Effects of Variations in East Asian Snow Cover on Modulating Atmospheric Circulation over the North Pacific Ocean

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ABSTRACT

At least four different modeling studies indicate that variability in snow cover over Asia may modulate atmospheric circulation over the North Pacific Ocean during winter. Here, satellite data on snow extent for east Asia for 1971–95 along with atmospheric fields from the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis are used to examine whether the circulation signals seen in model results are actually observed in nature. Anomalies in snow extent over east Asia exhibit a distinct lack of persistence. This suggests that understanding the effects of east Asian snow cover is more germane for short- to medium-range weather forecasting applications than for problems on longer timescales. While it is impossible to attribute cause and effect in the empirical study, analyses of composite fields demonstrate relationships between snow cover extremes and atmospheric circulation downstream remarkably similar to those identified in model results. Positive snow cover extremes in midwinter are associated with a small decrease in air temperatures over the transient snow regions, a stronger east Asian jet, and negative geopotential height anomalies over the North Pacific Ocean. Opposing responses are observed for negative snow cover extremes. Diagnosis of storm track feedbacks shows that the action of high-frequency eddies does not reinforce circulation anomalies in positive snow cover extremes. However, in negative snow cover extremes, there are significant decreases in high-frequency eddy activity over the central North Pacific Ocean, and a corresponding decrease in the mean cyclonic effect of these eddies on the geopotential tendency, contributing to observed positive height anomalies over the North Pacific Ocean. The circulation signals over the North Pacific Ocean are much more pronounced in midwinter (January–February) than in the transitional seasons (November–December and March–April).

1. Introduction

Over the past decade, a considerable amount of research has focused on the El Niño–Southern Oscillation (ENSO) phenomenon as a source of climate fluctuations. However, as ENSO events only account for a portion of climate variability across the globe (Ting et al. 1996), other internal forcing mechanisms need to be investigated. Of these, one of the most important is arguably snow cover, which during winter covers on average 46 $\times$ 10^6 km^2 (approximately half) of the Northern Hemisphere land surface, with significant regional and interannual variability in most months (Robinson 1993).

In addition to the well-documented influence of Eurasian snow cover on the south Asian summer monsoon, there is accumulating modeling evidence that Eurasian snow cover may influence atmospheric circulation in the extratropics during winter. In the modeling study by Walland and Simmonds (1997), the surface boundary conditions of the Melbourne University general circulation model (GCM) were altered by prescribing anomalously extensive and reduced Northern Hemisphere snow cover, and run for 660 days in a perpetual January simulation. The differences between the two runs (high snow minus low snow) showed that, in addition to the expected decreases in air temperature and increases in sea level pressure (SLP) over land areas, there were significant nonlocal effects on atmospheric circulation. Particularly notable was a strengthening of the North Pacific storm track and deepening of the Aleutian low. In a similar study, Walsh and Ross (1988) ran the National Center for Atmospheric Research (NCAR) CCM0B forecast model for 30 days for three cases of extensive and reduced Eurasian snow cover. The differences between the two model runs showed a deeper Aleutian low and lower central pressures of North Pacific cyclones when snow cover was more extensive.

Modeling studies of the effects of snow cover on the south Asian summer monsoon also reveal downstream effects of Eurasian snow cover during winter. In a sensitivity experiment conducted with the Japanese Meteorological Research Institute (MRI) GCM, Yamazaki

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(1989) decreased the surface albedo over east Asia in January, and found SLP over the North Pacific Ocean to be higher in the perturbed run than in the control run (pressure differences locally exceeded 8 hPa), suggesting a weaker Aleutian low at times of decreased snow extent. In other experiments with the MRI-GCM, Yasunari et al. (1991) artificially increased spring snow cover over Eurasia. Consistent with the results of Yamazaki (1989), the 500-hPa height surface over the North Pacific Ocean in the perturbed run was over 40 m lower than in the control run, indicating a deeper Aleutian low in response to increased snow extent.

Most recently, Watanabe and Nitta (1998) used the University of Tokyo Center for Climate System Research GCM to examine the relative impacts of east Asian snow cover and sea surface temperature (SST) anomalies on atmospheric circulation during the winter of 1988/89. This winter was characterized by reduced snow cover over east Asia and below-normal SSTs in the tropical Pacific Ocean (La Niña conditions), higher air temperatures over east Asia, below-normal SLP over the Arctic Ocean, and a weak Aleutian low. Model sensitivity experiments showed that artificial negative snow cover anomalies over east Asia in autumn produced strong surface warming over east Asia, as well as reductions in SLP and 500-hPa height over the Arctic Ocean. Most important, negative snow cover anomalies were manifested in increases in SLP and 500-hPa height over the North Pacific Ocean, hence simulating the observed weakening of the Aleutian low. In a separate experiment forced with observed global SST anomalies for 1988/89, similar reductions in SLP were simulated over the Arctic Ocean, but there were larger increases in SLP over the North Pacific Ocean than in the low snow run. There was little change in east Asian snow cover in the SST runs. In both the low snow and SST runs, feedbacks associated with synoptic-scale eddy activity played a strong role in reinforcing the circulation anomalies.

To summarize, results from at least four different models using a variety of experimental designs suggest that circulation over the North Pacific Ocean responds strongly to Eurasian snow cover (or surface albedo) anomalies. Given the remarkable similarity between these model results, it is justified to examine whether such circulation signals are actually observed in nature. Our approach is to quantify the timescales of variability in east Asian snow extent, and then diagnose attendant circulation changes using composites of climate fields for snow cover extremes. Important aspects of this issue are the influence of seasonality and the role of storm track feedbacks in reinforcing circulation anomalies.

2. Data

a. Snow extent

Use is made of the weekly National Oceanic and Atmospheric Administration (NOAA) snow cover charts for the period 1971–95. These charts are based on manual interpretation of visible satellite imagery, and subsequently digitized to the National Meteorological Center (NMC) primitive equation grid. This is an 89 × 89 Northern Hemisphere grid on a polar stereographic projection. Cell size ranges from 16 000 to 42 000 km^2. Only cells interpreted to be at least 50% snow covered are considered snow covered.

The snow-covered area over east Asia (105° to 150°E) was determined for each week. Restricting attention to east Asia assumes that, by influencing the meridional temperature gradient in the vicinity of the east Asian jet, variations in east Asian snow cover will be most important in influencing atmospheric circulation over the North Pacific. The chosen area, although fairly small, was defined to avoid including the (perhaps spurious) variations in snow extent over the Tibetan Plateau. The Tibetan Plateau has historically been one of the most difficult areas for snow mapping. In this area, snow cover is patchy and ephermal, and often resembles cloud cover. The values of weekly snow-covered area were linearly interpolated to daily values, which provides more days for analysis. Use is made of true anomalies (i.e., not standardized) to focus attention on absolute changes in snow extent.

b. NCEP–NCAR fields

To assess effects of snow cover on atmospheric circulation, use is made of daily analyzed fields from the National Centers for Environmental Prediction (NCEP)–NCAR NCEP/NCAR reanalysis project (Kalnay et al. 1996). Unfortunately, the reanalyses from 1973–95 were inadvertently run using 1973 snow cover for every year. These errors will most strongly affect variables heavily influenced by the model's treatment of the surface energy budget (e.g., the 2-m air temperature), and are less of a problem at higher levels. Through comparison of the modeled and observed 2-m air temperatures over the transient snow regions over Asia and the United States, NCEP personnel conclude that the snow cover problem has a minimal effect on the temperature fields. This issue is discussed in more detail by Clark et al. (1999). Nevertheless, we restrict attention to fields of 850-hPa and 700-hPa temperature, sea level pressure, and winds and geopotential height at 700, 500, and 300 hPa. These are designated as ''A'' (i.e., analyzed) variables meaning that they are strongly constrained by data assimilation (e.g., rawinsonde reports). We are aware of the recently completed NCEP–Department of Energy Atmospheric Model Intercomparison Project Reanalysis (1979 onward) that incorporates fixes to a number of problems (including snow cover) identified in the original NCEP–NCAR effort. However, we feel that use of the NCEP–NCAR fields is justified based on both the longer record available and our use of A variables only.

TABLE 1. Number of days (and % of record) when anomalies in east Asian snow extent are $>500\ 00\ \mathrm{km}^2$ ($<-500\ 000\ \mathrm{km}^2$) for the three temporal windows.

	Positive anomalies		Negative anomalies	
	No. days	%	No. days	%
Nov–Dec	294	21	294	21
Jan–Feb	136	10	092	07
Mar–Apr	246	17	246	17

3. Methods

Our approach has three main steps: 1) quantify the timescales of variability in snow extent over eastern Asia, 2) examine changes in atmospheric circulation associated with snow cover extremes, and 3) diagnose the role of storm track feedbacks in reinforcing circulation anomalies. Analyses in steps two and three are based on composites of climate fields, constructed for days that had a snow cover anomaly exceeding 500 000 km^2. Composites of sea level pressure are constructed separately for November–December (ND), January–February (JF), and March–April (MA) to assess seasonalities in the circulation response. The number of days in each composite is documented in Table 1. The local statistical significance in each of the circulation composites was evaluated from *t* tests (Panofsky and Brier 1963). To account for day to day persistence, we use an effective sample size computed on the basis of the first-order autocorrelation at each grid point (Mitchell et al. 1966).

Storm track feedbacks are examined because previous work (e.g., Lau 1988) shows that eddy activity plays a strong role in reinforcing circulation anomalies. Our diagnosis uses the transient eddy meridional temperature flux at 700 hPa (as an indicator of high-frequency eddy activity), as well as computations of the feedback of these eddies on the mean flow. The eddy feedback (S) is computed at 300 hPa following Holopainen et al. (1982):

$$S = -\nabla^{-2}(\boldsymbol{\nabla} \cdot \overline{\mathbf{V}'\zeta'}), \tag{1}$$

where $\mathbf{V}$ is the velocity vector and ζ is the relative vorticity (computed from the wind field). The overbar represents a 5-day moving average, and the primes departures from that average. Equation (1) describes the convergence of the vorticity flux associated with synoptic-scale transient eddies, and may be considered as the forcing of the mean streamfunction induced by synoptic-scale transients (Hoskins et al. 1983).

4. Results and discussion

a. *Timescales of variability in snow extent*

Plots of the seasonal march of east Asian snow extent for each year are provided in Fig. 1 (solid lines). Reproduced in every panel for reference is the climatological mean seasonal march in snow extent (dotted lines). It is apparent that, like air temperature, anomalies in snow extent are of much smaller magnitude than the seasonal cycle. Also, the weekly anomalies do not generally persist for much longer than a month. Note from Fig. 1 that the year 1988/89 examined by Watanabe and Nitta (1998) is one of the few years in the satellite record for which snow cover anomalies persisted for an extended period of time. Large anomalies in snow extent (e.g., $>500\ 000\ \mathrm{km}^2$) tend to occur more frequently in transitional seasons than in midwinter (see Table 1).

The lack of persistence in east Asian snow cover anomalies beyond about a week is also evident in the lag-correlation statistics presented in Table 2. In a regional assessment of snow cover variability, Frei (1997) showed that snow cover in east Asia exhibited the lowest persistence of all regions in the Northern Hemisphere. The low persistence may in part reflect a negative (self-regulating) snow cover feedback suggested by Walland and Simmonds (1997). They suggest that the cooling by anomalously extensive snow cover strengthens the Siberian high over eastern Asia, increasing the static stability of the lower troposphere. This results in a decrease in precipitation, limiting further advance of the snow field. Similarly, anomalously reduced snow cover weakens the Siberian high and decreases the static stability of the lower troposphere, resulting in increases in precipitation and advance of snow cover.

The relatively short timescale of snow cover variability in east Asia is somewhat at odds with observational analyses that show significant relationships between extremes in Eurasian snow cover in autumn and atmospheric circulation over the Northern Hemisphere during winter (e.g., Foster et al. 1983; Cohen and Entekhabi 1999; Watanabe and Nitta 1999). Invoking Occam's Razor, the most straightforward interpretation of our results is that the lack of persistence in east Asian snow cover negates the utility of snow extent as a predictor in seasonal climate outlooks. However, it may be possible to consider snow cover anomalies in autumn acting as a precursor (or a ''trigger'') to influence atmospheric circulation in the subsequent winter. The physical basis for such a relationship, however, is not clear.

The short timescale is also very important with regard to the interpretation of our results that follow. Since the timescale of snow cover variability is not much longer than the timescale of synoptic variability, it is impossible to separate the effect of variations in snow extent on atmospheric circulation from the effect of atmospheric variability on snow extent. One can only determine whether the associations between snow cover extremes and atmospheric circulation are consistent with model results.

b. *Associations between extremes in snow extent and circulation in midwinter*

Composites of the 850-hPa temperature field, 300-hPa zonal wind, and 500-hPa height for midwinter (Jan-

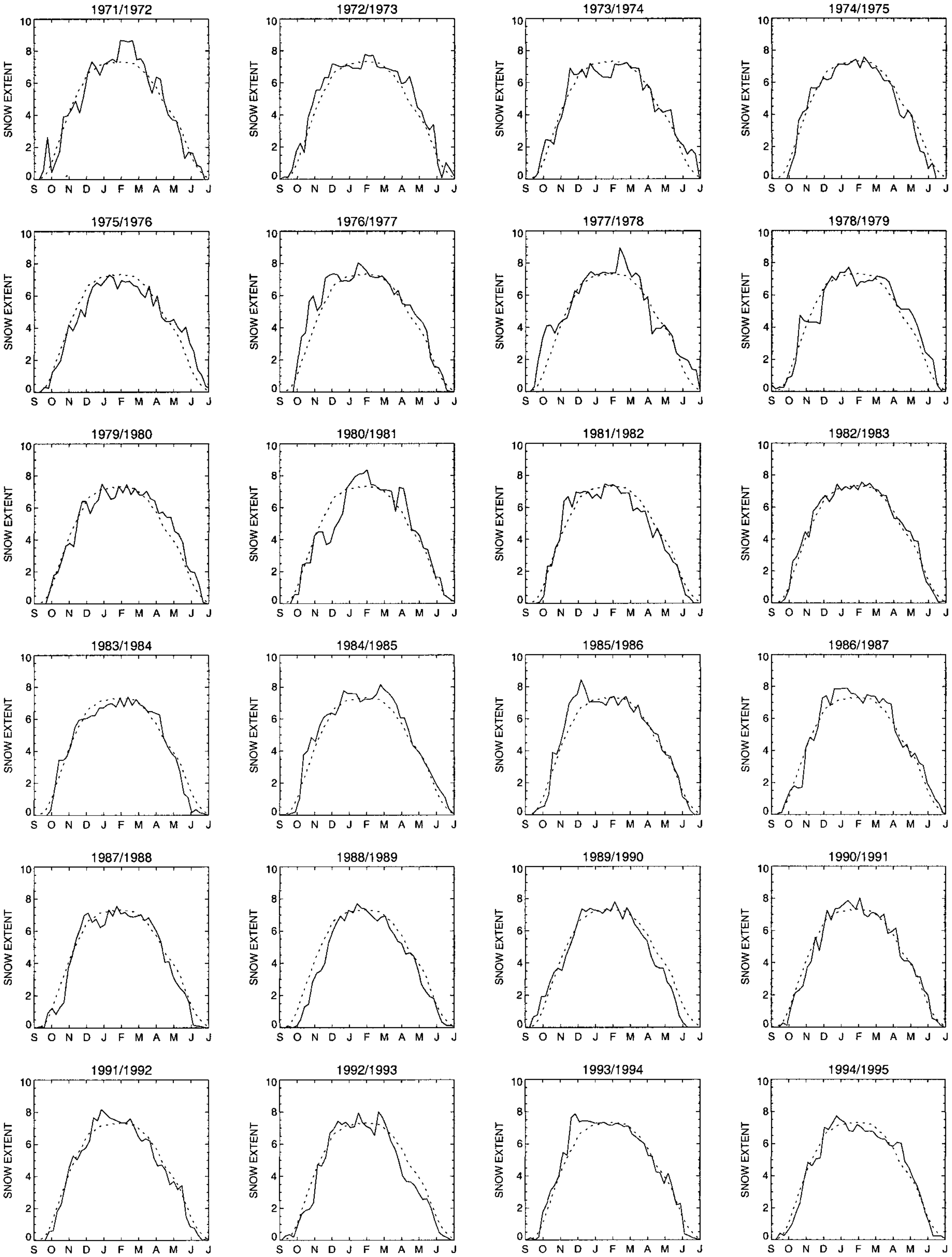

FIG. 1. Seasonal cycle of snow-covered area in east Asia (105°–150°E) as given by the weekly NOAA snow charts for each year of the satellite record (solid lines). Reproduced in every panel for reference is the climatological mean seasonal march in snow extent (dotted lines). Units are in million km^2.

TABLE 2. Lag-correlation coefficients of the east Asian snow extent time series.

Lag	r
1 week	0.65
2 weeks	0.37
3 weeks	0.22
4 weeks	0.09

uary–February) are presented in Fig. 2 for days when anomalies in east Asian snow extent are greater than 500 000 km^2 (positive extremes) and in Fig. 3 for days when anomalies are less than 500 000 km^2 (negative extremes). In positive snow cover extremes, the temperature anomalies at 850 hPa show a small cooling (1°–2°C) over the transient snow regions in east Asia (Fig. 2). This result is not surprising due to the increased albedo. Similar results are documented in many previous studies (e.g., Namias 1985; Cohen and Rind 1991; Leathers and Robinson 1993; Groisman et al. 1994; Leathers et al. 1995). Other things being equal, one would expect the below-normal air temperatures to strengthen the local meridional temperature gradient in the vicinity of the east Asian jet, and increase the strength of the zonal wind. Indeed, the 300-hPa zonal wind composites show a strengthening and eastward expansion of the east Asian jet. Consistent with these changes, the 500-hPa height composites in positive snow cover extremes depict amplification of the tropospheric wave train over North America (note also the southward shift in the eastern North American jet evident in the zonal wind composites). Signals for negative snow cover extremes generally mirror those for positive extremes (Fig. 3). Note the small positive temperature anomalies over the transient snow regions in east Asia, the weakening and contraction of the east Asian jet, and the dampening of the tropospheric wave train over North America.

These associations between snow and circulation cannot, however, necessarily be attributed to the effects of snow cover variations in actively forcing atmospheric circulation. An equally plausible scenario is that the snow cover variations in east Asia are simply a response to variations in atmospheric circulation. On synoptic timescales, a baroclinic wave may deposit snow in east Asia (increase snow cover) and migrate eastward and deepen over the North Pacific Ocean, without any influence of the snow cover itself. On longer timescales,

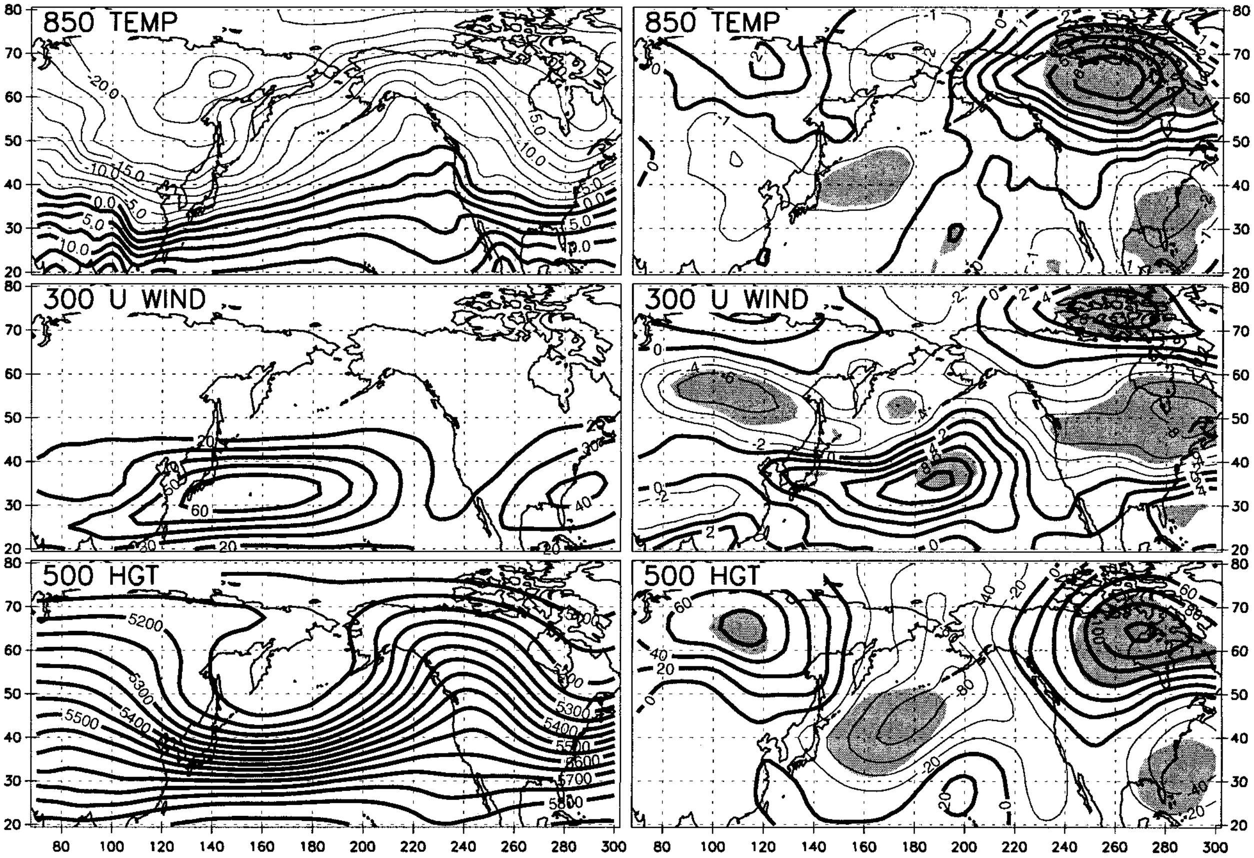

FIG. 2. Composites of 850-hPa air temperature (°C), 300-hPa zonal wind (m s^{-1}), and 500-hPa geopotential height (m) for positive snow cover extremes in Jan–Feb. The total fields are displayed on the left and the anomalies are displayed on the right. Areas locally significant at 95% are shaded.

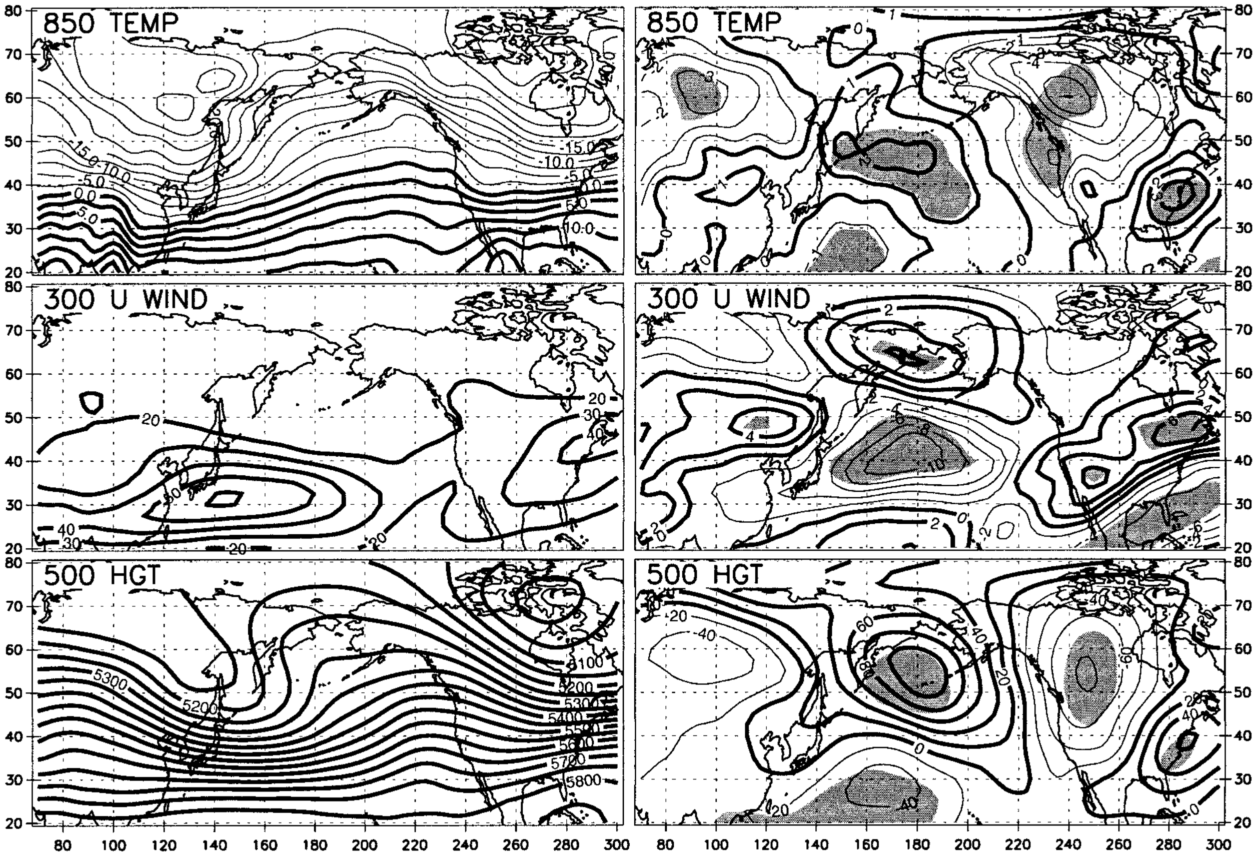

FIG. 3. Composites of 850-hPa air temperature (°C), 300-hPa zonal wind (m s^{-1}), and 500-hPa geopotential height (m) for negative snow cover extremes in Jan–Feb. The total fields are displayed on the left and the anomalies are displayed on the right. Areas locally significant at 95% are shaded.

the composites in Figs. 2 and 3 may simply depict a wave train emanating from the tropical Pacific influencing east Asian snow cover as a by-product. Composites of SST (not shown) do reveal negative SST anomalies in the tropical Pacific Ocean (La Niña conditions) when east Asian snow cover is below normal. No significant SST signals are evident in the tropical Pacific in positive east Asian snow cover extremes. The tropical SST anomalies in negative snow cover extremes will contribute to the circulation anomalies in Fig. 3. In a model study of the relative impacts of east Asian snow cover anomalies and tropical Pacific SST anomalies on circulation during the 1988/89 La Niña event, Watanabe and Nitta (1998) demonstrated that the effects of snow cover forcing were roughly 60% of the amplitude of the effects of tropical SST anomalies.

Of interest in our results is that the small snow cover anomalies (Fig. 1) and the small temperature anomalies (Figs. 2 and 3) are associated with large changes in atmospheric circulation downstream. This suggests that, if variations in snow cover are actively forcing changes in circulation, the signals associated with snow cover must be amplified by the internal dynamics of the climate system. Numerous investigations have shown that barotropic forcing by high-frequency transient eddies can play a strong role in reinforcing anomalies in geopotential height. This has been shown for extremes of the PNA (or PNA-like) teleconnection pattern, where the forcing induced by transient eddies is collocated with the geopotential height anomalies (e.g., Lau 1988). Klasa et al. (1992) show that the forcing by the high-frequency eddies can induce the observed height anomalies associated with extreme phases of the PNA teleconnection on a timescale of 6–10 days. Similar arguments have been invoked to explain part of the extratropical response to El Niño events (e.g., Hoerling and Ting 1994). The role of nonlinear feedbacks associated with synoptic-scale eddies is examined in the following section.

c. Storm track feedbacks

Composites of the transient eddy meridional temperature flux (used as a proxy of high-frequency eddy activity) computed from the reanalysis data at 700 hPa, and the associated forcing of these eddies on the mean flow [Eq. (1)] are presented in Fig. 4 (positive snow cover extremes) and Fig. 5 (negative snow cover ex-

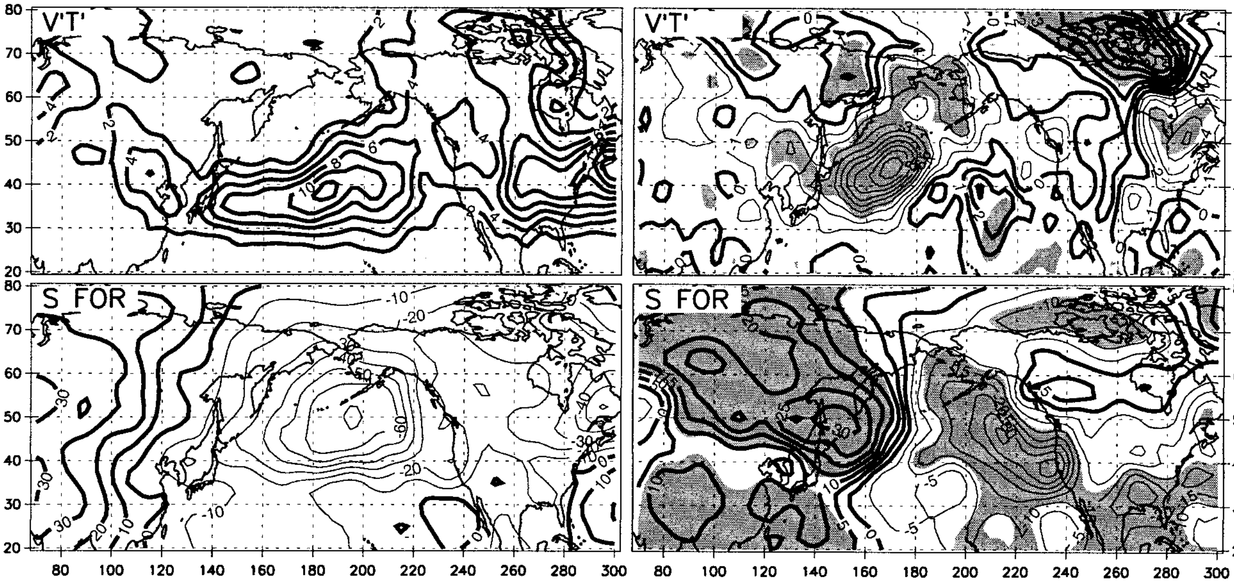

FIG. 4. The high-frequency meridional temperature flux ($v'T'$) at 700 hPa (top) and the barotropic forcing of the mean streamfunction as determined by the convergence of the vorticity flux (bottom) for positive snow cover extremes in Jan–Feb. The total fields are displayed on the left and the anomalies are displayed on the right. Areas locally significant at 95% are shaded.

tremes) for midwinter (January–February). In the eddy-forcing composites, negative values locally induce cyclonic circulation (negative geopotential tendency) and positive values induce anticyclonic circulation (positive geopotential tendency). In positive snow cover extremes, results for the total field show both strong high-frequency eddy activity and a strong cyclonic forcing of these eddies on the mean flow in the central North Pacific Ocean. However, in the western Pacific Ocean the anomaly composites actually show significant reductions in eddy activity and a reduction in the cyclonic forcing of the mean flow. Significant increases in the cyclonic forcing of the mean flow are evident in the eastern Pacific Ocean, although these increases are located farther east of the strongest height anomalies (Fig. 2), and will not act to reinforce the circulation anomalies. In negative snow cover extremes, significant decreases in eddy activity and the cyclonic forcing of the

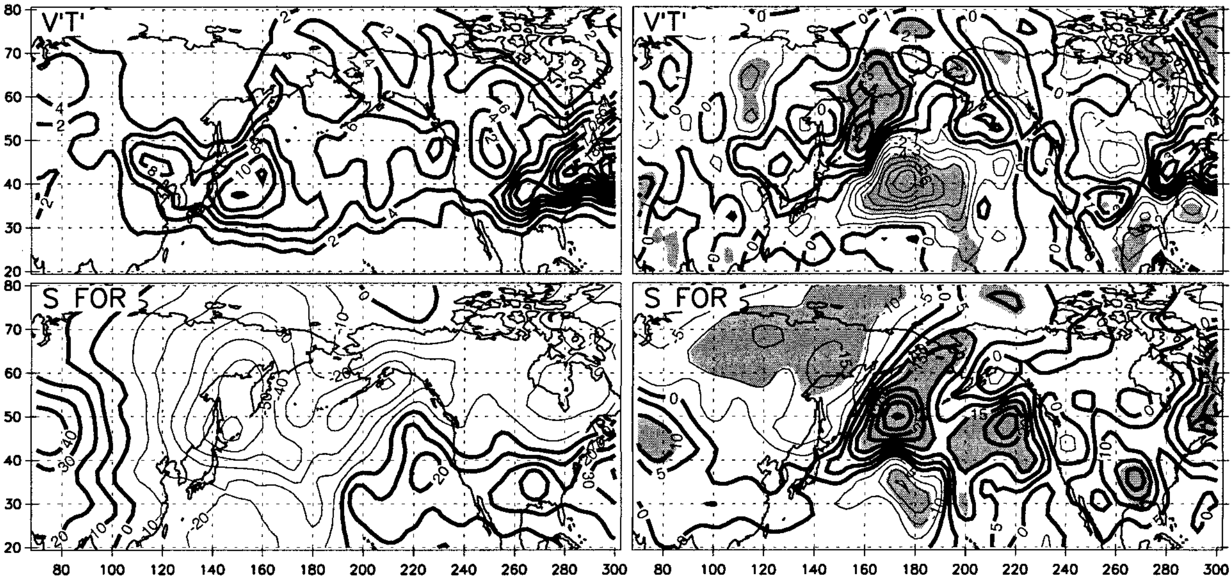

FIG. 5. The high-frequency meridional temperature flux ($v'T'$) at 700 hPa (top) and the barotropic forcing of the mean streamfunction (bottom) for negative snow cover extremes in Jan–Feb. The total fields are displayed on the left and the anomalies are displayed on the right. Areas locally significant at 95% are shaded.

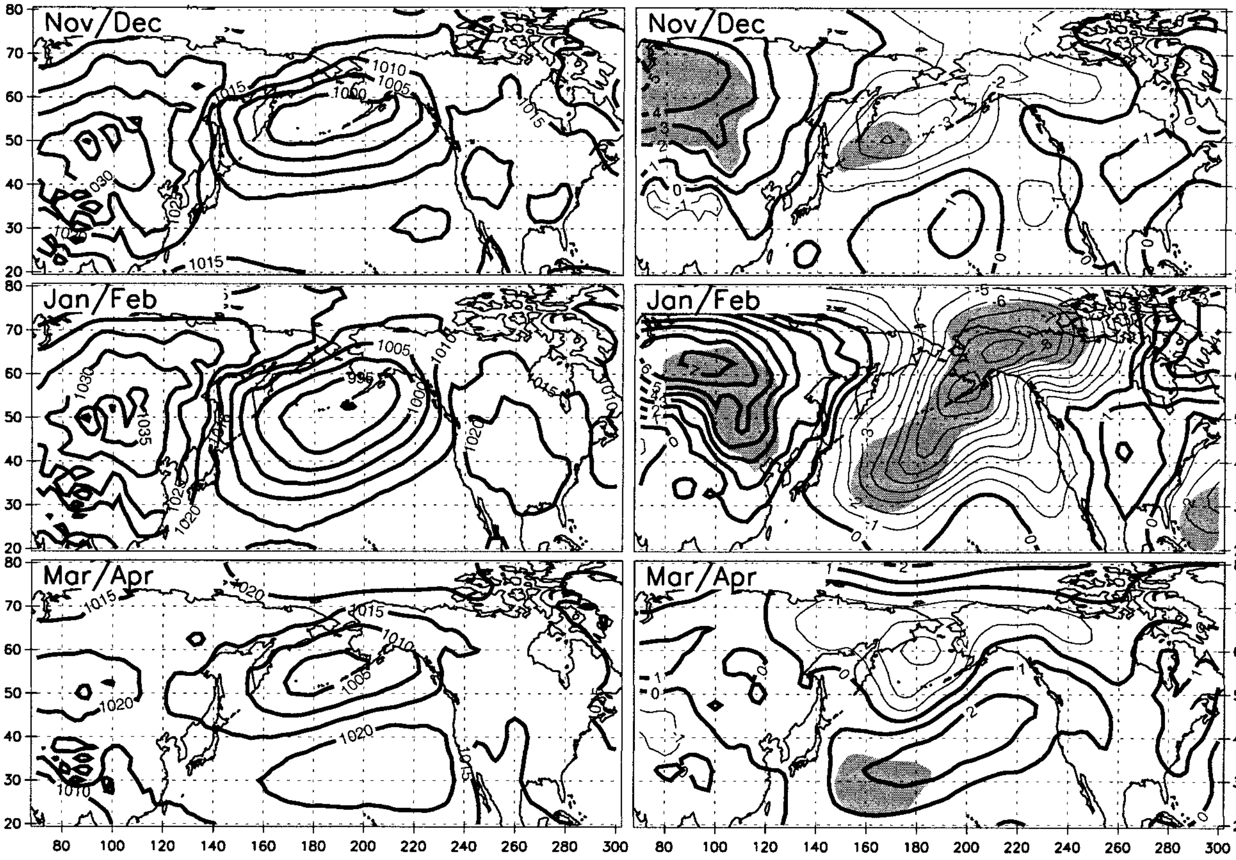

FIG. 6. Composities of SLP (hPa) for positive snow cover extremes in Nov–Dec (top), Jan–Feb (middle), and Mar–Apr (bottom). The total fields are displayed on the left and the anomalies are displayed on the right. Areas locally significant at 95% are shaded.

mean flow are found over the central North Pacific (Fig. 5). Contrary to the positive extremes, the eddy forcing is collocated with the height anomalies (Fig. 3), thus contributing to the observed circulation anomalies.

The reduction in storm activity in the western Pacific Ocean in positive snow cover extremes in midwinter (Fig. 4) occur during periods when the baroclinicity in the lower troposphere and the intensity of the upper-level jet stream is significantly above average. By comparison, composites of high-frequency eddy activity and eddy feedbacks for positive snow cover extremes in the transitional seasons (not shown) depict an increase in eddy activity and an increase in the cyclonic forcing of the mean flow. These seasonal differences appear to be related to the midwinter suppression of high-frequency eddy activity in the western Pacific Ocean. Using 20 yr of daily data from the NMC operational analyses, Nakamura (1992) demonstrated that baroclinic wave activity is positively correlated with the strength of the upper-tropospheric jet up to wind speeds of ~45 m s^{-1}. However, when the strength of the westerlies exceeds this value, as is common in midwinter, the correlation turns negative. Nakamura suggests that this occurs, in the broadest sense, because the baroclinic waves generated or triggered in a region of very strong westerlies are not able to remain in the region long enough to attain very large amplitudes. Our composites show the upper-tropospheric zonal wind speed in midwinter is significantly above normal in the positive east Asian snow cover extremes (Fig. 2). Upper-level westerlies over broad areas of the North Pacific Ocean are frequently above 45 m s^{-1}. The eddy suppression in the western Pacific Ocean (Fig. 4) is hence in accord with Nakamura's view. In negative snow cover extremes, the upper-level jet is significantly weaker than normal over broad areas of the western and central Pacific Ocean (Fig. 3), with many composite members falling into the regime where changes in the strength of the zonal wind are positively correlated with baroclinic wave activity. In turn, Fig. 5 reveals decreases in high-frequency eddy activity, and a decrease in the mean cyclonic forcing of these eddies on the height field. In support of these results, in their model simulation with negative east Asian snow cover anomalies, Watanabe and Nitta (1998) found that feedbacks from high-frequency transient eddies contributed to the positive anomalies in geopotential height over the North Pacific Ocean.

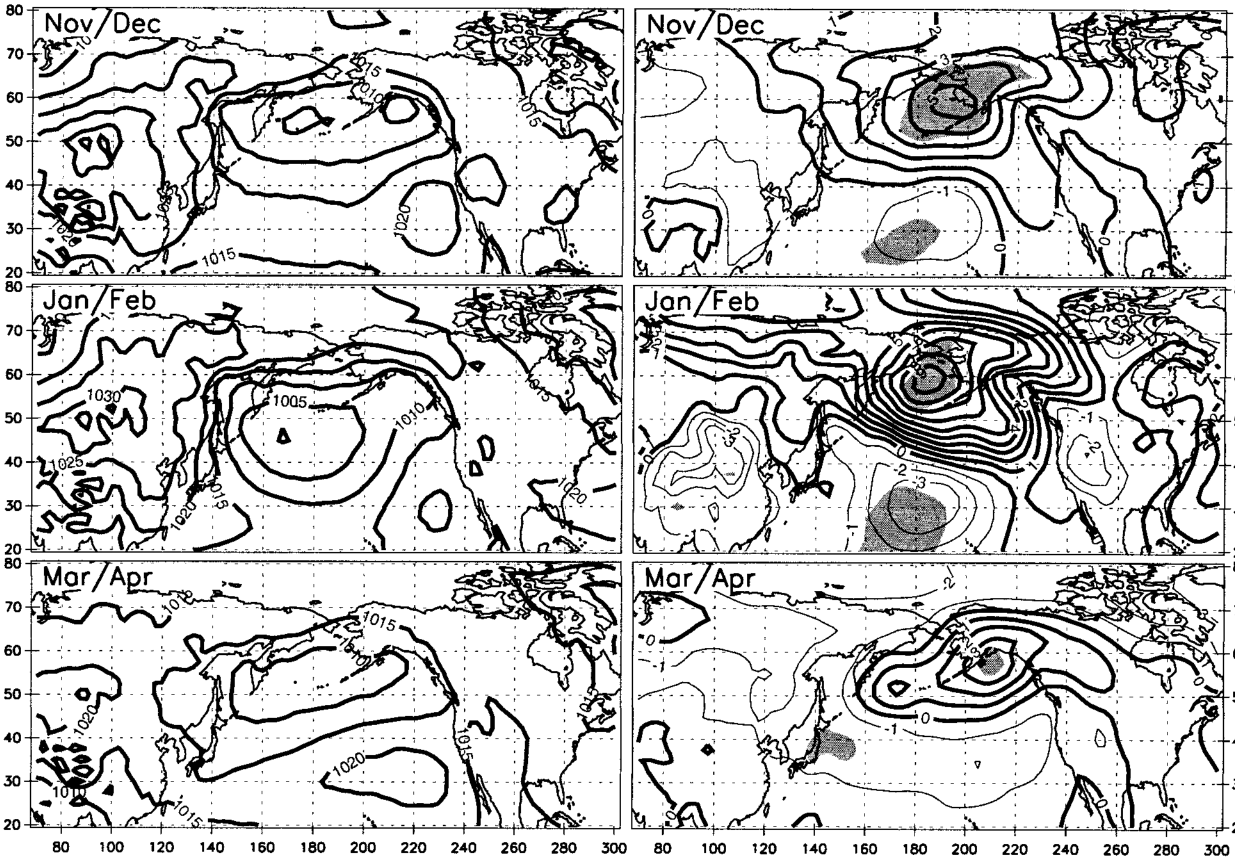

FIG. 7. Composites of SLP (hPa) for negative snow cover extremes in Nov–Dec (top), Jan–Feb (middle), and Mar–Apr (bottom). The total fields are displayed on the left and the anomalies are displayed on the right. Areas locally significant at 95% are shaded.

d. Seasonal variations

To illustrate seasonal changes in the circulation signals, we constructed composites of SLP for ND, JF, and MA for positive (Fig. 6) and negative (Fig. 7) snow cover extremes. It is apparent that the circulation signals over the North Pacific Ocean are much more pronounced during midwinter than in the other temporal windows. Similar seasonal contrasts are evident in composites of the 300-hPa zonal wind and 500-hPa height (not shown). In the context of a possible snow cover forcing, this result represents somewhat of a paradox, as the east Asian snow cover anomalies are much smaller in the middle of winter than in the other temporal windows (see Fig. 1 and Table 1).

A priori, one would expect the smaller snow cover anomalies to be associated with a smaller remote signal, but the opposite appears to be true. In the broadest sense, one may interpret this result as reflecting the stronger and eastward-extended east Asian jet in midwinter. With an eastward-extended jet, the region of highest cyclonic shear will tend to be shifted east, and thus perturbations in the meridional temperature gradient over east Asia may have a stronger influence on the amplitude of the wave train over North America than in the transitional seasons when the jet is contracted. Another possible explanation is that the perturbations in the temperature field associated with snow cover anomalies are located closer to the east Asian jet in midwinter, and thus may exert a stronger influence on downstream circulation (Holton 1992). On the other hand, it may be simply that the snow deposited by migratory baroclinic waves over east Asia is less likely to be reflected in anomalies in snow extent as snow cover in the middle of winter is already extensive. With regard to these hypotheses, recall that Nakamura (1992) shows that baroclinic wave activity in the western Pacific is actually suppressed in midwinter when the low-level regional baroclinicity and the strength of the east Asian jet is maximized. Further modeling studies are needed to clarify these issues.

5. Summary and conclusions

Existing modeling studies suggest that variations in Eurasian snow extent have a strong influence on atmospheric circulation over the North Pacific Ocean. The goal of the present investigation is to assess if the signals seen in model climates are actually observed in nature. Examination of weekly satellite data shows that snow extent anomalies over east Asia exhibit a distinct lack of persistence. This demonstrates that understanding the effect of east Asian snow cover is more germane for short- to medium-range weather forecasting applications than for problems on longer timescales. Observed associations between snow cover extremes and atmospheric circulation lend support to the model results. Specifically, positive snow cover extremes over east Asia are associated with a small decrease in air temperatures over the transient snow regions, a stronger east Asian jet, and an amplification of the 500-hPa wave train over North America. By restricting our analysis primarily to analyzed fields above the boundary layer and downstream of the Eurasian continent, we are not overly concerned with potential contamination of our results by NCEP's inadvertent use of 1973 snow cover throughout the period examined in this study.

An interesting aspect of these relationships is that the relatively small snow cover and temperature anomalies over east Asia are associated with large and significant changes in circulation over the North Pacific Ocean. This suggests that, if variations in snow cover are actively forcing changes in circulation, the signals associated with snow cover must be amplified by the internal dynamics of the climate system. Diagnosis of storm track feedbacks shows that the action of high-frequency eddies does not reinforce circulation anomalies in positive snow cover extremes. However, in negative snow cover extremes, our analysis reveals significant decreases in high-frequency eddy activity over the central North Pacific Ocean, and a corresponding decrease in the mean cyclonic effect of these eddies on the geopotential tendency, thus contributing to the observed positive height anomalies over the North Pacific Ocean. The circulation signals over the North Pacific Ocean are much more pronounced in midwinter (JF) than in the transitional seasons (ND and MA), despite the observation that large snow cover anomalies are more frequent in the transitional seasons.

The obvious caveat of our study is that we cannot separate cause from effect. Given the remarkable similarity between circulation responses simulated by models and the signals indentified in our empirical study, a reasonable interpretation of our results is that east Asian snow cover is actively forcing downstream circulation anomalies. However, an equally plausible explanation is that east Asian snow cover is simply responding to variations in atmospheric circulation. On synoptic timescales, a baroclinic wave may deposit snow in east Asia (increased snow cover), migrate eastward, and deepen over the North Pacific Ocean, without any influence of the snow cover itself. On longer timescales, our composites may simply depict a wave train emanating from the tropical Pacific, that influences east Asian snow cover as a by-product. Since the modeling studies reviewed earlier have used large and persistent snow cover anomalies that are rarely observed in nature, we argue that our findings point to the need for further model sensitivity studies using more realistic snow cover anomalies.

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