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1 Air-sea Humidity Effects on the Generation of
2 Tropical Atlantic SST Anomalies during the ENSO
3 Events

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7 After the mature stage of the ENSO events in the boreal winter, SST and
8 latent heat flux anomalies over the tropical Atlantic during the following spring
9 show large amplitude north of the equator but small one south of the equa-
10 tor. The linear decomposition analyses of the latent heat flux anomalies in-
11 dicate that the contribution from wind speed anomaly shows an equatorial
12 antisymmetric structure with same magnitude but opposite polarity between
13 north and south of the equator, while the contribution from anomalous air-
14 sea humidity difference counters to that from wind speed anomaly south of
15 the equator. These results suggest an important role of anomalous air-sea
16 humidity difference on forming latent heat flux anomaly and significantly mod-
17 ifies the conventional view of wind speed as the dominant effect in ENSO-
18 induced tropical Atlantic SST changes.

1. Introduction

19 Sea surface temperature anomalies (SSTAs) in the eastern tropical Pacific during the
20 El Niño and the Southern Oscillation (ENSO) events affect thermal structure in most of
21 the tropical atmosphere [e.g. *Wallace et al.*, 1998, and references therein]. Specifically,
22 in the tropical Atlantic, positive (negative) SSTAs are observed in the northern tropical
23 Atlantic during the March-May (MAM) period after the mature stage of the ENSO warm
24 (cold) events, while no significant SSTAs are observed in the southern tropical Atlantic
25 near the equator [*Covey and Hastenrath*, 1978; *Curtis and Hastenrath*, 1995; *Giannini*
26 *et al.*, 2000]. In the southern tropical Atlantic, total SST variance during the boreal
27 spring-summer season explained by ENSO is less than 10% [*Enfield and Mayer*, 1997; *Liu*
28 *et al.*, 2004] although a SST response to ENSO has appeared during October-December
29 period [*Reason et al.*, 2000; *Colberg et al.*, 2004]. If we focus only on the SST variability
30 after the mature stage, we would expect that the atmosphere-ocean variability over the
31 southern tropical Atlantic is not related to the ENSO variability.

32 For the SST variability in the northern tropical Atlantic, many previous studies in-
33 dicated an important contribution from surface wind speed changes during the ENSO
34 events [*Curtis and Hastenrath*, 1995; *Enfield and Mayer*, 1997; *Klein et al.*, 1999; *Gi-*
35 *annini et al.*, 2000; *Hastenrath*, 2000; *Lau and Nath*, 2001; *Alexander and Scott*, 2002].
36 Over the northern tropical Atlantic, the positive (negative) SSTAs are collocated with
37 anomalous surface southwesterlies (northeasterlies) after the mature stage of the ENSO
38 warm (cold) events. These surface wind anomalies induce changes in evaporation from
39 the ocean surface, contributing to the formation of SSTAs in this region. An observational

40 analysis by *Curtis and Hastenrath* [1995] showed that, after the surface wind anomalies
41 appear over the northern tropical Atlantic in January-February period during the ENSO
42 warm (cold) events, anomalous southeasterlies (northwesterlies) over the southern tropi-
43 cal Atlantic emerge in the following MAM period. These cross-equatorial southerlies are
44 also presented by *Huang et al.* [2002], who use an atmosphere-ocean general circulation
45 model coupled over the Atlantic region. Over the southern tropical Atlantic, however, the
46 surface wind speed changes after the mature stage of the ENSO events do not accompany
47 significant SSTAs in these observational and modeling studies.

48 Recent studies pointed out an important contribution from anomalous air-sea humidity
49 and temperature differences in forming the tropical Atlantic SSTAs after the mature stage
50 of the ENSO events [*Saravanan and Chang*, 2000; *Chiang and Sobel*, 2002; *Chiang and*
51 *Lintner*, 2005; *Chikamoto and Tanimoto*, 2005]. *Chiang and Sobel* [2002] suggested that
52 tropospheric temperature variability over the tropics associated with the ENSO events
53 can change surface air humidity and surface temperature over the tropical Atlantic under
54 the strict quasi-equilibrium (SQE) concept [*Emanuel et al.*, 1994; *Brown and Bretherton*,
55 1997] which states the conservation of the convective available potential energy (CAPE).
56 These surface humidity and temperature variations may produce changes in air-sea hu-
57 midity and temperature differences, inducing local change in SST through surface latent
58 and sensible heat flux variations. *Chikamoto and Tanimoto* [2005] indicated that SSTAs
59 in the Caribbean Sea are mainly formed by anomalous air-sea humidity difference that
60 correlated with temperature anomalies in the free atmosphere over the tropical Atlantic
61 after the mature stage of the ENSO events.

62 In this study, we will examine why no significant SSTAs are observed in the southern
63 tropical Atlantic despite the fact that surface wind anomalies are found in the same
64 region after the mature stage of the ENSO events. Over the tropical Atlantic, previous
65 observational studies indicated that latent heat flux anomaly is the major contributor to
66 surface net heat flux anomaly, while radiative heat fluxes associated with cloud changes
67 and ocean dynamics are the minor contributor near the equator after the mature stage
68 of the ENSO events [*Curtis and Hastenrath*, 1995; *Klein et al.*, 1999; *Alexander and*
69 *Scott*, 2002]. Therefore, we will focus on the relative importance among anomalous air-
70 sea humidity difference and surface wind anomaly in forming SSTAs over the southern
71 tropical Atlantic.

2. Data

72 To capture the ENSO-related variability over the tropical Atlantic, we employ the 2° x
73 2° monthly surface fluxes based on individual marine meteorological reports archived in
74 Comprehensive Ocean-Atmosphere Data Set (COADS) [*Woodruff et al.*, 1987] during a
75 1950-1995 period (for more details see *Tanimoto et al.* [2003]). Since this non-assimilated
76 data may contain sampling errors in the region of few marine reports, we also use monthly
77 surface fluxes during a 1982-2002 period based on the National Centers for Environmental
78 Prediction-Department of Energy Atmospheric Model Intercomparison Project-II Reanal-
79 ysis (NCEP2) [*Kanamitsu et al.*, 2002], in which the atmospheric boundary layer humidity
80 tends to depend on model parameterizations of cumulus convection and boundary layer
81 physics, and the National Oceanic and Atmospheric Administration optimum interpo-
82 lation SST version 2 (OISST) [*Reynolds et al.*, 2002]. Vertical profiles of temperature

83 and humidity at Ascension Island (8°S, 14°W; cross mark in Fig. 2d) are taken from
84 the radiosonde observations in Comprehensive Aerological Reference Data Set (CARDS)
85 [*Eskridge et al.*, 1995] from February 1971 to July 2001.

86 To represent the magnitude of the ENSO warm and cold events, we extract eight warm
87 (cold) years of 1957/58, 65/66, 72/73, 82/83, 87/88, 91/92, 94/95, and 97/98 (1955/56,
88 67/68, 70/71, 73/74, 75/76, 84/85, 88/89, and 99/00) from SSTAs in the Niño3 region
89 as described in *Chikamoto and Tanimoto* [2005]. Hence, we take the warm (cold) events
90 of 7 (7) years in the longer record of COADS and of 5 (3) years in the shorter records
91 of NCEP2 and OISST. We analyze composite difference maps between the ENSO warm
92 and cold events (hereafter, simply referred to as composite). The vertical profiles derived
93 from CARDS consist of 354 (304) samples during the ENSO warm (cold) events.

3. Results

94 Figure 1 shows composite difference maps of SSTAs in MAM period, surface wind and
95 latent heat flux anomalies in February-March-April (FMA) period. In both datasets of
96 COADS and NCEP2, anomalous surface southwesterlies of 1 m s^{-1} extending from the
97 Caribbean Sea to the west coast of Africa are observed (Figs. 1a and 1c), showing reduced
98 climatological easterly trade winds. Under these anomalous surface winds, significant
99 positive SSTAs greater than 0.4°C and negative latent heat flux anomalies less than -10
100 W m^{-2} are also observed (Figs. 1a-d). Surface heat flux anomalies of -10 W m^{-2} are
101 nearly equivalent to an increase in SST of 0.4°C for 3-month in mixed layer of 50-m depth.
102 In the region north of 20°N , anomalous surface westerlies show enhancing climatological
103 westerly winds, contributing negative SSTAs off the east coast of North America.

104 Over the southern tropical Atlantic, anomalous surface southeasterlies over 0-10°S band
 105 are as much as 1 m s⁻¹ in magnitude, showing enhanced climatological southeasterly
 106 trade winds. Nevertheless, magnitude of latent heat flux anomalies over the southern
 107 tropical Atlantic in the same band are less than half those of northern tropical Atlantic.
 108 In addition, no significant SSTAs are observed in the southern tropical Atlantic from
 109 equator to 20°S. This result suggests that some other factors may reduce latent heat flux
 110 anomalies. In the region south of 20°S, positive SSTAs are not consistent with enhanced
 111 latent heat fluxes in COADS, suggesting importance of ocean dynamics such as meridional
 112 Ekman heat transport [*Colberg et al.*, 2004].

To evaluate the contributions from wind speed anomaly and from anomalous air-sea
 difference in specific humidity (corresponding to saturation specific humidity anomaly at
 the sea surface $q_o^{*'}$ minus air specific humidity anomaly q_a'), we approximately represent
 the latent heat flux anomaly by three linearized components as in *Enfield and Mayer*
 [1997] and *Tanimoto et al.* [2003]:

$$F'_{lh} \approx \rho c_e L_e \{ W' (\bar{q}_o^* - \bar{q}_a) + \bar{W} (q_o^{*'} - q_a') \} \quad (1)$$

113 where F'_{lh} is the latent heat flux (upward positive), and the overbar and prime indicate the
 114 monthly climatological mean and anomaly, respectively (for more details see *Chikamoto*
 115 *and Tanimoto* [2005]). On the right-hand side of (1), the first and the second terms repre-
 116 sent contributions from wind speed anomaly (W') and from anomalous air-sea difference
 117 in specific humidity ($\Delta q'$) to the total amount of latent heat flux anomalies, respectively.

118 Figure 2 shows composite difference maps of W' and $\Delta q'$ components to total latent heat
 119 flux anomalies. Over the northern tropical Atlantic, reduced latent heat fluxes caused by

120 W' component extending from the Caribbean Sea to the west coast of Africa are observed
121 (Figs. 2a and 2c), consistent with anomalous surface southwesterlies in Figs. 1a and 1c.
122 Over this region, $\Delta q'$ components are not so apparent in both datasets (Figs. 2b and 2d).
123 As a result, reduced latent heat flux mainly induced by the W' component contributes in
124 forming positive SSTAs in the northern tropical Atlantic as suggested by previous studies
125 [*Curtis and Hastenrath, 1995; Enfield and Mayer, 1997; Klein et al., 1999; Giannini et al.,*
126 *2000; Lau and Nath, 2001*]. Over the southern tropical Atlantic, by contrast, reduced
127 latent heat fluxes caused by the $\Delta q'$ component are observed in NCEP2 and OISST (Fig.
128 2d), countering the increased latent heat fluxes caused by the W' component (Figs. 2a and
129 2c). In COADS, the $\Delta q'$ component also tends to show reduced latent heat fluxes over
130 the southern tropical Atlantic with latitude band 0-10°S although there are some missing
131 values in this region (Fig. 2b). Monthly plots of $\Delta q'$ represents the similar structures with
132 the same polarity in MAM period (not shown).

133 Once positive SSTAs are formed in the northern tropical Atlantic during late winter
134 associated with the ENSO warm events, negative anomalies of sea level pressure (SLP)
135 are also observed over that region. These negative SLP anomalies produce an anomalous
136 southerly flow across the equator through anomalous meridional SLP gradient. In the
137 off-equatorial region, these anomalous southerlies are altered by Coriolis force, thereby
138 inducing anomalous southwesterlies over northern tropical Atlantic and southeasterlies
139 over southern one, respectively [*Xie and Philander, 1994; Chang et al., 1997; Xie and*
140 *Tanimoto, 1998; Okumura et al., 2001; Chiang et al., 2002*]. Over the tropical Atlantic,
141 these wind anomalies in FMA period tend to show the equatorial antisymmetric structure

142 of W' component between north and south of the equator, as we have seen in Figs. 2a and
 143 2c. Thus, the W' component acts to produce the equatorial antisymmetric structure in
 144 the latent heat flux anomaly field, while the $\Delta q'$ component acts to reduce this equatorial
 145 antisymmetric structure.

146 The $\Delta q'$ component is divided into $q_o^{*'}$ and q_a' components as in Eq. (1). Figure 3 shows
 147 a meridional plot of the $q_o^{*'}$ and the q_a' components averaged over the tropical Atlantic from
 148 70°W to 0° . The $q_o^{*'}$ components in both datasets show positive anomalies north of the
 149 equator, while those components are quite small south of the equator (dashed line in Fig.
 150 3) because positive SSTAs are observed only north of the equator. The q_a' components, on
 151 the other hand, show positive anomalies in both hemispheres extending from 10°S to 30°N
 152 (solid line in Fig. 3), where the signal is statistically significant at the 95% level. Over the
 153 southern tropical Atlantic, therefore, $q_o^{*'} - q_a'$ results in significant negative anomalies of the
 154 $\Delta q'$ components. *Chikamoto and Tanimoto* [2005] indicated the important contribution
 155 of q_a' in forming SSTAs in the northern tropical Atlantic during the mature stage of the
 156 ENSO events (the January-February period). Following this stage (the MAM period), the
 157 significant q_a' component still persists in the northern tropical Atlantic as we have seen in
 158 Fig. 3, while $q_o^{*'} - q_a'$ becomes quite small due to the SSTA formation over that region.
 159 As a result, significant $\Delta q'$ component is observed only south of the equator in the FMA
 160 period.

4. Discussion

161 To examine the formation of positive q_a' over the southern tropical Atlantic, we made
 162 vertical profiles of anomalous air humidity and temperature based on NCEP2 averaged

163 over the southern tropical Atlantic (40°W - 0°, 0 - 10°S; solid line) and at Ascension
164 Island (8°S, 14°W; dashed line) based on CARDS as shown in Fig. 4. In both profiles,
165 significant positive anomalies in specific humidity (above the 90% level) are observed in
166 the lower atmosphere (Fig. 4a), contributing to the reduced latent heat fluxes caused by
167 $\Delta q'$ component over the southern tropical Atlantic (Figs. 2b and 2d). In the middle and
168 upper troposphere, positive air temperature anomalies are observed above 900 hPa in both
169 datasets (Fig. 4b). This temperature warming stabilizes the atmosphere above the plane-
170 tary boundary layer, increasing the moisture storage capacity in the lower atmosphere. In
171 fact, the atmospheric layer between 900 and 800 hPa is stabilized during the ENSO warm
172 events (Fig. 4c). In the lower atmosphere, the increase in the moisture storage capacity is
173 associated with an increase in air specific humidity, so as to conserve CAPE. This increase
174 in air specific humidity produces the q'_a component south of the equator, countering the
175 W' component. Previous studies indicated that tropospheric temperature warming is ob-
176 served in the whole tropics after the ENSO warm events [*Wallace et al.*, 1998]. According
177 to *Chiang and Sobel* [2002] and *Chiang and Lintner* [2005], this tropospheric temperature
178 warming accompanies an increase in equivalent potential temperature in the planetary
179 boundary layer under the SQE concept [*Brown and Bretherton*, 1997; *Emanuel et al.*,
180 1994]. Our vertical profiles actually show the large positive specific humidity anoma-
181 lies in the planetary boundary layer, while temperature anomalies in the same layer are
182 essentially zero (Figs. 4a and 4b). These results are consistent with the suggestion pro-
183 posed by *Chiang and Sobel* [2002] and *Chiang and Lintner* [2005]: the increase in q'_a ,
184 rather than changes in wind speed, associated with the tropospheric temperature warm-

185 ing during the ENSO warm events affects the underlying SSTAs over the tropical Atlantic
186 through reduced latent heat fluxes, resulted in new warmer SST state equilibrating to the
187 tropospheric temperature warming above.

5. Summary

188 We examined why no significant SSTAs are observed in the southern tropical Atlantic
189 over 0-10°S band after the mature stage of the ENSO events. Based on the linearized com-
190 ponent of latent heat flux anomalies, we showed that the W' component has the equatorial
191 antisymmetric structure over the tropical Atlantic (Fig. 2), while the q'_a component is the
192 equatorial symmetric structure associated with tropospheric temperature warming (Fig.
193 3). These anomalous wind speed and humidity effects tend to reinforce each other in the
194 northern tropical Atlantic but opposes each other in the southern tropical Atlantic. As a
195 result, latent heat flux anomaly and hence SSTA showed the large amplitude north of the
196 equator and small one south of the equator after the mature stage of the ENSO events.

197 Our analysis suggests two surface processes involved in anomalous latent heat fluxes in
198 the tropical Atlantic associated with the ENSO events. One is the W' component, which is
199 associated with trade wind changes in the tropical Atlantic affected by the ENSO forcing
200 [*Chiang et al., 2002; Czaja et al., 2002*], and further maintained by air-sea interaction
201 confined in the tropical Atlantic [*Xie and Philander, 1994; Chang et al., 1997; Xie and*
202 *Tanimoto, 1998; Okumura et al., 2001*]. The other is the q'_a component, which is probably
203 induced by the atmospheric thermodynamic remote response to the ENSO events. The
204 combination of these internal and external forcing may explain the reason why the tropical
205 Atlantic SST variability tends to show larger fluctuations in the northern hemisphere

206 than in the southern one [*Houghton and Tourre, 1992; Enfield and Mayer, 1997; Xie and*
207 *Tanimoto, 1998; Tanimoto and Xie, 2002*]. Recent numerical experiments indicate that
208 radiative heat fluxes act against latent heat fluxes in the tropical Atlantic [e.g. *Chiang*
209 *and Lintner, 2005*]. Accurate surface observations of surface heat flux components are
210 highly desired.

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Figure 1. Composite difference maps of (a, c) SSTAs (contour: °C) during the MAM period and surface wind anomalies (vector: m s^{-1}) during the FMA period and (b, d) latent heat flux anomalies (contour: W m^{-2}) during the FMA period between the ENSO warm and cold events. Left (right) panels are based on COADS (NCEP2 and OISST). Zero contours are omitted. Warm (cold) colors in bottom panels indicate heat gain (loss) from the ocean.

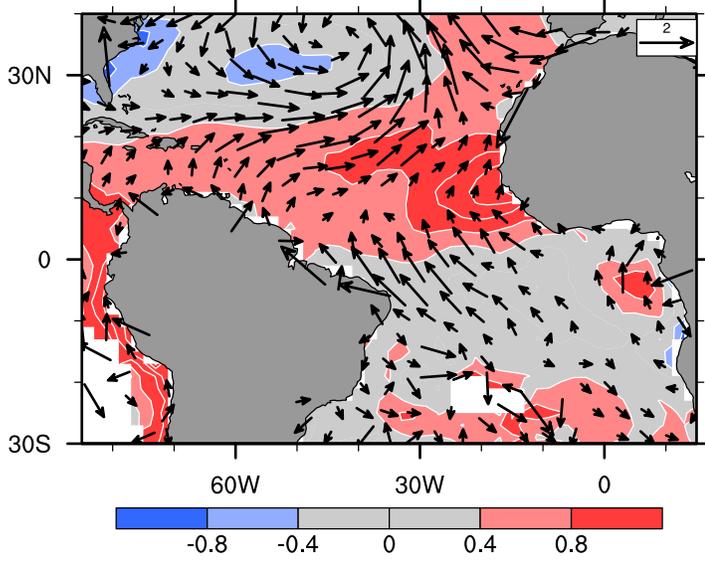
Figure 2. Same as Figs. 1b and 1d, but for contributions from (a, c) wind speed anomalies (W') and (b, d) air-sea difference in specific humidity ($\Delta q'$) to latent heat flux anomalies. Cross mark in (d) indicates the station at Ascension Island.

Figure 3. Latitude distributions of contributions from saturation specific humidity at the sea surface (q_o^{*} : dashed lines) and from air specific humidity anomaly (q_a' : solid lines) to latent heat flux anomalies based on (a) COADS and (b) NCEP2 and OISST. These anomaly components are zonally averaged over the tropical Atlantic (70°W - 0°). Units are W m^{-2} . Difference between the q_o^{*} and q_a' components is identical to the $\Delta q'$ component.

Figure 4. Vertical profiles of (a) specific humidity anomaly, (b) temperature anomaly based on NCEP2 averaged over the southern tropical Atlantic (40°W - 0° , 0 - 10°S ; solid lines) and CARDS (8°S , 14°W ; dashed lines) in the FMA period. Vertical temperature profiles during the ENSO warm and cold events based on CARDS are also plotted by solid and dashed line in (c), respectively.

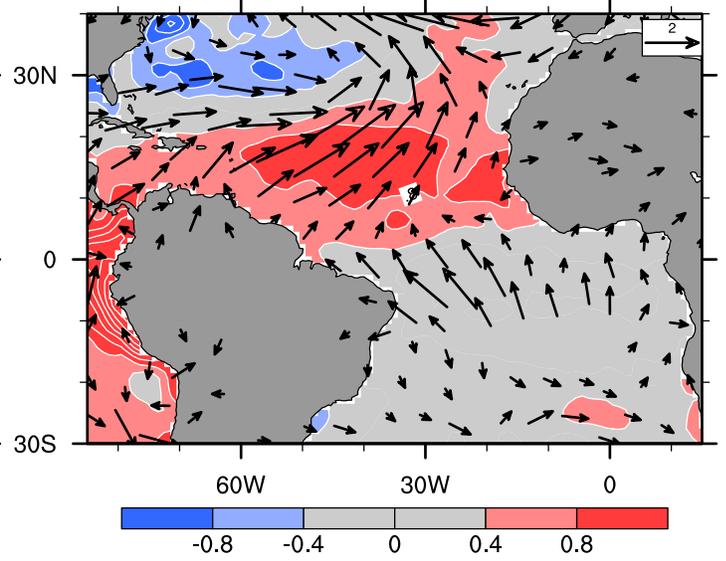
COADS

(a) SST (MAM) & surface wind (FMA)

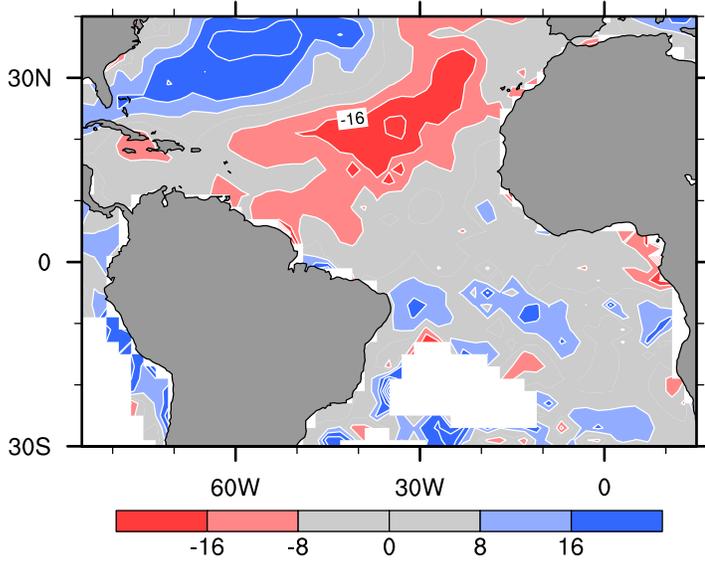


NCEP2 & OI SST

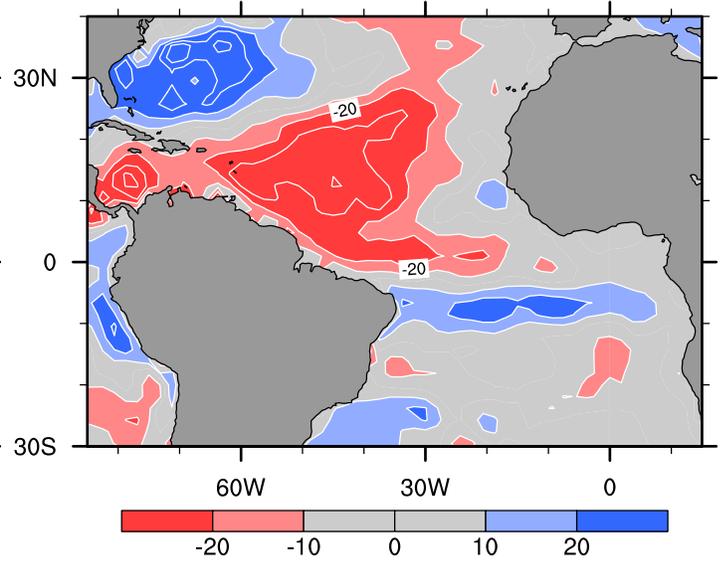
(c) SST (MAM) & surface wind (FMA)



(b) latent heat flux (FMA)

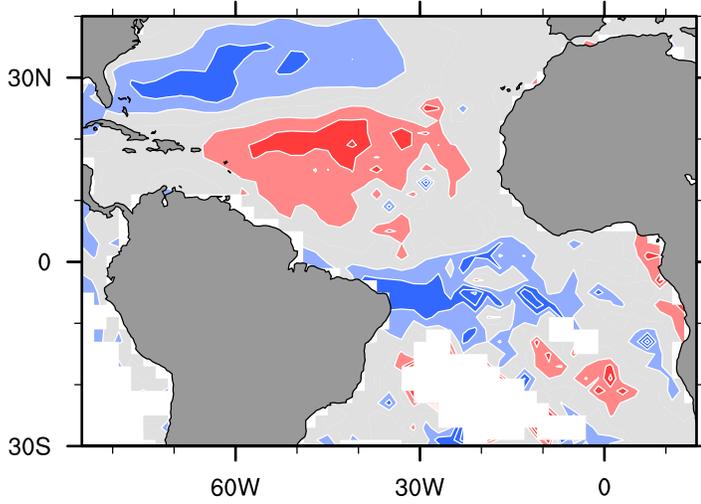


(d) latent heat flux (FMA)

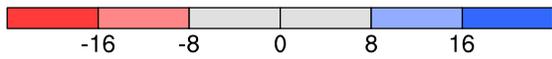
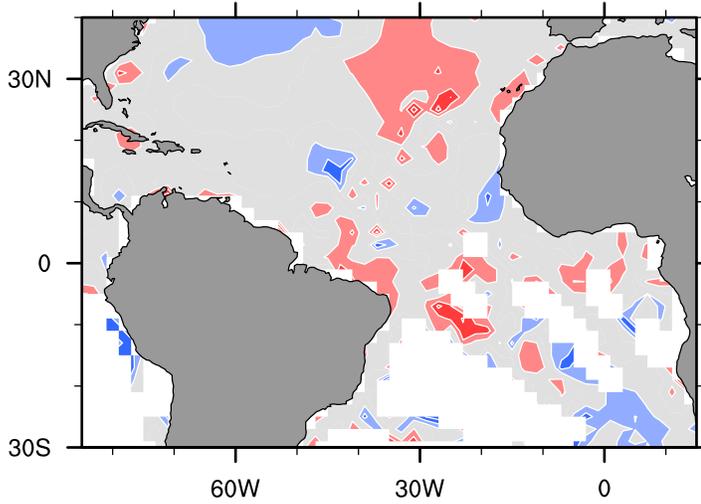


COADS

(a) W' component

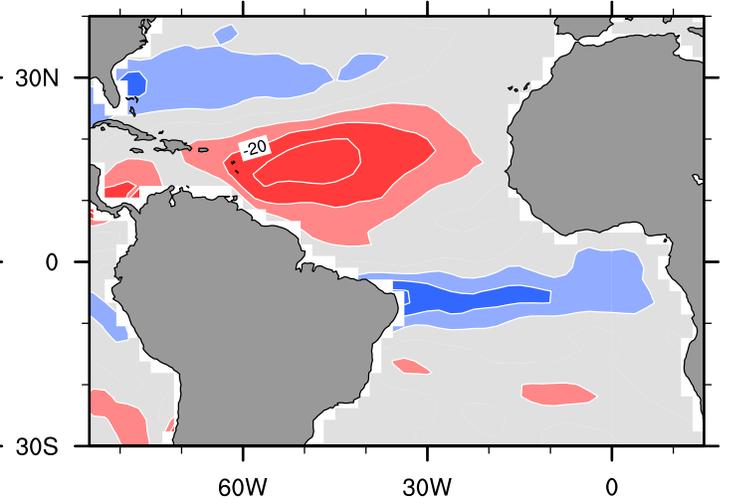


(b) $\Delta q'$ components



NCEP2 & OI SST

(c) W' component



(d) $\Delta q'$ components

