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Taiwan Yushan Snowfall Activity and Its Association with Atmospheric Circulation from 1979 to 2009

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ABSTRACT

Yushan is the most famous location for snow in Taiwan, while snowfall in the subtropical zone is rare. When it is snowing in Yushan, people are experiencing unusually cold and wet weather elsewhere in Taiwan. In this study, Yushan snowfall activity from 1979 to 2009 and the related atmosphere circulation were examined with the Taiwan Central Weather Bureau's Yushan weather station observations and the National Centers for Environmental Prediction/Department of Energy (NCEP/DOE) reanalysis atmospheric data.

To provide a quantitative measure of snowfall events, a snowfall activity index (SAI) was defined in this study. The time series of yearly SAIs shows that Yushan snowfall activity for an active year, such as 1983 (SAI =39 153) was ∼118 times larger than for an inactive year, such as 1999 (SAI=331).

Our analyses show that snowfall activity is closely related to the position of the East Asian Trough (EAT) and the strength of the West Pacific High (WPH). In active years, when the EAT shifted eastward and the strength of WPH increased, an anomalous anticyclone occurred in the West Pacific. This anticyclone introduced anomalous southwesterly flows along the southeastern cost of mainland China and over Taiwan, resulting in a wetter-than-normal atmosphere that favored snowfall. Alternatively, in inactive years, a drier-than-normal atmosphere resulted in sluggish snowfall seasons.

Key words: Yushan, snowfall activity, atmospheric circulation

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1. Introduction

Yushan (23.28°N, 120.56°E), part of the Central Mountain Range (CMR) of Taiwan, is geographically located on the Tropic of Cancer and has a subtropical marine climate. Due to the steep terrain (its main peak, elev. 3952 m, is the highest in East Asia) and its particular location on the pathway of the Siberian high-pressure systems moving from high latitudes across Asia and out over the ocean, snowfall that typically only appears in the temperate and frigid zones occurs in Yushan when cold air moves south and sufficient moisture is present. While snowfall in the subtropical zone is rare, snowfall in Yushan results from the interaction between synoptic-scale circulation, moisture, and terrain. When it is snowing in Yushan, unusually cold and wet weather is occurring elsewhere in Taiwan.

Many studies have indicated that the interaction of the CMR with atmospheric circulation, especially typhoon circulation, produces significant variations in pressure, wind, and precipitation distribution (Wu and Kuo, 1999; Wu, 2001; Hsiao et al., 2010). Most of these studies have focused on the relationship of the CMR with summer weather systems. In winter, the East Asian winter monsoon (EAWM) dominates Asia. The EAWM circulation is affected by factors such as the El Niño/Southern Oscillation (ENSO; Wang et al., 2000), North Pacific Oscillation (NPO; Wu and Huang, 1999), etc. Most research regarding the

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EAWM has concentrated on rainfall variability (Wangwongchai et al., 2005; Xin et al., 2006; Fu et al., 2008; Wan el al., 2009; Zhou, 2010), temperature variability (Zhou and Wang, 2008; Shiu et al., 2009), the influence of cold waves (Liu et al., 2005), and even global warming (Kimoto, 2005). However, the study of the interaction between the CMR and winter atmospheric circulation, especially snowfall events, is rare; only Qi and Chen (1995) published their investigation of snowfall in Taiwan. Heretofore, there has been no systematic study of the snowfall in Yushan.

This study investigated the connection between Yushan snowfall activity and synoptic-scale atmospheric circulation in a climatologic sense. In section 2, data sources used in this study are introduced, including the CWB data from the Yushan weather station, and the National Oceanic and Atmospheric Administration (NOAA) reanalysis data. A snowfall activity index (SAI) was defined in this study as a measure of Yushan snowfall activity. Section 3 portrays temporal and spatial features of Yushan snowfall events and their associated atmospheric circulation patterns. To illustrate the climate effects on snowfall activity, active and inactive years were classified according to their SAIs. The atmospheric circulation patterns of the two distinct categories are compared in section 4. Possible climate controls responsible for the interannual variability of SAI are also discussed. Section 5 summarizes the major findings of this study.

2. Data and method

2.1 *Data of Yushan weather station*

A data set compiled by the CWB of Yushan weather station observations from 1979 to 2009 (1-h intervals) was used to examine snowfall events. The Yushan weather station is located on the northern peak of Yushan (elev. 3853 m), and it is the highest weather station in East Asia. Since 1943, Yushan station observations have been compiled according to international meteorological code (3-h intervals) for international meteorological broadcasting. In this study, quality-control procedures were performed on the data of Yushan station to ensure continuity of data regarding snowfall events during the study period.

In this study, the "solid-state precipitation 1" group of the CWB weather data table was adopted as a measure of the temporal characteristics of snowfall events in Yushan. Nine types of precipitation-related events were encoded in the "solid-state precipitation 1" group. Following CWB regulations, the snowfall events were classified into three categories according to their strength: light, moderate, or heavy. Light snow, corresponding to code 1 in the "solid-state precipitation 1" group, was defined as snowfall with strength $S \leqslant 1.0$ mm h^{-1}. Moderate snowfall, corresponding to code 2 in the "solid-state precipitation 1" group, was defined as snowfall with strength between 1.0 mm h^{-1} and 3.0 mm h^{-1}. Heavy snowfall, corresponding to code 3 in the "solid-state precipitation 1" group, was defined as snowfall with strength $S >3.0$ mm h^{-1}.

2.2 *Atmosphere date*

The National Oceanic and Atmospheric Administration/Earth System Research Laboratory (NOAA/ESRL) Physical Sciences Division's atmospheric data were also used to investigate the background atmospheric circulation during the snowfall season. NCEP/DOE Reanalysis II data was used a state-of-the-art analysis/forecast system to perform data assimilation from 1979 to 2009. This data included major atmospheric parameters (e.g., geopotential height, relative humidity, horizontal wind, etc.) at 17 pressure levels from 1000 hPa to 10 hPa, with horizontal resolution of $2.5° \times 2.5°$.

2.3 *Snowfall activity index* (*SAI*)

In temperate and frigid zones, as a general rule, heavy snow means a total accumulation of $\geqslant$10 cm during a 12-h period or a snowfall of 15 cm or more during a 24-h period (Ahrens, 1994). But snowfall events in subtropical zones are rare. The intensity of snow on Yushan is different from that in temperate and frigid zones. A snowfall event usually lasts a few hours in Yushan, and the snow melts quickly.

To provide a quantitative measure of snowfall activity, SAIs were established by summing snowfall duration multiplying accumulated snow cover at Yushan station every year during the period 1979–2009 (unit: cm h). SAIs represents the snow activities at Yushan, while the annual magnitude signifies the strength of Taiwan snowfall activity in a particular year.

3. Climatological characteristics

3.1 *Climatology of snowfall activity*

Figure 1 shows the annual cycles of monthly SAI, snowfall, and accumulated snow durations averaged over 1979–2009, illustrating the seasonal cycle of snowfall activity. Notably, some accumulated snow durations in October were without snowfall. Accumulated snow durations alone were not adequate to describe the snowfall activity. To determine comprehensive snowfall activity, we used accumulated snowfall multiplied by snowfall of duration to define the SAI.

Although snow events can occur from late October to early May, winter (January, February, March, or JFM) is the most active season, accounting for >93%

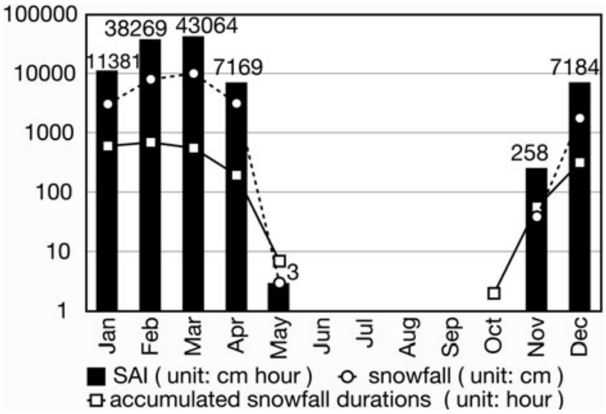

Fig. 1. Annual cycle of monthly SAI (snowfall activity index), snowfall, and accumulated snow durations averaged during 1979–2009. The vertical coordinate is a logarithm.

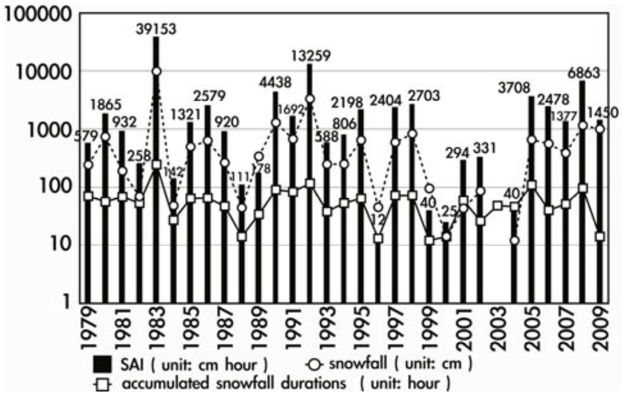

Fig. 2. Same as Fig. 1, but the series of yearly SAI. The annual SAI was derived by summing monthly SAI during winter. The vertical coordinate is a logarithm.

of the annual SAI. Since winter accounts for most of the annual SAI, we therefore focused our analyses solely on the winter composite, except where otherwise mentioned.

Figure 2 displays the time series of yearly SAI during 1979–2009, which describes the degree of interannual variability of snowfall activity. Notably, magnitudes of SAI exhibit marked interannual variation. For active snowfall years such as 1983 (SAI=39 152) and 1992 (SAI=13 259), SAIs ∼100–1000 times larger than those in 1999 (SAI=25), 2000 (SAI=40), 2002 (SAI=331) and 2003 (SAI=0) were calculated. Therefore, the result shown in Fig. 2 suggests a strong climatic effect on Yushan snowfall activity. The climate patterns responsible for such strong interannual variability in Yushan snowfall activity are examined in section 4.

Figure 3 displays the occurrence of snowfall events averaged over winters from 1979 to 2009. To elaborate, snowfall events of various strengths are displayed separately. Climatologically, Yushan most frequently experienced light snowfall with a seasonal frequency in the range of 10–11 days (Fig. 3a). Moderate snowfall was also observed with a seasonal frequency in the range of 4–5 days (Fig. 3b). The frequency of heavy snowfall (Fig. 3c), although relatively rare, was quite pronounced in several years, such as 1983, 1986, 1990, and 2007.

The annual mean occurrence of snowfall events over the period 1979–2008 was ∼24 days (Tsai and Liu, 2009). However, Qi and Chen (1995) reported an annual average of ∼28 days for the period 1961–1990. The decrease of annual mean occurrence of snowfall events in our study period was ∼14.3%. As indicated in Fig. 3, occurrence frequencies of light and moderate snowfall decreased over the study period.

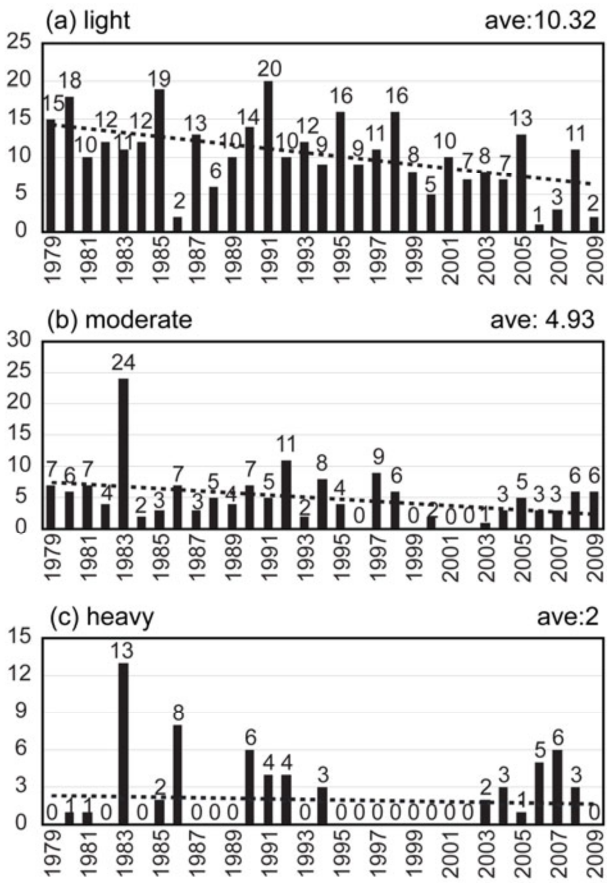

Fig. 3. Yearly occurrence frequencies of (a) light snowfall, (b) moderate snowfall, and (c) heavy snowfall at Yushan. The annual occurrence frequencies derived by summing up monthly snowfall days during winter.

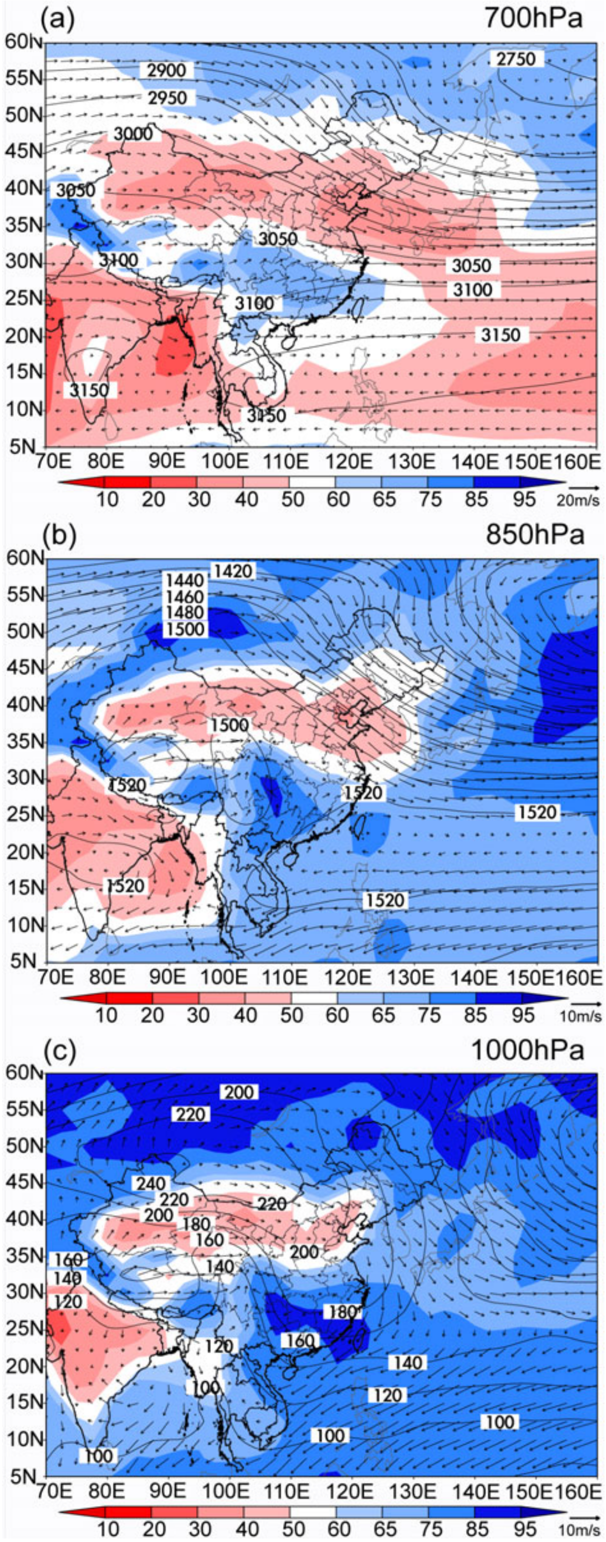

Fig. 4. The 1979–2009 winter circulation patterns in lower troposphere over East Asia at (a) 700 hPa (b) 850 hPa, and (c) 1000 hPa, respectively. The geopotential height (solid), winds (vector), and relative humidity (colors) are displayed simultaneously.

3.2 *Mean atmospheric circulation*

To understand the background synoptic circulation favoring snowfall events, analyses of the mean circulations during winter were conducted. Figure 4 displays the patterns in the lower troposphere at 1000 hPa, 850 hPa, and 700 hPa, respectively. Notably, a large-scale wet zone (RH >75%) was situated over 100°–125°E. At 1000 hPa (Fig. 4c), the wet zone covered an area from southern China to the northern Philippines. In contrast, Mongolia and northern China were both capped by the dry zone (RH <40%). Notably, the appearance of the West Pacific High (WPH) southeast of the Asian continent played an important role in the maintenance of this wet zone. Precisely speaking, the southwesterly flows along the edge of the WPH (Fig. 4b) brought wet and warm air from the South China Sea northeastward to maintain the wet zone.

The East Asia Trough (EAT, whose position was defined as the mean longitude of EAT averaged over 30°–50°N.) is also important for the wet zone. To be precise, the strength of the EAT represents the strength of the EAWM. There is a significant correlation between interannual variations of the EAWM and winter rainfall over southeastern China (Zhou, 2010). Because the strength and position of the WPH and the EAT exhibit substantial fluctuations, the way that their changes and interactions influence snowfall activity was an important focus of this study. This investigation is further discussed in section 4.

4. Inter-comparisons between active years and inactive years

As shown in Fig. 2, 1983, 1990, 1992, 2005, and 2008 were years of greater snowfall activity and 1988, 1996, 1999, 2000, 2003, and 2004 were years of less snowfall activity during the studied period, 1979–2009. To understand how atmospheric circulation influences Yushan snowfall activity, we compared spatial distribution of snowfall events and their associated atmospheric circulations between active years (1983, 1990, 1992, 2005, and 2008) and inactive years (1988, 1996, 1999, 2000, 2003, and 2004), particularly during winter.

4.1 *Snowfall activity*

Figure 5 shows the annual cycle of monthly SAIs for both active years and inactive years. As the figure indicates, snowfall events occurred much more frequently in active years than in inactive years. Major differences in SAI appear in winter (JFM). Differences in SAI in other seasons seem to be relatively small, suggesting a drastic change of atmospheric circulation between active years and inactive years, particularly

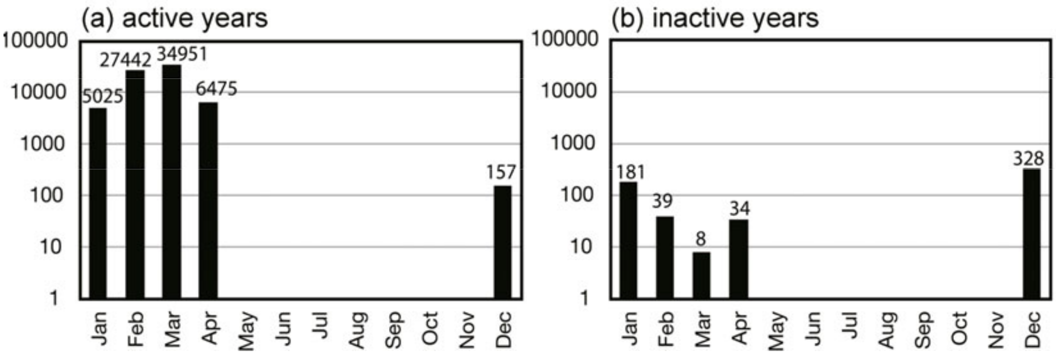

Fig. 5. Annual cycle of monthly SAI for (a) active years and (b) inactivity years. The vertical coordinate is a logarithm.

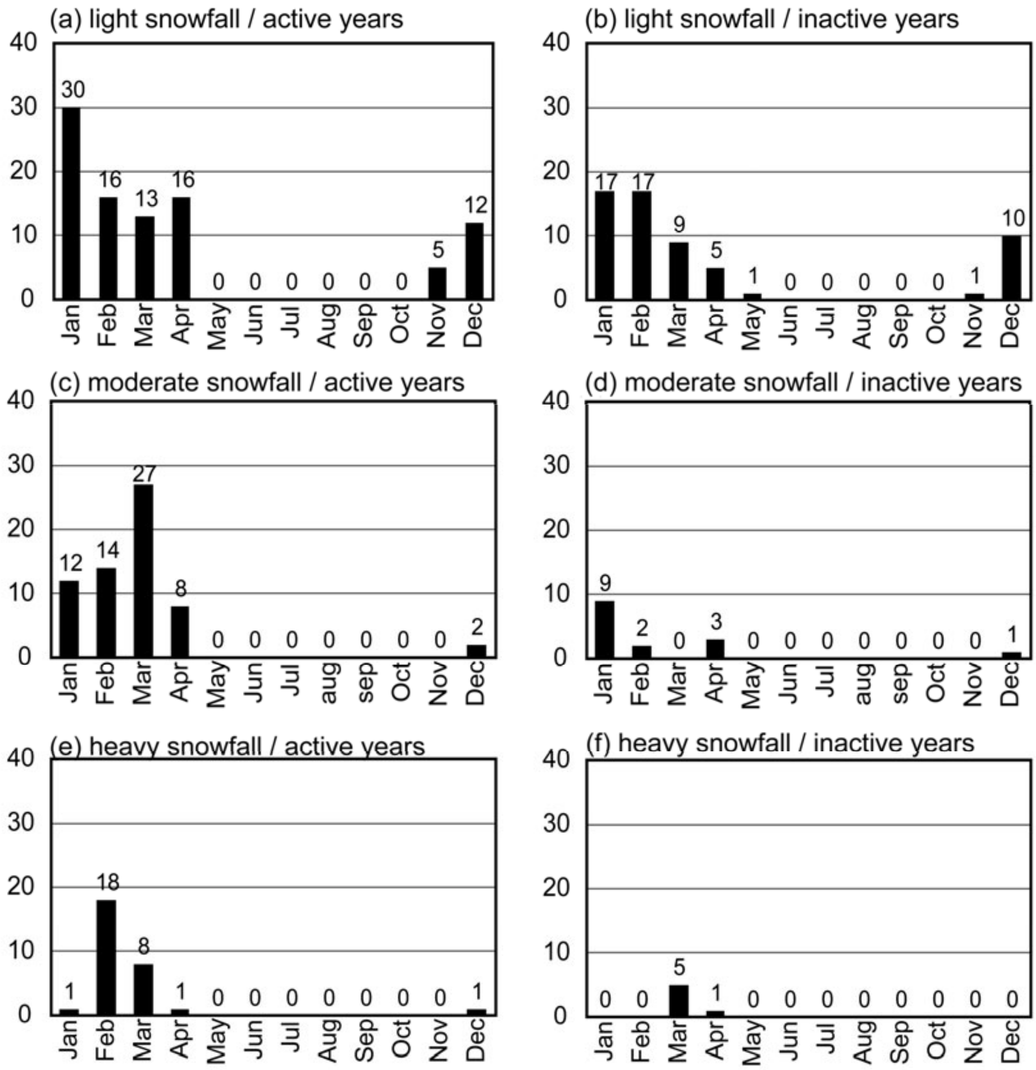

Fig. 6. Snowfall events of various strengths displayed separately, including [(a), (b)] light snowfall, [(c), (d)] moderate snowfall, and [(e), (f)] heavy snowfall. The occurrence frequency is units of days.

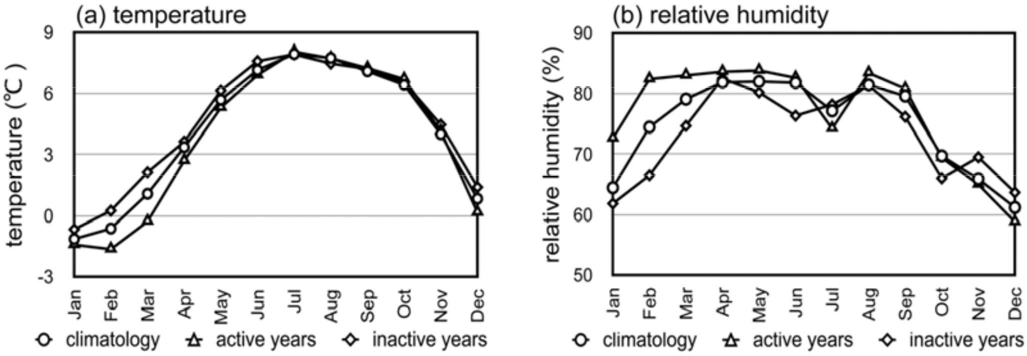

Fig. 7. Annual cycle of (a) monthly temperature and (b) relative humidity.

in the winter.

Figure 6 shows a comparison of the frequency of snowfall events between active years and inactive years. Three strengths of snowfall (light, medium, and heavy) were observed. Striking differences became evident when the plots from active years (Figs. 6a, c, e) were compared to plots from inactive years (Fig. 6b, d, f). During the winters of active years, the frequency of snowfall events was 36–37 days. Snowfall frequency during inactive years was lower than in active years; it decreased to 13–14 days.

Temperature and relative humidity (RH) are the major components for structuring snowfall; Fig. 7 thus shows the comparison of the temperature and RH between active years and inactive years. Average temperature (−1.11°C) during the winters of active years (Fig. 7a) was relatively cold. Average RH (80%) during the winters of active years (Fig. 7b) was relatively wet. During inactive years, the average temperature was 0.57°C and the average RH was 67%. These results are consistent with the frequent occurrence of snowfall events, in which cold and conditions create favorable snowfall conditions.

4.2 *Atmospheric circulation*

A comparison of the synoptic circulation patterns in the lower troposphere between active years and inactive years can be seen in Fig. 8. To enhance their differences, the anomalous fields (without climatology) are displayed rather than the total fields. During the winters of active years (Figs. 8a, c, and e), anomalous anticyclones occurred over the western North Pacific. This anticyclonic pattern introduced anomalous southwesterly flows along the southeastern coast of China and over Taiwan. Zhou (2010) pointed out that these anomalous winds actually enhanced the moisture supply to southeastern China. When superimposed on the mean circulation (Fig. 4), the prevailing northwesterly flows over southern Mongolia and northern China were immediately weakened and the southwesterly flows were stronger, resulting in a wetter-than-normal atmosphere and an extremely active snowfall season. During the winters of inactive years (Figs. 8b, d, and e), the anomaly pattern changed in sign, exhibiting a low intensity anomaly in northeastern China extending to an anomalous cyclone over the Philippines (Figs. 8d, and e). In association with northern low intensity anomalous cyclone, the prevailing northwesterly flows over southern Mongolia and northern China were directly enhanced, resulting in a drier-than-normal atmosphere and a sluggish snowfall season.

The EAWM is characterized by an upper-level jet stream and the EAT (Chen et al., 2000; Jhun and Lee, 2004). In a developed baroclinic system, the upper-level flows link to surface synoptic-scale patterns closely. In Fig. 9, circulation patterns at 500 hPa during active years and inactive years are presented. The 500-hPa level was selected because it contains an excellent mix of small-scale and large-scale systems that illustrate the linkage of the upper-level flows to surface synoptic systems. During the winters of active years (Fig. 9a), the position of the EAT was ∼141°E. Westerly flows (i.e., jet streams) developed near the EAT between 27.5°N and 37.5°N, and the narrow jet axis was located at ∼32.5°N/150°E. The strong WPH (5880 m) appeared on the Pacific Ocean. On the other hand, during the winters of inactive years (Fig. 9b), the circulation was characterized by the westward shift of the EAT at ∼135°E. The range and strength of the jet axis were larger and stronger compared to those of active years. This change introduced strong northwesterly flows over mainland China and Taiwan to enhance the dry zone (Figs. 8b, d, and f).

As discussed previously, the Yushan snowfall activity, the EAT, and the WPH are closely related. To assess their relation quantitatively, yearly SAI values, strength of WPH, and the position of the EAT during 1979–2009 were compared. Also, to understand whether the strength of the EAT was important, the

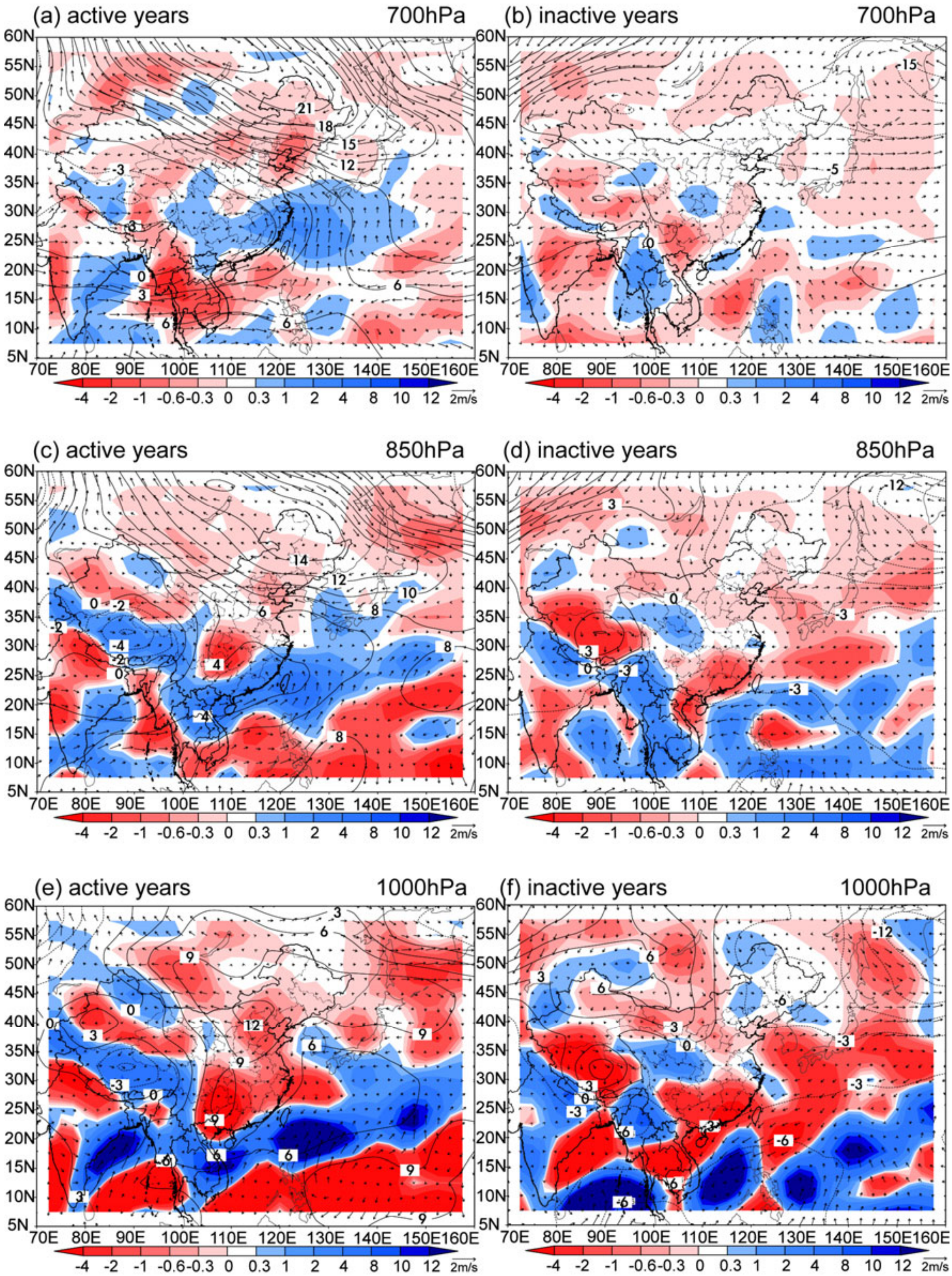

Fig. 8. Same as in Fig. 4, but for the anomalous circulation patterns for active years (a, c, e) and inactive years (b, d, f). The geopotential height (solid), winds (vector), and water vapor convergence (colors) are display simultaneously.

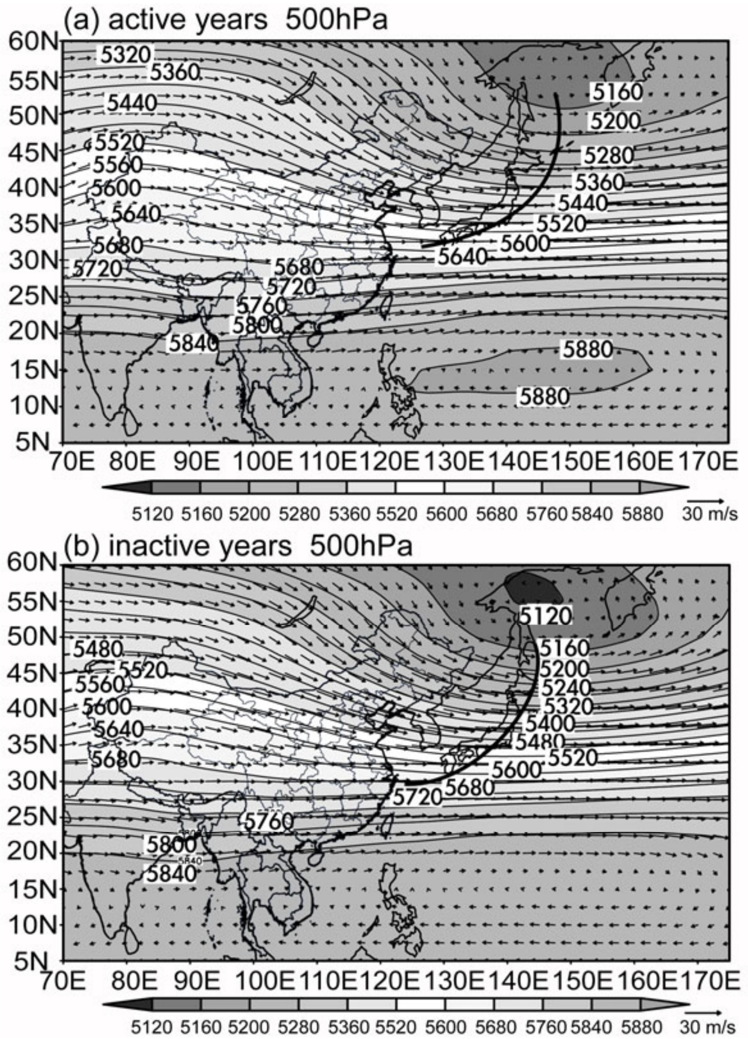

Fig. 9. General circulation patterns evaluated at 500 hPa during the winter of (a) active years and (b) inactive years. The East Asian Trough is denoted by a thick line.

strength of low-level wind, yearly values of EAT strength, and low-level wind (850 hPa and 700 hPa) strength were also compared. The strength of WPH was defined as the mean between 10°–20°N and 110°–130°E. The strength of low-level wind was defined as the averaged over the region between 15°–25°N and 100°–120°E. The correlation coefficients between the SAI and various indices are summarized in Table 1. As show in Table 1, the relation between Yushan snowfall activity and the position of EAT was noteworthy, with a correlation coefficient of 0.64 (satisfying the p-test at the 95% confidence level). On the contrary, the strength of the EAT appears to have been relatively weak, with a correlation coefficient of 0.11. Table 1 also shows that the position of the EAT had significant correlations with various indices.

5. Summary and conclusions

In this study, CWB Yushan weather station observations were used to examine Yushan snowfall activity during the period 1979–2009. A snowfall activity index (SAI) provided a measure of the seasonal snowfall activity, i.e., a summation of the durations of all snowfall events occurring in Yushan in each year. To portray the circulation changes associated with interannual variations of snowfall activity, the NCEP/DOE atmospheric data were analyzed.

The observation data showed that winter (JFM) was the most active season for all snowfall events oc-

Table 1. Correlation coefficients between the SAI and various indices. The EAT position was defined as the mean longitude of EAT averaged over 30°–50°N, while the strength of EAT was referred to as the mean geopotential height averaged over 30°–50°N/130°–150°E, both evaluated at 500 hPa. The strength of WPH was defined as the mean between 10°–20°N and 110°–130°E. The strength of low-level wind was defined as the averaged over the region between 15°–25°N and 100°–120°E.

	SAI	Position of EAT (500 hPa)	Strength of EAT (500 hPa)	Strength of WPH (700 hPa)	Strength of WPH (850 hPa)	VWND (850 hPa)	VWND (700 hPa)
SAI	1.00						
Position of EAT (500 hPa)	0.64*	1.00					
Strength of EAT (500 hPa)	0.11	0.41	1.00				
Strength of WPH (700 hPa)	0.42*	0.49*	0.28	1.00			
Strength of WPH (850 hPa)	0.45*	0.51*	0.27	0.92*	1.00		
VWND (850 hPa)	0.26	0.44*	0.23	0.67*	0.61*	1.00	
VWND (700 hPa)	0.50*	0.51*	0.28	0.37	0.28	0.66*	1.00

*Significant at 5% level.

curring in Taiwan, accounting for 93% of the annual SAI. However, Taiwan is located in the southern periphery of the subtropical zone; its steep terrain and monsoonal-type circulation as well as their interaction result in various climatic characteristics, especially snowfall phenomena like those which usually occur during winter in temperate zones.

During the winter, the cold surge from northern China and the southwesterly flow from the northern South China Sea provides a favorable environment for snowfall occurrences on Yushan. The background atmospheric circulation indicates that the East Asian Trough (EAT) and the West Pacific High (WPH) may play important roles in the maintenance of the moisture supply. Specifically, high-pressure systems of Siberia and Mongolia created the northwesterly flows that carried cold air behind the EAT, and the wet zone was maintained by the WPH, creating favorable conditions for snowfall.

Yushan snowfall activity manifested substantial interannual variations during 1979–2009. A comparison between atmospheric circulation during active years (1983, 1990, 1992, 2005, and 2008) and inactive years (1988, 1996, 1999, 2000, 2003, and 2004) shows that the position of the EAT and strength of the WPH may explain such variations by introducing an anomalous pressure dipole over Asia. In active years, when the EAT shifted eastward and the strength of WPH increased, and an anticyclonic anomalies occurred. These anticyclones introduced anomalous southwesterly flows along the southeastern coast of China and over Taiwan, resulting in a wetter-than-normal atmosphere that favored snowfall activity. Alternatively, during inactive years, when the EAT shifted westward and the strength of WPH decreased, the northern weak anomalous cyclone, whose prevailing northwesterly flows were directly enhanced, resulted in a drier-than-normal atmosphere and sluggish snowfall seasons.

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