Physical Mechanisms of the Wintertime Surface Air Temperature Variability in South Korea and the near-7-Day Oscillations

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ABSTRACT

The first three principal modes of wintertime surface temperature variability in Seoul, South Korea (37.33°N, 126.59°E), are extracted from the 1979–2008 observed records via cyclostationary EOF (CSEOF) analysis. The first mode represents the seasonal cycle, the principle physical mechanism of which is associated with the continent–ocean sea level pressure contrast. The second mode mainly describes the overall wintertime warming or cooling. The third mode depicts subseasonal fluctuations of surface temperature. Sea level pressure anomalies to the west of South Korea (eastern China) and those with an opposite sign to the east of South Korea (Japan) are a major physical factor both for the second mode and the third mode. These sea level pressure anomalies with opposite signs alter the amount of warm air to the south of South Korea, which changes the surface temperature in South Korea. The PC time series of the seasonal cycle is significantly correlated with the East Asian winter monsoon index and exhibits a conspicuous downward trend. The PC time series of the second mode exhibits a positive trend. These trends imply that the wintertime surface temperature in South Korea has increased and the seasonal cycle has weakened gradually over the past 30 yr; the sign of greenhouse warming is clear in both PC time series.

The near-7-day oscillations are a major component of high-frequency variability in much of the analysis domain and are a manifestation of Rossby waves. Rossby waves aloft result in the concerted variation of physical variables in the atmospheric column. Due to the stronger mean zonal wind, the disturbances by Rossby waves propagate eastward at ~8–12 m s⁻¹; the passing of Rossby waves with alternating signs produces the near-7-day temperature oscillations in South Korea.

1. Introduction

One of the strongest manifestations of greenhouse warming in South Korea is the increasing wintertime surface temperature (Ryoo et al. 2004). Although the observation records clearly show this warming, a detailed examination or explanation of the nature of this warming has not been attempted in any serious manner. It is extremely important to understand how the increasing concentration of greenhouse gases alters the wintertime physical mechanisms in South Korea and how the changing physical mechanisms, in turn, alter the surface temperature in South Korea.

On a short time scale, short waves propagating in the northwesterly flow initiate descent in the region of the East Asian coast. These short waves usually initiate rapid cyclogenesis in the highly baroclinic flow off the Korean Peninsula (Boyle 1986).

Cold surges are one of the dominant wintertime features in South Korea. A composite of six individual cold-air outbreaks over South Korea during 1985–86 shows that the development of a surge over South Korea is preceded by a ridge to the west of Lake Baikal and a trough over the East Asian coast (Boyle 1986; Park and Kim 1987). This wavelike disturbance accompanied by a cold-air outbreak experiences a systematic structural change as it propagates southeastward with a phase speed of ~10° day⁻¹ from Lake Baikal toward South Korea. This wave, with a cold trough and a warm ridge, is typically characterized by a wavelength of about 4000 km (Park and Kim 1987). Active transient disturbances—a zone of strong baroclinicity—develop over East Asia near the downstream region of the climatological jet during cold surges (Blackmon et al. 1977). The cold surge circulation has a strong effect on the zonal momentum budget in the
vicinity of the maximum East Asian jet (Boyle 1986). A composite of cold surge events also showed that an upper-level baroclinic wave of $\sim 60^\circ$ wavelength propagates eastward from the west of Lake Baikal toward the eastern coast of China with a phase speed of $12^\circ \text{ day}^{-1}$ causing a cold-air outbreak in South Korea (Ryoo et al.

Cold surges during winter not only dominate local weather but also have a strong impact on the extratropical and tropical planetary-scale circulations in East Asia (Chang and Lau 1982). The East Asian cold surge has been studied as one of most conspicuous features of the Asian winter monsoon. Cold surges along the south China coast enhance the local Hadley circulation over East Asia by strengthening cold advection over northern China, which in turn causes additional upper-level divergence over the equatorial South China Sea (Chang et al. 1979; Chang and Lau 1980, 1982; Chu and Park 1984).

In contrast to daily weather changes in the middle latitudes, which are mostly characterized by baroclinic disturbances, the causes of low-frequency atmospheric variability are not well understood (Wallace and Blackmon 1983). During the winter monsoon, it is frequently observed that a huge anticyclone over Siberia dominates the low-level circulation over Asia, giving rise to strong northerly and northeasterly winds covering the entire region of central and northern China and the South China Sea. Indeed, the variability of the wintertime temperature in South Korea on a monthly temporal scale is roughly explained in terms of the strength of the Siberian high and the Aleutian low. Cold winters are accompanied by the intensification of the Siberian high and/or the Aleutian low, which develops a stronger East Asian jet in the upper troposphere (Kang 1988; Ryoo et al. 2002; Yang et al. 2002). Under these conditions, the monthly winter temperature in South Korea is significantly influenced by stronger lower-tropospheric northerly monsoonal flow over the eastern coast of Asia (Kang 1988; Yang et al. 2002). In fact, the intensification of the Siberian high and the Aleutian low is positively correlated with the winter temperature in South Korea (Ryoo et al. 2002).

While some of physical mechanisms that lead to surface temperature variability on various time scales have been investigated, it is largely unknown how greenhouse warming affects these physical mechanisms. Thus, the primary focus of this study is on understanding the physical mechanisms associated with the variability of the wintertime surface temperature in South Korea. Specifically, this study attempts to address how greenhouse warming manifests itself in different physical processes governing wintertime surface temperature variations. The physical mechanism of the $\sim 7$-day oscillations, also called the three-cold-day/four-warm-day events, is also investigated in order to address if greenhouse warming caused any changes in either the magnitude or the nature of this particular phenomenon.

The data employed in this study are described in section 2, followed by a description of the CSEOF analysis, which is the major analysis tool in the present study, and the regression technique, which is used to extract physically consistent patterns of key variables. The latter technique is used to understand the physical mechanism of the major modes of surface temperature variability and the $\sim 7$-day oscillations. The results of the analysis are discussed in section 4 with specific emphasis on the physical nature of the surface temperature variability in South Korea. Concluding remarks and the summary are presented in section 5.

2. Data

The 30-yr (1979–2008) observations of surface temperatures in Seoul, South Korea ($37.33^\circ \text{N}, 126.59^\circ \text{E}$), were acquired from the Korea Meteorological Administration. The data are from a daily averaged time series at a station in Seoul. Then, $2.5^\circ \times 2.5^\circ$ arrays of daily temperatures, geopotential heights, and winds at standard levels from 1000 to 200 hPa were extracted from the daily National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset for the same period (Kalnay et al. 1996). In addition to these data, daily NCEP–NCAR 2-m air temperature and 10-m wind were used in the analysis; they come at a zonal resolution of 1.875$^\circ$ with 94 Gaussian levels in the meridional direction. The potential vorticity (PV) was calculated by first calculating potential temperature $\theta$ in the form

$$
\theta = T \frac{p}{p_0} R \frac{\partial \psi}{\partial p},
$$

where $R$ is the universal gas constant and $\psi$ is the specific heat capacity at constant pressure. Then, PV is given by

$$
\psi = g(f + \zeta) \frac{\partial \theta}{\partial p},
$$

where (2) was evaluated using finite differencing between two adjacent pressure levels.

To investigate the wintertime variability, 120 days from 17 November through 16 March were taken from each winter for the 29 winter seasons in the record. Thus, each year represents 120 winter days. For leap years, 29 February was averaged with 28 February to have a nested period of exactly 120 days. The same 120 winter days were used for all the datasets employed in the present study. The analysis domain is composed of East
Asia (22.5°–72.5°N, 97.5°–152.5°E) for all the variables except PV. The PV data were analyzed over the entire zonal band extending from 30° to 80°N; this is to facilitate the computation of zonal wavenumbers of Rossby waves.

3. Method

a. CSEOF analysis

To separate the physical processes from the datasets, the CSEOF technique was employed (Kim et al. 1996; Kim and North 1997). In this method, space–time data, $T(r, t)$, are written as a linear superposition of the CSEOFs:

$$T(r, t) = \sum_n LV_n(r, t)PC_n(t),$$  \hspace{1cm} (3)

where $LV_n(r, t)$ and $PC_n(t)$ are cyclostationary loading vectors and principal component (PC) time series, respectively. The CSEOF representation of the data is different from the EOF representation in that the loading vectors are time dependent and periodic; that is,

$$LV_n(r, t) = LV_n(r, t + d),$$  \hspace{1cm} (4)

where $d$ is called the nested period. It is emphasized that the CSEOF loading vectors represent temporally evolving physical processes, whereas the PC time series represent the amplitude modulation of the physical processes on longer time scales. Examples of physical and dynamical interpretations of CSEOFs can be found in the recent literature (Seo and Kim 2003; Kullgren and Kim 2006; Kim et al. 2006; Lim and Kim 2007).

The nested period, $d$, represents the periodicity of the space–time covariance function and is associated with the inherent time scales of the physical processes. As can be seen in (4), the nested period should be long enough to include all of the different periods of the physical processes in the dataset; in fact, it should be the least common multiple of all of the different physical periods in a given dataset. In this study, the nested period is assumed to be 1 yr; this implies that the statistical properties of each physical process do not vary from one year to another although realizations of a physical process vary from one year to another. The nested period is an important caveat for the CSEOF technique. Nonetheless, finding a suitable nested period has not posed any serious problem in applying the CSEOF technique as demonstrated in the papers addressed above.

b. Regression analysis

To understand the detailed physical nature of physical processes, many important physical variables will be subject to CSEOF analysis in the present study. This means that physically and dynamically consistent patterns should be derived from many variables. This is accomplished in the following manner. A CSEOF analysis is conducted on each physical variable. Then, the PC time series of a target variable (say, temperature) is written as a linear regression of the PC time series of a predictor variable (say, sea level pressure). That is,

$$PCT_i(t) = \sum_n a_n^iPC_n(t) + \epsilon(t),$$  \hspace{1cm} (5)

where $PCT_i(t)$ is the target PC time series for mode $i$, $PC_n(t)$ is the predictor time series for mode $n$, and $\epsilon(t)$ is the regression error time series. The regression coefficients $a_n^i$ are determined such that the variance of the regression error time series is minimized. The degree of fitting for each mode is measured by $r_i^2 = 1 – \text{var}[\epsilon(t)]/\text{var}[PCT_i(t)]$.

Then, the spatiotemporal pattern of the predictor variable, $LVP_i(r, t)$, which is consistent with the pattern of the target variable, $LVT_i(r, t)$, is obtained by

$$LVP_i(r, t) = \sum_n a_n^iLV_n(r, t),$$  \hspace{1cm} (6)

where $LV_n(r, t)$ are the CSEOF loading vectors of the predictor variable. Note that $LVT_i(r, t)$ and $LVP_i(r, t)$ are called physically and dynamically consistent within the context of having (nearly) identical amplitude time series, not because of the identical physical evolution. In fact, the spatiotemporal evolution in $LVT_i(r, t)$ and $LVP_i(r, t)$ may, in general, be very different from each other. Note, on the other hand, that $LVT_i(r, t)$ and $LVP_i(r, t)$ have nearly identical amplitude time series. This regression method is equivalent to the so-called projection method when it is applied to EOFs.

4. Results and discussion

Modes of fluctuations of surface air temperature in Seoul have been identified via CSEOF analysis. CSEOF analysis on the wintertime surface air temperature extracts three principal modes of variability, which together explain about 50% of the total variability. In this section, physical and dynamical mechanisms of surface air temperature variability will be investigated based on the first three CSEOF modes extracted from the observational data.

CSEOF analysis has also been conducted on the 2-m surface air temperatures of the NCEP–NCAR daily reanalysis product over the same time interval. Then, regression analysis has been performed as described earlier using 20 predictor modes to identify physical evolution patterns in space and in time associated with the first three principle modes of variability of the wintertime
surface air temperatures in Seoul. Similarly, evolutionary patterns of different physical variables were identified to be consistent with each CSEOF of the observed surface air temperature in Seoul. As a check of the validity of the regressed surface air temperature patterns, the physical evolution pattern at 37.5°N, 127.5°E, the grid point closest to Seoul, was compared with that of the observed time series for the first three modes. The correlations are 0.954, 0.883, and 0.889 for the first three modes, respectively (see Figs. 1, 3, and 7). Thus, the regressed surface air temperature patterns appear to be reasonably consistent with the observed time series in Seoul.

a. The seasonal cycle

CSEOF analysis extracts the seasonal cycle as the first mode of variability, as expected. This mode explains ~33% of the total variability. Figure 1a shows the seasonal cycle of the temperature during the 120 winter days (17 November–16 March) in Seoul as identified from the actual observational data. As can be seen, the surface air temperature in Seoul is at its minimum typically between the end of January and the early February. The corresponding PC time series shows remarkable interannual fluctuations in the amplitude of the seasonal cycle (Fig. 1b). The period of the maximum spectral peak is ~4 yr (figure not shown). The amplitude of the seasonal cycle fluctuates significantly; Figs. 1a and 1b imply that the range of surface temperature variations during the wintertime in association with the seasonal cycle is approximately between 4° and 19°.

There is an interesting trend in the PC time series with a slope of $-0.0371 \text{ yr}^{-1}$ and an estimated error standard deviation of 0.0012. This trend cannot be rejected even at a 99% level; thus, the trend appears to be real. This trend indicates that the strength of the seasonal cycle has steadily decreased at the rate of about 1 unit per 30 years (see Fig. 1b). This implies that the difference between a maximum temperature and a minimum temperature during a winter season as shown in Fig. 1a has been decreasing in the mean sense although there are significant year-to-year variations, as shown in Fig. 1b.

Figure 2 shows the patterns of 2-m air temperature, sea level pressure, and 10-m wind that exhibit the same evolution as that of the surface air temperature in Seoul, shown in Fig. 1a. These patterns were obtained by projecting the regressed evolution of the physical variables onto the evolution of the surface air temperature in Seoul, as shown in Fig. 1a. The time series of the regressed 2-m air temperatures at a grid point closest to Seoul is correlated at 0.954 with the surface air temperature in Seoul, as shown in Fig. 1a. Temperature variations in Seoul as reflected in the seasonal cycle are associated with a general warming–cooling over the entire continental domain considered here (Fig. 2). A positive surface temperature anomaly in Seoul is associated with negative sea level pressure anomalies over the Asian continent and positive sea level pressure anomalies over the northwest Pacific. As a result, southeasterly wind anomalies develop strongly to the south of South Korea, transporting warm air into Seoul. A weakening seasonal cycle implies that the evolution of the patterns of physical variables shown in Fig. 2 from a positive phase to a negative one during winter, on average, has weakened in recent years.

Figure 2 depicts typical patterns of physical variables associated with the East Asian winter monsoon. In fact, the PC time series in Fig. 1b is highly correlated with the East Asian winter monsoon index (Jhun and Lee 2004). This confirms that the seasonal cycle of surface air temperature in Seoul is strongly influenced by the strength of the East Asian winter monsoon, which, in turn, is controlled by the contrasting sea level pressure anomalies between the continent and the ocean.

b. The second CSEOF mode: The subseasonal mode

The second mode describes the wintertime subseasonal fluctuations of surface air temperature in Seoul and explains ~11% of the total variability (Fig. 3a). As shown in Fig. 3, submonthly fluctuations are obvious on top of lower-frequency undulations. The corresponding PC time series shows that there is a noticeable upward trend with a slope of 0.0676 yr$^{-1}$ and an estimated error
standard deviation of 0.0029 (Fig. 3b); the trend is significant at the 99% level. According to the PC time series, the amplitude of this particular mode tends to be positive more often recently than 30 yr ago. This implies that the wintertime surface air temperature tends to be warmer recently than previously since the evolution pattern in Fig. 3a depicts primarily a warming in Seoul throughout the winter. In fact, the reconstruction of the surface temperatures in Seoul using the first two modes shows that the average temperature between 15 January and 15 February has risen by $\mathbf{3.8^\circ C}$ in the past 30 yr, which is consistent with the estimate based on the actual observational data (Fig. 4). The corresponding best auto-regressive (AR) spectrum indicates the maximum spectral peak at $\mathbf{4}$ yr. Thus, the wintertime average surface air temperature in Seoul fluctuates with approximately a 4-yr period.

Correlations between the evolution pattern of the regressed 2-m air temperature in Seoul (conveniently at $37.5^\circ$N, $127.5^\circ$E) and the loading vectors of the regressed variables were computed at each grid point for the second mode. Correlations were computed up to the lag of ±7 days to investigate the lead–lag relationship between the two variables. Figure 5 shows a map of the correlation between the 2-m air temperature anomalies and the sea level pressure anomalies for the second CSEOF mode. The correlation is strongest when the sea level pressure leads the 2-m air temperature in Seoul by 1 day. There are two distinct centers of action: one located over eastern China ($40^\circ$N, $112.5^\circ$E) and the other over northeastern Japan ($42.5^\circ$N, $140^\circ$E). Figure 5 indicates that, in general, negative sea level pressure anomalies are observed over eastern China and positive sea level pressure anomalies are observed over Japan in conjunction with positive surface air temperature anomalies in Seoul. The sea level pressure change over eastern China exerts a stronger influence on the surface air temperature in Seoul than that over Japan.

Figure 6 shows the connection between the 2-m air temperature anomalies at $37.5^\circ$N, $127.5^\circ$E and the sea level pressure anomalies at $40^\circ$N, $112.5^\circ$E and $42.5^\circ$N, $140^\circ$E associated with the second mode; the 2-m air temperature anomalies at $37.5^\circ$N, $127.5^\circ$E are reasonably regressed in terms of the two SLP anomalies at $40^\circ$N, $112.5^\circ$E and $42.5^\circ$N, $140^\circ$E. As shown in Fig. 6, the physical connection between the surface temperature anomalies in Seoul and the SLP anomalies in Fig. 5 is obvious ($\rho = 0.845$), showing clearly that the change in surface air temperature in Seoul is related to the development of the two opposite SLP anomaly patterns in Fig. 5.

Similar analysis with the zonal and meridional wind anomalies shows further that the 2-m air temperature
anomalies in Seoul are physically connected with the easterly wind anomalies and the southerly wind anomalies to the south of South Korea. The maximum correlations are $-0.653$ and $0.682$, respectively. According to the analysis, it can be inferred that the specific SLP anomaly patterns in Fig. 6 develop southeasterly wind anomalies to the south of South Korea, which transport warm air to the north thereby raising the surface temperature in Seoul (Fig. 7). When Seoul is warmer, most of the continental area in the domain and southern Japan tends to be warmer as well. Because of the widespread warming, it has been speculated that the warm/cold air in South Korea comes from Siberia. The present analysis, on the other hand, indicates that the cause of warming in Seoul is the introduction of warm southerly inflow. During the opposite phase, the reversed situation lowers the surface temperature in Seoul. Therefore, Fig. 3 indicates that winter will be warmer than normal in Seoul if the situation depicted in Fig. 5 (or, equivalently, Fig. 7) develops more strongly and/or persists longer.

It should be noted that the SLP anomaly pattern in Fig. 7 bears a strong resemblance with that of the seasonal cycle and suggests that the second CSEOF mode and the seasonal cycle share a similar physical/dynamical mechanism. A distinguishing characteristic of the SLP anomaly pattern in Fig. 7 is its intermittent nature instead of gradual variation during the wintertime as in the seasonal cycle as a comparison between Figs. 1a and 3a shows. In other words, the appearance of the patterns shown in Fig. 7 is sporadic during the wintertime. Another essential difference is that while the seasonal cycle depicted in Fig. 1 occurs every year without a sign change in its amplitude, the sign of the second mode changes from one year to another; this is reflected in the nonzero mean of the amplitude of the seasonal cycle (Fig. 1b) while the mean amplitude of the second mode is nearly zero (Fig. 3b). Once the mean amplitude of the seasonal cycle is removed, however, the two PC time series exhibit a strong negative correlation ($-0.55$). In fact, the trends in the two PC time series have opposite signs. The negative correlation persists even after trends are removed from the two time series ($-0.47$). This strong negative correlation, then, implies that the amplitude change of the seasonal cycle is, in general, accompanied by the change in the wintertime mean temperature as shown in the second CSEOF mode. Specifically, wintertime warming with a positive amplitude of the second mode tends to be followed by a decrease in the amplitude of the seasonal cycle. As addressed earlier, the PC time series of the seasonal cycle is significantly positively correlated with the East Asian winter monsoon index; a high East Asian winter monsoon index, then, implies not only the increased seasonal cycle in Seoul but also the decreased wintertime temperature in Seoul (Jhun and Lee 2004).
Further examination of the corresponding loading vectors indicates that the SLP pattern in Fig. 7 does not show any significant sign of propagation. Thus, the patterns of SLP anomalies and wind anomalies shown in Figs. 5 and 7 are essentially standing anomaly patterns. Figure 3b indicates that the average wintertime temperature has steadily increased in the past three decades with lower SLPs over the continent and higher SLPs over the northwestern Pacific. The positive trend in Fig. 3b has not risen above the level of natural variability but its presence is confirmed at a 99% confidence level.

c. The third CSEOF mode: The intraseasonal mode

Figure 8a shows the evolution of surface air temperature associated with the third CSEOF mode, which explains ~6% of the total variability. The physical evolution shown in Fig. 8a is populated with ~7–8-day oscillations with nearly zero mean through the winter. Thus, this mode does not contribute significantly to the overall wintertime warming or cooling in South Korea. Instead, this mode represents brief cooling–warming events on time scales of a few days. Figure 8b shows the corresponding PC time series with a very mild positive trend with a spectral peak at ~3.4 yr.

Figure 9 shows the patterns of the 2-m air temperature anomalies and the SLP and wind anomalies for the third CSEOF mode. These patterns are fairly similar to those of the second CSEOF mode except they extend beyond 60°N. As in the second CSEOF mode, the surface temperature in Seoul is associated with the SLP anomalies of opposite signs to the west and the east of South Korea and the ensuing wind anomalies to the south of South Korea. Thus, it is simply the temporal scale of the physical evolution that separates the first three CSEOF modes of the surface temperature in Seoul. Although the physics of the second CSEOF mode and that of the third mode appear to be similar, their origins are distinct; correlations between the two corresponding PC time series are nearly zero at a wide range of lags indicating that the two time series are nearly independent.

d. Physical mechanism of the three-cold-day/four-warm-day events

To validate the occurrence of three-cold-day/four-warm-day oscillations, 10-day high-pass filtering has been conducted on the 2-m air temperature anomalies over the study domain. Digital high-pass filtering has been conducted on the 120-day record for each year at each grid point. Then, the best AR spectrum for the 120-day record has been obtained based on the criterion autoregressive transfer (CAT) for each year at each grid point (Newton 1988). The resulting best AR spectra have been

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**Fig. 7.** The composite patterns of the (left) 2-m surface air temperatures, and (right) sea level pressure and 850-hPa wind associated with the second CSEOF mode of the surface air temperatures in Seoul. Dark shading denotes positive values and light shading negative values. For clarity of exposition, wind vectors of magnitude less than 0.1 m s\(^{-1}\) are not shown.

**Fig. 8.** (a) The third CSEOF mode of the wintertime surface air temperature in Seoul (solid line). The corresponding evolution of the regressed NCEP–NCAR 2-m surface air temperature at the nearest grid point (dotted line). Correlation is 0.889 between the two time series. (b) The amplitude time series of the third CSEOF mode of the wintertime surface air temperature.
averaged for all years at each grid point. Subsequently, the period of maximum spectral peak was determined based on this averaged AR spectrum. Figure 10 shows that the period of the maximum spectral peaks lies within 7–8 days for much of the domain including South Korea. Figure 10 suggests that 7-day oscillations, indeed, are a major component of the variability at a time scale of 10 days and less. Note, however, that the periods of maximum spectral peaks are somewhat sensitive to how the filtering is conducted; different high-pass filtering will yield somewhat different patterns of the periods of maximum spectral peaks. Thus, a firm conclusion cannot be drawn as to the presence of any rigorous periodicity and the exact period of oscillations in the surface temperature anomalies over the study domain. Nonetheless, this 7-day oscillations explain a significant fraction of the variability of the surface air temperatures over the data domain: 10%–36% in the raw data and 15%–64% aside from the seasonal cycle. Thus, the 7-day oscillations cannot be ignored despite the lack of knowledge concerning its exact periodicity.

This 7-day oscillations should also be reflected in the evolution of the leading CSEOFs of the surface air temperatures in Seoul, since they are a part of the physical evolution. Thus, 10-day high-pass filtering has been conducted on the first three CSEOF loading patterns of the surface air temperature anomalies in Seoul. To understand the physical mechanism, 10-day high-pass filtering has also been conducted on the regressed loading patterns of other physical variables.

A 10-day high-pass filtering of the seasonal cycle mode shows that it is a possible source of 7-day fluctuations in South Korea. Nonetheless, the amplitude of the filtered time series is much smaller than those of the other modes investigated (figure not shown). Therefore, the seasonal cycle does not appear to contribute significantly to the three-cold-day/four-warm-day events in South Korea; the seasonal cycle will not be addressed in the following, where a plausible physical mechanism of the three-cold-day/four-warm-day events is addressed.

Figure 11a shows the 10-day high-pass filtered evolution of the surface air temperature anomalies during the winter months as captured in the second CSEOF mode. The corresponding AR(17) spectrum shows the maximum peak at 7 days (Fig. 11b). The second CSEOF mode appears to be associated with the three-cold-day/four-warm-day events in South Korea; the filtered evolution captures 19% of the variability shown in Fig. 3a.

To understand the physics associated with this 7-day oscillations, the same filtering was conducted on the loading patterns of other physical variables regressed onto the second CSEOF of the surface air temperatures in Seoul. Then, a composite analysis was conducted on the resulting filtered loading patterns in the following manner. To obtain a positive composite patterns, $C^{+}(r)$,

$$C^{+}(r) = \frac{\sum_{T_{j}(t) > 0.1} T_{j}(t) LVP_{2}(r, t)}{\sum_{T_{j}(t) > 0.1} T_{j}(t)}$$

where $T_{j}(t)$ is the filtered surface temperature anomalies in Seoul (Fig. 11a) and $LVP_{2}(r, t)$ is the evolution of

![Figure 10. Peak period of maximum variability of the 10-day high-pass-filtered 2-m air temperature anomalies over the East Asian region. The shaded region represents the spectral peaks with periods between 7 and 8 days exclusive.](image)
a predictor variable regressed onto the second mode of the surface temperatures in Seoul. Note that (7) is essentially a weighted average of $LVP_2(r, t)$ with respect to the weights $T_f(t)$. Note also that $LVP_2(r, t)$ is averaged only when $T_f(t) > 0.1$ in order to capture the pattern associated with the positive phase of the ~7-day oscillations. Likewise, a negative composite pattern, $C^{-1}(r)$, is obtained as

$$C^{-1}(r) = \frac{\sum_{T_f(t) < -0.1} T_f(t) LVP_2(r, t)}{\sum_{T_f(t) < -0.1} T_f(t)}.$$  (8)

Figures 12a and 12b show the positive composite patterns of 2-m surface air temperatures, sea level pressure, and 850-hPa wind associated with the ~7-day oscillations extracted from the second CSEOF mode of the surface temperatures in Seoul. The negative composite patterns are essentially the same as the positive composite patterns but with an opposite sign. The patterns of the 2-m air temperatures derived from the NCEP–NCAR daily reanalysis data are generally consistent with the surface air temperatures in Seoul, with positive 2-m air temperatures around Seoul in the positive composite pattern. The sea level pressure and the low-level wind patterns reveal the physical mechanism associated with the surface air temperature oscillations in Seoul. It appears that the warm phase of the ~7-day oscillations in Seoul is associated with the development of a positive sea level pressure anomaly pattern over the western North Pacific and, to a lesser degree, a negative pressure anomaly pattern over eastern China. These two contrasting sea level pressure anomaly patterns develop southerly wind anomalies to the south of South Korea. During the cold phase, the situation reverses, and northerly wind anomalies are developed to the south of South Korea (figure not shown); from an observational point of view, this implies the reduction of warm southerly winds to the south of South Korea.

Correlations between the filtered 2-m air temperature anomalies in Seoul ($37.5^\circ$N, 127.5$^\circ$E) and the filtered sea level pressure anomalies at 42.5$^\circ$N, 147.5$^\circ$E and 27.5$^\circ$N, 120$^\circ$E are 0.69 and −0.69, respectively. The correlation with the meridional wind anomalies at 30$^\circ$N, 130$^\circ$E is 0.69. These values indicate that there are highly consistent changes among these 10-day high-pass filtered variables. There is no definite lead–lag relationship among these variables since the maximum correlation is found at lag zero although there is a slight hint of the sea level pressure anomalies leading the surface temperature anomalies in Seoul. This, however, cannot be confirmed from a daily dataset.

While, in the second CSEOF mode, the sea level pressure change over eastern China is more strongly correlated with the surface air temperatures in Seoul than is the North Pacific sea level pressure change, as shown in Fig. 5. The latter plays a more important role in the ~7-day surface temperature oscillations in South Korea; the North Pacific sea level pressure anomaly pattern is 3 times stronger than that over eastern China (see Fig. 12b). Note also that the sea level pressure anomaly pattern over Russia (northwestern domain) is not associated with significant wind anomalies; it is a reflection that friction significantly weakens the 2-m wind anomalies over the continent. This particular anomaly pattern over the continent does not seem to have a direct impact on the ~7-day oscillations of the surface temperature in Seoul. The physical features in Figs. 12a and 12b are similar to the patterns of the composite 850-hPa geopotential heights and winds in Chang and Chongyun (2004).

Figures 12c and 12d show the anomaly patterns at the 500-hPa surface associated with the ~7-day oscillations. The air temperature anomaly at 500 hPa is similar to that at the surface. The 500-hPa geopotential height anomaly is also similar to that of the sea level pressure anomaly, suggesting a nearly barotropic nature for the ~7-day oscillations. The geopotential height anomaly
pattern over South Korea and Japan, however, is shifted more toward the west than the sea level pressure anomaly pattern.

Figure 13a shows the 10-day high-pass-filtered evolution of the surface air temperature anomalies during the winter months as captured in the third CSEOF mode. The corresponding AR(6) spectrum shows the maximum peak at ~7 days (Fig. 13b). The third CSEOF mode appears to be associated with the three-cold-day/four-warm-day events in South Korea; the filtered evolution captures 25% of the variability shown in Fig. 8. The positive and negative composite patterns of the high-pass-filtered 2-m air temperature, sea level pressure, 850-hPa wind, 500-hPa air temperature, 850-hPa geopotential height, and 500-hPa wind anomalies associated with the third CSEOF are similar to those of the second CSEOF, indicating that the physical mechanism of the ~7-day oscillations in the third CSEOF is rather similar to that in the second CSEOF.

According to the present analysis, there is no apparent sign that these ~7-day oscillations have diminished in magnitude or disappeared recently. The amplitude time series of the second mode and the third CSEOF mode, major sources of ~7-day oscillations, show that the strength of the ~7-day oscillations has not weakened as far as these two modes are concerned; there is no observational evidence for ~7-day oscillations to have weakened or diminished.

e. Rossby waves associated with the three-cold-day/four-warm-day events

As examined above, the ~7-day oscillations in Seoul are closely linked with the sea level pressure anomalies to the west and east of South Korea. Further, the surface and 500-hPa patterns suggest that the physics of the ~7-day oscillations are associated with Rossby waves. Figure 14 shows the high-pass-filtered 500-hPa geopotential height anomalies (shaded) and vorticity (contoured) in the second and the third CSEOFs. Figure 14 shows eastward-propagating waves with an approximately 7-day period. A positive geopotential height anomaly, in general, is associated with negative vorticity and vice versa. Figure 14 suggests that the oscillations of sea level pressure and meridional wind anomalies in Figs. 12, and the ensuing temperature oscillations in Seoul, are due to the eastward propagation of these anomalies. Figure 14 suggests that “equivalent” barotropic Rossby waves are an important ingredient for the ~7-day oscillations. To confirm the barotropic Rossby wave origin of the ~7-day oscillations, CSEOF analysis was conducted on the potential vorticity, \(-g(f + \zeta)(d\theta/dp)\), within the standard layers over the entire circumference between 30° and 80°N (Bluestein 1993). The resulting CSEOFs were regressed onto the second and the third CSEOFs and then were 10-day high-pass filtered in order to extract the PV anomaly patterns associated with the ~7-day oscillations.
oscillations. Figure 15 shows the wavenumber-frequency spectrum of the resulting PV anomaly patterns. The second CSEOF mode exhibits rather broad maximum peaks between 7 and 9 days with wavenumbers between 5 and 6, which represent wavelengths of about 6000 km. The wavenumber-frequency spectrum for the third CSEOF mode depicts a much stronger maximum peak around 7 days with wavenumbers between 5 and 6. From these wavenumber-frequency spectra, it is clear that the 7-day oscillations are linked with Rossby waves with wavelengths of ~6000 km.

Figure 16 shows the vertical cross section of the physical variables as a function of time at (40°N, 130°E) for the high-passed third CSEOF mode. The relationship among the physical variables for the second CSEOF mode is very similar to that depicted in Fig. 16. At this location, the high-pass-filtered PV anomalies at 200 hPa explain ~28% of the total variance of the second CSEOF and ~51% of the third CSEOF, respectively. The PV anomalies align well with the geopotential height anomalies with an opposite sign (Fig. 16a). The maximum anomalies of PV and the geopotential height match closely, specifically for the third mode, and are observed near or above 300 hPa with the magnitude of PV and geopotential height simultaneously increasing or decreasing in general. The geopotential height anomalies are nearly uniform with height although there is a hint of geopotential height anomalies at the surface leading those aloft. This indicates that a column of vortex is tilted westward from the surface to 200 hPa. This westward tilt with height is also seen in a comparison between Figs. 12b and 12d.

The potential temperature anomalies are generally in phase with the PV anomalies below 300 hPa and are out of phase above 300 hPa (Fig. 16b). For negative PV anomalies, geopotential height anomalies throughout the atmospheric column should be positive; this thickening of the atmospheric column is reflected in the vertical warming below 300 hPa. Above 300 hPa, the level of the axis of the Rossby waves in the present analysis, positive geopotential height anomalies should gradually degrade back to normal; thinning of layers above 300 hPa is seen in the decreased temperature. Contrary to the geopotential height anomalies, however, potential temperature anomalies have maximum values below 500 hPa. This vertical structure of potential temperature clearly shows why the crossing of Rossby waves aloft is seen in the surface temperatures.

The vertical structures of the zonal wind anomalies and meridional wind anomalies are also nearly uniform with height (Figs. 16c and 16d). As Rossby waves with positive PV approach the location, positive meridional wind anomalies are observed and as they leave the location, negative meridional wind anomalies are observed; thus, meridional wind anomalies change sign during the passage of Rossby waves. The signs of the zonal wind anomalies depend on how Rossby waves pass the location. When the northern portion of the positive Rossby waves passes the location, easterly wind anomalies will be seen whereas westerly wind anomalies are found when the southern portion of positive Rossby waves passes the location. Thus, it is difficult to interpret Fig. 16c without the exact locations of the Rossby waves. Nonetheless, sign reversal of zonal wind anomalies is clearly seen during the passage of Rossby waves at the location.

The wavenumber and frequency of maximum wave energy are comparable with the theory of barotropic Rossby waves. Under the assumption of a barotropic basic state, the frequency of the barotropic Rossby waves is given by

$$\omega = -\beta k/(k^2 + l^2),$$

so that the zonal phase speed is

$$c_x = -\beta k/(k^2 + l^2).$$

Here, the angular wavenumber is determined in terms of wavelength as $k = 2\pi/\lambda$, and
\[ \beta = 2\Omega \cos\phi/R, \quad (11) \]

where \( \Omega \) is the angular speed of the earth's rotation, \( R \) is the earth's radius, and \( \phi \) is the latitude. At 35°N, the wavelengths \( \lambda \) of wavenumbers 5 and 6 are 6600 and 5500 km, respectively. Assuming that the meridional wavenumber and zonal wavenumber are the same, the period, \( T = 2\pi/|\omega| \), is 7.4 and 8.9 days for wavenumbers 5 and 6, respectively; the corresponding phase speeds are \(-10\) and \(-7\) m s\(^{-1}\). The eastward translation speed as inferred from Fig. 14 is approximately 8–12 m s\(^{-1}\). This implies a mean westerly flow of \(-15\)–\(-22\) m s\(^{-1}\), which is comparable to the wintertime tropospheric average mean zonal wind speed of \(-21\) m s\(^{-1}\). Above 400 hPa, where the majority of the Rossby wave energy resides, the mean zonal wind speed is much higher than \(-21\) m s\(^{-1}\), in which case the phase speed of the Rossby waves should increase. Although the vertical structures of the variables studied here are similar to those of the baroclinic Rossby waves in Lim and Wallace (1991), the phase speed of the Rossby waves as inferred from Fig. 14 is not consistent with that of the baroclinic Rossby waves. In fact, the propagation speed of the Rossby waves suggests that they are of strong barotropic nature. The vertical structures of the geopotential height and wind anomalies associated with the Rossby waves in Fig. 16 reflect that they are mixtures of barotropic and first baroclinic Rossby waves (Liberato et al. 2007; Castanheira et al. 2009). Further investigation is needed to understand the exact nature of these Rossby waves.

5. Summary and concluding remarks

The physical mechanism of the wintertime surface temperature variability in Seoul, South Korea, was investigated via CSEOF analysis of daily variables. The first three CSEOFs of the wintertime surface temperature in Seoul together explain \(-50\%\) of the total variability. The amplitude of the seasonal cycle exhibits a negative trend implying that the wintertime temperature range has been...
decreasing in Seoul. The seasonal cycle is shown to be associated with the contrasting sea level pressure anomalies over the Asian continent and the northwestern Pacific. As a result, the fluctuations of the amplitude of the seasonal cycle are significantly correlated with the East Asian winter monsoon index.

The second CSEOF mode represents subseasonal oscillations on top of the net wintertime warming–cooling. Thus, this mode primarily describes a net warming or cooling in Seoul during a given winter. The amplitude time series shows a positive trend indicating that the wintertime surface temperature has been increasing in Seoul. This mode is associated with the opposite sea level pressure anomalies over eastern China and Japan and the ensuing wind anomalies to the south of South Korea. When positive pressure anomalies reside over Japan and negative pressure anomalies are present over eastern China, southerly wind anomalies bring warmer air into South Korea resulting in positive temperature anomalies in Seoul. When negative pressure anomalies reside over Japan and positive pressure anomalies are in evidence over eastern China, the situation reverses. Although the Siberian high and the Aleutian low are essential ingredients for the surface temperature variability in South Korea, this study does not show any substantial indication that air masses coming directly from Siberia are a direct cause of temperature variations in South Korea.

The fluctuations of the amplitude of the seasonal cycle and those of the second CSEOF mode are significantly correlated with each other. The two corresponding PC time series are significantly correlated with the East Asian winter monsoon index, implying that both modes are influenced by a common source of variability. Gradual warming in the last three decades, in general, decreased the sea level pressure over the Asian continent and over the northwest Pacific. The effects of warming, however, are more significant over the continent because of the lower thermal inertia than that over the ocean. Thus, the net effect of the warming is a more significant sea level pressure decrease over the Asian continent than over the ocean, which produces more southerly wind anomalies to the south of South Korea. At the same time, the Asian continent produces less pronounced positive sea level pressure anomalies during the peak of the winter thereby decreasing the seasonal cycle of the temperature. The trends in the first two PC time series appear to be associated with the continent–ocean differential sea level pressure response to greenhouse warming; sea level pressure over the continent decreases more rapidly than that over the ocean (Trenberth et al. 2007). This not only increases the inflow of warm air into Seoul by decreasing the sea level pressure contrast (lower high pressure over Siberia and higher low pressure over Japan) between the continent and the ocean but also decreases the seasonal cycle. These distinct responses to greenhouse warming are reflected in the opposite linear trends in the two time series. Both effects result in a net warming near Seoul.

The third CSEOF mode describes intraseasonal oscillations. This mode produces no net warming or cooling, which is a critical difference between this mode and the second CSEOF mode. The physics of the third CSEOF mode are similar to those of the second mode. The opposite pressure anomalies over Japan and eastern China play a key role in producing the intraseasonal temperature variability in Seoul.

The second and the third CSEOF modes exhibit significant amounts of ∼7-day oscillations. A 10-day high-pass filtering shows that ∼7-day oscillations are prevalent
FIG. 16. A vertical section of PV (shaded) and (a) geopotential height, (b) potential temperature, (c) zonal wind, and (d) meridional wind as a function of time at 40°N, 130°E for the third CSEOF mode. The time interval is from 17 November through 26 December.
over most of East Asia and the western North Pacific. High-pass filtering of the wintertime surface temperature in Seoul, and the corresponding variability of the physical variables, show that the ~7-day oscillations are associated with opposite SLP anomalies to the east and to the west of South Korea. These SLP anomalies produce surface wind anomalies to the south of South Korea. Longitude–time plots of the sea level pressure anomalies and zonal wind anomalies for these modes exhibit eastward propagation, indicating a Rossby wave origin of the ~7-day oscillations.

The eastward propagation of PV anomalies induces changes in physical variables throughout the entire atmospheric column. Specifically, the passage of Rossby waves is clearly seen in the surface temperature. The wavenumber–frequency spectra of the PV anomalies for the filtered second and the third CSEOFs show that Rossby wave periods are 7–9 days for the second mode and ~7 days for the third mode and the wavenumbers are 5–6, equivalent to wavelengths of ~5500–6600 km at 35°N. The ~7-day oscillations in Seoul are due to the passing of Rossby waves, which induce the variability of the same sign throughout the atmospheric column below ~300 hPa. In this sense, these Rossby waves may be viewed as being of a nearly barotropic nature.

Rossby waves develop two opposite pressure anomalies: one to the west of South Korea and the other over Japan. These opposite pressure anomalies develop surface wind anomalies to the south of South Korea, which is an essential ingredient for the ~7-day oscillations of the surface temperature in Seoul. Rossby waves propagate southeastward from Siberia and this propagation induces changes in the entire atmospheric column; Rossby waves do not directly supply warm–cold air into South Korea from Siberia. It is the locations of the crests and troughs of Rossby waves with respect to South Korea that determine the surface temperatures in South Korea. Although the opposite SLP anomalies are seen in both the raw CSEOF modes and the high-pass-filtered modes, their structures and natures are different from each other. Whereas the continental SLP anomaly is stronger in the raw CSEOF modes, the maritime SLP anomaly to the east of South Korea is stronger in the high-pass-filtered modes. The most striking difference is the clear eastward propagation of SLP anomalies and other variables in the high-pass-filtered modes; the raw CSEOF modes do not exhibit eastward propagation clearly. In fact, when high-pass-filtered anomalies were removed from the raw CSEOF modes, the physical changes appear to be nearly stagnant.

The ~7-day oscillations, also called the three-cold-day/four-warm-day phenomenon in South Korea, are associated with both the speed of the Rossby waves and the speed of the mean zonal wind. The period of ~7-day oscillations is determined by the eastward propagation speed of the Rossby waves, which is the speed of the mean zonal wind minus the phase speed of the westward Rossby waves. The speed of eastward propagation should also match with the period of the Rossby waves so that alternating Rossby waves are periodically seen at the same location. In this respect, this specific phenomenon is an intricate interplay of Rossby waves and the mean zonal wind. The asymmetry between cold days and warm days is not clearly seen in the present study although warm days tend to be slightly longer than cold days.

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