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## Extratropical forcing of ENSO

Ghyslaine Boschat<sup>1</sup>, Pascal Terray<sup>2</sup>, Sébastien Masson<sup>3</sup>

*LOCEAN/IPSL, CNRS/IRD/UPMC/MNHN, Paris, France*

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<sup>1</sup> Corresponding author: Ghyslaine Boschat, LOCEAN-IPSL,  
Université Pierre et Marie Curie, BP100 – 4 place Jussieu, 75252 Paris cedex 05, France.  
Tel : +33 1 44 27 23 29  
E-mail : [gbolod@locean-ipsl.upmc.fr](mailto:gbolod@locean-ipsl.upmc.fr)

<sup>2</sup> Pascal TERRAY, LOCEAN-IPSL, UMR 7617 CNRS/IRD/UPMC/MNHN  
Université Pierre et Marie Curie, BP 100 - 4 Place Jussieu 75252 Paris cedex 05 France  
Tel : +33 1 44 27 70 78  
E-mail : [pascal.terray@locean-ipsl.upmc.fr](mailto:pascal.terray@locean-ipsl.upmc.fr)

<sup>3</sup> Sébastien MASSON, LOCEAN-IPSL,  
Université Pierre et Marie Curie, BP100 – 4 place Jussieu, 75252 Paris cedex 05, France.  
Tel : +33 1 44 27 27 48  
E-mail : [sebastien.masson@locean-ipsl.upmc.fr](mailto:sebastien.masson@locean-ipsl.upmc.fr)

21       **1. Abstract**

22       We present evidence that Sea Surface Temperatures (SSTs) in the North Pacific,  
23       South Atlantic and Indian Oceans (AO and IO, respectively) during late boreal winter,  
24       offer another important source of predictability for El Niño Southern Oscillation  
25       (ENSO). This new SST predictor may provide accurate prediction of the *amplitude* of  
26       ENSO events before their onset, for both El Niño and La Niña events which occurred  
27       during recent decades.

28       **2. Introduction**

29       According to many studies, the crucial set of information for ENSO forecasts lies  
30       in the spatial variation of the thermocline depth or heat content (Meinen and  
31       McPhaden, 2000; McPhaden 2003) and the low-frequency wind variability in the  
32       tropical Indo-Pacific region (Clarke and Van Gorder, 2003). An influence from high-  
33       frequency wind variability in the western Pacific region has also been suggested, but  
34       so far the most robust leading relationship has been observed with the Madden Julian  
35       Oscillation activity in late boreal spring or early summer, therefore after the ENSO  
36       onset period (Hendon et al., 2007).

37       Nevertheless, there has been growing evidence in the literature, that other tropical  
38       and extratropical regions may also be playing an important role for ENSO. First, a  
39       number of studies suggested a close link with SST anomalies in the tropical IO or AO,  
40       which may induce modulations of the Walker circulations (Kug et al., 2005;  
41       Dommenget et al., 2006; Rodriguez-Fonseca et al., 2009; Izumo et al., 2010; Frauen  
42       and Dommenget, 2012). Recently, there has also been a rising interest in the  
43       predictability offered by *extratropical* climate modes of variability. Vimont et al.  
44       (2003) and Wang et al. (2012) have implied a connection between the mid-latitude  
45       and tropical Pacific, whereby the winter atmospheric variability in the North Pacific

46 impacts subtropical SST variability and western Pacific equatorial wind anomalies,  
47 which may be responsible for exciting subsequent El Niño events. Several recent  
48 studies also emphasized the role of mid-latitude coupled variability in the South AO  
49 and IO during late boreal winter (Terry and Dominiak, 2005; Terry, 2011).

50 However, several open questions remain regarding the *pertinence* or added value  
51 of these new ‘extratropical’ precursors for the forecast of ENSO, compared to the  
52 conventional Pacific wind or heat content predictors, or the other tropical SST  
53 predictors. In this study, we combine the newly proposed sources of ENSO  
54 predictability in the North Pacific, South AO and IO, and evaluate the potential  
55 efficiency of this new SST predictor in predicting ENSO onset and amplitude across  
56 the “spring predictability barrier” (Webster and Yang, 1992). We present evidence,  
57 through statistical analyses of observations and a coupled ocean-atmosphere model  
58 simulation, that this new SST precursor may offer an important source of  
59 predictability for ENSO.

### 60 **3. Data and Methods**

61 We compare three precursors of ENSO in late boreal winter: the upper-ocean heat  
62 content (Z20 precursor) and low-frequency zonal wind stress variability (USTR  
63 precursor) in the tropical Pacific, and SST variability in the North Pacific, South AO  
64 and IO (new SST precursor). We focus our analysis on the recent period after 1979,  
65 since records of tropical Pacific heat content and SST in the South AO and IO are  
66 either sparse or inexistent before this date.

67 The depth of the 20°C isotherm (Z20) is used as a proxy of the thermocline depth  
68 or heat content in the tropical Pacific Ocean, and is extracted from the Simple Ocean  
69 Data Assimilation (SODA) reanalysis (Carton and Giese, 2008; SODA version 2.2.4),  
70 available until 2008. We examine atmospheric fields from the ERA-Interim reanalysis

71 (Dee et al., 2011) and SST fields from the Hadley Centre Global Sea Ice and Sea  
72 Surface Temperature (HadISST1.1) dataset (Rayner et al., 2003), both available until  
73 2011. For each field, monthly anomalies are calculated by applying the Seasonal-  
74 Trend decomposition procedure based on Loess (Cleveland et al., 1990), which filters  
75 out any long-term trends and annual cycle in the initial data.

76 Our goal is to predict the ENSO peak phase, which is defined by SST anomalies  
77 averaged from October to the following February (ONDJF) over the *entire* equatorial  
78 Pacific. The precursors are taken either from January to March (JFM) or February to  
79 April (FMA), 9 or 10 months prior to this typical ENSO peak phase. Sensitivity  
80 analyses have been performed with the precursors taken successively in JFM, FMA or  
81 from March to May (MAM), and for each case, we have chosen the season which  
82 offers the best skill for the following ENSO.

83 In order to compare the Z20, USTR and new SST precursors, we use the Singular  
84 Value Decomposition (SVD) method (Bretherton et al., 1992), which we apply  
85 separately between each precursor field during its peaking season and the following  
86 tropical Pacific SST field during boreal winter. Results are shown for the 1<sup>st</sup> SVD  
87 mode associated with each precursor in terms of the corresponding Expansion  
88 Coefficient (EC) time series, the ‘homogeneous’ map for the precursor (i.e regression  
89 map between the precursor field and its corresponding EC time series) and  
90 ‘heterogeneous’ map for the predicted ENSO field (i.e regression map between the  
91 tropical Pacific SST and the EC time series of the precursor field, indicating how well  
92 the grid point anomalies of the ENSO field can be predicted from the precursor’s EC  
93 time series). The statistics provided by the SVD are also efficient tools for quantifying  
94 the relevance of each ENSO precursor. The Squared Covariance Fraction (SCF)  
95 measures the relative importance of each SVD mode in reconstructing the covariance

96 matrix between the precursor field and tropical Pacific SSTs. The correlation  
97 coefficient ( $r$ ) between the EC time series of the two fields indicate how strongly  
98 related the coupled patterns are. Finally, we computed how much of Pacific SST  
99 variance each SVD mode explains, and the correlations between the SVD modes and  
100 the Niño3.4 SST time series during the following winter.

101 To test the robustness of our results, we also performed similar SVD analyses on a  
102 110-year control simulation of the SINTEX-F2 global coupled ocean-atmosphere  
103 general (CGCM) model, since it exhibits a realistic ENSO (Masson et al., 2012).

## 104 **4. Analysis and Results**

### 105 ***4.1 Heat content and zonal wind predictors***

106 We here examine the conventional Z20 and USTR predictors and assess their  
107 relationships with the following ENSO event, within our SVD framework (Fig. 1 and  
108 Table 1). During the 1979-2008 period, the 1<sup>st</sup> SVD mode between the Z20 precursor  
109 and ENSO is consistent with the predicting potential of heat content in the context of  
110 ENSO forecasting (McPhaden, 2003). Indeed, the Z20 pattern in Fig. 1 is marked by  
111 positive Z20 anomalies in the west-central tropical Pacific in spring and appears as a  
112 mixture of the two leading Empirical Orthogonal Functions (EOFs) of Pacific Z20  
113 variability (see Meinen and McPhaden, 2000); while the corresponding SST pattern  
114 (Fig. 1b) illustrates a typical El Niño peak phase during the following winter  
115 (consistent with figure 5 in McPhaden, 2003). This SST pattern also suggests that the  
116 performance of the Z20 precursor is degraded in the far eastern equatorial Pacific.

117 The statistics of this 1<sup>st</sup> SVD mode (shown in Table 1) confirm that Z20 anomalies  
118 during late boreal winter are strongly correlated with SST anomalies in the tropical  
119 Pacific ( $r=0.71$ ), and that this 1<sup>st</sup> SVD mode accounts for a significant 77.1% of  
120 tropical Pacific SST variance during the following winter. Consistently, the Z20  
121 expansion coefficients are highly correlated with the Niño3.4 SST time series in

122 December-January (0.76 correlation, see Table 1), and with the C index defined by  
123 Takahashi et al. (2011) to describe the regime of cold and weak-to-moderate ENSO  
124 events (0.77 correlation, see Table 1). Note, however, that its performance is only  
125 modest for the E index of Takahashi et al. (2011), which accounts for the extreme  
126 warm events in the eastern Pacific. In Fig. 1c, the correspondence between the  
127 standardized Z20 EC and Niño3.4 SST time series illustrates how well this Z20  
128 precursor is able to anticipate many El Niño (4/8) and La Niña (5/6) events during  
129 1979-2008. This predictor is particularly successful in predicting the transition from  
130 El Niño to La Niña phases (e.g. in 1983-84, 1987-88-89, 1998-99), but seems less  
131 skillful in capturing the amplitude of some extreme events, such as the 1982-83 El  
132 Niño, and also those occurring since the early 2000s (see Fig. 1c; McPhaden, 2012).

133 The SVD analysis between the USTR precursor over the [110°E-70°W; 10°S-  
134 10°N] domain in FMA and ENSO during the 1979-2011 period illustrates that  
135 westerly wind anomalies in the western Pacific during late boreal winter are  
136 associated with a typical El Niño peak phase during the following winter (Kug et al.,  
137 2005), similar to the SST pattern in Fig. 1b (not shown). Results (in Table 1) suggest  
138 that this precursor is also an efficient predictor for the ordinary cold and moderately  
139 warm ENSO events. Indeed, the corresponding 1<sup>st</sup> SVD mode accounts for a  
140 significant 78.4% of winter SST variance, and the highest correlation is once again  
141 obtained with the Niño3.4 and C indices (0.74 and 0.62 correlation, respectively).

#### 142 ***4.2 New combined extratropical SST predictor***

143 We now examine the predicting potential for ENSO which stems from  
144 extratropical SSTs. Results from the SVD between the new SST predictor and ENSO  
145 during the 1979-2011 period are shown in Fig. 2 and Table 1. The precursor fields  
146 (Fig. 2a) are characterized by anomalous SST dipoles in the North Pacific, South AO  
147 and IO during late boreal winter, consistent with patterns described by Vimont et al

148 (2003), Wang et al (2012) and Terray (2011). These extratropical features are  
149 associated with a typical El Niño peak phase during the following winter (Fig. 2b),  
150 similar although slightly warmer than the SST pattern in Fig. 1b, and with maximum  
151 SST anomalies reaching further east in the Pacific.

152 In terms of statistics, the results are also very promising for ENSO predictability.  
153 Although this 1<sup>st</sup> SVD mode explains one of the least variances during JFM in the  
154 precursor region (13.1%), it manages to describe the largest portion of winter SST  
155 variability in the tropical Pacific (79.6%) and reaches a maximum of 0.80 correlation  
156 with the Niño3.4 SST timeseries in winter (Table 1). This new SST predictor is able  
157 to fit *both* the timing and amplitude of ENSO events, and this not only in the  
158 transition from El Niño to La Niña events, but also when an El Niño develops from a  
159 previous neutral or La Niña state in the tropical Pacific (see Fig. 2c, e.g. in 1982-83,  
160 1995-96). Although its performance seems also degraded since the early 2000s, this  
161 SST predictor is also successful in capturing the amplitude of *extreme* El Niño events  
162 (both in 1982-83 and 1997-98). These results are consistent with the high correlation  
163 value obtained with the E index (0.48 in Table 1). However, the observed correlations  
164 between the different predictors and the Niño3.4 SST timeseries (or the E and C  
165 indices) given in Table 1 are not significantly different from each other according to a  
166 statistical test based on the Fisher's *Z* transformation, due to the shortness of the  
167 observed record (Fisher, 1970, p. 199).

#### 168 ***4.3. Robustness and predictive relationships***

169 In view of the short observational record, we performed similar SVD analyses with  
170 the simulated fields from the SINTEX-F2 CGCM (Table 1; Figs. 2d-f). Overall,  
171 results are quite consistent with observations, as this model exhibits a realistic  
172 simulation of the relationships of ENSO with both the Z20 and USTR precursors, and  
173 the new SST precursor. In Fig. 2d, the precursor SST pattern displays similar dipole

174 structures as in Fig. 2a (although the simulated SST signal is weaker in the South AO  
175 and shifted westwards in the North Pacific), and is also associated with an El Niño  
176 peak phase during the following winter, with warm SST anomalies mostly confined to  
177 the equatorial central Pacific compared to observations (Fig. 2e). The statistics for the  
178 CGCM also show higher correlation values for the new combined SST precursor  
179 compared to the Z20 and USTR predictors, although they miss the observed  
180 relationship between extratropical SSTs and the E index (see Table 1). Moreover, the  
181 correlation of the Niño3.4 SST timeseries with the SST precursor is now significantly  
182 higher from those derived from the Z20 and USTR precursors at a significance level  
183 of 0.05, thanks to the length of the simulation (Fisher, 1970).

184 By definition, the high values of the statistics in Table 1 may also partly result  
185 from the optimization problem solved by the SVD. In order to assess reliably the  
186 predictive potential of the new SST precursor, we also performed a cross-validation  
187 experiment of our SVD models. In this experiment, we treated the three precursors in  
188 the same objective manner, and re-computed each SVD analysis based successively  
189 on all years within the 1979-2008 time span, except one ‘forecast’ year. We then  
190 estimated the values of each precursor’s EC time series, by projecting the precursor  
191 field observed before the ‘forecast’ year onto the 1<sup>st</sup> SVD mode computed without  
192 this year in the cross-validation procedure. The correlation between the cross-  
193 validated SVD modes and Niño3.4 SST shows once again a high correlation for the  
194 SST precursor (0.75) compared to the Z20 and USTR precursors (0.67 and 0.65  
195 correlation respectively), although these bootstrapped correlations are again not  
196 significantly different at a significance level of 0.05 due to the shortness of the  
197 observed record. Similar results are obtained for the E index, while all the precursors  
198 have about the same skill for the C index.

199 In order to provide another test of the usefulness of extratropical SSTs for the  
200 prediction of ENSO, Fig A (in auxiliary material) presents the 1<sup>st</sup> and 2<sup>nd</sup> EOF modes  
201 from the same domain used in the SVD, in both observations and the CGCM. Since  
202 results are globally similar in observations and the model (see Fig. A), we will restrict  
203 our discussion to observations. Overall, these two EOFs provide some additional  
204 insight into the *nature* of the predictability offered by these extratropical SST regions  
205 during the 1979-2011 period. Indeed, although both EOF modes seem useful for  
206 ENSO prediction (0.27 and 0.59 correlation with Niño3.4 SST during the next winter,  
207 see Table A), the predictability offered by the 1<sup>st</sup> EOF mode is mostly linked to the  
208 biennial component of ENSO itself (-0.85 and 0.60 correlations with the concurrent  
209 Niño3.4 SST and Z20 EC time series, respectively), whereas the 2<sup>nd</sup> EOF mode  
210 captures a more *intrinsic* extratropical source of predictability, which is independent  
211 from the previous ENSO state (0.03 correlation with the concurrent Niño3.4 SST) and  
212 moderately linked to the Z20 EC time series (0.5 correlation). Surprisingly, this 2<sup>nd</sup>  
213 EOF has a higher correlation with the winter Niño3.4 SST time series than the 1<sup>st</sup>  
214 EOF, and is also a significant precursor of the E and C indices, as the 1<sup>st</sup> SVD mode  
215 (Table A). Interestingly, the spatial correlations between these first two EOF modes  
216 (Fig. Aa and b) and the 1<sup>st</sup> SST SVD mode (in Fig. 2a) are 0.35 and 0.80,  
217 respectively. Consistently, the 1<sup>st</sup> SVD mode is more correlated with the 2<sup>nd</sup> EOF time  
218 series (0.82) than with the 1<sup>st</sup> EOF (0.46). Thus, the source of ENSO predictability  
219 offered by the 1<sup>st</sup> SVD mode “combines” both the effects of the ENSO cycle itself  
220 and the extratropics, but seems to mainly stem from extratropical variability.

221 Finally, we developed various regression models for forecasting winter Niño3.4  
222 SST anomalies, using the USTR, Z20 and SST predictors and tested the accuracy of  
223 these models with a cross-validation procedure (Clarke and Van Gorder, 2003). In

224 these cross-validation experiments, we selected the EOF modes for each precutory  
225 field which offered the best prediction for the following ENSO: the 1<sup>st</sup> and 2<sup>nd</sup> EOF  
226 modes for extratropical SSTs (Fig. Aa-b), the 1<sup>st</sup> EOF mode for tropical Pacific wind  
227 anomalies and 2<sup>nd</sup> EOF mode for Z20 anomalies (same mode as shown in Meinen and  
228 McPhaden, 2000). To assess the forecast potential of each model, we then compared  
229 the observed Niño3.4 SST with the values calculated from regression equations based  
230 successively on all years within the common 1979-2008 time span, except the forecast  
231 year. The correlation coefficient between the observed and forecast Niño3.4 SST and  
232 the Root-Mean-Square-Error (RMSE) for each model are shown in Table 2, and  
233 overall support the proposition that extratropical SSTs are a useful parameter in  
234 ENSO forecasts. Indeed, the regression model with the SST predictor as sole input  
235 achieves a higher correlation score and lower RMSE than the model which uses both  
236 USTR and Z20 predictors (0.64 compared to 0.61 correlation, 0.75 compared to 0.78  
237 RMSE). When combining these 3 predictors, the performance of the multiple  
238 regression model is improved (with 0.71 correlation and 0.69 RMSE). Finally, when  
239 removing the USTR, the performance of the model is not degraded (see Table 2). This  
240 regression exercise thus illustrates how the inclusion of extratropical SSTs may  
241 improve the statistical models currently used to predict ENSO.

### 242 *3.4 Atmospheric variability associated with the new SST predictor*

243 In order to explore the predicting paths of the SST predictor, we have regressed the  
244 SST and atmospheric anomalies from the previous summer to the following boreal  
245 winter onto the first two leading EOFs of extratropical SSTs in observations. As  
246 expected, the regression of SST, SLP and 850 hPa wind anomalies onto the 1<sup>st</sup> EOF  
247 mode depicts the rapid transition from La Niña to El Niño (or El Niño to La Niña  
248 since the analysis is linear) and the related changes in teleconnection patterns

249 elsewhere (see Fig. B in auxiliary material). Note, however, that the ENSO signal  
250 predicted by this mode is of limited amplitude and only marginally significant.

251 Fig. 3 displays the maps of SST, SLP and 850 hPa wind anomalies regressed onto  
252 the 2<sup>nd</sup> EOF of JFM extratropical SSTs. During the previous JAS season, no coherent  
253 SST or SLP patterns are found in the tropics, nor in the extratropics, except in the  
254 South Pacific (Fig. 3a and g). From boreal fall to winter, a significant anomalous SLP  
255 dipole emerges in the central North Pacific (Fig. 3b) consistent with the “Seasonal  
256 Footprinting Mechanism” of Vimont et al. (2003), followed one season later by large  
257 anticyclonic anomalies over the South AO and IO, which reflect the occurrence of  
258 blocking events during late boreal winter or early boreal spring in the Southern  
259 Hemisphere (Fig. 3c). These atmospheric phenomena lead to the emergence of a  
260 boomerang warm SST structure (Fig. 3i-j) in the North Pacific (Vimont et al. 2003)  
261 and to subtropical SST dipoles in the South AO and IO (Hermes and Reason, 2005).  
262 Figs. 3c and i also suggest that the extratropical cold SST anomalies over the eastern  
263 IO and western North Pacific promote persistent westerly wind anomalies over the  
264 western equatorial Pacific from boreal winter to spring (Xu and Chan, 2001; Wang et  
265 al., 2012). This westerly equatorial wind signal is a possible trigger of El Niño onset,  
266 as it can induce eastward-propagating downwelling Kelvin waves along the  
267 thermocline, leading to an El Niño warming several months later.

268 However, there are also suggestions of additional predicting paths, not restricted to  
269 surface wind variability over the western equatorial Pacific. Indeed, from the  
270 JFM/AMJ season (Fig. 3c), a significant pattern emerges over the South Pacific,  
271 characterized by a weakening of the southeast trade winds and the development of an  
272 expanded trough. This slowdown of the Walker circulation induced by South Pacific  
273 atmospheric variability may be involved in El Niño onset (Van Loon, 1984; Clement

274 et al., 2011). South AO and IO anomalies could also be involved in this by remotely  
275 impacting the southwest Pacific through a modulation of the regional Hadley cell in  
276 boreal spring (Terray and Dominiak, 2005; Terray, 2011). By exciting Rossby waves,  
277 these modulations can induce a displacement of the westerly jet stream and low-level  
278 circulation in the South Pacific (Trenberth et al., 1998) and lead to the development of  
279 the southern branch of the traditional ‘horseshoe’ El Niño pattern (Fig. 3k-l).

## 280 **5. Conclusions and future work**

281 In this work, we demonstrate that, in addition to well-recognized precursors of El  
282 Niño onsets, extratropical SSTs in the North Pacific, South AO and IO during late  
283 boreal winter may provide some important information for the forecast of ENSO  
284 events. This new ‘combined’ SST precursor is most significantly correlated with the  
285 Niño3.4 SST time series during the post-1979 period, and offers some potential *added*  
286 *value* in the prediction of the *amplitude* of these ENSO events. We have further tested  
287 the performance of these predictors through various cross-validation experiments and  
288 shown that these promising predictive relationships are also quite well reproduced in a  
289 comprehensive CGCM.

290 Our regression analyses confirm that extratropical SST variability may be impacting  
291 ENSO through a modulation of wind variability in the western equatorial Pacific  
292 during boreal spring (Vimont et al., 2003; Terray, 2011; Wang et al., 2012), but not  
293 only. Our results also suggest that the extratropical atmospheric variability may play a  
294 significant role in ENSO development by modulating the southeast trades in the South  
295 Pacific during boreal spring, particularly for the extraordinary warm events, consistent  
296 with several recent studies (Chang et al., 2007; Clement et al., 2011).

297 Given the suspected importance of this extratropical forcing on ENSO, it now seems  
298 essential to gain a better understanding of the physical processes operating between

299 extratropical and tropical latitudes before the onset of ENSO events, as well as the  
300 relative contribution of each hemisphere in this prediction. Do each of these  
301 extratropical sectors play independently? Or does this important source of  
302 predictability for ENSO result from an interaction between the different basins?  
303 Another important question raised by this work is whether the observed relationship  
304 between extreme warm events and extratropical SSTs during recent decades is a  
305 future characteristic of a global warming climate.

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373 **Table 1:** Statistics associated with the 1<sup>st</sup> SVD modes between Z20, USTR or the new  
374 ‘combined’ SST precursor during late boreal winter and ENSO SST anomalies in the  
375 tropical Pacific during the following winter. The last 3 columns give the correlation  
376 between each SVD mode and various ENSO indices during the next December-  
377 January season: the Niño3.4 SST index, the C and E indices used in Takahashi et al.  
378 (2011). Results are given for observations (in red) and for the model (in blue). The  
379 correlation coefficients exceeding the 10%, 5% and 1% confidence levels according  
380 to the phase-scrambling bootstrap test of Ebisuzaki (1997) are followed by one  
381 asterisk (\*), two asterisks (\*\*), and three asterisks (\*\*\*), respectively.

<i>SVD results</i> <i>Precursor</i>	SCF (%)		r		Precursor var (%)		ENSO var (%)		Cor Niño3.4		Cor C index		Cor E index	
Z20	84.5	87	0.71	0.56	12.9	24.3	77.1	63.3	0.76***	0.55***	0.77***	0.52***	0.35	0.22**
Ustr	89.3	84.9	0.64	0.53	21.1	21.5	78.4	67.1	0.74***	0.54***	0.62***	0.54***	0.32	0.21*
‘combined’ SST	90.8	83.1	0.78	0.71	13.1	8.1	79.6	69	0.80***	0.71***	0.67***	0.70***	0.48**	0.11

\* P<0.1, \*\*P<0.05, \*\*\*P<0.01

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394 **Table 2:** Forecast skill of simple linear regression models using two (A and B), three  
 395 (D) or four (C) predictors in JFM as inputs for the prediction of the Niño3.4 time  
 396 series during the following December-January. As input for each model, we select the  
 397 EOF modes associated with the Z20, USTR and SST precursors, which offer the best  
 398 prediction for the following ENSO. The forecast skill of each model is assessed by the  
 399 cross-validated correlation and root-mean-square-error (RMSE) calculated between  
 400 the observed and forecast Niño3.4 time series, without involving the forecast year.  
 401

<b>Regression models</b>	<i>Selected EOF mode</i>	<i>Correlation</i>	<i>RMSE</i>
<b>A)</b> with SST predictors	SST (eof m1) + SST (eof m2)	0.64	0.75
<b>B)</b> with Z20 and USTR predictors	Z20 (eof m2) + USTR (eof m1)	0.61	0.78
<b>C)</b> with SST, Z20 and USTR predictors	SST (eof m1) + SST (eof m2) + Z20 (eof m2) + USTR (eof m1)	0.71	0.69
<b>D)</b> with SST and Z20 predictors	SST (eof m1) + SST (eof m2) + Z20 (eof m2)	0.72	0.68

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## Extratropical forcing of ENSO

Ghyslaine Boschat<sup>1</sup>, Pascal Terray<sup>2</sup>, Sébastien Masson<sup>3</sup>

*LOCEAN/IPSL, CNRS/IRD/UPMC/MNHN, Paris, France*

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<sup>1</sup> Corresponding author: Ghyslaine Boschat, LOCEAN-IPSL,  
Université Pierre et Marie Curie, BP100 – 4 place Jussieu, 75252 Paris cedex 05, France.  
Tel : +33 1 44 27 23 29  
E-mail : [gbolod@locean-ipsl.upmc.fr](mailto:gbolod@locean-ipsl.upmc.fr)

<sup>2</sup> Pascal TERRAY, LOCEAN-IPSL, UMR 7617 CNRS/IRD/UPMC/MNHN  
Université Pierre et Marie Curie, BP 100 - 4 Place Jussieu 75252 Paris cedex 05 France  
Tel : +33 1 44 27 70 78  
E-mail : [pascal.terray@locean-ipsl.upmc.fr](mailto:pascal.terray@locean-ipsl.upmc.fr)

<sup>3</sup> Sébastien MASSON, LOCEAN-IPSL,  
Université Pierre et Marie Curie, BP100 – 4 place Jussieu, 75252 Paris cedex 05, France.  
Tel : +33 1 44 27 27 48  
E-mail : [sebastien.masson@locean-ipsl.upmc.fr](mailto:sebastien.masson@locean-ipsl.upmc.fr)

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## 22 1. Abstract

23 | ~~\_\_\_~~We present evidence that Sea Surface Temperatures (SSTs) in the North Pacific,  
24 South Atlantic and Indian Oceans (AO and IO, respectively) during late boreal winter,  
25 offer another important source of predictability for El Niño Southern Oscillation  
26 (ENSO). This new SST predictor may provide accurate prediction of the *amplitude* of  
27 ENSO events before their onset, for both El Niño and La Niña events, ~~and especially~~  
28 ~~for the extreme warm events~~, which occurred during recent decades.

## 29 2. Introduction

30 According to many studies, the crucial set of information for ENSO forecasts lies  
31 in the spatial variation of the thermocline depth or heat content (Meinen and  
32 McPhaden, 2000; McPhaden 2003) and the low-frequency wind variability in the  
33 tropical Indo-Pacific region (Clarke and Van Gorder, 2003). An influence from high-  
34 frequency wind variability in the western Pacific region has also been suggested, but  
35 so far the most robust leading relationship has been observed with the Madden Julian  
36 Oscillation activity in late boreal spring or early summer, therefore after the ENSO  
37 onset period (Hendon et al., 2007).

38 | Nevertheless, there has been growing evidence in the literature, that other tropical  
39 and extratropical regions may also be playing an important role for ENSO. First, a  
40 number of studies suggested a close link with SST anomalies in the tropical IO or AO,  
41 which may induce modulations of the Walker circulations (Kug et al., 2005;  
42 Dommenges et al., 2006; ~~Jansen et al., 2009~~; Rodriguez-Fonseca et al., 2009; Izumo et  
43 al., 2010; Frauen and Dommenges, 2012). Recently, there has also been a rising  
44 interest in the predictability offered by *extratropical* climate modes of variability.  
45 Vimont et al. (2003) and Wang et al. (2012) have implied a connection between the

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46 mid-latitude and tropical Pacific, whereby the winter atmospheric variability in the  
47 North Pacific impacts subtropical SST variability and western Pacific equatorial wind  
48 anomalies, which may be responsible for exciting subsequent El Niño events. Several  
49 recent studies also emphasized the role of mid-latitude coupled variability in the  
50 South AO and IO during late boreal winter (Terray and Dominiak, 2005; Terray,  
51 2011).

52 However, several open questions remain regarding the *pertinence* or added value  
53 of these new ‘extratropical’ precursors for the forecast of ENSO, compared to the  
54 conventional Pacific wind or heat content predictors, or the other tropical SST  
55 predictors. In this study, we combine the newly proposed sources of ENSO  
56 predictability in the North Pacific, South AO and IO, and evaluate the potential  
57 efficiency of this new SST predictor in predicting ENSO onset and amplitude across  
58 the “spring predictability barrier” (Webster and Yang, 1992). We present evidence,  
59 through statistical analyses of observations and a coupled ocean-atmosphere model  
60 simulation, that this new SST precursor may offer an important source of  
61 predictability for ENSO, ~~by adding pertinent information regarding the amplitude of~~  
62 ~~events, especially for the extreme warm events (Takahashi et al., 2011).~~

### 63 3. Data and Methods

64 We compare three precursors of ENSO in late boreal winter: the upper-ocean heat  
65 content (Z20 precursor) and low-frequency zonal wind stress variability (USTR  
66 precursor) in the tropical Pacific, and SST variability in the North Pacific, South AO  
67 and IO (new SST precursor). We focus our analysis on the recent period after 1979,  
68 since records of tropical Pacific heat content and SST in the South AO and IO are  
69 either sparse or inexistent before this date.

70 The depth of the 20°C isotherm (Z20) is used as a proxy of the thermocline depth  
71 or heat content in the tropical Pacific Ocean, and is extracted from the Simple Ocean  
72 Data Assimilation (SODA) reanalysis (Carton and Giese, 2008; SODA version 2.2.4),  
73 available until 2008. We examine atmospheric fields (~~zonal wind stress (USTR), sea~~  
74 ~~level pressure (SLP), and 850hPa winds~~) from the ERA-Interim reanalysis (Dee et al.,  
75 2011) and SST fields from the Hadley Centre Global Sea Ice and Sea Surface  
76 Temperature (HadISST1.1) dataset (Rayner et al., 2003), both available until 2011.  
77 For each field, monthly anomalies are calculated by applying the Seasonal-Trend  
78 decomposition procedure based on Loess (Cleveland et al., 1990), which filters out  
79 any long-term trends and annual cycle in the initial data.

80 Our goal is to predict the ENSO peak phase, which is defined by SST anomalies  
81 averaged from October to the following February (ONDJF) over the *entire* equatorial  
82 Pacific. The precursors are taken either from January to March (JFM) or February to  
83 April (FMA), 9 or 10 months prior to this typical ENSO peak phase. Sensitivity  
84 analyses have been performed with the precursors taken successively in JFM, FMA or  
85 from March to May (MAM), and for each case, we have chosen the season which  
86 offers the best skill for the following ENSO.

87 In order to compare the Z20, USTR and new SST precursors, we use the Singular  
88 Value Decomposition (SVD) method (Bretherton et al., 1992), which we apply  
89 separately between each precursor field during its peaking season and the following  
90 tropical Pacific SST field during boreal winter. Results are shown for the 1<sup>st</sup> SVD  
91 mode associated with each precursor in terms of the corresponding Expansion  
92 Coefficient (EC) time series, the ‘homogeneous’ map for the precursor (i.e regression  
93 map between the precursor field and its corresponding EC time series) and  
94 ‘heterogeneous’ map for the predicted ENSO field (i.e regression map between the

95 tropical Pacific SST and the EC time series of the precursor field, indicating how well  
96 the grid point anomalies of the ENSO field can be predicted from the precursor's EC  
97 time series). The statistics provided by the SVD are also efficient tools for quantifying  
98 the relevance of each ENSO precursor. The Squared Covariance Fraction (SCF)  
99 measures the relative importance of each SVD mode in reconstructing the covariance  
100 matrix between the precursor field and tropical Pacific SSTs. The correlation  
101 coefficient ( $r$ ) between the EC time series of the two fields indicate how strongly  
102 related the coupled patterns are. Finally, we computed how much of Pacific SST  
103 variance each SVD mode explains, and the correlations between the SVD modes and  
104 the Niño3.4 SST time series during the following winter.

105 To test the robustness of our results, we also performed similar SVD analyses on a  
106 110-year control simulation of the SINTEX-F2 global coupled ocean-atmosphere  
107 general (CGCM) model, since it exhibits a realistic ENSO (Masson et al., 2012).

#### 108 **4. Analysis and Results**

##### 109 ***4.1 Heat content and zonal wind predictors***

110 We here examine the conventional Z20 and USTR predictors and assess their  
111 relationships with the following ENSO event, within our SVD framework (Fig. 1 and  
112 Table 1). During the 1979-2008 period, the 1<sup>st</sup> SVD mode between the Z20 precursor  
113 and ENSO is consistent with the predicting potential of heat content in the context of  
114 ENSO forecasting (McPhaden, 2003). Indeed, the Z20 pattern in Fig. 1 is marked by  
115 positive Z20 anomalies in the west-central tropical Pacific in spring and appears as a  
116 mixture of the two leading Empirical Orthogonal Functions (EOFs) of Pacific Z20  
117 variability (see Meinen and McPhaden, 2000); while the corresponding SST pattern  
118 (Fig. 1b) illustrates a typical El Niño peak phase during the following winter  
119 (consistent with figure 5 in McPhaden, 2003). This SST pattern also suggests that the  
120 performance of the Z20 precursor is degraded in the far eastern equatorial Pacific.

121 The statistics of this 1<sup>st</sup> SVD mode (shown in Table 1) confirm that Z20 anomalies  
122 during late boreal winter are strongly correlated with SST anomalies in the tropical  
123 Pacific ( $r=0.71$ ), and that this 1<sup>st</sup> SVD mode accounts for a significant 77.1% of  
124 tropical Pacific SST variance during the following winter. Consistently, the Z20  
125 expansion coefficients are highly correlated with the Niño3.4 SST time series in  
126 December-January (0.76 correlation, see Table 1), and with the C index defined by  
127 Takahashi et al. (2011) to describe the regime of cold and weak-to-moderate ENSO  
128 events (0.77 correlation, see Table 1). Note, however, that its performance is only  
129 modest for the E index of Takahashi et al. (2011), which accounts for the extreme  
130 warm events in the eastern Pacific (~~e.g. the 1982-83 El Niño event~~). In Fig. 1c, the  
131 correspondence between the standardized Z20 EC and Niño3.4 SST time series  
132 illustrates how well this Z20 precursor is able to anticipate many El Niño (4-out-of-8)  
133 and La Niña (5-out-of-6) events during 1979-2008. This predictor is particularly  
134 successful in predicting the transition from El Niño to La Niña phases (e.g. in 1983-  
135 84, 1987-88-89, 1998-99), but seems less skillful in capturing the amplitude of some  
136 extreme events, such as the 1982-83 El Niño, and also those occurring since the early  
137 2000s (see Fig. 1c ~~and~~ McPhaden, 2012).

138 The SVD analysis between the USTR precursor over the [110°E-70°W; 10°S-  
139 10°N] domain in FMA and ENSO during the 1979-2011 period illustrates that  
140 westerly wind anomalies in the western Pacific during late boreal winter are  
141 associated with a typical El Niño peak phase during the following winter (Kug et al.,  
142 2005), similar to the SST pattern in Fig. 1b (not shown). Results (in Table 1) suggest  
143 that this precursor is also an efficient predictor for the ordinary cold and moderately  
144 warm ENSO events. Indeed, the corresponding 1<sup>st</sup> SVD mode accounts for a

145 significant 78.4% of winter SST variance, and the highest correlation is once again  
146 obtained with the Niño3.4 and C indices (0.74 and 0.62 correlation, respectively).

#### 147 ***4.2 New combined extratropical SST predictor***

148 We now examine the predicting potential for ENSO which stems from  
149 extratropical SSTs. Results from the SVD between the new SST predictor and ENSO  
150 during the 1979-2011 period are shown in Fig. 2 and Table 1. The precursor fields  
151 (Fig. 2a) are characterized by anomalous SST dipoles in the North Pacific, South AO  
152 and IO during late boreal winter, consistent with patterns described by Vimont et al  
153 (2003), Wang et al (2012) and Terray (2011). These extratropical features are  
154 associated with a typical El Niño peak phase during the following winter (Fig. 2b),  
155 similar although slightly warmer than the SST pattern in Fig. 1b, and with maximum  
156 SST anomalies reaching further east in the Pacific.

157 In terms of statistics, the results are also very promising for ENSO predictability.  
158 Although this 1<sup>st</sup> SVD mode explains one of the least variances during JFM in the  
159 precursor region (13.1%), it manages to describe the largest portion of winter SST  
160 variability in the tropical Pacific (79.6%) and reaches a maximum of 0.80 correlation  
161 with the Niño3.4 SST timeseries in winter (Table 1). ~~Compared to the Z20 predictor,~~  
162 ~~this~~This new SST predictor is able to fit *both* the timing and amplitude of ENSO  
163 events, and this not only in the transition from El Niño to La Niña events, but also  
164 when an El Niño develops from a previous neutral or La Niña state in the tropical  
165 Pacific (see Fig. 2c, e.g. in 1982-83, 1995-96). Although its performance seems also  
166 degraded since the early 2000s, this SST predictor is particularly also successful in  
167 capturing the amplitude of *extreme* El Niño events (both in 1982-83 and 1997-98).  
168 These results are consistent with the ~~higher and significant~~ correlation value obtained  
169 with the E index (0.48 in Table 1), ~~and thus reflect the potential added value of~~  
170 ~~extratropical SSTs for the predictability of extreme warm ENSO regimes (Takahashi~~

171 et al., 2014). However, the observed correlations between the different predictors  
172 and the Niño3.4 SST timeseries (or the E and C indices) given in Table 1 are not  
173 significantly different from each other according to a statistical test based on the  
174 Fisher's Z transformation, due to the shortness of the observed record (Fisher, 1970,  
175 p. 199).

#### 176 ***4.3. Robustness and predictive relationships***

177 In view of the short observational record, we performed similar SVD analyses with  
178 the simulated fields from the SINTEX-F2 CGCM (Table 1; Figs. 2d-f). Overall,  
179 results are quite consistent with observations, as this model exhibits a realistic  
180 simulation of the relationships of ENSO with both the Z20 and USTR precursors, and  
181 the new SST precursor. In Fig. 2d, the precursor SST pattern displays similar dipole  
182 structures as in Fig. 2a (although the simulated SST signal is weaker in the South AO  
183 and shifted westwards in the North Pacific), and is also associated with an El Niño  
184 peak phase during the following winter, with warm SST anomalies mostly confined to  
185 the equatorial central Pacific compared to observations (Fig. 2e). The statistics for the  
186 CGCM also show higher correlation values for the new combined SST precursor  
187 compared to the Z20 and USTR predictors, although they miss the observed  
188 relationship between extratropical SSTs and the E index (see Table 1). Moreover, the  
189 correlation of the Niño3.4 SST timeseries with the SST precursor is now significantly  
190 higher from those derived from the Z20 and USTR precursors at a significance level  
191 of 0.05, thanks to the length of the simulation (Fisher, 1970).

192 By definition, the high values of the statistics in Table 1 may also partly result  
193 from the optimization problem solved by the SVD. In order to assess reliably the  
194 predictive potential of the new SST precursor, we also performed a cross-validation  
195 experiment of our SVD models. In this experiment, we treated the three precursors in  
196 the same objective manner, and re-computed each SVD analysis based successively

197 on all years within the 1979-2008 time span, except one ‘forecast’ year. We then  
198 estimated the values of each precursor’s EC time series, by projecting the precursor  
199 field observed before the ‘forecast’ year onto the 1<sup>st</sup> SVD mode computed without  
200 this year in the cross-validation procedure. The correlation between the cross-  
201 validated SVD modes and Niño3.4 SST shows once again a ~~higher-high~~ correlation  
202 for the SST precursor (0.75) compared to the Z20 and USTR precursors (0.67 and  
203 0.65 correlation respectively), ~~although these bootstrapped correlations are again not~~  
204 ~~significantly different at a significance level of 0.05 due to the shortness of the~~  
205 ~~observed record.~~ Similar results are obtained for the E index ~~(with a higher 0.42~~  
206 ~~correlation for the SST precursor, compared to 0.26 and 0.32 correlation for the Z20~~  
207 ~~and USTR precursors, respectively),~~ while all the precursors have about the same skill  
208 for the C index ~~(correlation between 0.65 and 0.67 for each precursor).~~

209 In order to provide another test of the usefulness of extratropical SSTs for the  
210 prediction of ENSO, Fig A (in auxiliary material) presents the 1<sup>st</sup> and 2<sup>nd</sup> EOF modes  
211 from the same domain used in the SVD, in both observations and the CGCM. Since  
212 ~~the results of this EOF analysis~~ are globally similar in observations and the model (see  
213 Fig. A), we will restrict our discussion to observations. Overall, these two EOFs  
214 provide some additional insight into the *nature* of the predictability offered by these  
215 extratropical SST regions during the 1979-2011 period. Indeed, although both EOF  
216 modes seem useful for ENSO prediction (0.27 and 0.59 correlation with ~~the~~ Niño3.4  
217 SST ~~index~~ during the next winter, see Table A), the predictability offered by the 1<sup>st</sup>  
218 EOF mode is mostly linked to the biennial component of ENSO itself (-0.85 and 0.60  
219 correlations with the concurrent Niño3.4 SST and Z20 EC time series, respectively),  
220 whereas the 2<sup>nd</sup> EOF mode captures a more *intrinsic* extratropical source of  
221 predictability, which is independent from the previous ENSO state (0.03 correlation

222 with the concurrent Niño3.4 SST) and moderately linked to the Z20 EC time series  
223 (0.5 correlation). Surprisingly, this 2<sup>nd</sup> EOF has a higher correlation with the winter  
224 Niño3.4 SST time series -than the 1<sup>st</sup> EOF, and is also a significant precursor of the E  
225 and C indices, as the 1<sup>st</sup> SVD mode (Table A). Interestingly, the spatial correlations  
226 between these first two EOF modes (Fig. Aa and b) and the 1<sup>st</sup> SST SVD mode (in  
227 Fig. 2a) are 0.35 and 0.80, respectively. Consistently, the 1<sup>st</sup> SVD mode is more  
228 correlated with the 2<sup>nd</sup> EOF time series (0.82) than with the 1<sup>st</sup> EOF (0.46). Thus, the  
229 source of ENSO predictability offered by the 1<sup>st</sup> SVD mode “combines” both the  
230 effects of the ENSO cycle itself and the extratropics, but seems to mainly stem from  
231 extratropical variability.

232 Finally, we developed various regression models for forecasting winter Niño3.4  
233 SST anomalies, using the USTR, Z20 and SST predictors and tested the accuracy of  
234 these models with a cross-validation procedure (Clarke and Van Gorder, 2003). In  
235 these cross-validation experiments, we selected the EOF modes for each precutory  
236 field which offered the best prediction for the following ENSO: the 1<sup>st</sup> and 2<sup>nd</sup> EOF  
237 modes for extratropical SSTs (Fig. Aa-b), the 1<sup>st</sup> EOF mode for tropical Pacific wind  
238 anomalies and 2<sup>nd</sup> EOF mode for Z20 anomalies (same mode as shown in Meinen and  
239 McPhaden, 2000). To assess the forecast potential of each model, we then compared  
240 the observed Niño3.4 SST with the values calculated from regression equations based  
241 successively on all years within the common 1979-2008 time span, except the forecast  
242 year. The correlation coefficient between the observed and forecast Niño3.4 SST and  
243 the Root-Mean-Square-Error (RMSE) for each model are shown in Table 2, and  
244 overall support the proposition that extratropical SSTs ~~may be a crucial~~ are a useful  
245 parameter in ENSO forecasts. Indeed, the regression model with the SST predictor as  
246 sole input achieves a higher correlation score and lower RMSE than the model which

247 uses both USTR and Z20 predictors (0.64 compared to 0.61 correlation, 0.75  
248 compared to 0.78 RMSE). When combining these 3 predictors, the performance of the  
249 multiple regression model is ~~significantly~~ improved (with 0.71 correlation and 0.69  
250 RMSE). Finally, when removing the USTR, the performance of the model is not  
251 degraded (see Table 2). This regression exercise thus illustrates how the inclusion of  
252 extratropical SSTs may improve the statistical models currently used to predict  
253 ENSO.

#### 254 ***3.4 Atmospheric variability associated with the new SST predictor***

255 In order to explore the predicting paths of the SST predictor, we have regressed the  
256 SST and atmospheric anomalies from the previous summer to the following boreal  
257 winter onto the first two leading EOFs of extratropical SSTs in observations. As  
258 expected, the regression of SST, SLP and 850 hPa wind anomalies onto the 1<sup>st</sup> EOF  
259 mode depicts the rapid transition from La Niña to El Niño (or El Niño to La Niña  
260 since the analysis is linear) and the related changes in teleconnection patterns  
261 elsewhere (see Fig. B in auxiliary material). Note, however, that the ENSO signal  
262 predicted by this mode is of limited amplitude and only marginally significant.

263 Fig. 3 displays the maps of SST, SLP and 850 hPa wind anomalies regressed onto  
264 the 2<sup>nd</sup> EOF of JFM extratropical SSTs. During the previous JAS season, no coherent  
265 SST or SLP patterns are found in the tropics, nor in the extratropics, except in the  
266 South Pacific (Fig. 3a and g). From boreal fall to winter, a significant anomalous SLP  
267 dipole emerges in the central North Pacific (Fig. 3b) consistent with the “Seasonal  
268 Footprinting Mechanism” of Vimont et al. (2003), followed one season later by large  
269 anticyclonic anomalies over the South AO and IO, which reflect the occurrence of  
270 blocking events during late boreal winter or early boreal spring in the Southern  
271 Hemisphere (Fig. 3c). These atmospheric phenomena lead to the emergence of a  
272 boomerang warm SST structure (Fig. 3i-j) in the North Pacific (Vimont et al. 2003)

273 and to subtropical SST dipoles in the South AO and IO (Hermes and Reason, 2005).  
274 Figs. 3c and i also suggest that the extratropical cold SST anomalies over the eastern  
275 IO and western North Pacific promote persistent westerly wind anomalies over the  
276 western equatorial Pacific from boreal winter to spring (Xu and Chan, 2001; Wang et  
277 al., 2012). This westerly equatorial wind signal is a possible trigger of El Niño onset,  
278 as it can induce eastward-propagating downwelling Kelvin waves along the  
279 thermocline, leading to an El Niño warming several months later.

280 However, there are also suggestions of additional predicting paths, not restricted to  
281 surface wind variability over the western equatorial Pacific. Indeed, from the  
282 JFM/AMJ season (Fig. 3c), a significant pattern emerges over the South Pacific,  
283 characterized by a weakening of the southeast trade winds and the development of an  
284 expanded trough. This slowdown of the Walker circulation induced by South Pacific  
285 atmospheric variability may be involved in El Niño onset (Van Loon, 1984; Clement  
286 et al., 2011). South AO and IO anomalies could also be involved in this by remotely  
287 impacting the southwest Pacific through a modulation of the regional Hadley cell  
288 | ~~during-in~~ boreal spring (Terray and Dominiak, 2005; Terray, 2011). By exciting  
289 Rossby waves, these modulations can induce a displacement of the westerly jet stream  
290 and low-level circulation in the South Pacific (Trenberth et al., 1998) and lead to the  
291 development of the southern branch of the traditional ‘horseshoe’ El Niño pattern  
292 (Fig. 3k-l).

## 293 **5. Conclusions and future work**

294 In this work, we demonstrate that, in addition to well-recognized precursors of El  
295 Niño onsets, extratropical SSTs in the North Pacific, South AO and IO during late  
296 boreal winter may provide some important information for the forecast of ENSO  
297 events. This new ‘combined’ SST precursor is most significantly correlated with the

298 Niño3.4 SST time series during the post-1979 period, and offers some potential *added*  
299 *value* in the prediction of the *amplitude* of these ENSO events. We have further tested  
300 the performance of these predictors through various cross-validation experiments and  
301 shown that these promising predictive relationships are also quite well reproduced in a  
302 comprehensive CGCM.

303 Our regression analyses confirm that extratropical SST variability may be impacting  
304 ENSO through a modulation of wind variability in the western equatorial Pacific  
305 during boreal spring (Vimont et al., 2003; Terray, 2011; Wang et al., 2012), but not  
306 only. Our results also suggest that the extratropical atmospheric variability may play a  
307 significant role in ENSO development by modulating the southeast trades in the South  
308 Pacific during boreal spring, particularly for the extraordinary warm events, consistent  
309 with several recent studies (Chang et al., 2007; Clement et al., 2011).

310 Given the suspected importance of this extratropical forcing on ENSO, it now seems  
311 essential to gain a better understanding of the physical processes operating between  
312 extratropical and tropical latitudes before the onset of ENSO events, as well as the  
313 relative contribution of each hemisphere in this prediction. Do each of these  
314 extratropical sectors play ~~separately, and~~ independently? Or does this important  
315 source of predictability for ENSO result from an interaction between the different  
316 basins? Another important question raised by this work is whether the observed  
317 relationship between extreme warm events and extratropical SSTs during recent  
318 decades is a future characteristic of a global warming climate.

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387

388 **Table 1:** Statistics associated with the 1<sup>st</sup> SVD modes between Z20, USTR or the new  
389 ‘combined’ SST precursor during late boreal winter and ENSO SST anomalies in the  
390 tropical Pacific during the following winter. The last 3 columns give the correlation  
391 between each SVD mode and various ENSO indices during the next December-  
392 January season: the Niño3.4 SST index, the C and E indices used in Takahashi et al.  
393 (2011). Results are given for observations (in red) and for the model (in blue). The  
394 correlation coefficients exceeding the 10%, 5% and 1% confidence levels according  
395 to the phase-scrambling bootstrap test of Ebisuzaki (1997) are followed by one  
396 asterisk (\*), two asterisks (\*\*) and three asterisks (\*\*\*), respectively.

<i>SVD results</i> <i>Precursor</i>	SCF (%)		r		Precursor var (%)		ENSO var (%)		Cor Niño3.4		Cor C index		Cor E index	
Z20	84.5	87	0.71	0.56	12.9	24.3	77.1	63.3	0.76***	0.55***	0.77***	0.52***	0.35	0.22**
Ustr	89.3	84.9	0.64	0.53	21.1	21.5	78.4	67.1	0.74***	0.54***	0.62***	0.54***	0.32	0.21*
‘combined’ SST	90.8	83.1	0.78	0.71	13.1	8.1	79.6	69	0.80***	0.71***	0.67***	0.70***	0.48**	0.11

\* P<0.1, \*\*P<0.05, \*\*\*P<0.01

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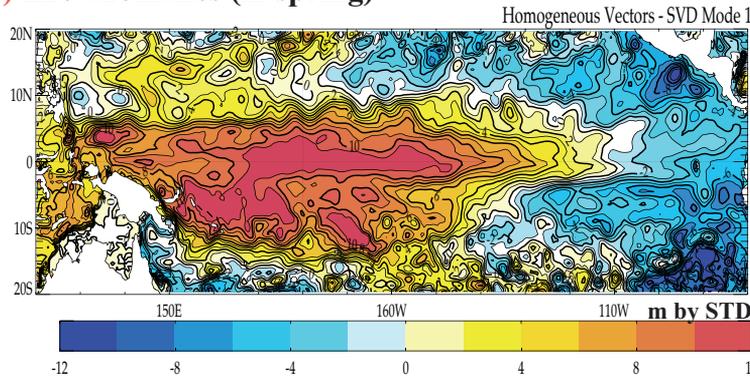
409 **Table 2:** Forecast skill of simple linear regression models using two (A and B), three  
 410 (D) or four (C) predictors in JFM as inputs for the prediction of the Niño3.4 time  
 411 series during the following December-January. As input for each model, we select the  
 412 EOF modes associated with the Z20, USTR and SST precursors, which offer the best  
 413 prediction for the following ENSO. The forecast skill of each model is assessed by the  
 414 cross-validated correlation and root-mean-square-error (RMSE) calculated between  
 415 the observed and forecast Niño3.4 time series, without involving the forecast year.  
 416

<b>Regression models</b>	<i>Selected EOF mode</i>	<i>Correlation</i>	<i>RMSE</i>
<b>A)</b> with SST predictors	SST (eof m1) + SST (eof m2)	0.64	0.75
<b>B)</b> with Z20 and USTR predictors	Z20 (eof m2) + USTR (eof m1)	0.61	0.78
<b>C)</b> with SST, Z20 and USTR predictors	SST (eof m1) + SST (eof m2) + Z20 (eof m2) + USTR (eof m1)	0.71	0.69
<b>D)</b> with SST and Z20 predictors	SST (eof m1) + SST (eof m2) + Z20 (eof m2)	0.72	0.68

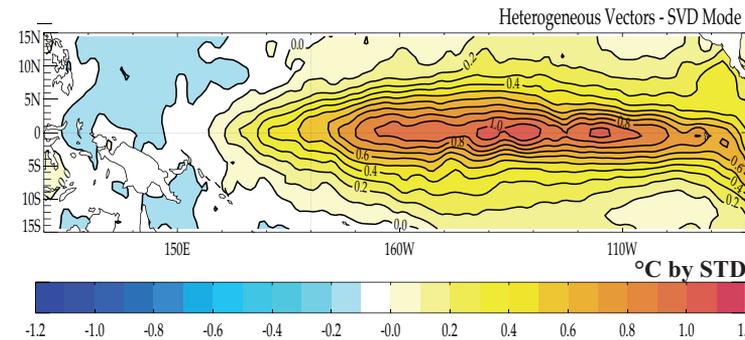
**Figure 1** : Observed 1st SVD mode between Z20 precursor over [110°E-70°W; 20°S-20°N] and tropical Pacific SST over [120°E-80°W; 15°S-15°N] during 1979-2008: **(a)** Z20 homogeneous map in JFM, **(b)** Pacific SST heterogeneous map in ONDJF, and **(c)** standardized Z20 EC time series in JFM (black curve) superimposed with the standardized Niño3.4 SST time series in the following December-January season (red curve). The blue (green) crosses indicate the number of predicted El Niño (La Niña) events (e.g. when both time series exceed a 0.75 standard deviation threshold).

SVD (Z20-ENSO) - obs

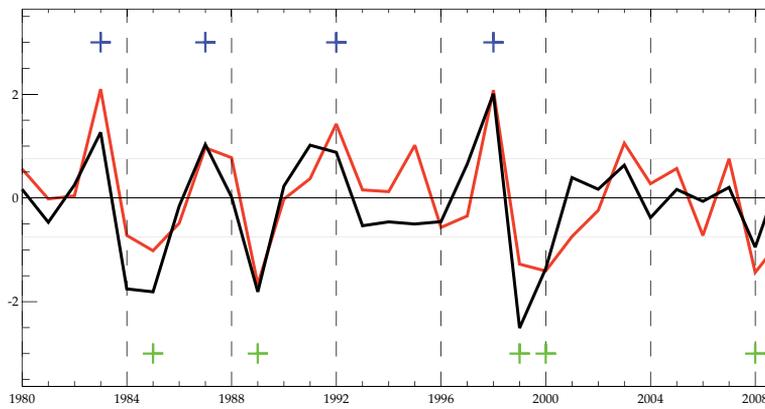
**a) Z20 anomalies (in spring)**



**b) SST anomalies (in winter)**



**c) Z20 Expansion Coefficient and Niño3.4 SST timeseries**



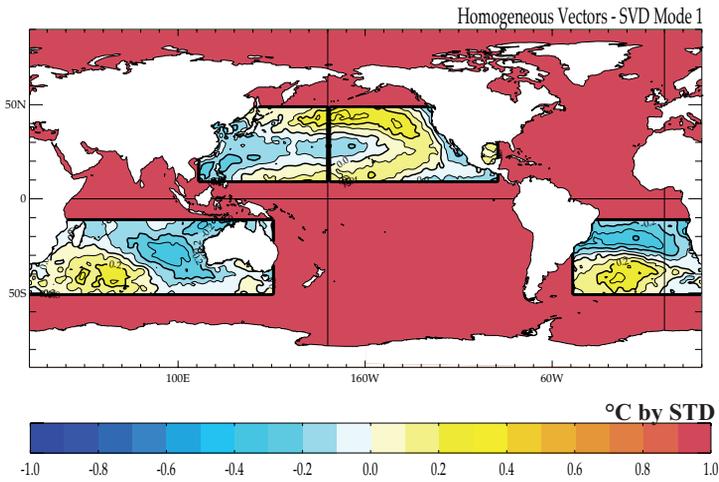
**Figure 2 :** As in Figure 1, but for the observed 1st SVD mode between the JFM extratropical SST precursor (over the North Pacific [110°E-90°W; 10°N-50°N], South Indian [25°E-150°E; 10°S-50°S] and South Atlantic [50°W-25°E; 10°S-50°S] Oceans) and winter tropical Pacific SST during the 1979-2011 period (**panels a,b,c**) and the SINTEX-F2 simulation (**panels d,e,f**). The SST EC time series manages to predict 12 out of the 20 El Niño events, and 14 out of the 24 La Niña events in this control simulation.

**SVD (Combined SST precursor-ENSO)**

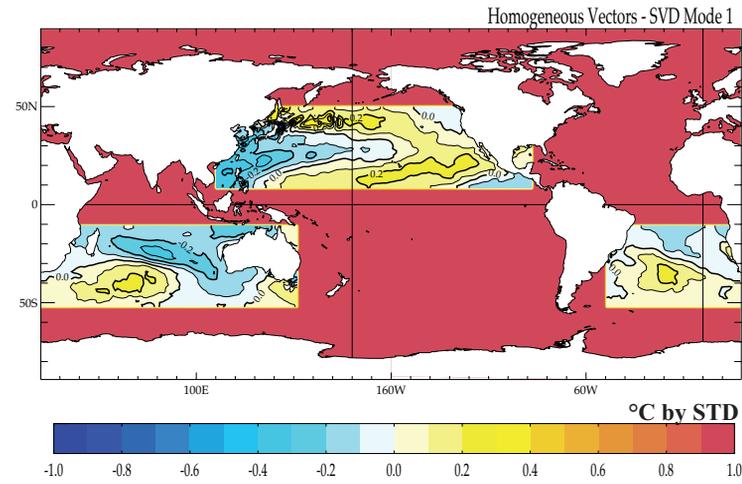
**OBSERVATIONS**

**MODEL**

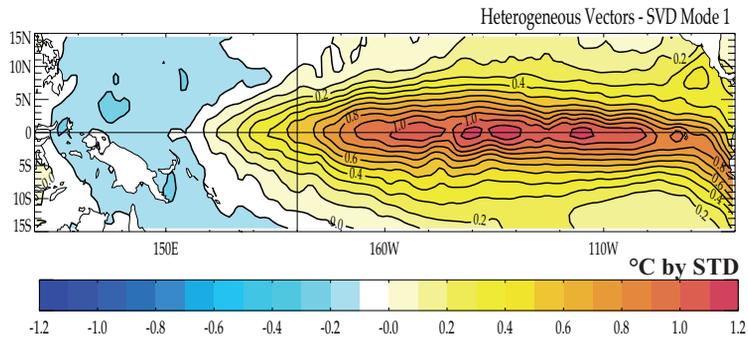
**a) SST anomalies (in spring)**



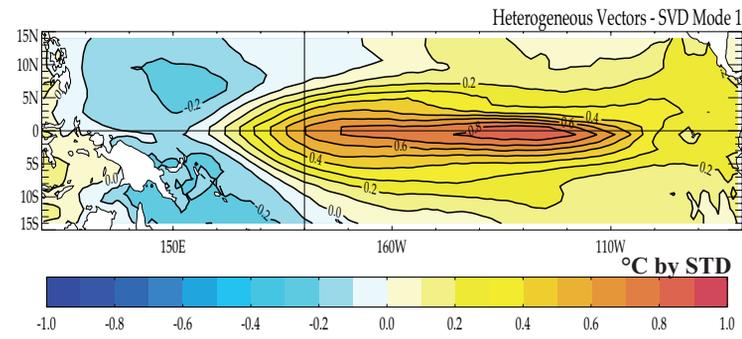
**d)**



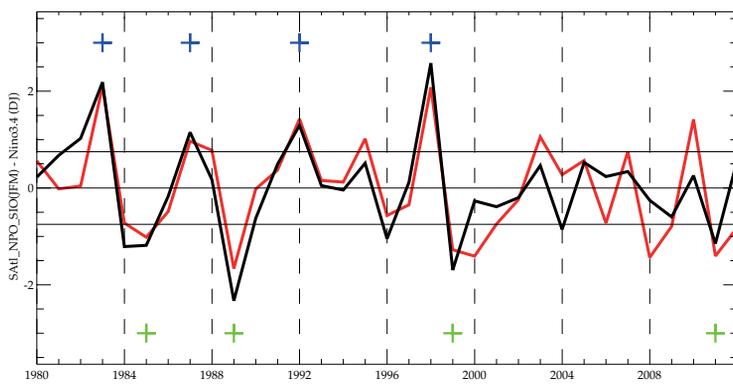
**b) SST anomalies (in winter)**



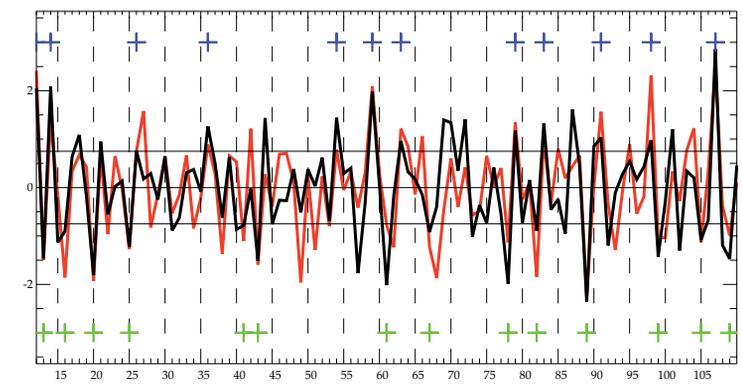
**e)**



**c) SST Expansion Coefficient and Nino3.4 SST timeseries**



**f)**



**Figure 3** : Sea Level Pressure (SLP, shading) and 850hPa wind (vectors) anomalies (a to f) and SST anomalies (g to l) regressed onto the 2nd EOF time series of extratropical SST in JFM (over the 1979-2011 period). Maps are shown from the previous boreal summer to the following boreal winter. The black contours and the wind vectors denote that the corresponding correlation coefficients are above the 90% confidence level following a phase-scrambling procedure with 999 samples

