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# The Climate Variabilities of Air Temperature Around the Korean Peninsula

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**ABSTRACT**

In this study, changes in climatological conditions around the Korean Peninsula are estimated quantitatively using various types of high order statistical analyses. The temperature data collected from Incheon station have been analyzed for the assessment of the climate variation. According to our analysis, the climate changes observed over the Korean Peninsula for the last century are similar to the global observational data in many respects. First of all, the warming trend [+1.5°C $(100\ \mathrm{yr})^{-1}$] and the overall evolving pattern throughout the century are quite similar to each other. The temperature change in the Korean Peninsula is about two to three times larger than that of the global scale which may partially be ascribed to the influence of urbanization at mid and high latitudes. In this work, a new Winter Monsoon Index (WMI) is suggested based on the European continental scale circulation index (EU1) pattern. Our WMI is defined as the normalized sea level pressure (SLP) difference in the winter period between the centers of the East Sea and west of Lake Baikal in Siberia, the two eastern centers of the EU1 action patterns. A strong similarity is found between the time series of the WMI and surface air temperature at Incheon. The WMI has decreased gradually since the 1920s but has shifted to a rapid increasing trend in the last two decades; it was in fact accompanied by a weakening of the Siberian High and a decreasing of the northerly during winter. Our findings of the close correlations between the surface air temperature at Incheon and the WMI strongly indicate that our newly suggested index is unique and can be used as an efficient tool to predict climate variability in Korea.

**Key words:** Winter Monsoon Index, climate variability

## 1. Introduction

Climate is a broad composite of the average conditions of various atmospheric variables for a given region (Ruddiman, 2000). According to IPCC (2002), the global average surface temperature has increased by about 0.6 ± 0.2 °C over the 20th century. The recent period of warming has been widely spread over the globe with the largest increases in the mid- and high-latitude regions in the Northern Hemisphere (NH). However, cooling is also evident in the northwestern North Atlantic and in the central North Pacific Oceans, but such a trend in the former region has recently been reversed. There is evidence that the recent patterns of regional temperature change are related to such phenomenon as the atmospheric/oceanic oscillations (e.g., North Atlantic/Arctic oscillation and Pacific decadal oscillation). Thus, changes in the regional temperature can be strongly influenced by variabilities of both regional and global scales over several decades. For example, the warming between 1910 and 1945 occurred initially in the North Atlantic. However, during the period of 1946 to 1975, a significant cooling was observed in the North Atlantic (and for most of the NH) with warming in a large part of most SH regions.

This paper presents the results of an empirical study carried out without any international coordination under the Climate Variability and Predictability program (CLIVAR). It aims to develop the description and understanding of the local climate variability adjacent to Korea during the last century. The Korean peninsula is located at the eastern boundary of the Asian continent, while being surrounded by marginal seas that constitute semi-enclosed seas with a broad opening to the south. It is also bordered by the Pacific Ocean across the Japanese archipelago. Therefore, the climate of the Korean peninsula is under the

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strong influence of both the continent and ocean, exhibiting a seasonally distinct pattern, i.e., the monsoon. The summer season is generally characterized by wet and warm weather (oceanic influence), while the winter season by dry and cold weather (continental influence).

Lau (1998) reviewed the possible roles of various forcing mechanisms such as internal dynamics of the atmosphere, anomalous sea surface temperature (SST), and land-surface processes (e.g., soil moisture or snow cover) in the evolution of the monsoon; he then classified the Asian monsoon into three major subsystems: (1) Southeast Asian monsoon, (2) South Asian (or Indian) monsoon, and (3) East Asian monsoon. The climate of far eastern mid-latitude Asian countries (e.g., Korea, Japan, and China) then corresponds to the third subsystem. Lau argued further that the East Asian summer monsoon is mostly dominated by internal dynamics, associated with extratropical processes. Such processes are suspected to be tied to the fluctuation of the subtropical jetstream and the displacement of the western Pacific subtropical anticyclone. According to his study, the East Asian monsoon is distinguished from the two other tropical subsystems, as they exhibit strong relationships with ENSO. It is thus suggested that the variations of the (tropical) monsoon precede those of the Southern Oscillation Index (SOI) and the ENSO (Webster and Yang, 1992). However, the relationships between the (extatropical) East Asian monsoon and ENSO have not been clearly elucidated yet. For example, Kang (1998) showed an insignificant relationship ($r = -0.13$) between the SOI and the seasonal mean air temperature in Korea, despite the observations of warmer winter and cooler summer temperature during ENSO years (see also Cha et al., 1999). In light of the weak correspondence between the strength of the temperature anomaly and the strength of ENSO, Kang (1998) suggested that the relationship between the Korean climate and ENSO is marginal (or indirect at best); other mechanisms may be more important to control the climate on the Korean peninsula. In addition, Ahn and Park (2000) found that the anomalies of temperature and precipitation over the Korean Peninsula are closely lag-correlated with the SST anomalies in the world ocean basins (such as Indian, Atlantic, and southern Pacific Oceans) relative to the equatorial Pacific. In the meantime, the SST in the Eastern Asian Marginal Seas is found to show significant coherency with that of the Equatorial Pacific Ocean on both the interannual and interdecadal timescales with phase lags of 5–9 and 18–22 months, respectively (Park and Oh, 2000).

The main purpose of the present study is to provide the fundamental description of the nature of interannual variations to secular trends in the local climate system on the Korean Peninsula. This work is in fact based on the systematic analysis of selected atmospheric climate data collected over the last century. Because climate-related research activities are still at the infant stage in Korea, only a few recent studies have been able to address this issue through analyses of particular atmospheric variables (e.g., air temperature and rainfall data: Kang, 1998; Cha et al., 1999) or oceanic variables (e.g., SST: Park and Oh, 2000). Those studies have focused mainly on the relationship between the regional interannual variability and ENSO. In the present study, atmospheric variables (e.g., air temperature) have been analyzed without any prejudice to ENSO, to complement previous work in a more complete and comprehensive manner. This type of basic empirical study should lay the foundations for the understanding of the mechanisms: They can determine the nature of the local climate variability, which will promote its predictability.

## 2. Data and methods

For the detailed analysis of atmospheric parameters investigated in this study, we used the monthly time series datasets of sea level pressure (SLP) and surface air temperature ($T_{\rm air}$) from four meteorological stations (Incheon, Gangnung, Ulleungdo, and Jeju) operated by the Korea Meteorological Administration (KMA). The geographical locations and relevant information of those stations are presented in Fig. 1 and Table 1, respectively. In addition, we also used Trenberth's monthly SLP data of the NH on a $5° \times 5°$ grid. For the derivation of winter monsoon index (WMI) in the Korean Peninsula, Trenberth's data (http://dss.ucar.edu/datasets/ds010.1/data/) were used.

In this work, a number of methods were employed to conduct time series analysis, i.e., from very simple statistics to spectral analysis. The basic input parameters used for our analysis are monthly time series data. A linear trend over the record length of each time series was first calculated to determine the secular trend. Time series data were then decomposed into several period bands by applying a low-pass filter with different half-amplitude passing windows (1, 7, and 20 years) or a band-pass filter for different period intervals (1–20, 1–7, and 7–20 years). The basic filter used is the Gaussian recursive filter introduced by Park and Gambéroni (1995).

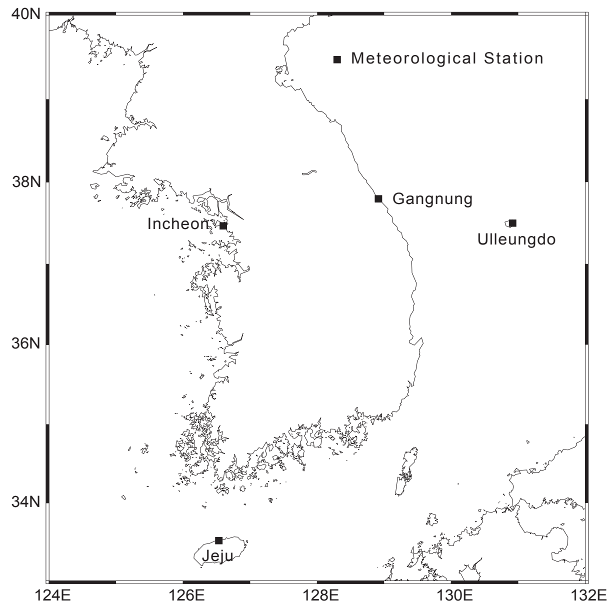


**Fig. 1.** Locations of the four meteorological stations (Incheon, Gangnung, Ulleungdodo and Jeju) investigated routinely (by KMA) in the present study.

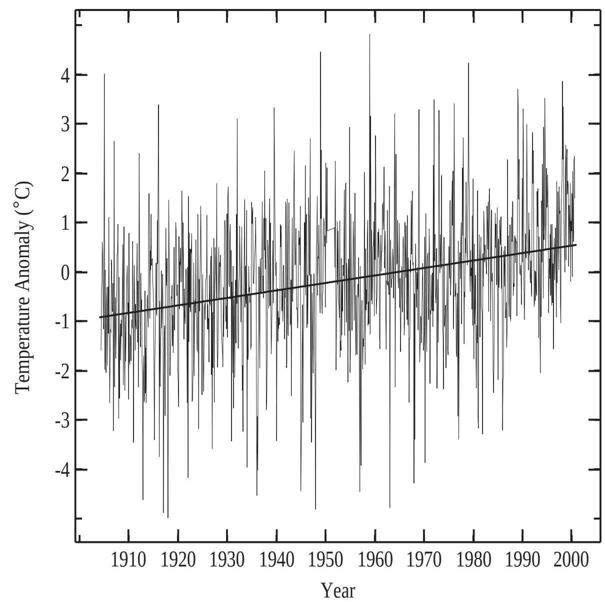


**Fig. 2.** Surface air temperature anomalies in relation to the long-term mean monthly temperatures at Incheon (between the period of 1904 and 2000). A linear trend is superimposed.

**Table 1.** The total duration of the data collection for the monthly surface air temperature ($T_{\rm air}$) and sea level pressure (SLP) from four KMA meteorological stations.

| | Total duration (years of measurement) | |
|---|---|---|
| Station | $T_{\rm air}$ | SLP |
| Incheon | 97 (1904–2000) | 49 (1952–2000) |
| Gangneung | 88 (1912–1999) | 75 (1926–2000) |
| Ulleungdodo | 61 (1939–1999) | 61 (1939–1999) |
| Jeju | 78 (1923–2000) | 75 (1926–2000) |

## 3. Results

### 3.1 *Variabilities of air temperature*

3.1.1 *Air temperature of Incheon*

The time series pattern of monthly air temperature anomaly at the Incheon station is presented in Fig. 2. It shows a clear warming tendency in the past century, with a linear trend of increase at $+1.5°{\rm C}\ (100\ {\rm yr})^{-1}$. This local trend is approximately three times larger than the global one $[+0.5°{\rm C}\ (100\ {\rm yr})^{-1}]$ (IPCC, 1996; Drake, 2000); this result thus suggests that the physical location of Korea is situated within a region where warming is more prominent in the global ]context.

In order to detect interannual, decadal, and long-term variability, the 7-year low-pass filtered time series is plotted (Fig. 3), with the 20-year low-pass filtered curve superimposed. This last curve indicates that the

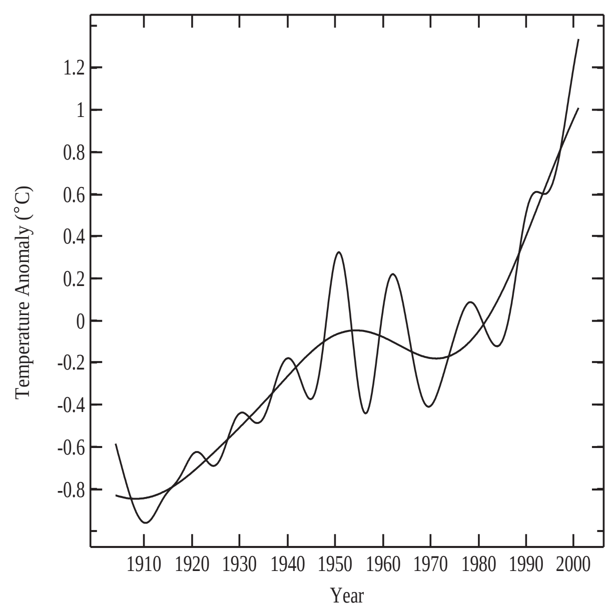


**Fig. 3.** Surface air temperature anomalies after being low-pass filtered at a 7-year interval (Incheon). The 20-year low-pass filtered curve is superimposed.

the air temperature at Incheon has not been increasing continuously over the past centuries. Instead, the warming (in the first half of the century) was interrupted by a weak cooling (between the mid-1950s and mid-1970s). Another warming period which started after 1980 is still active. This recent warming is somewhat stronger than that of the first half of the century.

A similar tendency, while much broader, has already been reported.

The observed variability of air temperature at Incheon may not simply be attributed to a local feature. Instead, it should rather be considered as a local manifestation of a global tendency. Understanding of such a secular variability may be of central importance to conclude whether the observed temporal trends are of anthropogenic or natural (interdecadal or long-term) origin; this will not be discussed further, as it is beyond the scope of the present study. Note that such interruption of warming (1950–1980) was confronted by the continuous accumulation of greenhouse gases; which should be a major dilemma for those who insist that the global warming is due mainly to anthropogenic perturbation. In addition, the length of the data record is not long enough to investigate such a long-term variability with any confidence. With the maximum record length of less than 100 years, our major interests in subsequent analyses will focus on changes on interannual to decadal timescales (1–20 years).

3.1.2 *Comparision of air temperature variation patterns with other sites*

The temporal patterns of Incheon were investigated most intensively because it has the longest record. It may be interesting to see to what extent Incheon datasets can represent the patterns for the Korean Peninsula. To this end, we made comparative analyses using the datasets from the three other meteorological stations (Gangnung, Jeju, and Ulleungdo). Figure 4 shows the result of the 20-year low-pass filtered time series analysis on surface air temperature at all four stations. The results of this analysis indicate a strong compatibility among all four stations in that there was a general warming trend [1.5–2.0°C $(100\,\mathrm{yr})^{-1}$] during the past century. Like the patterns of Incheon, all stations tend to share similar interdecadal variabilities. It is seen that the warming in the first half of the century was halted between 1955 and 1960, and a period of moderate cooling lasted up to the mid-1970s. Then, another warming period resumed from the early 1980s, with a more pronounced trend [up to 1°C $(20\,\mathrm{yr})^{-1}$] than before.

The most striking difference among all stations is however found to be a great disparity of temperature variation curves in the first half of the century; it in fact contrasts quite sharply with the much more compact and homogeneous pattern observed since 1960. This pattern of difference between epochs tends to be

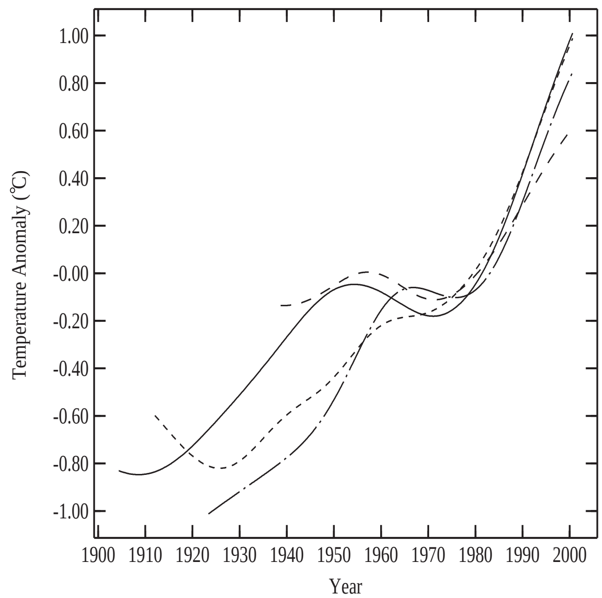


**Fig. 4.** The results of the low-pass filtered analysis of surface air temperature anomalies (at 20 years and from 4 stations): Incheon (solid), Gangnung (short dashed), Jeju (dash-dotted), and Ulleungdo (long dashed).

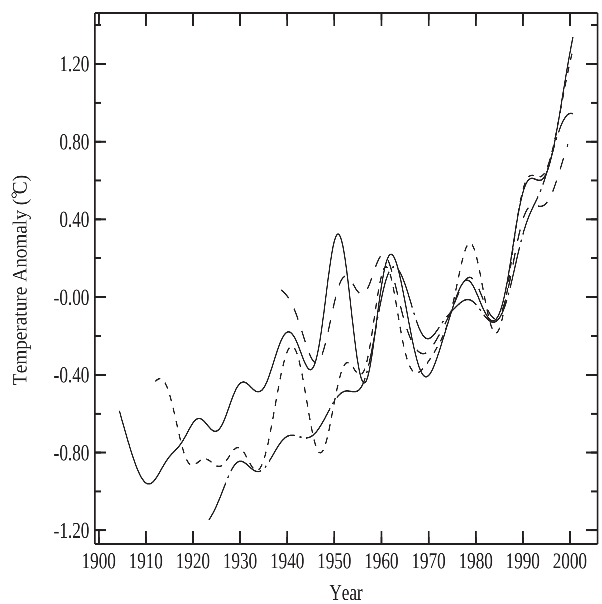


**Fig. 5.** Same as Fig. 4, except for low-pass filtering at a 7-year interval.

seen consistently in much less filtered (7-year low-passed) times series datasets (Fig. 5). Note also that a noticeable decadal variability existed at all stations from 1940, while a great visual coherency began to appear since 1960. In the case of the interannual band (1–7 years), however, the difference between epochs is not so evident; both epochs show good compatibility with highly homogenous and coherent patterns. One

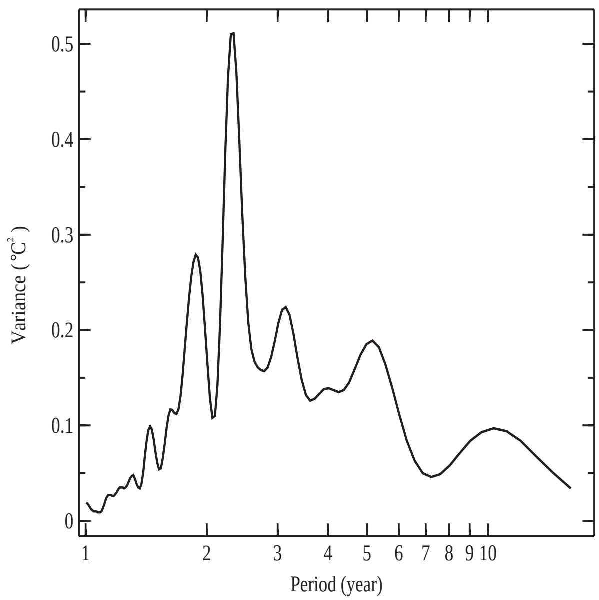


**Fig. 6.** Energy-conserving spectra of surface air temperature anomalies at Incheon. Results with $k$=4 of the Turkey window are shown only.

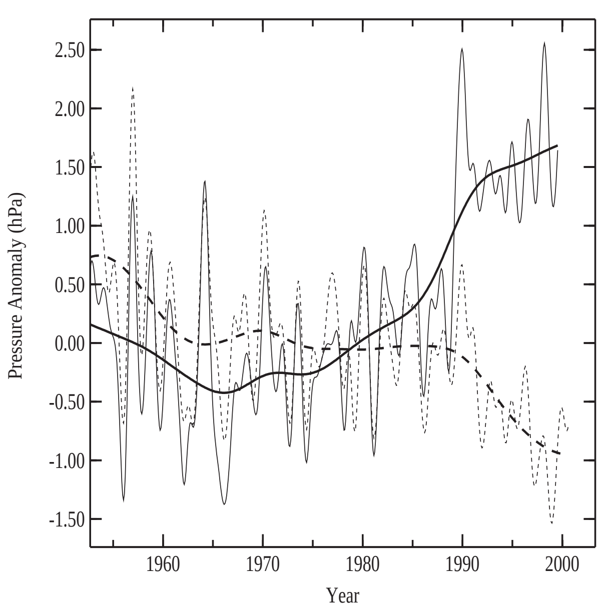


**Fig. 7.** SLP anomalies of low-pass filtering at a 1-year interval: Incheon (dashed line) vs. Ulleungdo (solid line). Superimposed smoothed curves are the 7-year low-pass filtered time series.

of the most clear conclusions from this analysis can thus be drawn such that the variability of surface air temperature at the Incheon site may be represented by strong signals of short-term climate changes; they have taken place on the Korean Peninsula since 1960 (at least in the southern part).

3.1.3 *Spectral analysis*

In order to quantify major periodicities and energy-containing period bands embedded in surface air temperature variations over the Korean Peninsula, we estimated spectra of the Incheon time series dataset. The time series used is the 1–20 year band-pass filtered one with interannual to decadal variability. Because it has the longest duration (97 years) of data coverage, the results of Incheon can be used to explain interannual to decadal variability over the Korean Peninsula, as mentioned previously.

Figure 6 indicates a spectral gap at a timescale of about 7 years which allowed separation of the interannual variability band (1 to 7 years) from the decadal variability band (7 to 20 years). The results show that the former can account for 82% of the energy, while the latter for the rest (18%). The interannual band can be further divided into four sub-bands: the 1.5–2 year band (14%), with a peak at 1.9 years; the 2–2.7 year band (22%), with a peak at 2.3 years; the 2.7–3.6 year band (14%), with a peak at 3.1 years; and the 3.6–7 year band (25%), with a peak at 5.2 years. Among all different types of sub-band intervals, the quasi-biennial band (centered at 2.3 years) appears to be the most dominant pattern of surface air temperature variations over the Korean Peninsula. Although temperature data for 97 years are not good enough to predict their long-term trend, they allow the analysis of periodicity of interannual variabilities. Hence, the results of the spectral analysis indicate the dominance of the quasi-biannual band (95% Cl). Although it is not feasible to discuss decadal variability with significant statistical confidence (e.g., 90%), the decadal variability shows a dominant periodicity of 11.1 years.

### 3.2 *Winter monsoon index and Korean winter air temperature*

3.2.1 *Atmospheric pressure gradient*

Surface atmospheric pressure is the most crucial and dynamic factor governing surface air circulation by geostrophy. Variations of SLP at two zonally separated stations (i.e., SLP gradient) can be a useful indicator of the changes in the N-S wind component between two stations. To check for such a possibility, we selected and examined Incheon and Ulleungdo as two representative zonal stations in our study area.

Long-term patterns of both mean monthly SLP differences between these stations are calculated by averaging the corresponding data for the period (1961–1990). Figures 7 and 8 show the resultant time series anomaly by the 1-year low-pass filter, with the super-

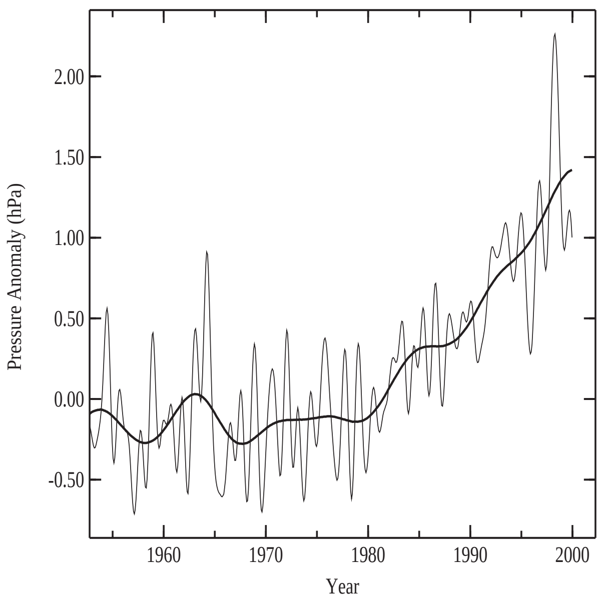


**Fig. 8.** SLP difference anomalies between Ulleungdo and Incheon are low-pass filtered at a 1-year interval. The superimposed smoothed curve is the 7-year low-pass filtered time series.

imposition of the 7-year low-pass filtered curves. The overall trends of SLP anomalies at the two sites (during the past 50 years) appear to contrast sharply, with an increasing tendency at Ulleungdo [+2 hPa $(50\,\mathrm{yr})^{-1}$] but a decreasing one at Incheon [$-1.5$ hPa $(50\,\mathrm{yr})^{-1}$]. While their interannual variations are in phase and of similar magnitude, their longer-term varibilities are quite different. In the case of Incheon, a noticeable SLP decrease is observed both before 1962 and after 1990, but such abrupt changes are not found for the rest of the period. At Ulleungdo, a noticeable SLP decrease is observed only before 1965, when minimum SLP is seen at the site on an interdecadal time scale. Since that time, SLP at Ulleungdo turns into an increasing trend, with the most abrupt changes between 1987 and 1990. At both sites, the year 1990 marks the "regime shift" (the greatest interannual to interdecadal variability), from which two SLP anomaly time series become divergent more pronouncingly.

The results of the SLP difference time series (Fig. 8) indicate two clear, distinguished trends both before and after 1980; whereas a nearly flat trend persisted during the former period, a rapid upward trend of 1.5 hPa $(20\,\mathrm{yr})^{-1}$ was dominant during the latter period. This implies that the southerly wind anomalies have grown since 1980; it is hence consistent with the rapid warming patterns of the air temperature time series at all four stations. We will come back to this point later in order to specifically describe the general trend of WMI winter air temperature over the Korean Peninsula.

### 3.2.2 *Winter monsoon index* (*WMI*)

In recent years, many efforts have been directed to the studies of oceanic and atmospheric variability around Korea in relation to the ENSO in the equatorial Pacific (Kang, 1998; Cha et al., 1998; Park and Oh, 2000). The results of those studies generally indicate the potential influences of ENSO on the Korean climate, such as (1) the eccentric tendency of warmer winters or cooler summers during El Niño years (Kang, 1998; Cha et al., 1998) or (2) a significant coherency in SST at periods of 2 to 3 years between the Korean seas and the central equatorial Pacific (Park and Oh, 2000). However, based on the quantitative evaluation of such a relationship, Kang (1998) demonstrated that there is practically no correlation ($r = -0.13$) between the Korean air temperature and the El Niño Index (defined by SOI multiplied by $-1$); but he showed that the correlation of the wintertime data (December to January) between the two series is marginally significant ($r = 0.21$). The use of such a low correlation would explain only 4% ($r^2 = 0.21 \times 0.21$) of the total variance, which may not be meaningful enough to provide the practical prediction of the regional climate.

For the latter objective, other atmospheric circulation indices that are far more sensitive than Southern Oscillation Index (SOI) may have to be developed to predict the Korean climate. Watanabe et al. (1987) addressed this point previously, showing a remarkable correlation ($r = -0.5$) between SST anomalies at Izuhara (Tsushima Island) for the 1934–1984 period and the zonal index of the winter season (December to February) in Far East Asia. This index, also called the "Winter monsoon Index (WMI)", is defined by the SLP difference between a point near Lake Baikal in Siberia (50°N, 105°E) and Hokkaido (45°N, 145°E), with the sign convention being the former minus the latter. These two points are not very far from the above-mentioned two eastern centers of action in the EU1 pattern. Watanabe et al. (1987) hence suggested that this index is a measure of the intensity of winter outbreaks of cold air masses on the Asian continent; as it can affect the amount of latent heat released from the sea, it can be responsible for the interannual variations of SST along the Japanese coast. (Note that this Monsoon Index used by Watanabe et al. corresponds to that of a technical report by the Japan Meteorological Agency (JMA) entitled "Report'84 of Abnormal Meteorological Phenomena").

For the purpose of our study, here we newly define WMI as the normalized anomalies of the winter SLP difference between the two eastern centers of action in

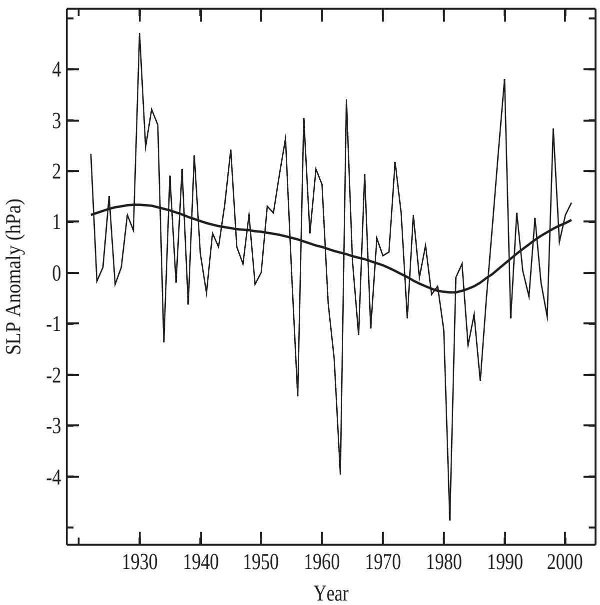


**Fig. 9.** Winter sea-level pressure anomalies at the center of the East Sea. The superimposed smoothed curve is the 20-year low-pass filtered time series.

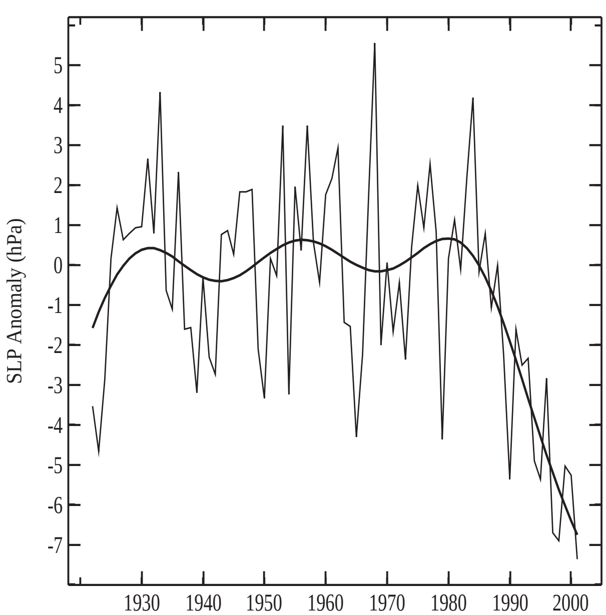


**Fig. 10.** Same as Fig. 9, except for west of Lake Baikal, Siberia.

the EU1 pattern. Our sign convention of the index results from the SLP difference, as explained above:

$$\text{SLP difference} = \text{SLP}(40°\text{N}, 135°\text{E}) - \text{SLP}(45°\text{N}, 95°\text{E})$$

The anomaly time series of this SLP difference is a departure from the long-term mean SLP difference (1961–1990). This anomaly time series can hence be normalized by dividing its standard deviation for the same reference period to yield WMI. Our WMI is however different from the above-mentioned JMA index of Watanabe et al. (1987) in several respects. First, the locations of the two reference points are different; ours are located at the two eastern centers of action in the EU1 pattern derived from the robust statistical analysis of Barnston and Livezey (1987). Second, our sign convention of WMI is the reverse of the JMA index in order to maintain an identical index phase with air temperature anomalies, thus giving a practical advantage in interpreting the results. Third, our normalization of the index permits direct comparison with other normalized atmospheric (or oceanic) parameters with different units. We will provide more detailed information on each procedure used for the derivation of WMI.

Before calculating the SLP difference, it may be interesting to see how the SLP at our two reference points has evolved during the past century. Using Trenberth's monthly SLP data in the NH (for the period of 1921–2000, as the data before 1921 have too many gaps), the winter-mean SLP values for each year were calculated by averaging SLP values between December and February. For the sake of simplicity, we assumed the winter season as the period between December and February. Anomalies were calculated as deviations from the long-term mean winter SLP which correspond to 1018.3 (the East Sea point) and 1037.1 hPa (the Siberian point). Figures 9 and 10 show the resultant winter SLP anomaly time series at those two points, with the 20-year low-pass filtered curves superimposed. It was noted that a remarkable change in the SLP trend occurred in the early 1980s at both points. In the East Sea (Fig. 9), the winter SLP gradually decreased by about 1.5 hPa (from the 1920s to the early 1980s) and then increased at a similar rate over the past 20 years. A considerably strong change is in fact observed at the Siberian point (Fig. 10) where winter SLP variations prior to 1980 do not show any noticeable long-term changes, except for an interdecadal variability with a small amplitude. This pattern however changed completely after 1980, with a rapid drop of SLP by as much as 7 hPa. The presence of the quasi-linear trend during this period also suggests a possibility that both persistent and unprecedented weakening of the Siberian High is still on its way.

To properly evaluate the winter SLP difference and its anomaly time series, the SLP difference (East Sea–Siberia) at each of the three winter months was calculated for a given year. The resulting differences of the three months were then averaged to yield the winter-mean SLP difference for that specific year. Second,

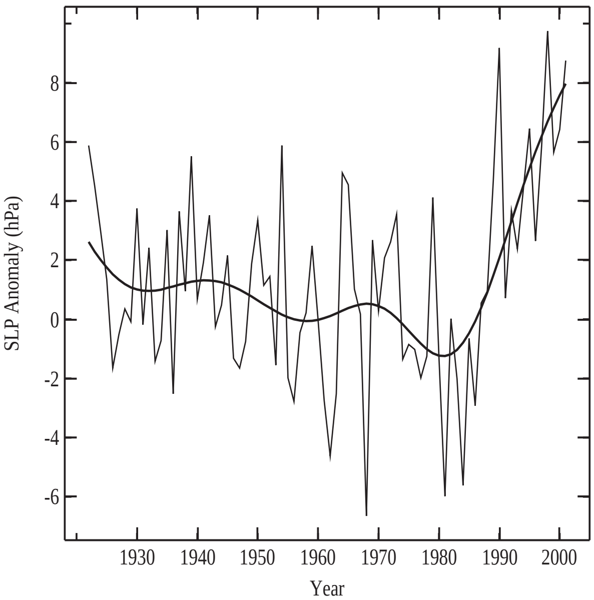


**Fig. 11.** Sea level pressure difference anomalies (East Sea–Siberia). The superimposed smoothed curve is the 20-year low-pass filtered time series.

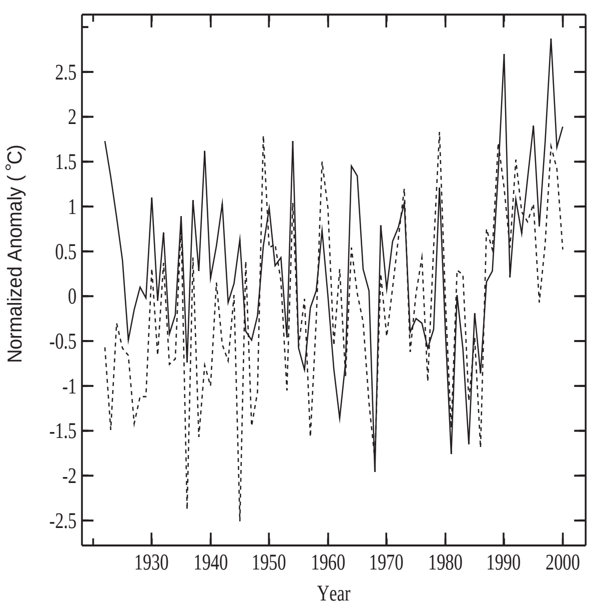


**Fig. 12.** A comparison of Winter Monsoon Index (WMI) time series (solid line) and normalized winter air temperature anomalies at Incheon (dashed line).

the long-term mean winter SLP difference (1961–1990) was calculated, yielding −18.7 hPa. Finally, the time series anomaly was obtained by subtracting these long-term mean values. Figure 11 shows the resulting SLP difference anomalies and their 20-year low-pass filtered curve. During the first 60 years of the record, there remained a weak drop of SLP difference; however, from the early 1980s, the trend was reversed completely so that its sign and strength jumped up to as much as 9 hPa (for the past two decades). This strongly suggests that the surface air circulation in Far East Asia has experienced an abrupt regime change since the early 1980s, marking a most dramatic turning point in regional climate change over the past centuries. By geostrophy, this change can be translated into a rapid weakening of winter outbreaks of cold air mass from the Asian continent, including a milder winter climate in the area. This important regime change is due to a spectacular weakening of the Siberian High since the early 1980s, as addressed previously (see Fig. 10). This in turn should have led to an unprecedented warming in Siberia in recent decades (Mann and Park, 1996). Following all the procedures involved in the derivation of SLP difference anomalies, our WMI was estimated by normalizing those values by their standard deviation. The resulting WMI time series is shown for comparison in Fig. 12, in combination with winter air temperature anomalies at Incheon, after normalization of a similar type. In fact, we were able to find a remarkable visual similitude between the two series, except for non-negligible differences in the period prior to 1950. More detailed comparison is given below.

### 3.2.3 *Relationship between winter monsoon index and korean winter air temperature*

A close examination of Fig. 12 indicates the possible inconsistencies between WMI and Korean winter air temperature (represented by Incheon) on a long-term scale (but not on interannual to decadal timescales). In order to examine this more closely, we present in Fig. 13 the 20-year low-pass filtering results of Fig. 12. The most remarkable pattern is found prior to 1950, with the trends of the two series being out of phase: a decreasing trend for WMI and an increasing trend for air temperature. This opposite phase is troublesome in the light of geostrophy, and it contradicts the idea that the warming (cooling) tendency of winter air temperature is coupled with an increasing (decreasing) tendency of WMI. As the upward trend of air temperature during the first half of the past century is a robust global feature, one may naturally inquire whether Trenberth's SLP data used for WMI are reliable or not for the period in question. Hence, we have raised a similar question for the air temperature at those four selected meteorological stations (see Fig. 4). The results of this analysis indicated that all curves showed similar trends since the 1950s, with a slightly decreasing trend up to the early 1980s. However, since then, the patterns turned abruptly into an upward direction until the end of the records. Therefore, some caution is required when interpreting these results;

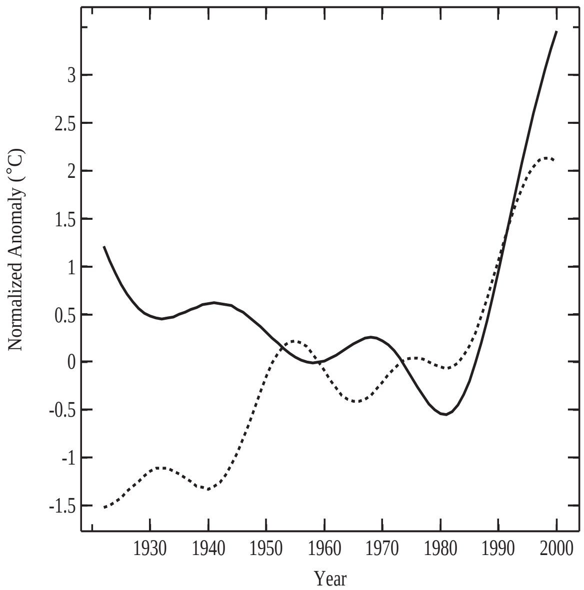


**Fig. 13.** Same as Fig. 12, except for low-pass filtered at 20 years.

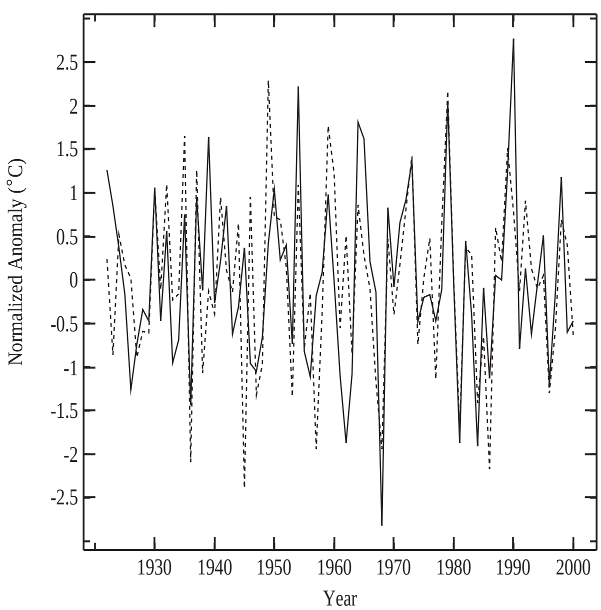


**Fig. 14.** Same as Fig. 12, except for high-pass filtered at 20 years. This 20-year high-pass filtering is equivalent to the 1-20 year band-pass filtering because the data used here are yearly data.

however, the validation of the measurement data is beyond the scope of the present study.

If we confine our interests to the variability of interannual to decadal timescales, their results tend to match each other very closely (Fig. 14). The correlation coefficient ($r$) between WMI and the Korean winter air temperature is 0.62 for these high-pass (<20 years) filtered time series. The strength of correlation increased further up to 0.82 with more recent datasets from after 1967. For comparison, the correlation coefficients for the unfiltered original time series were examined: the correlation coefficients were estimated as 0.57 for full data and 0.78 for partial data (posterior to 1967). All these coefficients are significant at a confidence level of 95% (or above). To our knowledge, it is the first time that such an excellent correspondence has been obtained between a weather parameter and an atmosphere circulation index on the Korea Peninsula.

## 4. Discussion and conclusions

In this study, we analyzed both monthly mean sea level pressure data of Trenberth and surface air temperature of four meteorological stations (Incheon, Gangnung, Ulleungdo, and Jeju) around the Korea Peninsula to account for the variabilities of air temperature in the region for the last century. These analyses enabled us to provide basic and unique descriptions of the nature of interannual and decadal climate variations with the prediction of long-term trends in the local climate around the Korea Peninsula.

According to our analyses, sea surface temperature at Incheon showed decadal and interdecadal trends that are highly compatible with the global patterns over the last century. Although the overall warming rate [+1.5°C $(100\,\mathrm{yr})^{-1}$] throughout the study period is almost three times larger than the global mean value, the general pattern of the evolution (such as weak cooling for the period of the mid-1950s to mid-1970s) is quite similar to the global pattern; it thus suggests that the changes in Korean climate may share the same basis of warming with those of the globe over the last century.

Although our temperature data are not related to ENSO (with the statistical significance), our spectral analysis shows that the interannual variability band of 1–7 years contains the dominant fraction of total energy (82%). In addition, the variability (at intervals of 2.3 years) is the most dominant feature with the imposition of decadal variation. On the other hand, the decadal variability (constituting 18% of the energy) has a dominant periodicity at 11.1 years.

In order to find a possible relationship between temperature variation (over the Korea Peninsula) and other variables (or parameters) other than ENSO-related ones (such as Niño–3.4 SST anomalies and SOI index), the atmospheric pressure gradient was analyzed between Ulleungdo and Incheon. The overall trends of SLP difference between them can be subdivided into two periods: before and after the early 1980s. In the former period, the trend is not strong enough. By contrast, a rapid upward trend [1.5 hPa $(20\ \mathrm{yr})^{-1}$] is found in the latter period, indicating a possible change in climate regime since the 1980s. Change in this SLP difference implies that the meridional wind has been developed anomalously as a southerly for the last two decades. To learn more about this relationship, we investigated the possible interactions between the winter monsoon and surface air temperature.

The WMI newly defined in this study is based on the study of Barnston and Livezey (1987), who categorized 13 different NH quasi-stationary wave patterns using the 700-hPa geopotential height. Based on their EU1 pattern covering both the whole Eurasian continent and the Korea Peninsula, WMI is defined as the normalized winter SLP difference between the centers of the East Sea and west of Lake Baikal in Siberia, the two eastern centers of action in the EU1 pattern. The results of our analysis indicated that the trend of WMI has also changed rapidly around the early 1980s. The change of WMI decreased gradually since the 1920s but has been increasing rapidly for the last two decades. Such a pattern is also seen consistently in the analyses of surface air temperature (at Incheon) and SLP difference (between Ulleungdo and Incheon). The close resemblance between the time series of WMI and surface air temperature (at Incheon) supports our finding in that the index defined in this study is efficient in explaining the winter climate variation in Korea in spite of some discrepancies between the two time series (e.g., before 1950 in the long-term scales). It is also seen that most research studying the Korean climates have paid attention to the indices related to the SST anomalies in the tropical Pacific (such as SOI and NINO indices). However, the use of WMI can also be recommended in future studies due to its remarkable coherency with the temperature anomalies in Korea.

The results of our study may imply that the Korean winter climate variability is more closely related with the higher latitude pressure pattern, such as EU1, rather than the tropical variations. Based on our analyses of WMI, surface air temperature and the SLP difference (between Ulleungdo and Incheon), it may be possible to infer that the climate in Korea should have experienced a rapid regime shift since the early 1980s.

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