Subseasonal mode of cold and wet climate in South China during the cold season: a climatological view

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ABSTRACT
The authors investigate the dominant mode of climatological intraseasonal oscillation (CISO) of surface air temperature (SAT) and rainfall in China, and discuss the linkage of cold and wet climate in South China (SC) with the Arctic circulation regime during the cold season (from November to March). Results show that a positive CISO displays a cold-dry climate in North China, whereas a cold-wet pattern prevails in SC with a quasi-30-day oscillation during the peak winter season. In SC, the intraseasonal variability of SAT is mainly regulated by a pair of propagating ISO modes at the 500-hPa geopotential height in the negative phase of Arctic Oscillation. It is demonstrated that the local cyclonic wave activity enhances the southward movement of the Siberian high, favoring an unstable atmosphere and resulting in the cold-wet climate over SC. Therefore, the cold-air activity acts as a precursor for subseasonal rainfall forecasting in SC.

1. Introduction
The intraseasonal oscillation (ISO) of the East Asian winter monsoon (EAWM) can alter the seasonal evolution of surface air temperature (SAT) and rainfall, and cause cold and wet extreme events in China during the cold season (from November to March). For instance, unexpected extreme cold spells with snowstorms attacked South China (SC) during January 2008, causing severe icing conditions and catastrophic damage for the local economy and society (Wen, Yang, and Kumar et al. 2009; Hong and Li 2009; Zhou et al. 2009; Shi, Xu, and Lu 2010). During January 2016, unexpected cold spells with low SAT repeatedly affected East Asia and, during 21–25 2016, broke the record in SC since observations began in 1961 (Cheung et al. 2016; Ma et al. 2018). Evidence shows that cold and wet events are mainly caused by an enhanced EAWM, with an intensified Siberian high in terms of sea level pressure (SLP) and East Asian trough (EAT) at 500 hPa, as well as a southward shift of the East Asian jet stream at 200 hPa (Boyle and Chen 1987; Chen, Graf, and Huang 2000; Wen et al. 2009; Song et al. 2015; Ma et al. 2018).

A cold and wet extreme event usually occurs during the cold season, displaying a seasonal phase-locking with enhanced atmospheric ISO activity (Wen et al. 2009; Song et al. 2015; Ma et al. 2018), although it varies with the interannual variations of Arctic sea-ice cover (Wu and Wang 2002; Cheung et al. 2018; Ma et al. 2018) or tropical sea surface temperature (Xu et al. 2018a). The climatological ISO components of SAT and rainfall reflect the seasonal phase-locking characteristics, which provides us with possible clues for the subseasonal forecasting of cold and wet events in China. In the present study, we investigate the climatological ISO (CISO) mode of SAT and rainfall during the cold season in China, and reveal its related circulation regime, with respect to the...
subseasonal variations of Arctic circulation from a climatological view.

2. Data and methods

The data utilized in this study include daily in-situ observed rainfall in China from 722 stations, provided by the National Meteorological Information Center of the China Meteorological Administration, and NCEP–DOE AMIP-II reanalysis atmospheric data, with a horizontal resolution of 2.5° × 2.5° (Kanamitsu et al. 2002). The climatology is defined as the 30-yr arithmetic average between 1981 and 2010, and the CISO is defined as the 10–90-day harmonic components relative to the annual cycle by harmonic analysis (Wang and Xu 1997; Wheeler and Hendon 2004; Song et al. 2016).

We apply the method of multivariate empirical orthogonal function (MV-EOF) analysis (Wang 1992) to reveal the subseasonal mode of the SAT and rainfall anomalies over China during the cold season (November to March). The degrees of freedom (DOF) for testing the statistical significance of the correlation are calculated according to the following equation (Yan, Zhong, and Zhu 2003):

\[
\text{DOF} = 2 \left( \frac{\Delta T}{T_1} - \frac{\Delta T}{T_2} \right) (N - 2),
\]

where \(\Delta T\) is the sampling interval; the periodic range of the harmonic analysis is \(T_1, T_2 (T_1 < T_2)\); and \(N\) is the number of independent samples. Besides, we use local cyclonic wave activity (LCWA, based on the 500-hPa geopotential height (GPH, \(z_{500}\))) to describe the quantities of cold-air activity (Chen et al. 2015; Huang and Nakamura 2015). Firstly, we select a contour value \(z_{0_{500}}\) and define an equivalent latitude \(\phi_e\) such that the area \(S\) bounded by \(z_{0_{500}}\) is

\[
S(z_{0_{500}}) = \int_{z \geq z_{0_{500}}} a^2 \cos \phi \lambda d\phi d\lambda,
\]

while

\[
\phi_e(z_{0_{500}}) = \arcsin \left[ 1 - \frac{S(z_{0_{500}})}{2na^2} \right],
\]

where \(a\) is the radius of Earth, \(\lambda\) is longitude, and \(\phi\) is latitude. Defining \(\tilde{z} = z_{500} - z_{0_{500}}\), we can obtain the LCWA \(A_s\) (Xue et al. 2017):

\[
A_s(\lambda, \phi_e) = \frac{a}{\cos \phi_e} \int_{\tilde{z} \leq 0, \phi \leq \phi_e} -\tilde{z}(\lambda, \phi) \cos \phi d\phi.
\]

Moreover, non-dimensional eigenvectors are used to standardize the combined meteorological fields.

3. The CISO mode and its related circulation regime

Figure 1 shows the first MV-EOF mode (MV-EOF1) of the ISO components of SAT and rainfall during the cold season. This mode accounts for 32.2% of the total ISO variance, and statistically passes the criterion of North et al. (1982). Corresponding to the positive phase of MV-EOF1, cold SAT prevails over most areas, centered over the lower reaches of the Yangtze River, while the Tibetan Plateau (TP) is characterized by warm SAT. Also, enhanced rainfall is observed in SC and the TP, with respect to cold and warm SAT, respectively (Figure 1(a)). Therefore, a cold-dry and cold-wet climate often prevails in North China and SC, respectively, in the area east of 115°E. The time series of the first principal component (PC1) is defined as the CISO index. It is found that cold SAT always occurs during December to February with respect to the cold period of the annual cycle of SAT in SC. The CISO index displays a seasonal phase-locking with the cold-wet climate in December and late-January, which most likely causes the
low temperature and snowstorms (Figure 1(b)). Wavelet analysis (Torrence and Compo 1998) shows that the CISO index exhibits a quasi-30-day periodicity (figure not shown). Because cold and wet extreme events usually occur in SC with enhanced atmospheric ISO activity (Wen et al. 2009; Song et al. 2015), we mainly focus on the ISO components of SAT and rainfall in SC, to discuss their relative importance for the CISO mode. The correlation coefficient of the CISO index with the ISO of SAT in SC is −0.90, which is greater than that of the ISO of precipitation (+0.45), suggesting a dominant role of SAT in SC on the intraseasonal time scale during the cold season.

The atmospheric circulation regime, correlated with the CISO index, exhibits a very distinct vertical structure in the GPH and potential temperature (PT) fields (Figure 2). Corresponding to a positive CISO index, an enhanced Siberian high at 850 hPa dominates East Asia, with strong northeasterly winds prevailing over most areas in China (Figure 2(a)). A cold anomalous cyclone at 500 hPa controls the lower reaches of the Yellow River, with significant cold advection (Figure 2(b)), conducive to a southward shift of the cold front. In contrast, a low-level airflow convergence of meridional winds is observed between 20° and 30°N below 500 hPa with an unstable atmospheric air temperature over SC, corresponding to enhanced rainfall over SC (Figure 2(c)). Therefore, the CISO mode of the SAT and rainfall in China reflects a typical cold front–dominant circulation regime during the analysis period.

To explore the origin of the cold-air activity, we calculate the lead–lag correlations of the CISO index with the ISO components of GPH and PT at 850 hPa, 500 hPa, and 200 hPa along 115°E (Figure 2(d–f)). The leading correlation coefficient of PT and GPH suggests that the signal of cold-air activity with higher pressure at 850 hPa can be tracked at 65°N before 15 days. It moves southward, accompanied by a warm low south of 30°N, before a cold and wet climate occurs in SC 15 days later (Figure 2(d)). At 500 hPa, it exhibits a southward movement of cold and cyclonic circulation with an enhanced warm anticyclone south of 30°N (Figure 2(e)). The correlation pattern of GPH at 200 hPa displays a dipole mode, with negative and positive centers in the polar and midlatitude regions, respectively (Figure 2(f)), and resembles the negative phase of the Arctic Oscillation (AO) (Thompson and Wallace 1998). Therefore, the cold-air activity is closely correlated with the ISO of Arctic circulation.

4. Impact of Arctic circulation

The AO is defined by the first EOF of SLP with a vertical baroclinic pattern below the midtroposphere of 50 hPa (Thompson and Wallace 1998). It has been considered as the dominant regulator of the cold-air activity affecting the climate over Eurasia (e.g. Wu and Wang 2002; Cheung et al. 2018). Figure 3 shows the first three leading EOF modes of the ISO components of 500-hPa GPH, accounting for 20.7%, 12.5%, and 9.7% of the total variance, respectively. The first EOF mode shows a seesaw pattern, with positive and negative loading
Figure 3. EOF analysis of the ISO components of daily climatological GPH at 500 hPa during the cold season: (a–c) the three EOF leading modes; (d) their corresponding PCs. (e) Lag correlations between PC2 and PC3, and with itself. The two black dashed lines represent the 90% confidence level, based on the Student’s t-test, and the number represents the lead–lag days.

Figure 4. Lead–lag correlations of the CISO index with the reconstructed GPH (color shading) at 500 hPa, along 115°E, based on (a) EOF1, (b) EOF1 + EOF2, (c) EOF2 + EOF3, and (d) EOF1 + EOF2 + EOF3. The number represents the lag days, and the gray dotted areas represent the 90% confidence level.
over the polar and midlatitude regions, respectively, consistent with the negative phase of the AO (Figure 3(a)). EOF2 is characterized by meridional dipole anomalies, but the positive and negative centers are southward in position, away from the polar region (Figure 3(b)). EOF3 shows a zonal dipole variation of GPH between the Iceland and Aleutian Islands region (Figure 3(c)). The lead–lag correlations of PC1 with PC2 and PC3 are not significant, but the correlation reaches a maximum when PC2 leads the variation of PC3 by seven days (Figure 3(d–e)). Therefore, EOF3 can be considered as the morphological change of EOF2, manifesting the spatial ISO propagation of the Arctic circulation.

The CISO components of SAT and rainfall in China can be ascribed to the joint impact of the first three modes of Arctic circulation. To verify this, we reconstruct the first three EOF modes of 500-hPa GPH, and calculate the lead–lag correlations of the CISO index with the reconstructed GPH anomalies based on the first three EOF modes (Figure 4). The impact of the AO alone exhibits a simultaneous response of the GPH anomalies over Eurasia, characterized by a tripole correlation pattern of the CISO index at 115°E (Figure 4(a)). The 500hPa GPH reconstructed by the first two EOF modes basically reflects the 10–20-day leading circulation anomaly of the CISO (Figure 4(b)). The sum of EOF2 and EOF3 can duplicate the southward movement of cold-air activity originating at 40°N (Figure 4(c)), but against the observed positive correlations at the latitudes of SC during the same time period (Figure 2(e)). When we reconstruct the three EOF modes together, the lead–lag correlations of the CISO index basically produce the southward propagation of cold-air activity (Figure 4(d)). Therefore, the negative phase of the AO, together with a pair of propagating modes of Arctic circulation, is jointly responsible for the cold and wet climate in SC.

5. Summary and discussion

The subseasonal variation of SAT and rainfall in China exhibits a quasi-30-day oscillation during the cold season, climatologically. Corresponding to the positive phase of the CISO mode, a cold and dry climate prevails in North China, but a cold and wet climate appears in SC. This mode is dominated by SAT anomalies in SC, and is caused by the cold front–related regime over East Asia. The cold-air activity originates from the Arctic region, and the negative phase of the AO together with a pair of propagating ISO modes can jointly enhance the Siberian high, which is conducive to the cold front’s southward movement. The cold front causes an unstable atmosphere and results in cold and wet events over SC, before then triggering subseasonal rainfall as a precursor.

A greater value of LCWA represents stronger cold-air activity. The subseasonal cold-air activity is nested in a cyclonic circulation at 500 hPa, which can be verified by diagnostic analysis of LCWA (Figure 5). Besides the considerable contribution of Arctic circulation, winter climate variations over China can also be affected by movement of the East Asian trough, India–Burma trough, and Urals–Siberia blocking (Cheung et al. 2012; Leung and Zhou 2016; Leung, Cheung, and Zhou 2017; Li, Chen, and Zhou 2017), as well as the variability of the Madden–Julian Oscillation, El Niño, and pan-Arctic sea-ice concentration (Jia et al. 2001; Zhang et al. 2015; Cheung et al. 2018; Xu et al. 2018b). Our work reveals a possible source of the frequency of cold-wet events in SC, as well as their seasonal phase-locking. In fact, the cold and wet climate over SC has changed, which most likely causes the high frequency of extreme events seen after 2000, consistent with the results of Wei, Chen, and Zhou (2011) and Cheung et al. (2016). The climate mean

\[ \text{Figure 5. (a) Spatial distribution of the correlation of the CISO index with LCWA. (b) Lead–lag correlation of the CISO index with LCWA at 115°E. The number represents the lag days, and the gray dotted areas represent the 90% confidence level.} \]
background is warming, with a larger enhanced amplitude of the ISO component, while the effect of the annual cycle of warming on the cold and wet climate needs further investigation. In addition, the interannual variation of cold and wet extreme events is continually complex, so it would also be worthwhile paying more attention to other impact factors over China in future work.

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Disclosure statement

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References

Boyle, J. S., and T. J. Chen. 1987. "Synoptic Aspects of the Wintertime East Asian Monsoon." In Monsoon Meteorology, edited by C. P. Chang and T. N. Krishnamurti, 125–160. Oxford: Oxford University Press.

Chen, G., J. Lu, D. A. Burrows, and L. R. Leung. 2015. "Local Finite-Amplitude Wave Activity as an Objective Diagnostic of Midlatitude Extreme Weather." Geophysical Research Letters 42: 10952–10960. doi:10.1002/2015GL066959.

Chen, W., H. F. Graf, and R. H. Huang. 2000. "The Interannual Variability of East Asian Winter Monsoon and its Relation to the Summer Monsoon." Advances in Atmospheric Sciences 17 (1): 48–60. doi:10.1007/s00376-000-0042-5.

Cheung, H. N., N. Keenleyside, N. E. Omrani, and W. Zhou. 2018. "Remarkable Link between Projected Uncertainties of Arctic Sea Ice Decline and Winter Eurasian Climate." Advances in Atmospheric Sciences 35 (1): 38–51. doi:10.1007/s00376-017-7156-5.

Cheung, H. N., W. Zhou, Y. T. Leung, C. M. Shun, S. M. Lee, and H. W. Tong. 2016. "A Strong Phase Reversal of the Arctic Oscillation in Midwinter 2015/16: Role of the Stratospheric Polar Vortex and Tropospheric Blocking." Journal of Geophysical Research: Atmosphere 121 (22). doi:10.1002/2016JD025288.

Cheung, H. N., W. Zhou, H. Y. Mok, and M. C. Wu. 2012. "Relationship between Ural-Siberian Blocking and the East Asian Winter Monsoon in Relation to the Arctic Oscillation and the El Niño-Southern Oscillation." Journal of Climate 25 (12): 4242–4257. doi:10.1175/JCLI-D-11-00225.1.

Hong, C. C., and T. Li. 2009. "The Extreme Cold Anomaly over Southeast Asia in February 2008: Roles of ISO and ENSO." Journal of Climate 22 (13): 3786–3801. doi:10.1175/2009JCLI2864.1.

Huang, C. S. Y., and N. Nakamura. 2015. "Local Finite-Amplitude Wave Activity as a Diagnostic of Anomalous Weather Events." Journal of the Atmospheric Sciences 73: 211–229. doi:10.1175/JAS-D-15-0194.1.

Jia, X. L., L. J. Chen, F. M. Ren, and C. Y. Li. 2001. "Impacts of the MJO on Winter Rainfall and Circulation in China." Advances in Atmospheric Sciences 28 (3): 521–533. doi:10.1007/s00376-010-9118-z.

Kanamitsu, M., W. Ebisuzaki, J. Woollen, and G. L. Potter. 2002. "NCEP–DOE AMIP-II Reanalysis (R-2)." Bulletin of the American Meteorological Society 83: 1631–1643. doi:10.1175/BAMS-83-11-1631.

Leung, Y. T., H. N. Cheung, and W. Zhou. 2017. "Meridional Displacement of the East Asian Trough and Its Response to ENSO Forcing." Climate Dynamics 48 (1–2): 335–352. doi:10.1007/s00382-016-3077-8.

Leung, Y. T., and W. Zhou. 2016. "Direct and Indirect ENSO Modulation of Winter Temperature over the Asian–Pacific–American Region." Scientific Reports 6 (1): 36356. doi:10.1038/srep36356.

Li, X. Z., Y. Q. Chen, and W. Zhou. 2017. "Response of Winter Moisture Circulation to the India-Burma Trough and Its Modulation by the South Asian Waveguide." Journal of Climate 30 (2): 1197–1210. doi:10.1175/JCLI-D-16-0111.1.

Ma, S. M., C. W. Zhu, B. Q. Liu, T. J. Zhou, Y. H. Ding, and Y. J. Orsolini. 2018. "Polarized Response of East Asian Winter Temperature Extremes in the Era of Arctic Warming." Journal of Climate 31: 5543–5557. doi:10.1175/JCLI-D-17-0463.1.

North, G. R., T. L. Bell, R. F. Cahalan, and F. J. Moeng. 1982. "Sampling Errors in the Estimation of Empirical Orthogonal Functions." Monthly Weather Review 110 (7): 699. doi:10.1175/1520-0493(1982)110<0699:SEITEO>2.0.CO;2.

Shi, X. H., X. Xu, and C. Lu. 2010. "The Dynamic and Thermodynamic Structures Associated with a Series of Heavy Precipitation Events over China during January 2008." Weather & Forecasting 25 (4): 1124–1141. doi:10.1175/2010WAF2223351.

Song, L., L. Wang, W. Chen, and Y. Zhang. 2015. "Intraseasonal Variation of the Strength of the East Asian Trough and Its Climatic Impacts in Boreal Winter." Journal of Climate 29 (7): 160209114948000. doi:10.1175/JCLI-D-14-00834.1.

Song, Z. H., C. W. Zhu, J. Z. Su, and B. Q. Liu. 2016. "Coupling Modes of Climatological Intraseasonal Oscillation in the East Asian Summer Monsoon." Journal of Climate 29: 6363–6382. doi:10.1175/JCLI-D-15-0794.1.

Thompson, D. W. J., and J. M. Wallace. 1998. "The Arctic Oscillation Signature in the Wintertime Geopotential Height and Temperature Fields." Geophysical Research Letters 25 (9): 1297–1300. doi:10.1029/98GL00950.

Torrence, C., and G. P. Compo. 1998. "A Practical Guide to Wavelet Analysis." Bulletin of the American Meteorological Society 79: 61–78. doi:10.1175/1520-0477(1998)079<0061:APGTA>2.0.CO;2.

Wang, B. 1992. "The Vertical Structure and Development of the ENSO Anomaly Mode during 1979–1989." Journal of Atmospheric Sciences 49 (8): 698–712. doi:10.1175/1520-0469(1992)049<0698:TVSADO>2.0.CO;2.

Wang, B., and X. Xu. 1997. "Northern Hemisphere Summer Monsoon Singularities and Climatological Intraseasonal..."
Oscillation.” *Journal of Climate* 10 (10): 1071–1085. doi:10.1175/1520-0442(1997)010<1071:NHSMSA>2.0.CO;2.

Wei, K., W. Chen, and W. Zhou. 2011. “Changes in the East Asian Cold Season since 2000.” *Advances in Atmospheric Sciences* 28 (1): 69–79. doi:10.1007/s00376-010-9232-y.

Wen, M., S. Yang, A. Kumar, and P. Zhang. 2009. “An Analysis of the Large-Scale Climate Anomalies Associated with the Snowstorms Affecting China in January 2008.” *Monthly Weather Review* 137 (3): 1111–1131. doi:10.1175/2008MWR2638.1.

Wheeler, M. C., and H. H. Hendon. 2004. “An All-Season Real-Time Multivariate MJO Index: Development of an Index for Monitoring and Prediction.” *Monthly Weather Review* 132: 1917–1932. doi:10.1175/1520-0493(2004)132<1917:AARMMI>2.0.CO;2.

Wu, B. Y., and J. Wang. 2002. “Winter Arctic Oscillation, Siberian High and East Asian Winter Monsoon.” *Geophysical Research Letters* 29 (19): 1897. doi:10.1029/2002GL015373.

Xu, K., Q. L. Huang, C. Y. Tam, W. Q. Wang, S. Chen, and C. W. Zhu. 2018a. “Roles of Tropical SST Patterns during Two Types of ENSO in Modulating Wintertime Rainfall over Southern China.” *Climate Dynamics* 1–16. doi:10.1007/s00382-018-4170-y.

Xu, X. P., F. Li, S. P. He, and H. J. Wang. 2018b. “Subseasonal Reversal of East Asian Surface Temperature Variability in Winter 2014/15.” *Advances in Atmospheric Sciences* 35 (6): 737–752. doi:10.1007/s00376-017-7059-5.

Xue, D. K., J. Lu, L. T. Sun, G. Chen, and Y. C. Zhang. 2017. “Local Increase of Anticyclonic Wave Activity over Northern Eurasia under Amplified Arctic Warming.” *Geophysical Research Letters* 44: 1–10. doi:10.1002/2017GL072649.

Yan, H. M., M. Zhong, and Y. Z. Zhu. 2003. “The Determination of Degrees of Freedom for Digital Filtered Time series—An Application in the Correlation Analysis between Length of Day Variation and SOI (In Chinese).” *Acta Astronomica Sinica* 44 (3): 324–329. doi:10.15940/j.cnki.0001-5245.2003.03.011.

Zhang, R. H., T. R. Li, M. Wen, and L. K. Liu. 2015. “Role of Intraseasonal Oscillation in Asymmetric Impacts of El Niño and La Niña on the Rainfall over Southern China in Boreal Winter.” *Climate Dynamics* 45 (3–4): 559–567. doi:10.1007/s00382-014-2207-4.

Zhou, W., J. C. L. Chan, W. Chen, J. Ling, J. G. Pinto, and Y. P. Shao. 2009. “Synoptic-Scale Controls of Persistent Low Temperature and Icy Weather over Southern China in January 2008.” *Monthly Weather Review* 137: 3978–3991. doi:10.1175/2009MWR2952.1.