A unified complex index to characterize two types of ENSO simultaneously

Zhiyuan Zhang, Baohua Ren & Jianqiu Zheng

It is widely considered the El Nino-South Oscillation (ENSO) has several different types which can be simply classified as eastern Pacific (EP) type and central Pacific (CP) type. However, indices proposed so far can only characterize one single type of ENSO. In this paper, we develop a unified index which can characterize two types of ENSO simultaneously. The new index named as unified complex ENSO index (UCEI) is defined in the complex plane whose real part is NINO3 + NINO4 and imagine part is NINO3-NINO4. The modulus (r) and quadrants (θ) represent the ENSO strength and the ENSO types, respectively. Apart from the EP and CP types, the UCEI could further distinguish the MIX type of ENSO. Besides, the UCEI can capture the type-transforming processes within one ENSO event. Applying UCEI on historical events from 1950 to 2017 demonstrates the new index could be a very useful tool for the research of different types of ENSO.

El Nino-South Oscillation (ENSO) is the most influential pattern of the global climate with sea surface temperature anomalies (SSTA) over the tropical central and eastern Pacific Ocean. It is widely considered that the ENSO has several different types. Based on the SSTA distribution, it can be classified as the eastern Pacific (EP) type (or Cold Tongue type) and the central Pacific (CP) type (or Modoki type, Warm Pool type)1–8. The EP ENSO is the traditional type of ENSO which locates most of the anomalies over the eastern Pacific while the CP type known as the new type of ENSO which appears more frequently in recent decades has much more anomalies in the central Pacific6. For some events, the anomalies over the central and eastern Pacific are relatively both high which cannot be simply divided into EP or CP type and this type is generally called the MIX ENSO7.

The early indices, such as NINO4 (N4) [160°E-150°W, 5°S-5°N] and NINO3 (N3) [150°W-90°W, 5°S-5°N] are widely used to capture the anomalies in the central Pacific and eastern Pacific, respectively. However, N3 and N4 cannot well distinguish EP and CP ENSO as the anomalies in N3 (or N4) region will extend to the neighboring N4 (or N3) region. Trenberth and Stepaniak recognized the gradient between the central and eastern Pacific is necessary to completely describe ENSO and raised the Trans-Nino index (TNI) which is defined as the NINO12 subtracts N41. Then Ashok et al proposed the El Nino Modoki index (EMI) which uses the anomalies over the central Pacific subtract the eastern and western pacific3. Li et al further adjusted the proportions of three regions of the EMI and proposed the improved El Nino Modoki index (IEMI) which could monitor the weak CP ENSO events better5. Ren and Jin developed NCT/NWP as a pair of indices to characterize EP and CP types of ENSO. The NCT and NWP are defined as NCT = N3 - α N4, NWP = N4 - α N3; α = 0.4 when N3*N4 > 0; α = 0 when N3*N4 < 0. The NCT and NWP demonstrate N3 and N4 could be suitable to distinguish EP and CP ENSO based on an appropriate combination10.

However, the existing indices can only characterize one type of ENSO. It is not convenient enough to determine the ENSO type as at least two indices are required. Not only that, in some cases, values of EP and CP indices are both high which makes the determination difficulty. So, whether one could develop a unified index that could characterize two types of ENSO simultaneously? In this paper, we introduce a novel index which could well achieve this purpose.

Results
To better descrit how we construct the new index, we demonstrate the averaged SSTA distributions of 1997–1998, 2004–2005 and 1991–1992 El Nino events as the examples that represent the EP, CP and MIX types, respectively (Fig. 1). As the figure clearly shows that the warming anomalies of the EP El Nino mostly located in the region N3 and a small amount of anomalies extend to the region N4 (Fig. 1a). If we use N3 − N4, the result is
definitely a positive number. In contrast, the warming anomalies of the CP type of El Nino mainly concentrate in
the region N4 and very few anomalies appear in the region N3 (Fig. 1b). Then the result of N3 \(-\) N4 is a negative
number. As for the MIX type of El Nino, the anomalies over the regions N3 and N4 are nearly equal (Fig. 1c). N3 \(-\) N4 is very small which could be regarded as approximately equal to 0. Taking into account the situation of
La Nina, we further introduce the variable N3 + N4. The phase of N3 + N4 is positive for El Nino and negative for
La Nina regardless of the type. Therefore, we could determine the type of El Nino (as well as La Nina) by the phase
of N3 + N4 and N3 \(-\) N4 which can be summarized as follows:

\[
\begin{align*}
N3 + N4 > 0 & \quad N3 - N4 > 0 \quad \text{EP El Nino} \\
N3 + N4 > 0 & \quad N3 - N4 < 0 \quad \text{CP El Nino} \\
N3 + N4 < 0 & \quad N3 - N4 < 0 \quad \text{MIX El Nino} \\
N3 + N4 < 0 & \quad N3 - N4 > 0 \quad \text{EP La Nina} \\
N3 + N4 > 0 & \quad N3 - N4 > 0 \quad \text{MIX La Nina} \\
N3 + N4 < 0 & \quad N3 - N4 < 0 \quad \text{CP La Nina}
\end{align*}
\]

On the basis of the above analysis, we introduce a complex plane whose real part is the N3 + N4 while imagine
part is the N3 \(-\) N4. Figure 2a shows the monthly scatter plots of N3 + N4 and N3 \(-\) N4 in the complex plane
from 1950 to 2017. As the Fig. 2a demonstrates the complex plane is divided into six regions that refer to EP, CP
and MIX type of El Nino and La Nina respectively. In Practical application, the polar form is more suitable to
descript ENSO events. Because in polar form, the strength of ENSO could be represented by r while the deter-
mination of ENSO types could be achieved by only \(\theta\). The the correspondence between \(\theta\) and ENSO types is as
follows:

\[
\begin{align*}
\theta & \in (15^\circ, 90^\circ) \quad \text{EP El Nino} \\
\theta & \in (-15^\circ, 15^\circ) \quad \text{MIX El Nino} \\
\theta & \in (-90^\circ, -15^\circ) \quad \text{CP El Nino} \\
\theta & \in (-165^\circ, -90^\circ) \quad \text{EP La Nina} \\
\theta & \in (-195^\circ, -165^\circ) \quad \text{MIX La Nina} \\
\theta & \in (-270^\circ, -195^\circ) \quad \text{CP La Nina}
\end{align*}
\]

It should be noted that the threshold of MIX type (15°) is not randomly selected. We assume the threshold of MIX
type in the first quadrant is \(\alpha\). Larger the \(\alpha\), more significant the difference between N3 and N4 within the MIX
region \((-\alpha \sim \alpha), (-180 - \alpha \sim -180 + \alpha))\). According to this monotonic relationship, we change \(\alpha\) from 1 to 90
and for each angle apply a two-tailed Students’s t-test on the N3 and N4 within the threshold. Statistical analyze
demonstrates that when \(\alpha < 15\), difference between N3 and N4 is not significant while \(\alpha > 15\), difference is sig-
nificant (at 95% confidence level). Therefore, 15 is a suitable threshold of MIX type of ENSO. We also examine the

Figure 1. Examples of Averaged SSTA patterns of (a) EP El Nino, (b) CP El Nino and (c) MIX El Nino.
Coloring areas passed 99% confidence level from a two-tailed Student’s t test. Two boxes indicate the regions N3
(left) and N4 (right), respectively.
influence of asymmetry in El Nino-La Nina on the threshold of MIX ENSO, respectively. The threshold for MIX El Nino (La Nina) of all El Nino (La Nina) is 14° (17°), respectively.

After above analysis, we introduce a novel ENSO index called Unified Complex ENSO index (UCEI) which is defined as follows:

$$ UCEI = (N3 + N4) + (N3 - N4)i = re^{i\theta}, $$

where

$$ r = \sqrt{(N3 + N4)^2 + (N3 - N4)^2} = \sqrt{2(N3^2 + N4^2)} $$

$$ \theta = \begin{cases} 
\arctan \frac{(N3 - N4)}{(N3 + N4)} & N3 + N4 > 0 \\
\arctan \frac{(N3 - N4)}{180} - N3 + N4 < 0 
\end{cases} $$

Figure 2. Scatter plots of UCEI (a), time series of r (b), \( \theta \) (c) of UCEI and composite UCEI (d) from 1950 to 2017. ENSO types are denoted by different color. In this research, values of r that less than 0.5, between 0.5 and 1.0, 1.0 and 2.0, greater than 2.0 are determined as neutral, weak, moderate and strong, respectively.
The r represents the ENSO strength while θ determines the ENSO type. Figure 2b–d display the time series of r, θ and UCEI from 1950 to 2017. A 3 month-running smoothing was applied for N3 and N4.

Figure 3a shows the composite SSTA distributions of different types determined in Fig. 2a. Coloring areas passed 99% confidence level from a two-tailed Student’s t test. As we can see, even though the classification is based on only N3 and N4 regions, the composite distributions show the complete and typical EP, CP and MIX patterns in the whole tropical Pacific including the secondary feature regions such as the far eastern Pacific, off-equatorial regions and western Pacific which are consistent with the observation results. This demonstrates that the classification method of UCEI is very effective in distinguish different types of ENSO.

As Fig. 3a shows, the spatial distribution characteristics of El Nino and La Nina of each type are nearly the same. But strength and frequency of occurrence are obviously asymmetry in El Nino and La Nina. Statistical results based on the UCEI demonstrate that the averaged strength of EP, CP and MIX El Nino are 2.03 (102 months), 0.79 (91 months), 1.37 (137 months). As for La Nina, the averaged strength for EP and MIX types are 0.98 (134 months), 1.12 (49 months), 1.57 (175 months). Months that r less than 0.5 are determined as normal months and not selected. As we can see, the strength of EP La Nina is less than half of EP El Nino while CP and MIX types of La Nina are stronger than El Nino. In terms of frequency, CP La Nina appeared far less than CP El

Figure 3. Composite SSTA (a), SLPA and UWMDA (b) distributions of different types of El Nino and La Nina classified by UCEI from 1950 to 2017. Coloring areas and vectors passed 99% confidence level from a two-tailed Student’s t test. Month numbers and averaged r of UCEI are shown in brackets. Red boxes indicate the regions IOD, N3 and N4, respectively.
Nino while EP and MIX La Nina are more frequently than El Nino. All these lead to a result that EP and CP La Nina are both inactive compared with EP and CP El Nino and MIX type becomes the dominant pattern of La Nina. Previous researches also show that EP and CP La Nina are not clear as those of El Nino (Kug and Ham, 2011).

SSTA distributions in the Indian Ocean are also shown in the Figure. As the Fig. 3a shows, EP El Nino is related with warmer SSTA over western Indian Ocean than the eastern regions which indicates a positive Indian Ocean Dipole (IOD) while EP La Nina has few correlations to the Indian Ocean. In the case of CP El Nino, eastern Indian Ocean is warmer than the western regions which indicates a negative IOD. But the symmetrical correlation of CP La Nina in very weak. However, MIX El Nino and La Nina both have strong and broad correlation with the Indian Ocean that MIX El Nino/La Nina is linked with positive/negative IOD.

As the ENSO is a coupled ocean and atmosphere phenomenon, atmospheric features of different types of ENSO are also identified based on UCEI. Figure 3b is the same as 3a but for sea level pressure anomalies (slpa) and zonal wind anomalies (uwnda). EP El Nino has a strong dipole pattern with positive slpa widely spread over eastern Indian Ocean and western Pacific Ocean and negative slpa over eastern Pacific Ocean accompanied with easterlies over eastern Indian Ocean and westerlies over central Pacific Ocean. EP La Nina has a symmetrical but weaker pattern and no significant zonal wind anomalies over Indian Ocean. MIX El Nino has a similar pattern of EP El Nino but few gradients of negative slpa. The pattern of MIX La Nina is symmetrical to MIX El Nino. It should be noticed that MIX La Nina is the only type of La Nina that accompanied with westerlies over the Indian Ocean which are highly related to IOD events.

Phase locking properties of different types of ENSO are also identified by the UCEI. Figure 4 shows the sum of r based on calendar month of each type of El Nino/La Nina months from 1950 to 2017. Months that r < 0.5 are determined as normal months. ENSO type is determined by the θ of UCEI.
the traditional strong El Nino events. The UCEI can not only capture the type-transforming but also predict it. As the ENSO type is determined by the quantized $\theta$, we could easily predict the trend of type-transforming in the next few months by the linear fit of $\theta$. The historical ENSO events determined by UCEI from 1950 to 2017 are shown in Table 1. We examine the durations of three types of ENSO events that without type-transforming. The result shows the averaged durations of EP, CP and MIX ENSO are 14, 16 and 9 months which are close to the result of previous research that EP ENSO for 15 months and CP ENSO for 8 months. We noticed CP ENSO only appeared 3 times during 1950–1977 but 9 times during 1977–2016 which demonstrates the tendency that CP type of ENSO appeared more frequently.

Summary and Discussion
In this study, we develop a unified complex ENSO index (UCEI) which can characterize and distinguish EP and CP types of ENSO simultaneously. Based on the different features of EP and CP ENSO in regions N3 and N4, we construct the complex plane of $N_3 + N_4$ and $N_3 - N_4$. The El Nino type could be determined by the sign of $N_3 + N_4$ and $N_3 - N_4$. According to the significant test of difference between $N_3$ and $N_4$, the MIX ENSO could be further distinguished. Using the polar form, the ENSO type could be determined only by the argument ($\theta$). And the ENSO strength could be represented by the modulus ($r$). Hence, we could characterize EP, CP and MIX ENSO simultaneously with the new index. As the previous indices can only characterize a specific type of ENSO, such an index will be a very convenience tool for the researches on the different types of ENSO.

Previous indices generally adopt the way that using strength of EP and CP type of ENSO to describe ENSO events. Among them, NCT and NWP have something in common with UCEI. They are both constructed by NINO3 and NINO4 without additional defined areas and complicated operations. The Correlation coefficients between $r$ ($r$ flips to $-r$ when negative phase) and NCT, NWP, NCT + NWP are 0.89, 0.60, 0.99, respectively. As we can see, NCT or NWP only represents the decomposed strength of ENSO (EP or CP) which is not actual strength of ENSO. To determine the ENSO type, we also need a comparison of two indices. Therefore, the UCEI adopts a new way that using ENSO strength (not the component EP or CP strength) and ENSO type to describe ENSO events. The advantage of this way is that we can get the ENSO strength and types directly. Therefore, UCEI is more intuitive and convenient in practical application. However, the UCEI also has some deficiencies. For example, the generally used statistical analysis based on traditional indices such as auto-correlation, lead-lag correlation, and dominant frequency of each type of ENSO in the dynamical forecast models might be hard performed by UCEI.

Figure 5. The UCEI evolutions during 1957–1958 El Nino (a), 2007–2009 La Nina (b) and 2007–2009 El Nino (c), respectively. Black arrows indicate time points of subplots in (d–f), respectively. (d–f) Are the SSTA distributions at different times corresponding to the (a–c) events. Values great than 0.5 and less than $-0.5$ are filled with color.
The SSTA data used in this study is the monthly mean anomalies of Hadley Centre Sea Ice and Sea Surface Temperature data set\(^1\). We choose the time period from Jan1950 to Jan2017. The monthly mean zonal wind and sea level pressure data\(^2\) were from the NCEP reanalysis-derived data provided by the NOAA/OAR/ESRL PSD (Boulder, Colorado, USA) on their website at http://www.esrl.noaa.gov/psd/.

**Table 1.** ENSO events determined by UCEI from 1950 to 2017. An El Niño or La Niña event is determined when the r of UCEI exceeds 0.5 for at least 5 months. The ENSO strength are categorized as weak, moderate and strong when the maximum of r belongs to (0.5, 1), (1, 2), (2, +∞), respectively. In order to eliminate short-term noise signals, ENSO type that lasts for no more than 3 months is ignored.

| No. | ENSO events     | phase(strength) | Type       |
|-----|-----------------|-----------------|------------|
| 1   | 1950–1951       | La Niña (Weak)  | MIX        |
| 2   | 1951–1952       | El Niño (Moderate) | EP>MIX    |
| 3   | 1953            | El Niño (Weak)  | MIX        |
| 4   | 1954–1956       | La Niña (Moderate) | EP>MIX    |
| 5   | 1957–1959       | El Niño (Moderate) | EP>MIX>CP |
| 6   | 1963–1964       | El Niño (Moderate) | EP>MIX    |
| 7   | 1964–1965       | La Niña (Moderate) | EP>MIX>CP |
| 8   | 1965–1966       | El Niño (Moderate) | EP>MIX>CP |
| 9   | 1967–1968       | La Niña (Weak)  | EP         |
| 10  | 1968–1970       | El Niño (Moderate) | MIX>EP>MIX|
| 11  | 1970–1972       | La Niña (Moderate) | EP>MIX>EP |
| 12  | 1972–1973       | El Niño (Strong) | EP         |
| 13  | 1973–1976       | La Niña (Moderate) | EP>MIX>CP>MIX |
| 14  | 1976–1977       | El Niño (Moderate) | EP         |
| 15  | 1977–1978       | El Niño (Weak)  | CP>MIX     |
| 16  | 1979–1980       | El Niño (Weak)  | EP>CP      |
| 17  | 1982–1983       | El Niño (Strong) | EP         |
| 18  | 1983–1986       | La Niña (Moderate) | Mix>EP     |
| 19  | 1986–1988       | El Niño (Moderate) | Mix       |
| 20  | 1988–1989       | La Niña (Strong) | EP>Mix     |
| 21  | 1990–1992       | El Niño (Moderate) | CP>Mix     |
| 22  | 1994–1995       | El Niño (Moderate) | CP>Mix>CP |
| 23  | 1995–1997       | La Niña (Moderate) | EP         |
| 24  | 1997–1998       | El Niño (Strong) | EP         |
| 25  | 1998–2001       | La Niña (Moderate) | Mix       |
| 26  | 2002–2003       | El Niño (Moderate) | CP>Mix     |
| 27  | 2004–2005       | El Niño (Weak)  | CP         |
| 28  | 2005–2006       | La Niña (Moderate) | EP>Mix     |
| 29  | 2006–2007       | El Niño (Weak)  | Mix        |
| 30  | 2007–2009       | La Niña (Moderate) | EP>Mix>CP>Mix |
| 31  | 2009–2010       | El Niño (Moderate) | Mix       |
| 32  | 2010–2012       | La Niña (Strong) | Mix>CP>Mix |
| 33  | 2014–2016       | El Niño (Strong) | Mix>CP>Mix>EP>Mix |

**Data**

The SSTA data used in this study is the monthly mean anomalies of Hadley Centre Sea Ice and Sea Surface Temperature data set\(^1\). We choose the time period from Jan1950 to Jan2017. The monthly mean zonal wind and sea level pressure data\(^\text{13}\) were from the NCEP reanalysis-derived data provided by the NOAA/OAR/ESRL PSD (Boulder, Colorado, USA) on their website at http://www.esrl.noaa.gov/psd/.

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Author Contributions
Z. Zhang designed and organised this research with advice from B. Ren. Z. Zhang analysed the data, performed the experiments and wrote the main manuscript text. Z. Zhang, B. Ren and J. Zheng discussed the results and reviewed the manuscript.

Additional Information
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