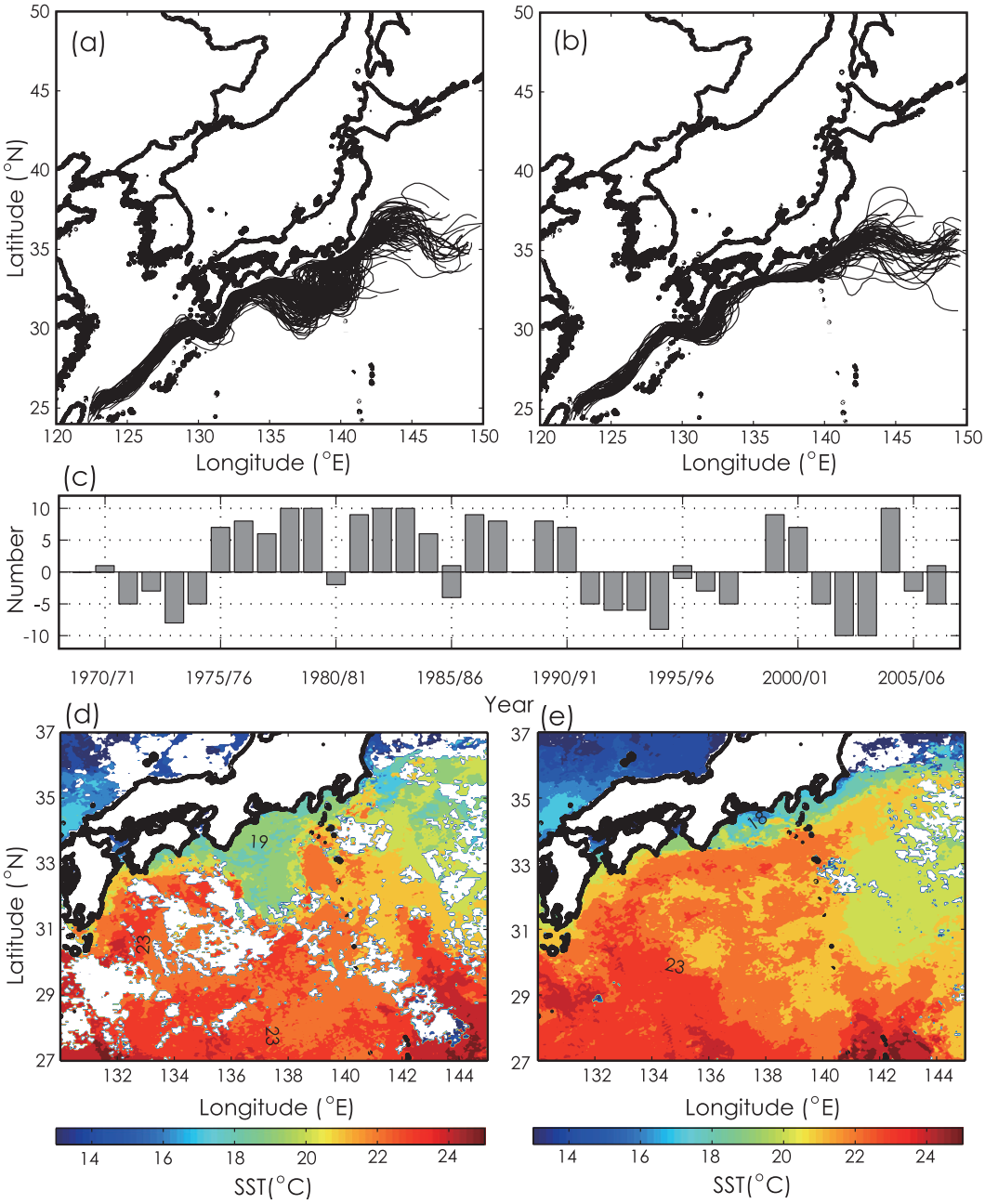

FIG. 1. Composites of Kuroshio paths for the (a) large-meander and (b) straight path states. (c) Time series of the number of paths for the large-meander (positive) and the straight (negative) states for bimonthly data from November to March in the period 1969/70–2006/07. Typical SST fields for (d) the large-meander path state in February 2005 and (e) the straight path in February 2004 based on AVHRR Pathfinder L3 monthly nighttime SST version 5 from NASA JPL.

ones. As a result, 139 cyclone tracks were used for the analysis in this study.

3. Cyclone track responses to Kuroshio path states

Based on cyclone track data shown in Figs. 2c,d, frequency distributions of cyclone tracks were calculated with respect to the large-meander and straight path states (Fig. 3). The meander and straight path states contain 61 and 27 cyclone tracks, respectively, and the neutral path state contains 51 cyclone tracks. Focusing on the sea area off the south coast of Japan, we see a remarkable difference between the meander and straight path states: for the meander path state (Fig. 3a),

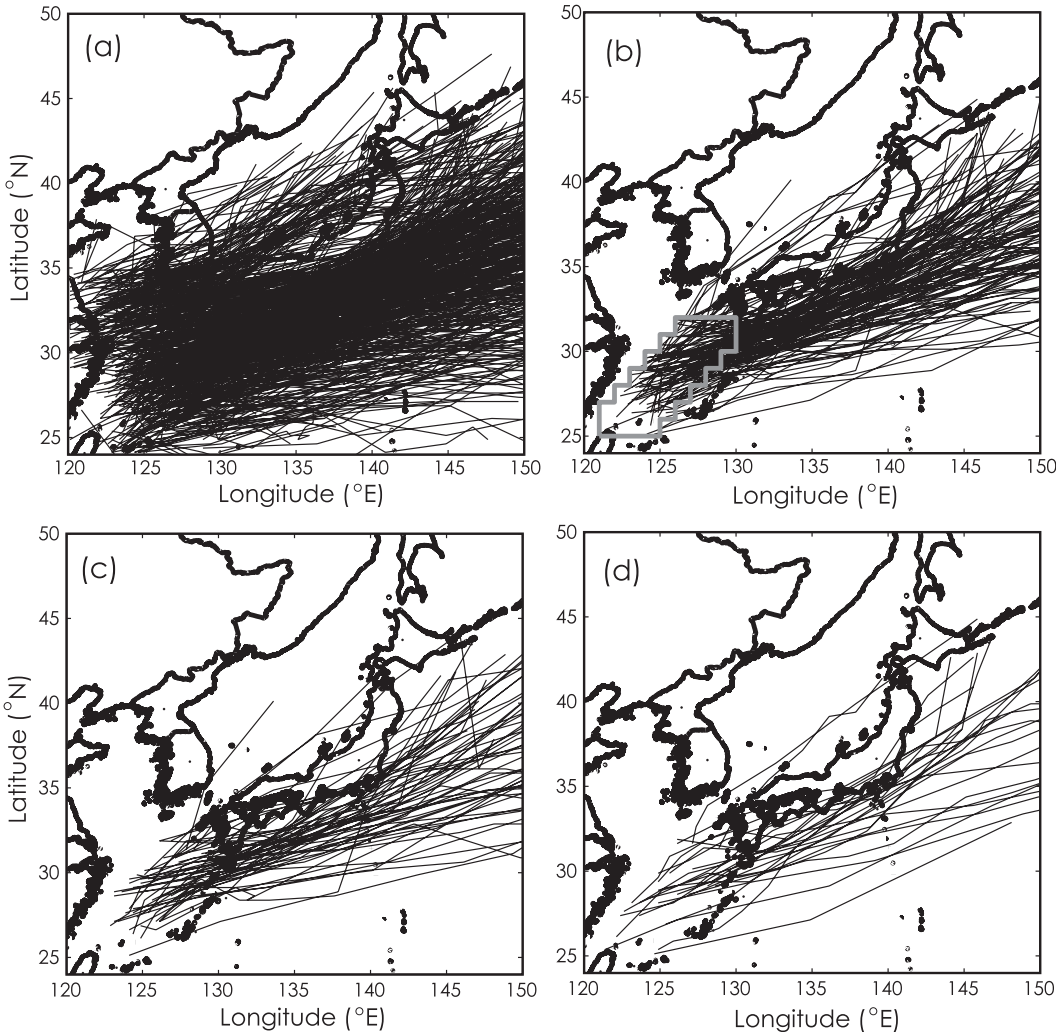

FIG. 2. Composites of cyclone tracks: (a) all tracks and (b) tracks selected only for the south-coast cyclones, defined as those originating from the area delimited by gray solid lines and progressed to the north of 30°N, with central pressures less than 1000 hPa when they progressed past 150°E. (c),(d) As in (b), but for the (c) large-meander and (d) straight path states.

the cyclone track axis indicated by a chain of high-frequency areas is found about 2° in latitude away from the coast around the region of the meander path (137°–140°E). In comparison, the cyclone track axis for the straight path state is attached to the south coast (Fig. 3b). The two distributions are significantly different at the 95% confidence level by the rank sum test for data along the 138.75°E line in the area 29°–36°N (Figs. 4a,b). There is no significant difference between the two states in the area upstream to the bimodal path region (Figs. 4c,d), indicating that the meridional shift of the cyclone track revealed in Figs. 3a,b is likely caused not by a change in initial location of the cyclone but by the bimodal Kuroshio paths themselves.

The cyclone frequency distribution in a larger domain shows prominent differences to the east of 140°E (Figs. 3c,d). Tracks for the large-meander path state are dispersive and widely distributed with small magnitudes, and the track density maxima shown in Fig. 3a to the south of the Japanese coast disappear around 142°E. On the other hand, tracks for the straight path state are highly concentrated even to the east of 142°E. Consequently, the bimodal Kuroshio paths affect cyclone paths not only in the local area south of Japan but also in the remote area east of Japan.

Another important characteristic of cyclones is their development rate, which is determined here by the maximum pressure decrease rate, using the 12-hourly values (6-hourly values after 1996) within the area

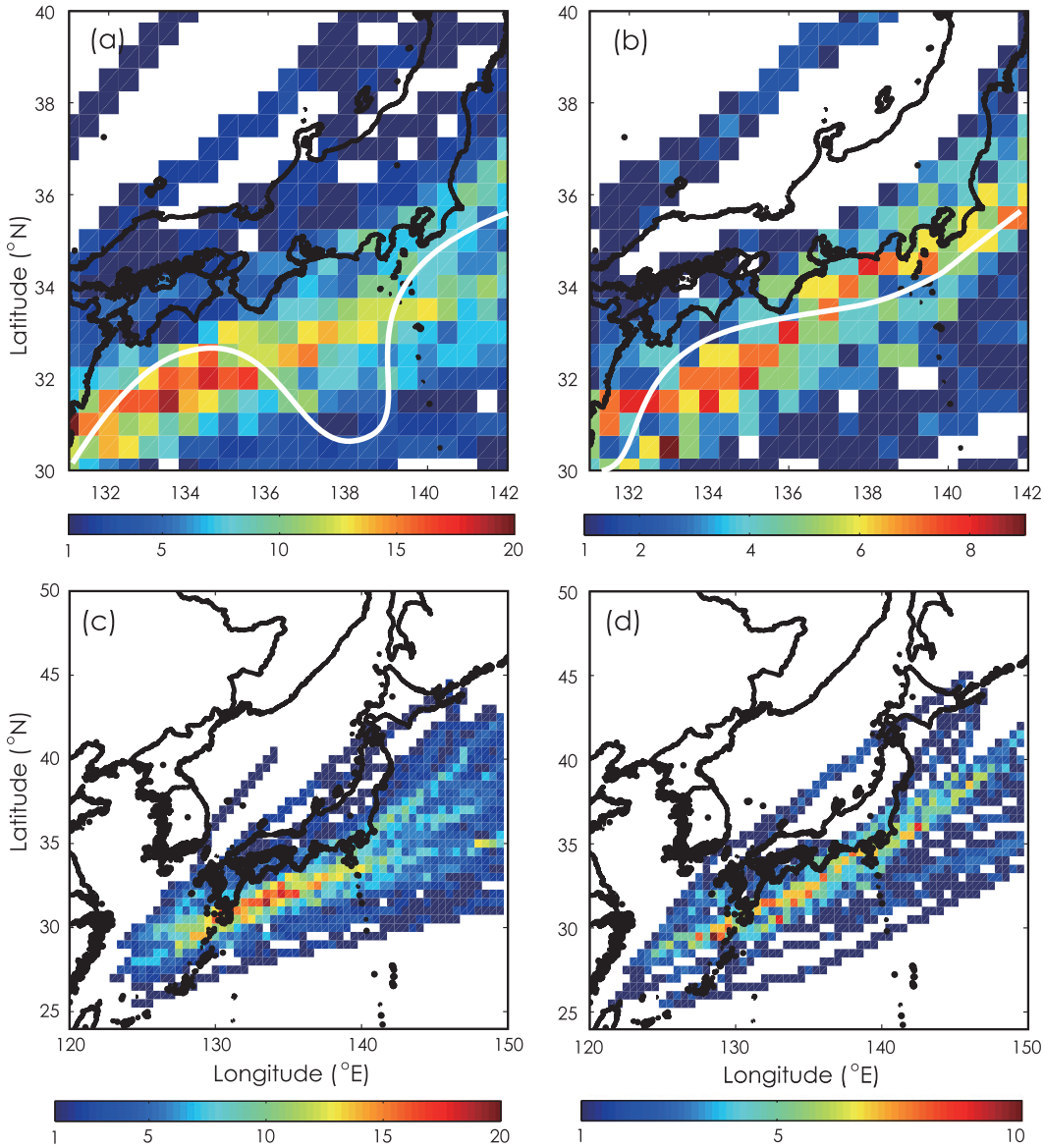

FIG. 3. Frequency distribution of cyclone tracks on a 0.5° × 0.5° grid with respect to the Kuroshio path state: (a),(c) the large-meander path state and (b),(d) the straight path state, for (a),(b) the area off the south coast of Japan and (c),(d) the entire domain of the dataset. White thick solid lines in (a) and (b) denote the typical large-meander and straight paths, respectively, which are taken from Kawabe (1995).

between 130° and 145°E (Fig. 5). The average maximum decrease rate is -0.70 hPa h^{-1} for the large-meander path state compared to -0.99 hPa h^{-1} for the straight path state, which are significantly different at the 95% confidence level. This indicates that cyclones tend to develop faster during the straight path state than during the meander path state. The faster growth of cyclones in the straight path state might be due to low-level baroclinicity or diabatic heating associated with latent air–sea heat flux: the cool water pool (Fig. 1d) for the large-mender path state yields weaker SST gradients across the cyclone track axis over the bimodal Kuroshio path region and also may yield smaller evaporation, leading to weaker diabatic heating in the atmosphere. These mechanisms should be closely examined using atmospheric numerical model in future, since it is generally difficult to identify the mechanisms from observed data. In particular, the reanalysis dataset that covers the analysis period of this study is only National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis 1, whose resolution may

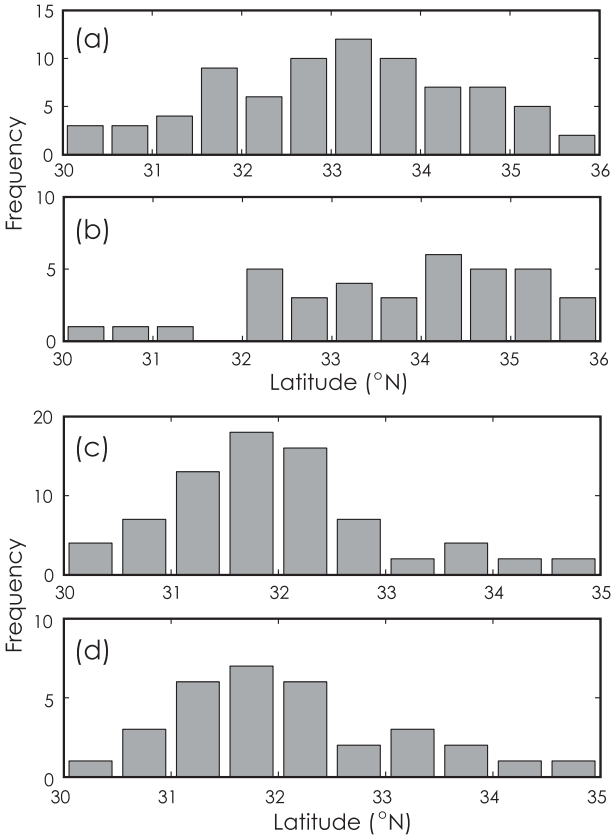

FIG. 4. Frequency distributions of cyclone tracks as functions of latitude along (a),(b) 138.75°E and (c),(d) 134.25°E: (a),(c) the large-meander path state and (b),(d) the straight path state.

be too coarse to capture the possible atmospheric parameter changes associated with transitions between the bimodal Kuroshio path states with migration amplitude of about 1.5° in latitude.

Apart from the effect of the path changes of the Kuroshio, the variations of large-scale atmospheric circulations might influence storm tracks around Japan. It was reported that the western Pacific (WP) pattern (Nakamura et al. 1987) and intensity of the East Asian winter monsoon (Yoshiike and Kawamura 2009) influence the East Asian storm tracks. To know the influence of the large-scale atmospheric circulation anomalies on the current analysis, we examined composites of zonal winds at 250 hPa with respect to the large-meander and straight path states, using the NCEP–NCAR Reanalysis 1 dataset, and confirmed that there is no significant difference between the two states even at the 80% confidence level over the entire study area. The difference in cyclone tracks between the bimodal Kuroshio path states is therefore independent of large-scale atmospheric circulation anomalies.

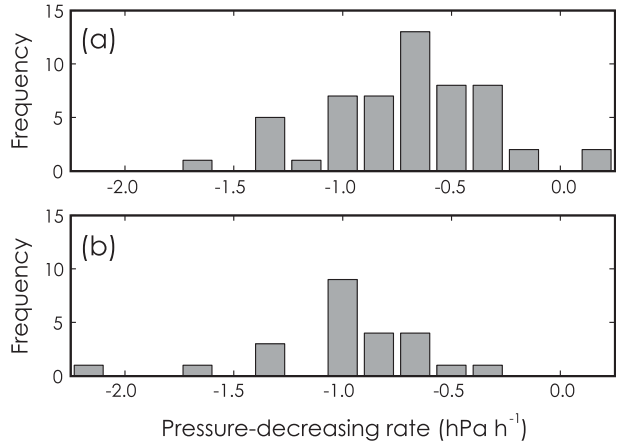

FIG. 5. Frequency distributions of south-coast cyclones as functions of pressure-decreasing rates for the (a) large-meander and (b) straight path states.

4. Impact on snowfall in Tokyo

Since south-coast cyclones often bring significant snow to the area around Tokyo as noted in the introduction, we test whether the large-meander and straight path states are related to snowfall events around Tokyo. We examined daily-mean air temperatures and rain or snow amounts provided by JMA both on the day of and on the day following the passage of a south-coast cyclone through 138°E, which is where the typical large-meander path takes its southernmost position. Out of the two days examined, the one with the larger rain or snow amount at Tokyo was chosen in order to obtain representative samples for rain or snow conditions associated with south-coast cyclones.

Figure 6 shows that snowfall events frequently occurred for 12 out of 58 cyclone passages (21%) for the large-meander path state, compared to none of the 25 cyclone passages for the straight path state and to 4 out of 44 cyclone passages (9%) even for the neutral state. The snowfall events are likely to occur in association with air temperatures lower than about 5°C. Such an air temperature condition occurs in the situation where a south-coast cyclone passes between 31° and 34°N for the meander path state. South-coast cyclones located too close to the Japanese coast probably cannot bring snow to the coastal area, because warm air blowing into the cyclone from the south increases coastal air temperatures (as explained by JMA's web page, http://www.jma.go.jp/jma/kishou/jma-magazine/0601/index.html, in Japanese). Most of south-coast cyclones that advance south of 31.4°N (five events) do not bring snowfalls in Tokyo even for the meander paths (Fig. 6a). This is probably related to drier conditions of nonsnowfall events; the relative humidity was 85% in average for 12

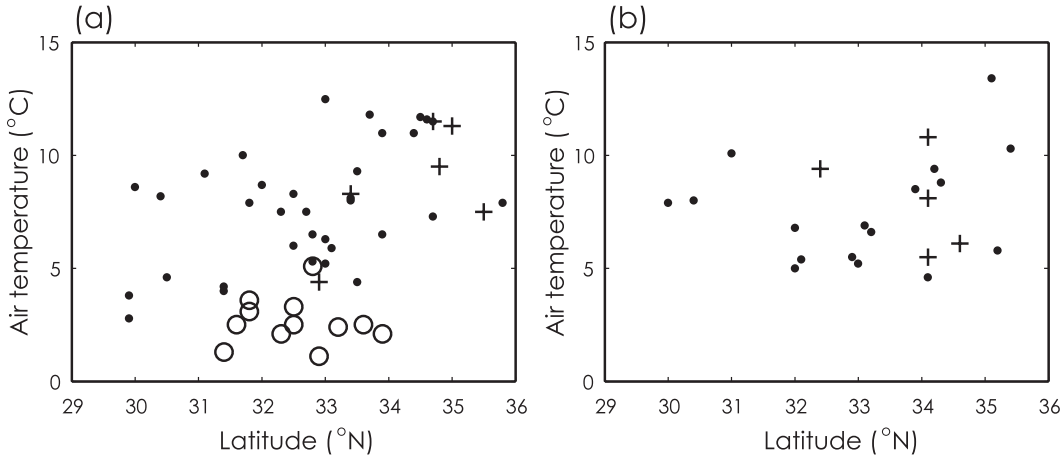

FIG. 6. Relations of the daily-mean air temperature in Tokyo (35.69°N, 139.76°E) to the location of the south-coast cyclone at 138°E with respect to the (a) large-meander and (b) straight path states. Open circles denote snowfall events, while crosses are heavy rainfall events where the rain amount exceeds 30 mm day^{-1}.

snowfall events while 64% in average for 5 nonsnowfall events, suggesting that cyclones located too far from Tokyo cannot bring moist air from the Pacific to that area. The humidity difference is, however, not statistically significant, and thus further investigations will be needed. The aforementioned tendency of south-coast cyclones to be located further southward for the meander path state than the straight path state (Figs. 3, 4) may explain at least partly why the south-coast cyclones for the meander path state are more likely to bring snow to Tokyo than those for the straight path state.

One might argue that the more frequent snowfall events for large-meander path states rather than straight path states can be a spurious relation in association with a combination of less frequent meander path states in recent years compared to previous years (Fig. 1c) and a tendency for warmer Tokyo air, possibly due to global warming and/or an enhanced heat island phenomenon. However, if we subtract the winter-mean air temperature anomalies in each year from the daily air temperatures and repeat the analysis, the results remain essentially unchanged. The more frequent snowfall events for the meander path state are therefore not a spurious relation associated with long-term air temperature changes.

Another interesting point in Fig. 6 is that, even if the south-coast cyclones pass through the latitudinal range from 31° to 34°N, air temperatures colder than 5°C occur only for meander path states and not for straight ones. One possibility explaining this may be smaller ocean-to-atmosphere heat fluxes associated with the cool water pool appearing inshore of the meander path (Xu et al. 2010), but further investigations are necessary.

5. Conclusions

In this study, we reported that the tracks and development rates of cyclones that advance along the south coast of Japan over the western North Pacific vary substantially in association with the large-meander and straight path states. To the authors' knowledge, this is the first study to report that the behavior of extratropical cyclones is influenced by interannual-to-decadal WBC variability using observed data. The meander and straight paths are exceptional WBC path changes in the sense that they occur before the separation of these currents from the coast. Other WBC path changes occur after their separation from the coast, such as in the Kuroshio Extension and the Gulf Stream Extension (Kelly et al. 2010). Therefore, the state changes between the meander and straight paths may exert a more direct impact on land climate than the path changes of the WBC extensions.

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