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The asymmetric response of Yangtze river basin summer rainfall to El Niño/La Niña

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Abstract

The Yangtze river basin, in South East China, experiences anomalously high precipitation in summers following El Niño. This can lead to extensive flooding and loss of life. However, the response following La Niña has not been well documented. In this study, the response of Yangtze summer rainfall to El Niño/La Niña is found to be asymmetric, with no significant response following La Niña. The nature of this asymmetric response is found to be in good agreement with that simulated by the Met Office seasonal forecast system. Yangtze summer rainfall correlates positively with spring sea surface temperatures in the Indian Ocean and northwest Pacific. Indian Ocean sea surface temperatures are found to respond linearly to El Niño/La Niña, and to have a linear impact on Yangtze summer rainfall. However, northwest Pacific sea surface temperatures respond much more strongly following El Niño and, further, correlate more strongly with positive rainfall years. It is concluded that, whilst delayed Indian Ocean signals may influence summer Yangtze rainfall, it is likely that they do not lead to the asymmetric nature of the rainfall response to El Niño/La Niña.

1. Introduction

In the summer following a winter El Niño event, the Yangtze river basin often experiences greater than average rainfall (Wang et al 2001, Zhang et al 2007, Li et al 2016, Xie et al 2016), sometimes leading to extensive flooding with significant loss of life and economic impact (Zong and Chen 2000, Gong and Ho 2002, Zheng et al 2006).

Understanding the mechanisms whereby El Niño events can influence Yangtze river rainfall with this long (6 month) lag is the subject of considerable ongoing research. One mechanism is via the interaction of the El Niño Southern Oscillation (ENSO) with the annual cycle over the Pacific (the so-called Combination Mode, or ‘C-Mode’; Stuecker et al 2013, 2015, 2017, Zhang et al 2016). Following a winter El Niño event, interaction with the annual cycle causes an anomalously strong anticyclone to form rapidly in the northwest Pacific (NWP). During winter and spring, the prevailing winds in this region are northeasterly. The anomalously strong anticyclone acts to increase the strength of these winds on its eastward flank, and decrease the strength of these winds on its westward flank. Due to the fact that stronger winds lead to more evaporation-induced cooling, this acts to warm the western and cool the eastern flanks of the anticyclone. The anomalously cool sea surface temperatures (SSTs) on the eastern flank then drive a westward Rossby Wave response which acts to further enhance the anticyclone, thus leading to a positive feedback and enabling the strong anticyclone to persist through winter and spring (Wang et al 2000, 2003). Another mechanism is via the SST in the Indian Ocean (Xie et al 2009, 2010, 2016). The Indian Ocean (IO) SST lags that in the Niño 3.4 region (Trenberth 1997), such that anomalously warm
SSTs are observed in the IO in the spring following a winter El Niño event. This warm SST leads to a second IO warming in the summer, exciting warm atmospheric Kelvin waves which propagate into the NWP, suppressing convection and energizing the anticyclone there, contributing to its persistence into the summer.

A unification of these mechanisms, along with the excitation of the Indian Ocean Dipole (IOD; Saji et al 1999) during the onset of El Niño, was recently proposed by Xie and Zhou (2017). Here the C-Mode leads to the onset of the anomalously strong anticyclone in the NWP (the subtropical high) during the peak phase of El Niño. The IOD and anomalously strong Walker circulation following El Niño lead to the formation of warm IO SSTs. These warm SSTs interact with the NWP and act to sustain the anticyclonic flow there through to the summer (this interaction is termed the IPOC mechanism in Xie and Zhou 2017). Associated with this anticyclonic flow are poleward moisture-bearing winds from the South China Sea (SCS) through South East China to the Yangtze river basin (He et al 2015), leading to greater than average rainfall there during the summer season.

The signal of above-average summer rainfall in the Yangtze river basin, following a winter El Niño, is predictable at seasonal time scales and is well simulated (Li et al 2016) by the Met Office’s seasonal forecasting system, GloSea5 (MacLachlan et al 2015). Furthermore, this signal is observed in both high and low phases of the Pacific Decadal Oscillation (see figures 5(a) and (e) of Feng et al 2014). However, to fully understand the interannual variability in Yangtze river rainfall during summer, it is also necessary to understand the response following La Niña (Zhou et al 2014). Is the response of Yangtze river rainfall to El Niño/La Niña symmetric in the sense that below average rainfall might be expected in the summer following La Niña? If not, where in the chain of mechanisms described above might the asymmetry occur? These questions are addressed below since, whilst there are many existing studies exploring the asymmetries between El Niño and La Niña (Wu et al 2010, Okumura and Deser 2010, Okumura et al 2011, McGregor et al 2013, An and Kim 2017), none focus explicitly on rainfall in the Yangtze river basin.

For simplicity, El Niño events are not split into central Pacific and eastern Pacific types in this study (the effects of both types on the east Asian summer monsoon are documented in Zhou et al 2014).

In what follows, the observational and reanalysis datasets, and the seasonal forecasting system used in this study are described in section 2. Results are presented in section 3, with discussion and conclusions given in section 4.

2. Description of datasets and model

The following observational and reanalysis datasets are used:

- Precipitation—the Global Precipitation Climatology Project (GPCP; Adler et al 2003), and the Global Precipitation Climatology Centre (GPCC; Schneider et al 2014),
- Sea surface temperature (SST)—the Hadley Centre sea Ice and Sea Surface Temperature data set (HadISST Rayner et al 2003),
- Mean sea level pressure (MSLP)—the variance adjusted HadSLP2r dataset, a near-real-time update of the Hadley Centre Sea Level Pressure dataset (HadSLP2; Allan and Ansell 2006),
- Meridional wind at 850hPa (v850)—the ERA-Interim reanalysis (ERA-I; Dee et al 2011).

Seasonal hindcasts are from the Met Office Global Seasonal forecast system version 5 (GloSea5; MacLachlan et al 2015), with the climate model updated to use the Global Coupled version 2 configuration. This version couples the Met Office Unified Model Global Atmosphere 6.0 (MetUM GA6.0) configuration with the Joint UK Land Environment Simulator land surface model, the Nucleus for European Modelling of the Ocean, ocean model and the Los Alamos Sea Ice Model, as described in Williams et al (2015). The atmosphere and land surface model horizontal resolution is 0.833°×0.556°, and the ocean and sea-ice model horizontal resolution is 0.25°. A 24 member hindcast ensemble is used, with eight members initialised on each of 25th April, 1st May, and 9th May. Ensemble mean June–July–August (JJA) means are used for each of the 20 hindcast years (1992–2011).

3. Results

3.1. Response following El Niño/La Niña

In order to compute anomalous precipitation following El Niño and La Niña events, we use the December–January–February (DJF) mean Niño 3.4 index, defined as the area average of SSTs over the region 5°S–5°N and 190°E–240°E with the time average removed. Years in which this index exceeds 0.5 K are El Niño years, those in which it falls below −0.5 K are La Niña years, and all others are control (or neutral) years.

Figure 1 shows JJA mean precipitation anomalies (El Niño minus control and La Niña minus control) for GPCP observations and GloSea5 forecasts. Area averaged summer precipitation over the Yangtze river basin (defined as the region 25°N–35°N and 91°E–122°E as in Li et al 2016) is found to be 0.24 mm day−1 greater than average following El Niño in GPCP, with GloSea5 showing a similar value of around 0.26 mm day−1 (approximately 0.5 standard deviations). Thus the observed strong positive anomaly in precipitation following El Niño is in good agreement with the GloSea5 ensemble mean response (Li et al 2016).

Following La Niña no signal is found over the Yangtze river basin, where there is essentially no
Figure 1. Precipitation anomalies (JJA) for (a, b) GPCP and (c, d) GloSea5, following (a, c) winter El Niño and (b, d) winter La Niña events. Yellow boxes show the Yangtze river basin (25°N–35°N, 91°E–122°E) and the Niño 3.4 region (5°S–5°N, 170°E–240°E). Area averaged anomalies of precipitation over the Yangtze river basin are (a) 0.24, (b) −0.01, (c) 0.26, and (d) 0.03 mm day$^{-1}$. The precipitation anomalies plotted are everywhere normalised by their local standard deviation (the standard deviation area averaged over the Yangtze river basin is 0.48 mm day$^{-1}$). HadISST data are used to compute the DJF Niño 3.4 index. The 20 years corresponding to 1992–2011 JJA (comprising seven El Niño years, eight La Niña years and five control years) are used in all panels. All data are detrended.

The response of Yangtze summer precipitation to El Niño/La Niña is therefore highly asymmetric, since the magnitude of the Niño 3.4 index during La Niña events is around 3/4 of its magnitude during El Niño events (not shown), but the response in summer precipitation is an order of magnitude smaller following La Niña, and found to be statistically significantly different to minus 3/4 of the El Niño response at the 90% confidence level. Note that the rainfall response in El Niño years is strongly influenced by super El Niño events (those of size $>2$ K) and so the fact that El Niño events tend to be stronger than La Niña events is important (Wu et al 2010). Nevertheless, the highly asymmetric nature of the response (and the fact that the response is of the same sign, rather than the opposite sign, over much of the Yangtze basin following both El Niño and La Niña) makes it likely that at least one of the mechanisms acting to increase precipitation following El Niño events (i.e. the ENSO C-Mode or IO SSTs; Stuecker et al 2015, Xie et al 2009) either does not operate following La Niña or operates in a different way, as discussed further below.

Over the central Pacific, the anomalous summer precipitation following La Niña is essentially the same (not the opposite) as that following El Niño. This is easily explained by the fact that precipitation over the Pacific is very quickly influenced by sea surface temperatures and that, in the Niño 3.4 region, a lower than average temperature is found in summers following both a winter El Niño event and a winter La Niña event (due to La Niña events persisting far longer than El Niño events—see figure 4(a) below). However, this is unrelated to the signal seen in summer rainfall over the Yangtze river basin, which correlates strongly with the winter Niño 3.4 index and has zero correlation with the summer Niño 3.4 index (see the supplementary information for more details available at stacks.iop.org/ERL/13/024015/mmedia). Also note that the Pacific–Japan pattern (Kosaka and Nakamura 2006) associated with anomalously high rainfall over the Maritime Continent and around the southern tip of Japan, and anomalously low rainfall to the east of the Philippines (see also figure 2 of Xie et al 2009) is also similar following both El Niño and La Niña.

Figure 2 shows anomalous MSLP (in JJA) in HadSLP2r and GloSea5, following winter El Niño and La Niña events. As mentioned above, there is a strong link
between MSLP in the NWP and Yangtze river rainfall, with high pressure causing anticyclonic flow and therefore northward moisture-bearing winds over the SCS and into China (Li et al. 2016). Figure 2 shows strong anticyclonic anomalies in the NWP following El Niño, but also shows weak anticyclonic anomalies in the NWP following La Niña. Thus, as expected from figure 1, the response of MSLP to El Niño/La Niña is asymmetric and is also significantly stronger following El Niño. GloSea5 reproduces this effect but predicts an anticyclone which is stronger than in the observations (following both El Niño and La Niña). This is a common model bias (Dong et al. 2017, Guo et al. 2017), although it should be noted that the MSLP response in ERA-I is comparable in magnitude to that seen in GloSea5 (not shown). Furthermore, the El Niño minus La Niña response (the difference between figure 2 panels a and b for the observations, and panels c and d for GloSea5) in GloSea5 reproduces that in the observations very closely (not shown), demonstrating that the model corroborates the observed El Niño/La Niña asymmetry in this response despite an underlying bias. The anticyclonic anomalies in the

NWP and cyclonic anomalies south of this over the Maritime Continent following both El Niño and La Niña (figure 2) are consistent with the Pacific–Japan pattern in precipitation being similar in both cases (figure 1).8

Reasons for this asymmetric response in MSLP in the NWP were put forward by Wu et al. (2010), who suggested that the weaker (but same signed) response following La Niña (see figure 2 of Wu et al. 2010) was due both to La Niña events being weaker than El Niño events and also to La Niña events occurring further west, such that cyclonic flow following La Niña is seen over the SCS instead of the NWP (see also figure 2 of Guo et al. 2017). They ran model sensitivity experiments to demonstrate the influence of both of these differences on the MSLP response.9

As in the case of Yangtze summer precipitation, JJA NWP MSLP correlates strongly with the winter Niño 3.4 index and has zero correlation with the summer Niño 3.4 index, demonstrating again that this is a lagged rather than instantaneous response to

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7 In this paper NWP refers to an extended region around the NWP area, defined as 0°N–40°N and 120°E–150°E. This region is not used for any composite analysis, but it is believed to be an important region for the asymmetry of the Yangtze rainfall response to El Niño and La Niña (see figures 5 and 6 below).

8 Following ‘control’ winters (no strong El Niño or La Niña) there are cyclonic anomalies in the NWP (when compared against climatology), associated with anomalously low summer Yangtze rainfall (not shown).

9 These differences in the MSLP response to winter ENSO are more evident when using March–April–May (MAM) MSLP, rather than JJA (as shown in figures 2(a) and (b)).
Figure 3 shows the response, following El Niño and La Niña, in the JJA mean meridional wind field at 850 hPa ($v_{850}$) for (a, b) ERA-I and (c, d) GloSea5. Yellow boxes show the SCS region (18°N–30°N, 105°E–114°E) and the Niño 3.4 region (5°S–5°N, 190°E–240°E). Units are m s$^{-1}$. Area averaged anomalies of $v_{850}$ over the SCS region are (a) 0.97, (b) 0.18, (c) 0.94, and (d) 0.38 m s$^{-1}$. The 20 years corresponding to 1992–2011 JJA are used in all panels. All data are detrended.

El Niño/La Niña. Stuecker et al. (2015) showed how interaction of El Niño with the annual cycle leads to an anomalous anticyclone developing quickly in the NWP following El Niño. It seems likely that the opposite does not occur following La Niña due to the differences pointed out by Wu et al. (2010).

3.2. Sources of asymmetry

As discussed above, the asymmetric nature of the response of summer Yangtze river precipitation to El Niño/La Niña raises the question of where in the chain of mechanisms leading to this lagged response the asymmetry is likely to occur. We have already discussed how the C-Mode may be consistent with this asymmetric response, and now consider IO SSTs. Following Xie et al. (2009), figure 4 shows the correlation of the winter Niño 3.4 index with rolling 3 month means of the Niño 3.4 index (panel (a)) and SSTs area averaged over the Indian Ocean (the IO index; panel (b)), for El Niño years and La Niña years, for the HadISST dataset. We now use a November–December–January (NDJ) mean Niño 3.4 index to allow a direct comparison with figure 1 of (Xie et al. 2009), but using a DJF mean Niño 3.4 index instead makes no difference to the results (not shown). As before, El Niño years are defined as those for which the NDJ Niño 3.4 index exceeds 0.5 K, and La Niña years as those for which the NDJ Niño 3.4 index falls below −0.5 K. The auto-correlation of the Niño 3.4 index (figure 4(a)) demonstrates the different persistence times of El Niño and La Niña referred to above. By the summer (JJA) following an El Niño event, the auto-correlation is negative (i.e. has changed sign), whereas it is still positive (i.e. remains the same sign) in the JJA following a La Niña event (see also figure 13 of Wu et al. 2010).
This is indicative of anomalously cold SSTs in the Niño 3.4 region in summers following both El Niño and La Niña events, leading to the similar responses in precipitation, MSLP, and v850 found over the central Pacific in both cases (figures 1–3).

The correlation of the Niño 3.4 index with the IO index (figure 4(b)) demonstrates that the response of the IO to El Niño/La Niña is symmetric (see also Kubota et al 2016). The IO warms following El Niño events, and it cools equally following La Niña events. March–April–May (MAM) is highlighted in figure 4(b), since this is when the anomalously strong/weak downwelling over the Indian Ocean following El Niño/La Niña anchors the warming/cooling there that persists through to the summer (noted for the El Niño case in Xie et al 2016). The symmetric warming/cooling of the IO is demonstrated further in figure 4(c), which shows a linear relationship between the NDJ Niño 3.4 index and MAM IO index in the HadISST dataset. The similarity of the gradients of the regression lines for positive and negative NDJ Niño 3.4 index demonstrates that there is no significant asymmetry in the response of the IO to positive/negative values of the Niño 3.4 index. Using JJA rather than MAM IO SSTs leads to similar conclusions (not shown). Thus, if the IO SSTs themselves are important for driving the asymmetry seen in the summer Yangtze river rainfall response to El Niño and La Niña, then this asymmetry must come from the response of Yangtze river rainfall to warm and cool IO SSTs.

This asymmetric response (or lack thereof) is not easy to prove. We cannot perform model sensitivity experiments where warm SSTs are imposed over the IO. Following an El Niño event the associated increased descent over the IO leads to clear skies and anomalously warm SST, whereas in model sensitivity experiments the imposed warm IO SSTs will drive ascent over the IO and thus completely different circulation patterns to those observed (Copsey et al 2006). However, it is possible to more generally suggest regions where asymmetries arise using just the HadISST observations. Figure 5 shows the correlation of MAM SST with...
JJA Yangtze rainfall (motivation for choosing MAM is given in the previous paragraph). Significant correlations are found in the NWP and IO, as expected, demonstrating that these are the main regions influencing Yangtze summer rainfall.

Figures 6(a) and (b) show the correlations of MAM SST with the NDJ Niño 3.4 index for years in which this index is positive (figure 6(a)) and negative (figure 6(b)). Stippling shows the regions where the correlations in these panels are statistically significantly different from each other. With the exception of a small region in the southeast IO, these correlations are found to be positive in the IO in both cases, and not significantly different from each other. Thus IO SSTs respond symmetrically to El Niño and La Niña events (the IO warms as much following El Niño events as it cools following La Niña events). This is an equivalent result to that shown by the red and green regression lines in figure 4(c). However, MAM SSTs in the NWP are found to respond much more strongly in years following a positive NDJ Niño 3.4 index than a negative NDJ Niño 3.4 index. This is consistent with the above discussion of figure 2 that an anomalous anticyclone spins up quickly in the NWP following El Niño (due to the ENSO C-Mode; Stuecker et al 2013) with no such response following La Niña. There are also significant differences east of the Maritime Continent, but these are directly associated with the Niño 3.4 region and, as shown in figure 5, are not relevant to Yangtze summer rainfall.

Figures 6(c) and (d) show the correlations of MAM SST with JJA Yangtze rainfall in years where there is anomalously positive (figure 6(c)) and anomalously negative (figure 6(d)) rainfall (i.e. years with more/less than average rainfall respectively). These show that the response of JJA Yangtze rainfall to SSTs in the IO is linear (with warmer than average SSTs leading to increased rainfall, and cooler than average SSTs leading to reduced rainfall). In the NWP, however, there are significant differences between these correlations (although at a reduced confidence level). The response of rainfall to NWP SSTs is stronger in anomalously positive rainfall years than in anomalously negative rainfall years. Furthermore, correlations throughout much of the NWP have a different sign in figure 6(c) and (d). This suggests that, not only do SSTs in the NWP respond asymmetrically to ENSO, but also that JJA Yangtze rainfall is related asymmetrically to a change in SSTs in the NWP.

We now consider again the mechanism put forward by Xie and Zhou (2017). The excitation of the IOD during the onset of El Niño was shown to be equal and opposite to that during the onset of La Niña by Li et al (2014). We have just shown that IO SSTs both respond linearly to El Niño/La Niña events and have a linear impact on JJA Yangtze rainfall, suggesting that the IPOC mechanism is linear. However, the ENSO C-Mode and the onset of an anomalous anticyclone in the NWP is a likely source of asymmetry, leading SSTs in the NWP to respond much more strongly following El Niño than following La Niña. Further it appears that JJA Yangtze rainfall is asymmetrically related to changes of SST in this region. It is therefore concluded that, whilst the IO plays an important role in driving the Yangtze river valley summer precipitation response to ENSO, it is unlikely to influence the asymmetric component of this response to El Niño/La Niña. The NWP, however, likely plays an important role in this asymmetric component.

4. Conclusions

The response of summer rainfall over the Yangtze river basin to winter El Niño/La Niña events is found to be asymmetric. Following a winter El Niño event, an anomalously strong anticyclone forms in the NWP, driving poleward, moisture-bearing winds from the South China Sea, through South East China to the
Yangtze river basin, leading to anomalously high precipitation there. However, following a winter La Niña event, no significant signal is found, in MSLP, meridional wind or precipitation. This observed asymmetric response is in good agreement with the ensemble mean response simulated by the current Met Office seasonal forecast system, GloSea5. In addition, but unrelated to the lagged response to winter ENSO found in the NWP, signals in summer precipitation, mean sea level pressure and meridional velocity over the central Pacific are similar following El Niño and La Niña. This is due to the fact that La Niña events generally persist into the summer, whereas El Niño events generally oscillate into La Niña conditions by the summer.

The mechanism of Xie and Zhou (2017) for the influence of El Niño on summer rainfall over the Yangtze river basin is considered. This mechanism involves the interaction of ENSO with the annual cycle (the ENSO C-Mode; Stuecker et al 2015), and the active role of SSTs over the Indian Ocean (IO; Xie et al 2009, 2016). Using observational datasets, correlations of spring SSTs with the winter Niño 3.4 index demonstrate that IO SSTs respond linearly to ENSO, warming following an El Niño event and cooling following a La Niña event, whilst NWP SSTs respond asymmetrically with a much stronger response following El Niño than following La Niña. Furthermore, correlations of spring SSTs with summer Yangtze rainfall demonstrate that the impact of SSTs in the IO on summer Yangtze rainfall is linear, with warmer/lower than average IO SSTs leading to above/below average summer Yangtze rainfall, whilst the relation between changes to SSTs in the NWP and summer Yangtze rainfall is highly asymmetric. Thus, the ENSO C-Mode mechanism, considered essential for triggering the response of NWP MSLP to ENSO (Xie and Zhou 2017), and subsequent evolution in the NWP is potentially consistent with the observed asymmetric response in Yangtze summer rainfall to El Niño/La Niña, with the IO playing no role in the asymmetric component of this response.

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The data from all the GloSea5 simulations used in this study are stored on the Met Office archive and are available upon request.

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