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► **To cite this version:**

Ghyslaine Boschat, Pascal Terray, Sébastien Masson. Extratropical forcing of ENSO. *Geophysical Research Letters*, 2013, 40, pp.1605-1611. 10.1002/GRL.50229 . hal-00873386

HAL Id: hal-00873386

<https://hal.science/hal-00873386>

Submitted on 30 May 2016

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Extratropical forcing of ENSO

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To be submitted to *Geophysical Research Letters*

February 2013

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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 1st 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 1st 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 1st 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 1st 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 1st 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 1st 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 1st 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 1st and 2nd 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 1st 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 2nd 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 2nd
213 EOF has a higher correlation with the winter Niño3.4 SST time series than the 1st
214 EOF, and is also a significant precursor of the E and C indices, as the 1st SVD mode
215 (Table A). Interestingly, the spatial correlations between these first two EOF modes
216 (Fig. Aa and b) and the 1st SST SVD mode (in Fig. 2a) are 0.35 and 0.80,
217 respectively. Consistently, the 1st SVD mode is more correlated with the 2nd EOF time
218 series (0.82) than with the 1st EOF (0.46). Thus, the source of ENSO predictability
219 offered by the 1st 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 1st and 2nd EOF
226 modes for extratropical SSTs (Fig. Aa-b), the 1st EOF mode for tropical Pacific wind
227 anomalies and 2nd 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 1st 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 2nd 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.

306 **Acknowledgments:** This work has been financially supported by the EMBRACE EU
307 project (N°228320). Simulations were performed on the IDRIS super computer.

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373 **Table 1:** Statistics associated with the 1st 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

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

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To be submitted to *Geophysical Research Letters*

~~December 2012~~

February 2013

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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 1st 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 1st 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 1st 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 1st 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 1st 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 1st 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 1st 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 1st and 2nd 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 1st
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 2nd 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 2nd EOF has a higher correlation with the winter
224 Niño3.4 SST time series -than the 1st EOF, and is also a significant precursor of the E
225 and C indices, as the 1st SVD mode (Table A). Interestingly, the spatial correlations
226 between these first two EOF modes (Fig. Aa and b) and the 1st SST SVD mode (in
227 Fig. 2a) are 0.35 and 0.80, respectively. Consistently, the 1st SVD mode is more
228 correlated with the 2nd EOF time series (0.82) than with the 1st EOF (0.46). Thus, the
229 source of ENSO predictability offered by the 1st 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 1st and 2nd EOF
237 modes for extratropical SSTs (Fig. Aa-b), the 1st EOF mode for tropical Pacific wind
238 anomalies and 2nd 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 1st 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 2nd 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.

319 **Acknowledgments:** This work has been financially supported by the EMBRACE EU
320 project (N°228320). Simulations were performed on the IDRIS super computer.

321

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388 **Table 1:** Statistics associated with the 1st 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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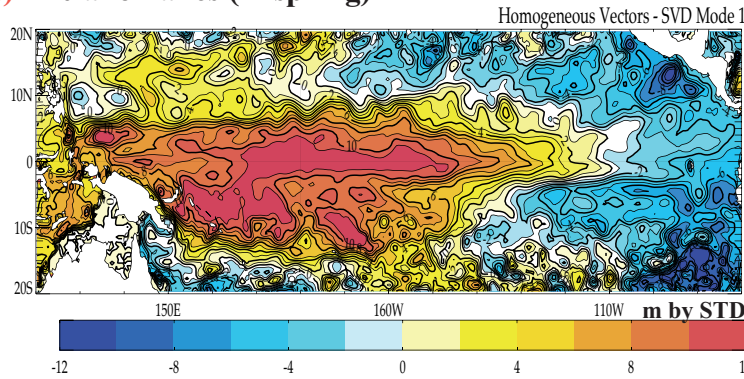
409 **Table 2:** Forecast skill of simple linear regression models using two (A and B), three
 410 (D) or four (C) predictors in JFM as inputs for the prediction of the Niño3.4 time
 411 series during the following December-January. As input for each model, we select the
 412 EOF modes associated with 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

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

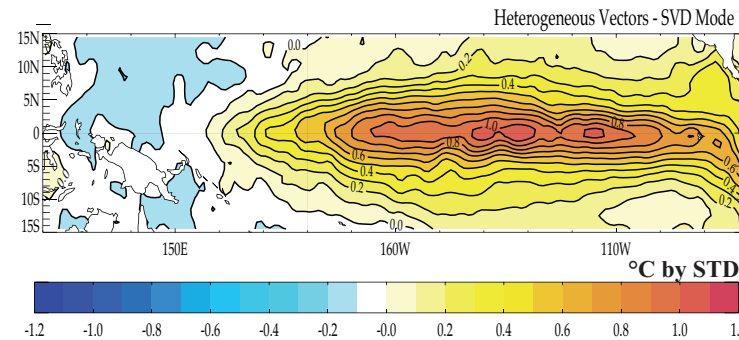
Figure 1 : Observed 1st SVD mode between Z20 precursor over [110°E-70°W; 20°S-20°N] and tropical Pacific SST over [120°E-80°W; 15°S-15°N] during 1979-2008: **(a)** Z20 homogeneous map in JFM, **(b)** Pacific SST heterogeneous map in ONDJF, and **(c)** standardized Z20 EC time series in JFM (black curve) 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

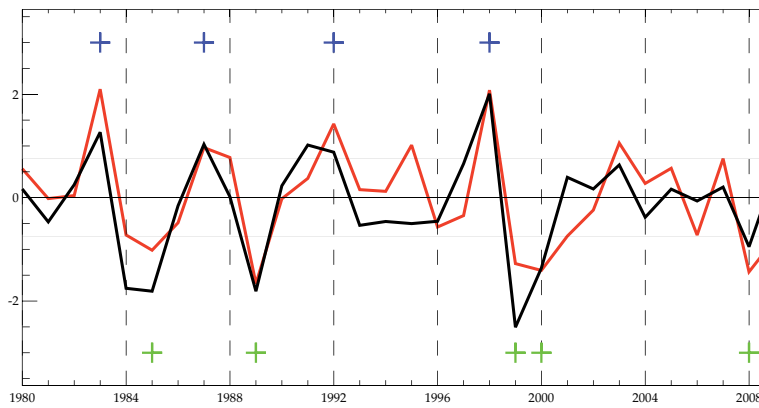


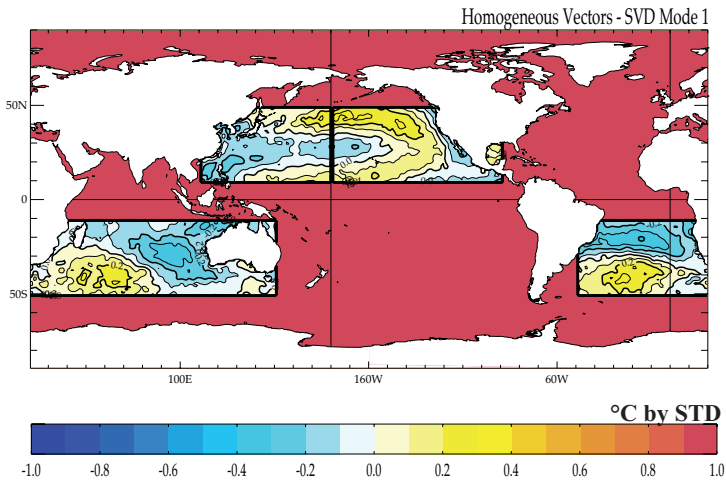
Figure 2 : As in Figure 1, but for the observed 1st SVD mode between the JFM extratropical SST precursor (over the North Pacific [110°E-90°W; 10°N-50°N], South Indian [25°E-150°E; 10°S-50°S] and South Atlantic [50°W-25°E; 10°S-50°S] Oceans) and winter tropical Pacific SST during the 1979-2011 period (**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)

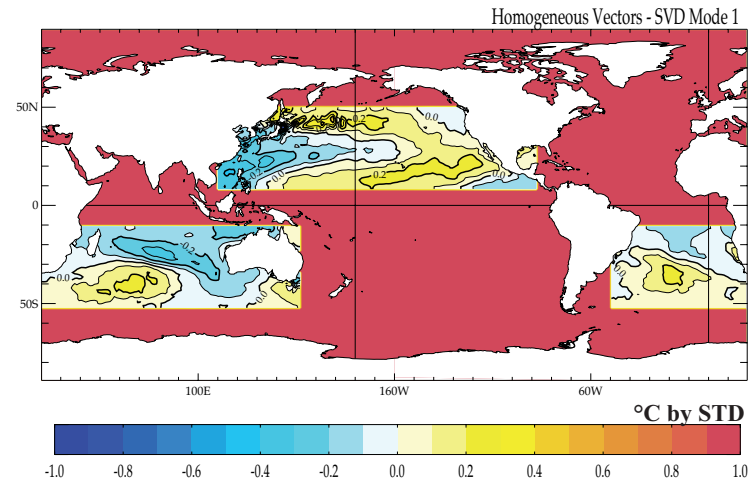
OBSERVATIONS

MODEL

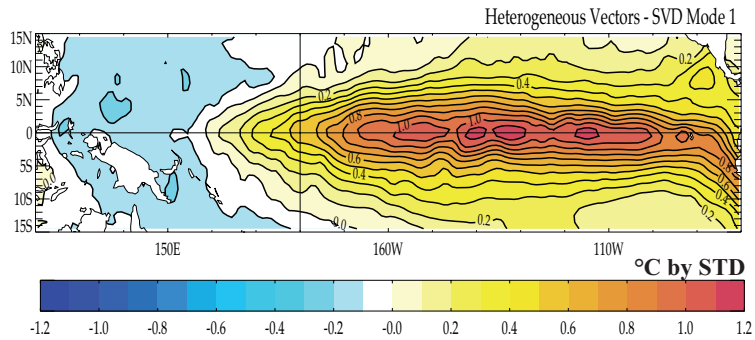
a) SST anomalies (in spring)



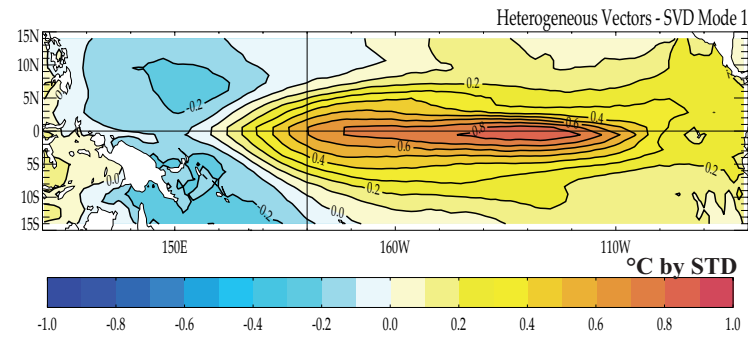
d)



b) SST anomalies (in winter)



e)



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

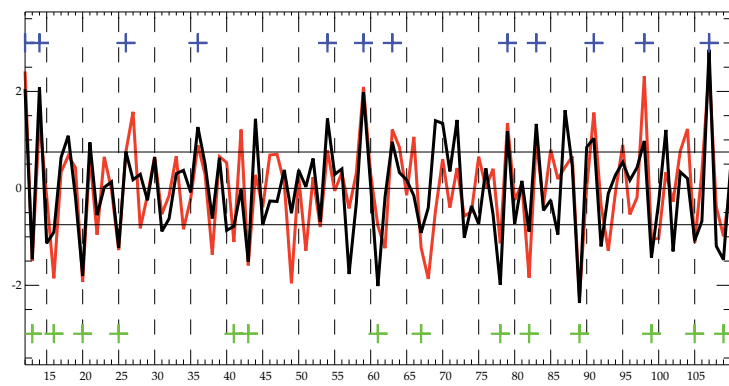
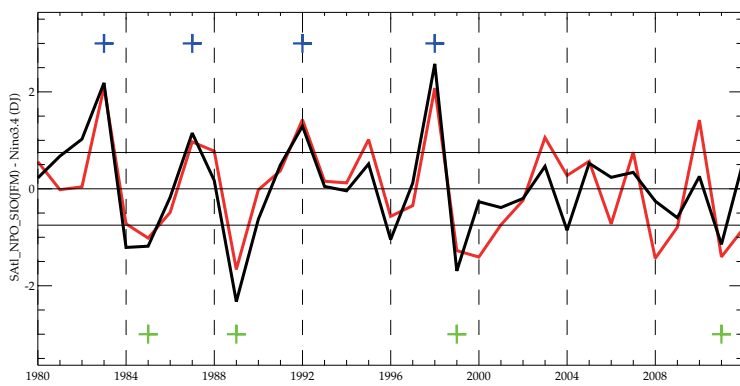


Figure 3 : Sea Level Pressure (SLP, shading) and 850hPa wind (vectors) anomalies (a to f) and SST anomalies (g to l) regressed onto the 2nd EOF time series of extratropical SST in JFM (over the 1979-2011 period). Maps are shown from the previous boreal summer to the following boreal winter. The black 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

