Subseasonal and Interannual Temperature Variability in Relation to Extreme Temperature Occurrence over East Asia*

HIROYUKI ITO
Department of Meteorology, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, Hawaii

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

SHANG-PING XIE
Department of Meteorology, and International Pacific Research Center, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, Hawaii, and Institution of Oceanography, University of California, San Diego, La Jolla, California

(Manuscript received 17 September 2012, in final form 6 May 2013)

ABSTRACT

This study investigates interannual variability in the frequency of occurrence of daily surface air temperature (SAT) extremes over East Asia in summer and winter between 1979 and 2009. In particular, this study examines the dominant seasonal SAT patterns, as obtained through empirical orthogonal function (EOF) analysis, and the associated variability in SAT extreme occurrence. Overall, the authors find that changes in extreme temperature occurrence associated with these dominant patterns are impacted by both shifts and narrowing/broadening of the subseasonal SAT probability distribution functions (PDFs). In summer, the leading pattern features large SAT anomalies in midlatitude East Asia centered over Mongolia. Over this center of action, positive SAT anomalies are accompanied by decreased precipitation and soil moisture, which increases the ratio of sensible to latent heat flux. Consequently, subseasonal SAT variance increases, resulting in an enhanced occurrence of positive SAT extremes relative to a simple SAT PDF shift. In winter, the leading pattern, which is highly correlated with the Arctic Oscillation, features large loadings in high-latitude Siberia that decay southward. In contrast with summer, large-scale dynamics play a larger role in the leading pattern: positive SAT anomalies are accompanied by a weakened and northward-shifted storm track, reduced subseasonal SAT variance, and a more pronounced decrease of cold extreme occurrence relative to a simple PDF shift. Finally, a brief look at the secular trends suggests that both shifts and narrowing/broadening of the PDF may also impact long-term trends in SAT extreme occurrence over some regions of East Asia.

1. Introduction

Extreme weather and climate events, such as heat waves, drought, and cold surges, are of great concern for society because of their severe impacts on life, property, and economy. The number of such extremes, and the associated economic losses, has increased worldwide due primarily to higher population density in hazardous areas (Munich Re 2003; Bouwer 2011), but climate change likely has contributed as well (Munich Re 2010; Peterson et al. 2012). Various communities have recognized the value of studying temperature extremes to reduce the socioeconomic risk (Beniston and Stephenson 2004). In East Asia, as in many parts of the world, the impacts of climate extremes have been remarkable; for example, the severe heat wave in summer 2010 caused several hundred fatalities in Japan alone. The occurrence of abnormal warm spells has dramatically changed in the past few decades, at least partly in association with

* International Pacific Research Center Contribution Number 994 and School of Ocean and Earth Science and Technology Contribution Number 8963.
global warming (Christidis et al. 2005; Hansen et al. 2013; Wen et al. 2013). Although the relationship of extreme occurrence to both seasonal-mean climate and large-scale atmospheric circulation patterns has been studied on the global and regional scales (Scaife et al. 2008; Higgins et al. 2002; Kenyon and Hegerl 2008), few studies target interannual variability in extreme temperature occurrence in East Asia.

Changes in extreme occurrence may be due both to shifts in the probability distribution without change in shape (seasonal-mean shift) and to changes in the probability distribution shape, such as that owing to a change in subseasonal standard deviation. Substantial changes in the frequency of rare events can result from a relatively small shift or change in the probability distribution function (PDF) of climate variables. Under the assumption that daily-mean surface air temperature (SAT) follows a Gaussian distribution with fixed shape, an increase in the frequency of extreme hot days is generally accompanied by a decline in the opposite extremes (Fig. 1a). However, changes in the standard deviation of the distribution might be more effective in changing the number of extremes than the simple distribution shift (Fig. 1b) (Katz and Brown 1992). In reality, both the shift and shape-change effects are at work and will complicate the simple pictures above (Fig. 1c).

While a previous study shows that the distribution of seasonal-mean temperature has shifted in the positive direction and its variation has increased in the last few decades (Hansen et al. 2013), the present study focuses on interannual variability of the temperature distributions that affect the frequency of SAT extremes.

There is an extensive body of literature on interannual and interdecadal variations in the seasonal-mean climate of East Asia. East Asia’s climate is controlled in large part by the variability of the East Asia monsoon (Chang et al. 2006; Webster 2006). In summer, seasonal-mean atmospheric circulations in East Asia and the western North Pacific respond to both local forcing from underlying sea surface temperature (SST) anomalies, particularly during early summer (Wu et al. 2010), and from remote forcing through El Niño–Southern Oscillation (ENSO) and associated Indian Ocean SST variations (Wu et al. 2009; Xie et al. 2009, 2010; Kosaka and Nakamura 2010; Chowdary et al. 2011; Hu et al. 2011; Zhou et al. 2011). Also, snowfall over the Tibetan Plateau and the phase of the Arctic Oscillation (AO) in spring leads circulation anomalies over East Asia in summer (Seol and Hong 2009; Zhou et al. 2011). Important factors for the summer climate of East Asia are two atmospheric teleconnections, the Silk Road pattern along the midlatitude Asian jet and the Pacific-Japan
pattern from the tropical western North Pacific (Wakabayashi and Kawamura 2004; Nitta 1987; Kosaka and Nakamura 2006; Yasunaka and Hanawa 2006; Kosaka et al. 2012). In addition, blocking episodes associated with variability of the Okhotsk high strongly impact summertime temperatures in East Asia, particularly Japan (Nakamura and Fukamachi 2004). On inter- decadal time scales, the East Asian summer monsoon has undergone a secular weakening since the late 1970s, which has resulted in a “southern China flood and northern China drought” rainfall trend pattern (Zhou et al. 2009; Zhou et al. 2011).

In winter, the northerly monsoonal circulations vary in response to ENSO (Tomita and Yasunari 1996; Miyazaki and Yasunari 2008; Chan and Li 2004) and the AO (Xie et al. 1999; Gong and Ho 2004; Thompson and Wallace 2000; Wu and Wang 2002). Anomalous circulation patterns modulate intense midlatitude cyclones that develop over East Asia where a strong lower-tropospheric baroclinicity and intensified jet aloft exist.

Cold surges are often associated with the transient eddies, hence contributing to subseasonal SAT variations (Nakamura et al. 2002; Wang et al. 2010). The present study investigates interannual variations in SAT extremes in relation to the seasonal mean and variance of the SAT distribution over East Asia. We further investigate relevant physical mechanisms for anomalies of extreme temperature occurrence in an effort to promote better understanding of the predictability of SAT extremes. Important questions to be addressed include how extreme temperature occurrences respond to changes in both the seasonal-mean SAT and subseasonal SAT variance. What are the physical mechanisms for shifts and shape changes in the SAT distribution on interannual time scales? We relate PDF changes in SAT to the leading patterns of climate variability in East Asia. We focus on SAT rather than precipitation variability because temperature tends to be better organized in space than precipitation. Both summer and winter are examined.

The rest of the paper is organized as follows. Section 2 describes the data and methods. Sections 3 and 4 present results for summer and winter, respectively, including the climatology, interannual variability, extreme SAT occurrences, and subseasonal SAT probability distributions. Section 5 is a summary with discussion.

2. Data and methods

a. Data sources

We define East Asia as the region from 20° to 60°N and 90° to 160°E. This region includes the eastern half of the Tibetan Plateau and Gobi Desert (Fig. 2a). The daily- and monthly-mean surface and upper-level climate variables, on a 1.1° latitude–longitude grid, are obtained from the Japanese 25-yr Reanalysis Project (JRA-25; Onogi et al. 2007). In the analysis of surface shortwave, longwave, sensible heat, and latent heat flux variability, we acknowledge substantial uncertainty in the reanalysis-derived products, but we focus on the most robust variability supported by additional analysis. We also use the monthly model-calculated soil moisture of 0.5° latitude–longitude resolution from the Climate Prediction Center (CPC); the monthly gridded data for air temperature and precipitation from the University of Delaware (UD) product (http://www.esrl.noaa.gov/ psd); the National Oceanic and Atmospheric Administration (NOAA) extended reconstructed SST, version 3b (ERSST.v3b; Smith et al. 2008), with 2° latitude–longitude resolution; and station data from the National Climatic Data Center (NCDC). All of the daily and monthly data cover a 31-yr period from 1979 to 2009. Here, 29 February in leap years was removed so that each winter season has the same number of calendar days.

The seasonal cycle is defined by calendar day means that are smoothed by a centered 21-day moving average. The daily-mean SAT anomalies are obtained by removing the seasonal cycle. We then calculate the number of cold and warm extreme days, which, following the model of Kenyon and Hegerl (2008), are defined as those days below the 10th and above the 90th percentiles of the climatological SAT distribution at each grid point or station, respectively. The JRA-25 has been shown to perform reasonably well in capturing temperature extremes over China (Mao et al. 2010), and we perform comparisons with station data to ensure the robustness of our results. The seasonal-mean and subseasonal standard deviation of SAT are obtained by calculating the mean and standard deviation of the daily-mean SAT anomalies for each season, respectively. The linear trend is removed from the seasonal time series, though we provide some discussion of the long-term trend in section 5.

To identify the influence of the circulation patterns associated with patterns of large-scale climate variability, we examine relationships with climate indices from three dominant modes. We use the monthly-mean AO index; the projection time series for the leading empirical orthogonal function (EOF) of monthly-mean Northern Hemisphere sea level pressure for all months during 1979–2000 (Thompson and Wallace 2000); and the Southern Oscillation index (SOI), the normalized time series of the difference in monthly-mean sea level pressure anomalies between Tahiti and Darwin (Ropelewski and Jones 1987) from NOAA/CPC. We also use the
Pacific decadal oscillation (PDO) index obtained from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) at the University of Washington website (http://jisao.washington.edu/pdo). The PDO index is defined as the projection time series for the leading EOF of North Pacific monthly SST variability, poleward of 20°N for the 1900–93 period (Mantua et al. 1997). All indices are normalized by subtracting the mean and dividing by the standard deviation for the 1979–2009 period. Positive (negative) years are defined when an index is greater (less) than or equal to 0.5 (−0.5) and neutral years are defined when an index is within ±0.5.

b. Analysis of interannual variability of temperature extremes

To examine the effect of subseasonal SAT variance change on extreme temperature occurrence, we first extract the leading EOFs of seasonal-mean SAT variability for both summer and winter. The EOF analysis is applied to detrended seasonal-mean SAT anomalies, where the anomalies are weighted by the square root of cosine latitude to ensure correct geographical weighting. We next regress the number of cold and warm extreme days onto the corresponding principal components (PC), and then we sum the regression coefficients to define a quantity we call the “asymmetric occurrence between warm and cold extremes” corresponding to that EOF pattern. The reasoning for this calculation is as follows. For a symmetric temperature distribution that shifts right or left without a change in shape with each leading PC, the sum of warm and cold extreme occurrence regression coefficients would be zero, as changes in warm extremes for one EOF phase balance the changes in cold extremes for the opposite phase (Fig. 1a). A nonzero sum, however, provides one indication that changes in temperature distribution shape over some regions have a substantial impact on extreme temperature occurrence. In the following sections, we examine this asymmetric occurrence between warm and cold extremes in conjunction with changes in subseasonal temperature variance to illustrate regions where broadening or narrowing of the subseasonal temperature distributions impacts extreme temperature occurrence (as depicted in Fig. 1c).

c. Mechanisms of subseasonal temperature variance change

To elucidate the mechanisms of subseasonal temperature variance change, we examine the relationships between the leading summer and winter East
Asian temperature EOFs and the dominant terms of the subseasonal potential temperature variance budget. To derive the potential temperature variance budget, we begin with the potential temperature tendency equation

$$\frac{\partial \theta}{\partial t} + u_j \frac{\partial \theta}{\partial x_j} = Q \left( \frac{p_0}{C_p} \right)^K,$$

(1)

where $\theta$ is the potential temperature, $u_j = (u, v, w)$ is the surface wind component, $x_j = (x, y, z)$ is spatial position, $Q$ is the diabatic heating rate per unit mass, $C_p$ is the specific heat capacity of air at constant pressure, $p_0$ is a reference pressure of 1000 hPa, $p$ is the surface pressure, and $K$ is $R/C_p = 0.286$. We then decompose $\theta, u,$ and $Q$ into the seasonal mean, denoted by an overbar, and a deviation from the seasonal mean, denoted by a prime. Thus, (1) becomes

$$\frac{\partial (\bar{\theta} + \theta')}{\partial t} + (\bar{u}_j + u'_j) \frac{\partial (\bar{\theta} + \theta')}{\partial x_j} = (Q + Q') \left( \frac{p_0}{C_p} \right)^K.$$

(2)

With the knowledge that the time scale of individual weather systems is much smaller than a season, we apply Reynolds averaging to yield

$$\frac{\partial \bar{\theta}}{\partial t} + u_j \frac{\partial \bar{\theta}}{\partial x_j} + u_j \frac{\partial u' \theta'}{\partial x_j} = (Q + Q') \left( \frac{p_0}{C_p} \right)^K.$$

(3)

Subtracting (3) from (2), multiplying by $2\theta'$, and then Reynolds averaging yields the budget equation for subseasonal potential temperature variance:

$$\frac{\partial \bar{\theta}^2}{\partial t} = -u_j \frac{\partial \bar{\theta}^2}{\partial x_j} - 2u_j \frac{\partial u' \theta'}{\partial x_j} + \frac{\partial u' \theta'^2}{\partial x_j} + 2 \left( \frac{p_0}{C_p} \right)^K \frac{Q \theta'}. $$

(4)

Here, (4) states that four terms contribute to the time rate of change of subseasonal potential temperature variance: 1) mean advection, 2) the product of eddy heat fluxes with the mean potential temperature gradient, which we shall term “storm-track production,” 3) eddy transport, and 4) a diabatic heating covariance term, that is, a term driven by the covariance between potential temperature and diabatic heating deviations from the seasonal mean. In the following analysis, we discuss the dominant terms that contribute to subseasonal temperature variance changes in association with the leading patterns of variability, which then impact the occurrence of temperature extremes over East Asia.

3. Results for summer

a. Climatology

We first examine the summer [June–August (JJA)] climatology in East Asia. The cool moist Okhotsk and warm moist Ogasawara (Bonin) air masses create a large SAT gradient over the Kuroshio–Oyashio extension region (Fig. 2b). Over the Asian continent, a strong SAT gradient exists between the wet eastern and dry western China, which also differentiates wet Siberia from the dry Gobi Desert. Subseasonal SAT variance is larger relative to surroundings over Mongolia and the western North Pacific to the east of northern Japan, where the SAT gradient is also large. A major axis of eddy kinetic energy [EKE $\equiv \frac{1}{2}(u'^2 + v'^2)$], where $u'$ and $v'$ in this case are high-pass-filtered zonal and meridional wind, respectively, with a cutoff period of 9 days at 500 hPa broadens through northeastern China and Mongolia, and a minor ridge extends into southeastern China in association with the meiyu–baiu rainband (Fig. 2c) (Sampe and Xie 2010). A region of large subseasonal SAT variance to the east of Japan seems to be influenced by storm activity and the associated transport of heat over the sea surface across the climatological SST front.

Over the Mongolian region, the southerly monsoonal flow and northerlies from Siberia converge, placing a local maximum of subseasonal SAT variance (Fig. 2b). This maximum of subseasonal variability is related to a strong mean SAT gradient to the north of the Gobi Desert, suggestive of the advection by storms along the East Asian subtropical westerly jet (Zhang et al. 2006). In addition, soil moisture probably also plays a role.

b. Leading pattern of interannual variability

The leading EOF of detrended summertime (JJA) East Asian SAT anomalies, which accounts for 27% of the total SAT variance, is presented in Fig. 3. The present study uses the standardized PC of this EOF as a climate index for the leading pattern of interannual
SAT variability in East Asia \[\text{denoted hereafter as PC1 (JJA)}\], and shown in Fig. 3a; the spatial pattern shall be designated as EOF1 (JJA). This pattern shows large loadings around Mongolia and in a zonal band extending through northern Japan (Fig. 3b). The corresponding PC exhibits both pronounced interannual and interdecadal variability and is correlated with the SOI in the preceding winter \[\text{November–February (NDJF)}\] at 0.42 and with the concurrent PDO (JJA) index at –0.56. Both correlations are significant at the 5% level. PC1 (JJA), however, is not significantly correlated with indices of dominant planetary-scale wave trains, that is, with neither the circumglobal teleconnection (CGT) \[\text{(Ding and Wang, 2005; } r = 0.15\text{)}\] nor the Silk Road pattern \[\text{(Kosaka et al. 2009; } r = 0.26\text{)}\].

The SST regression with PC1 (JJA) (Fig. 3c) shows an elongated warming in the western North Pacific, consistent with the SST pattern identified to be associated with warming in northeastern China \[\text{(Wu et al. 2010)}\]. The SST pattern is also suggestive of a relationship with the negative phase of the PDO \[\text{(Schneider and Cornuelle 2005)}\], as supported by the significant correlation noted above, with a particularly strong connection to the positive SST anomalies in the Kuroshio extension regions. SST anomalies in the North Indian Ocean point toward the ocean basin’s role in relaying the ENSO effect on the western North Pacific climate via an atmospheric Kelvin wave–induced Ekman divergence mechanism \[\text{(Xie et al. 2009)}\]. The delayed warming of the tropical Indian Ocean (TIO) in the summer following El Niño induces tropical convection anomalies that emanate an equatorial Kelvin wave. The resulting northeasterly surface winds and low-level divergence over the western North Pacific suppress convection, which promotes the development of an anomalous anticyclone through a positive feedback mechanism. The opposite response is expected in the summers following La Niña. Thus, the TIO response contributes to a pronounced development of atmospheric anomalies over the western North Pacific and East Asia during the summer of an ENSO decay year \[\text{(Yang et al. 2007; Wu et al. 2009, 2010; Xie et al. 2010; Chowdary et al. 2010)}\]. Indeed, it has been recognized that the dipole pattern of SAT in south and northeast China is a signature of the Indian Ocean.
SST effect (Hu et al. 2011). Thus, ENSO, PDO, and Indian Ocean SST are considered as contributing factors for the leading pattern of East Asian summer SAT variability, although the fairly modest ENSO and PDO correlations also suggest the importance of internal atmospheric variability.

This leading EOF appears to be closely related to the second EOF of upper-tropospheric (200–500 hPa) temperature identified by Zhang and Zhou (2012). Both of these two EOF patterns are significantly correlated with ENSO in the preceding winter, which suggests that both patterns are closely tied to the decaying phase of ENSO. Zhang and Zhou (2012) argue that the second EOF of upper-tropospheric temperature results, in part, from both remote ENSO forcing and local moist processes, as discussed above.

c. Extreme SAT occurrence

Next, we focus on the relationship between PC1 (JJA) and extreme temperature occurrence. Figure 4a shows...
that the leading EOF of summertime SAT is associated with positive geopotential height anomalies in the midtroposphere, most pronounced over the region of maximum SAT anomalies (Fig. 3b). In addition, the subseasonal SAT standard deviation also increases over this region of maximum warmth centered on Mongolia (Fig. 4b). Associated with this broad area of warmth, the number of cold extreme days is significantly reduced in a swath from Siberia to the western North Pacific (Fig. 4c). In contrast, the number of warm extreme days increases in a similar region to that of cold extremes decreases, except for the northern Philippine Sea (Fig. 4d). These mirrored spatial patterns are suggestive of the effect of a shift in the SAT distribution by the change in seasonal-mean SAT. However, the spatial pattern of the asymmetric occurrence between cold and warm extremes related to the leading mode shows large amplitudes of 2–4 days season$^{-1}$ over Mongolia and northeastern China, the same region with largest increases in the subseasonal SAT standard deviation, and of 4–8 days season$^{-1}$ in the northern Philippine Sea (Fig. 4e). Thus, the results of Fig. 4 suggest that the broadening of the subseasonal temperature distribution contributes to an enhancement of extreme temperature occurrence over Mongolia and northeastern China (Fig. 4e) during the positive phase of EOF1.

Next, we turn our attention toward possible mechanisms that result in enhanced subseasonal temperature variance and extreme temperature occurrence over the central part of the East Asian domain. Figure 5a illustrates the regression of the seasonal net surface energy imbalance $(Q_S - Q_L - Q_H - Q_E)$ on PC1 (JJA), where $Q_S$, $Q_L$, $Q_H$, and $Q_E$ are the solar shortwave, outgoing longwave, sensible heat, and latent heat fluxes, respectively. The net surface energy flux regressions are rather modest, suggesting that the total surface flux anomalies are not driving the increase in mean and extreme temperatures. However, what may be more important than the net surface flux is the partitioning between sensible and latent heat fluxes. For example, a significant contributor of the severe European heat wave in the summer of 2003 was an increase in sensible heat fluxes at the expense of latent heat fluxes in response to increasingly negative soil moisture anomalies (Black et al. 2004; Ferranti and Viterbo 2006; Fischer et al. 2007). To expound further, consider a typical summertime convective boundary layer in which the dominant energy
balance is between sensible heat flux convergence and turbulent heat transport. In this case, the primary means by which the mean boundary layer temperature changes is through the sensible heat flux. In this case, the fourth term on the rhs of (4) suggests that an increasing co-variance between subseasonal temperature and subseasonal surface sensible heat flux would contribute to a broadening of the subseasonal temperature distribution, thus increasing the occurrence of positive SAT extremes. Furthermore, Fig. 5b supports this interpretation, as the enhancement of the subseasonal temperature variance that exacerbates extreme temperature occurrence over Mongolia is generally associated with the increased covariance between subseasonal potential temperature and sensible heat flux, as captured in term four of (4).

As expected, the increased covariance between potential temperature and sensible heat flux is accompanied by the decreased covariance between potential temperature and latent heat flux (Fig. 5c), which suggests that the positive SAT extremes and the broadening of the subseasonal temperature distribution over Mongolia are associated with an increased Bowen ratio \( R_B = \frac{Q_H}{Q_E} \). This increase in the sensible heat flux at the expense of latent heat flux is apparently related to negative precipitation and soil moisture anomalies over the region (Fig. 5d), drawing a similarity to the extreme European heat wave of 2003 (Ferranti and Viterbo 2006; Fischer et al. 2007). This point is further supported by Fig. 6, which focuses on the region of maximum SAT anomalies in the positive phase of EOF (JJA) but for all summer periods, not just those periods associated with high projections onto EOF (JJA). Even with this expanded scope, we see a rather strong relationship between the seasonal-mean temperature anomaly and the subseasonal temperature standard deviation (Fig. 6a; \( r = 0.63 \)). Consistent with the discussion above, these increases in the SAT mean and subseasonal standard deviation are associated with reduced precipitation and soil moisture (Fig. 6b). The correlation between the seasonal-mean SAT (subseasonal SAT standard deviation) and soil moisture over this region is \(-0.56\) \((-0.60\)), whereas the correlation between the Bowen ratio and soil moisture anomalies is \(-0.52\).

We can examine the changes in PDF shape in further detail by focusing on the SAT anomaly distributions for the positive and negative phases of PC1 (JJA) at Ulan Bator, Mongolia (Fig. 7), a station in the region of the largest loadings on EOF1 (JJA). The PDF estimates in Fig. 7 are smoothed with a normal kernel function. In years of the positive phase, the SAT distribution shifts to the right and the standard deviation becomes larger, hence broadening the distribution (Fig. 8a).

This broadening results in a substantially greater increase in warm extreme days than a decrease in cold extreme days. Distributions based on the station data are similar to those of the reanalysis data in terms of mean shift and narrowing/broadening of the distribution (Fig. 7b). These results are in good agreement with the linear regression results presented in the preceding section. Therefore, both distribution shifts and narrowing/broadening are influential on extreme SAT occurrence in particular regions such as Mongolia.

4. Results for winter

a. Climatology

The surface winter [December–February (DJF)] climatology features dominant northwesterly monsoonal flows between the Siberian high and Aleutian low (Fig. 8a). The SAT gradient is larger in south- and northeastern China and along to the Kuroshio–Oyashio extension. Subseasonal SAT variability is large along two zonal bands of large mean SAT gradients, north- and southeast of the Tibetan Plateau, respectively. There, storm activity is high as measured by the meridional eddy heat flux standard deviation in the lower troposphere [i.e., \( \sigma(\omega^T) \) at 850 hPa, where primes indicate the deviation from seasonal mean] and EKE in the mid troposphere (Fig. 8b). These two major storm-track
axes are associated with the polar and subtropical jets. Large eddy heat flux is consistent with the storm tracks as well as subseasonal SAT variations. Large subseasonal SAT variability in the Sea of Okhotsk is most likely due to sea ice variability (Ohshima et al. 2006).

b. Leading pattern of interannual variability

Similar to the summer analysis, EOF analysis is applied to the detrended winter (DJF) seasonal-mean SAT. The leading EOF [EOF1 (DJF)], explaining 45% of the total variance, is a monopole pattern with large loadings over Siberia that gradually decreases southward toward eastern China, the Korean Peninsula, and Japan (Fig. 9a). This mode is strongly related to the AO, with a correlation of 0.72 that is statistically significant at the 1% level. The normalized PC time series of this AO-like mode [PC1 (DJF)] is used as an index for the leading pattern of interannual SAT variability in East Asian winter.

We examine surface and upper-level climate variables by linear regression analysis with the leading PC. Anomalous low pressure in the polar region, intensified westerlies between 50° and 70°N, and suppressed meridional polar air intrusion into midlatitudes are prominent features characteristic of the positive phase of the AO (Figs. 9a,c) (Thompson and Wallace 2000; Xie et al. 1999). Advection of the climatological temperature by...
anomalous wind in the lower troposphere seems to be an important mechanism for generating the seasonal SAT anomalies, particularly over Siberia (Figs. 9a,b).

c. Extreme SAT occurrence

The mechanisms for winter subseasonal SAT variability are somewhat different from those of summer. In contrast with summer, when patterns of warming are associated with increased subseasonal SAT variance over a broad region, EOF1 (DJF) is associated with reduced subseasonal SAT variance over a broad region of warming. In particular, the subseasonal SAT standard deviation decreases in two banded regions, one from southern Siberia to northern China, and the other along the south China coast, respectively (Fig. 10a). Associated with the positive phase of EOF1 (DJF), the number of cold extreme days decreases throughout the domain whereas that of warm extreme days increases over the regions to the north of 35°N (Figs. 10b,c). As in the summertime analysis, the asymmetric occurrence between the number of cold and warm extreme days through linear regression is similar in distribution to the subseasonal SAT standard deviation anomaly (Fig. 10d), though of opposite sign in this case. Thus, the reduced subseasonal variance (narrowing of the temperature distribution) that accompanies the warming results in a greater decrease in the number of cold extreme days than the increase of the warm extreme days.

Given the contrasting behavior between summer and winter subseasonal temperature variance, the dominant mechanisms regulating variance changes must also be different. One would suspect that large-scale dynamics would play a greater role in winter, given the increased baroclinicity, increased teleconnection pattern variability, and decreased solar heating in winter. Returning to the subseasonal potential temperature variance budget, we see that the second term on the rhs of (4) potentially captures important large-scale dynamical processes, as this storm-track production term entails a product of eddy heat fluxes with the seasonal-mean potential temperature gradient. Figure 11a confirms that the broad region of subseasonal temperature variance reductions in the northwest and northeast part of

![Figure 9](https://example.com/figure9.png)

**Fig. 9.** Regressions of (a) SAT (color shading; °C) and 925-hPa wind (arrows), (b) 850-hPa horizontal temperature advection (color shading; 10⁻² K s⁻¹) and 850-hPa wind (arrows), and (c) 500-hPa geopotential height (color shading; m) on PC1 (DJF). In (a), the SAT climatology is contoured at intervals of 4°C. In (b), the climatology of 850-hPa potential temperature is contoured at intervals of 5 K, and elevation greater than 2000 m is shaded in gray. In (c), the 500-hPa height climatology is contoured at intervals of 100 m, and the box represents the East Asia domain. Color shading is applied to values that are statistically significant above the 10% level.)
the domain (Fig. 10a) are generally associated with some of the strongest negative storm-track production regres-
sions (Fig. 11a). We further isolate the effects of eddy
heat flux and temperature gradient changes by perform-
ing the storm-track production regressions with the eddy
heat fluxes held constant (Fig. 11b) and with the seasonal-
mean temperature gradient held constant (Fig. 11c). These
calculations suggest that both temperature gradient de-
creases (Fig. 11b) and eddy heat flux decreases (Fig. 11c)
contribute to the decrease in subseasonal temperature
variance, although the eddy heat flux decreases con-
tribute more strongly to regional variations.

As in the summer analysis, we also examine PDF es-
timates of daily-mean SAT anomalies related to PC1
(DJF) at Ulan Bator because of the large loadings in
EOF1 (DJF) over East Asia (Fig. 9a). In the regression
analysis (Fig. 10), cold days decrease by 7 and warm days
increase by 5, yielding an asymmetry of 2 days. In
the reanalysis data, the seasonal-mean SAT shifts to
the right and the standard deviation decreases during the
positive phase (Fig. 12a). As a result, the decrease in
the number of cold extreme days is greater than the increase
in the number of warm extreme days. Both the shift
and shape change in the SAT distribution evidently
contribute to changes in the number of extreme SAT
occurrences. The shift of the distribution is consistent
between reanalysis and station data, although the
change in standard deviation is less pronounced in sta-
tion data than in the reanalysis (Fig. 12b). Overall, the
examination of the PDFs supports the linear regression
analysis of Fig. 10.

5. Summary and discussion

We analyze interannual variability of seasonal mean
and subseasonal variance of SAT in East Asia in order
to examine mechanisms associated with the frequency of
extreme SAT occurrence. Our results show that in asso-
ciation with the dominant patterns of interannual
variability, the distribution shifts because of seasonal-
mean temperature change are most influential on the
number of extreme days. In addition, changes in the
distribution shape, namely those associated with sub-
seasonal temperature variance change, have some re-
gional effect on the number of extreme days.

We examine physical mechanisms for the distribution
shifts and shape changes. In summer, the leading pattern
of interannual SAT variability in East Asia features

Fig. 10. Regressions of (a) subseasonal SAT std dev (color shading; °C), (b) cold extreme occurrence (color shading; days season$^{-1}$), (c) warm extreme occurrence (color shading; days season$^{-1}$), and (d) the asymmetric occurrence between cold and warm extremes [i.e., sum of (b) and (c); color shading; days season$^{-1}$] on PC1 (DJF). Line contours at intervals of 0.5°C in (a) are the regression of seasonal-mean SAT, and the line contours at intervals of
0.1°C in (b)–(d) are the regressions of subseasonal SAT std dev on PC1 (DJF). Locations with an “x,” “o,” or “*” indicate regressions that are statistically significant at the 10% level, with the same conventions as in Fig. 4.
large loadings over Mongolia, and the corresponding PC is significantly correlated with the preceding winter ENSO and concurrent PDO. The region of greatest warming during the positive phase of this leading mode also corresponds with a broadening of the subseasonal SAT distribution, which exacerbates the occurrence of warm temperature extremes. This PDF broadening appears to be closely related to the increasing covariance between subseasonal temperature and sensible heat flux deviations. This finding suggests that changes in the Bowen ratio owing to variations in precipitation and soil moisture are important modifiers of summertime temperature distributions and extreme temperature occurrence over some regions such as Mongolia and northeastern China.

In winter, the leading mode of interannual SAT variability is highly correlated with the AO. The seasonal-mean anomalies of SAT are largely due to advection of the climatological SAT by anomalous winds in the lower troposphere, with the largest amplitudes over the Siberia and Mongolia. In contrast with summer, positive temperature anomalies associated with the leading mode accompany a reduction in subseasonal temperature variance, which results in a pronounced decrease in cold temperature extremes, relative to a simple PDF shift. This reduction in subseasonal temperature variance appears to be closely linked with large-scale dynamical processes, namely the combined influence of reduced eddy heat fluxes and a reduced seasonal-mean temperature gradient.

Our results for both summer and winter suggest that changes in subseasonal variance associated with the dominant patterns of SAT variability substantially impact the frequency of SAT extremes in some regions, particularly over the interior region centered on Mongolia. Our analyses of the asymmetric occurrence between warm and cold extremes are supported by the examination of probability distribution function estimates of daily SAT anomalies at Ulan Bator, a representative location that exhibits pronounced interannual SAT variability, in both atmospheric reanalysis and station data. We made similar PDF estimate comparisons at other stations including Harbin, Shanghai, and Chengdu in China; Irkutsk in Russia; and Sapporo and Tokyo in Japan, and the results show good agreement (not presented).

This study has implications for the predictability of extreme SAT occurrence in East Asia, given that modes of interannual climate variability are important for extreme occurrence. In the case of ENSO, numerical weather prediction models overall are successful in predicting western North Pacific atmospheric anomalies summer several months in advance (Chowdary et al. 2010), which is identified as influential on seasonal-mean SAT variability in East Asia via atmospheric teleconnections (Hu et al. 2011). This would suggest promise for some extreme temperature predictability
on seasonal time scales during summer. In the case of winter, however, when variability that is dominated by the AO, the seasonal prediction is more challenging because the AO is dominated by internal atmospheric variability (Feldstein 2000) and its coupling with the ocean is weak. Finally, we comment on the trends, which we have excluded from our analysis so far. In summer, positive temperature trends dominate almost the entire region, with a particularly large warming trend [3°–5°C (31 yr)\(^{-1}\)] centered over Mongolia (Fig. 13a). Several previous

Fig. 12. As in Fig. 7, but for PC1 (DJF) at Ulan Bator.

Fig. 13. The following summer (JJA) linear trends for the 1979–2009 period: (a) seasonal-mean SAT [°C (31 yr)\(^{-1}\)], (b) std dev of subseasonal SAT [°C (31 yr)\(^{-1}\)], and the number of (c) cold and (d) warm extreme occurrences [days (31 yr)\(^{-1}\)].
studies identified notable increases of warm extremes because of the large positive trend in mean temperature in northern, northeastern, and southeastern China (Qian and Lin 2004; Qian et al. 2010; Xu et al. 2011; You et al. 2010), a significant part of which is likely attributable to anthropogenic forcing (Wen et al. 2013). Weak trends of increasing cold extremes in central China have been recognized while the rest of the regions show decreasing trends of cold extreme days (Gong et al. 2004). In addition, Fig. 13b also indicates an increasing trend of the SAT subseasonal standard deviation [1°C–2°C (31 yr)] over Mongolia, which generally coincides with negative precipitation trends (not shown). Both of these warming and distribution-broadening trends are associated with a greater increase in the number of warm extreme days [15–25 days (31 yr)] than a decrease in the number of cold extreme days [5–15 days (31 yr)]; Figs. 13c,d]. The similarity between the analysis of interannual variability and long-term trends suggests that the interactions among soil moisture, sensible heat fluxes, temperature distributions, and extreme temperatures also are important on longer time scales. In support of this perspective, Schär et al. (2004) perform a regional modeling study to show that summer temperature distributions over Europe are projected to broaden substantially in the 21st century under global warming, apparently in relation to reductions in precipitation and soil moisture, which would greatly exacerbate extreme temperature occurrence. The modeling study of Brabson et al. (2005) shows similar projections and suggests similar reasoning for Britain. Based on the evidence presented here, we speculate that the region centered on Mongolia also is particularly susceptible to similar temperature distribution broadening and extreme temperature increases under global warming in response to feedbacks with soil moisture.

In winter, the linear trend of seasonal-mean SAT shows strong warming in the Sea of Okhotsk and cooling on the northern flank of the Tibetan Plateau, whereas the rest of the domain has warmed from 1°C to 2°C over 31 years (Fig. 14a). There is an increasing trend in subseasonal SAT variability from northern to southeastern China and a decreasing trend at higher latitudes through Japan (Fig. 14b) (Gong and Ho 2004). Overall, a broad region in the northern half of the domain has experienced both a warming trend and a reduction in subseasonal temperature variance, which bears some similarity to the analysis of interannual variability. Consequently, the reduction in cold extremes in regions of mean warming generally exceeds any increase in warm extremes (Figs. 14c,d). However, the large internal variability of the winter climate makes it difficult to detect significant changes in extreme temperature trends over a 31-yr period (Wen et al. 2013).
Overall, our results suggest that different mechanisms relating to land surface/atmosphere interactions and large-scale dynamics may alter the shape of local temperature distributions, which can affect the occurrence of extreme temperatures. Future work may refine the attribution of such changes to local temperature distributions and extreme temperatures over East Asia. For example, Wen et al. (2013) recently detected a significant influence of greenhouse gases and land use changes on extreme temperature occurrence over China, but questions remain about how these two factors separately affect extreme temperatures. Future work with multi-model ensembles and additional observational analysis is warranted. In any case, the analysis presented here suggests that the interannual variability of subseasonal temperature distributions and extreme temperature occurrence may provide important clues about relevant mechanisms on longer time scales.

Acknowledgments. We thank Drs. Kevin Hamilton and Yi-Leng Chen for helpful comments that improved the quality of this work. We also thank two anonymous reviewers for comments and suggestions that greatly benefited this study. This work is supported by the Japan Agency for Marine-Earth Science and Technology, and the U.S. National Science Foundation.

REFERENCES


