On the Seasonal Cycle of the Equatorial Atlantic Ocean

TIANMING LI AND S. G. H. PHILANDER

Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, New Jersey

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ABSTRACT

Although the seasonal cycle of the equatorial Atlantic and Pacific Oceans have many similarities, for example, an annual signal is dominant at the equator even though the sun ''crosses'' the equator twice a year, different processes determine the seasonal cycles of the two oceans and in the Atlantic different processes are important in the east and west. In the Gulf of Guinea in the eastern equatorial Atlantic, the seasonal cycle of surface winds is primarily in response to seasonal variations in land temperatures so that annual changes in sea surface temperatures are, to a first approximation, the passive response of the ocean to the winds. The seasonal cycle of the western equatorial Atlantic has similarities with that of the equatorial Pacific—both are strongly influenced by ocean–atmosphere interactions in which the surface winds and sea surface temperature patterns depend on each other—but only in the western equatorial Atlantic are the seasonal variations in sea surface temperature influenced by vertical excursions of the thermocline. These results are obtained by means of a general circulation model of the atmosphere and a relatively simple coupled ocean–atmosphere model.

1. Introduction

The tropical Atlantic and Pacific Oceans have very similar seasonal cycles. For example, at the equator an annual signal is prominent, in both components of the winds and in sea surface temperatures, even though the sun ''crosses'' the equator twice a year. In the Pacific, that annual signal is attributable to the asymmetry of the time-averaged fields relative to the equator (Li and Philander 1996). The Atlantic has a similar asymmetry—the warmest surface waters and the intertropic convergence zone (ITCZ) where rainfall has a maximum, are mostly north of the equator—so that the same processes could, in principle, be responsible for the similar seasonal cycles in the two oceans. In this paper we argue that, despite the similarities, different processes determine the seasonal cycle in the Atlantic and Pacific. First, we explain why the factors that contribute to the asymmetries of the time-averaged states are different in the Atlantic and Pacific.

On a water-covered globe, easterly trade winds near the surface would prevail everywhere in the Tropics. The presence of continents modifies the easterlies significantly in the Indian Ocean where monsoons are dominant, less so in the Atlantic and Pacific where asymmetries relative to the equator, of the time-averaged conditions, are the principal consequences of the continents. The asymmetries in the Atlantic and Pacific are similar—for example, an ITCZ that is mostly north of the equator—but are caused by different aspects of the continental geometries in the two oceans. What matters most in the case of the Atlantic is the bulge of western Africa to the north of the Gulf of Guinea; in response to solar radiation that is symmetrical about the equator, this bulge attains far higher temperatures than the adjacent ocean and induces northward, cross-equatorial winds that favor oceanic upwelling and low sea surface temperatures south of the equator. In the case of the Pacific the slope of the western coast of the Americas relative to meridians appears to be the critical factor; the winds around the subtropical high pressure zones are parallel to the coast south of the equator, where they induce coastal upwelling and low SSTs, but north of the equator the winds tend to be nearly perpendicular to the coast at the latitudes of Panama and the surface waters remain warm (Philander et al. 1996).

In the Pacific Ocean the asymmetry relative to the equator, of the time-averaged conditions, is principally responsible for the annual harmonic at the equator even though, at that latitude, the variations in solar radiation have a significant semiannual signal (Li and Philander 1996). Because of the asymmetry, the time-averaged winds are northward so that the net wind at the equator is intense once a year (typically in August) and weak once a year (typically in March). Sea surface temperatures therefore acquire an annual harmonic because they are influenced by evaporation, which depends on the total wind speed. The contribution of this particular mechanism to the annual harmonic in SST in the Pacific is modest; to explain the magnitude of the observed

Corresponding author address: Dr. Tianming Li, Naval Research Laboratory, 7 Grace Hopper Ave., Monterey, CA 93943.
E-mail: li@nrlmry.navy.mil

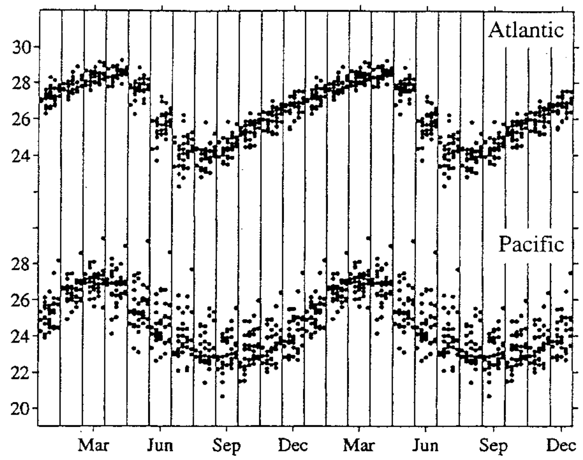

FIG. 1. Observed monthly mean sea surface temperatures in the eastern equatorial Atlantic (4°S–4°N, 16°W–4°E) and Pacific (4°S–4°N, 104°–86°W) oceans, grouped by calendar month (adopted from Mitchell and Wallace 1992).

annual harmonic, additional mechanisms such as upwelling and interactions between the ocean and atmosphere have to be invoked (Chang and Philander 1994).

This paper concerns the annual harmonic in the equatorial Atlantic Ocean. Even though its amplitude is similar to that of the annual harmonic in the Pacific (see Fig. 1) the processes that determine that amplitude turn out to be different in the two oceans. Calculations to be presented here indicate that continental geometry influences the seasonal cycle of the winds far more in the Atlantic than the Pacific. First, in section 2, we explore the relative importance of land and ocean surface temperature fluctuations to the seasonal wind fluctuations by using an atmospheric general circulation model (GCM). Next, in section 3, we study the role of ocean–atmosphere interactions by means of a relatively simple coupled model. The final section discusses the results.

2. Relative importance of land and ocean temperatures in determining the seasonal cycle of winds in the Tropics

The tool for our studies in this section is the GFDL R30 atmospheric general circulation model (Manabe and Hahn 1981; Philander et al. 1996). Diagnosis of results from a simulation of atmospheric variability over a period of 35 yr indicates that the model, when forced with seasonally varying solar radiation and with specified sea surface temperatures, successfully reproduces many aspects of the seasonal cycle in atmospheric conditions and in land temperatures. We used the model, forced with seasonally varying solar radiation, for two experiments. In case A, the specified sea surface temperature corresponds to the observed seasonally varying field. In case B, the specified sea surface temperature is time independent; it corresponds to the observed time-averaged field. In both cases the model calculates seasonal variations in land temperatures from the downward shortwave radiation, the upward longwave radiation, and latent and sensible heat fluxes.

At certain locations on the equator in the Atlantic, there is surprisingly little difference between the winds in the two experiments mentioned above. That is especially the case in the Gulf of Guinea where it matters relatively little to the north–south winds in Fig. 2a whether or not the sea surface temperatures vary seasonally. This means that the seasonal changes in those winds depend primarily on land surface temperature variations. This is in sharp contrast to the meridional winds in the eastern equatorial Pacific (shown in Fig. 2c), which are seen to have practically no seasonal variation unless the sea surface temperatures vary seasonally.

Whereas the meridional winds are dominant on the equator in the eastern Atlantic and Pacific, the zonal winds become more prominent in the western parts of both oceans. Figure 2b shows that, in the western equatorial Atlantic, the seasonal variations of the zonal winds once again are practically independent of sea surface temperature changes. (Note that these variations are modest in comparison with the time-averaged winds.) In the equatorial Pacific those seasonal variations depend strongly on the seasonal sea surface temperature changes, as is evident in Fig. 2d.

Figure 3 shows the seasonal variations of the meridional component of the wind, as a function of latitude in the eastern and western parts of the Atlantic, in our two sets of experiments. The left-hand panels confirm that, in the eastern tropical Atlantic, the seasonal variations in the meridional winds are determined primarily by seasonal variations in land temperatures. That is not the case in the western tropical Atlantic, however. Figures 3c and 3d show that there is hardly any north–south movement of the ITCZ (defined to be where the meridional component of the wind vanishes) when sea surface temperatures are independent of time but significant movement when sea surface temperatures vary seasonally.

In the equatorial Atlantic (and Pacific) the seasonal extremes in temperatures are in March and September. If, in a model, sea surface temperatures are assigned the annual mean value then, in March, the temperature gradient across the equator is larger than it ought to be, while in September it is smaller than it ought to be. That is probably the reason why, in the calculations in which sea surface temperatures are assigned their annual mean values, the southeast trades are too intense in March and too weak in September.

3. The role of ocean–atmosphere interactions

The results in section 2 indicate that over the western tropical Atlantic the seasonal north–south movements of the ITCZ depend on seasonal variations in sea surface temperatures. Those winds, on the other hand, contrib-

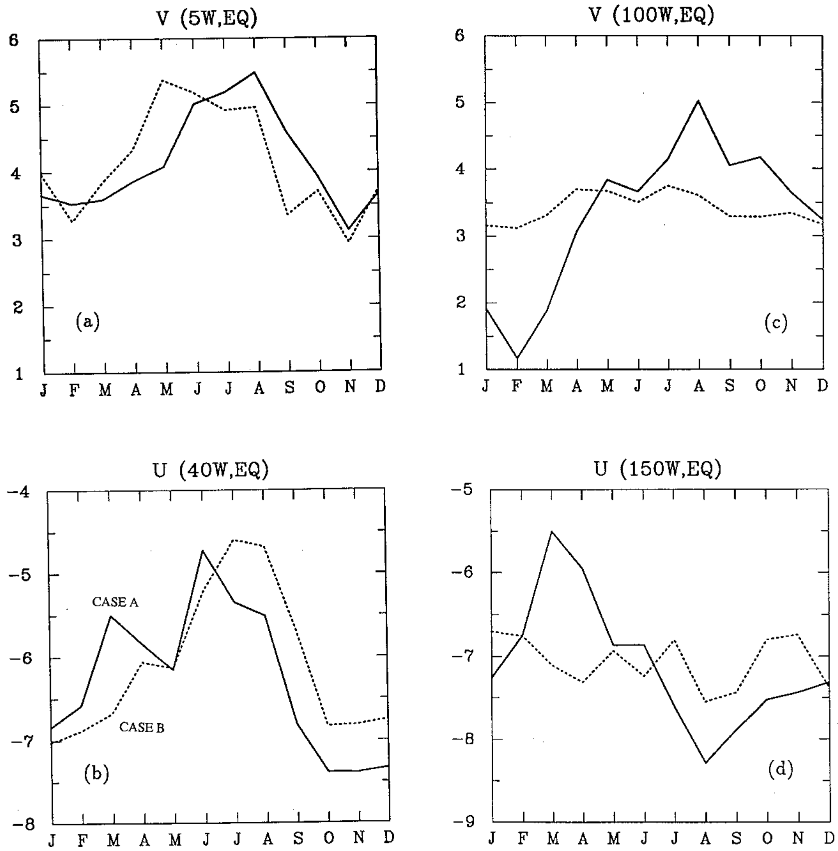

FIG. 2. The GCM simulations of zonal (U) and meridional (V) components of surface winds at certain locations at the equator. The solid lines represent case A in which seasonally varying sea surface temperatures are specified. The dotted lines represent case B in which a climatological annual mean SST field is used. The left-hand panels are for points on the equator in the Atlantic; the right-hand panels are for points on the equator in the Pacific.

ute significantly to the changes in SST (Philander 1990). This circular argument, in which the winds both depend on and determine changes in sea surface temperatures, suggests that interactions between the ocean and atmosphere ought to come into play. To explore those interactions we use the relatively simple coupled ocean–atmosphere model used by Li and Philander (1996) in a study of the seasonal cycle of the tropical Pacific.

The oceanic component of the coupled model is the one described by Cane (1979) and Zebiak and Cane (1987), a linear, reduced-gravity upper ocean with a varying thermocline depth. Sea surface temperature is determined by three-dimensional dynamic processes and by thermodynamic processes that include shortwave radiation and latent heat fluxes at the surface.

In the one-layer atmospheric model the driving terms correspond to pressure forces generated by the temperature gradients at the surfaces below the atmosphere in accordance with the mechanism proposed by Lindzen and Nigam (1987).

For a vertically averaged steady-state boundary layer flow, we have

$$EU - \beta y V = -\frac{\partial \phi}{\partial x} + A\frac{\partial T_s'}{\partial x}, \tag{3.1}$$

$$EV + \beta y U = -\frac{\partial \phi}{\partial y} + A\frac{\partial T_s'}{\partial y}, \tag{3.2}$$

$$\varepsilon \phi = -C_0^2\left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y}\right), \tag{3.3}$$

where U and V represent the mean zonal and meridional wind components in the boundary layer; ϕ is the geopotential height at the top of the boundary layer; E = 1/2.5 day^{-1} denotes a boundary layer friction coefficient; ε = 1/30 min^{-1} is an inverse timescale for cumulus convection adjustment; $A = (gH_0/2T_0)[1 - (2\gamma/3)]$ and $C_0^2 = gH_0$ respectively measure the strength of the pressure gradient force induced by surface temperature gradients and the barotropic gravity wave speed in the boundary layer; H_0 = 3000 m is the depth of the boundary layer; and T_0 = 288 K is a reference temperature. The parameter γ, which represents a temper-

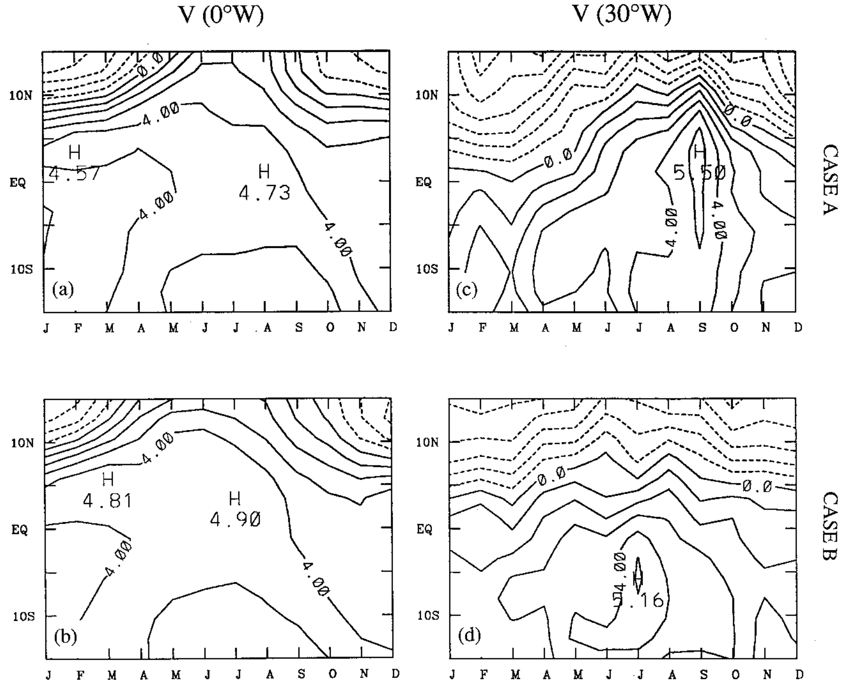

FIG. 3. The time–latitude sections of the GCM simulated meridional component of surface winds at 0°W (left panels) and 30°W (right panels) in two cases. The upper panels are the case (case A) when seasonally varying SST fields are specified and the lower panels are the case (case B) when a climatological annual mean field is used.

ature lapse rate, is assigned the value 0.3 over the ocean, 0.5 over land.

Climatological annual mean SST and land surface temperatures, surface wind, and ocean subsurface temperature fields (at 50 m) are specified as the basic state. The model covers the tropical Atlantic region from 30°S to 30°N and from 70°W to 10°E, with a realistic description of coastal geometry. To eliminate possible discontinuities in the surface temperature field between the ocean and land interface, a five-point smoothing method is applied only for the land region adjacent to the ocean. The model starts from an initial state of rest and is forced

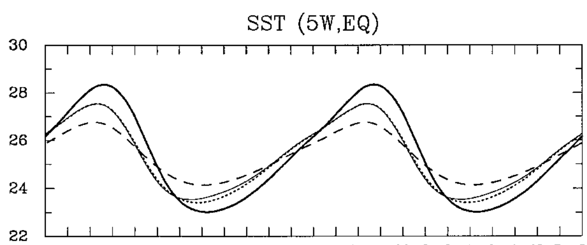

FIG. 4. The contribution of different processes to seasonal variations of sea surface temperatures at 5°W, 0°N in a relatively simple coupled ocean–atmosphere model. The SST variations are determined strictly by evaporation in the case of the dashed line, by evaporation and the divergence of surface currents in the case of the thin solid line, by those processes plus thermocline movements (the dotted line), and by all these processes plus low-level stratus cloud feedbacks in the case of the heavy solid line.

with the observed seasonally varying solar radiation at top of the atmosphere.

This model, in the absence of sea surface temperature variations, reproduces seasonal wind variations in response to seasonal changes in land temperatures. We explore how the evaporation induced by those winds influences sea surface temperatures by suppressing cloud effects and dynamic effects in the ocean model. The dashed line in Fig. 4 shows that, in the Gulf of Guinea, this one mechanism, evaporation, can account for approximately 60% of amplitude of the observed cycle that is close to the heavy solid line in Fig. 4. The thin solid line shows the model results when dynamical processes in the ocean are included. Those processes correspond primarily to divergence of the surface currents. Vertical movements of the thermocline were found to have little effect on the seasonal variations in sea surface temperatures. [To include the effect of thermocline movements, we followed Neelin (1991) by assuming a simple relationship between subsurface temperature and thermocline depth anomalies, $T_{sub} = \lambda h'$, where $\lambda = 0.2$°C m^{-1}]. To obtain a realistic amplitude for the annual cycle, the model has to take into account the combined effects of evaporation, oceanic dynamics, and cloud feedbacks that involve low-level stratus clouds over cold surface waters [see Li and Philander (1996) for a discussion of the cloud effects]. The thick solid line in Fig. 4 shows the model results in this case.

They are practically indistinguishable from the observed seasonal variation in SST at this location.

The factors that control seasonal variations in sea surface temperature in the western equatorial Atlantic have been established by the measurements of Weingartner and Weisberg (1991). A significant difference between the east and west is in the role of vertical movements of the thermocline. Whereas those movements have practically no seasonal variations in the east, they have a large amplitude in the western Atlantic. Of particular importance is the shoaling of the thermocline in the west from June and July onward. It causes the heat flux into the ocean to warm a surface layer with decreasing depth. Therefore, temperatures increase. Maximum sea surface temperatures are attained in March and April. Thereafter, temperatures fall, primarily because of the divergence of the surface currents in response to the intensification of the easterly winds. During this period the deepening thermocline is a secondary factor. Nowhere in the equatorial Pacific is there a region where the same processes control seasonal sea surface temperature variations because in the Pacific, the thermocline does not have large seasonal vertical movements (M. McPhaden 1994, personal communication).

4. Summary

The principal result from the calculations described here is that the influence of land effects on the seasonal cycle is far greater in the tropical Atlantic than in the Pacific. It is especially in the Gulf of Guinea that the seasonal changes in the north–south component of the wind are primarily in response to seasonal variation in the land temperatures. This result suggests that seasonal changes in sea surface temperatures in the eastern tropical Atlantic represent, to the first order, the passive response of the ocean to the changes in the winds.

Ocean–atmosphere interactions do contribute to the seasonal cycle in the western half of the Atlantic where they strongly influence the annual north–south march of the ITCZ. Along the equator in the western portion of the Atlantic the wind-induced thermocline movements and associated subsurface temperature variations have significant influence on the annual cycle in SST.

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