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Why Were Sea Surface Temperatures so Different in the Eastern Equatorial Atlantic in June 2005 and 2006?

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ABSTRACT

A comparison of June 2005 and June 2006 sea surface temperatures in the eastern equatorial Atlantic exhibits large variability in the properties of the equatorial cold tongue, with far colder temperatures in 2005 than in 2006. This difference is found to result mainly from a time shift in the development of the cold tongue between the two years. Easterlies were observed to be stronger in the western tropical Atlantic in April–May 2005 than in April–May 2006, and these winds favorably preconditioned oceanic subsurface conditions in the eastern Atlantic. However, it is also shown that a stronger than usual intraseasonal intensification of the southeastern trades was responsible for the rapid and early intense cooling of the sea surface temperatures in mid-May 2005 over a broad region extending from 20°W to the African coast and from 6°S to the equator. This particular event underscores the ability of local intraseasonal wind stress variability in the Gulf of Guinea to initiate the cold tongue season and thus to dramatically impact the SST in the eastern equatorial Atlantic. Such intraseasonal wind intensifications are of potential importance for year-to-year variability in the onset of the African monsoon.

1. Introduction

Sea surface temperature (SST) variability in the tropical Atlantic Ocean is greatest in the Gulf of Guinea, displaying amplitudes of up to 7°C on seasonal time scales (Merle et al. 1980; Picaut 1983). This seasonal variability is primarily due to equatorial upwelling and the formation of a cold tongue in boreal summer (Weingartner and Weisberg 1991). SST cooling associated with the establishment of the seasonal cold tongue is correlated with the northward migration of the intertropical convergence zone (ITCZ) and thus influences the regional climate and the West African monsoon (WAM) (Wagner and Da Silva 1994; Janicot et al. 1998; Vizzy and Cook 2001, 2002; Gu and Adler 2004; Okumura and Xie 2004). Despite many studies about

the circulation and heat storage in the tropical Atlantic (Merle 1980; Philander and Pacanowski 1986a), detailed processes that induce the formation of the annual cold tongue are still poorly understood.

Furthermore, the Gulf of Guinea exhibits an important SST interannual variability that has often been compared to the El Niño events in the Pacific, although with a weaker amplitude (e.g., Hisard 1980; Philander 1986; Zebiak 1993). During the pioneer field programs Français Ocean et Climat dans l'Atlantique Equatorial (FOCAL) and Seasonal Response of the Equatorial Atlantic (SEQUAL) carried out in 1982–84, dramatic differences were observed in the Gulf of Guinea between the 1983 boreal summer, with cold SST, and the 1984 boreal summer, with abnormally warm SST (Philander 1986; Hisard et al. 1986). These differences were explained by the existence of anomalies in the wind forcing in the western part of the tropical Atlantic Ocean that induced large changes in the vertical thermal distribution of the Gulf of Guinea (e.g., Adamec and O'Brien 1978;

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Servain et al. 1982; Houghton and Colin 1986; Hisard and Hénin 1987). In particular, Servain et al. (1982) found no significant correlation between the local wind stress and the SST at nonseasonal time scales, thus discounting the importance of local wind forcing for the interannual SST variability in the eastern equatorial Atlantic.

Within the oceanic component Etude de la circulation océanique et du climat dans le Golfe de Guinée (EGEE) of the African Monsoon Multidisciplinary Analysis (AMMA) program (Redelsperger et al. 2006), repeated oceanic surveys of the Gulf of Guinea were made in June 2005 (EGEE-1) and May–July 2006 (EGEE-3) (Bourlès et al. 2007). The oceanic conditions observed during these two cruises exhibited very different patterns that are similar to those observed in 1983 and 1984. The aim of the present paper is to identify the mechanisms responsible for the observed differences in SST conditions between 2005 and 2006. To do so, satellite SST and altimetric observations are analyzed, along with surface fields of the operational analyses from the European Centre for Medium-Range Weather Forecasts (ECWMF), and hydrographic measurements from EGEE-1 and EGEE-3, to infer the respective roles of local processes in the Gulf of Guinea and basin-scale adjustment of the equatorial thermocline to interannual variability in winds in the western equatorial Atlantic.

This paper is structured as follows: section 2 describes the differences in SST conditions in the Gulf of Guinea in June 2005 and June 2006. In section 3, the potential role of basin-scale preconditioning is discussed. The effects of intraseasonal Southern Hemispheric wind intensifications on local cooling in the Gulf of Guinea are then evidenced in section 4, while in section 5 we analyze the spatial distribution of these wind intensifications. Finally, our results are discussed and summarized in section 6.

2. SST conditions in June 2005 and 2006

The horizontal distribution of SST in mid-June 2005 (Fig. 1a) shows the presence, in the eastern equatorial Atlantic, of a broad tongue of cold water extending from 1°N to 5°S and from 25°W to the African coast. In this region, temperatures as low as 22°C were observed between 10°W and 0°E and along the African coast. The equatorial cold tongue is delimited from warmer waters both north and south of the equator by intense fronts that undulate on horizontal scales of ~800–1000 km. However, its southeastern boundary is not clearly separated from a coastal upwelling signature beyond 10°S. Unlike in the Southern Hemisphere, where a large zonal gradient in SST is observed along 7°S, with a 6°C difference over the basin width, no such zonal gradient is present north of the cold tongue.

The situation was quite different in June 2006 (Fig. 1b) when SSTs were observed to be warmer in the Gulf of Guinea than in 2005. If a cold tongue was again present near the equator, its intensity was significantly weaker, with SSTs everywhere greater than 25°C, that is, 3°C warmer than in 2005. Also, no mesoscale activity was visible on its northern and southern boundaries. In 2006, the cold tongue did not extend southward beyond 5°S, being now disconnected from the cold waters farther south in the eastern basin, thus reducing the zonal SST gradient that was observed along 7°S in 2005. Finally, north of the equator and east of 10°W, SSTs were observed to be 1°C warmer in 2006 than in 2005.

In this paper, we focus on the region between 10°S and 4°N and 4°W and 4°E (Fig. 1), away from coastal upwelling zones along the African coast. This area corresponds to the region of maximum upwelling during the cold season (Weingartner and Weisberg 1991). Figure 2 summarizes the differences between 2005 and 2006 in the month-to-month evolution of the latitudinal structure of zonally averaged SSTs in this region. In March, the north-to-south distributions of SST were similar in 2005 and 2006, and displayed a weak north-to-south gradient. After March, cooling started between the equator and 4°S. This cooling continued until July in 2005 and August in 2006, attaining a maximum near 2°S, while the south-to-north gradient increased with time between 4°N and 10°S. The latitudinal variations of SST in June and July 2006 were very similar to those in May and June 2005, respectively, indicating that the cooling rates between March and June differed between 2005 and 2006 and that the 2006 cooling was one month delayed compared to the cooling of 2005. These conditions lasted about two months. The gap nearly vanished in August when the differences in SST were again smaller between the two years. Furthermore, the 2005 maximum cooling rate occurred from April to June with a temperature drop of 4°C at 2°S while most of the cooling in 2006 occurred from June to August (temperature drop of 3°C at 2°S). As the decrease in temperature was similar from April to August (i.e., between the warm and cold seasons) during the two years (of the order of 6°C), the main difference in SST resulted rather from a different timing in the setup of the cold tongue season, which started earlier in 2005 than in 2006, than from a difference in the amplitude and intensity of the equatorial cold tongue itself.

3. Basin-scale preconditioning

Year-to-year variability in the equatorial cold tongue onset and intensity is mostly related to year-to-year variability in the zonal slope of the thermocline, in

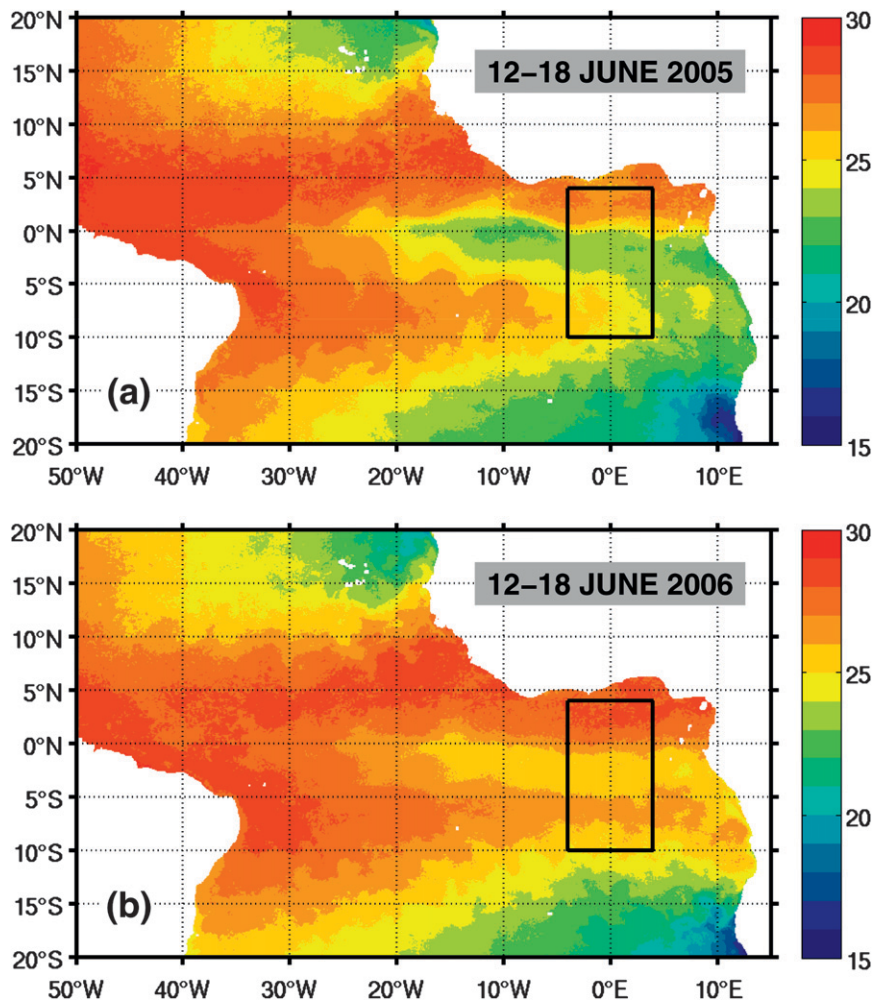


FIG. 1. Horizontal distribution of SSTs in (a) mid-June 2005 and (b) 2006. SST data are from the operational OSI-SAF project (information online at <http://www.osi-saf.org/index.php>) and are time averaged between 12 and 18 Jun of each year. Unit: °C.

response to changes in the trade winds over the western equatorial Atlantic (e.g., Moore et al. 1978; Servain et al. 1982; Houghton 1991; Zebiak 1993; Illig et al. 2006). Figure 3 displays the mean horizontal distribution of ECMWF zonal wind stress prior to the cold tongue seasons in 2005 and 2006. In April–May 2005 and 2006, easterlies blew over the entire equatorial Atlantic except in the vicinity of the African coast, being maximum (greater than 0.09 N m^{-2}) near 10°N , 45°W and 12°S , 15°W on both sides of the ITCZ. However, easterlies were significantly stronger south of 5°N in boreal spring 2005, with anomalies exceeding 0.01 N m^{-2} along the equator and 0.03 N m^{-2} near 10°S , generating a steeper zonal slope of the thermocline that could ultimately outcrop in the Gulf of Guinea. The upper-oceanic structures along 10°W , observed from hydrographic profiles in June 2005 during the EGEE-1 cruise

and in June 2006 during the EGEE-3 cruise (Fig. 4), are compatible with such a basin-scale adjustment. They reveal an equatorward shoaling of the thermocline, represented by the 20°C isotherm, and of the mixed layer depth in both years, but with double the amplitude in 2005 compared to 2006. Near the equator, the 20°C isotherm and the mixed layer depth were observed, respectively, at 30 and 10 m from 3°S to 1°N in 2005, whereas they were both about 20 m deeper in 2006. This change in the depth of the equatorial thermocline led to an outcropping of cold thermocline waters in June 2005 but not in June 2006. At 10°S , the thermocline was conversely deeper in 2005 (120-m depth) than in 2006 (100-m depth).

The year-to-year change in the zonal slope of the thermocline can also be inferred from satellite altimeter observations (Katz et al. 1986; Provost et al. 2006). Sea

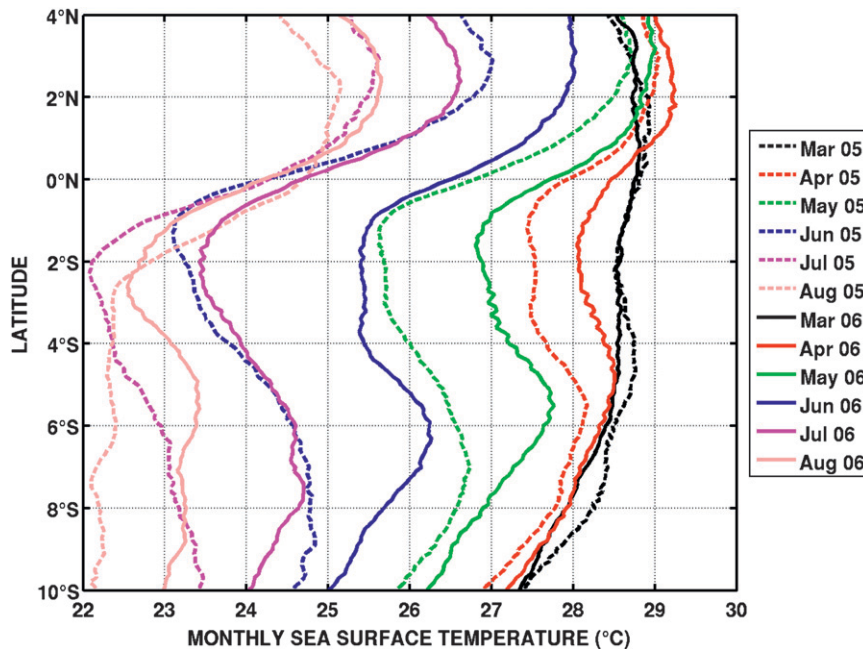


FIG. 2. Monthly evolution of the latitudinal distribution of zonally averaged SSTs between 4°W and 4°E. OSI-SAF SST data are zonally averaged between 4°W and 4°E. Continuous and dashed lines refer, respectively, to 2005 and 2006, and each color corresponds to a specific month (see legend).

level anomalies (SLAs) from the Archive, Validation and Interprétation des données de Satellites Océanographiques (AVISO) dataset are used to compare the temporal evolution patterns of sea surface heights along the equator in 2005 and 2006 (Fig. 5). AVISO SLAs are anomalies relative to the mean spatial distribution of the sea surface heights averaged over 7 yr (1993–99) of the Ocean Topography Experiment (TOPEX)/Poseidon data. SLAs became negative at the end of April 2005 east of 10°W and mid-May 2005 from 30° to 10°W, whereas SLAs remained positive as late as mid-June in 2006, except in the easternmost part of the basin (beyond 0°E) where SLAs were negative from April onward during both years. Note the presence between 20° and 10°W, from mid-May to mid-August 2005, of westward propagations of negative SLAs associated with tropical instability waves (TIWs), which are not observed in 2006. The corresponding SLA differences along the equator between 2006 and 2005 (Fig. 6b) reveal a long period (from mid-April to mid-July) and large region (from 25°W to 10°E) of positive anomalies, with negative anomalies during the same period west of 30°W. These observations provide evidence that the zonal gradient in SLAs along the equator was stronger from mid-April to mid-June 2005 than during the corresponding period in 2006, in agreement with a steeper thermocline in late boreal spring 2005. The comparison

of a Hovmöller longitude–time diagram of the SLAs and the zonal wind stress shows that the negative anomalies in 2005 with respect to 2006, east of 20°W, originated from the western equatorial Atlantic when two successive month-long, stronger than normal easterlies were observed in April 2005 and May 2005 when compared to 2006 (Fig. 6a). These anomalies then propagated along the equator, with a spatial structure and an estimated eastward phase speed (1.3 m s^{-1}) compatible with a second baroclinic equatorially trapped Kelvin wave, and finally reached the eastern equatorial Atlantic one month later, respectively, in May and June (Fig. 6b). These eastward propagations can be observed from 35°W in SLAs in April–May 2005 (dashed lines in Fig. 5a), but not during the corresponding period in 2006 (Fig. 5b), indicating that a basin-scale equatorial adjustment occurred in 2005 and was likely to precondition the earlier appearance of the cold tongue in the eastern equatorial Atlantic in 2005. Such an eastward-propagating mechanism should, however, be limited to a narrow region, equatorward of 3°–4° in latitude, where the equatorial Kelvin waves are present, and should imply a temporal phase lag, with respect to longitudes, of the impact of the thermocline shoaling on the surface properties. In 2006, the mid-June reversal of the SLA zonal gradient was more rapid, even though some evidence of an eastward propagation of negative anomalies

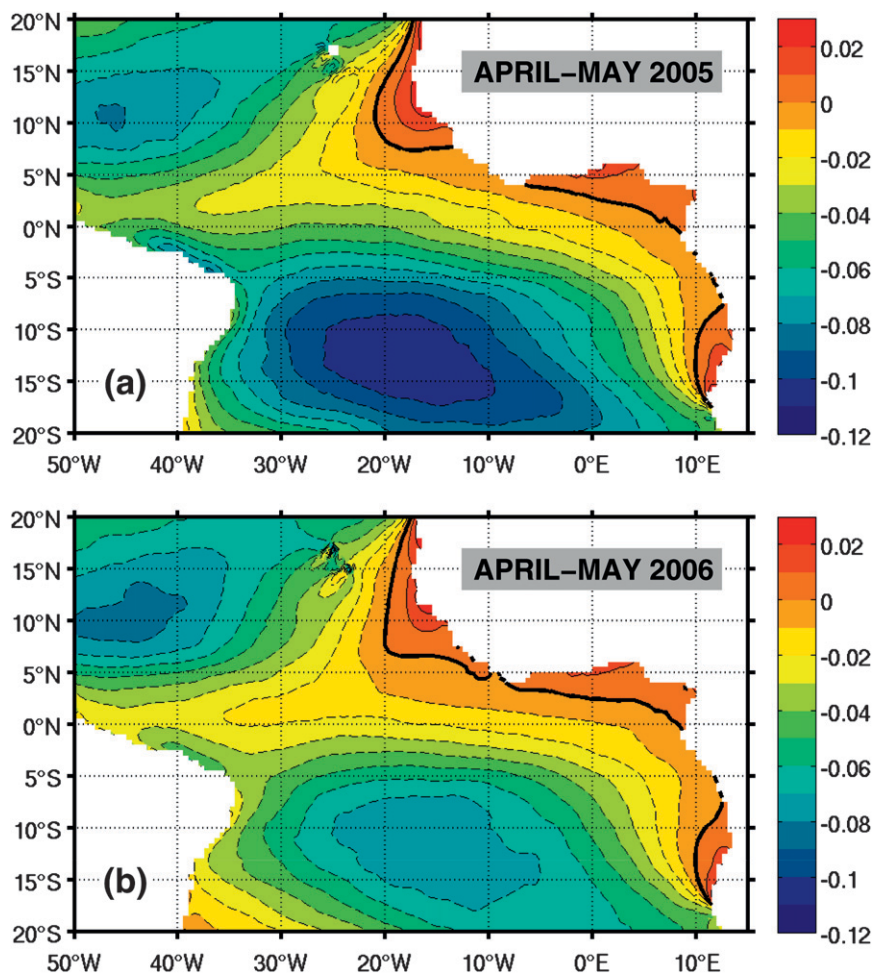


FIG. 3. Horizontal distribution of mean zonal wind stress in April–May (a) 2005 and (b) 2006. Zonal wind stresses are derived from the 6-hourly operational ECMWF model analyses. Unit: N m^{-2} .

can be found in the SLAs (dashed line in Fig. 5b) and in the SLA differences between 2006 and 2005 (Fig. 6b).

4. Analysis of the cooling

a. Temporal evolution of SST

Finescale differences in the evolution of SST in 2005 and in 2006 are presented in the latitude–time Hovmöller diagrams of zonally averaged SSTs over 4°W – 4°E (Figs. 7a and 7b). Three regions can be identified both in 2005 and 2006: 1) north of the equator, where the SSTs, although cooling, were the warmest over the course of the boreal summer season; 2) from the equator to 4°S , where SSTs decreased earlier, as soon as April; and 3) from 5° to 10°S , where cooling appeared later in the season. In both years, these three regions were separated by, respectively, sharp (between zones 1 and 2) and weaker (between zones 2 and 3) meridional gradients.

In 2005, the cooling increased sharply in mid-May from the equator to 4°S , leading to a 2°C decrease in SST in about one week (Fig. 7a). In 2006, the cooling was comparatively smoother in time and began later. Maximum SST differences between 2006 and 2005 (Fig. 7c) appear suddenly in mid-May between 1°N and 6°S , maintaining values greater than 2°C until the beginning of July between the equator and 4°S . Positive differences cancel out progressively from mid-July to mid-August, and SSTs then remained similar in 2005 and 2006 till the end of the year. Note that during this last period, meridional displacements of the northern boundary of the cold tongue induced patches of positive–negative SST differences at the equator.

A closer look at the time evolution of temporal variations in spatially averaged SSTs between 4°S and the equator (region 2 above) confirms that the development of the equatorial cold tongue is not smooth and

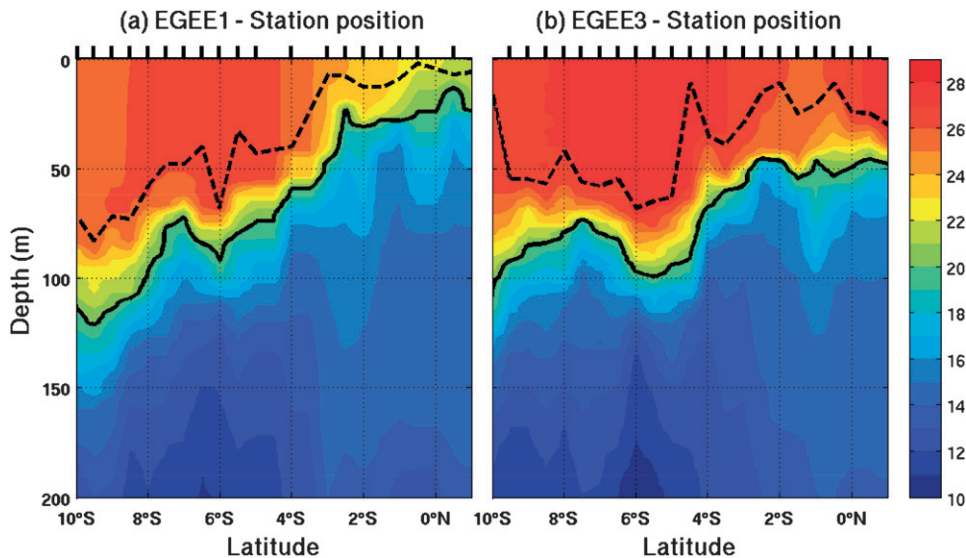


FIG. 4. Meridional section of temperature along 10°W in June 2005 and 2006. Data were collected (a) in June 2005 during EGEE-1 and (b) in June 2006 during EGEE-3. Continuous and dashed lines refer, respectively, to the 20°C isotherm and to the mixed layer depth, which was computed as the depth where the temperature differs from the SST by 0.3°C. Ticks above the two plots correspond to the locations of the hydrographic stations.

continuous (Fig. 8, bottom panels). Instead the formation of the cold tongue results from the succession of intense and short-duration cooling events (Fig. 8, bottom panels), which take place from March to May in both 2005 and 2006. The mid-May 2005 event is the strongest and of the longest duration, peaking at $-0.3^{\circ}\text{C day}^{-1}$ and exceeding $-0.2^{\circ}\text{C day}^{-1}$ during one week, with no equivalent at the same period in 2006. This particular event was able to create a difference of 2°C in SST conditions between June 2005 and June 2006, but the cold tongue in both years started developing sooner, in mid-April, when two strong cooling events greater than $0.2^{\circ}\text{C day}^{-1}$ occurred in 2005 and 2006. Cooling events, separated by warming events of weaker magnitude, are observed until mid-August. Note that the strongest cooling events (greater than $0.2^{\circ}\text{C day}^{-1}$) are found between mid-May and mid-June in 2005, and one month later in 2006 (between mid-June and mid-July).

Finally, a Hovmöller longitude–time diagram of the meridionally averaged SSTs between 4°S and the equator shows that the sudden cooling in mid-May 2005 was not confined to 0°E, but took place simultaneously over a broad region extending from 20°W to 8°E, with no evidence of a time phase lag with respect to longitude (Fig. 9a). Since no such intense cooling was present in mid-May 2006 at any longitude (Fig. 9b), the cooling event of mid-May 2005 led to 2°C colder temperatures than in 2006, which persisted until the end of July 2005 west of 15°W (Fig. 9c).

b. Heat fluxes

Sea surface heat fluxes and wind stress can impact locally the heat content and turbulent mixing within the mixed layer. Hovmöller diagrams of ECMWF net heat fluxes indicate, both in 2005 and 2006, a net heating between 1°N and 4°S (Fig. 10), which acts against the development of the equatorial cold tongue. Such a negative feedback between the seasonal cold tongue and the heat fluxes has long been documented (e.g., Foltz et al. 2003; Foltz and McPhaden 2006). South of the equator, heat fluxes are negative, thus contributing to the cooling of the southern part of the cold tongue (Fig. 10). However, a cooling of the order of 5°C from the beginning of May to the end of July (as observed along 8°S in 2005 and 2006) would require a mean heat flux of -130 W m^{-2} when distributed over a 50-m-thick surface mixed layer. Such an estimate is far stronger than the observed mean net heat flux over this period (Fig. 10). This suggests that heat fluxes are not the unique contributor to the cooling south of 7°S.

The heat flux differences between 2006 and 2005 (Fig. 10c) show that the cooling was less intense in 2006 than in 2005 from April to June south of 7°S (Fig. 10c), in agreement with the observed colder SSTs in 2005 at these latitudes (Fig. 8c). On the contrary, between 6°S and the equator, more heat was gained at the ocean surface in 2005 than in 2006; heat fluxes then partly counterbalance SST anomalies between the two years.

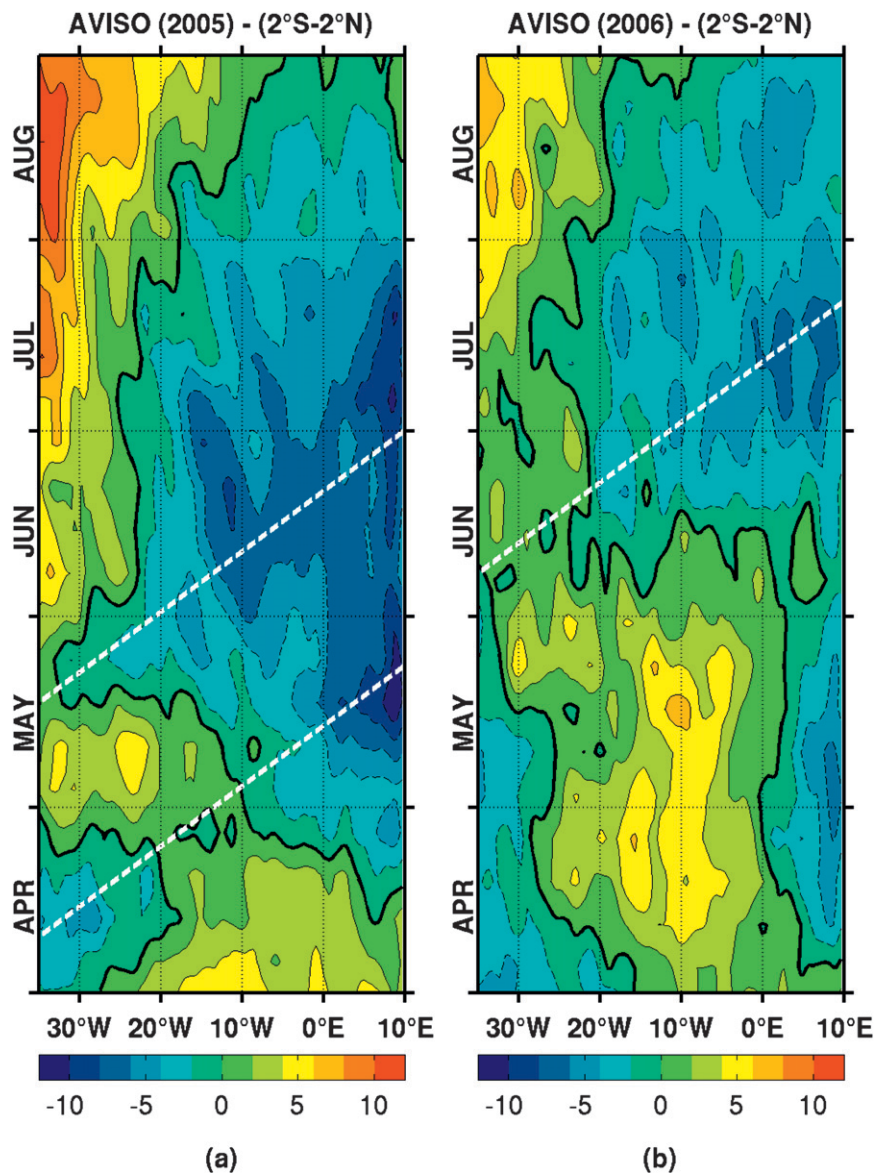


FIG. 5. Hovmöller longitude–time diagrams of AVISO SLAs along the equator in (a) 2005 and (b) 2006. AVISO SLAs are meridionally averaged between 2°S and 2°N. Dashed lines refer to negative values. Dashed white lines refer to the eastward propagation of Kelvin waves with phase velocities of 1.3 m s^{-1} , corresponding to a second baroclinic mode. Unit: cm.

Verification of heat flux anomalies between 2005 and 2006 shows that they were dominated by latent heat flux anomalies (not shown) originating from the colder SST conditions in 2005. Moreover, strong intraseasonal fluctuations of the net heat flux can be observed between 4°S and the equator both in 2005 and 2006 (Figs. 10a and 10b), but their amplitude (lower than 100 W m^{-2} , which corresponds to an SST variability of $0.04^\circ\text{C day}^{-1}$ when distributed over a 50-m-thick mixed layer) is far weaker than the magnitude of the cooling events. The latent heat flux, and consequently the net surface heat flux, are

thus the result of SST differences between 2005 and 2006, and not the cause of the observed changes in the cooling rates over the cold tongue between the two years.

c. Regional impact of the intraseasonal wind intensifications

Hovmöller diagrams of wind stress magnitude derived from the operational ECMWF model analyses (Figs. 7d–f) show the presence of intense intraseasonal wind intensifications in the Southern Hemisphere, when

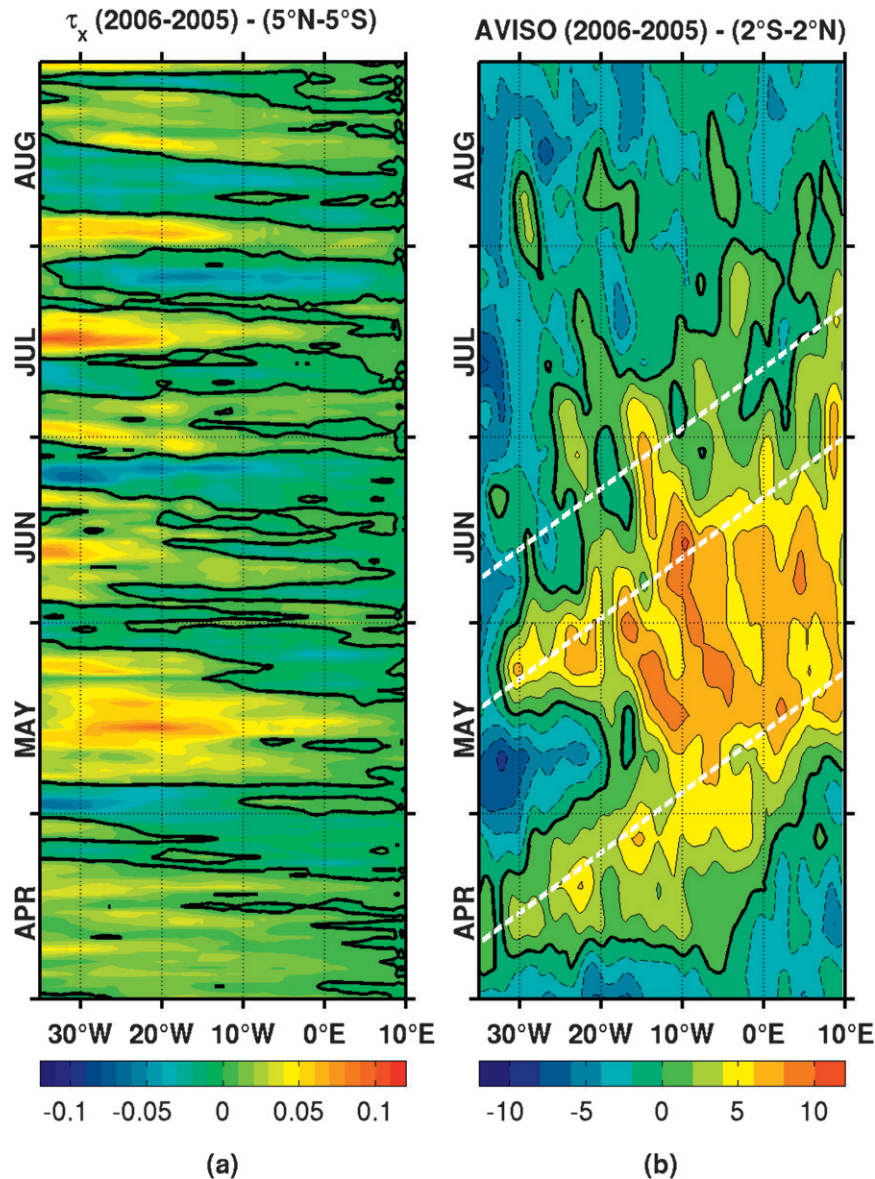


FIG. 6. Hovmöller longitude–time diagrams of 2006 minus 2005 differences in (a) ECWMF zonal wind stress and (b) AVISO SLAs near the equator. Data are meridionally averaged between 5°S and 5°N for wind stress and between 2°S and 2°N for SLAs. Dashed white lines refer to the eastward propagation of Kelvin waves with phase velocities of 1.3 m s^{-1} , corresponding to a second baroclinic mode. Units: N m^{-2} (cm) wind stress (SLAs).

seasonal trades are at their maximum in this region, at times even crossing the equator (for instance in mid-May 2005). Wind stress maxima were comparatively stronger in 2005 than in 2006 from April to mid-June and weaker after June, even though intraseasonal intensifications of winds continued to occur after mid-June 2005.

Wind stress (Fig. 7f) and SST (Fig. 7c) differences between 2005 and 2006 show that the strong wind intensification of mid-May 2005 coincided with the be-

ginning of the strong SST difference observed between the two years, thus suggesting that it was directly responsible for the quick, increased cooling observed in May 2005 between 1°N and 7°S. More generally, most cooling events between 4°S and the equator in Fig. 8 (bottom panel) coincide with intraseasonal intensifications of the southeast trades (Fig. 8, top and middle panels), indicating that local winds (though weaker at these latitudes than more southward) can give rise to

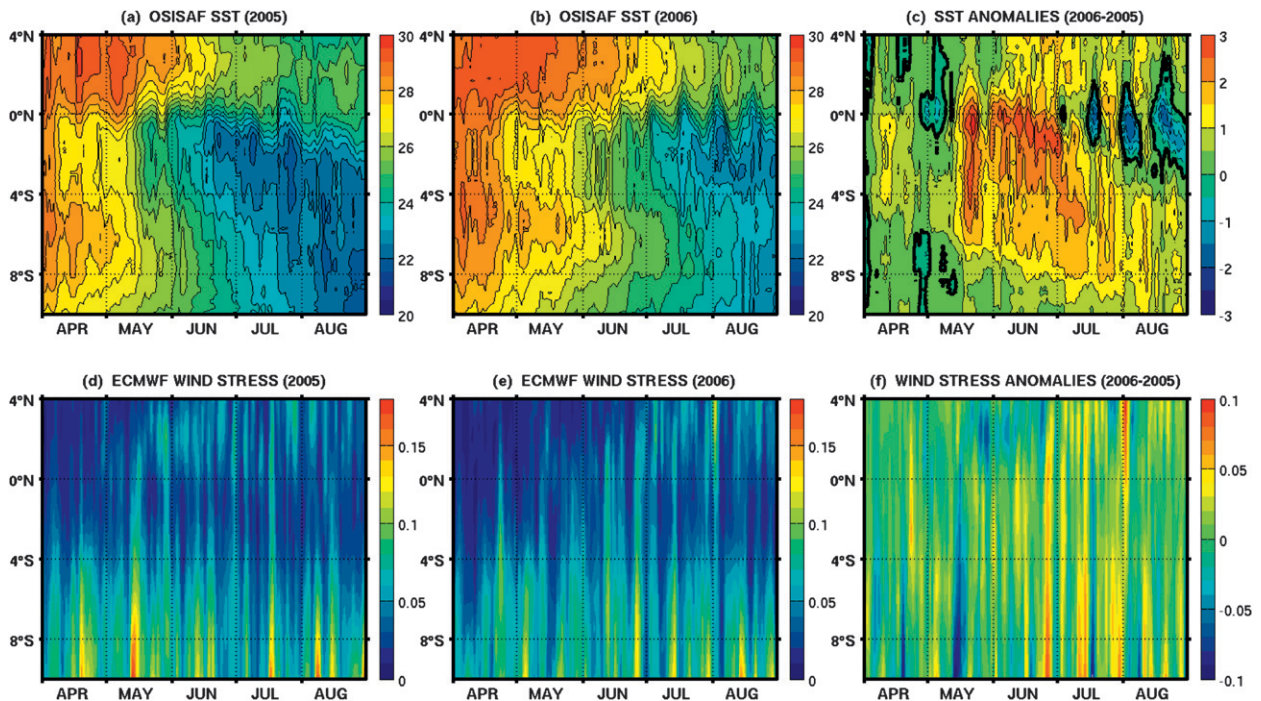


FIG. 7. Hovmöller latitude–time diagrams of SST and magnitude of the wind stress along the box 4°W – 4°E . (a)–(c) OSI-SAF SST data and (d)–(f): ECMWF wind stress magnitudes: (a),(d) 2005, (b),(e) 2006, and (c),(f) 2006 minus 2005. All data are zonally averaged between 4°W and 4°E . Intervals between contours are 0.5°C for SST and 0.01 N m^{-2} for wind stress.

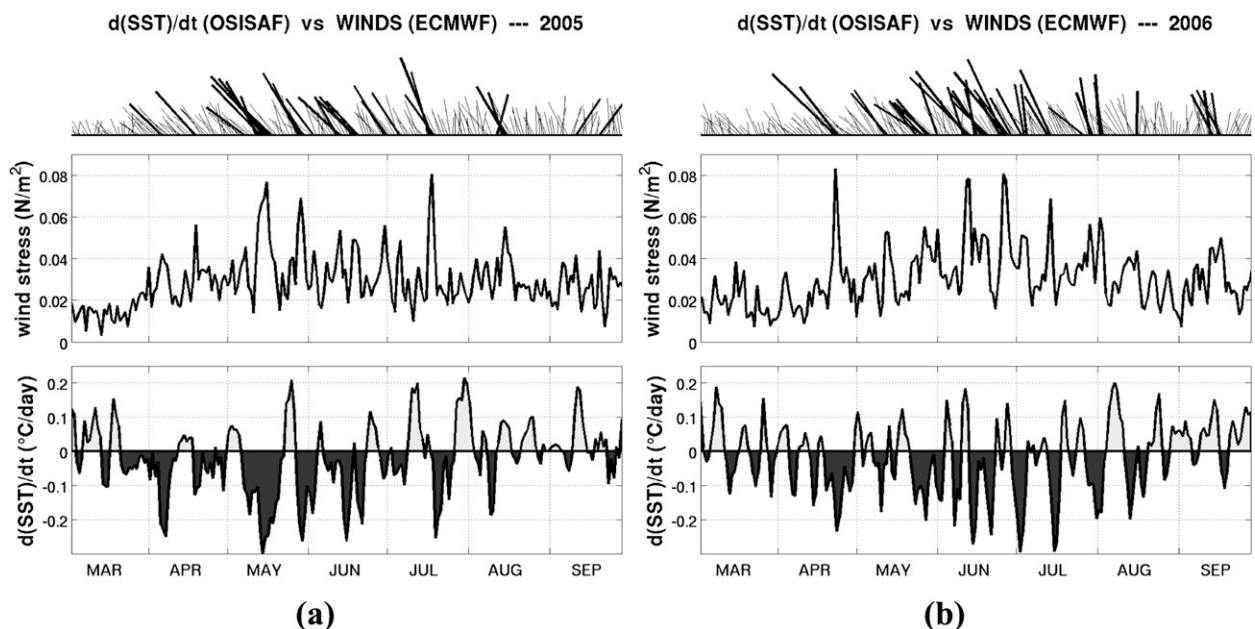


FIG. 8. Temporal evolution of ECMWF wind stress (top) direction, (middle) magnitude, and (bottom) OSI-SAF SST time gradients for (left) 2005 and (right) 2006. All data are averaged between 4°S and the equator in latitude and between 4°W and 4°E in longitude. A 3-day running average has been applied to the SST data to filter out the day-to-day noise. Time index (in months) extends from March to September. Wind stresses exceeding 0.04 N m^{-2} are indicated by thick lines in the top panels. Units: $^{\circ}\text{C day}^{-1}$ (N m^{-2}) for the SST time gradient (the wind stress).

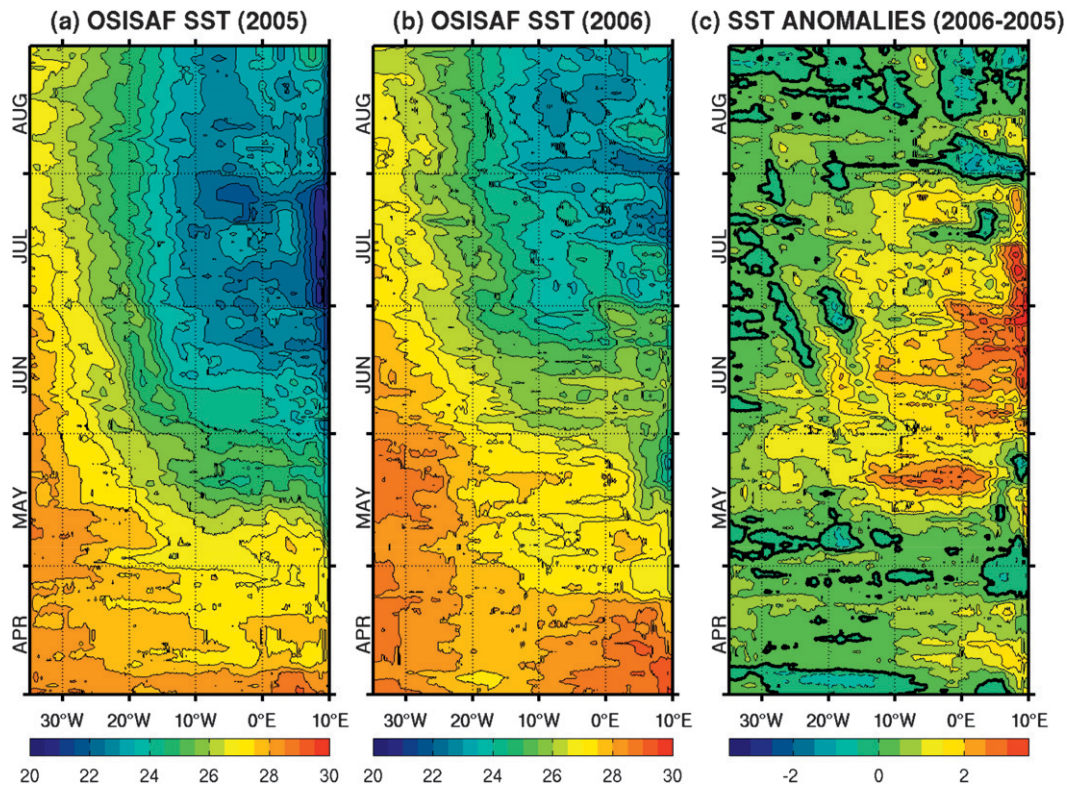


FIG. 9. Hovmöller longitude–time diagrams of OSISAF SST data meridionally averaged between 4°S and the equator: in (a) 2005, (b) 2006, and (c) the resulting 2006 minus 2005 anomalies. Time axis (months) extends from April to August. Unit: °C.

intense, short-duration cooling events. Note that there is an overall close correspondence between the amplitude of the cooling and the magnitude of the local wind stress, both being stronger in May and July 2005, and from June to July 2006. In April of both years, the large cooling event that initiated the cold tongue development was also associated with an intensification of southeasterlies, even though the stronger intraseasonal winds in 2006 did not lead to a more intense cooling that year. After mid-August, the cooling events disappeared at the same time as the intraseasonal wind fluctuations, and the SST differences between the two years cancel out (Fig. 7c).

These events point out that intraseasonal intensifications of the southeast trades are mostly able to enhance local mixing at the mixed layer base to induce extra SST cooling, which ultimately generates persistent cold anomalies for the cold tongue and thus accelerates the onset of the cold tongue season. This process is more efficient when wind intensifications are the strongest, and when and where mixed layers are shallow, as was the case in 2005 in the Gulf of Guinea, south of the equator, when the basin-scale preconditioning had greatly shoaled the mixed layer in the eastern Atlantic from mid-May.

The undulations of the northern SST front are seen to be in phase with the wind intensifications, with amplitudes that increase in time and are at a maximum when the SST front is sharpest, for instance after mid-June in 2006 (Figs. 7b and 7e). This meridional migration of the northern SST front brings the warm waters of the Northern Hemisphere south of the equator, thus contributing to the warming events that are seen in Fig. 8. Also note the progressive southward shift of the SST difference from 6°S in mid-May to 10°S in mid-August (Fig. 7c), which is compatible with the observed warmer SST south of 6°S in 2006 (Figs. 2 and 8a). This southward shift induces a net cooling along of 1.5°C along 8°S between 1 May and 1 July, which is compatible with a mean negative heat flux difference of the order of 40 W m^{-2} (as observed in Fig. 10c) distributed over a 50-m-thick surface mixed layer.

5. Spatial distribution of the intraseasonal Southern Hemispheric winds

Our analysis suggests that the cold tongue season in 2005 was not uniquely initiated by the equatorially trapped oceanic response to remote variability in near-

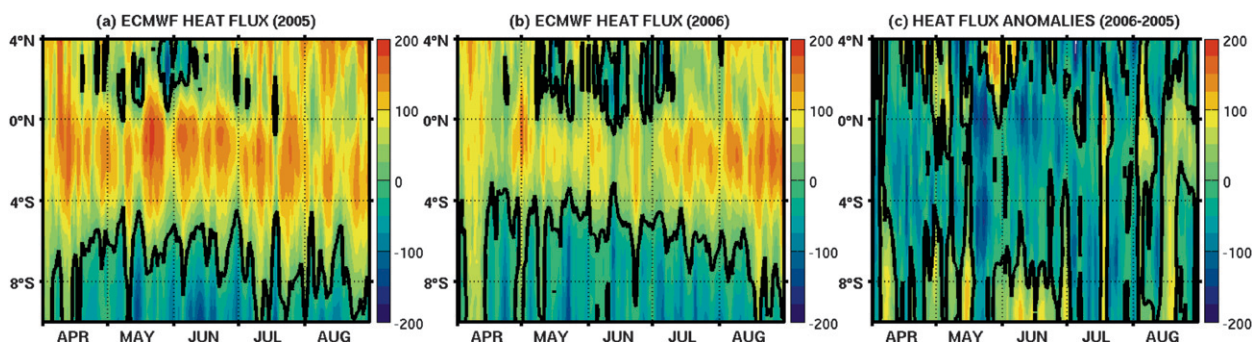


FIG. 10. Hovmöller latitude–time diagrams of ECMWF net sea heat fluxes along the box 4°W – 4°E , in (a) 2005, (b) 2006, and (c) the resulting 2006 minus 2005 anomalies. ECMWF net heat fluxes are zonally averaged between 4°W and 4°E . Positive fluxes are into the ocean. Time axis (months) extends from April to August. Units: W m^{-2} and interval between contours is 50 W m^{-2} .

equatorial winds west of 10°W , whose effect was essentially to precondition the subsurface conditions in the eastern Atlantic. Instead, a strong Southern Hemispheric intraseasonal wind intensification in the Gulf of Guinea was found to be responsible for the sudden and intense SST cooling in the eastern Atlantic in mid-May 2005.

The spatial distribution of this particular wind event can be inferred from Fig. 11, which presents the ECMWF wind stress on 11 May 2005 (Fig. 11a) and the subsequent wind stress anomalies with respect to this date each three days after from 14 to 20 May 2005 (Figs. 11b–d). The wind stress field is dominated by the southeast trades south of, and northeast trades north of, the intertropical convergence zone that lies along a line extending from 4°N west of 36°W to 8°N near 15°W . Southeast and northeast trades are the tropical westward components of the Azores and St. Helena anticyclones, respectively. On 11 May 2005, maximum wind stresses were found west of 6°W . Near the equator (from 6°S to 6°N), the wind stress was mainly northward west of 10°W , as part of the St. Helena anticyclone, while it is seen to almost vanish within the whole longitudinal extent of the Gulf of Guinea. Three days later, at the peak of the Southern Hemispheric wind event of mid-May 2005, intense southeasterly winds blew over the Gulf of Guinea from 10°S to the equator, with a magnitude that is comparable to the wind stress amplitude three days before west of 10°W (Fig. 11b). This southeasterly wind intensification was at its maximum south of 10°S , but reached the equator from 15°W to 5°E . Note the concomitant reinforcement of the easterlies between 8°S and 8°N west of 30°W . Subsequently, the wind event in the Gulf of Guinea disappears, simultaneously with its weaker equatorial counterpart west of 30°W , finally giving place to an off-equatorial weakening of the easterlies beyond 8° in latitude in each hemisphere on 20 May 2005 (Fig. 11d). It is noteworthy that both the longitudinal and lat-

itudinal extents of this wind intensification coincide with the location of the intense cooling that was evidenced in mid-May 2005 north of 10°S .

The spatial structure of this wind intensification is not specific to mid-May 2005. A comparison of longitude–time diagrams of the zonal wind stress along the equator and of the meridional wind stress between 10°S and the equator for 2005 and 2006 (not shown) indicates that the strongest meridional wind events in the Gulf of Guinea (in mid-May 2005, mid-June 2005, and in the second half of June 2006) coincide with zonal wind anomalies of comparable magnitude west of 15°W near the equator. This suggests that the strongest Southern Hemispheric intraseasonal winds east of 15°W and the strongest near-equatorial intraseasonal winds west of 20°W both result from the variability of the St. Helena anticyclone that manifests itself as an intensification of the southerlies in the Gulf of Guinea and of the easterlies in the western part of the equatorial Atlantic.

However, though simultaneous, these intraseasonal wind intensifications have distinctly different impacts on the SST in the Gulf of Guinea. In the western Atlantic they mainly act as a remote forcing to shoal the thermocline a few weeks later in the eastern Atlantic through equatorial ocean adjustment. In contrast, in the Gulf of Guinea, they provide a local and quick mechanism to cool the SST (as in mid-May 2005).

6. Discussion and conclusions

Focusing on the variability of sea surface temperatures in the eastern equatorial cold tongue provides insight into the interaction between the fluxes and hydrodynamics in developing strong SST gradients. In this paper we have focused our analysis on the central part of the cold tongue, between 4°W and 4°E . Farther east, the cold tongue is known to be strongly influenced by coastal upwelling whose dynamics is beyond the scope

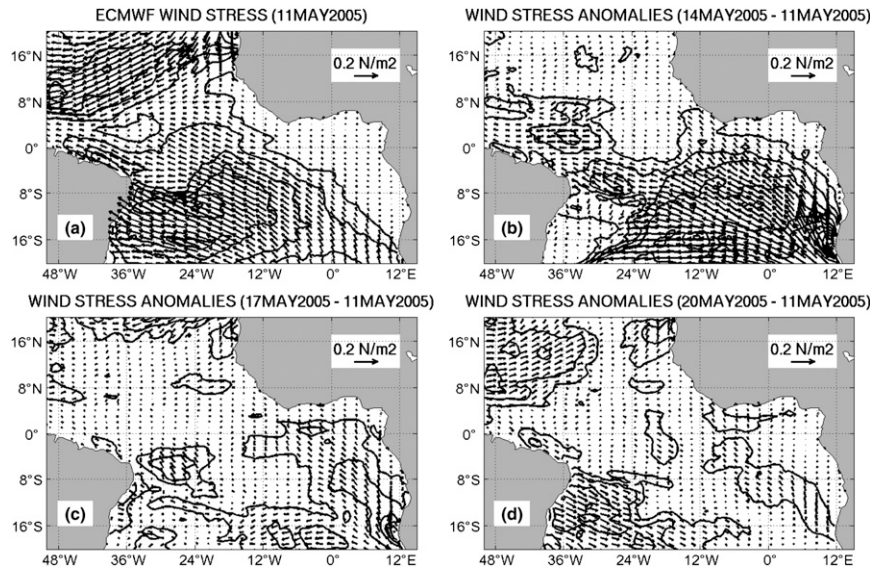


FIG. 11. Horizontal distribution of ECMWF wind stress for (a) 11 May 2005, and subsequent wind stress anomalies vs 11 May 2005 for (b) 14, (c) 17, and (d) 20 May 2005. Wind stress (anomalies) magnitude is shown in contours. Interval between contours is 0.025 N m^{-2} .

of the present study. West of this region, tropical instability waves are an additional contributor to the ocean mixed layer heat budget (e.g., Weisberg and Weingartner 1988; Jochum et al. 2004; Peter et al. 2006). The comparison of SST (Fig. 1) and sea level anomalies (Fig. 5) indicates that tropical instability waves occurred earlier and were more intense in 2005 than in 2006, suggesting that they were closely linked to the setup and westward extension of the equatorial cold tongue.

SSTs were observed to be colder in the Gulf of Guinea in June 2005 than in June 2006. However, the differences in SST between the two years were less pronounced in March and August. The main difference is thus more closely related to a time shift of the cold tongue onset (approximately a 5-week delay between 2005 and 2006) than to a change in the intensity of the cooling for the whole cold season. One part of this difference is explained by the preconditioning phase, due to stronger easterlies west of 20°W in 2005 that induced a shallower thermocline in the Gulf of Guinea, in agreement with the equatorial mode of tropical Atlantic variability (Houghton 1989, 1991).

The existence of intraseasonal variability in SST in the Gulf of Guinea along the equator, corresponding to the meridional displacement of the SST front, was determined by Garzoli (1987), Houghton and Colin (1987), and Athie and Marin (2008) to be forced by 15-day intraseasonal anomalies in the meridional wind stress, through the excitation of oceanic mixed Rossby–gravity waves. Intraseasonal intensifications of the southeast trades are shown here to also be a major contributor to

the SST cooling south of the equator. In particular, 2005 provides evidence of a specific strong wind intensification in mid-May that had a dramatic effect on the onset of the cold tongue, considerably cooling the SST by more than 2°C south of the equator over a little more than a week (Fig. 12a). This intense and quick cooling in mid-May 2005, which had no equivalent in 2006, accounted for most of the SST difference between 20 May 2005 and 20 May 2006 (cf. Figs. 12b and 12a). Instead of a progressive development of the cold tongue in 2005, this suggests a stepwise evolution of the SST in response to this wind event. This quick cooling induced persistent cold SST anomalies, suggesting a short-duration irreversible mechanism. Our comparison of successive intraseasonal intensifications of the southeast trades in 2005 and 2006 has shown that their impact on SST depended crucially upon their intensity, their equatorward extension, and the local oceanic conditions at the time of their occurrence. This indicates that intraseasonal winds must meet a minimum threshold and be supported by subsurface preconditioning, such as shallow mixed layers, to be efficient in cooling the SST. This was in particular the case in 2005 when the mixed layer and thermocline were shallower after the basin-scale preconditioning in response to stronger easterlies in the west.

Similar results were presented for the eastern Pacific by Zhang and McPhaden (2006), who showed that local wind stress was able to work with, or against, remote wind stress forcing from the western Pacific to modulate the intensity of the SST cooling and the amplitude of ENSO events. In the Atlantic, numerical simulations by

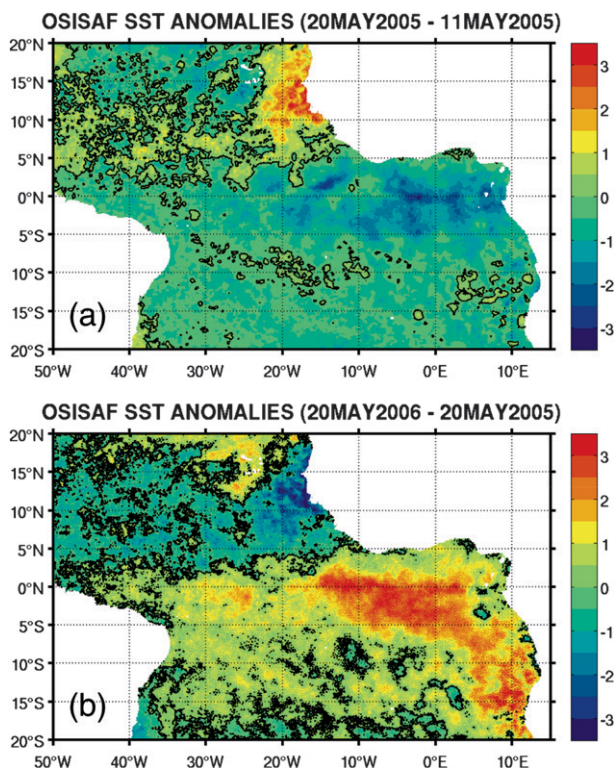


FIG. 12. Horizontal distribution of OSI-SAF SST differences (a) between 20 and 11 May 2005 and (b) between 20 May 2006 and 20 May 2005. Contours refer to the zero isoline. Unit: $^{\circ}\text{C}$.

Cane (1979) and Philander and Pacanowski (1986b) suggested that the boreal summer intensification of southerly wind stresses in the eastern Atlantic could generate local upwelling near 1°S due to the divergence of seasonal surface currents, but that this mechanism was not strong enough to generate the observed cold tongue (Adamec and O'Brien 1978). However, our analysis suggests that the presence of intense wind intensifications prior to the monsoon season in the Gulf of Guinea, whose amplitude is far larger than the seasonal variations of the southerly wind stress in the Gulf of Guinea, was crucial for the cold tongue onset in 2005.

The strongest intraseasonal intensifications of winds in 2005 and 2006, west and east of 10°W , are shown to be the concomitant equatorial manifestations of the temporal variability of the St. Helena anticyclone in the Southern Hemisphere. Such intraseasonal variations in both the north- and southeast trade winds of the tropical Atlantic were previously documented by Foltz and McPhaden (2004) for periods between 30 and 70 days, who showed that they were linked to changes in the subtropical highs. West of 10°W , this variability manifests itself as strong westward wind anomalies that intensify easterlies and trigger the delayed basin-scale

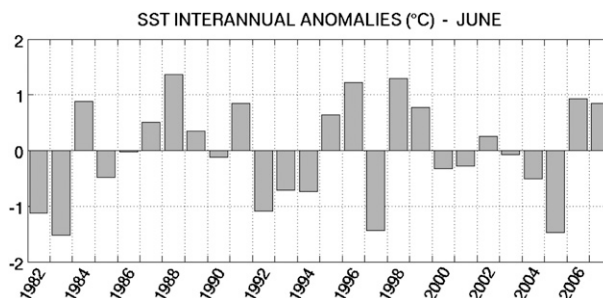


FIG. 13. Interannual anomalies of monthly SST (June) averaged over the region 4°S – 0°N and 4°W – 4°E , from the Reynolds et al. (2002) monthly SST dataset. SST anomalies are computed relative to a mean June climatological value of 25.02°C over the period 1982–2007. Unit: $^{\circ}\text{C}$.

adjustment of the equatorial thermocline. East of 10°W , this variability induces intense southerly wind anomalies that likely intensified the mixing at the base of the mixed layer and thus cooled SSTs locally. The earlier onset of the cold tongue season in 2005 was thus favored by the equatorially trapped shoaling of the thermocline in the Gulf of Guinea that was remotely forced by stronger easterlies one month before in the west, but was triggered locally by the sudden intensification of mixing processes in response to stronger southerlies over the whole extent of the Gulf of Guinea. The mechanism for the generation of these intraseasonal intensifications of southeast trades, both originating from the South Atlantic, still needs to be investigated.

This dependence of the cold tongue development on mixed layer variability underscores the importance of near-surface oceanic processes in the eastern tropical Atlantic. Interannual anomalies in net heat fluxes in boreal summer are not the cause of the observed SST differences between 2005 and 2006 from 6°S to 1°N , but rather are the consequence of a reduced cooling over warmer waters in 2006 by latent heat fluxes. The local effect of winds and of subsurface oceanic conditions are thus thought to be the major drivers of the 2005 and 2006 observed differences in SST for this region in boreal summer, whereas surface heat fluxes mainly act as a negative feedback on SST (e.g., Foltz et al. 2003; Foltz and McPhaden 2006).

The SST conditions in June 2005 and June 2006 correspond to extreme events for the period 1982–2007 (Fig. 13): the SST in June 2005 was among the coldest of the months of June for the last 26 yr (along with 1983 and 1997), while the SST in June 2006 was one of the warmest (along with 1984, 1988, 1996, 1998, 1999, and 2007). The succession of two extreme cold and warm events on two consecutive years is not particular to 2005 and 2006, but was also observed in 1983 and 1984 and

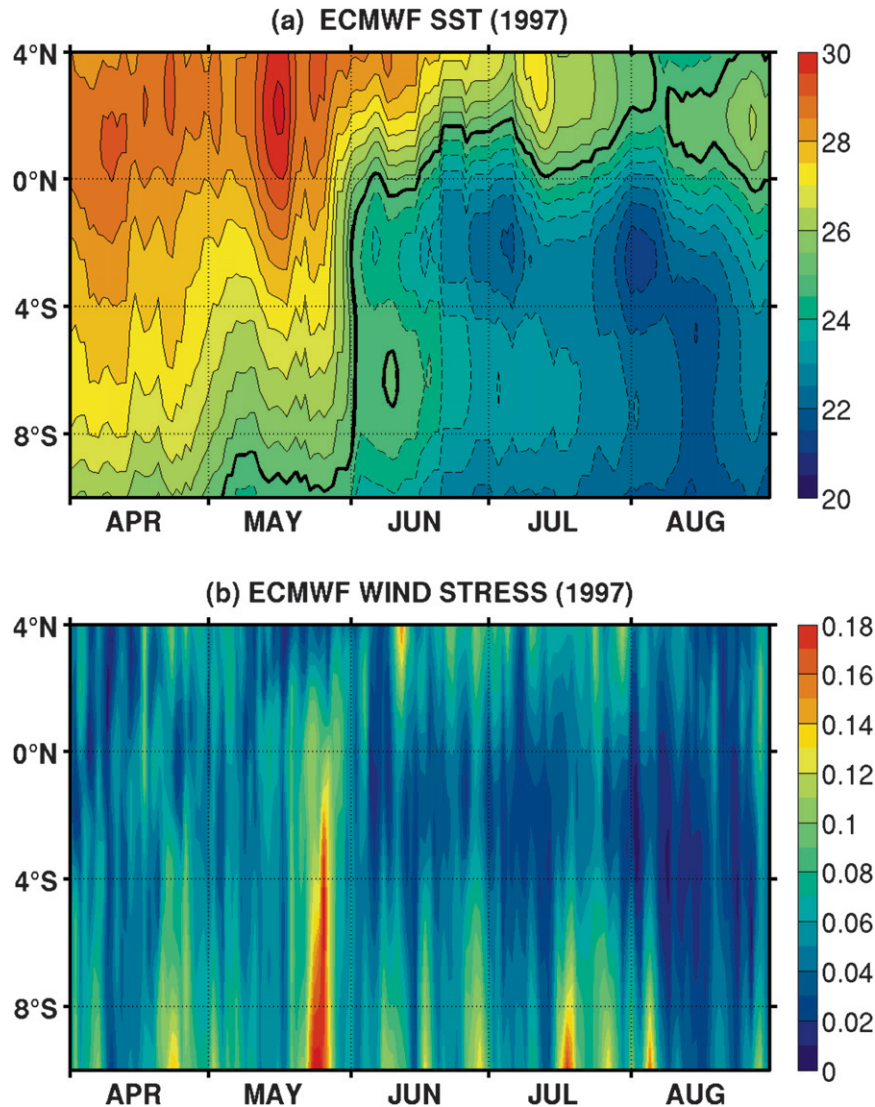


FIG. 14. Hovmöller latitude–time diagrams of ECMWF (a) SST and (b) wind stress along the box 4°W–4°E in 1997. Time axis (in months) extends from April to August. Units: °C (N m^{-2}) for SST (wind stress).

1997 and 1998. In 1997, intraseasonal intense winds were present, as in 2005, in the second half of May from 10°S to the equator (Fig. 14a), along with a quick cooling of 3°C of the SST in less than one week from 6°S to 1°N (Fig. 14b), suggesting that a similar scenario took place in 1997 and in 2005.

Year-to-year variability in the timing of the cold tongue onset, and the associated meridional SST gradient over the Gulf of Guinea, may play an important role for the intensity and northward jump of the African monsoon and related precipitation (Opoku-Ankomah and Cordery 1994; Kouadio et al. 2003; Gu and Adler 2004). Preliminary results from the AMMA program indicate that both the WAM and the cold tongue ap-

peared earlier during 2005 and later in 2006 (Janicot and Sultan 2007; Lebel et al. 2007; Janicot et al. 2008). The analyses in progress within the framework of the AMMA program will help to elucidate the mechanisms at play for the onset of the cold tongue and its influence on the WAM system.

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