Observed Relationship of Spring and Summer East Asian Rainfall with Winter and Spring Eurasian Snow

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ABSTRACT

This study investigates the relationship between spring and summer rainfall in East Asia and the preceding winter and spring snow cover/depth over Eurasia, using station rainfall observations, satellite-observed snow cover, satellite-derived snow water equivalent, and station observations of the number of days of snow cover and snow depth. Correlation analysis shows that snow-depth anomalies can persist from winter to spring whereas snow cover anomalies cannot in most regions of Eurasia. Locally, snow cover and snow-depth anomalies in February are not related in most regions to the north of 50°N, but those anomalies in April display consistent year-to-year variations. The results suggest that the winter snow cover cannot properly represent all the effects of snow and it is necessary to separate the winter and spring snow cover in addressing the snow–monsoon relationship.

Spring snow cover in western Siberia is positively correlated with spring rainfall in southern China. The circulation anomalies associated with the western Siberian spring snow cover variations show an apparent wave pattern over the eastern Atlantic through Europe and midlatitude Asia. Spring snow cover over the Tibetan Plateau shows a moderate positive correlation with spring rainfall in southern China. Analysis shows that this correlation includes El Niño–Southern Oscillation (ENSO) effects. In contrast to the Indian summer monsoon rainfall for which the ENSO interferes with the snow effects, the Tibetan Plateau snow cover and ENSO work cooperatively to enhance spring rainfall anomalies in southern China. In comparison, ENSO has larger impacts than the snow on spring rainfall in southern China.

1. Introduction

Year-to-year variations of the Asian summer monsoon have important societal and economic impacts for Asian countries. The interannual variability of monsoon is affected by anomalous states of lower boundary conditions, including sea surface temperature (SST), snow cover/mass, and soil moisture (Charney and Shukla 1981). As an important component in the climate system, snow cover/mass influences the thermal characteristics of the land surface and lower troposphere through modulating radiation, moisture, and energy budget (e.g., Namias 1985; Walsh et al. 1985; Cohen and Rind 1991; Karl et al. 1993; Groisman et al. 1993).

There are numerous empirical studies on the impacts of winter–spring snow cover/mass over Eurasia and the Himalayas on the Indian summer monsoon (Blanford 1884; Walker 1910; Hahn and Shukla 1976; Dey and Bhanu Kumar 1983; Dickson 1984; Khandekar 1991; Parthasarathy and Yang 1995; Yang 1996; Sankar-Rao et al. 1996; Matsuyama and Masuda 1998; Kripalani et al. 1996, 2003; Bamzai and Shukla 1999; Kripalani and Kulkarni 1999; Robock et al. 2003; Fasullo 2004; Dash et al. 2005; Singh and Oh 2005). Numerical modeling with different atmospheric general circulation models (AGCMs) has been performed to understand the influence of anomalous snow cover/mass on the Indian summer monsoon (Barnett et al. 1989; Yasunari et al. 1991;
Previous studies indicate that the snow–Indian summer monsoon relationship is influenced by El Niño–Southern Oscillation (ENSO). The snow–monsoon correlation is found to diminish during ENSO years (Sankar-Rao et al. 1996; Yang 1996; Matsuyama and Masuda 1998; Fasullo 2004). There is one view that the snow–Indian summer monsoon correlation is a product of ENSO forcing (Corti et al. 2000). However, there may be snow effects independent of ENSO (Ferranti and Molteni 1999; Corti et al. 2000).

There are relatively fewer studies on the influence of snow on the East Asian monsoon compared to the Indian monsoon. Zhao (1984) found an inverse relationship between Eurasian snow cover and the northern Chinese monsoon for the period 1971–80. Yang and Xu (1994) found that the Eurasian winter snow cover during 1972–88 is positively correlated with the following summer rainfall in northern and southern China and negatively in central, northeast, and western China. Kripalani et al. (2002) revealed that the winter–spring snow depth over the western Eurasia is negatively related, whereas the snow depth over the eastern Eurasia is positively related, with the Korean summer monsoon rainfall. Although the Tibetan Plateau snow can be considered as a subset of the Eurasian snow mass, both its variability and persistence show distinct features (e.g., Fasullo 2004) and previous studies discuss the effects of the Tibetan Plateau snow separately. The relationship between the Tibetan Plateau snow cover/depth and the East Asian monsoon rainfall has been studied using different datasets (Chen and Yan 1979, 1981; Guo and Wang 1986; Zhang 1986; Chen 1991; Wei and Luo 1994; Xu et al. 1994; Chen and Wu 2000; Wu and Qian 2000, 2003; Zhang et al. 2004). Chen and Yan (1979, 1981) found that excessive snow cover over the Tibetan Plateau in boreal winter–spring is accompanied by above-normal May–June rainfall in southern China. Chen and Wu (2000) found that boreal summer rainfall in central China along the mid- and low reaches of the Yangtze River has a positive correlation, whereas that in northern and southern China has a negative correlation, with the Tibetan Plateau snow depth in the previous winter–spring. A similar relationship was pointed out by Wu and Qian (2003). Such a relationship also appears in interdecadal changes (Chen and Wu 2000; Zhang et al. 2004).

A few previous studies use the snow cover averaged over a large area of Eurasia as an index to address the relationship between Eurasian snow cover and East Asian summer rainfall (e.g., Yang and Xu 1994). Because the snow anomalies are often opposite over western and eastern Eurasia (Kripalani and Kulkarni 1999; Fasullo 2004; Dash et al. 2005), it is not proper to use the whole Eurasian snow as an index. It is unknown which region of snow is most likely related to the East Asian monsoon rainfall. In this study, we survey the regions where the snow cover/depth anomalies may have a significant relationship with the East Asian summer monsoon rainfall.

Anomalous snow affects the thermal state of the land surface and the overlying air through the snow-albedo and snow-hydrological effects (e.g., Barnett et al. 1989). The excessive snow cover/mass decreases the surface temperature by reflecting more solar radiation. In snow-covered regions, more solar radiation is used to melt snow and the wetter land surface leads to more surface latent heat flux. The resulted change in the surface air temperature modulates the atmospheric circulation both locally and remotely. The impact of the Tibetan Plateau snow on the East Asian monsoon circulation has been indicated in previous studies (e.g., Kripalani et al. 2002; Wu and Qian 2003; Zhang et al. 2004). However, the specific processes for the influence of anomalous snow on the East Asian summer rainfall are not yet clear. In this study, we examine the circulation changes associated with anomalous snow cover to understand the snow–East Asian monsoon connection.

ENSO interference with the snow–monsoon relationship could also be present for the East Asian monsoon. There are three suggested possibilities: 1) snow and monsoon variability are both induced by ENSO forcing and the snow–monsoon relationship is a product of ENSO influence, 2) snow effects are independent of ENSO, and 3) there are snow anomalies both dependent on and independent of ENSO. These possibilities will be investigated in this study. In particular, we will
analyze whether the snow–East Asian monsoon rainfall relationship is affected by ENSO.

Overall, this study will address the following questions: What are the regions where the snow cover/depth variations have significant correlation with the East Asian rainfall anomalies? What are the circulation anomalies associated with anomalous snow cover/depth in these regions? How is the snow–East Asian rainfall relationship interfered by ENSO? To address above questions, we use both satellite snow cover and snow water equivalent (SWE) data and station observations for the number of days of snow cover and snow depth. Note that snow cover has limitations especially in winter because the snow-hydrological effect cannot be estimated properly based on the snow cover. In spring, however, as will be demonstrated later, snow cover and snow-depth anomalies are quite consistent. Because the snow–monsoon relationship may depend on the season, we consider both the winter and spring snow cover/depth anomalies. The persistence of snow cover/depth anomalies will also be examined.

Our analyses reveal that spring rainfall variability in southern China is significantly related to spring snow cover anomalies over the western Siberia, and that the previously identified positive correlation between the Tibetan Plateau spring snow cover/depth and southern China spring rainfall includes ENSO effects. It is found that the Tibetan Plateau snow and ENSO work cooperatively to induce spring rainfall anomalies in southern China, which is distinct from the Indian summer rainfall in which ENSO interferes with the snow effects. The organization of the rest of the text is as follows. In section 2, we describe the datasets used in this study. In section 3, we examine the mean and variability of snow cover/depth, and the persistence of the snow cover/depth anomalies. Section 4 focuses on the snow–rainfall relationship. In section 5, we examine circulation anomalies associated with anomalous snow cover. Section 6 discusses the impacts of ENSO on the snow–rainfall relationship. Summary and discussions are provided in section 7.

2. Datasets

a. Station rainfall data

We use monthly station rainfall data at 160 stations in mainland China, 33 stations in Japan, 9 stations in South Korea, and 4 stations in Taiwan. The Chinese station data are provided by the Chinese Meteorological Data Center. Station data in Japan and South Korea are derived from the version-2 Global Historical Climate Network (GHCN) of the National Oceanic and Atmospheric Administration/National Climate Data Center (NOAA/NCDC). This dataset has been subjected to quality control checks (Vose et al. 1992). Rainfall data for four stations in Taiwan are provided by M.-M. Lu, Central Weather Bureau of Taiwan. We restrict our analysis of rainfall to the region of 20°–50°N, 95°–145°E with 189 stations in total. Our analysis is made for the period of 1951–2000 and only for the spring [March–May (MAM)] and summer [June–August (JJA)] rainfall. These station rainfall data have been used in several previous studies (Wu and Wang 2002; Wu 2002; Wu et al. 2003). Note that September is usually not included in summer rainfall for East Asia and the use of June–September (JJAS) instead of JJA will not affect the analysis.

b. Northern Hemisphere EASE-Grid Weekly Snow Cover and Sea Ice Extent version 3


These snow cover and sea ice measurements are derived from satellite observations. Snow-cover extent is based on the digital NOAA/National Environmental Satellite, Data, and Information Service (NESDIS) weekly Northern Hemisphere snow charts, revised and regridded to the EASE-Grid. The original NOAA/NESDIS weekly snow charts are derived from the manual interpolation of Advanced Very High Resolution Radiometer (AVHRR), Geostationary Operational Environmental Satellite (GOES), and other visible-band satellite data. (More information about the data processing and quality control procedures is available online at http://nsidc.org/data/nsidc-0046.html.)

The Northern Hemisphere EASE-Grid Weekly Snow Cover and Sea Ice Extent version 3 data are obtained from the National Snow and Ice Data Center (NSIDC) from their Web site (online at ftp://sidads.colorado.edu/pub/DATASETS/snow_and_sea_ice). There are some gaps in the snow cover data: 4 weeks spanning 1–28 July 1968, 21 weeks spanning 2 June–26 October 1969, and 12 weeks spanning 5 July–26 September 1971. The present analysis only uses the snow cover for the period from 1979 onward. These snow-cover data are first converted to regular 1° × 1° grids for the purpose of our analyses. This is done simply by setting the value at a regular grid to that at the nearest EASE grid. Then, the snow cover percentiles are con-
structured for winter [November–February (NDJF)] and spring (MAM). November is grouped with DJF because the snow has a high percentage coverage in November.

The Climate Diagnostics Center (CDC) derives monthly percent of snow coverage from the weekly EASE-Grid snow cover (Robinson et al. 1993). These monthly mean snow cover percentage data are on 1° × 1° grids for the period of January 1971–December 1995. These data are provided by the NOAA–Cooperative Institute for Research in Environmental Sciences (CIRES) CDC, Boulder, Colorado (available online at http://www.cdc.noaa.gov/, or by anonymous ftp at ftp.cdc.noaa.gov/Datasets/snowcover). We use these CDC-derived monthly snow cover percentage data mainly for the purpose of confirming our derivation of seasonal mean snow coverage based on the weekly snow cover. Comparison demonstrates that the results are quite consistent.

c. Satellite-derived monthly EASE-Grid snow water equivalent

This dataset comprises monthly satellite-derived SWE climatologies spanning November 1978–March 2005 (Armstrong et al. 2005). The data are gridded to the Northern and Southern Hemisphere 25-km EASE-Grids (available online at ftp://sidads.colorado.edu/pub/DATASETS/snow). The SWE is derived from the Scanning Multichannel Microwave Radiometer (SMMR) and selected SSM/I (More information about this dataset is available online at http://nsidc.org/data/nsidc-0271.html.) We convert the SWE to regular 1° × 1° grids using the same way as the weekly snow cover data. These data include the percentage frequency of visible snow derived from weekly data for those pixels with no microwave-derived SWE, which are indicated by negative values between −100 and −1. These frequency observations are excluded in the present analysis.

d. The former Soviet Union hydrological snow surveys, 1966–96

The former Soviet Union hydrological snow surveys are based on observations made by personnel at 1345 sites throughout the former Soviet Union between 1966 and 1990, and at 303 of those sites between 1991 and 1996 (Krenke 2003). There are three types of data in this dataset which are synoptic, station, and transect. In this study, we use the station data from the meteorological station itself, which are monthly station summaries rather than daily measurements. These data include the number of days of snow cover within the month and the mean snow depth at the station for the first 10 days, the second 10 days, and the final days of the month. NSIDC has implemented a quality control process to identify errors and correct the data where possible. (Details of the data processing and quality control are available online at http://nsidc.org/data/g01170.html. These station snow data are obtained from the NSIDC online at ftp://sidads.colorado.edu/pub/DATASETS/NOAA/G01170/.) The present study only uses the data for the period 1966–90, which has more available station observations.

e. NCEP–DOE reanalysis version 2

The National Centers for Environmental Prediction–Department of Energy (NCEP–DOE) reanalysis version 2 (Kanamitsu et al. 2002) outputs are provided by NOAA–CIRES CDC (available online at http://www.cdc.noaa.gov/). The reanalysis variables are available starting from January 1979. We use monthly mean winds and geopotential height at 200 hPa on regular 2.5° × 2.5° grids, and surface (10 m) winds, surface pressure, and surface skin temperature on the T62 Gaussian grid with a horizontal resolution of about 1.9° × 1.9°.

3. Mean, variability, and persistence

In this section, we discuss the mean and standard deviation of seasonal mean snow cover/depth, the persistence of snow cover/depth anomalies, and the relationship between snow cover and snow-depth anomalies.

a. Mean and variability

Figure 1 shows mean and standard deviation of snow-cover percentage in NDJF and MAM. High snow coverage is seen in high latitudes and mountainous regions. In NDJF, the region with high snow coverage over 90% extends southward to 50°N (Fig. 1a). In MAM, high snow cover region shrinks northward and the 90% coverage is only seen north of 60°N (Fig. 1b). High standard deviations are seen in regions where the mean snow coverage has a large gradient and from there the variability decreases poleward (Figs. 1c,d). The variability is large in mountainous regions. The largest standard deviation is seen over the Tibetan Plateau. In NDJF, the variability is small north of 65°N (Fig. 1c) where snow cover persists almost through the whole winter. In MAM, the variability increases significantly between 55° and 65°N (Fig. 1d) with the northward retreat of zones of large gradient of mean snow cover. Large variability is seen in a broad region surrounding the Lake of Baikal where there is a large gradient in the
The number of days of snow cover from station observations displays similar features (not shown) as the snow cover percentage.

Similarly, Fig. 2 shows mean and standard deviation for seasonal mean SWE. The mean SWE is large in high latitudes and decreases equatorward both in NDJF and MAM (Figs. 2a,b). The variability is high in regions of large mean and higher at high latitudes than in the subtropics (Figs. 2c,d). This feature is distinct from the snow cover. Relatively high variability is also seen over the Tibetan Plateau. The mean and variability of snow depth from station observations show features (not shown) similar to those of the SWE.

b. Persistence of snow cover/-depth anomalies

Large snow cover/-depth anomalies have been observed in both winter and spring. A question is whether winter and spring snow anomalies have similar features, or, in other words, whether snow anomalies can persist from winter to spring. The answer to this question depends on the snow variable examined and the region, as noted in previous studies. For example, the correlation pattern of the snow depth with the Indian summer monsoon rainfall shows persistence from November to April (Kripalani and Kulkarni 1999). Composite snow-depth anomalies based on Indian summer rainfall display similar patterns in DJF and MAM (Dash et al. 2005). Fasullo (2004) calculated the correlation of snow cover averaged in different regions between winter and spring. Their lag correlation shows that the persistence of snow cover anomalies is small except for the region of 20°–40°N, 80°–120°E. As the snow cover anomalies display certain spatial pattern, averages over large areas may smear out regional features.

Here, we examine the persistence of snow cover/-depth anomalies for each grid or station. The lag correlation between winter and spring anomalies is used to measure the persistence, following previous studies (e.g.,
Fasullo 2004). This is done for the snow cover percentage, SWE, number of days of snow cover, and snow depth as they may have different persistence. The results are shown in Fig. 3.

For snow cover percentage, the persistence is small [correlation coefficient (cc) < 0.4] in mid- and high latitudes (Fig. 3a). Moderate persistence (0.4 < cc < 0.6) is seen in the Tibetan Plateau region, consistent with Fasullo (2004). Some persistence is also seen over southern Europe, Scandinavia, and Mongolia–northeast China. Overall, snow-cover anomalies differ in winter and spring. This is consistent with previous studies. For example, composite snow cover anomalies have different distributions in winter and spring (Bamzai and Shukla 1999; Robock et al. 2003; Fasullo 2004). As such, it is necessary to separate winter and spring snow cover in addressing the snow–monsoon relationship. The lag correlation for the number of days of snow cover (Fig. 3c) is somewhat larger than that for the snow cover percentage, but is still not high. Moderate persistence is seen around the Aral Sea and northwest to the Black Sea.

Distinct from snow cover, the SWE and snow-depth anomalies have a high persistence (cc > 0.6) from winter to spring (Figs. 3b,d) in large regions. High persistence is also seen over the Tibetan Plateau for SWE (Fig. 3b). Because of this, winter and spring snow-depth anomalies tend to have similar features, as do the correlations of winter and spring snow depth with the summer rainfall (Kripalani and Kulkarni 1999; Dash et al. 2005). Note, however, that the SWE anomalies have relatively low persistence in the region of western Siberia.

c. Relationship between snow cover and snow depth

Many previous have studies used snow cover to address the influence of anomalous snow on circulation and rainfall. A question is whether snow cover can properly represent the effects of snow. This is linked to the relationship between snow cover and snow mass.

![Fig. 2: Same as in Fig. 1, but for SWE for the period 1979–2004.](image-url)
Here, we examine the local correlation between snow depth and the number of days of snow cover from station observations. The number of days of snow cover is a quantity with characteristics similar to the snow cover percentage. Thus, this should give some information whether the snow cover is representative of the snow mass.

The correlation between the snow cover and snow depth may depend on the season. Here, we show correlation between the number of days of snow cover and snow depth for two typical months: February and April (Fig. 4). February is the month when the snow depth reaches the largest (Dash et al. 2005) and the snow has the maximum coverage (Sankar-Rao et al. 1996). April is the time when the snow is melting. In April the snow depth and the number of days of snow cover have a relatively high correlation (Fig. 4b). This indicates that during the snow-melting season (spring), the snow cover and snow depth may have similar anomalies and the snow cover may be used to understand the effects of snow. In comparison, the correlation in February is small except for the region south of 50°N (Fig. 4a).

Note that weak correlation is seen in regions that are covered by snow throughout the winter. In such regions, snow cover has little variability and presumably its year-to-year change is not related to that of snow depth. As such, it is not proper to use the snow cover to address the effects of snow in winter, especially in high latitudes.

We have also examined the local correlation between the SWE and the CDC-constructed monthly snow cover (figures not shown). The correlation coefficients display similar seasonal and spatial dependence as in Fig. 4. In addition, the correlation in the Tibetan Plateau region reaches 0.5 in February and 0.7 in April, indicating that snow cover anomalies are more representative of snow-depth anomalies in this region compared to high latitudes.
4. Snow–rainfall relationship

In this section, we first extract dominant modes for MAM and JJA rainfall variability. Then, we search for regions where the interannual variability in snow has an apparent correlation with the rainfall. Last, we select area-mean snow as reference to correlate with station rainfall for confirmation of the snow–rainfall relation.

a. Modes of rainfall variability

To search for regions where the snow anomalies may have significant correlation with the East Asian monsoon, we start with deriving an index to represent the East Asian monsoon rainfall. Here, we derive such an index using EOF analysis. We only consider the leading EOF mode, which explains the largest fraction of the rainfall variability and represents a robust spatial pattern of rainfall anomalies. In this study, we only consider spring and summer rainfall for the following reasons. In most regions, summer rainfall explains the largest percent of annual total rainfall and has the largest interannual variability (Wu et al. 2003). In southern China and east of 110°E, the percent of rainfall falling in spring is close to that in summer and the observed variability is nearly the same as that in summer. Previous studies have found some relationship between spring and summer rainfall in China with previous winter–spring snow, especially over the Tibetan Plateau (Chen and Yan 1979, 1981; Chen and Wu 2000; Wu and Qian 2003).

We perform EOF analysis for MAM and JJA station rainfall in the East Asian region (20°–50°N, 95°–145°E). The leading EOF modes obtained are shown for MAM and JJA in Figs. 5a,b, respectively. The percentage variance explained by the leading mode is 22% for MAM and 15% for JJA, respectively. The leading mode is well separated from the rest modes according to the criteria of North et al. (1982).

MAM rainfall EOF1 shows dominant rainfall in southern China (Fig. 5a). This mode is used to represent rainfall variability in southern China in the present study. The time coefficient of this mode is shown in Fig. 5c. For comparison, we also include area-mean MAM rainfall for the region of 23°–28°N, 110°–120°E. The temporal evolution in EOF1 and area-mean rainfall is quite coherent, with a correlation coefficient of 0.94 for the period 1951–2000.

JJA rainfall EOF1 shows positive rainfall in central China–Japan, and negative rainfall in the southeast coast of China and in northern China (Fig. 5b). This mode is used to represent rainfall variability in the Yangtze River region in this study. The time coefficient for this mode is displayed in Fig. 5d, along with area-mean rainfall for the region of 28°–32°N, 105°–120°E. The temporal evolution in EOF1 and the above area-mean rainfall is quite consistent with a correlation coefficient of 0.78 for the period 1951–2000.

b. Correlation of snow cover/depth variations with rainfall modes

To find regions of snow cover/depth that have a significant relationship to rainfall variability, we correlate the EOF1 of rainfall variability with gridpoint snow cover and SWE, station snow depth, and the number of days of snow cover. Note that the presence of a correlation may or may not be indicative of a causal relationship. It is possible that a significant correlation appears between snow and rainfall because they are both related to an external forcing (e.g., ENSO), but not to each other.

Figure 6 shows the correlation of snow cover percentage in NDJF and MAM with the MAM or JJA rainfall EOF1 for the period 1979–2000. A correlation coefficient of 0.36, 0.42, and 0.54 reaches the 90%, 95%, and 99% confidence level, respectively, assuming 20 degrees of freedom for the 22-yr period. There are a few regions where the correlation is significant. For MAM rainfall, the MAM snow cover shows a significant positive correlation in western Siberia (Fig. 6b). Moderate correlation is seen over the Tibetan Plateau in MAM. The NDJF snow cover shows moderate nega-
tive correlation in southern Siberia and northeast China (Fig. 6a). For JJA rainfall, the snow cover in southwest Russia shows moderate negative correlation in MAM (Fig. 6d) and positive correlation in NDJF (Fig. 6c). Note that the correlation is generally weak in the East Asian monsoon region where the mean and variability of snow cover is small, suggesting that local snow anomalies do not have prominent effects on the East Asian monsoon.

The correlation distribution in NDJF and MAM is not similar. This is because of the weak persistence of snow cover anomalies from winter to spring as discussed in the previous section. In some regions, opposite correlation is seen in MAM and NDJF. As such, analysis using NDJF and MAM may lead to different results and it is necessary to separate winter and spring snow cover in diagnosing the monsoon–snow relationship.

For JJA rainfall, its correlation with the MAM snow cover is generally weak. Though some moderate correlation is seen between JJA rainfall and NDJF snow cover, it is hard to justify whether there is a physical connection between them. For these reasons, no further discussions will be presented for JJA rainfall and we will focus on MAM rainfall in the following analysis.

Figure 7 is similar to Figs. 6a,b except for the number of days of snow cover from station observations for the period 1966–90. For MAM rainfall, compared to the
correlation with the snow cover (Fig. 6b), the positive correlation in western Siberia in MAM shifts southeastward and the negative correlation appears over northern Europe (Fig. 7b). In NDJF, the correlation shows differences from that of snow cover. The correlation is generally weak except for central Europe where moderate negative correlation is seen (Fig. 7a).

The correlation with the number of days of snow cover is calculated for a period (1966–90) different from that of the snow cover (1979–2000). To see whether the correlation difference seen above is due to changes in the record, we calculate the above correlations for a same period 1979–90. The correlation patterns are basically the same. In conclusion, the discrepancies seen in the correlation of snow cover and the number of days of snow cover may be due to the differences in the nature of the datasets themselves (satellite versus station data) and/or in the quality of the data.

Figure 8 shows similar correlation maps for snow depth from station observations. In MAM, a distribution of correlation similar to that of the number of days of snow cover is seen. In comparison, the negative correlation over northern Europe is weaker (Fig. 8b versus 7b). The distribution of correlation in NDJF (Fig. 8a) resembles that in MAM (Fig. 8b), presumably due to the persistence of snow-depth anomalies. Compared to the correlation with the number of days (Fig. 7a), the positive correlation over western Siberia is much larger.

We have also examined the correlation for the SWE (figures not shown). The correlation distribution for the MAM SWE looks similar to that for the MAM snow cover. In particular, significant positive correlation with respect to the MAM rainfall EOF1 appears in western Siberia and the Tibetan Plateau. The correlation distribution for the NDJF SWE displays noticeable differences from that of the NDJF snow cover.
In summary, there are three features worthy of noting. First, the correlation distribution in MAM displays similarity whereas that in NDJF displays large discrepancies for different snow variables. Second, the correlation in NDJF and MAM shows resemblance for station snow depth, but not for the other variables. Third, the spring rainfall in southern China shows consistent correlation in western Siberia and the Tibetan Plateau with different snow variables in MAM.

c. Correlation of station rainfall variations with area-mean snow covers

To confirm the snow–rainfall correlations identified in section 4b, we take area-mean snow cover and correlate it with station rainfall. For MAM rainfall, we select two regions for both MAM snow cover. One region is western Siberia (55°–65°N, 60°–90°E) where the positive correlation is quite high. Another region is the Tibetan Plateau (30°–40°N, 80°–100°E) where moderate positive correlation is seen. The latter region is chosen for comparison with previous studies on the relationship between the Tibetan Plateau snow cover/depth and China’s rainfall, as reviewed in the introduction. The above two regions are highlighted in Fig. 6. The results for the MAM rainfall are shown in Fig. 9. We also calculate correlation coefficients between area-mean snow cover and area-mean rainfall or the rainfall EOF1. The correlation coefficients are listed in Table 1.

The MAM snow cover over 55°–65°N, 60°–90°E displays a positive correlation with MAM rainfall in southern China (Fig. 9a). This confirms the correlation analysis with the MAM rainfall EOF1 as an index. Positive correlation is also seen in central China. Some negative correlation appears in northeast China. The correlation
coefficient between the above area-mean snow cover and the area-mean MAM rainfall in southern China (or the MAM rainfall EOF1) is 0.47 and 0.56, respectively (Table 1).

The MAM snow cover in the Tibetan Plateau region shows positive correlation with the MAM rainfall in southern China (Chen and Yan 1979, 1981; Chen and Wu 2000). The region of significant correlation, however, is small. Positive correlation is also seen in eastern Japan and north-northeast China. The correlation with area-mean MAM rainfall in southern China and the MAM rainfall EOF1 is 0.21 and 0.32, respectively (Table 1). Note that the distribution of correlation in Fig. 9b resembles that of ENSO (Fig. 3e of Wu et al. 2003; also see Fig. 12a later in this paper).

Table 1. Correlation coefficients calculated for the period 1979–2000. In the table, snowMAM1 and snowMAM2 refer to MAM snow cover averaged over the region of 55°–65°N, 60°–90°E, and 30°–40°N, 80°–100°E, respectively. RainMAM refers to MAM rainfall averaged over the region of 23°–28°N, 110°–120°E. RainMAM EOF1 refers to MAM rainfall EOF1. Niño-3.4 refers to the region of 5°S–5°N, 170°–120°W. TNI is the Trans-Niño SST index as defined by Trenberth and Stephaniak (2001).

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* Correlation coefficient reaching the 95% confidence level.
** Correlation coefficient reaching the 99% confidence level.

5. Circulation anomalies

To understand how anomalous snow occurs and how it connects with rainfall variability, we analyze circulation anomalies associated with anomalous snow cover. Here, we only consider the connection of MAM snow cover with MAM rainfall. The connection of NDJF and MAM snow cover with JJA rainfall is difficult to explain because of the time lags involved and thus is not discussed. Also, the correlation of NDJF snow cover with the following MAM rainfall may not be physical because winter snow cover cannot properly represent the effects of snow. Note that the identified correlation does not guarantee a cause–effect relationship and further analyses are needed to reveal the physical processes linking anomalous snow cover and rainfall.

Figure 10 shows the simultaneous correlation of MAM 200-hPa winds and height, surface skin temperature, surface pressure, and winds with the MAM snow cover in the region of 55°–65°N, 60°–90°E. It is apparent that high snow cover corresponds to low surface temperature (Fig. 10b). The circulation pattern indicates that snow cover may respond to the circulation anomalies. High snow cover and low surface temperature occur in the region where low-level northerly winds are anomalously strong (Fig. 10c). These northerly winds bring cold air from the high latitudes. The circulation anomalies show a wave pattern upstream with a nearly barotropic vertical structure (Figs. 10a,c), suggesting that some remote forcing may be responsible for the formation of the circulation anomalies. On the other hand, the anomalous low pressure–height center over western Siberia displays a westward tilt.
Fig. 10. Correlation coefficient of (a) 200-hPa height (shading) and winds (vectors), (b) surface skin temperature, and (c) surface pressure (shading) and 10-m winds (vectors) with respect to area-mean MAM snow cover over 55°–65°N, 60°–90°E for the period 1979–2000. The scale for the vectors is indicated at the bottom right of the respective panel. The CI is 0.2 with dashed contours for negative correlation and zero contours suppressed.
with altitude and the negative pressure–height anomalies show an upward intensification (Figs. 10a,c). This feature is consistent with the negative surface temperature anomalies associated with excessive snow cover. The negative surface pressure anomalies extend south–eastward from west of the Lake of Baikal to the sub–tropics and an anomalous trough forms in the subtropics along 100°–110°E (Fig. 10c). Correspondingly, southern China experiences anomalous low–level convergence that contributes to above–normal rainfall (Fig. 9a).

Figure 11 shows the partial correlation (Zar 1998) of different variables with respect to MAM snow cover in the Tibetan Plateau region after removing the effects of ENSO as represented by DJF SST in the Niño–3.4 region (5°S–5°N, 170°–120°W). The partial correlation is calculated using the following formula:

\[
    r_{12,3} = \frac{r_{12} - r_{13}r_{23}}{\sqrt{(1 - r_{13}^2)(1 - r_{23}^2)}},
\]

where \( r_{ij} \) refers to the conventional correlation between \( i \) and \( j \) and indices 1, 2, and 3 represent the specific variable, the MAM snow cover, and the DJF Niño–3.4 SST, respectively. From Fig. 11, high snow cover corresponds to low surface air temperature over the Tibetan Plateau (Fig. 11b). Different from Fig. 10, the correlation between the circulation and snow cover is weaker over the Eurasian continent, whereas significant correlation appears in the Tropics. There are three interesting circulation features to note. First, locally high snow cover and low surface temperature correspond to high surface pressure and upper–level cyclonic winds (Figs. 11a,c). This indicates a baroclinic vertical structure, which is consistent with negative surface temperature anomalies associated with anomalous Tibetan Plateau snow cover. Second, in the Tropics, upper–level heights are anomalously high across the Atlantic through the western Pacific, and a low–level anomalous high develops over the western North Pacific and low–level anomalous easterlies appear over the equatorial western–central Pacific (Figs. 11a,c). Third, there is a band of anomalous low surface pressure and associated low–level convergent winds along 40°N over East Asia (Fig. 11c). Low–level anticyclonic winds are seen over northeastern China, which corresponds to above–normal MAM rainfall (Fig. 9b).

6. ENSO effects

As reviewed in the introduction, ENSO may contribute to or interfere with the snow–monsoon relationship. Indeed, rainfall anomalies associated with anomalous Tibetan snow cover very much resemble those associated with ENSO (e.g., Wu et al. 2003). Thus, there is a question whether the snow–East Asian monsoon rainfall correlation found above is affected by ENSO. For this purpose, in this section, we examine the ENSO–monsoon and ENSO–snow relationship and discuss the snow–monsoon relationship excluding the ENSO impacts.

a. ENSO–rainfall correlation

The impacts of ENSO on the East Asian monsoon have been addressed in previous studies (e.g., Wang et al. 2000; Wu et al. 2003). Here, we reexamine the ENSO–East Asian monsoon relationship by showing the correlation of MAM and JJA rainfall with preceding DJF Niño–3.4 SST. Figure 12a shows the correlation of DJF Niño–3.4 SST with preceding MAM rainfall. Table 1 gives the correlation coefficients between DJF Niño–3.4 SST and area–mean rainfall. We also list in Table 1 the correlation coefficients calculated with respect to the MAM Trans–Niño index (TNI; Trenberth and Stepaniak 2001). The TNI is given by the difference between normalized SST anomalies averaged in the Niño–1 + 2 region (0°–10°S, 90°–80°W) and the Niño–4 region (5°S–5°N, 160°E–150°W).

ENSO has a significant correlation with the MAM rainfall in large parts of China and Japan (Fig. 12a). Compared to the correlation with the western Siberia MAM snow cover (Fig. 9a), the distribution of correlation displays orthogonal features. Compared to the correlation with the Tibetan Plateau MAM snow cover (Fig. 9b), the distribution of correlation is similar, but the correlation coefficient is generally larger. The correlation of DJF Niño–3.4 SST with MAM rainfall in southern China and the MAM rainfall EOF1 is 0.37 and 0.47, respectively (Table 1). The corresponding correlation for the MAM TNI is 0.41 and 0.58, respectively. In comparison, the correlation is higher than that with the Tibetan Plateau snow cover (0.21 and 0.32, respectively).

b. ENSO–snow correlation

Figures 12b,c display the correlation of DJF Niño–3.4 SST with snow cover in NDJF and MAM. The DJF Niño–3.4 SST has no appreciable correlation with the NDJF snow cover except for a few small regions (Fig. 12b). Note that the difference using DJF and NDJF Niño–3.4 SST is small. This is confirmed by using NDJF Niño–3.4 SST to recalculate the correlation (not shown). Also, using the MAM Niño–3.4 SST has little impact since the correlation coefficient between the DJF and MAM Niño–3.4 SST is high (0.88).
FIG. 11. Same as in Fig. 10, but for partial correlation with respect to the area-mean MAM snow cover over 30°–40°N, 80°–100°E after removing the ENSO effects.
ENSO shows a significant positive correlation with the MAM snow cover over the Tibetan Plateau and the region around 65°N, 125°E (Fig. 12c). The correlation coefficient of the DJF Niño-3.4 SST (MAM TNI) with area-mean snow in the Tibetan Plateau region is 0.41 (0.36) (see Table 1). Though this correlation is slightly below the 95% confidence level, we cannot exclude the possibility that the ENSO and Tibetan Plateau snow variations may be connected. This connection may involve both ENSO forcing on snow and impacts of snow on tropical Pacific SST evolution. Previous studies indicate that ENSO forcing can lead to anomalous snow through modulating circulations (e.g., Ferranti and Molteni 1999) or via a stationary wave teleconnection mechanism (Shaman and Tziperman 2005). On the other hand, snow could induce anomalous winds over the equatorial Pacific, which contributes to the ENSO development (Barnett et al. 1989).

One problem is how ENSO impacts the Tibetan Plateau snow cover. We examined the partial correlation of different variables with the DJF Niño-3.4 SST after removing the effects of the Tibetan Plateau MAM snow cover (figures not shown). An anomalous low forms over the Tibetan Plateau. This may indicate the role of ENSO in setting up the large-scale circulation for anomalous snow cover over the Tibetan Plateau. The ENSO signal in the Tibetan surface air temperature, however, is not clear. Because of the persistence of both SST and snow cover anomalies, the ENSO–snow connection may involve both simultaneous and delayed effects. Further research is needed to address this question.

c. Dependence and independence of the Tibetan Plateau snow effects on ENSO

Previous studies indicate the influence of ENSO on the snow–Indian summer monsoon relationship. The snow–Indian monsoon correlation is stronger without ENSO (Yang 1996; Sankar-Rao et al. 1996; Matsuyama...
and Masuda 1998; Fasullo 2004). Some studies conclude that the apparent snow–Indian summer rainfall correlation may be due to the influence of ENSO on both snow and rainfall variations (Corti et al. 2000). According to Table 1, while snow cover anomalies in most of the selected regions show noticeable correlation with East Asian spring and summer rainfall anomalies, these snow cover variations have weak correlation with the DJF Niño-3.4 SST. As such, ENSO does not affect the snow–rainfall relationship for these regions. For the Tibetan Plateau region, however, a positive correlation of 0.41 is present, suggesting that the Tibetan snow cover may be related to ENSO. Since ENSO affects the rainfall, it may be asked whether the snow–rainfall relationship is affected by ENSO and whether the ENSO influence is destructive or constructive. To address these questions, we calculate the partial correlation between the Tibetan Plateau snow cover or ENSO and rainfall with the effect of the other factor excluded. The results are shown in Fig. 13.

After removing the ENSO effects, the distribution of correlation between the Tibetan Plateau MAM snow cover and MAM rainfall keeps a similar pattern (Fig. 13a versus Fig. 9b). The correlation values, however, are reduced. After removing the snow effects, the distribution of correlation between the Niño-3.4 DJF SST and MAM rainfall also maintains the same pattern (Fig. 13b versus Fig. 12a). The correlation values are only slightly reduced. It is apparent that ENSO has a higher correlation with MAM rainfall than the Tibetan Plateau snow.

The partial correlation between the Tibetan Plateau MAM snow cover and the MAM rainfall EOF1 is reduced to 0.16 after removing ENSO effects; the partial correlation between the DJF Niño-3.4 SST and the MAM rainfall EOF1 is reduced to 0.39 after removing the Tibetan Plateau snow effects. The reduction of the correlation is more for the Tibetan Plateau snow cover than for the Niño-3.4 SST. As such, ENSO and Tibetan Plateau snow seem to cooperate in enhancing spring rainfall anomalies in southern China. This differs from the Indian summer rainfall for which the snow–rainfall correlation is higher after removing ENSO years and ENSO interferes with the snow effects. The higher partial correlation with the DJF Niño-3.4 SST indicates that ENSO has a larger impact on southern China spring rainfall than the Tibetan Plateau snow.

7. Summary and discussion

In this study, we use station rainfall observations, satellite-observed snow cover, satellite-derived snow water equivalent, and station observations of the number of days of snow cover and snow depth to investigate the relationship between the spring and summer East Asian rainfall and the previous winter and spring Eurasian snow. Analysis demonstrates that snow-depth anomalies have high persistence from winter to spring, whereas the persistence for snow cover anomalies is low. In high latitudes where there is snow cover almost throughout the winter, snow cover and snow-depth anomalies in winter have no noticeable correlations. In contrast, those anomalies in spring are quite consistent. The results indicate that the winter snow cover may not properly represent the effects of snow for regions where the snow coverage is high. For these regions, it is necessary to distinguish the winter and spring snow cover in diagnosing the snow–monsoon relationship.

The year-to-year changes in spring rainfall in south-
ern China are positively correlated with anomalous spring snow cover over western Siberia. These snow-cover anomalies are associated with an obvious circulation pattern over the eastern Atlantic through Eurasia. Spring snow cover over the Tibetan Plateau displays a moderate positive correlation with spring rainfall in southern China during 1979–2000. This correlation, however, may include ENSO effects. Partial correlation analysis suggests that the Tibetan Plateau spring snow and ENSO work cooperatively for spring rainfall anomalies in southern China. In comparison, ENSO has larger impacts than the Tibetan Plateau snow.

The present study is mainly a correlation analysis and thus the causal relationship cannot be determined. The circulation anomalies shown indicate some signals of snow effects, but the signals are not strong, indicating that snow impacts on the East Asian rainfall are not predominant. Further work is necessary to understand the physical processes linking the snow and rainfall anomalies.

The present study is constrained by the limited length of the available snow data and the statistical relationship identified via the correlation analysis may include stochastic effects (Gershunov et al. 2001). The dependence of the correlation on the snow variables used may indicate this effect. The conclusions of the present study needs to be tested when longer records are available.

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