Jia Huang, Renhe Zhang

Department of Atmospheric and Oceanic Sciences & Institute of Atmospheric Sciences, Fudan University, and CMA-FDU Joint Laboratory of Marine Meteorology, Shanghai, and Innovation Center of Ocean and Atmosphere System, Zhuhai Fudan Innovation Research Institute, Zhuhai, China.

Corresponding author: Renhe Zhang (rhzhang@fudan.edu.cn)

Key Points:

- A new ENSO index is defined based on the outgoing long wave radiation anomalies over the equatorial Pacific.
- The new index well represents ENSO and its interannual variation defined by the sea surface temperature anomalies in the equatorial Pacific.
- Compared to the existing ENSO indices, the new index can better depict the impact of ENSO on the East Asian winter monsoon.

Abstract

The existing ENSO indices are defined based on the sea surface temperatue anomalies (SSTAs) in different regions of the equatorial Pacific. Considering that the tropical convective activities are closely related with ENSO and the impact of ENSO on the large-scale atmospheric circulation is mainly through the release of latent heat caused by the associated convective anomalies, a new ENSO index, the tropical convection index ($I_{TC}$), is defined based on the zonal dipole distribution of outgoing long wave radiation anomalies over the equatorial Pacific. The $I_{TC}$ index can well represent ENSO events and their interannual variation. Compared to the existing ENSO indices, the $I_{TC}$ index is more closely related to the East Asian winter monsoon (EAWM) and can better depict the impact of ENSO on the EAWM. The $I_{TC}$ index provides a new index for ENSO monitoring, predicting and impact, eliminating the inconvenience that numerous existing ENSO indices may have caused.

**Plain Language Summary**

It is well known that ENSO can significantly affect the weather and climate worldwide. However, at present there are many ENSO indices which are defined by the sea surface temperature anomalies (SSTAs) in the different regions of the equatorial Pacific. Such numerous ENSO indices may cause inconvenience in understanding ENSO itself and its impacts as well as ENSO monitoring and predicting. Therefore it is tempting to define a generalized ENSO index. Considering that the tropical convective activities are closely related with ENSO and the impact of ENSO on the large-scale atmospheric circulation is mainly through the release of latent heat caused by the associated convective anomalies, in this study a new ENSO index is defined based on the outgoing long wave radiation anomalies over the equatorial Pacific which represent the convective activities. It is demonstrated that the index defined by the tropical convection anomalies can well depict the ENSO events and their interannual variation defined by the

SSTAs in the equatorial Pacific. In addition, compared to the existing ENSO indices, the new index defined in this study is more closely related to the East Asian winter monsoon (EAWM) and can better reflect the impact of ENSO on the EAWM.

## 1 Introduction

The weather and climate in East Asia are mainly controlled by the East Asian monsoon. The East Asian summer and winter monsoons prevail in summer and winter seasons, respectively. Previous studies have shown that the El Niño-Southern Oscillation (ENSO) phenomenon that occurs in the equatorial central and eastern Pacific can significantly affect the East Asian monsoon. Because ENSO generally peaks in winter, then rapidly decays, and no longer exists in summer (Wang et al., 2000; Song et al., 2019), therefore ENSO influences the East Asian winter monsoon (EAWM) directly but the East Asian summer monsoon (EASM) indirectly. It has been confirmed that the bridge connecting ENSO and EAWM is an anomalous anticyclone over the western North Pacific (WNPAC) in the lower troposphere (Zhang et al., 2017; Li et al., 2017). Regarding the formation mechanism of the WNPAC, Zhang et al. (1996) pointed out that in the El Niño mature phase, the convective cooling anomalies over the western tropical Pacific induce an atmospheric Rossby wave response in the lower troposhere, resulting in the generation of the WNPAC. The atmospheric circulation and water vapor transport associated with the WNPAC have significant impacts on the East Asian monsoonal circulation and precipitation in the East Asian region (Zhang et al., 1999; Zhang & Sumi, 2002). However, the impact of El Niño on the EASM is a kind of lagged impact (Zhang et al., 2017), and is indirect through the summertime sea surface temperature anomalies (SSTAs) related to ENSO in other tropical oceans instead of the equatorial central and eastern Pacific. Wang et al. (2000) proposed that the local air-sea interaction in the western North Pacific maintains the WNPAC from winter to summer because of the positive feedback mechanism of wind-evaporation-sea surface temperature. Yang et al. (2007) and Xie et al. (2009) pointed out that in the summer after the mature period of El Niño, the abnormally warm tropical Indian Ocean stimulates the equatorial Kelvin wave and induces Ekman divergence in the western North Pacific, leading to the occurrence of WNPAC. Rong et al. (2010) found that the warm sea temperature anomaly in the tropical North Atlantic in the summer following an El Niño can also stimulate eastward equatorial Kelvin waves, which play an important role in the maintenance of the WNPAC in the following summer.

There are a variety of indices that characterize ENSO events, such as the mean SSTAs in Niño1+2, Niño3, Niño3.4, Niño4 and NiñoC regions, respectively (Li & Zhai, 2000). Since the eastern-Pacific (EP) and the central-Pacific (CP) type of ENSO were proposed, the index used to characterize the CP type of El Niño events has been also adopted. Although such many ENSO indices are beneficial for understanding the details of ENSO events, it is inconvenient for the definition of ENSO and the study of ENSO impacts. In fact, different studies in ENSO impacts on the East Asian monsoon have adopted different ENSO indices, and the results obtained are significantly different (Zhang et al., 2017). Therefore, an appropriate ENSO index is important in understanding ENSO itself and the influence of ENSO on the East Asian monsoon because of the dependence of the influence on current ENSO indices.

As mentioned above, the effect of El Niño on the EAWM is through the WNPAC, which is a Rossby wave response of the tropical atmosphere to the anomalous convective activities associated with ENSO in winter. Therefore, it is tempting to directly select the tropical convection anomalies associated with ENSO events to define the ENSO index instead of SSTAs for better reflecting the impact of ENSO on the EAWM. Considering that the ENSO in winter has a direct impact on the EAWM, this study will focus on the boreal winter season. Based on the above considerations, this study will define a new ENSO index by using the convection anomalies over the tropical Pacific in the winter of ENSO years, and then further explore the relationship between ENSO and EAWM based on the new index we defined. This study provides a new idea in defining ENSO and will be beneficial for further understanding the influence of ENSO, especially on EAWM.

## 2 Data

The data used in this study are: (1) the NCEP / NCAR monthly mean reanalysis data with a horizontal resolution of 2.5°× 2.5° (Kalnay et al., 1996), in which the sea level pressure (SLP) and $u$,$v$ wind fields in each layer are used; (2) NOAA outgoing long wave radiation (OLR) data with a horizontal resolution of 2.5°×2.5°, which can well reflect tropical convective activities. The analysis period of this study is from June 1974 to December 2020. Winter refers to the months from December of the current year to February of the following year. For example, the winter of 1982/83 included the December in 1982 as well as the January and February in 1983.

The current definitions of El Niño indices using SSTAs are as follows: Niño1+2 index (averaged SSTAs in 0°–10°S, 90°W–80°W); Niño3 index (averaged SSTAs in 5°S–5°N, 150°W–90°W); Niño3.4 index (averaged SSTAs in 5°S–5°N, 170W°–120°W); Niño4 index (averaged SSTAs in 5°S–5°N, 160°E–150°W); NiñoC index( averaged SSTAs in 0°–10°S , 180°–90°W).

This study also uses the eastern Pacific El Niño index ($N_{CT}$) and central Pacific El Niño index ($N_{WP}$) defined by Ren and Jin (2011): $\mathbf{N}_{\mathrm{CT}}=\mathbf{N_3}-\mathbf{N_4}$, $\mathbf{N}_{\mathrm{WP}}=\mathbf{N_4}-\mathbf{N_3}$, where *N3* represents the Niño3 index, and *N4* the Niño4 index. If $N3N4 > 0$, then $= 2/5$, otherwise $= 0$.

## 3 Definition of tropical convection index

Wang et al. (2000) defined a WNPAC index as the averaged sea level pressure anomalies in the Philippine Sea (10°–20°N, 120°–150°E). Considering that the WNPAC is caused by the convective anomalies over tropical western Pacific associated with El Niño (Zhang et al., 1996), we calculate the correlation coefficients between the WNPAC index and OLR field over the tropical Pacific (Fig. 1). It can be seen from Figure 1 that the correlation coefficients show an obvious east-west dipole pattern. The WNPAC is correlated positively with the OLR over the western equatorial Pacific and negatively with that over the equatorial central and eastern Pacific. The dipole pattern of correlation coefficient is consistent with the distribution of OLR anomalies during El Niño mature phase obtained by Zhang et al. (1996, 1999). According to Zhang et al. (1996, 1999), the decreased (increased) SST in the equatorial western (central and eastern ) Pacific during the El Niño mature phase inhibites (enhances) the development of convections and leads to the positive (negative) OLR anomalies. The convective cooling anomalies in the equatorial western Pacific stimulates the atmospheric Rossby wave response,resulting in the occurence of the WNPAC.

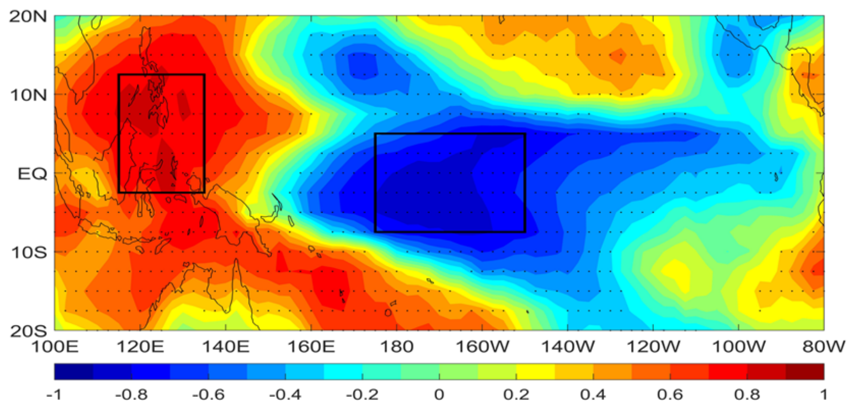


**Figure 1**. Correlation coefficients between the WNPAC index and OLR field. The black dots represent the correlation coefficients exceeding the 95% significance level.

Considering the physical linkages of the dipole distribution of OLR anomalies with the WNPAC and El Niño events, we select the region 2.5°S–12.5°N, 115°E–135°E in the equatorial western Pacific and the region 7.5°S–5°N, 175°E–150°W in the equatorial central and eastern Pacific region. Based on the zonal difference of averaged OLR anomalies between the two regions in winter, a new equatorial convection index ($I_{TC}$) is defined to represent El Niño events for its influence on the EAWM. The $I_{TC}$ index is defined as:

$$I_{\mathrm{TC}} = \mathrm{OLR}^*_W - \mathrm{OLR}^*_{\mathrm{CE}}$$

where $\mathrm{OLR}^*_W$ and $\mathrm{OLR}^*_{\mathrm{CE}}$ represent the standardized OLR anomalies averaged in the regions of the equatorial western Pacific (2.5°S–12.5°N, 115°E–135°E) and the equatorial central and eastern Pacific (7.5°S–5°N, 175°E–150°W), respectively.

Figure 2 shows the time evolutions of $I_{TC}$ index and WNPAC index in winter. It can be seen that the two indices have very consistent interannual variations. The correlation coefficient between them is as high as 0.885, which is statistically significant exceeding the 99% significance level. It shows that the larger (smaller) the anomalous zonal difference of equatorial convective activity is, the larger (smaller) the WNPAC index and the stronger (weaker) the WNPAC. The high correlation coefficient indicates the close relation of the WNPAC with the dipole pattern of anomalous tropical convective activities in winter.

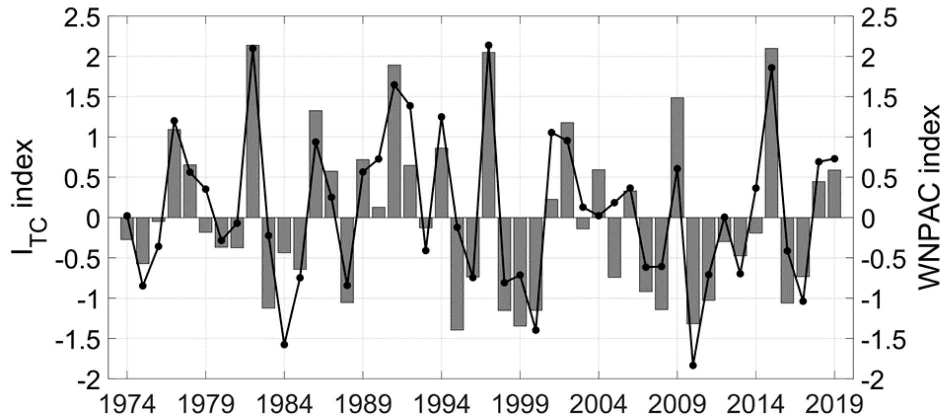


**Figure 2**. Time evolutions of the $I_{TC}$ index (column) and WNPAC index (curve) in winter.

### 4 Representativity of the $I_{TC}$ index for ENSO

In order to investigate the representativity of the $I_{TC}$ index for ENSO, we calculated the correlation coefficients of the $I_{TC}$ index with the existing ENSO indices. As shown in Figure 3a, the $I_{TC}$ index is significantly correlated with all 7 ENSO indices of Niño1+2, Niño3, Niño3.4, Niño4, NiñoC, $N_{CT}$, and $N_{WP}$, with the highest correlation coefficient reaching 0.911 between the $I_{TC}$ and Niño3.4 indices. The lowest correlation coefficient (0.486) is between the $I_{TC}$ and $N_{WP}$ indices, indicating the central Pacific El Niño is different from a conventional one (Larkin & Harrison, 2005; Ashok et al., 2007; Kug et al., 2009). However, all correlation coefficients, including the lowest one, are statistically significant exceeding the 99% significance level. This indicates that the interannual variation of the dipole pattern of equatorial convection anomalies reflected by the $I_{TC}$ index is consistent with that of ENSO indices. The $I_{TC}$ index can well represent the interannual variation of ENSO and can reflect the unified characteristics of multiple ENSO indices in the interannual timescale.

We further calculated the correlation coefficients of the WNPAC index with various ENSO indices (Fig. 3b). It can be seen from Figure 3b that the WNPAC index, same as the $I_{TC}$ index, is also significantly correlated with each of ENSO indices, and all correlation coefficients exceed the 99% significance level. The highest and lowest correlation coefficients are 0.856 and 0.483 with the Niño3.4 and $N_{WP}$, respectively. In fact, Trenberth (1997) recommended to use Niño3.4 index to express ENSO. Here we can see that the Niño3.4 index has the closest relation with the WNPAC, indicating the superiority for using this index to represent the impact of ENSO on the EAWM. The lowest correlation coefficient between the WNPAC index and $N_{WP}$ may be attributed to the much weaker response of the WNPAC to the central Pacific El Niño compared to the eastern Pacific El Niño as proposed by Su et al. (2013). In the winters of El Niño and La Niña years, positive and negative values of the $I_{TC}$ index appear, respectively, which are in consistency with the previous studies, that is, anomalous anticyclone and cyclone over the western North Pacific occur during the El Niño and La Niña mature phases, respectively (Zhang et al., 2015; Gao et al., 2019), which further confirms the relationship between the WNPAC and convection anomalies associated with ENSO proposed by Zhang et al. (1996).

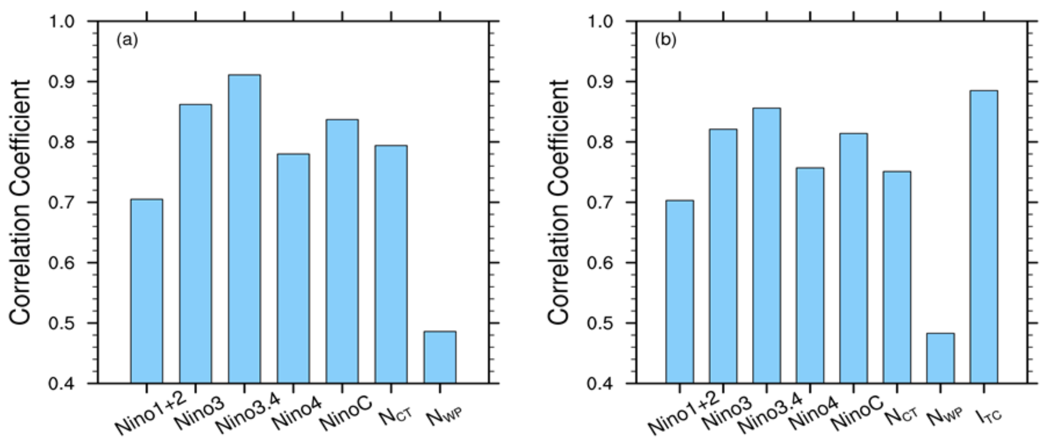


**Figure 3**. Correlation coefficients of (a) the $I_{TC}$ index and (b) the WNPAC index with each of ENSO indices.

Although ENSO indices are closely related to the WNPAC, as shown in Figure 3b, all the correlation coefficients between the WNPAC index and each of ENSO indices are lower than the correlation coefficient between the WNPAC index and $I_{TC}$ index, which reaches 0.885. Of course, it is not surprising that the WNPAC index has the best correlation with the $I_{TC}$ index because the $I_{TC}$ index is defined according to the convection anomalies associated with the WNPAC index. However, the significant correlations between the $I_{TC}$ index and various ENSO indices reflect that the $I_{TC}$ index can well represent the ENSO events. Therefore, the $I_{TC}$ index can replace the ENSO indices defined by SSTAs, and in such a way a direct bridge is established between ENSO and the WNPAC. The stronger (weaker) the ENSO, the larger (the smaller) the $I_{TC}$ index, and the stronger (weaker) the WNPAC.

## 5 Relations of the $I_{TC}$ index with the EAWM

The above analysis shows that the $I_{TC}$ index defined by the wintertime tropical convection can well represents all ENSO indices defined by the SSTAs in the equatorial central and eastern Pacific, and it is an indicator that can comprehensively reflect ENSO events. Compared with all ENSO indices, the $I_{TC}$ index has the highest correlation coefficient with the WNPAC in winter. It can be inferred that the $I_{TC}$ index can better reflect the impact of ENSO on the EAWM. In order to confirm this inference, we will compare the $I_{TC}$ index to all ENSO indices in their relations with the EAWM in this section.

At present, there are a large number of indices describing EAWM from different aspects, and Wang and Chen (2010) summed up 18 indices of EAWM. In addition to these EAWM indices, Zhang et al. (1996) defined the East Asian monsoon index by using the meridional winds in the lower troposphere along the coast of East Asia firstly and used it in the study of ENSO impacts on the East Asian monsoon. Therefore, a total of 19 EAWM indices are selected in the present study. Table 1 gives the definitions and brief descriptions for all these 19 EAWM indices.

**Table 1.** *19 East Asian Winter Monsoon indices and their definitions*

| Number | Index | Defining variable(s), level (hPa) and regions | Reference |
|---|---|---|---|
| | I(JiLR) | v, 1000 hPa, (10°–30°N, 115°–130°E) | Ji and Sun ( |
| | I(LuE) | v, 1000 hPa, (7.5°–20°N, 107.5°–120°E) | Lu and Cha |
| | I(ChenJ | v, 1000 hPa, (15°–30°N, 115°–130°E) | Chen and Su |
| | I(YangS) | v, 850 hPa, (20°–40°N, 100°–140°E) | Yang et al. |
| | I(ChenW | v, 10 m, (10°–25°N, 110°–130°E) and (25°–40°N, 120°–140°E) | Chen et al. |
| | I(HuZZ) | -v, 10 m, (15°–40°N, 115°–130°E) | Hu et al. (2 |
| | I(WangHJ) | u, v, 850 hpa, (25°–50°N, 115°–145°E) | Wang and J |
| | I(Jhun) | u, 300 hPa, (27.5°–37.5°N, 110°–170°E) minus (50°–60°N, 80°–140°E) | Jhun and Le |
| | I(XuSY | SLP gradient, (30°–40°N, 100°–120°E) minus (30°–40°N, 130°–140°E) | Xu and Ji ( |
| | I(GuoQY) | SLP gradient, (10°–60°N, 110°–160°E) | Guo (1994) |
| | I(ShiN | SLP gradient, (20°–50°N, 110°–160°E) | Shi (1996) |
| | I(WuBY) | SLP gradient, (20°–70°N, 110°–160°E) | Wu and Wa |
| | I(ChanCL | SLP gradient, (35°–55°N, 100°–120°E) minus (35°–55°N, 150°–170°E) | Chan and L |
| | I(Wang) | SLP gradient, (40°–70°N, 110°–160°E) | Wang et al. |
| | I(GongDY) | SLP, (40°–60°N 70°–120°E) | Gong et al. |
| | I(SunBM) | Φ, 500 hPa, 30°–45°N, 125°–145°E) | Sun and Li |
| | I(CuiXP) | Φ, 500 hPa, (35°–40°N, 110°–130°E) | Cui and Sun |
| | I(WangL) | Φ, PC1, 500 hPa, (25°–50°N,100°–180°E) | Wang et al. |
| | I(ZhangRH) | v, 850 hPa, (20°–30°N, 110°–130°E) | Zhang et al. |

Figure 4 shows the correlation coefficients of each ENSO index (including the $I_{TC}$ index) with the 19 EAWM indices, respectively. Considering that the correlation coefficients between different EAWM indices and ENSO indices are either positive or negative, all the correlation coefficients in Figure 4 are taken to be their absolute values for the convenience of comparison. It can be seen from Figure 4 that some correlation coefficients are significantly correlated with ENSO but some not. Wang and Chen (2010) demonstrated that the EAWM indices which can well describe the interannual variability of EAWM may have significant correlation with ENSO, while those reflecting poorly the interannual variability are not well correlated with ENSO. However, it is obvious that the correlations of the $I_{TC}$ index with EAWM are better than those of ENSO indices on the whole. Among 19 correlation coefficients of the $I_{TC}$ index with the EAWM indices, the 13 ones are the highest compared to the correlation coefficients of each ENSO index with the EAWM indices. We further calculated the averageed correlation coefficients of each ENSO index with the 19 EAWM indices and they are 0.290, 0.299, 0.302, 0.293, 0.298, 0.274, and 0.202 for the indices of Niño1+2, Niño3, Niño3.4, Niño4, NiñoC, $N_{CT}$, and $N_{WP}$, respectively. All of them are lower than the averaged correlation coefficient of the $I_{TC}$ index with the 19 EAWM indices (0.372), indicating that the $I_{TC}$ index we defined has the closest relationship with the EAWM.

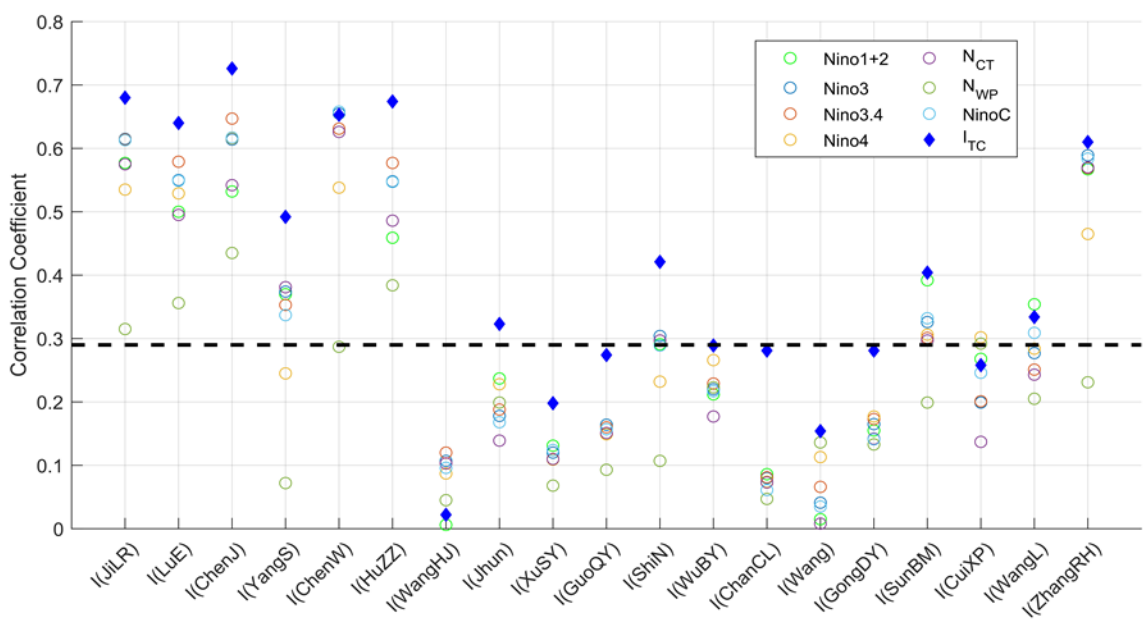


**Figure 4**. Correlation coefficients of each ENSO index (including the $I_{TC}$ index) with each of 19 East Asian winter monsoon indexes. The abscissa is for the19 East Asian winter monsoon indices. The circles with different colors represent different ENSO indices of Niño1+2, Niño3, Niño3.4, Niño4, NiñoC, $N_{CT}$ and $N_{WP}$. The blue rhomb is for the $I_{TC}$. The dashed heavy line indicates the correlation coefficient of 0.29, which is statistical significant at the 0.05 significance level.

Therefore, in general the $I_{TC}$ index can well reflect not only the ENSO events, but also its impact on the EAWM. According to Zhang et al. (2017), it is easy to give a physical explanation for the closest relations of the $I_{TC}$ index with ENSO and EAWM. In the winter of an El Niño (La Niña) year, the east-west dipole distribution of convection anomalies over the tropical Pacific are caused by the suppressed (enhanced) convection associated with the negative (positive) SSTAs in the tropical western Pacific and enhanced (suppressed) convection associated with the positive (negative) SSTAs in the central and eastern tropical Pacific. Such dipole distribution of convection anomalies is exactly a reflection of the anomalous Walker circulation related to ENSO and, therefore, result in a close relationship between the $I_{TC}$ index and ENSO. Meanwhile, the convective cooling (heating) anomalies over the tropical western Pacific indicated by the $I_{TC}$ index stimulate the atmospheric Rossby wave response and produce an anomalous anticyclone (cyclone) over the western North Pacific, which enhances (declines) the southwesterly flows along the coast of East Asian and thus weakens (strengthens) the EAWM.

## 6 Conclusion and Discussion

Based on the characteristics of convective activities over the equatorial Pacific during the mature period of ENSO in winter, this study defines a new index, the $I_{TC}$ index, to represent ENSO, and illustrates the relationship among the $I_{TC}$ index, ENSO, WNPAC, and EAWM. The following main conclusions are obtained:

(1) The $I_{TC}$ index represents the zonal difference between the tropical convection anomalies in the equatorial western Pacific and those in the equatorial central and eastern Pacific, and is significantly related to all ENSO indices defined by the equatorial SSTAs. The $I_{TC}$ index reflects the anomalous Walker circulation in ENSO events, and so its interannual variation is in good agreement with the ENSO.

(2) Compared with all ENSO indices, the $I_{TC}$ index shows the highest positive correlation with the WNPAC index, with a correlation coefficient as high as 0.885. The $I_{TC}$ index defined by convection anomalies over the tropical Pacific has a better reflection than the ENSO indices defined by SSTAs for the influence of ENSO on the WNPAC, the bridge connecting ENSO and EAWM. The larger (smaller) the $I_{TC}$ index, the larger (smaller) the WNPAC index, and the stronger (weaker) the WNPAC.

(3) Compared with all ENSO indices, the $I_{TC}$ index shows the best correlation with the EAWM on the whole, indicating the superiority of the $I_{TC}$ index in describing the impact of ENSO on the EAWM compared to the ENSO indices defined by the SSTAs. A larger (smaller) $I_{TC}$ index corresponds to a stronger (weaker) WNPAC, which increases (reduces) the southwesterly winds along the coast of East Asia, and thus weakens (strengthens) the EAWM.

In fact, ENSO's effect on the large-scale atmospheric circulation is mainly through affecting the tropical convection which releases abnormal latent heat.

Therefore, using the tropical convection anomalies associated with ENSO to define the ENSO index can reflect straightforward the impact of ENSO on atmospheric circulation compared to using the ENSO indice defined by SSTAs. As shown by the results obtained in this study, the $I_{TC}$ index defined by tropical convection anomalies can not only well reflect the ENSO events, but also is closely related to the EAWM. The results of this study put forward a new idea for defining the index of ENSO as well as its influence on the atmospheric circulation. Aditionally, using tropical convection to define the ENSO index can overcome the inconvenience caused by many existing ENSO indices in the study of ENSO impacts. It is also expected to be beneficial for improve ENSO monitoring and predicting.

Acknowledgments

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**Data Availability Statement**

All data used in this manuscript are publicly available. The NCEP / NCAR month-ly mean reanalysis data is provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA at https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html. The outgoing longwave radiation (OLR) data is obtained from NOAA Interpolated Outgoing Longwave Radiation Data Record at https://psl.noaa.gov/data/gridded/data.interp_OLR.html.

**References**

Ashok, K., Behera, S. K., Rao, S. A., Weng, H., & Yamagata, T. (2007). El Niño Modoki and its possible teleconnection. *Journal of Geophysical Research*, 112. https://doi.org/10.1029/2006JC003798

Chan, J. C. L., & Li, C. (2004). The East Asia Winter Monsoon.In C.-P. Chan (Eds.), *East Asia Monsoon* (pp. 54–106). Hackensack, NJ: World Scientific Publishing Co. Pte. Ltd. https://doi.org/10.1142/9789812701411_0002

Chen, J., & Sun, S. Q. (1999). East Asian winter monsoon anomaly and variation of global circulation. Part I: A comparison study on strong and weak winter monsoon. *Atmospheric Science*, *23*(1), 101–111. (in Chinese). https://doi.org/10.3878/j.issn.1006-9895.1999.01.12

Chen, W., Graf, H. F., & Ronghui, H. (2000). The interannual variability of East Asian Winter Monsoon and its relation to the summer monsoon. *Advances in Atmospheric Sciences*, *17*(1), 48–60. https://doi.org/10.1007/S00376-000-0042-5

Cui, X. P., & Sun, Z. B. (1999). East Asian winter monsoon index and its varation analysis. *Jour-nal of Nanjing Institute of Meteorology*, (3), 321–325. (in Chinese). https://doi.org/10.3969/j.issn.1674-7097.1999.03.005

Gao, R., Zhang, R., Wen, M., & Li, T. (2019). Interdecadal changes in the asymmetric impacts of ENSO on wintertime rainfall over China and atmospheric circulations over western North Pacific. *Climate Dynamics*, *52*(12), 7525–7536. https://doi.org/10.1007/S00382-018-4282-4

Gong, D. Y., Wang, S. W., & Zhu, J. H. (2001). East Asian Winter Monsoon and Arctic Oscillat-ion.*Geophysical Research Letters*, *28*(10), 2073–2076. https://doi.org/10.1029/2000GL012311

Guo, Q. Y. (1994). Relationship between the variations of East Asian winter monsoon and tem-perature anomalies in China. Quarterly Journal of Applied Meteorology, *5*(2), 218–225. (in Chi-nese). https://doi.org/CNKI:SUN:YYQX.0.1994-02-012

Hanley, D. E., Bourassa, M. A., O'Brien, J. J., Smith, S. R., & Spade, E. R. (2003). A Quantitati-ve Evaluation of ENSO Indices. *Journal of Climate*, *16*(8), 1249–1258. https://doi.org/10.1175/1520-0442(2003)16%3c1249:AQEOEI%3e2.0.CO;2

Hu, Z.-Z., Bengtsson, I. L., & Arpe, K. (2000). Impact of global warming on the Asian winter m-onsoon in a coupled GCM. *Journal of Geophysical Research*, *105*, 4607–4624. https://doi.org/10.1029/1999JD901031

Ji, L., Sun, S., Arpe, K., & Bengtsson, L. (1997). Model Study on the Inter-annual Variability of Asian Winter Monsoon and Its Influence. *Advances in Atmospheric Sciences*, *14*(1), 1–22. https://doi.org/10.1007/S00376-997-0039-4

Jhun, J. G., & Lee, E. J. (2004). A New East Asian Winter Monsoon Index and Associated Char-acteristics of the Winter Monsoon. *Journal of Climate*, *17*(4), 711–726. https://doi.org/10.1175/1520-0442(2004)017%3c0711:ANEAWM%3e2.0.CO;2

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., et al. (1996). The N-CEP/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society*, *77*(3), 437–471. https://doi.org/10.1175/1520-0477(1996)077%3c0437:TNYRP%3e2.0.CO;2

Kug, J. S., Jin, F. F., & An, S. I. (2009). Two Types of El Niño Events: Cold Tongue El Niño a-nd Warm Pool El Niño. *Journal of Climate*, *22*(6), 1499–1515. https://doi.org/10.1175/2008JCLI2624.1

Larkin, N. K., & Harrison, D. E. (2005). On the definition of El Niño and associated seasonal av-erage U. S. weather anomalies. *Geophysical Research Letters*, *32*(13). https://doi.org/10.1029/2005GL022738

Li, T., Wang, B., Wu, B., Zhou, T., Chang, C.-P., & Zhang, R. (2017). Theories on formation of an anomalous anticyclone in western North Pacific during El Niño: A review. *Journal of Meteor-ological Research*, *31*(6), 987–1006. https://doi.org/10.1007/S13351-017-7147-6

Li, X., & Zhai, P. (2000). On indices and indicators of ENSO episodes(in

Chinese). *Acta Meteo-rologica Sinica*,*58*(1), 102–102. https://doi.org/10.3321/j.issn:0577-6619.2000.01.010

Lu, E., & Chan, J. C. L. (1999). A Unified Monsoon Index for South China. *Journal of Climate*, *12*(8), 2375–2385. https://doi.org/10.1175/1520-0442(1999)012%3c2375:AUMIFS%3e2.0.CO;2

Ren, H., & Jin, F. (2011). Niño indices for two types of ENSO. *Geophysical Research Letters*,

*38*(4). https://doi.org/10.1029/2010GL046031

Rong, X., Zhang, R., & Li, T. (2010). Impacts of Atlantic sea surface temperature anomalies on Indo-East Asian summer monsoon-ENSO relationship. *Chinese Science Bulletin*, *55*(22), 2458–2468. https://doi.org/10.1007/S11434-010-3098-3

Shi, N. (1996). Features of the East Asian winter monsoon intensity on multiple time scale in re-cent 40 years and their relation to climate. *Quarterly Journal of Applied Meteorology*, *7*(2), 175–182. (in Chinese). https://doi.org/CNKI:SUN:YYQX.0.1996-02-006

Song, X, Zhang R., & Rong X. (2019) Influence of intraseasonal oscillation on the asymmetric d-ecays of El Niño and La Niña. *Advances in Atmospheric Sciences*, *36* (8), 779–792. https://doi.org/10.1007/s00376-019-9029-6

Su, J., Zhang, R., & Zhu, C. (2013) ECHAM5-simulated impacts of two types of El Niño on the winter precipitation anomalies in South China. *Atmospheric and Oceanic Science Letters*, *6* (5), 360–364. https://doi.org/10.3878/j.issn.1674-2834.13.0013

Sun, B., & Li, C. Y. (1997). Relationship between the disturbances of East Asian trough and tro-pical convective activities in boreal winter. *Chinese Science Bulletin*, (5), 54–58. (in Chinese). https://doi.org/10.3321/j.issn:0023-074X.1997.05.015

Trenberth, K. E. (1997). The definition of El Niño. *Bulletin of the American Meteorological Soc-iety, 78*(12), 2771–2778. https://doi.org/10.1175/1520-0477(1997)078%3c2771:TDOENO%3e2.0.CO;2

Trenberth, K. E., & Stepaniak, D. P. (2001). Indices of El Niño Evolution. *Journal of Climate*, *14*(8), 1697–1701. https://doi.org/10.1175/1520-0442(2001)014%3c1697:LIOENO%3e2.0.CO;2

Wang, B., Wu, R., & Fu, X. (2000). Pacific-East Asian teleconnection:How does ENSO affect E-ast Asian climate? *Journal of Climate*, *13*(9), 1517–1536. https://doi.org/10.1175/1520-0442(2000)013%3c1517:PEATHD%3e2.0.CO;2

Wang. H. J., & D. B. Jiang. (2004). A new East Asian winter monsoon intensity index and atmo-spheric circulation comparison between strong and weak composite. *Quaternary Sciences*, *24*, 19–27. (in Chinese). https://doi.org/10.3321/j.issn:1001-7410.2004.01.003

Wang, L., Chen, W., Zhou, W., & Huang, R. (2009a). Interannual Variations of East Asian Trou-gh Axis at 500 hPa and its Association with the East Asian Winter Monsoon Pathway. *Journal of Climate*, *22*(3), 600–614. https://doi.org/10.1175/2008JCLI2295.1

Wang, L., Huang, R., Gu, L., Chen, W., & Kang, L. (2009b). Interdecadal variations of the East Asian winter monsoon and their association with quasi-stationary planetary wave activity. Journ-al of Climate, *22*(18), 4860–4872. https://doi.org/10.1175/2009JCLI2973.1

Wang, L., & Chen, W. (2010). How well do existing indices measure the strength of the East As-ian winter monsoon. *Advances in Atmospheric Sciences*, *27*(4), 855–870. https://doi.org/10.1007/S00376-009-9094-3

Wu, B, Y., & J. Wang. (2002). Winter Arctic Oscillation, Siberian High and East Asian winter monsoon. *Geophysical Research Letters*. *29*. https://doi.org/10.1029/2002GL015373

Xie, S. P., Hu, K., Hafner, J., Tokinaga, H., Du, Y., Huang, G., et al. (2009). Indian Ocean capa-citor effect on Indo–Western Pacific climate during the summer following El Niño. *Journal of Climate*, *22*(3), 730–747. https://doi.org/10.1175/2008JCLI2544.1

Xu, S. Y., & J. J. Ji. (1965) The climate and weather features during the outbreak period of Chin-a's winter monsoon. *Geographical Symposium*, *9*. 85–101. (in Chinese).

Yang, J., Liu, Q., Xie, S.-P., Liu, Z., & Wu, L. (2007). Impact of the Indian Ocean SST basin m-ode on the Asian summer monsoon. *Geophysical Research Letters*, *34*(2). https://doi.org/10.1029/2006GL028571

Yang, S., Lau, K. M., & Kim, K. M. (2002). Variations of the East Asian jet stream and Asian-P-

acific-American winter climate anomalies. *Journal of Climate*, *15*(3), 306–325. https://doi.org/10.1175/1520-0442(2002)015%3c0306:VOTEAJ%3e2.0.CO;2

Zhang, R., Sumi, A., & Kimoto, M. (1996). Impact of El Niño on the East Asian Monsoon : A d-iagnostic study of the '86/87 and '91/92 events. *Journal of the Meteorological Society of Japan*, *74*(1), 49–62. https://doi.org/10.2151/JMSJ1965.74.1_49

Zhang, R., Sumi, A., & Kimoto, M. (1999). A diagnostic study of the impact of El Niño on the p-recipitation in China. *Advances in Atmospheric Sciences*, *16*(2), 229–241. https://doi.org/10.1007/BF02973084

Zhang, R., & Sumi, A. (2002). Moisture circulation over East Asia during El Niño episode in no-rthern winter, spring and autumn. *Journal of the Meteorological Society of Japan*, *80* (2), 213–227, https://doi.org/10.2151/jmsj.80.213

Zhang, R., Li, T., Wen, M., & Liu, L. (2015). Role of intraseasonal oscillation in asymmetric im-pacts of El Niño and La Niña on the rainfall over southern China in boreal winter. *Climate Dyna-mics*, *45*(3), 559–567. https://doi.org/10.1007/S00382-014-2207-4

Zhang, R., Min, Q., & Su, J. (2017). Impact of El Niño on atmospheric circulations over East Asia and rainfall in China: Role of the anomalous western North Pacific anticyclone. *Science China-Earth Sciences*, *60*(6), 1124–1132. https://doi.org/10.1007/S11430-016-9026-X