MJO Modulation on 2009/10 Winter Snowstorms in the United States*

JA-YEON MOON AND BIN WANG

International Pacific Research Center, School of Ocean and Earth Science Technology, University of Hawaii at Manoa, Honolulu, Hawaii

KYUNG-JA HA

Division of Earth Environmental System, Pusan National University, Busan, Korea

(Manuscript received 16 January 2011, in final form 24 June 2011)

ABSTRACT

During the winter of 2009/10, a number of record-breaking snowfall events registered in the eastern United States are shown to have been modulated by the pulsation of tropical MJO through an atmospheric teleconnection pattern. The intraseasonal variability over the eastern subtropical Pacific near Mexico (the equatorial central Pacific) had reached the maximum (second largest) strength since 1979/80. From late December to mid-February, the convection over these two regions experienced a remarkable wet–dry–wet cycle; correspondingly, the daily snowfall over the eastern United States also exhibited a wet–dry–wet cycle. As the MJO convection reached the central Pacific, a teleconnection pattern extended to North America, resulting in a westward-tilted deep anomalous trough anchored over the eastern United States, producing a low-level pressure dipole anomaly with an anticyclone (cyclone) centered at the U.S. West (East) Coast. The convection over the Indian Ocean varied in phase with the central Pacific convection, reinforcing the extratropical atmospheric teleconnection pattern. As a result, the enhanced high-latitude cold air penetrated southward, affecting the central and eastern United States. Meanwhile, warmer moist air was transported from the tropical central Pacific by the existing El Niño through Mexico to the southern United States along with the upper-level subtropical westerly jet, which extended from the subtropical Pacific to the Atlantic Ocean. As such, the eastern United States was located in a convergence zone between the enhanced cold air from the high latitude and the warm, moist air supplied from the subtropics, resulting in favorable conditions for extremely heavy snowfall.

1. Introduction

During the Northern Hemisphere winter, a large amount of precipitation occurring over the United States comes from the storms tracking across the North Pacific, which bring most of their precipitation to the western United States, and from the storms along the East Coast of the United States and Atlantic Canada, which bring the bulk of their precipitation to the mid-Atlantic and New England states. The maximum frequency of storms in North America in the latitude band of 40°–50°N is found over the Gulf of Alaska, the Great Lakes, and the Gulf Stream off the U.S. East Coast (Reitan 1974). Storms in these regions can last for several days or more and are usually accompanied by persistent circulation anomaly patterns (Dole and Gordon 1983) that project strongly upon the leading atmospheric teleconnection patterns, for example, the Pacific–North American (PNA) pattern (Wallace and Gutzler 1981).

Like most regions of the globe, the United States experiences climate variations on time scales ranging from the intraseasonal to decadal (Higgins et al. 2000a). On the interannual time scale, ENSO affects the precipitation distribution by altering rainfall patterns across the West, Midwest, and southeastern part of the United States. Many studies have provided evidence for a linkage between ENSO and regional precipitation variability in the United States (Cayan and Peterson 1989; Ropelewski and Halpert 1996; Mo and Higgins 1998a; Higgins et al.

* School of Ocean and Earth Science Technology Contribution Number 8532 and International Pacific Research Center Contribution Number 835.

Corresponding author address: Prof. Kyung-Ja Ha, Division of Earth Environmental System, Pusan National University, San 30, Changjeon-Dong, Geumjeong-Gu, Busan 609-735, Korea.
E-mail: kjha@pusan.ac.kr

DOI: 10.1175/JCLI-D-11-00033.1

2000b; Schubert et al. 2008). On intraseasonal time scales, several studies have established a linkage between tropical intraseasonal variability and U.S. weather. When MJO is active, a Rossby wave train originates from the western Pacific, often contributing to anomalous precipitation along the west coast of North America (Higgins and Mo 1997; Jones 2000). The wet (dry) episodes along the West Coast are related to the location of tropical heating associated with a tropical 20–60-day oscillation (Mo and Higgins 1998b). There is a general understanding regarding the association of the extratropical anomaly in the North Pacific sector with the MJO convection, which can affect the weather in the western United States.

However, only a few studies have noted how the MJO is linked to the weather in the eastern United States, the Atlantic, and the European sectors. Recently, atmospheric teleconnection patterns of Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) have been suggested to be linked to MJO, which influences weather in the eastern United States as well as the North Atlantic and European sectors (Cassou 2008; L'Heureux and Higgins 2008; Lin et al. 2009). During boreal winter, the MJO impact coincides with the seasonal amplification of the AO, in which the shift of the tendency and sign of the AO index corresponds to the eastward progression of the convectively active phase of the MJO. The structure of the AO in the geopotential height and surface air temperature fields significantly varies based on the phase of the MJO; the AO index results in a preference for negative polarity in which the anomalously cold (warm) air is prevalent over the upper Midwest and New England (western United States) during the MJO phases 7–8 [convection over the Western Hemisphere; see L'Heureux and Higgins (2008)]. Lin et al. (2009) indicated that when MJO is detected in phases 6–8 (from the western Pacific to the Western Hemisphere), the NAO index is negative 5–15 days later, which can influence the weather in eastern North America and Europe.

During the winter of 2009/10, heavy snowstorms dumped a tremendous amount of snow over the central to eastern parts of the United States, with the largest amounts recorded over the mid-Atlantic region. Snow cover for December in the contiguous United States was the greatest ever recorded for that month; for example, Dulles International Airport, in Washington, D.C. (73.2″), Baltimore, Maryland (80.4″), and Philadelphia, Pennsylvania (78.7″), had their snowiest winters on record. Much of northwestern Europe also experienced an anomalously cold and snowy winter [see http://www.ncdc.noaa.gov/special-reports/2009-2010-cold-season.html and http://www.knmi.nl/cms/content/79165/ for U.S. and European climate summaries, respectively (Seager et al. 2010)]. In 2010, there were also three separate snowstorms occurring on 5–6, 9–11, and 24–28 February. Two successive heavy snowstorms, which produced the highest amount of snowfall since the last century, occurred in early February 2010; a massive snowstorm hit the U.S. East Coast and a huge and extremely dangerous snowstorm affected several mid-Atlantic states, including North Carolina, Delaware, Washington, D.C., Pennsylvania, Virginia, and Maryland.

Precise attribution of the causes of these extreme snowstorm events is difficult, largely because the processes involve multiple time scales. In the winter of 2009/10, two major modes of climate variability, AO (NAO) and El Niño, were active. Starting in May 2009, an El Niño gradually developed, with its maximum phase occurring in the winter of 2009, and then decayed in the spring of 2010. At the same time, the AO had its strongest negative phase since 1950, consistent with the negative phase of the NAO, which allowed high-latitude cold air to penetrate deeply into the southern United States, bringing cold and snowy weather. Seager et al. (2010) explored the connections between these two phenomena (the NAO and El Niño) and the Northern Hemisphere's (NH's) seasonal snow anomalies (especially in the United States and northwestern Europe). They suggest that the negative phase of NAO caused positive snow anomalies across eastern North America and in northern Europe because of the cold temperature advection and the El Niño–induced southward displacement of the storm track, which increased snowfall in the southern United States. Both the NAO and El Niño affect the snowfall amount and frequency over seasonal and longer time scales.

However, why did the snowstorms mostly occur in December 2009 and February 2010, given the seasonal background of El Niño and the seasonal amplification of the strong negative AO impacts? In the present study, we attempt to explain the rhythm of this heavy snowstorm phenomenon in terms of MJO teleconnection. The MJO convection was abnormally strong and persistent to the east of the date line, which extends to the subtropical eastern Pacific, and it affected the extreme snowfall events in the United States. Our result helps to explain the intraseasonal variability over the eastern U.S.–Atlantic sector and its regulation of extreme weather. Section 2 describes the data and the analysis methodology. In section 3, we briefly analyze the intraseasonal variance during the 2009/10 winter. Section 4 explains the MJO's impact on the extratropics, especially in the United States, through its generation of wet–dry–wet spells and its influence on the daily snowfall over the United States through teleconnection. The conclusions and discussion are presented in section 5.

2. Data and methodology

The daily data of the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) global reanalysis of atmospheric fields (Kalnay et al. 1996) and Advanced Very High Resolution Radiometer (AVHRR) mean outgoing longwave radiation (OLR) are used in this study. We also used the daily AO index, available from National Oceanic and Atmospheric Administration/Climate Prediction Center (NOAA/CPC; see http://www.cpc.ncep.noaa.gov). The daily AO index is obtained by projecting daily data onto the first empirical orthogonal function (EOF) of monthly 1000-hPa geopotential height anomalies from NCEP–NCAR reanalysis. The boreal winter is from 1 December 2009 to 28 February 2010 (90 days), and the horizontal resolution is 2.5° latitude–longitude. Ground station snowfall daily data over the United States was obtained from the National Climatic Data Center. The intraseasonal anomaly is obtained from 30–60-day bandpass filtering using a Lanczos window (Duchon 1979).

3. Atmospheric intraseasonal variance during the winter of 2009/10

Figure 1 displays the intraseasonal variance (ISV) of OLR and 300-hPa streamfunction (SF300), as measured by the standard deviation of the intraseasonal anomaly during the 2009/10 winter period. It is noteworthy that the intraseasonal convection in the 2009/10 winter (shading) was abnormally active along the equator from the Indian Ocean to the eastern Pacific, with a notable northward shift over the Indian Ocean and western Pacific. The eastward extension of the MJO convection into the eastern Pacific is a consequence of the effects of El Niño (Fink and Speth 1997; Kessler 2001; Moon et al. 2011). Two salient ISV intensification centers were detected over the Philippine Sea and in the vicinity of Mexico. In particular, the enhanced ISV around Mexico was as strong as that over the equatorial regions, reaching its first historic maximum since 1979/80 (Fig. 2). The enhanced ISV from the central Pacific to Mexico is a common feature of the ISV during El Niño (Fig. 3 of Moon et al. 2011), but the enhanced ISV over the Indian Ocean and western Pacific and the extremely strong ISV over the vicinity of Mexico are the abnormal characteristics found in the 2009/10 winter. The four key regions of enhanced ISV are marked by the boxes in Fig. 1a and will be used in Fig. 2 to show the year-to-year variability of ISV.

The large ISV of the upper-level streamfunction during the 2009/10 winter was concentrated in two latitude bands—one at 20°–40° and the other at 60°–80°N, excluding the Arctic Ocean. The yearly mean ISV of SF300 (contour) shows maximum centers located over the North Pacific and North Atlantic to northwestern Eurasia. Compared to the mean standard deviation, the 2009/10 winter shows decreased intraseasonal variability over most of the North Pacific sector, including the western United States and northeast Russia, and increased ISV over eastern North America–Greenland, the Mediterranean, East Asia, and the subtropical eastern Pacific. The enhanced ISV along the subtropics is related to the OLR ISV, which also elongates from the tropical Indian Ocean to the subtropical eastern Pacific in Fig. 1a.

Figure 2 shows the time series of the OLR ISV from 1979/80 to 2009/10, averaged over four key regions from Fig. 1a. In area I (the subtropical eastern Pacific), the variability in 2009/10 was the strongest since 1979/80. Its interannual variability has no evident relationship with ENSO variability. However, this region can be influenced considerably by the twin subtropical trough and cloud bands established around the date line because the North Pacific midlatitude jet strengthens and shifts eastward when the El Niño condition prevails. The ISV over area II (the equatorial central Pacific) increases during El Niño. The ISV in the 2009/10 winter was the second highest in all 31 yr. For areas III and IV, the winter of 2009/10 ranks fifth. The amplitude of ISV over the Indian Ocean and western Pacific are not as much as that over the central Pacific and subtropical eastern Pacific; however, these regions have large ISV compared to other years. Figures 1a and 2 indicate that the intraseasonal activity along the equator over the Indian Ocean and western Pacific in the Northern Hemisphere was equally strong, while those over the central Pacific and the subtropical eastern Pacific were extremely strong. Overall, the MJO variability in the 2009/10 winter had zonally extended, meridionally compacted, and shifted to north close to the extratropics.

Figure 3 shows time–longitude Hovmöller diagrams of the intraseasonal (contour) and total (shading) OLR anomalies over the tropics (5°S–5°N) and subtropics (15°–25°N) where the enhanced ISV was prominent. Together with the diagrams, the MJO (Wheeler and Hendon 2004) and AO index are presented. Along the equator, there are two prominent 40-day MJO events propagating eastward from the western Indian Ocean to the east of the date line. Note that the MJO convection bursts in the Indian Ocean are nearly in phase with those over the central Pacific; both regions show two wet periods in late December 2009 and early February 2010, with a prominent dry spell in January. As seen later, this wet–dry–wet cycle over the central Pacific and Indian Ocean play an important role in regulating extreme weather in North America. In the subtropics, three main regions show significant ISO: the Philippine Sea, Mexico, and northwest

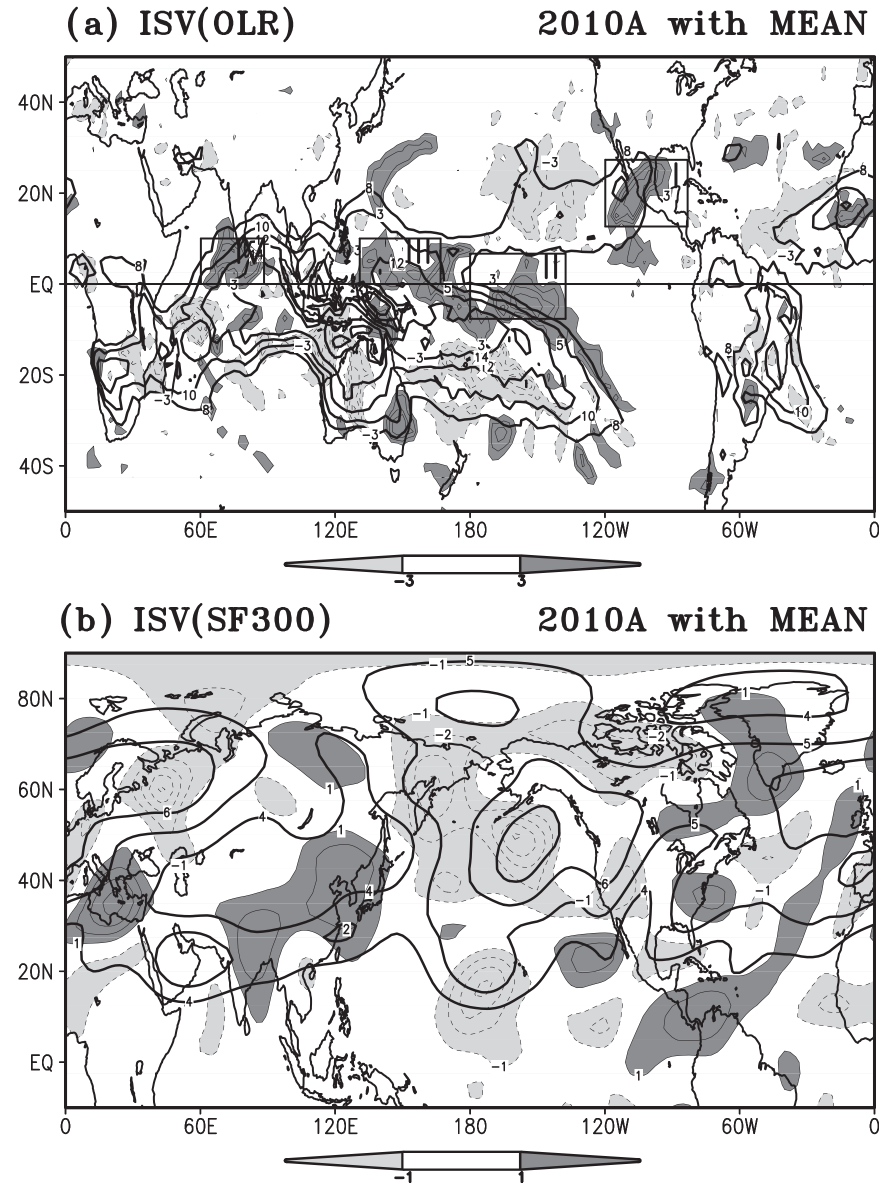

FIG. 1. ISV anomalies (shaded) for (a) OLR (W m^{-2}) and (b) 300-hPa streamfunction (10^{-6} m s^{-1}) during the 2009/10 winter and the mean ISV (contour, 1979/80–2009/10). The ISV is measured by the standard deviation of intraseasonal anomaly during each season of the year. Enhanced OLR ISVs of four key regions are marked in the box as I (15°–25°N, 120°–80°W), II (5°S–5°N, 180°–140°W), III (0°–10°N, 130°–170°E), and IV (0°–10°N, 60°–90°E).

Africa. Among these regions, the Mexico center exhibits maximum convective activity in early January and mid-February, with each period persisting for more than 2 weeks. These two periods lag behind the wet period over the equatorial central Pacific (to the east of the date line) by about 5–7 days. In both regions of the tropics and subtropics, the intraseasonal anomalies evolve in phase with total convection anomalies. In the tropics, the persistent total convection anomalies found near the date line indicate the seasonal transition of El Niño during the winter and enable the MJO convection to be more active to the east of the date line. This can be identified from Wheeler and Hendon's (2004) MJO index (thick solid and dashed), which shows longer a status of phases 7–8 than phases 1–2 in an El Niño year. In Fig. 3b, it is noteworthy to detect the tendency of the AO index with the MJO index; the AO index rapidly decreases during phases 7–8 and increases during phases 3–4, which corresponds well with the previous study (L'Heureux and Higgins 2008). It is found that the

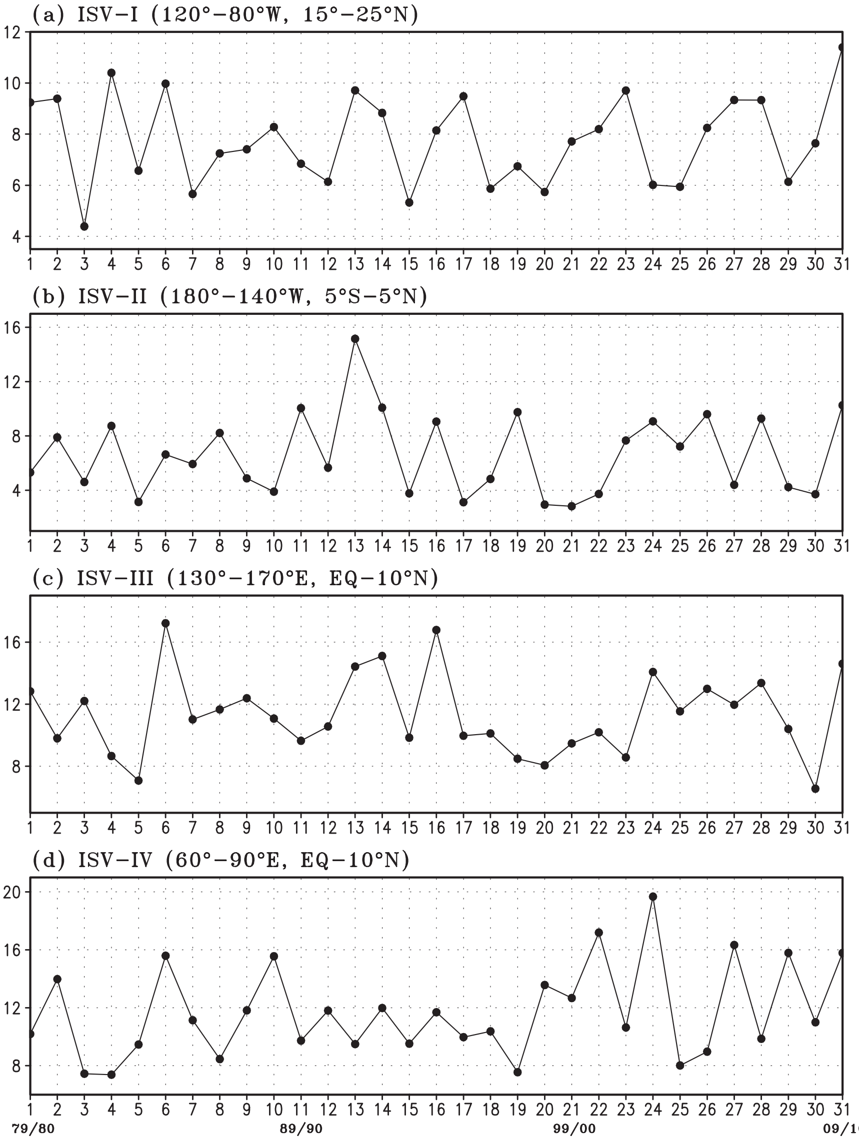

FIG. 2. Time series of area-averaged OLR (W m^{-2}) ISV over the four key regions marked in Fig. 1a (I–IV) from the winter of 1979/80 to 2009/10.

decrease (increase) of the AO index in accordance with the MJO phases 7–8 (3–4) precedes the wet (dry) periods over the central tropical Pacific in Fig. 3a.

When MJO convection is active in the central Pacific, the U.S. and Atlantic sectors have more chances of being affected by the tropics (Cassou 2008; Lin et al. 2009), and this can be enhanced during El Niño. Hence, the results presented in Figs. 1–3 indicate that the salient intraseasonal signals in 2009/10 winter could potentially impact weather and climate over North America and the Atlantic sector. In the next section, we will investigate how the wet–dry–wet episodes of MJO convection over the tropical central Pacific and the extremely enhanced convection over the subtropical eastern Pacific had modulated the atmospheric intraseasonal variance and the daily snowfall over the United States.

4. MJO modulation on U.S. snowfall through teleconnection

Two wet and one dry episode are identified based on the convection over the central Pacific (Fig. 3a, below −5 W m^{-2}); they are 16 December–6 January (the first wet episode), 9–28 January (the dry episode), and 31 January–19 February (the second wet episode). Figure 4 shows the horizontal maps of the 30–60-day OLR and 850-hPa temperature (shading) and 300- and 850-hPa streamfunction (contour) on the day that the convection

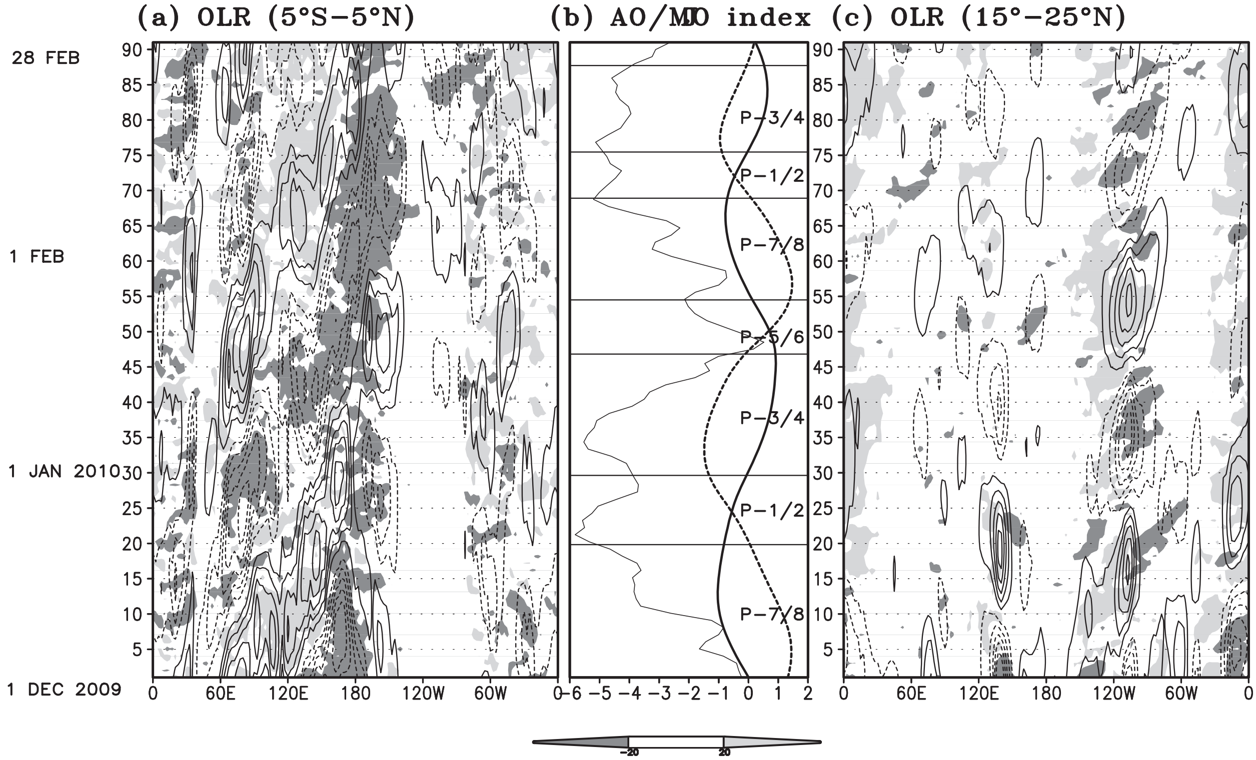

FIG. 3. Time–longitude Hovmöller diagrams of intraseasonal OLR over the (a) tropics (5°S–5°N) and (c) subtropics (15°–25°N), and the (b) MJO index (RMM1: thick solid curve, RMM2: thick dashed curve) by Wheeler and Hendon (2004) and the AO index (thin line) from 1 Dec 2009 to 28 Feb 2010. RMM1 and RMM2 indicate the pair of principal component time series that form the MJO index, called the Real-time Multivariate MJO series.

reaches its maximum during each episode. The convective anomalies during the first (Fig. 4a) and second (Fig. 4e) wet episodes exhibit extremely similar patterns; the enhanced convection associated with MJO shows two dominant areas over the tropical central Pacific and Indian Ocean, respectively. The enhanced convection is also seen from Mexico to the southern United States. The strength of the negative anomaly over the east of the date line is comparable to that over the Indian Ocean, which shows the MJO feature that occurs during El Niño (Roundy et al. 2010; Moon et al. 2011). However, it is unusual that the MJO convection over the central Pacific maintains strength and extends toward Mexico and the southern United States when the ensuing MJO convection has already matured over the Indian Ocean. Figure 4c is the dry episode, which shows almost opposite OLR patterns to those of the two wet episodes.

In the upper level (300 hPa), the streamfunction anomalies of the two wet episodes exhibit sharp contrasts to those of the dry episode. The two wet episodes have very similar patterns in the global domain. The anticyclonic anomalies to the north of the convection are found along the 10°–20°N band, except for the central Pacific, which is closer to the equator. Further north, a string of elongated cyclonic anomalies cover almost the entire longitude belt between 20° and 50°N with centers of the cyclonic anomalies located in Saudi Arabia, East Asia, the subtropical North Pacific, Baja California, and central-eastern North America. Surprisingly, the dry episode has almost the same pattern, but with reversed polarities, manifesting an obvious and robust linkage between the tropics and extratropics on the intraseasonal time scale. Hence, the atmospheric intraseasonal circulation anomaly over North America and the Atlantic was dramatically influenced by the pulsation of MJO convection. Note that the center of the cyclonic anomaly positioning over the eastern United States in the first wet episode further shifted to the north in the second wet episode. This anomaly, with the anticyclonic anomaly to its northeast (near Greenland), was able to channel high-latitude cold air to penetrate the southern United States, which aggravated the circulation anomaly associated with the negative phase of NAO. In the subtropical Pacific, the elongated cyclonic anomalies at Baja California can transport moisture from the tropical eastern Pacific through Mexico to the southeastern United States, which can act as an important moisture source for snowfall over the United States.

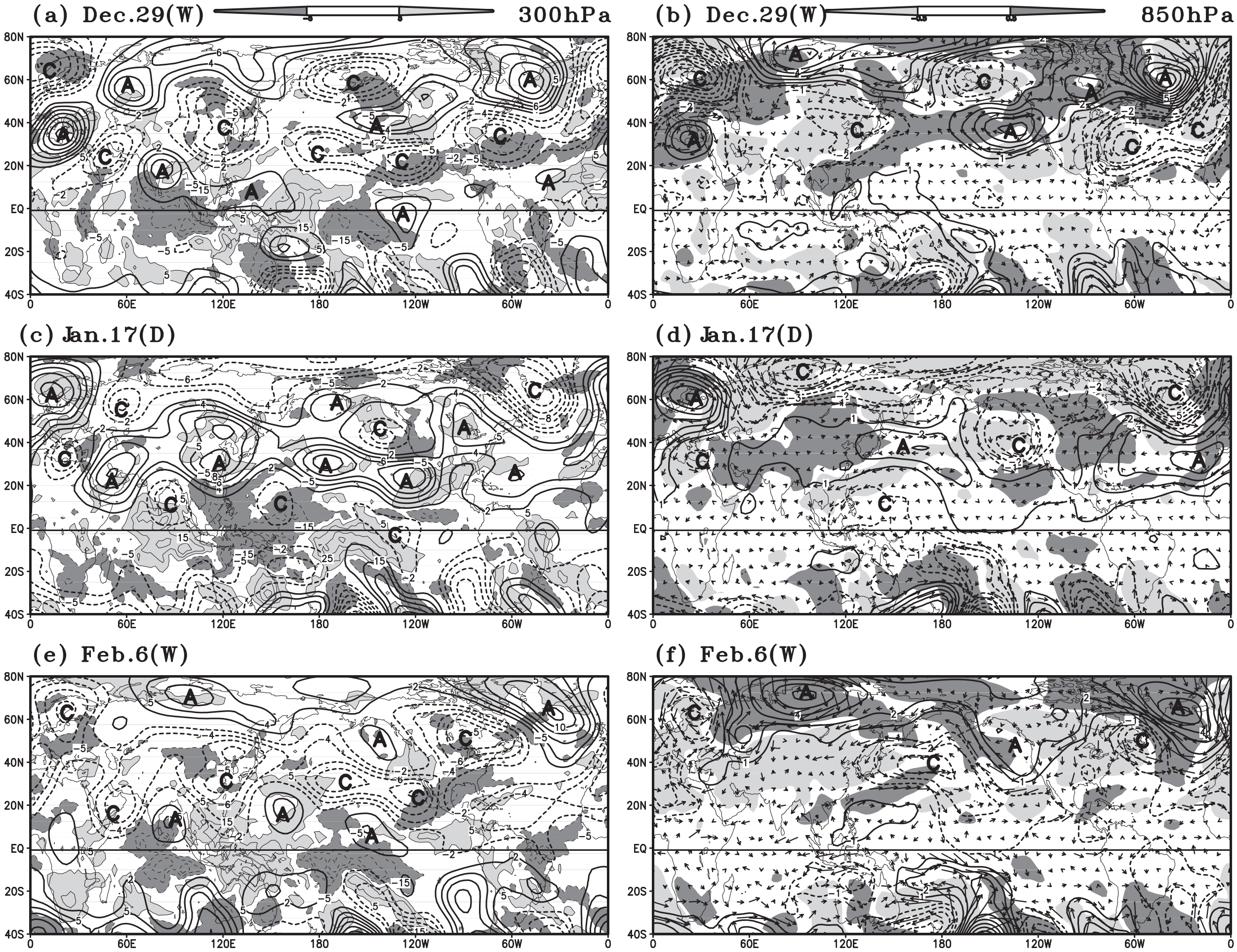

FIG. 4. Intraseasonal anomalies of (a),(c),(e) OLR and 300-hPa streamfunction, and (b),(d),(f) 850-hPa streamfunction and temperature on the day when convection over the tropical central Pacific reached its maximum (minimum for dry episode) during (a),(b) the first wet, (c),(d) the dry, and (e),(f) the second wet episodes on 29 Dec, 17 Jan, and 6 Feb, respectively. The OLR and 850-hPa temperature are shaded. The 300- and 850-hPa streamfunction (contour), and 850-hPa horizontal wind (vectors) are shown. OLR: W m^{-2}, streamfunction: 10^{-6} m s^{-1}, and temperature: K.

In the low level (850 hPa), barotropic circulation anomalies prevail from the mid- to high latitudes. In the wet episodes, robust cyclonic centers are located over East Asia, eastern North America, and northwestern Europe. The first wet episode has an enhanced cyclonic anomaly over Alaska and the northeastern Atlantic Ocean. As the wet and dry episodes alternate, the Pacific Northwest and the eastern United States experience contrasting atmospheric anomaly patterns, including temperature distribution. In both wet periods, most of the United States has cold air flowing down from Canada between a dipole pattern consisting of a warm high in the west and a cold low in the east. During the dry period, the anomaly pattern is just opposite. Hence, the teleconnection associated with MJO over North America is highly dependent on the tropical central Pacific's dry–wet phase. Note that the decreasing (increasing) tendency of the AO index evolved in concert with MJO phase 7–8 (3–4), and the negative maximum (minimum) peak corresponded with the wet (dry) MJO episodes in Fig. 3b, in which the cold air from the high-latitude to the eastern United States will be reinforced (counterbalanced) during the wet (dry) episode of MJO by the NAO (AO)-related circulation anomalies.

Closer examination of the upper- and low-level anomalies over the United States in both wet episodes reveals that the deep ridge and trough remaining in the western and eastern United States tilts westward with height, so that the center of the low-level cyclonic anomaly is more to the east than the upper-level cyclonic flow. This feature is more robust in the second wet episode, which implies that the tilted structure features baroclinic disturbance with upward motion to the low-level cyclonic area and cold air advection to the low-level anticyclonic area. This

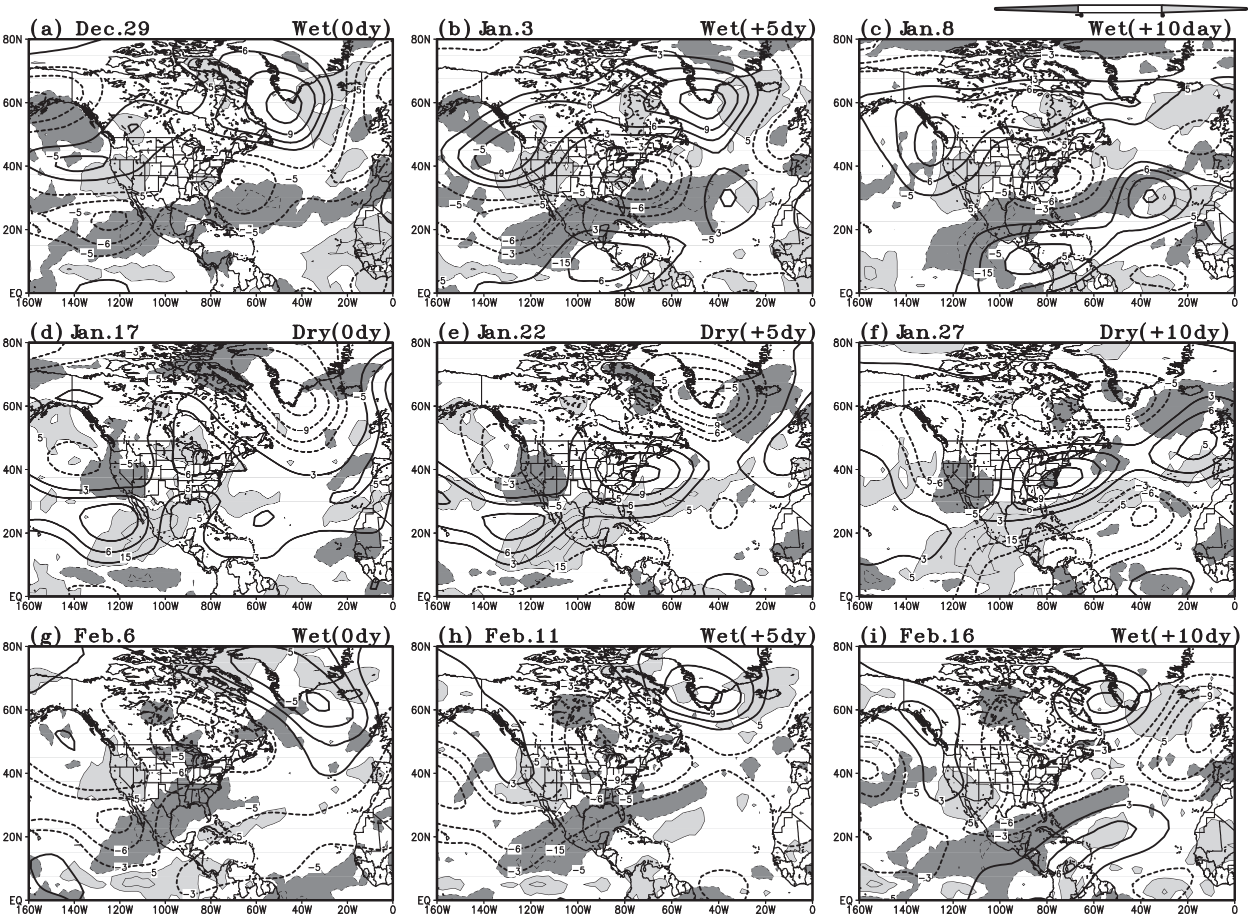

FIG. 5. Intraseasonal anomalies of OLR (W m^{-2}; shading) and 300-hPa streamfunction (10^{-6} m s^{-1}; contour) on (a) 29 Dec, (d) 17 Jan, and (g) 6 Feb (the peak days of the corresponding dry–wet episodes), and their time lag maps at (b),(e),(h) +5 and at (c),(f),(i) +10 days.

unstable structure in the midlatitude can trigger any synoptic-scale phenomena to develop into severe weather systems with the warm, moist air provided from the subtropical ocean.

Because the MJO response in the extratropics may reflect the lagged impact from the tropical heating far away, the horizontal maps of the 30–60-day OLR and 300-hPa streamfunction during each dry–wet episode from the maximum (0 day) to +5 and +10 days later are shown in Fig. 5, focusing on North America and the North Atlantic sector. The upper-level cyclonic (anticyclonic) circulation anomalies in the midlatitude have three maximum centers in a wet (dry) episode: the West Coast of the United States, the East Coast of the United States, and the northwestern coast of Europe. To the north and south of these centers, there are elongated circulation anomalies with reversed signs lasting through the examined time interval. In both wet episodes, the upper-level trough centered over the eastern United States and the elongated convection from Mexico to the southern United States becomes strongest at the +5-day lag, while the anticyclonic flow slightly to the south of the convection intensifies at the +10-day lag. It is remarkable that the convection is linked together from the tropical central Pacific through the southern United States to the western coast of Europe in both wet episodes. This elongated moisture stream acts as a moisture source, not only over the United States, but also to the western Eurasian continent. In the dry episode, the western United States is influenced by the enhanced convection and the cyclonic circulation anomaly located to the west of the Pacific Northwest. This result is consistent with the study by Mo and Higgins (1998b). In both episodes, the atmospheric teleconnection pattern maintains its structure with time evolution, although this teleconnection pattern contains an accumulative heating effect from the previous time.

Figure 6 displays the evolution of the 30–60-day 300-hPa zonal wind (contour), seasonal mean anomaly of the westerly (thick contour), and active convection

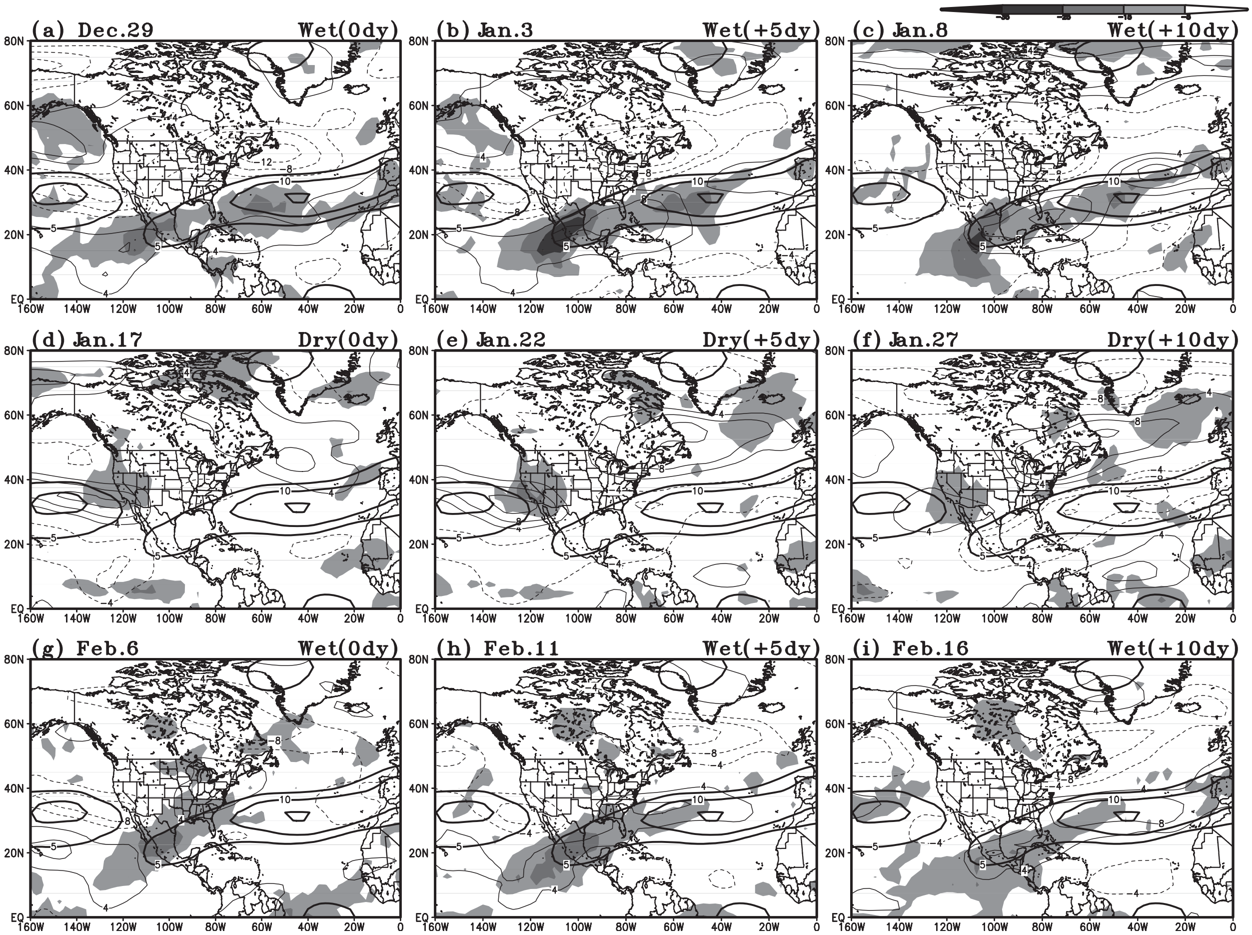

FIG. 6. As in Fig. 5, but for OLR (only for active convection below -5 W m^{-2}; shading) and 300-hPa zonal wind (thin color contour). The seasonal mean westerly anomalies above 5 m s^{-1} (thick contour) are noted.

(shading below -5 W m^{-2}) in three episodes. In the two wet episodes, the enhanced subtropical and polar westerly extends from the Pacific to the North Atlantic with a slow eastward migration. In the subtropics, the center of the westerly maximum develops to the south of the upper-level cyclonic flow where the pressure gradients are the largest. The enhanced and extended subtropical westerly transports warm, moist air from the Pacific to western Europe from 0 to +10 days. It is noteworthy that in the second wet episode on 6 February, there was a northward shift of the westerly to the northeastern states, which concurred with the heaviest snowfall since the last century. In contrast to the wet episode, during the dry episode the enhanced westerly reaches the West Coast of the United States and the far north over eastern Canada to the North Atlantic Ocean.

How was the intraseasonal anomaly related to the seasonal background? The seasonal mean anomaly of the 2009/10 subtropical jet extended to the West Coast of the United States in the Pacific sector and shifted southward in the Atlantic sector compared to the mean climate, which resulted from the influence of El Niño (i.e., the eastward extension over the Pacific and the southward shift of the jet). In the wet episode the enhanced subtropical westerlies are amplified by the seasonal wind anomaly. However, in the dry phase the enhanced westerly from the North Pacific to the U.S. West Coast is strengthened by the extended seasonal mean subtropical jet.

As shown in Fig. 4, a deep trough with a westward tilt in height was found over the United States at day 0 in each wet episode. Figure 7 displays how the low-level part of the deep trough evolves with time during the wet and dry MJO episodes. In both the wet and dry episodes, a prevalent zonal dipole is found over the entire United States, with the strongest intensity at the +5-day lag. As time evolves, the anticyclonic circulation anomaly over the western United States in the wet episodes increases its influence toward the southeast, resulting in the southward movement of the extremely cold air mass from the

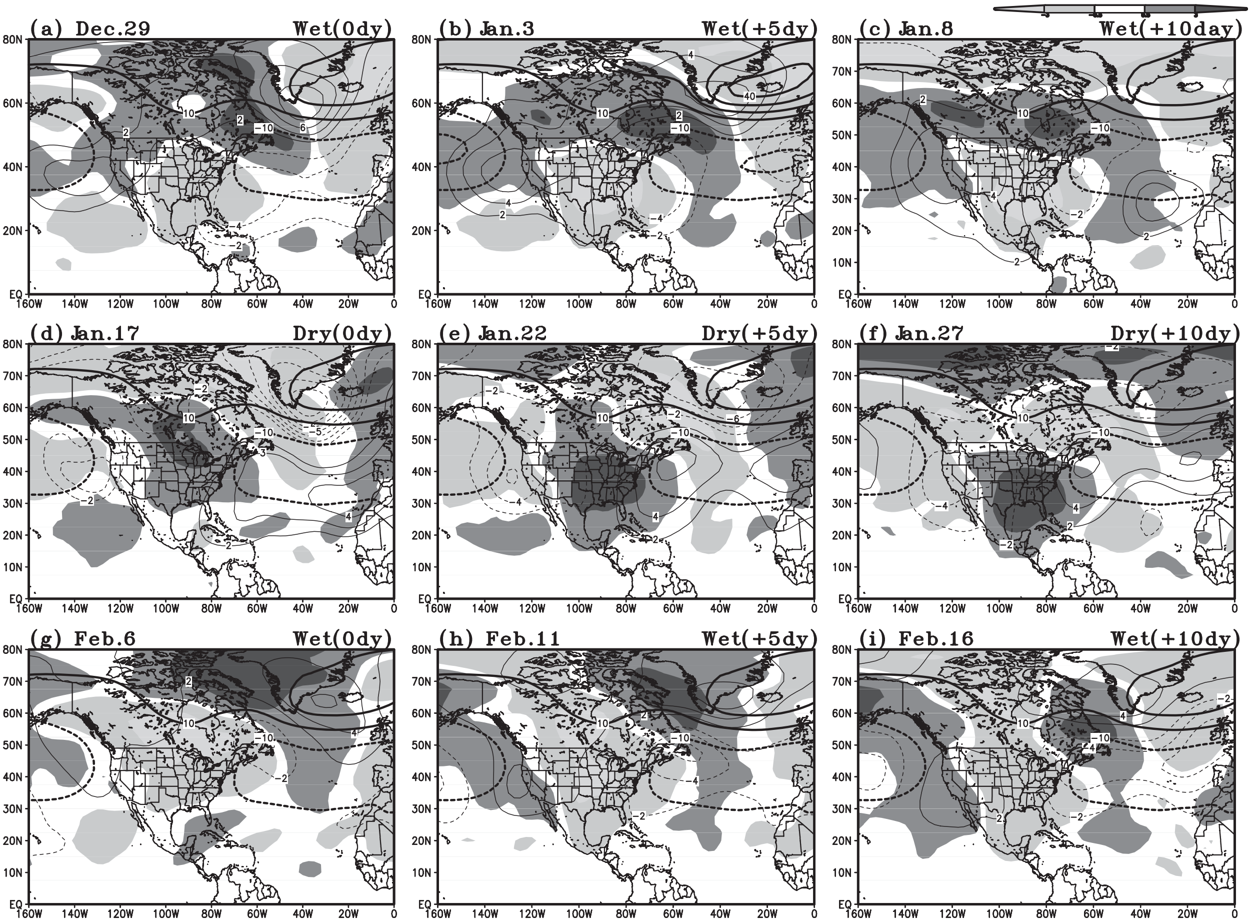

FIG. 7. As in Fig. 5, but for 850-hPa streamfunction (10^{-6} m s^{-1}; contour, black) and temperature (K, shaded). The thick contour denotes the regressed 1000-hPa geopotential height anomaly by the AO index (negative phase).

northern central-eastern United States to farther south. As shown in Fig. 4, the second wet episode shows a more northward shift to Canada at 0 day, but it eventually intensifies to the south. The most consistent feature from this dipole is the eastward shift of its structure with the upper-level trough (Fig. 5), which can generate descending air to the western side and rising air to the eastern side of the upper-level trough. In the dry episode, enhanced cold air is found along the West Coast of the United States and eastern Canada. Hence, the western and eastern parts of the United States are affected by the opposite polarity of the circulation anomalies through the MJO teleconnection. In the wet episode, the cold air moving southward and moist air coming from the subtropical Pacific Ocean can act to fuel the snowstorms in the eastern United States.

How was the intraseasonal anomaly related to the seasonal amplification of the negative AO (NAO)? The regressed 1000-hPa (unfiltered) geopotential height anomaly of the daily AO index is plotted (thick contour) in Fig. 7 by multiplying −1.0 to highlight the negative phase of AO (NAO). As expected, the positive (negative) height anomaly prevails to the north (south) of 60°N latitude, with a large amplitude over the North Pacific and North Atlantic sectors. In the wet episode the cyclonic (anticyclonic) anomaly in the eastern (western) United States is reinforced (offset) by the AO regressed cyclonic anomaly, while in the dry phase the opposite feature with the U.S. West Coast was strengthened. Thus, the meridional dipole in the MJO teleconnection pattern from over the North Atlantic Ocean to Greenland will be amplified during the wet phase and will affect the eastern North America with cold air penetration from the pole.

Figure 8 shows the zonal vertical cross sections averaged between 30° and 45°N at each time lag during the wet and dry episodes. There is a pronounced zonal dipole in each episode. During the wet episode, a deep ridge and a trough are found at day 0 in the western and eastern United States, respectively, which then intensified. There is a descent in the western (eastern) part of the

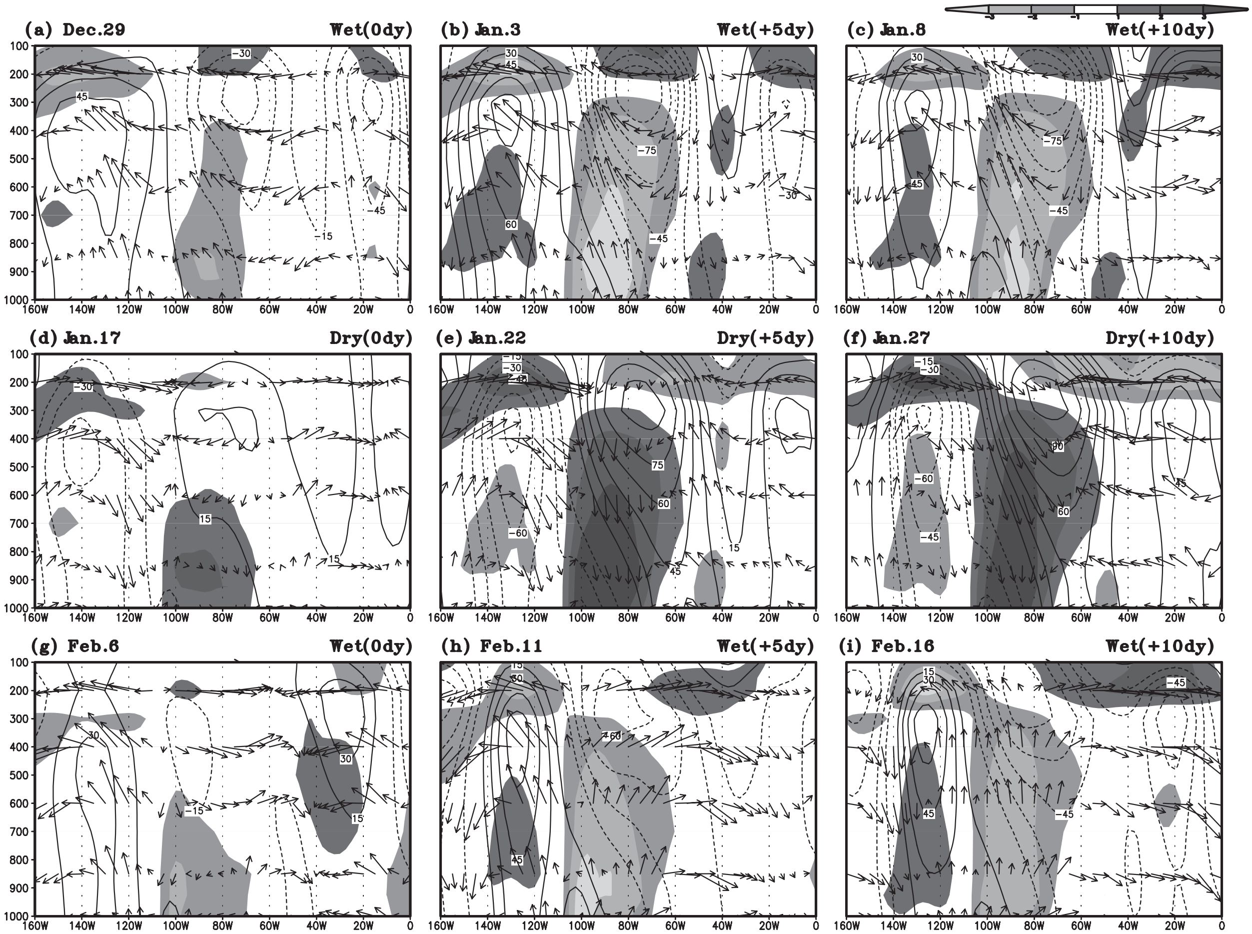

FIG. 8. As in Fig. 5, but for the zonal vertical cross sections of geopotential height (contour), temperature (shading), zonal wind, and upward motion (vector) averaged between 30° and 45°N. OLR: W m^{-2}, temperature: K, wind: m s^{-1}, and streamfunction: 10^{-6} m s^{-1}, respectively. The vertical motion was enlarged by a factor of 10^2.

ridge (trough) and upward motion to the western side of the trough. In the low level, the maximum cold temperature anomaly prevails at the ascent area just beneath and to the left of the upper-level trough. This region has a baroclinic structure with minimum temperature in the column. It is clear that the atmospheric teleconnection pattern produces a baroclinic trough over the eastern United States during the wet episode, which favors the development of synoptic disturbance. Because the second wet episode has a more northward shifted structure than the first wet episode, the features averaged over the latitude band covering the United States show a weaker intensity. Nevertheless, its westward tilt is more significant than the first wet episode and the deep trough extends farther eastward to reach to the western coast of Europe.

Based on the results shown in Figs. 7–8, we notice that the western (30°–45°N, 120°–105°W) and eastern (30°–45°N, 100°–70°W) United States tend to have opposite signs during the wet and dry MJO episodes.

Figure 9 shows the time series of OLR, 300-, and 850-hPa streamfunctions, and the daily snowfall amount averaged over the western and eastern regions of the United States. In Fig. 9a, the first maximum of the tropical convection over the central-eastern Pacific occurs in late December 2009, with the second maximum in early February 2010. The evolution of the MJO convection over this area corresponds to the seasonal cycle of El Niño in Fig. 3a (shading). The time interval between the two maxima is about 40 days. After 5–7 days, the convection over the subtropical eastern Pacific through the Gulf of Mexico reaches maximum. Hence, the convective activities of the two areas have coherent evolution with a time lag of about 5–7 days. In the upper level, the cyclonic (anticyclonic) anomaly prevails over most of the U.S. regions, except for the West Coast area during the wet (dry) episode. The enhanced upper-level cyclonic flow in Fig. 9b is maximized in the eastern United States about 7 days after the central Pacific convection peak and is

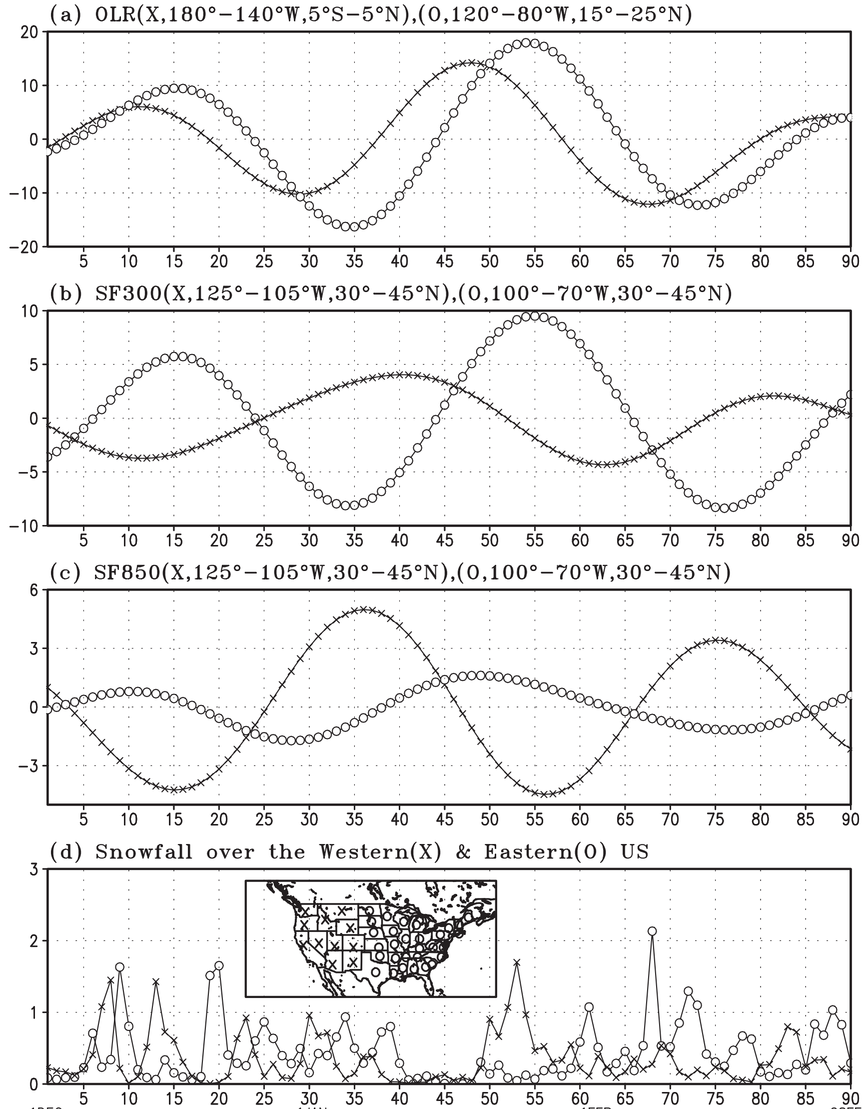

FIG. 9. Time series of area-averaged intraseasonal anomalies of (a) OLR over 5°S–5°N, 180°–140°W (×) and 15°–25°N, 120°–80°W (o), and (b) 300-hPa streamfunction over 30°–45°N, 125°–105°W (×) and (c) 850-hPa streamfunction over 30°–45°N, 100°–70°W (o). (d) Daily snowfall amount (in.) averaged over western (×) and eastern (o) United States from 1 Dec 2009 to 28 Feb 2010.

almost simultaneous with the subtropical convection burst. In the western United States, the opposite signals evolve with a weaker intensity because the center of the anticyclone lies farther west. The low-level circulation anomalies over the western and eastern parts also have opposite correlations with each other (Fig. 9c). The signal over the eastern Untied States is weaker than that in the western United States because the center of the cyclone is located along the East Coast. In Fig. 9d, the daily snowfall over the western United States seems to have an opposite tendency to that of the eastern United States. From December to early January, most of the events in the eastern United States also have a time lag with those in the western part of the country, while in mid-January to late February, the opposite tendency predominates. Although the daily variability is influenced by systems with multiple time scales, it is interesting to note that the eastern U.S. snowfall event during the 2009/10 winter has significant correlation with the extratropical intraseasonal circulation variability, which is modulated by the tropical MJO. When the deep trough is active over the eastern United States, the daily snowfall increases in the eastern and decreases in the western United States. Hence, the eastern United

States experiences a wet phase of snowfall from late December to early January, followed by a dry phase in mid- to late January, and then a second wet phase with extreme events embedded. During the dry phase, the western United States had enhanced snowfall, with the maximum amount falling during the peak dry episode in the tropics.

5. Conclusions and discussion

The present study investigates the relationship between the heavy snowstorm clusters over the United States during the winter of 2009/10 and MJO variability. In the winter of 2009/10, there was extremely strong intraseasonal variability of convection over the subtropical eastern Pacific, which was closely related to the strengthened variability over the tropical central Pacific by El Niño. Intraseasonal activity was also reinforced over the Indian Ocean and western Pacific slightly north of the equator, representing intensified MJO in an extended longitudinal domain from the Indian Ocean all the way to the far eastern Pacific. The intraseasonal variability in the upper-level extratropics was enhanced both over the subtropics on the Eurasian continent and from the eastern Pacific to the eastern United States, while it weakened over the North Pacific and high latitudes.

The tropical central Pacific had experienced marked dry–wet conditions in phase with the tropical Indian Ocean, slightly leading those over the subtropical eastern Pacific. Hence, the extratropics were influenced by coordinated anomalous heating in the three regions. Based on dry–wet episodes over the tropical central Pacific, we identified three episodes: the first wet (16 December–6 January), the dry (9–28 January), and the second wet (31 January–19 February) episodes. The representative feature of each episode was obtained at its maximum over the tropical central Pacific (day 0) and day +5 and +10. The upper- and lower-level circulations associated with the dry and wet episodes showed mirror image patterns with the signs reversed, manifesting the obvious linkage of MJO modulation on the extratropics. In the wet episodes, a deep trough anchored over the central-eastern United States and tilted westward with height. Hence, the low level had a dipole pattern of anticyclone (west) and cyclone (east), while the upper level maintained a cyclonic circulation over the entire United States except for the West Coast. As a result, the enhanced cold air from the high latitude penetrated southward, and the central to eastern United States was plunged into intense cold weather during the wet episodes. Hence, the baroclinic disturbance developed over the central to eastern United States. Moreover, the intraseasonal westerly anomalies were amplified by the anomalous seasonal mean subtropical jet during the wet episodes, but were offset during the dry episode. An elongated moisture stream from the subtropical eastern Pacific through the southern United Sates to the western coast of Europe, associated with this enhanced westerly, provided warm and moist air to the United States.

The synoptic disturbance occurring over the eastern United States favored the development of severe snowstorms with the support of increased baroclinic instability resulting from warm and moist air confronting the cold air mass. Daily mean snowfall showed contrasting intraseasonal variations between the western and eastern United States during the wet–dry MJO episodes. During December, most of the events in the eastern United States had a time lag with the western part of the country, while from mid-January to mid-February, an opposite tendency predominated. It is interesting to note that eastern U.S. snowfall events during the winter of 2009/10 showed significant coherence with the extratropical intraseasonal variability modulated by MJO.

In this study, we provide a new perspective on the MJO modulation on synoptic-scale weather phenomena of winter snowstorms over the United States. In winters when an El Niño and a negative AO (NAO) combine, how do these modes affect the intraseasonal anomaly?

In the 2009/10 winter, there was a strong coupling between the convection and SSTs east of the date line lasting through March by the prevailing El Niño, and the negative phase of AO persisted with its record-high strength. The MJO convection was enhanced and lasted longer than normal years over the central-eastern tropical Pacific as a known MJO signal during El Niño. The seasonal mean subtropical jet extended much more eastward to the West Coast of the United States and shifted southward in the Atlantic sector. As a result, the eastward-extended subtropical westerly has reinforced (offset) the intraseasonal anomaly during the wet (dry) episode of MJO in the eastern United States with the transportation of the warm, moist air from the subtropical eastern Pacific. Meanwhile, the negative phase of the AO (NAO) caused a meridional dipole over the North Atlantic sector, in phase with the MJO teleconnection during the wet phase. Thus, the cyclonic (anticyclonic) anomaly in the eastern (western) United States and the anticyclone (cyclone) to the north was reinforced (offset), while in the dry phase the opposite feature was dominant. Our results suggest that the eastern United States during the 2009/10 winter was placed in the location where the combined effect of MJO, El Niño, and AO could actively result in extremely heavy snowfall during the wet cycle of MJO.

Acknowledgments. This work was funded by the Climate Dynamics Program of the National Science Foundation under Award AGS-1005599. This GRL work is supported by the National Research Foundation of Korea(NRF) grant (2011-0021927) funded by the Korea government (MEST).

REFERENCES

Cassou, C., 2008: Intraseasonal interaction between the Madden–Julian Oscillation and the North Atlantic Oscillation. *Nature,* **455,** 523–527.

Cayan, D. R., and D. H. Peterson, 1989: The influence of the North Pacific atmospheric circulation on streamflow in the west. *PA-CLIM, Geophys. Monogr.,* Vol. 55, Amer. Geophys. Union, 375–397.

Dole, R. M., and N. D. Gordon, 1983: Persistent anomalies of the extratropical Northern Hemisphere wintertime circulation: Geographical distribution and regional persistence characteristics. *Mon. Wea. Rev.,* **111,** 1567–1586.

Duchon, C. E., 1979: Lanczos filter in one and two dimensions. *J. Appl. Meteor.,* **18,** 1016–1022.

Fink, A., and P. Speth, 1997: Some potential forcing mechanisms of the year-to-year variability of the tropical convection and its intraseasonal (25-70 day) variability. *Int. J. Climatol.,* **17,** 1513–1534.

Higgins, R. W., and K. C. Mo, 1997: Persistent North Pacific circulation anomalies and the tropical intraseasonal oscillation. *J. Climate,* **10,** 223–244.

——, A. Leetmaa, Y. Xue, and A. Barnston, 2000a: Dominant factors influencing the seasonal predictability of U.S. precipitation and surface air temperature. *J. Climate,* **13,** 3994–4017.

——, J.-K. E. Schemm, W. Shi, and A. Leetmaa, 2000b: Extreme precipitation events in the western United States related to tropical forcing. *J. Climate,* **13,** 793–820.

Jones, C., 2000: Occurrence of extreme precipitation events in California and relationships with the Madden–Julian oscillation. *J. Climate,* **13,** 3576–3587.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kessler, W. S., 2001: EOF representation of the Madden–Julian oscillation and its connection with ENSO. *J. Climate,* **14,** 3055–3061.

L'Heureux, M. L., and R. W. Higgins, 2008: Boreal winter links between the Madden–Julian oscillation and the Arctic Oscillation. *J. Climate,* **21,** 3040–3050.

Lin, H., G. Brunet, and J. Derome, 2009: An observed connection between the North Atlantic Oscillation and the Madden–Julian oscillation. *J. Climate,* **22,** 364–380.

Mo, K. C., and R. W. Higgins, 1998a: Tropical influences on California precipitation. *J. Climate,* **11,** 412–430.

——, and ——, 1998b: Tropical convection and precipitation regimes in the western United States. *J. Climate,* **11,** 2404–2423.

Moon, J.-Y., B. Wang, and K.-J. Ha, 2011: ENSO regulation of MJO teleconnection. *Climate Dyn.,* **37,** 1133–1149, doi:10.1007/s00382-010-0902-3.

Reitan, C., 1974: Frequencies of cyclones and cyclogenesis for North America, 1951–1970. *Mon. Wea. Rev.,* **102,** 861–868.

Ropelewski, C. F., and M. S. Halpert, 1996: Quantifying southern oscillation–precipitation relationships. *J. Climate,* **9,** 1043–1059.

Roundy, P. E., K. MacRitchie, J. Asuma, and T. Melino, 2010: Modulation of the global atmospheric circulation by combined activity in the Madden–Julian oscillation and the El Niño–Southern Oscillation during boreal winter. *J. Climate,* **23,** 4045–4059.

Schubert, S. D., Y. Chang, M. J. Suares, and P. J. Pegion, 2008: ENSO and wintertime extreme precipitation events over the contiguous United States. *J. Climate,* **21,** 22–39.

Seager, R., Y. Kushnir, J. Nakamura, M. Ting, and N. Naik, 2010: Northern Hemisphere winter snow anomalies: ENSO, NAO and the winter of 2009/10. *Geophys. Res. Lett.,* **37,** L14703, doi:10.1029/2010GL043830.

Wallace, J. M., and D. S. Gutzler, 1981: Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Wea. Rev.,* **109,** 784–812.

Wheeler, M. C., and H. H. Hendon, 2004: An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. *Mon. Wea. Rev.,* **132,** 1917–1932.