

# *Impact of ENSO longitudinal position on teleconnections to the NAO*

Article

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1 **Impact of ENSO longitudinal position on teleconnections to**  
2 **the NAO**

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## Abstract

23

24 While significant improvements have been made in understanding how the El  
25 Niño–Southern Oscillation (ENSO) impacts both North American and Asian climate,  
26 its relationship with the North Atlantic Oscillation (NAO) remains less clear.  
27 Observations indicate that ENSO exhibits a highly complex relationship with the  
28 NAO-associated atmospheric circulation. One critical contribution to this ambiguous  
29 ENSO/NAO relationship originates from ENSO’s diversity in its spatial structure. In  
30 general, both eastern (EP) and central Pacific (CP) El Niño events tend to be  
31 accompanied by a negative NAO-like atmospheric response. However, for two  
32 different types of La Niña the NAO response is almost opposite. Thus, the NAO  
33 responses for the CP ENSO are mostly linear, while nonlinear NAO responses  
34 dominate for the EP ENSO. These contrasting extra-tropical atmospheric responses  
35 are mainly attributed to nonlinear air-sea interactions in the tropical eastern Pacific.  
36 The local atmospheric response to the CP ENSO sea surface temperature (SST)  
37 anomalies is highly linear since the air-sea action center is located within the Pacific  
38 warm pool, characterized by relatively high climatological SSTs. In contrast, the EP  
39 ENSO SST anomalies are located in an area of relatively low climatological SSTs in  
40 the eastern equatorial Pacific. Here only sufficiently high positive SST anomalies  
41 during EP El Niño events are able to overcome the SST threshold for deep convection,  
42 while hardly any anomalous convection is associated with EP La Niña SSTs that are  
43 below this threshold. This ENSO/NAO relationship has important implications for  
44 NAO seasonal prediction and places a higher requirement on models in reproducing

45 the full diversity of ENSO.

## 46 **1. Introduction**

47       The El Niño–Southern Oscillation (ENSO) is the predominant source of global  
48 inter-annual climate variability arising from coupled ocean-atmosphere interactions in  
49 the tropical Pacific (Bjerknes 1969; Wyrski 1975; Schopf and Suarez 1988; Jin 1997;  
50 Neelin et al. 1998; Wallace et al. 1998). ENSO has received widespread attention due  
51 to its pronounced climate impacts around the globe (e.g., van Loon and Madden 1981;  
52 Ropelewski and Halpert 1987, 1996; Trenberth and Caron 2000). For instance, ENSO  
53 exhibits impacts on the North American climate via forced atmospheric Rossby waves  
54 known as the Pacific-North America (PNA) teleconnection pattern (Hoskins and  
55 Karoly 1981; Wallace and Gutzler 1981). Furthermore, ENSO affects East Asian  
56 climate through a modulation of the anomalous low-level anticyclone over the  
57 western North Pacific (WNP) (e.g., Zhang et al. 1996; Wang et al. 2000). The WNP  
58 anomalous anticyclone originates from the nonlinear interactions between ENSO and  
59 the warm pool annual cycle (Stuecker et al. 2015; Zhang et al. 2016) and is further  
60 amplified by local (Wang et al. 2000; Stuecker et al. 2015) and remote (Yang et al.  
61 2007; Xie et al. 2009, 2016; Stuecker et al. 2015) air-sea coupled processes. In  
62 contrast, the linkages between ENSO and climate variability over the North  
63 Atlantic-European sector are much less clear.

64       Interannual variability of North Atlantic-European climate in winter is strongly  
65 affected by another prominent atmospheric circulation pattern—the North Atlantic  
66 Oscillation (NAO). This pattern represents a large-scale seesaw between the  
67 subtropical and polar atmospheric mass. Numerous efforts have been made to explore

68 possible impacts of ENSO on NAO variability since the ENSO/NAO relationship can  
69 provide potential seasonal predictability for the climate in Europe (see an extensive  
70 review by Brönnimann 2007a). Early research argued that no ENSO-related climate  
71 impacts could be identified over the North Atlantic and adjacent Western Europe (e.g.,  
72 Rogers 1984; Ropelewski and Halpert 1987; Halpert and Ropelewski 1992). This  
73 viewpoint was supported by subsequent studies, indicating that no significant  
74 ENSO/NAO connection can be detected (e.g., Trenberth and Caron 2000; Quadrelli et  
75 al. 2001; Wang 2002). However, this viewpoint was recently challenged by both  
76 observational analyses and various modeling experiments (e.g., Fraedrich and Muller  
77 1992; Fraedrich 1994; Dong et al. 2000; Cassou and Terray 2001; Merkel and Latif  
78 2002; Moron and Gouirand 2003; Gouirand et al. 2007; Brönnimann et al. 2007b;  
79 Ineson and Scaife 2009; Li and Lau 2012a). It is argued that despite large internal  
80 variability, a negative NAO-like atmospheric anomaly pattern usually coincides with  
81 canonical El Niño events, characterized by a colder and drier-than-normal climate  
82 over Western Europe during late winter. Correspondingly, La Niña events display  
83 approximately opposite impacts on the NAO.

84 The non-stationary behavior of the ENSO/NAO relationship is possibly  
85 associated with different modulating factors, such as natural variability in the  
86 extratropical circulation (Kumar and Hoerling 1998), tropical volcanic eruptions  
87 (Brönnimann et al. 2007b), other climate signals independent of ENSO (e.g., Mathieu  
88 et al. 2004; Garfinkel and Hartman 2010), and decadal changes of the background  
89 state (Wu and Zhang 2015). Moreover, the ambiguity of the ENSO/NAO relationship

90 can be partly attributed to large inter-event variability of both ENSO and the NAO,  
91 partly due to short observational records, especially for earlier studies. It is worth  
92 mentioning that ENSO's impacts on the NAO are strongly seasonally modulated, with  
93 North Atlantic atmospheric anomalies that are approximately opposite in early winter  
94 (i.e., November-December) to those in late winter (i.e., January-March) (Moron and  
95 Gouirand 2003), which could also lead to discrepancies between different studies.

96 ENSO exhibits a considerable degree of diversity in its sea surface temperature  
97 (SST) anomaly pattern, which also affects its connection with the NAO. In recent  
98 decades, a new type of El Niño has been observed frequently in the central Pacific  
99 (CP hereafter), which differs considerably from the traditional El Niño that features a  
100 SST anomaly center over the Eastern Pacific (EP hereafter) (Larkin and Harrison  
101 2005; Ashok et al. 2007; Weng et al. 2007; Kao and Yu 2009; Kug et al. 2009; Ren  
102 and Jin 2011). Many studies have reported the importance in their distinct regional  
103 climate impacts (e.g., Weng et al. 2007; Feng et al. 2010; 2016; Feng and Li 2011,  
104 2013; Lee et al. 2010; Zhang et al. 2011, 2013, 2014; Xie et al. 2012; Yu et al. 2012).  
105 Similarly, La Niña events can also be separated into two types based on their SST  
106 anomaly patterns (Zhang et al. 2015). It is argued that these two ENSO types seem to  
107 have different impacts on the NAO (Graf and Zanchettin 2012; Zhang et al. 2015).  
108 However, this argument still needs further investigation based on more detailed  
109 observational and modeling analyses.

110 To date, the dynamical mechanisms addressing how tropical SST anomalies  
111 associated with ENSO influence the NAO variability have not been fully addressed.



112 The atmosphere over the North Pacific is usually proposed to serve as the bridge  
113 linking the ENSO-associated diabatic heating in the tropical Pacific with atmospheric  
114 circulation anomalies over the North Atlantic (e.g., Wu and Hsieh 2004; Graf and  
115 Zanchettin 2012). The PNA-like teleconnection pattern over the North Pacific usually  
116 extends downstream to the North Atlantic and leads to a change in the quasi-stationary  
117 wave structures, which can be enhanced by eddy-mean flow interactions (e.g., Cassou  
118 and Terray 2001; Pozo-Vázquez et al. 2005; Graf and Zanchettin 2012). The  
119 stratosphere might also act as a mediator to connect the signal between the Pacific and  
120 Atlantic basins (e.g., Castanheira and Graf 2003; Ineson and Scaife 2009; Bell et al.  
121 2009). As an additional pathway, several previous studies reported that ENSO could  
122 cause northern tropical Atlantic SST anomalies (e.g., Wolter 1987; Curtis and  
123 Hastenrath 1995; Alexander et al. 2002), which then further affect the North Atlantic  
124 atmospheric circulation (e.g., Watanabe and Kimoto 1999; Robertson et al. 2000).  
125 Finally, the ENSO-forced downstream development process of synoptic eddies  
126 provides a pathway to affect the NAO (e.g., Li and Lau 2012a,b; Drouard et al. 2015).  
127 In this argument, the low-frequency atmospheric circulation anomaly (ridge or trough)  
128 over the eastern Pacific and North America is emphasized, which modulates the  
129 meridional propagation of synoptic wave packets over the North Atlantic, which then  
130 favors occurrence of different NAO phases.

131 As discussed above, there appears little scientific consensus on the ENSO/NAO  
132 relationship and its associated physical mechanisms. For example, can a statistically  
133 significant relationship between ENSO and NAO variability be identified? If so,

134 which dynamical mechanisms are responsible for this relationship? Our previous  
135 work provided an evidence for the existence of different types of La Niña based on  
136 their different impacts on the NAO (Zhang et al. 2015). The present study extends this  
137 analysis and investigates the linear and nonlinear relationships between ENSO and  
138 NAO and discusses the dominant mechanisms by using both observations and a suite  
139 of numerical model experiments. As we shall demonstrate, predominantly linear and  
140 nonlinear NAO responses are found associated with the CP and EP ENSO types,  
141 respectively. We will attribute this difference mainly to the varying atmospheric  
142 responses to the eastern tropical Pacific SST anomalies.

143 In the reminder of this paper, section 2 introduces the data, methodology,  
144 definition of ENSO events, and our experimental design. Section 3 illustrates  
145 uncertainties of the ENSO/NAO relationship. The different linkages between the  
146 NAO and the two distinct ENSO types are examined in section 4. Further evidence of  
147 this complex ENSO/NAO relationship is shown in section 5. Possible dynamical  
148 mechanisms for the different ENSO/NAO relationships are discussed in section 6. The  
149 major conclusions are summarized and discussed in section 7.

150

## 151 **2. Data, Methodology, definition of ENSO events, and Experimental** 152 **design**

### 153 **2.1 Data and Methodology**

154 Monthly SST anomalies associated with ENSO were examined based on the  
155 Hadley Centre sea ice and SST data set (HadISST) version 1.1 (Rayner et al. 2003).

156 The atmospheric circulation was investigated using National Center for  
157 Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR)  
158 reanalysis-1 data (Kalnay et al. 1996). Precipitation data are taken from the Global  
159 Precipitation Climatology Centre (GPCC) (Rudolf et al. 2005). We also utilized the  
160 global monthly land surface temperature analysis collected from the Global Historical  
161 Climatology Network version 2 and the Climate Anomaly Monitoring System  
162 (GHCN\_CAMS) (Fan and van den Dool 2008). To describe the NAO-associated  
163 atmospheric activity, the NAO index is defined as the difference in normalized  
164 sea-level pressure (SLP) zonally-averaged from 80°W to 30°E between 35°N and  
165 65°N (Li and Wang 2003). Other NAO indices, such as the index defined by Hurrell  
166 (Hurrell 1995) and Climate Prediction Center (CPC;  
167 <http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml>) were also  
168 examined and the conclusions remain the same.

169 Our analyses in this paper cover the period 1948-2014 and anomalies for all  
170 variables were computed as the deviations from a 30-year climatological mean  
171 (1981–2010). A 6-120 month band-pass filter was applied to each dataset using the  
172 second-order Butterworth filter designed by Parks and Burrus (1987), to focus on  
173 ENSO-related interannual variability. The first and last three years of the datasets  
174 were removed in the following analyses to avoid possible boundary distortion  
175 associated with the band-pass filtering. Linear correlation and composition analyses  
176 were used to investigate the ENSO/NAO relationship. Statistical significance was  
177 determined using the two-tailed Student's t-test.

## 178 **2.2 Definition of ENSO events**

179 ENSO events usually reach their peak phase during boreal winter  
180 (December-January-February, DJF). However, the largest impact of ENSO on the  
181 NAO can usually be found during late winter (January-February-March, JFM) (e.g.,  
182 Zhang et al. 2015). Thus, we use the DJF Niño3.4 index (SST anomalies averaged  
183 over 5°S–5°N and 120°–170°W) as a measure of ENSO and the NAO index  
184 calculated in JFM to characterize the NAO. The CPC definition is utilized to identify  
185 ENSO winters based on a threshold of  $\pm 0.5^{\circ}\text{C}$  of the Niño3.4 SST anomalies for five  
186 consecutive overlapping seasons. Many regional ENSO indices are able to separate El  
187 Niño events into two types (i.e., Ashok et al. 2007; Kao and Yu 2009; Ren and Jin  
188 2011), however they fail to effectively distinguish different La Niña types (Zhang et al.  
189 2015), especially during the period before the 1980s (Ren et al. 2013). Here we  
190 identify different ENSO types by the spatial distribution of SST anomalies, same as  
191 our previous definition (Zhang et al. 2011, 2013, 2014, 2015), which can effectively  
192 distinguish two types for both El Niño and La Niña events. The events are classified  
193 into EP (CP) ENSO winters if the largest SST anomaly center occurs east (west) of  
194 150°W during the developing and mature (September to February) ENSO phases.  
195 Among them, two El Niño events (1987/88, 2006/07) and three La Niña events  
196 (1970/71, 1999/00, 2007/08) are defined as a mixed type (or basin-wide mode) since  
197 the SST anomalies cover both EP and CP regions. Here, ENSO years are labeled  
198 Year(0)/Year(1), where 0 and 1 refer to the ENSO developing and decaying year,  
199 respectively. Some ENSO events coincide with tropical volcanic eruptions, which

200 strongly affect the atmospheric circulation over the North Atlantic and Europe for  
201 about 1-2 years after the eruption (e.g., Robock 2000; Driscoll et al. 2012). Hence,  
202 ENSO events (i.e., 1982/83 and 1991/92) following major tropical volcanic eruptions  
203 are excluded in our analysis. Especially for the 1991 Pinatubo eruption, the second  
204 largest eruption in the 20<sup>th</sup> century, its climate impacts over Europe can be detected  
205 after several years following the eruption (e.g., Xiao and Li 2011). To exclude these  
206 volcanic eruption signals, the following two and four years were removed after the  
207 1982 and 1991 eruptions, respectively. The two types of ENSO winters analyzed in  
208 this paper are listed in Table 1. Each category features 8 samples, other than the CP  
209 El Niño group, which contains 9 events.

210

### 211 **2.3 Experimental design**

212 To examine the possible impacts of ENSO SST anomalies on the NAO, modeling  
213 experiments were conducted using the Geophysical Fluid Dynamics Laboratory  
214 (GFDL) global Atmospheric Model version 2.1 (AM2.1) (The GFDL Global  
215 Atmospheric Model Development Team, 2004) with a horizontal resolution of 2.5°  
216 longitude×2° latitude. As a reference state, climatological (seasonally varying) SSTs  
217 were used to force the atmospheric model. Additionally, a suite of sensitivity  
218 experiments (EPW, CPW, EPC, and CPC) was designed (Table 2). For the first  
219 simulation (EPW), the SST anomalies for composites of the EP El Niño events listed  
220 in Table 1 were imposed on the monthly climatological SST from October to February  
221 in the tropical Pacific (30°S-30°N, 120°E-90°W) (Table 2). Anomalies outside of the

222 region were set to zero to limit our analysis to the effects of tropical Pacific SST  
223 anomalies. We note that the SST anomalies outside of the tropical Pacific also play  
224 some role in ENSO-induced climate impacts, which are not considered in this paper.  
225 The other three experiments (CPW, EPC, and CPC in Table 2) are the same as the  
226 EPW experiment, except that the SST anomalies are the composites for other different  
227 ENSO types (the CP El Niño, EP La Niña, and CP La Niña events in Table 1). Each  
228 simulation is integrated for 15 years and the last 10 years of the integrations were used  
229 to avoid influences of the initial conditions. A composite of these 10 years removes  
230 most of the internal variability.

231

### 232 **3. Uncertainties of the ENSO/NAO relationship**

233 First, we investigate the time series of the DJF Niño3.4 and JFM NAO indices  
234 (Fig. 1a). These two indices display conspicuous interannual variability that is only  
235 weakly anti-correlated ( $R=-0.23$ , insignificant at the 95% confidence level). Also, no  
236 robust linear relationship can be established when considering sliding correlations  
237 with 11- and 21-year windows respectively (Fig. 1b). To address possible influences  
238 of volcanic eruption events on the ENSO/NAO relationship, we further calculate the  
239 correlation coefficient between the Niño3.4 and NAO indices after removing the  
240 previously defined eruption years from both time series. After removing this influence,  
241 we detect a weak but statistically significant (at the 95% confidence level)  
242 relationship ( $R=-0.33$  in Table 3), suggesting that in general El Niño events (as  
243 measured by DJF Niño3.4) tend to be accompanied by a negative NAO phase, and La

244 Niña events by a positive NAO.

245       Next, we show a scatterplot of Niño3.4 and NAO indices during the ENSO  
246 winters (Fig. 2). Most (14 of 17) El Niño events are accompanied by a negative NAO  
247 phase, consistent with many previous studies (e.g., Brönnimann 2007a; Li and Lau  
248 2012a). Only three El Niño events (i.e., 1953/54, 1972/73, 2002/03) coincide with a  
249 weak positive NAO phase. However, no simple relationship is detected between the  
250 Niño3.4 and NAO indices for La Niña events. Around half of the La Niña winters  
251 exhibit a positive NAO phase, while the other half are accompanied by a negative  
252 NAO phase. We hypothesize that this unstable La Niña/NAO relationship could  
253 explain the weak correlation between the Niño3.4 and NAO indices. To better  
254 understand the different NAO response to La Niña, we show the composite SST  
255 anomaly patterns during La Niña/NAO+ (Fig. 3a) and La Niña/NAO- (Fig. 3b)  
256 winters. La Niña winters corresponding to a positive NAO phase exhibit a negative  
257 SST anomaly center, strongest over the central equatorial Pacific west of 150°W with  
258 relatively weak anomalies in the eastern equatorial Pacific, which is the characteristic  
259 pattern of the CP La Niña (Zhang et al. 2015). In contrast, the SST anomalies  
260 associated with La Niña/NAO- events have maximum negative SST anomalies in the  
261 equatorial eastern Pacific east of 150°W, which resembles the SST anomaly pattern of  
262 the EP La Niña. This suggests that the NAO responses are very sensitive to the zonal  
263 location of La Niña-related SST anomalies, which have been described in our  
264 previous study (Zhang et al. 2015). This separation of La Niña events with regard to  
265 NAO phase is also evident in Figure 2. This suggests that ENSO has indeed a close

266 connection with the NAO, which was not easily detected in earlier studies due to the  
267 nonlinear La Niña/NAO relationship.

268

#### 269 **4. Inconsistent linkages between the NAO and two types of ENSO**

270 Next, we investigate ENSO event composites to further examine the relationship  
271 between the NAO and the two types of ENSO. First, we show the SST anomaly  
272 patterns to demonstrate the validity of two-type ENSO classification (Fig. 4). It can be  
273 seen that the SST anomaly patterns related to the different ENSO types are well  
274 separated. They are characterized by a different zonal location of the SST anomalies  
275 and the corresponding near-surface wind anomalies (SST maxima at approximately  
276 165°W and 115°W for CP and EP ENSO respectively). Note that the SST anomaly  
277 patterns associated with the two La Niña types are almost the same as those shown in  
278 Figure 3 associated with different phases of the NAO. Furthermore, it can be seen that  
279 the SST amplitude is larger for EP El Niño than for CP El Niño. In contrast, the SST  
280 amplitude for EP La Niña is smaller than for CP La Niña.

281 To examine the extra-tropical response, Northern Hemisphere composite SLP  
282 anomalies for the different ENSO types are shown in Figure 5. We observe an  
283 atmospheric Rossby wave response to diabatic heating caused by positive SST  
284 anomalies in the tropical Pacific. Positive PNA-like atmospheric circulation patterns  
285 are seen during both EP and CP El Niño winters, albeit with different spatial extent  
286 and amplitude (Fig. 5a, b). Compared to the EP El Niño composite, we observe  
287 negative SLP anomalies over the North Pacific for CP El Niño that are shifted



288 southeastward and have a larger extent. Importantly, both EP and CP El Niño winters  
289 exhibit extra-tropical atmospheric responses of the same sign over the Atlantic. In  
290 comparison, the negative NAO-like SLP response (characterized by weakened  
291 subtropical high and polar low) is larger for CP than EP El Niño events, despite the  
292 larger SST amplitude during EP El Niño events. Unlike the CP El Niño events, the EP  
293 El Niño-associated SLP anomalies over the North Atlantic are relatively weak and are  
294 significant only above the 80% confidence level, thus exhibiting a certain degree of  
295 uncertainty. This uncertainty could be due to the large diversity in the amplitude of EP  
296 El Niño events (Toniazzo and Scaife 2006). Differences in teleconnection patterns  
297 associated with the two El Niño types can also be observed in the Southern  
298 Hemisphere (Lim et al., 2013; Wilson et al., 2014, 2016). In the Northern Hemisphere,  
299 both La Niña types are characterized by negative PNA-like atmospheric circulation  
300 anomalies that appear as a response to the negative SST anomalies in the tropical  
301 Pacific (Fig. 5c,d). Correspondingly, positive SLP anomalies are evident for both  
302 types over the North Pacific, indicating a weakened Aleutian low. In contrast, the CP  
303 La Niña-associated SLP anomalies are displaced southeastward compared to the EP  
304 La Niña, which is similar to the Pacific signal seen for the two El Niño types. Despite  
305 these similar anomalies over the North Pacific, an almost opposite atmospheric  
306 anomaly is observed over the North Atlantic and Western Europe for the two La Niña  
307 types. The EP La Niña events exhibit a negative NAO-like atmospheric response  
308 (weakened subtropical high and polar low) with its center located over the eastern  
309 North Atlantic and Western Europe (Fig. 5c). In contrast, the CP La Niña events are

310 accompanied by a positive NAO-like atmospheric anomaly pattern (strengthened  
311 subtropical high and polar low) with its center located over the western-to-central  
312 North Atlantic (Fig. 5d). These NAO-like responses to different ENSO types can in  
313 fact be seen for almost the entire troposphere over the North Atlantic (Fig. 6),  
314 exhibiting a quasi-barotropic structure. Notably, the North Atlantic response seems  
315 weak for mid-latitude negative anomalies during EP El Niño events (Fig.6a).

316 The subtropical jet is usually argued to serve as a mediator linking ENSO and the  
317 North Atlantic atmosphere (e.g., Graf and Zanchettin 2012). Figure 7 shows the  
318 composite 300 hPa zonal wind anomalies during different types of ENSO winters. For  
319 both types of El Niño events, the zonal wind anomalies exhibit a tripolar structure and  
320 tilt slightly northeastward (Fig. 7a,b). These anomalies extend zonally from the North  
321 Pacific toward the North Atlantic. Similar to Figure 5a, the EP El Niño-associated  
322 anomalies are relatively weak over the North Atlantic and statistically significant only  
323 above the 80% confidence level. In contrast, the CP El Niño-associated anomalies  
324 exhibit a larger zonal extent and amplitude than those for EP El Niño. Overall, the  
325 Atlantic subtropical westerly jet tends to be weakened for both El Niño types,  
326 corresponding to the negative NAO-like atmospheric responses. A very similar  
327 meridional structure of 300 hPa zonal wind anomalies is observed for the two La Niña  
328 types over the North Pacific, but with farther northward displacement by about 10° for  
329 EP La Niña compared to CP La Niña (Fig. 7c,d). The CP La Niña-related zonal wind  
330 anomalies extend to the North Atlantic and Western Europe region, where  
331 anomalously weak upper-level winds are found as far east as the Mediterranean. In

332 contrast, the EP La Niña-associated zonal wind anomalies are more zonally  
333 constrained (more like a wave train structure) and of almost opposite structure over  
334 the North Atlantic. Consistent with the NAO response, a weakened and strengthened  
335 Atlantic jet concurs with EP and CP La Niña events, respectively (Fig. 7c,d).  
336 Interestingly, the 300 hPa wind response to CP ENSO is quite linear, with roughly  
337 equal and opposite patterns in response to CP El Niño and CP La Niña (Fig. 7b,d).  
338 This is not the case for EP ENSO where the response is distinctly nonlinear.  
339 Corresponding to the different Atlantic jet anomalies, the activity of the synoptic  
340 eddies (2-10-day timescale) is weakened over the North Atlantic for the two El Niño  
341 types and EP La Niña events, while it is strengthened for CP La Niña events (not  
342 shown). Again, the eddy response to ENSO forcing from the CP region is quite linear,  
343 while it is nonlinear for EP ENSO.

344

## 345 **5. Observed and simulated evidence for a complex ENSO/NAO** 346 **relationship**

### 347 5.1 Observed surface temperature anomalies associated with different ENSO types

348 We use the observed surface temperature data to further investigate the identified  
349 complex ENSO/NAO relationship. Previous studies have pointed out that the  
350 anomalous surface climate conditions (such as temperature) over Western Europe and  
351 even Eurasia are closely associated with NAO phase (for a review, refer to Jones et al.  
352 2003). Motivated by our previous analyses we hypothesize that different ENSO types  
353 may give rise to distinct climate anomalies over Eurasia. As shown in Section 4, the

354 negative NAO-like responses to the two El Niño types and EP La Niña events are  
355 accompanied by a weakened Atlantic jet (Fig. 7a-c), which limits the transport of  
356 warm and moist air from the North Atlantic to the northern Eurasian land areas.  
357 Simultaneously, the strengthened zonal winds south of the Atlantic jet core (Fig. 7a-c)  
358 lead to enhanced warm and moist air transported into southern Eurasia. As expected,  
359 northern Eurasia (roughly north of 40°N) experiences a colder than normal winter  
360 during the two types of El Niño and EP La Niña (Fig. 8a-c). At the same time, the  
361 southern part of Eurasia tends to experience warmer than normal winters. In contrast,  
362 CP La Niña events tend to result in positive NAO-like atmospheric anomalies and a  
363 strengthened Atlantic jet. Therefore, warmer and wetter air can be transported into  
364 northern Eurasia, which results in positive surface temperature anomalies in Europe  
365 during CP La Niña winters (Fig. 8d). Precipitation anomaly differences are  
366 approximately co-located with the surface temperature anomalies, characterized by  
367 reduced precipitation for the two El Niño types and EP La Niña and enhanced  
368 precipitation for CP La Niña over northern Eurasia (not shown), albeit with much  
369 larger spatial non-uniformity. Although EP and CP El Niño events have similar  
370 impacts on the Eurasian climate, a remarkable difference is evident in the spatial  
371 extent and amplitude of the climate anomalies (Fig. 5 and 8).

372

## 373 5.2 Experiments of ENSO forcing on European climate variability

374 We utilize a series of general circulation model experiments to verify the  
375 identified NAO impacts of tropical SST anomalies associated with different ENSO

376 types (as listed in Table 2 and described in Section 2.3). Figure 9 shows the  
377 anomalous sea-level pressure (SLP) responses to the different prescribed ENSO  
378 forcings. Simulated EP and CP El Niño winters are both characterized by a  
379 strengthened Aleutian Low and negative NAO phase (Fig. 9a,b), which is roughly  
380 consistent with the observations. Both EP and CP La Niña forcings generate a  
381 weakened Aleutian Low. However, they simulate almost opposite atmospheric  
382 responses over the North Atlantic (Fig. 9c,d), which can also be seen in experiments  
383 conducted with the NCAR Community Atmospheric Model version 5 (CAM5; Zhang  
384 et al. 2015). Consistent with observations, opposite NAO responses are found when  
385 the EP and CP La Niña-related SST anomalies are imposed. It is notable that the  
386 simulated atmospheric responses over Western Europe are weaker than what we see in  
387 the observations (Figure 5c and 9c).

388 We further inspect the subtropical jet anomalies in these experiments, since it  
389 plays an important role in connecting the ENSO signal with the North Atlantic  
390 atmosphere. Figure 10 displays the simulated 300 hPa zonal wind anomalies during  
391 winter for different ENSO types. Consistent with the observations (Fig. 7a,b), the  
392 simulated zonal wind anomalies exhibit a tripolar structure over the North Pacific and  
393 extend zonally from there toward the North Atlantic for both types of El Niño events.  
394 The weakened Atlantic jet is also well reproduced in these experiments. Moreover,  
395 almost opposite 300 hPa wind responses are well reproduced in the CP La Niña  
396 experiments. Also consistent with the observations, the simulated zonal wind  
397 anomalies are mostly confined west of 60°W with an opposite structure over the

398 North Atlantic for the EP La Niña compared to CP La Niña events. The fact that these  
399 features are simulated in our idealized experiments suggests that the different NAO  
400 responses to EP and CP ENSO may be robust. We note that some obvious differences  
401 exist in the EP El Niño composites between the observations and the model  
402 simulation, but importantly they both consistently capture the positive PNA phase and  
403 negative NAO phase. These differences could be partly explained by the large  
404 inter-event variability in amplitude of EP El Niño events. In particular, the super El  
405 Niño events (e.g., 1972/73 and 1997/98) display pronounced differences in local  
406 air-sea coupled features and in the SST anomalies outside of the tropical Pacific  
407 region, which are not considered in our experimental design.

408

## 409 **6. Possible mechanisms for the unstable ENSO/NAO relationship**

410 Our analyses so far demonstrated that different ENSO types exhibit complex  
411 linkages with the NAO phase. CP ENSO (i.e., CP El Niño and CP La Niña) displays  
412 linear impacts on the NAO. In contrast, EP ENSO (i.e., EP El Niño and EP La Niña)  
413 shows nonlinear impacts on the NAO. To explore possible reasons for these  
414 differences, we decompose analysis into linear and nonlinear SST and atmospheric  
415 anomalies associated with the two ENSO types (Fig. 11). The degree of nonlinearity is  
416 determined by adding composites from two opposing phases of ENSO. Should the  
417 result be zero (i.e., the patterns associated with a particular field are exactly equal and  
418 opposite for El Niño and La Niña phases), then the ENSO response is perfectly linear.

419 Precipitation associated with tropical deep convection is a good indicator of the

420 linearity of the impacts of tropical SST anomalies, with the caveat that precipitation  
421 observations over the ocean are only available after the late 1970s. Thus, we use SLP  
422 anomalies to explore the local atmospheric response over the tropical Pacific instead  
423 of precipitation. Positive SST and negative SLP anomalies are evident in the eastern  
424 tropical Pacific, while negative SST and positive SLP anomalies exist in the western  
425 tropical Pacific for the linear part of EP ENSO (Fig. 11a), thus displaying typical EP  
426 ENSO features. In contrast, the linear SST anomalies for the CP ENSO are shifted  
427 westward to the central and western tropical Pacific (Fig. 11b). Correspondingly, the  
428 linear part of negative SLP anomalies exhibits the same westward shift for CP ENSO  
429 events. Importantly, CP ENSO does not exhibit a significant nonlinear component  
430 over the equatorial Pacific (Fig. 11d is mostly near-zero). This implies that negative  
431 and positive CP ENSO events will also not excite nonlinear teleconnection anomalies  
432 over the extra-tropics. Although almost no nonlinear SST anomaly appears over the  
433 tropical Pacific for the EP ENSO, we observe a strong nonlinear SLP anomaly  
434 response to the EP ENSO (Fig. 11c), whose amplitude is comparable to the linear  
435 component (compared to Fig. 11a).

436       Next, we examine the experimental results to verify the different relationships  
437 between SST forcing and atmospheric responses for these two ENSO types. For the  
438 linear part, the observed SLP features are well captured by the experiments forced  
439 with EP ENSO-related SSTs in the tropical Pacific. For example, positive and  
440 negative SLP anomalies emerge over the western and eastern tropical Pacific,  
441 respectively (Fig. 12a). Similarly, the tropical Pacific SST forcing associated with CP

442 ENSO can reproduce the westward extension of the SLP response compared to EP  
443 ENSO (Fig. 12b). In comparison, relatively large negative SLP anomalies are seen in  
444 the eastern tropical Pacific for the EP nonlinear component (Fig. 12c), which cannot  
445 be seen for the CP case (Fig. 12d). Consistent with the observations, the atmospheric  
446 responses to the two types of ENSO are very different over the eastern tropical Pacific,  
447 despite a systematic bias in the northern and western tropical Pacific for both EP and  
448 CP ENSO events. These biases are possibly attributed to a combination of the  
449 idealized experimental design (SST anomalies are set to zero outside of the tropical  
450 Pacific), a one-way forcing from the ocean to atmosphere without considering  
451 coupled ocean-atmosphere feedbacks, and model mean state biases.

452 Tropical convection depends critically on the total SST (climatology plus  
453 anomalies), thus convection and associated SLP anomalies usually exhibit a nonlinear  
454 relationship with SST anomalies. As the CP region is located near the eastern edge of  
455 the tropical Pacific warm pool with relatively high climatological SSTs, anomalous  
456 convection exhibits a quasi-linear relationship with SST anomalies. In contrast, the  
457 climatological SSTs are well below the SST threshold for convection in the EP region.  
458 Therefore, negative SST anomalies have only a small impact on local convection,  
459 while positive SST anomalies associated with EP El Niño events can lead to strong  
460 local convection and precipitation anomalies.

461 The linear and nonlinear components of the simulated precipitation are shown in  
462 Fig. 13 to confirm the greater nonlinear atmospheric responses to ENSO in the eastern  
463 tropical Pacific. The composite difference between positive and negative phases of



464 ENSO (the linear response) shows positive precipitation anomalies in the eastern  
465 equatorial Pacific ( $155^{\circ}$ - $90^{\circ}$ W,  $5^{\circ}$ S- $5^{\circ}$ N) for both EP and CP ENSO (the latter of  
466 approximately half amplitude compared to EP ENSO). For the simulated nonlinear  
467 component, positive precipitation anomalies are evident in the eastern Pacific for the  
468 EP ENSO forcing (indicating a high degree of nonlinearity), with amplitude  
469 comparable to the CP linear component. In contrast, almost no nonlinear precipitation  
470 anomalies are seen for the CP ENSO forcing. The degree of nonlinearity could also be  
471 diagnosed as the ratio of the magnitudes of nonlinear to linear components.

472 Hence, the nonlinear relationship between SST and atmospheric response can be  
473 well reproduced by the model experiments. We emphasize that these nonlinear  
474 convection anomaly responses result in very different teleconnection patterns over the  
475 extra-tropics. Therefore, this nonlinearity is likely an important factor for determining  
476 the distinct NAO responses to different ENSO types in the observation.

477

## 478 **7. Conclusions and Discussion**

479 We use reanalysis data in conjunction with ENSO and NAO indices of the  
480 1948-2014 period to determine impacts of different ENSO types (central and east  
481 Pacific events, CP and EP) on North Atlantic climate variability. A stable  
482 relationship is found between ENSO and atmospheric anomalies in the North Pacific  
483 region. However, no consistent linear relationship is found between ENSO and the  
484 NAO. We found that the complex ENSO/NAO relationship is mainly modulated by  
485 the different ENSO flavors once the impacts of volcanic activity are removed. Both

486 types of El Niño (EP and CP) are accompanied by a negative NAO phase over the  
487 North Atlantic, albeit with different intensities. In contrast, almost opposite  
488 atmospheric anomaly structures are detected over the North Atlantic for the two  
489 types of La Niña. A positive NAO phase is associated with CP La Niña winters,  
490 while a negative NAO phase is associated with the EP La Niña winters. Moreover,  
491 these results based on the reanalysis data are evidenced by the observed land surface  
492 temperature over the Eurasian region and reproduced by the experiments driven by  
493 imposed tropical Pacific SST anomalies associated with ENSO. We note that the  
494 composite NAO-associated atmospheric anomalies for EP ENSO events, especially  
495 for EP El Niño, are weaker than those to CP ENSO events. This difference may be  
496 due to different zonal locations of the ENSO-related air-sea action center. Compared  
497 to CP ENSO events, the EP ENSO-associated SST anomalies are located in the  
498 eastern tropical Pacific where the climatological SSTs are colder. These different  
499 background states likely explain why the atmospheric responses to the same SST  
500 anomaly amplitude are weaker. In addition, the large diversity among amplitude of  
501 EP El Niño events increases the uncertainty in their climate impacts.

502 While CP ENSO events display linear impacts on the North Atlantic  
503 atmospheric circulation, EP ENSO events exhibit nonlinear impacts. These varying  
504 extra-tropical atmospheric responses to two different ENSO types are mainly related  
505 to local nonlinear air-sea coupling in the tropical Pacific. Although the SST  
506 anomalies for our ENSO type composites are quasi-linear, we observe very different  
507 local atmospheric responses due to the nonlinear SST threshold for deep convection.

508 Thus, our conclusion is that nonlinear local atmospheric responses can further lead to  
509 different extra-tropical atmospheric anomalies (such as the NAO) since they will  
510 excite different wave propagation patterns through the troposphere.

511 Although ENSO originates in the tropical Pacific, its impacts can be detected in  
512 remote oceans through the so-called atmospheric bridge mechanism (e.g., Klein et al.  
513 1999; Alexander et al. 2002). Some studies reported that ENSO-associated tropical  
514 Atlantic SST anomalies could serve as a mediator to connect the tropical Pacific SST  
515 anomalies with the NAO (e.g., Watanabe and Kimoto 1999; Robertson et al. 2000). As  
516 seen previously (Fig. 4a,b), pronounced positive SST anomalies are evident in the  
517 northwestern tropical Atlantic during EP Niño events, which are absent during CP El  
518 Niño events. In contrast, negative SST anomalies occur in the northern tropical  
519 Atlantic for both EP and CP La Niña events (Fig. 4c,d). Our experiments show that  
520 only tropical Pacific SST anomaly forcings associated with different ENSO types can  
521 well reproduce the observed NAO responses, suggesting that tropical Atlantic SST  
522 anomalies are not a key factor for the NAO responses to ENSO. Moreover, our  
523 previous experiments suggested that these tropical Atlantic SST anomalies during  
524 ENSO events could play a minor role for the NAO (Zhang et al. 2015). To further  
525 investigate possible effects of tropical Atlantic SST anomalies on the extra-tropical  
526 atmospheric circulation, we show in Fig. 14 the partial correlation coefficient of the  
527 observed SLP anomalies with SST anomalies in the tropical North Atlantic ( $0^{\circ}$ – $30^{\circ}$ N,  
528  $20^{\circ}$ – $80^{\circ}$ W), after the ENSO influence was linearly removed. Pronounced positive and  
529 negative SLP anomalies emerge over the north and south of the North Atlantic

530 respectively, a pattern that resembles a negative NAO phase. However, no significant  
531 Aleutian Low anomalies can be found over the Pacific basin. This indicates that SST  
532 anomalies in the tropical North Atlantic could have some contribution to the NAO  
533 although they are not able to induce large-scale extra-tropical atmospheric circulation  
534 anomalies in the same way as ENSO. However, SST anomalies in the tropical North  
535 Atlantic seem unable to explain diverging NAO responses to different ENSO types.

536         A scientific question that remains unresolved is how the tropical Pacific SST  
537 anomalies associated with different ENSO types result in varying NAO responses. To  
538 explore possible effects of stratospheric processes, we inspected the signal of the  
539 zonal wind anomalies at 60°N (Fig. 15) and found no significant signal propagation  
540 from the stratosphere to troposphere. This result is supported by our model  
541 experiments (not shown). However, we cannot fully exclude the possibility that the  
542 stratosphere plays a role in the ENSO/NAO connection due to sparse input  
543 observations to the reanalysis assimilation scheme, and poor performance of the  
544 model at upper levels. For example, a recent study argued that ENSO have impacts on  
545 climate over Northern Atlantic and Eurasia mainly through the stratospheric pathway  
546 (Butler et al. 2014).

547         Another possible cause of the divergent NAO responses to different ENSO types  
548 could be the downstream development of synoptic eddies. The low-frequency  
549 atmospheric anomalies over the northeast Pacific are very important for the  
550 propagation of the Pacific jet (Drouard et al. 2015). For example, the ridge anomaly  
551 over the northeastern Pacific can deflect the Pacific jet while the trough anomaly in

552 this location can maintain the Pacific jet extending in a zonal orientation. Therefore,  
553 during both types of El Niño events the trough anomaly over the northeastern Pacific  
554 favors a zonally oriented propagation of the Pacific jet. In contrast, the zonal location  
555 of the Northern Pacific SLP anomalies for both La Niña types differs significantly  
556 (Figure 5c,d). During CP La Niña, high SLP anomalies are shifted southward  
557 (compared to EP La Niña) and the northeastern Pacific is characterized by weak  
558 negative SLP anomalies. Thus, the Pacific jet extends zonally from the Pacific to the  
559 North Atlantic. For the EP La Niña, high SLP anomalies are located over the  
560 northeast Pacific, which act to deflect the Pacific jet. According to the study by  
561 Drouard et al. (2015), the different propagation orientation of the Pacific jet could  
562 result in varying downstream eddy structures and thus cause opposite NAO phases.

563 This paper adds to the body of work stating the importance of taking ENSO  
564 diversity into account when considering its impacts on remote climate variability.  
565 Coupled dynamical seasonal prediction models in use at various meteorological  
566 agencies must therefore be able to simulate the range of ENSO diversity in terms of  
567 its longitudinal location in order to correctly capture any additional skill offered to the  
568 NAO.

569

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578

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790 **Figure Captions**

791 Figure 1. (a) Time series of normalized DJF-Niño3.4 (red) and JFM-NAO (blue)  
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796 Figure 2. Scatterplot of the JFM-NAO index as a function of the normalized  
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800 Figure 3. Composite SST (contour in °C) and near-surface wind (vector in m/s)  
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805 Figure 4. Composite SST (contour in °C) and near-surface wind (vector in m/s)  
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808 level. The near-surface wind anomalies below the 80% confidence level are  
809 omitted.

810 Figure 5. Composite SLP anomalies (hPa) for (a) EP El Niño, (b) CP El Niño, (c) EP  
811 La Niña, and (d) CP La Niña. Horizontal and diagonal lines, and cross-hatched  
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814 Figure 6. Meridional-vertical geopotential height anomalies (m) zonally averaged  
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822 Figure 8. Composite surface air temperature ( $^{\circ}\text{C}$ ) for (a) EP El Niño, (b) CP El Niño,  
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836 Figure 12. Same as Figure 12, except that the SLP anomalies (hPa) are the ensemble  
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838 Figure 13. Precipitation anomalies (mm/d) over the eastern equatorial Pacific  
839 ( $155^{\circ}\text{--}90^{\circ}\text{W}$ ,  $5^{\circ}\text{S--}5^{\circ}\text{N}$ ) for EP El Niño minus EP La Niña (EPW-EPC), EP El Niño  
840 plus EP La Niña (EPW+EPC), CP El Niño minus CP La Niña (CPW-CPC), and  
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842 Figure 14. Partial correlation coefficient between the SLP and SST anomalies over the  
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845 Figure 15. Time-height diagram of zonal wind anomalies (m/s) in NCEP reanalysis  
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847 Niña and (d) CP La Niña. Shading indicates values exceeding the 90% and 95%  
848 confidence level respectively.



850 Table 1. Two types of ENSO years (excluding major tropical volcanic eruption  
 851 events).

	<b>El Niño</b>	<b>La Niña</b>
EP type (8,8)	1951/52, 1952/53, 1963/64, 1965/66, 1969/70, 1972/73, 1976/77, 1997/98	1954/55, 1955/56, 1964/65, 1967/68, 1971/72, 1984/85, 1995/96, 2005/06
CP type (9,8)	1953/54, 1957/58, 1968/69, 1977/78, 1979/80, 1986/87, 2002/03, 2004/05, 2009/10	1973/74, 1974/75, 1975/76, 1988/89, 1998/99, 2000/01, 2010/11, 2011/12

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853 Table 2. List of the conducted SST perturbation experiments.

<b>Experiment</b>	<b>Description of the SST perturbation</b>
EPW	Positive anomalies associated with EP El Niño winters are imposed in the tropical Pacific (30°S–30°N, 120°E–90°W)
CPW	As in EPW but for the CP El Niño winters
EPC	Negative anomalies associated with EP La Niña winters are imposed in the tropical Pacific (30°S–30°N, 120°E–90°W).
CPC	As in EPC but for the CP La Niña winters

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855 Table 3. Linear correlation coefficients (R) between DJF-Niño3.4 and JFM-NAO  
 856 indices (with sample size n) for different episodes. Asterisks indicate correlation  
 857 coefficients exceeding the 95% confidence level.

	All years	All years except volcano years	All years except volcano and EP La Niña years	El Niño and CP La Niña years	All years except volcano and ENSO years
n	61	55	47	25	22
R	-0.23	-0.33*	-0.50*	-0.63*	-0.04

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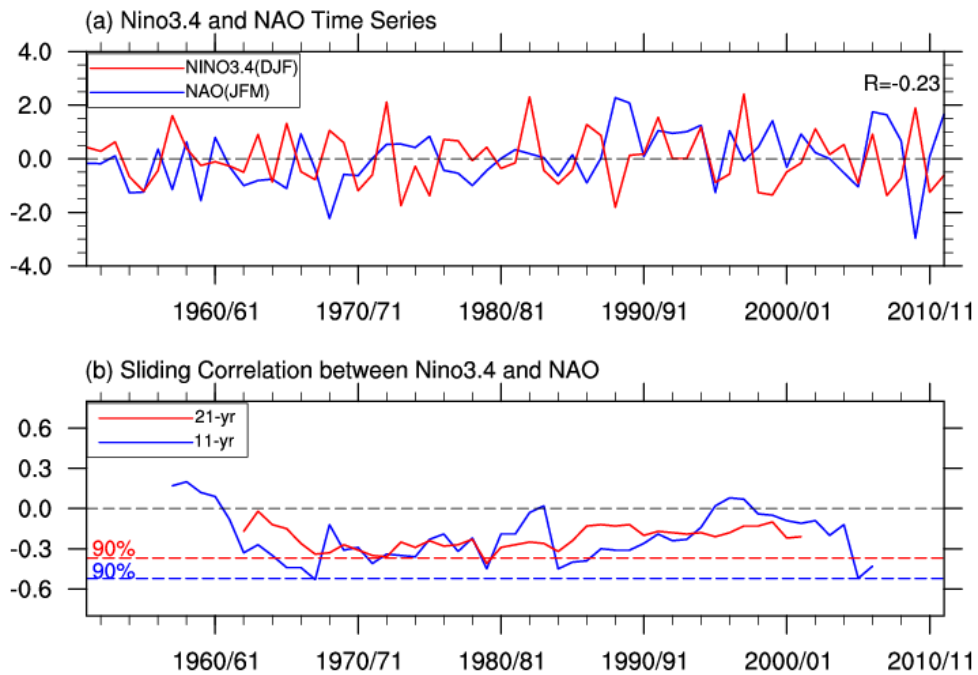
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869 Figure 1. (a) Time series of normalized DJF-Niño3.4 (red) and JFM-NAO (blue)

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873 for the 11- and 21- year windows, respectively.

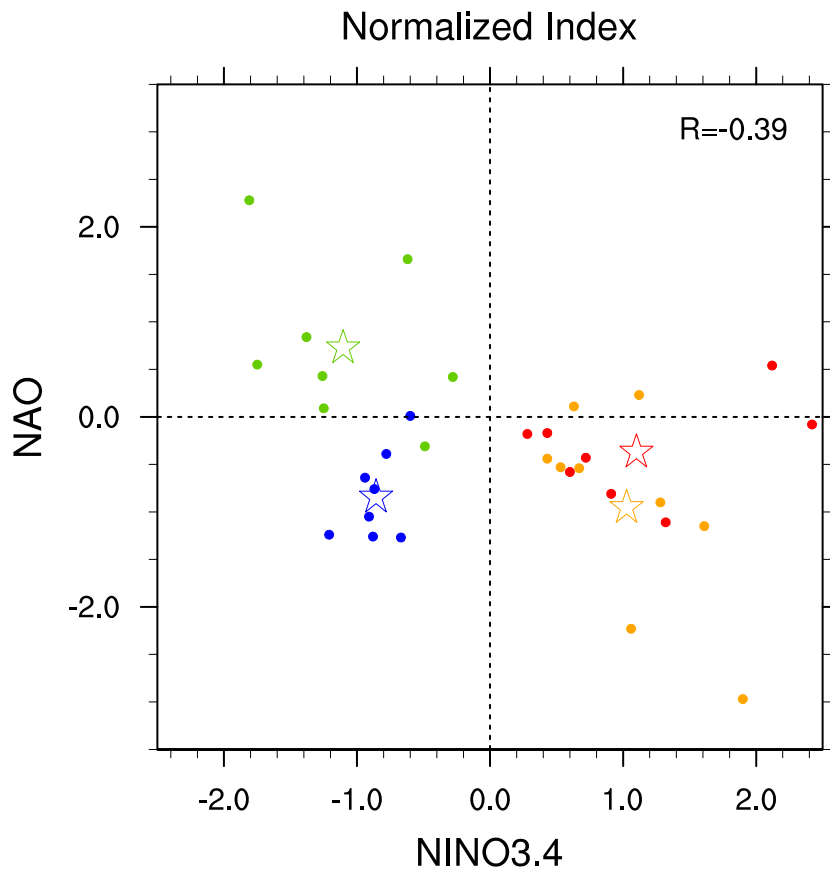
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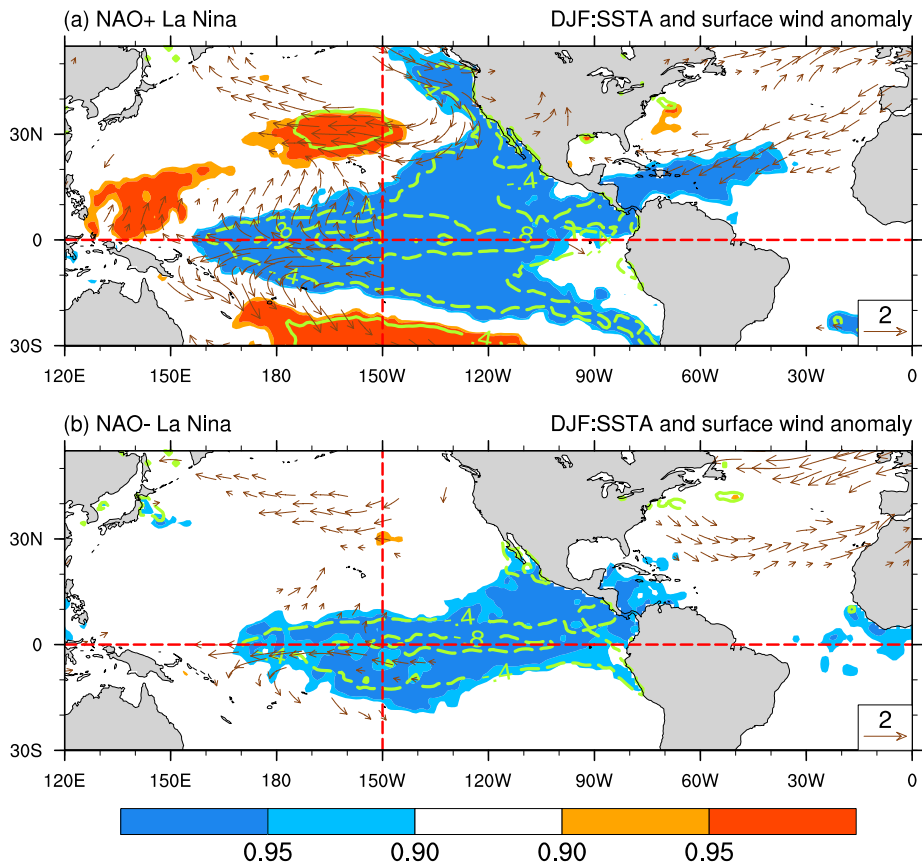
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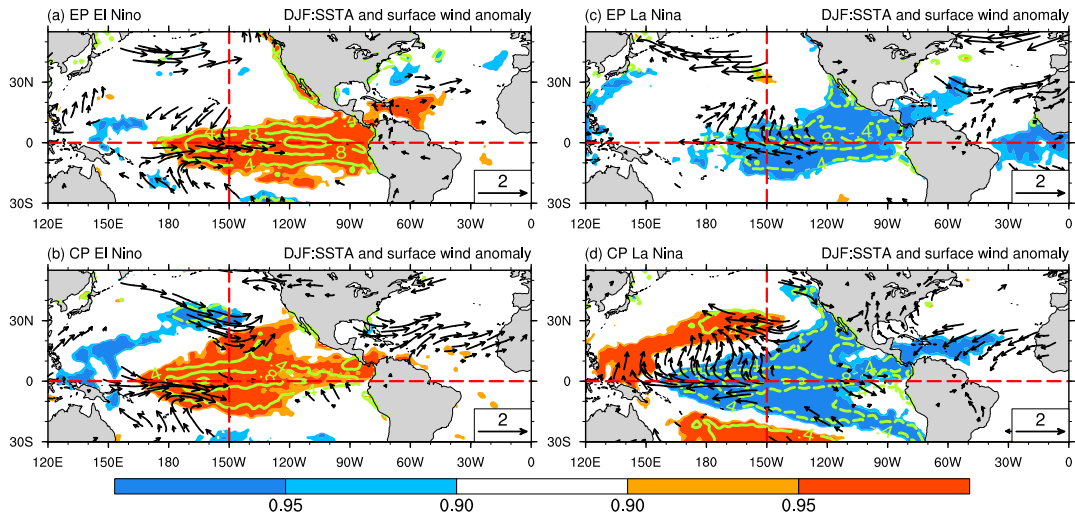
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929 The near-surface wind anomalies below the 80% confidence level are omitted.

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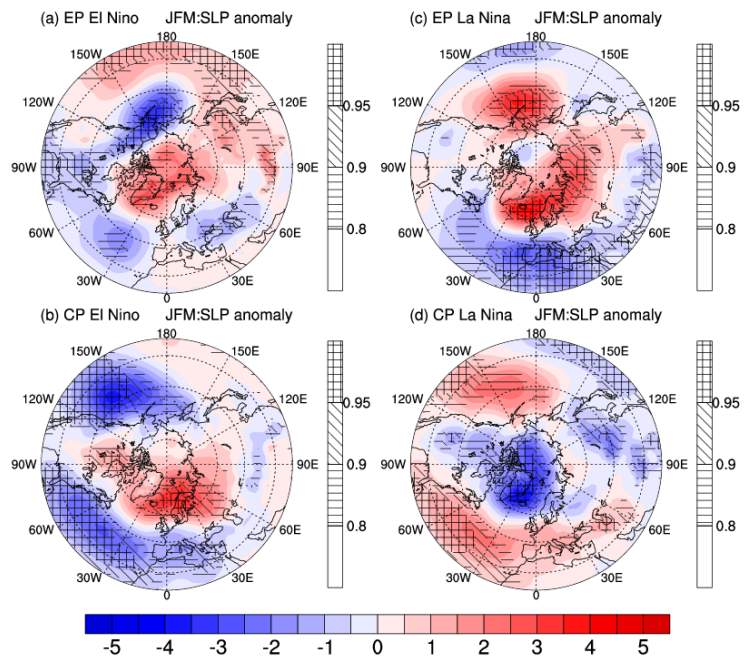
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961 Figure 6. Meridional-vertical geopotential height anomalies (m) zonally averaged

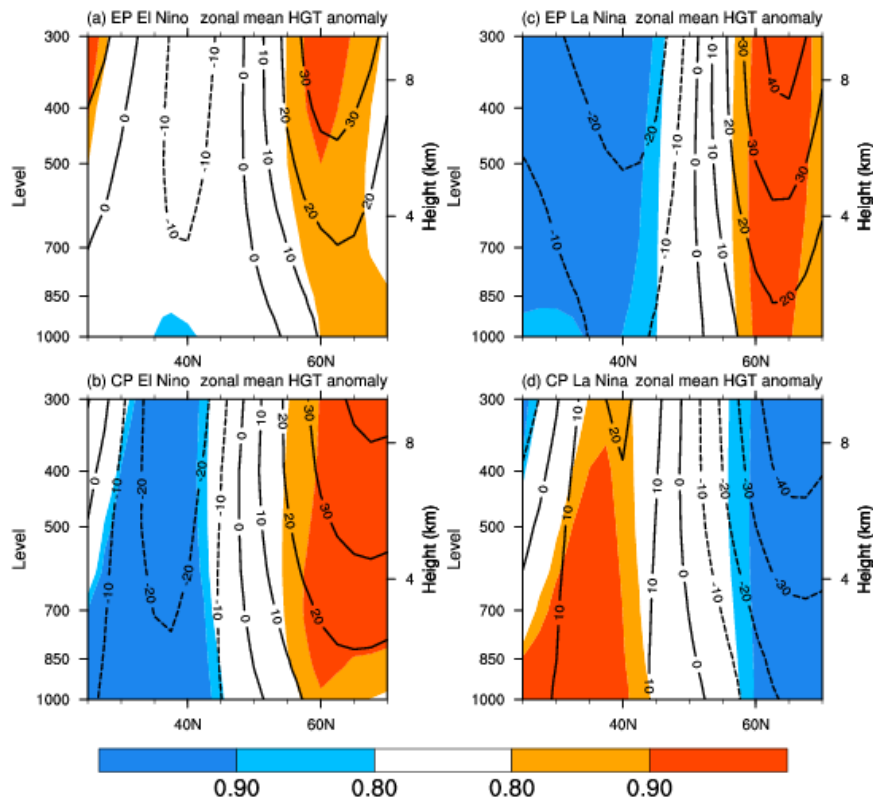
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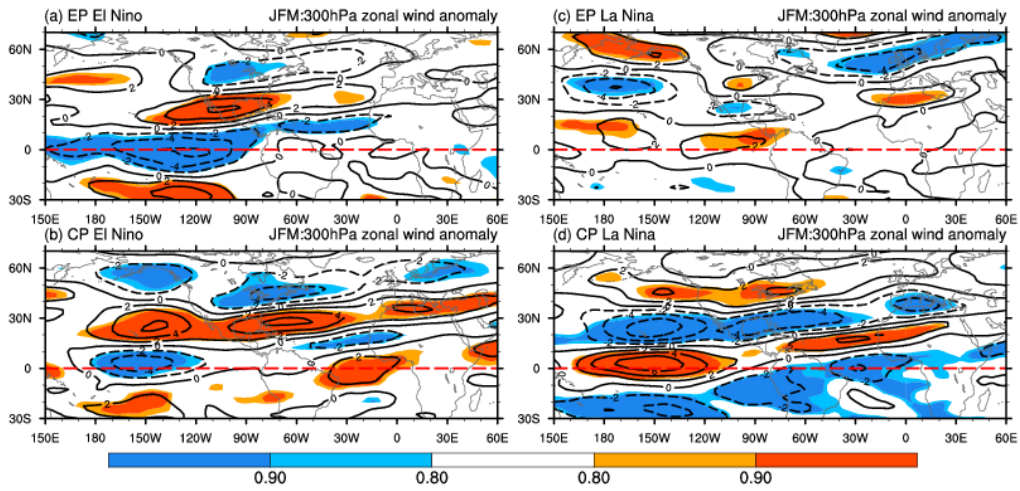
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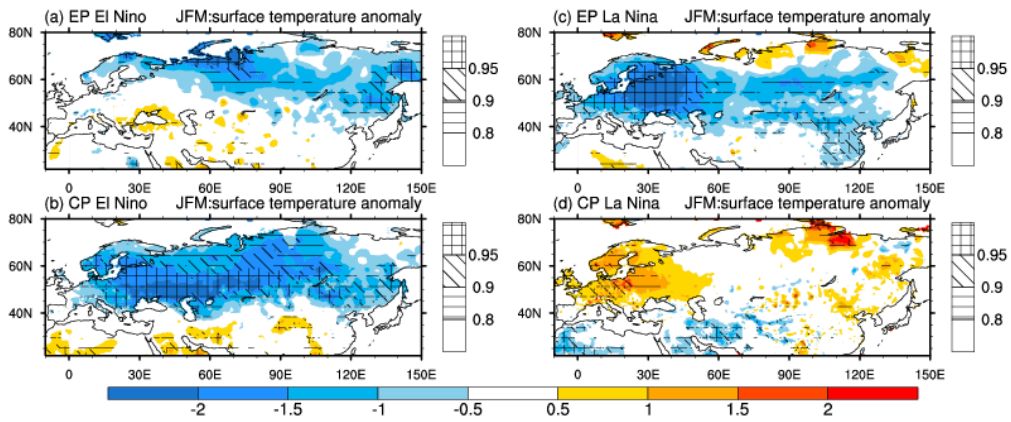
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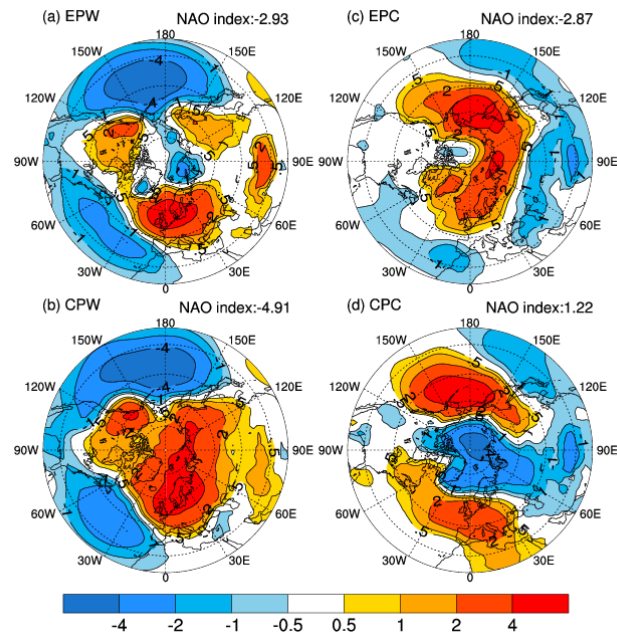
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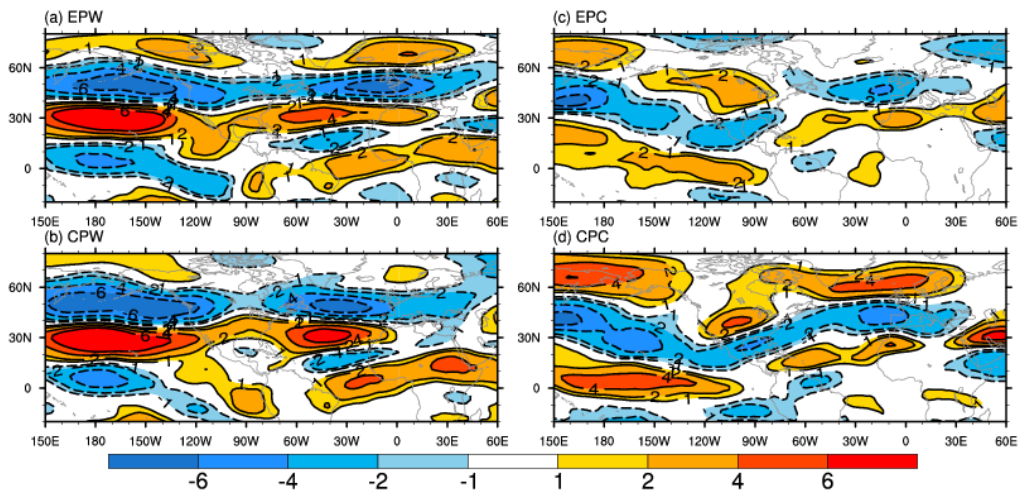
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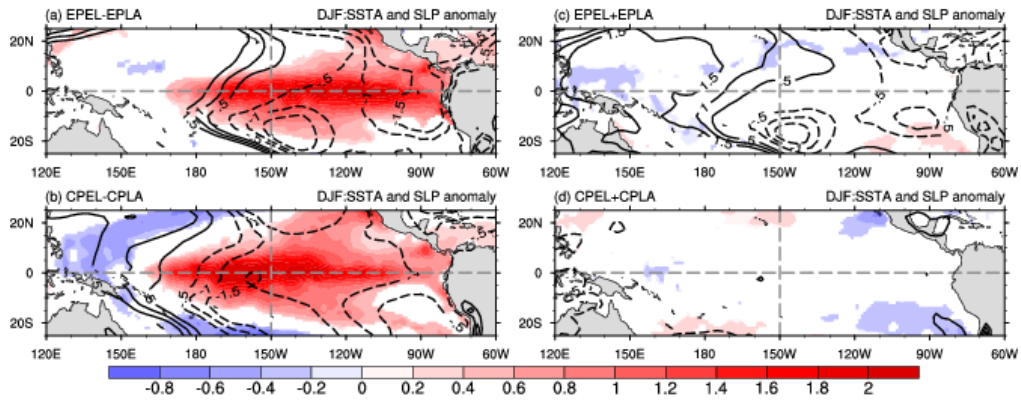
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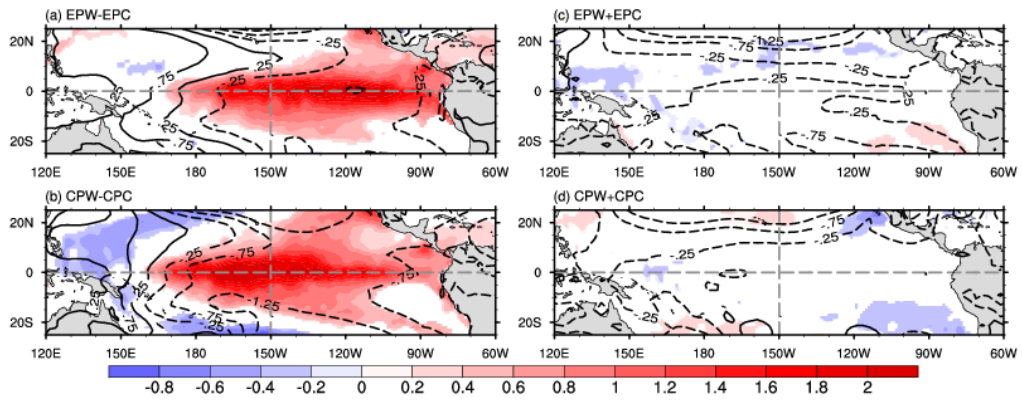
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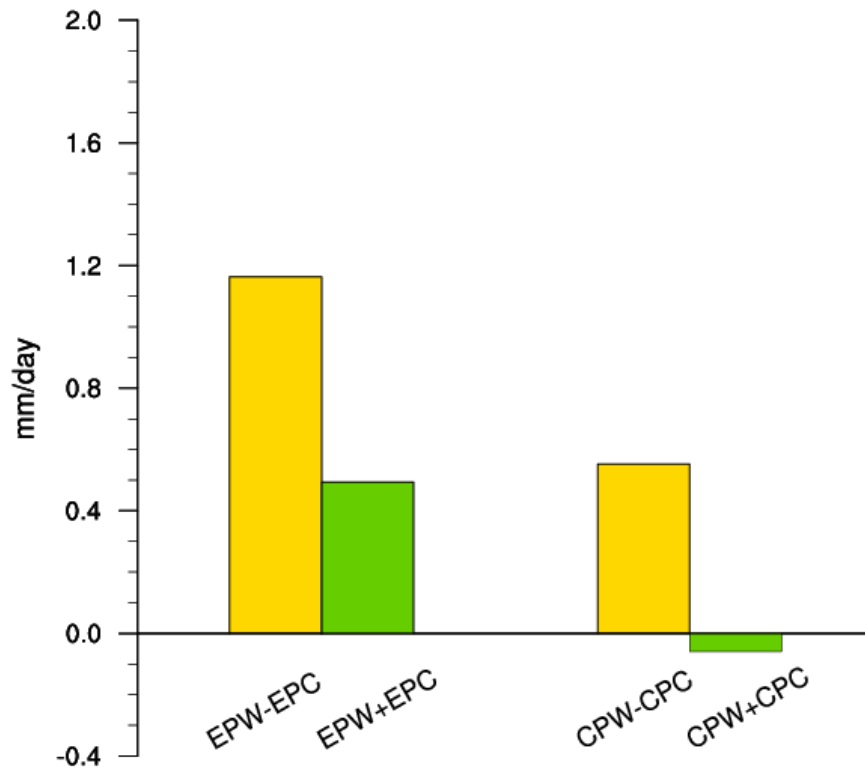
1044 mean from the model experiments.

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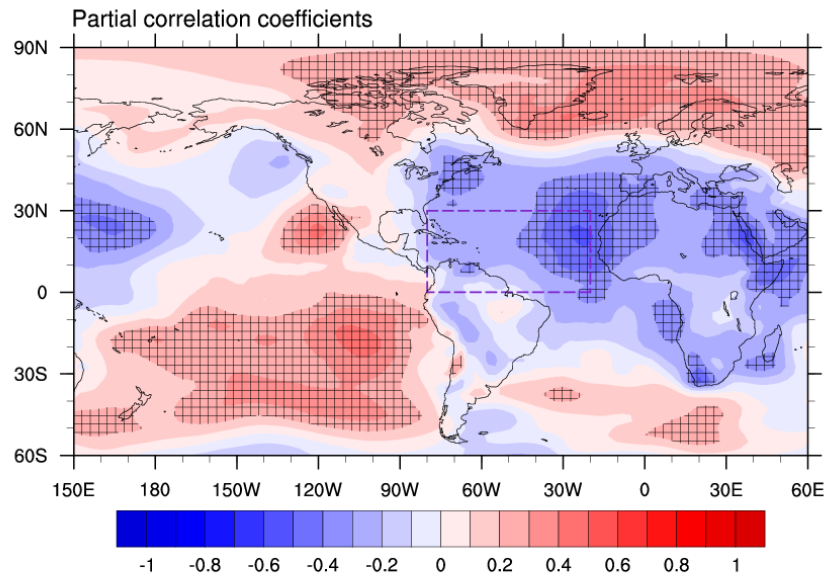
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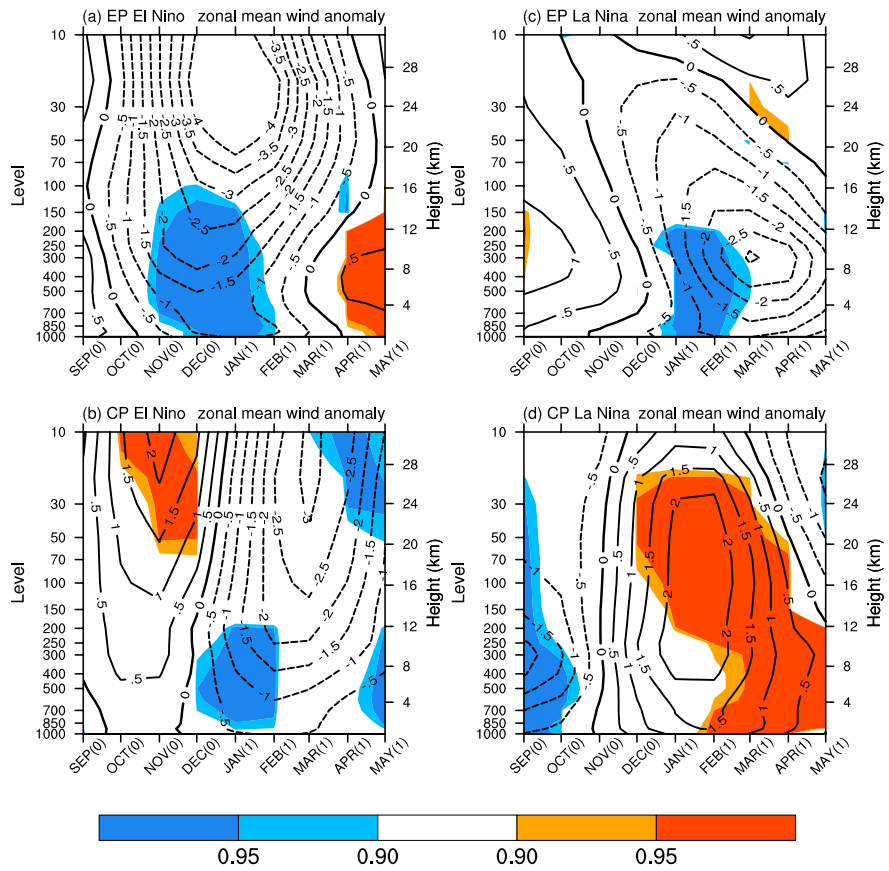
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