Which hazardous meteorological quantities in a spatial mode analysis possess the strongest correlations with ENSO phases

Deliverable D2.1

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1 Introduction

The El Niño-Southern Oscillation (ENSO) is the dominant seasonal to inter-annual climate variation generated through coupled interaction between atmosphere and ocean in the tropical Pacific (BJERKNES, 1969) and oscillates between anomalously warm (El Niño) and cold (La Niña) state. ENSO exerts its influence on large-scale changes in climate regionally as well as remotely through atmospheric teleconnections, affecting extreme weather events worldwide (Alexander, 2002; Diaz et al., 2001; McPhaden et al., 2006) . There is ample evidence for the close relationship between ENSO and climate anomalies across the globe (Luo and Lau, 2020; Wallace et al., 1998; White et al., 2014) .

In recent decades, a new type of sea surface temperature anomaly (SSTA) patterns in the tropical Pacific has shown up more frequently: SSTA starts from the central tropical Pacific, which is known as central Pacific (CP) ENSO or ENSO-Modoki (Ashok et al., 2007). It can lead to very distinct impact on climate compared to a traditional eastern-Pacific (EP) type of ENSO (Geng et al., 2020). Therefore, we discuss these two types of ENSO's influence separately in this report.

El Niño tends to decay rapidly in the next boreal Spring (Jong et al., 2020). While in terms of La Niña, it usually developed after an El Niño event, or it persists for more than 1 year so that there exist 2-year or even 3-year La Niña event (McPhaden et al., 2006). The second-year La Niña is the persisting state of certain La Niña and this different time-duration La Niña may have different influence on weather anomalies, which is also considered in this report.

For exploring the correlation between different types of ENSO and weather anomalies, here we apply statistical methods including composite analysis and correlation analysis to find out which

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meteorological variable shows the most obvious response to ENSO in spatial mode. In this report, the meteorological variables we mainly considered are extreme temperature and precipitation.

2 Different types of ENSO

In this report, El Niño and La Niña is separated based on the Oceanic Niño index (ONI) and Niño3.4 index, which are the most commonly used indices to define El Niño and La Niña (Capotondi and Sardeshmukh, 2015). ONI is a 3-month moving mean of sea surface temperature anomalies (SSTA) relative to a 30-year climatology in the Niño3.4 basin. This centered 30-year base period is updated every 5 years so that El Niño and La Niña can be defined by their contemporary climatology, and future adjustments to the base period will not influence the historical classification of ENSO phases. The Niño3.4 index uses a 5-month running mean of SSTA of the Niño3.4 region. (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_change.shtml; https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni).

- **El Niño**

El Niño events are defined when the Niño3.4 exceeds 0.4 for at least 6 months or ONI exceeds 0.5 for a period of consecutive 5 months or more. In recent decades, a new type of tropical Pacific SST warm pattern has shown up more frequently, named “El Niño-Modoki”, or also called CP El Niño. When CP El Niño occurs, a SST anomalous warming is observed in the central equatorial Pacific while an anomalous cooling is in the western and eastern Pacific (Ashok et al., 2007). It has been proved that the mechanism behind EP El Niño and

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CP El Niño is totally different (Feng et al., 2010; Geng et al., 2020; Yeh et al., 2014).

Considering that these two different types of El Niño may lead to very diverse impact on global climate, in this report we divide all El Niño events since 1951 as EP El Niño and CP El Niño based on the research from Yu et al. (2012; GRL) (https://www.ess.uci.edu/~yu/2OSC/) . We take the same criteria as their research and select all the different types of El Niño years as well as their development period (see Table.1 and Table.2). El Niño Summer and Winter are defined seriously based on the value of ONI. The consequence is that some years are defined as El Niño Winters, while the Summer of the same year may not be considered as El Niño Summer (in this case, the reason is that the El Niño starts after the Summer, therefore the Winter is counted without including this year's Summer as El Niño period). Fig.1 and Fig.2 are the examples showing the spatial patterns of EP Niño and CP Niño based on SST monthly data from the Hadley center.

Table.1 El Niño events since 1950 and their types

Type	Years
EP El Niño	1951-1952; 1969-1970; 1972-1973; 1976-1977; 1982-1983; 1986-1987; 1997-1998; 2006-2007;
CP El Niño	1953-1954; 1957-1958; 1958-1959; 1963-1964; 1965-1966; 1968-1969; 1977-1978; 1987-1988; 1991-1992; 1994-1995; 2002-2003; 2004-2005; 2009-2010; 2014-2015; 2018-2019;

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Table.2 El Niño development period

Developing Summer(0) of EP El Niño	**Developing Winter(0)of EP El Niño**	**Developing Summer(0) of CP El Niño**	**Developing Winter(0)of CP El Niño**
1951; 1972 1982; 1997;	1951; 1969; 1972; 1976; 1982; 1986; 1997; 2006;	1953;1957;1963; 1965; 1968; 1987; 1991; 2002; 2004; 2009; 2015	1953; 1957; 1958; 1963; 1965; 1968; 1977; 1987; 1991; 1994; 2002; 2004; 2009; 2015; 2018

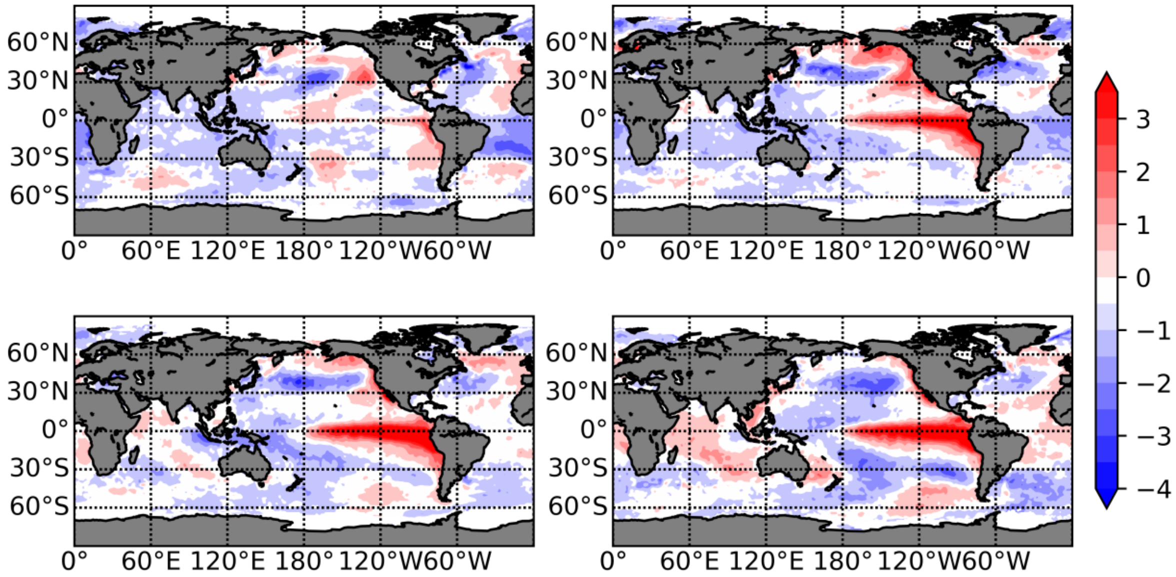

Fig.1 Example of EP El Niño (sea surface temperature anomalies of 4 seasons in 1997, from up (left) to bottom (right): Spring, Summer, Autumn, Winter. Unit: °C)

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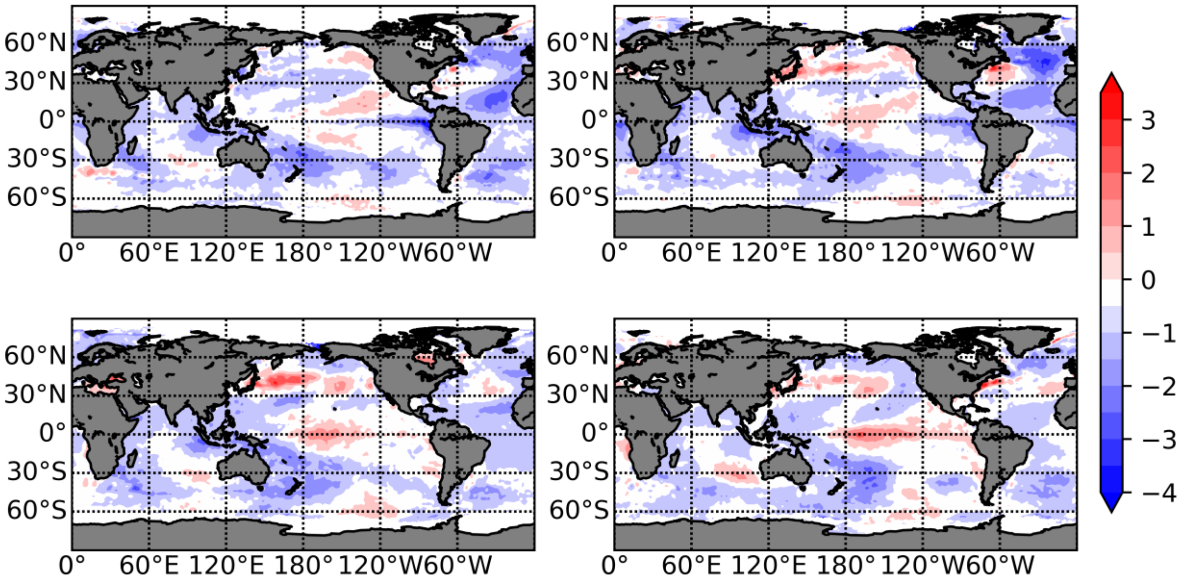

Fig.2 Example of CP El Niño (sea surface temperature anomalies of 4 seasons in 1994; from up (left) to bottom (right): Spring, Summer, Autumn, Winter. Unit: °C)

- **La Niña**

We define La Niña events based on the similar rule to El Niño, using ONI and Niño3.4 index: when the Niño3.4 is lower than -0.4 for at least 6 months or ONI is lower than -0.5 for a period of consecutive 5 months or more. There are several research focusing on the division of La Niña type, we divide La Niña events combining the conclusion of these research (see Table.3). Fig.3 and Fig.4 are the examples of spatial patterns of different types of La Niña.

Table.3 La Niña events since 1950 and their types

Type	**Years**
EP La Niña	1954-1956; 1984-1985; 1995-1996; 2005-2006; 2007-2009; 2010-2012; 2017-2018;
CP La Niña	1964-1965; 1970-1971; 1973-1974; 1974-1976; 1988-1989;1998-2001;

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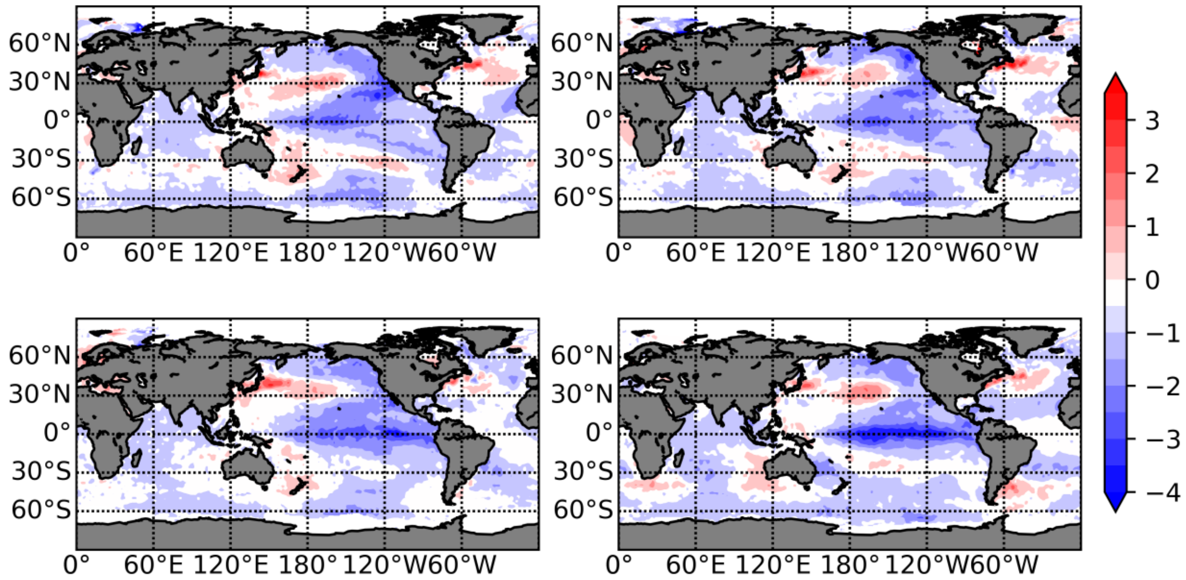

Fig.3 Example of EP La Niña (sea surface temperature anomalies of 4 seasons in 2005; from up (left) to bottom (right): Spring, Summer, Autumn, Winter. Unit: °C)

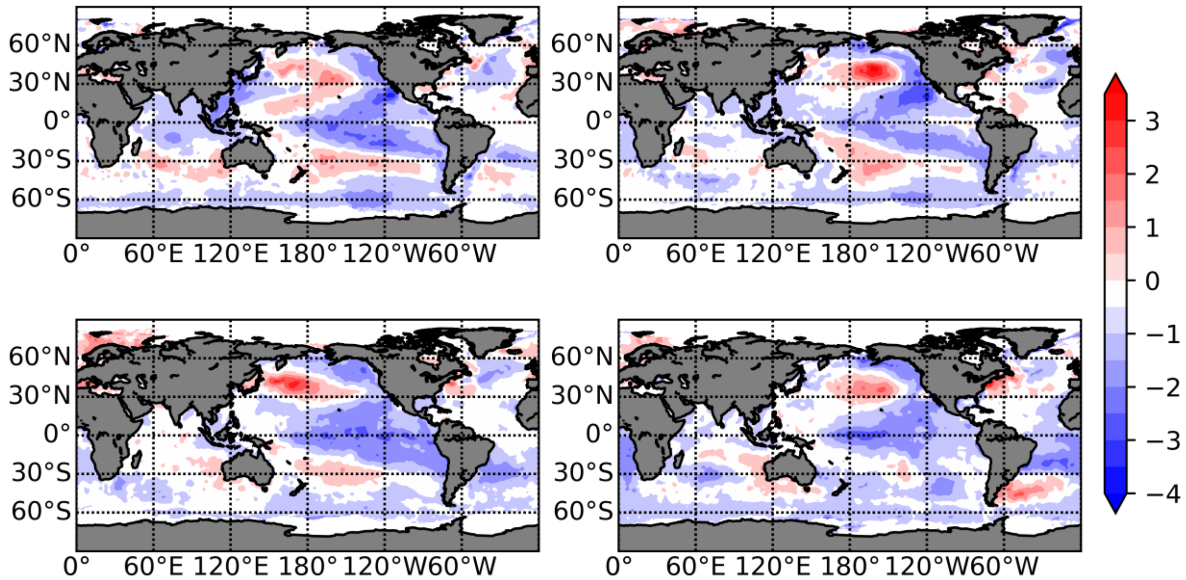

Fig.4 Example of CP La Niña (sea surface temperature anomalies of 4 seasons in 1999; from up (left) to bottom (right): Spring, Summer, Autumn, Winter. Unit: °C)

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- **Multi-year La Niña cycle**

Nonlinearity and asymmetry exist in the development and duration of ENSO warm phase (El Niño) and cold phase(La Niña), which leads to multiyear ENSO evolution (Jong et al., 2020). For duration, a La Niña event tends to persist until the next Summer and continue to intensify in the subsequent Winter, which is known as a multiyear La Niña event. El Niño is quite different and tends to decay rapidly in next boreal Spring. In terms of development, it is indicated from ONI (Oceanic Niño Index) that all the first-year La Niña transitioned from El Niño Winters. In other words, it means that there exist two different cases in "developing La Niña" (La Niña Summer) period: 1) an El Niño transits to La Niña; 2) a La Niña persists from one to the next year. This difference in the prior ENSO condition (El Niño or La Niña) may cause different teleconnections in these two different La Niña Summers. Therefore, we also include this concern when exploring ENSO's influence on meteorological variables.

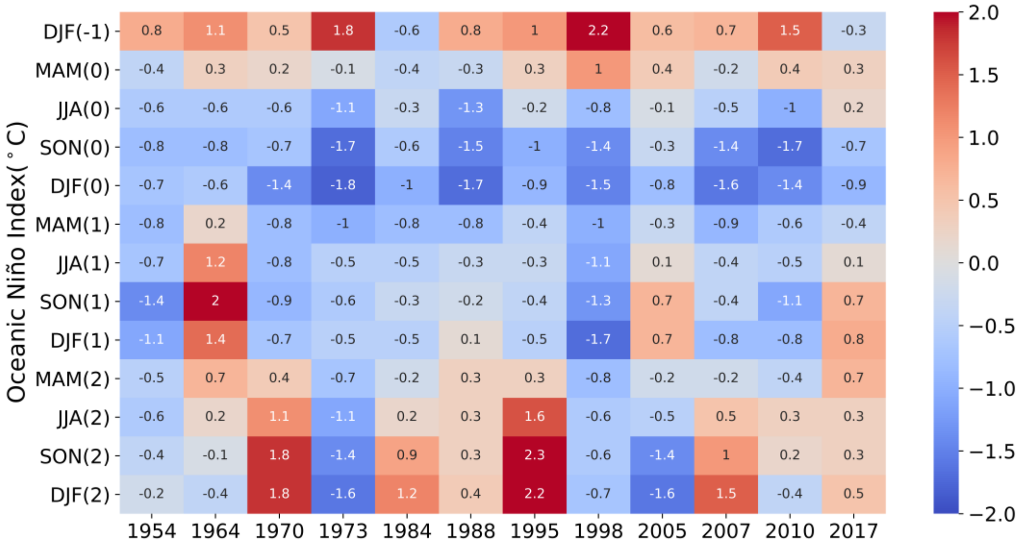

Fig.5 Temporal distribution of La Niña events

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Table.4 Different types of La Niña Summer

	Persisting Summer	**Transition Summer**
1-year La Niña: 1964, 1988, 1995, 2005, 2017	/	1964, 1988, 1995, 2005, 2017
2-year La Niña: 1954, 1970, 1984, 2007, 2010,	1955, 1971, 1985, 2008, 2011	1954, 1970, 1984, 2007, 2010,
3-year La Niña: 1974, 1998	1974, 1975, 1999, 2000	1973, 1998

3 ENSO's effect on temperatures

- **Data and method**

1) ERA5 from ECMWF: 2m air temperature

For analyzing temperature, we calculate seasonal temperature anomalies and extreme high/low temperature events separately by using the ERA5 dataset (hourly dataset on single level, from 1979 to present). In terms of calculating seasonal temperature anomalies, firstly, we convert hourly data into monthly dataset, and take MAM (March, April, May) as Spring, JJA (June, July, August) as Summer, SON (September, October, November)as Autumn, DJF (December, January, February) as Winter. We calculate seasonal average temperature based on monthly data. We take 1981-2010 as climatology period and obtain seasonal temperature anomalies by subtracting climatology temperature from seasonal average temperature.

In order to calculate extreme high/low temperature events, we use percentile threshold method to define extreme events. We convert original hourly dataset into daily data. We take 90% percentile of daily temperature as the threshold, if the daily temperature is higher than this threshold, it is regarded as an extreme high temperature event; taking

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10% percentile of daily temperature as the threshold for extreme low temperature event, which occurs if daily temperature is lower than the threshold. We conduct composite analysis to explore ENSO's influence on extreme temperature events. The composite analysis is to compare the extreme frequency from two groups, to see if there is any significant difference between them. We divide the whole dataset into two groups, namely the ENSO-year group and Normal-year group. We calculate the difference of extreme event frequency between these two groups of data (The color bar in the Fig.6-Fig.17 indicates the extreme event frequency. The unit in the figures is days/season.).

In this report, we apply composite analysis to seasonal extreme high/low temperature event frequency of ENSO developing years compared with normal years in Summer and Winter. In the composite analysis, we discuss ENSO's impact under different phases of ENSO (El Niño and La Niña separately) as well as different types of ENSO (CP ENSO and EP ENSO; persisting La Niña Summer and transition La Niña Summer). A Student's T-test is applied to test the statistical significance of the results.

- **Results**

1) ENSO's impact on extreme high temperature event

a) ENSO's impact during developing Summer and Winter

We can see from Fig.6 that El Niño and La Niña exert different impact on some areas. According to the significant area shown in Fig.6, Eurasia prone to experience less extreme high temperature event during La Niña Winter and Summer, while in this area there seems no much impact from El Niño. Areas have the risk to suffer more extreme high temperature events including South Africa and South America in boreal El Niño developing Winter (Summer for south hemisphere). In La Nina developing years, these two areas show the opposite response to

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ENSO's influence. From Fig.7, it shows that south hemisphere experience more frequent extreme high temperature event in Summer when El Niño occurs, specifically, in South Africa, western area of Australia, and South America.

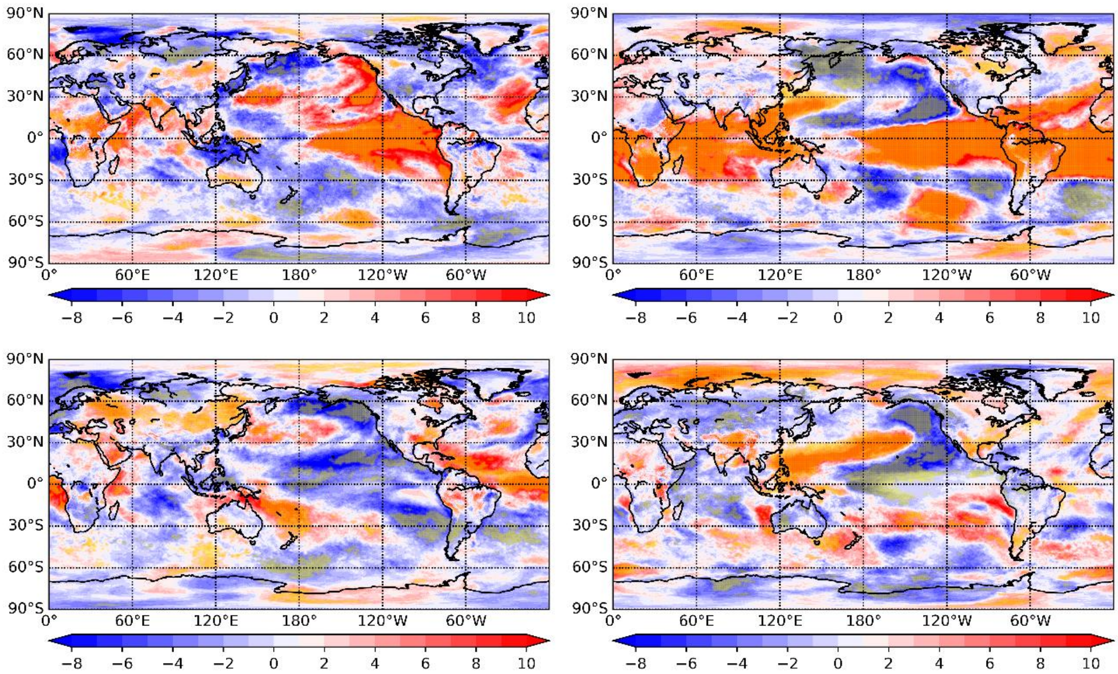

Fig.6 Composite of extreme high temperature frequency in ENSO developing year (left: boreal Summer, right: Winter. Upper: El Niño; bottom: La Niña; yellow shade area denotes the 90% confidence using a two-tailed Student's T-test)

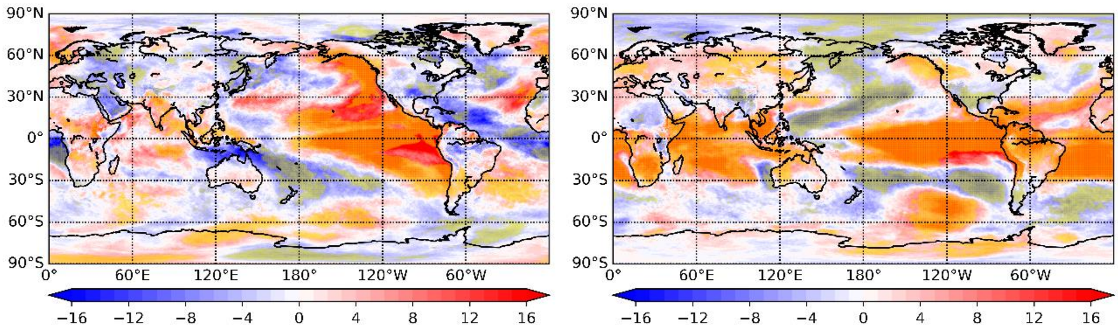

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Fig.7 Composite of extreme high temperature frequency in ENSO developing year (El Niño-La Niña; left: boreal Summer, right: Winter. Yellow shade area denotes the 90% confidence using a two-tailed Student's T-test)

b) Different types of El Niño's impact during developing Summer and Winter

In order to explore the impact of different types of El Niño, we make composite analysis of EP El Niño years and CP El Niño years separately. The result is shown in Fig.8-Fig.10 Comparing these results, it implies that compared to EP El Niño, CP El Niño is more related to more frequent extreme high temperature events, especially in South America, South Africa and south-east Asia. In the developing Summer, there are more cooling areas of EP El Niño Summer compared to CP El Niño Summer.

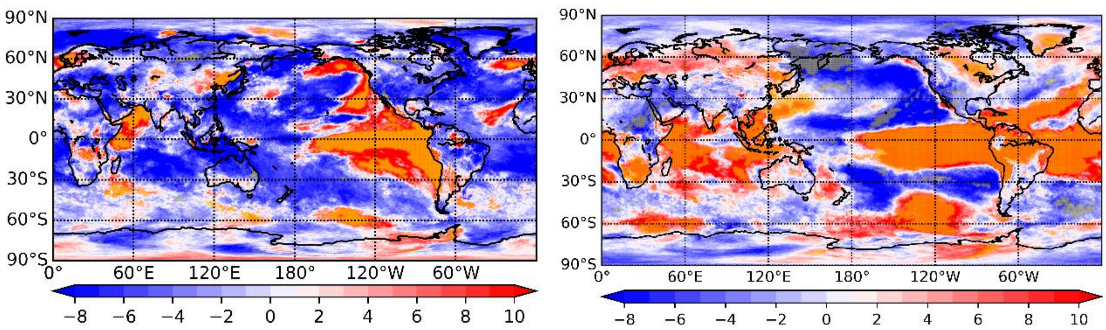

Fig.8 Composite of extreme high temperature frequency in EP El Niño developing year (left: boreal Summer, right: boreal Winter. yellow shade area denotes the 90% confidence using a two-tailed Student's T-test)

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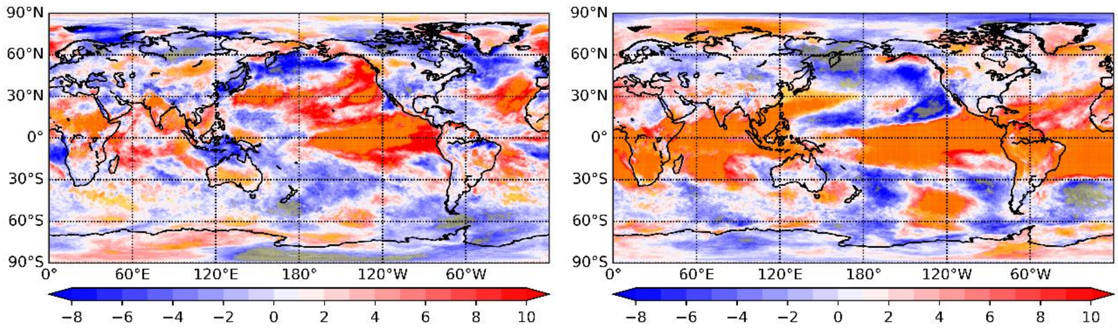

Fig.9 Composite of extreme high temperature frequency in CP El Niño developing year (left: boreal Summer, right: boreal Winter. yellow shade area denotes the 90% confidence using a two-tailed Student's T-test)

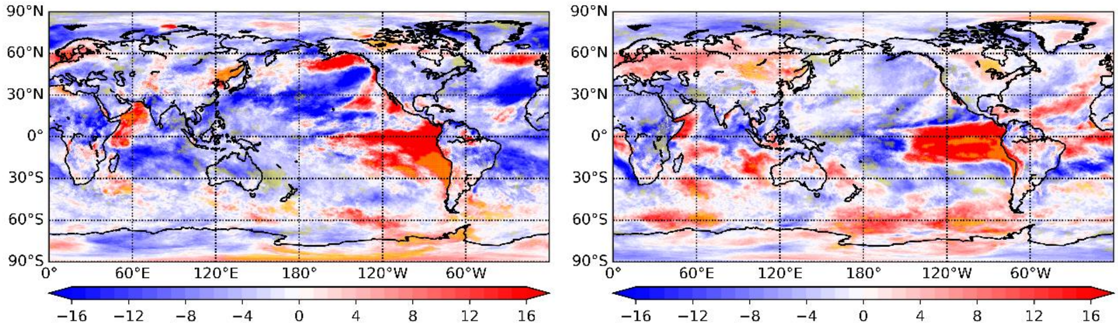

Fig.10 Composite of extreme high temperature frequency between CP El Niño and EP El Niño in developing year (EP-CP; left: boreal Summer, right: boreal Winter. yellow shade area denotes the 90% confidence using a two-tailed Student's T-test)

c) Multi-year La Niña's impact during developing Summer

Unlike an El Niño, which tends to decay quickly in the following Spring, a La Niña event can persist into next Summer, forming a multiyear La Niña event. In addition, a La Niña event can developed from an El Niño in the Summer when the ENSO phase transitions from warm phase into cold phase. Therefore, there exits two kinds of ENSO developing Summer for La Niña: persisting Summer and transition Summer (ref: ENSO Teleconnections and Impacts on U.S. Summertime Temperature during a Multiyear La Niña Life Cycle). From Fig.11, we can see that there are more extreme high temperature events in La Niña

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transition Summers, specifically in Europe, part of North America and South America, Northern area of Africa.

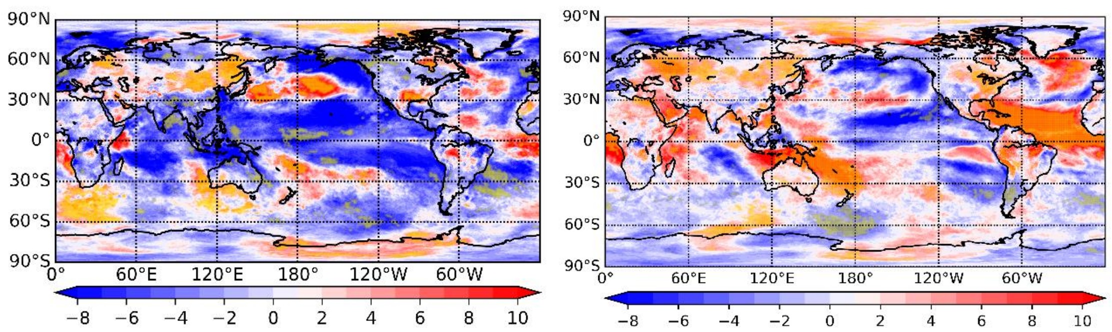

Fig.11 Composite of temperature anomalies of different La Niña Summers (left: persisting boreal Summer, right: transition boreal Summer. yellow shade area denotes the 90% confidence using a two-tailed Student's T-test)

2) ENSO's impact on extreme low temperature event of ENSO developing Summer and Winter

Similarly, we explore ENSO's impact on extreme low temperature event during ENSO developing Summer and Winter.

From Fig.12, we can see that during El Niño developing years, extreme low temperature events prone to occur less in South America, South Africa and North America in Winter. During La Niña years, Eurasia is likely to experience more frequent extreme low temperature events in Winter as well as some part of South America.

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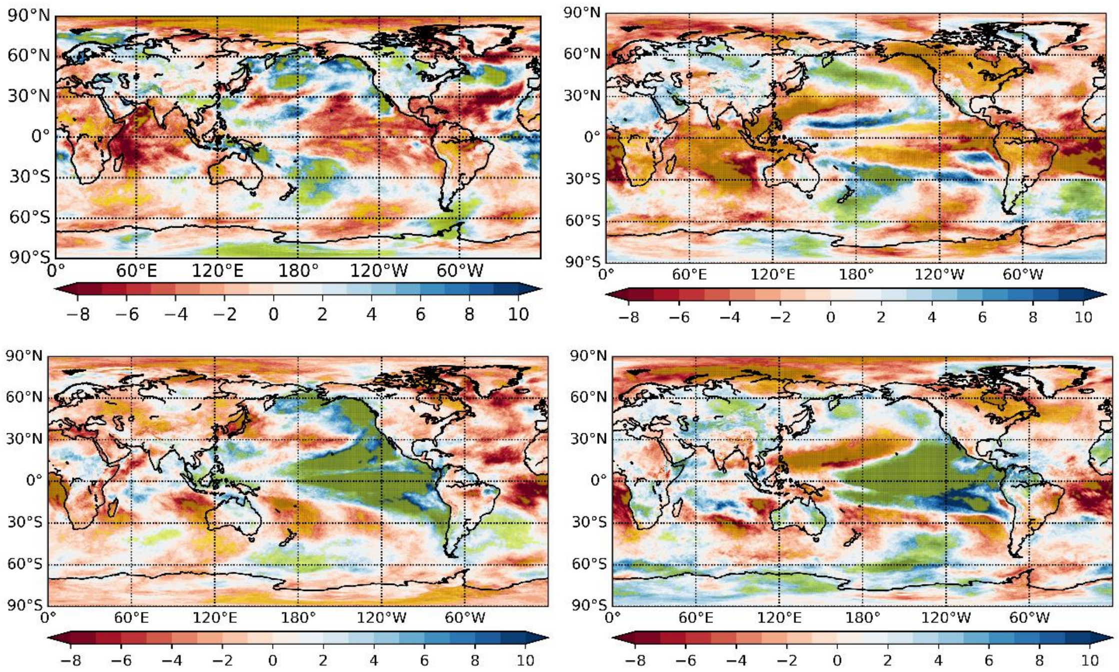

Fig.12 Composite of extreme low temperature frequency in ENSO developing year (left: boreal Summer, right: boreal Winter. Upper: El Niña; bottom: La Niña; yellow shade area denotes the 90% confidence using a two-tailed Student's T-test)

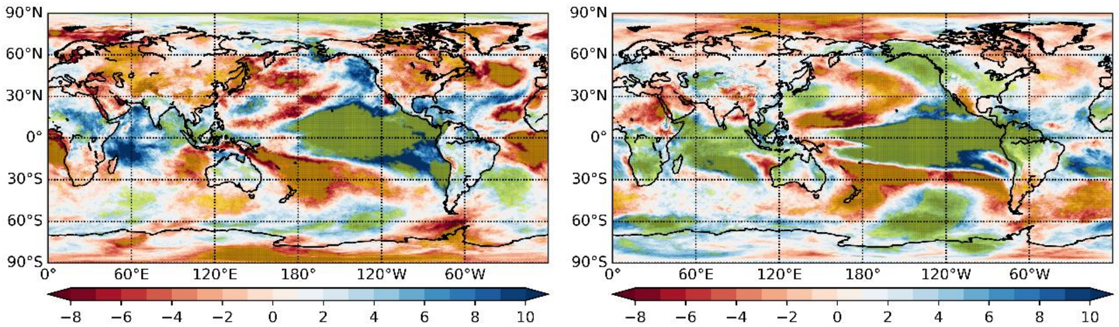

Fig.13 Composite of extreme low temperature frequency in ENSO developing year (La Niña- El Niño; left: boreal Summer, right: boreal Winter. Yellow shade area denotes the 90% confidence using a two-tailed Student's T-test)

a) Different types of El Niño's impact during developing Summer and Winter

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For different types of El Niño, the impact on extreme low temperature event in land areas is obvious in North America, South America, Australia and South Africa. Comparing the difference between EP El Niño and CP El Niño's impact from Fig.16, it indicates that Norther Europe and some part of Australia tend to have more extreme low temperature events in EP El Niño years compared with CP El Niño years. While in some part of Asia, there are more extreme low temperature events in CP El Niño years.

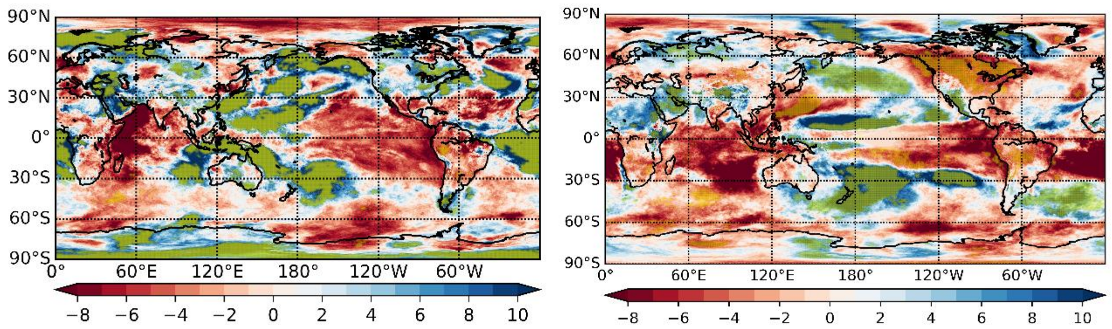

Fig.14 Composite of extreme low temperature frequency in EP El Niño developing year (left: boreal Summer, right: boreal Winter. yellow shade area denotes the 90% confidence using a two-tailed Student's T-test)

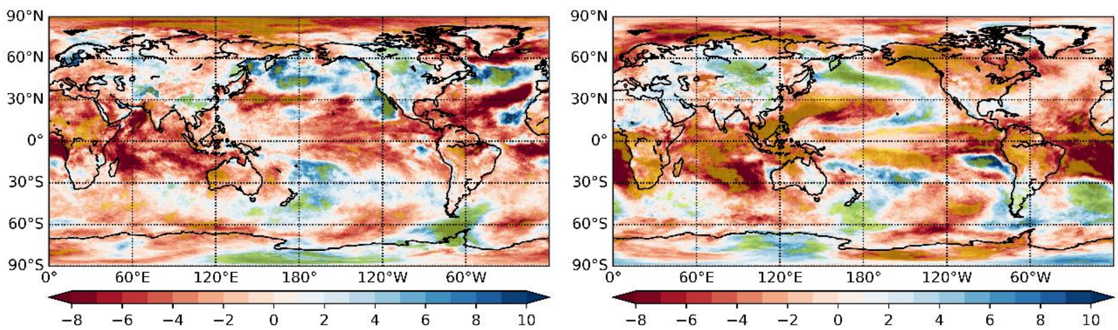

Fig.15 Composite of extreme low temperature frequency in CP El Niño developing year (left: boreal Summer, right: boreal Winter. yellow shade area denotes the 90% confidence using a two-tailed Student's T-test)

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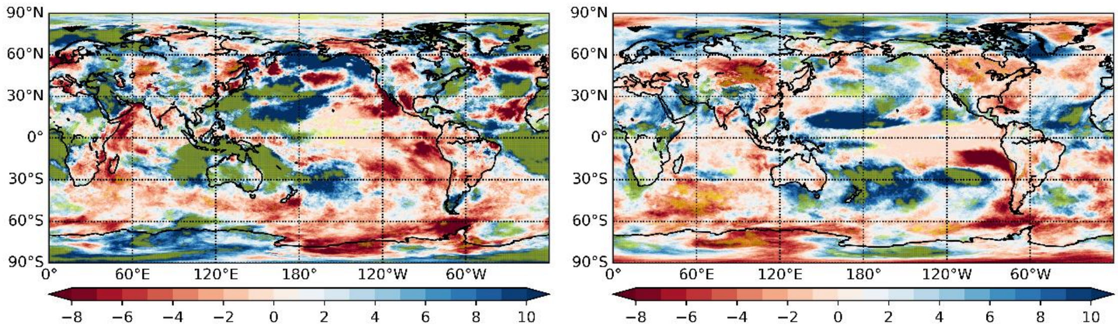

Fig.16 Composite of extreme low temperature frequency between CP El Niño and EP El Niño in developing year (EP-CP; left: boreal Summer, right: boreal Winter. yellow shade area denotes the 90% confidence using a two-tailed Student's T-test)

b) Multi-year La Niña's impact during developing year

Comparing La Niña's persisting Summer and transition Summer, opposite impact pattern exist in South Africa, South America and south Asia. While in Eurasia, there is little difference in these two different Summers, extreme low temperature events tend to be less in La Niña Summer.

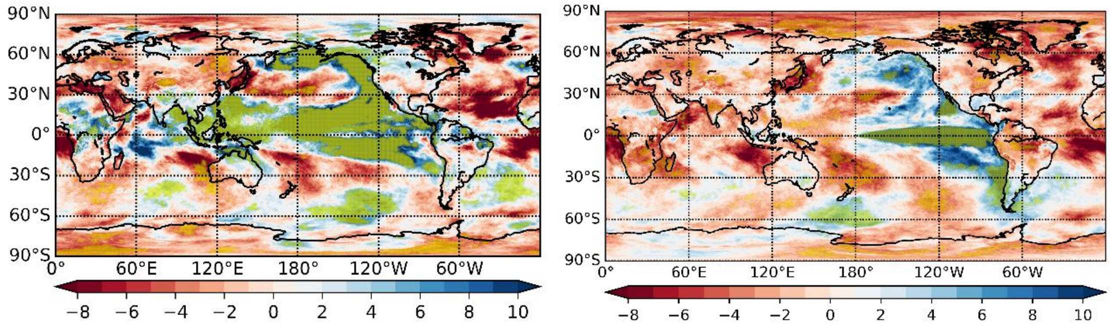

Fig.17 Composite extreme low temperature frequency of different La Niña Summers (left: persisting boreal Summer, right: transition boreal Summer. yellow shade area denotes the 90% confidence using a two-tailed Student's T-test)

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4 ENSO's effect on precipitation

ENSO is known as the strongest large-scale forcing for inter-annual variability of global precipitation, especially in the land region of monsoon areas (Oldenborgh et al., 2000; Wang et al., 2020, 2000).

- **Data and method**

We use precipitation data from the Climate Prediction Center Merged Analysis of Precipitation (CMAP) dataset (Xie and Arkin, 1997) . This dataset is constructed from an analysis of gauge data and satellite-derived precipitation estimates. It is a monthly dataset from 1979/01-present covering global area, with spatial resolution 2.5-degree latitude*2.5-degree longitude.
(Data is from https://psl.noaa.gov/data/gridded/data.cmap.html).
In this report, we take mean enhanced monthly data from this dataset, which provides global data by filling in gaps with precipitation forecasts from the NCEP/NCAR reanalysis. The overlapping estimates are weighted according to their fit with the gauge-based analysis, ensuring the most accurate values. The data quality is best in the tropics while weakens towards the Polar Regions.
Since the precipitation data is a monthly dataset, we use a different analysis method from analyzing temperature cases. In order to explore the relationship between ENSO and precipitation spatial mode, we use correlation analysis method. We firstly obtain climatological monthly precipitation data from the dataset, taking 1981-2010 as climatology period, the result is shown in Fig.18. From Fig.18, we can see that monthly precipitation in every two months show similar spatial pattern. Based on this, we divide the precipitation in whole year into bimonthly data, and the year of ENSO developing period is defined as year (0), the year following is defined as year (1). Therefore, the period is separated

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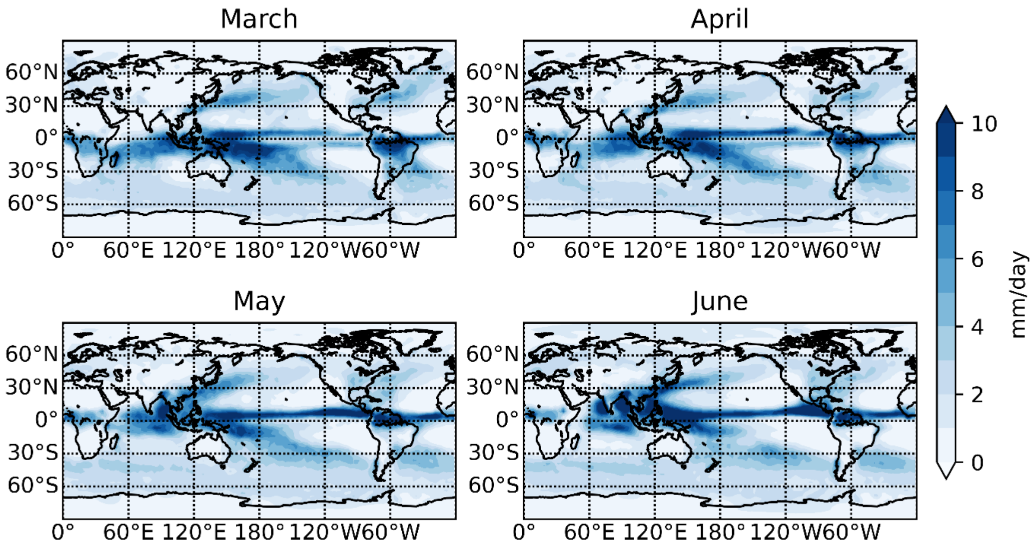
as March-April (MA (0)), May-June (MJ (0)), July-August (JA (0)), September-October (SO (0)), November-December (ND (0)), January-February (JF (1)), March-April (MA (1)). In this report, we explore ENSO's influence on bimonthly mean precipitation anomalies (which has been normalized) from MA (0) to MA (1) by using correlation analysis. The oceanic Niño index (ONI) is defined by 3-month running mean SST anomalies in the Niño-3.4 region (58°N–58°S, 120°–170°W), which is also known as the Niño-3.4 index. We use oceanic Niño index (ONI) to measure the intensity of ENSO. Considering ENSO normally matures and reaches towards the peak at the end of the calendar, we define the ENSO developing year as year (0), the following year as year (1). December (0)–January (1)–February (1) mean (denoted as DJF) ONI is used to identify ENSO events.

We apply correlation analysis between ONI and bimonthly precipitation to explore ENSO's effect on precipitation. A student's T-test is applied to test the statistical significance of the correlation coefficient.



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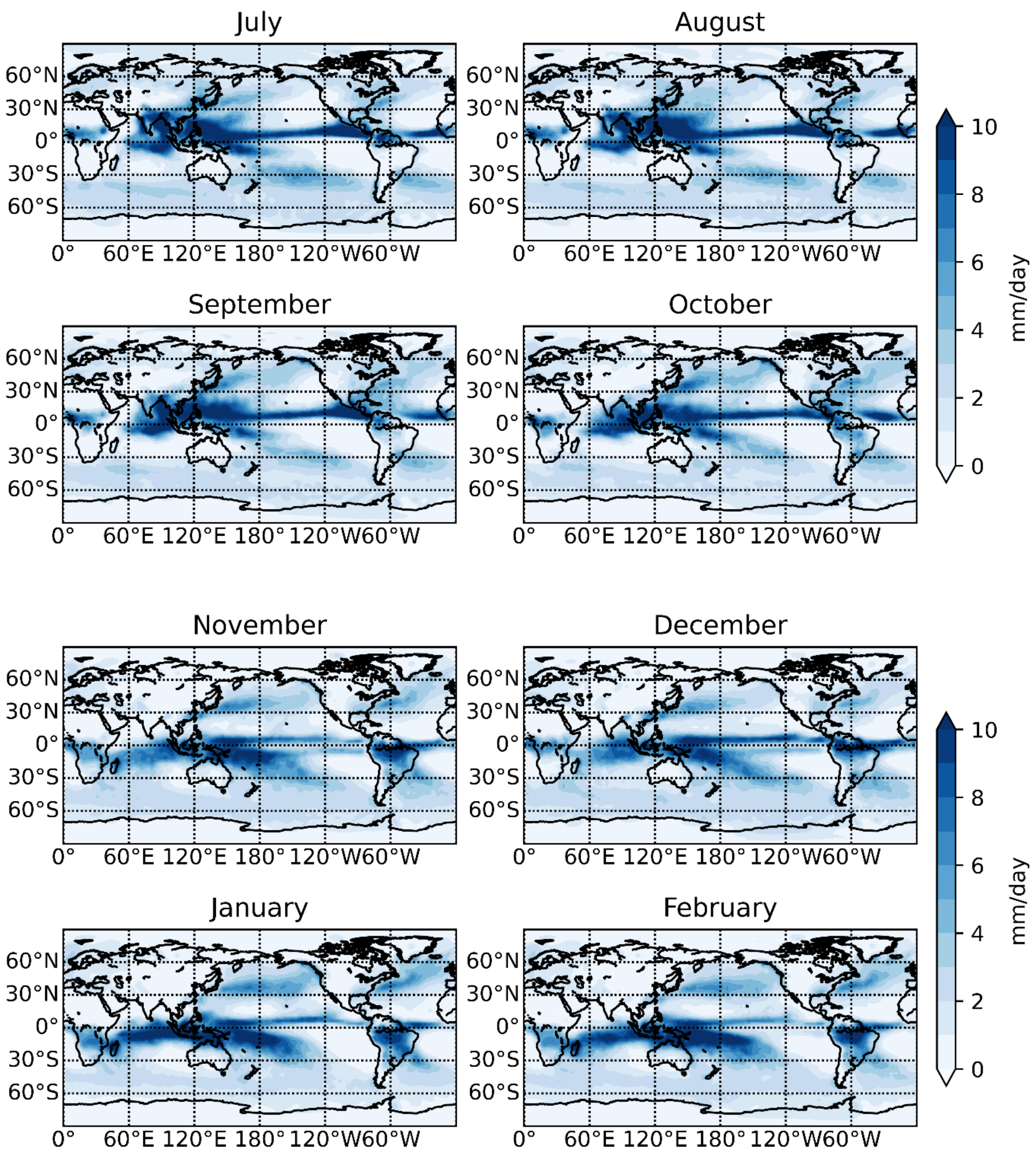

Fig.18 Climatological monthly mean precipitation rate (unit: mm/day; the precipitation data is derived from CMAP dataset from 1981-2010)

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- **Result**

We obtain the evolution of relationship between precipitation and ENSO by calculating the correlation coefficient between bimonthly (from MJ (0) to MA (1)) mean precipitation anomalies and DJF ONI. According to Fig.19, some areas experience a relationship transition with time. In Southern Europe, there is a transition from August to September, from negative correlation to positive correlation. During boreal Summer and Autumn, from MJ (0) to SO (0), precipitation in most region of Asia is negatively correlated with ENSO, indicating in an El Niño year these regions are anomalously drier and wetter in a La Niña year. While since November, there shows large positive correlated region in large area of Asia, especially in southeastern China, and this positive relationship persist until next April. We can also observe similar variation of spatial pattern in North America as well as opposite reversal pattern in South America (from positive correlation to negative correlation). In our future work, we will discuss separately in these sub-regions to see how ENSO influences these areas.

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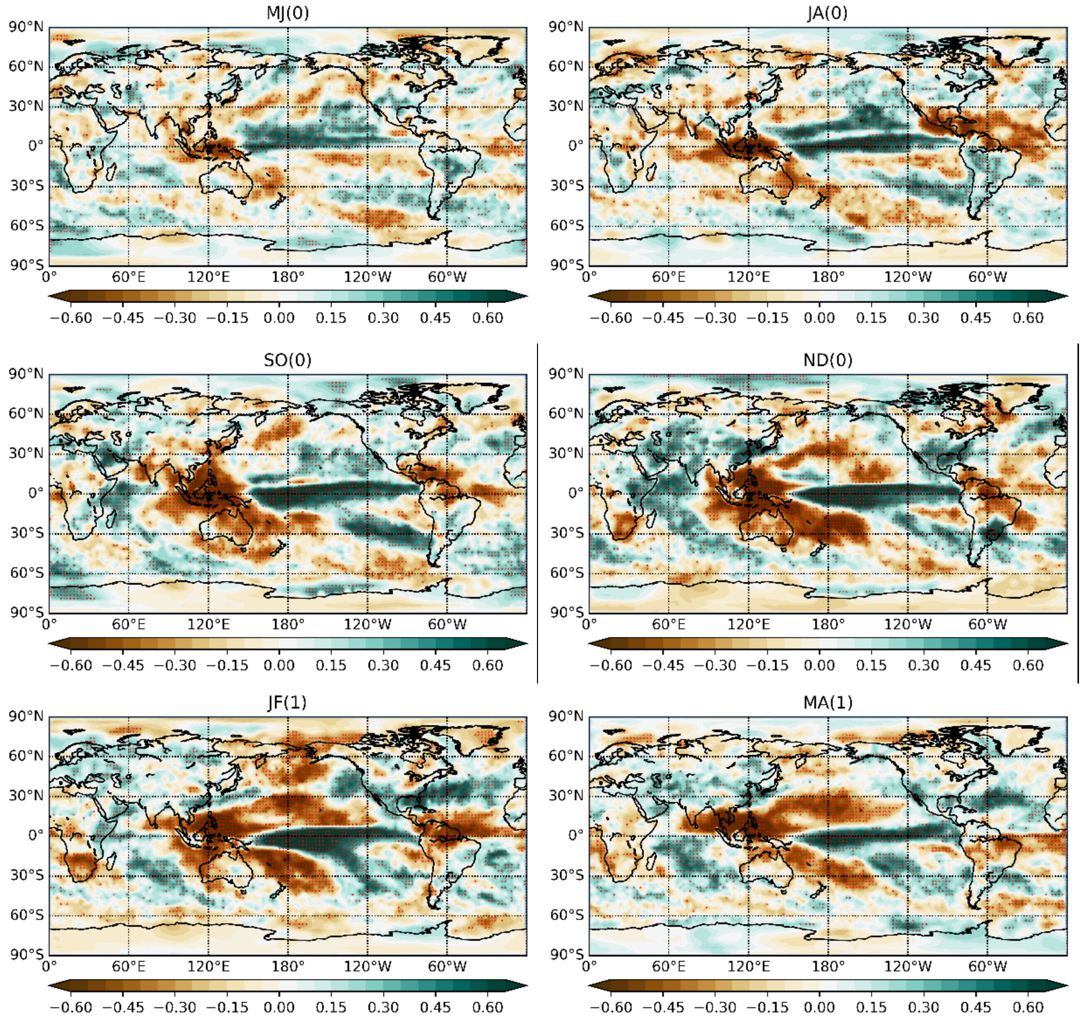

Fig.19 Relationship between bimonthly mean precipitation anomalies and ENSO (Color shading illustrates correlation coefficients; from up (left) to bottom (right): MJ (0), JA (0); SO (0), ND (0); JF (1), MA (1); red dots indicate the area where the correlation coefficients are statistically significant above 95% confidence level)

Conclusion and discussion

According to our analysis, it is shown that ENSO exerts its influence on spatial mode of temperature and precipitation in some areas in the globe. Different types of ENSO have distinct impact on these meteorological variables.

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Specifically, in terms of extreme high temperature events, South Africa and South America tend to experience more extreme high temperature events during El Niño developing Summer and Winter, while these two regions are more likely to have less extreme high temperature events during La Niña developing Summer and Winter. In Eurasia, ENSO's influence in developing Summer and Winter differs from each other, especially during cold phase of ENSO (La Niña years). In La Niña Summer, Eurasia tends to have more extreme high temperature events. While during La Niña Winters, it shows the opposite tendency. When we furtherly divide El Niño events into EP El Niño and CP El Niño, we can see another difference. CP El Niño has the influence pattern as what we described above. However, for EP El Niño events, it is different during developing Summer and Winter. Eurasia and South America shows similar affected pattern: during EP El Niño Summer, these two areas tend to have less extreme high temperature events; during EP El Niño Winter, they tend to have more extreme high temperature events. When we discuss La Niña's impact, we find that persisting La Niña Summer and transition La Nina Summer show totally different influencing pattern in South Asia, South America, and part of Europe.

In terms of extreme low temperature event, the main influencing area still include South Africa and South America. Similarly, El Niño and La Niña also show the opposite influence on these two regions: less extreme low temperature events during El Niño developing Summer and Winter, and more extreme low temperature events in La Niña developing seasons. For different El Niño's impact, during EP El Niño's developing Summer, Europe and North America tend to have more extreme low temperature events. In EP El Niño's Winter, North America shows the opposite trend while Europe and North Africa tend

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to experience more extreme low temperature events. For La Niña cases, Africa, America as well as part of Australia behave differently during La Nina persisting Summer and transition Summer. For Eurasia, there is not much difference during these two different La Niña cases.

As for precipitation, we discuss ENSO's influence on bimonthly precipitation anomalies. We find that Eurasia and America experience a pattern transition with time in the relationship with ENSO. In Europe, this transition occurs during August to September; in Asia and North America, it occurs during October to November.

This report is part of our project work; it provides the information of spatial relationship between different types of ENSO and meteorological variables including temperature and precipitation. It is the basis of our next step work, for analyzing ENSO's influence in separate areas and explore the teleconnection and real-related extreme weather events, as the final aim of our project is to assess the economic loss caused by ENSO-related natural disasters. This report can also provide us some information of which areas show similar patterns to ENSO, therefore we can furtherly explore the problem like some synchronized teleconnection from ENSO using climate network.

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