Observed Structure of Convective Anomalies

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1. Introduction

One of the major thrusts of TOGA, and of COARE in particular, is to improve our understanding of the mechanisms by which variations of sea surface temperature (SST) force perturbations in the overlying atmosphere. Several different forcing mechanisms have been developed for use in simple models. The purpose of this study is to compare variance and correlation statistics derived from observed wind, SST, and convection data to try to diagnose the relative importance of some of these mechanisms.

Three coupling mechanisms will be considered. Gill (1980) developed a simple model in which the low-level atmospheric circulation is driven by deep convection, a mechanism we refer to as "interior heating". Zebiak (1986) adapted and extended this model by parameterizing the link between SST and convection in terms of anomalous latent heat flux from the ocean surface over warm SST anomalies, which acts as a trigger for the convection that provides most of the heating. Using a different approach, Neelin and Held (1987) parameterized the effect of variations in SST on the overlying atmosphere in terms of changes in the gross moist static stability, which governs deep convection and low-level convergence. In this model the ocean-atmosphere coupling is local and thermodynamic in nature. A third, entirely different ocean-atmosphere coupling mechanism was explored by Lindzen and Nigam (1987), who proposed that the atmospheric boundary layer could be approximated by a homogenous slab and SST gradients are dynamically equivalent to surface pressure gradients, which then drive the low-level circulation directly. In this model deep convection is a dynamically passive byproduct of pressure gradient-driven low-level convergence whereas convection plays a fundamental role forcing the circulation in the other models.

Comparison of these different mechanisms suggests how they might be differentiated in observed data, although it seems plausible that each of the mechanisms is operative to some extent. The static stability scheme should results in high local correlation between fluctuations of SST and deep convection. The interior heating and surface gradient schemes can be differentiated if there is significant vertical structure in the convergence field, since surface temperature gradients ought to be relatively more effective at forcing the wind field right at the ocean surface, and interior heating ought to be relatively more effective at forcing winds well above the surface in the lower troposphere. We therefore base this study on a comparison of the geographical distribution of variance and correlations among SST, outgoing longwave radiation (OLR; a proxy for deep convection), and convergence at the surface and at 850 mb.

2. Data and analysis procedure

We use monthly mean fields of SST, OLR, NMC-analyzed 850 mb winds, and surface winds analyzed subjectively from ship reports, for the 9-year period January 1979- December 1987 (108 months). The surface wind data were derived from wind stress analyses produced at Florida State University and the other fields were provided

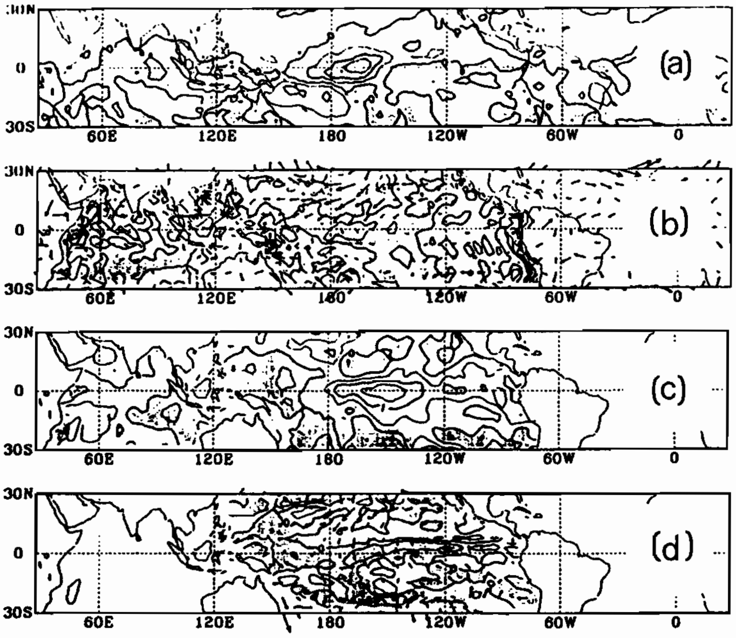

FIG.1. Monthly mean anomalies for January 1987, defined relative to the January average at each gridpoint for years 1979-1987 (negative values shaded). (a) OLR, (b) v_{850} and $\nabla \cdot v_{850}$, (c) SST, (d) v_s and $\nabla \cdot v_s$.

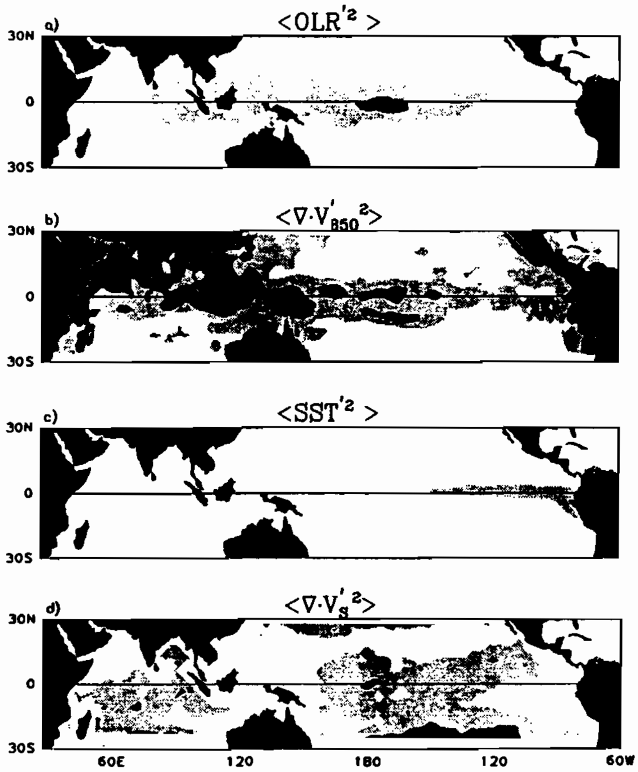

FIG.2. Variance of monthly anomalies for the period Jan. 1979 - Dec. 1987. (a) OLR : variance > 200 $W^2.m^{-4}$ lightly stippled, > 400 heavily stippled. (b) $\nabla \cdot v_{850}$: variance > $1x10^{-12}$ s^{-2} lightly stippled, > $2x10^{-12}$ heavily stippled. (c) SST : variance > 1 K^2 lightly stippled. (d) $\nabla \cdot v_s$: variance > $10x10^{-12}$ s^{-2} lightly stippled, > $20x10^{-12}$ heavily stippled.

by the NMC Climate Analyses Center. All data have been interpolated to a common 2.5°x2.5° latitude-longitude (ϕ, λ) grid extending from 30°N to 30°S across the Indian and Pacific Oceans (Indian Ocean surface wind analyses were available only through December 1986). The surface and 850 mb wind fields chosen for this study were derived completely independently from each other so there is no inherent vertical coupling between them.

Climatological monthly means were calculated at each gridpoint by averaging over the nine-year period, and monthly anomalies were then formed by subtracting the monthly climatological value from each gridpoint. Wind divergence fields were derived from the centered difference calculation

$$\nabla\cdot v = (1/a\cos\phi)\ \partial u/\partial\lambda + (1/a\cos\phi)\ \partial(v\cos\phi)/\partial\phi$$

(where a is the radius of the earth) without additional smoothing.

3. An example: January 1987

Figure 1 shows anomalies of OLR, SST, and the surface and 850 mb wind and divergence fields for January 1987 (during the mature phase of the 1986-87 ENSO warm event). These plots illustrate the significant vertical structure that can be present in the low-level convergence field. The upper panels show the OLR and v_{850} anomaly fields. The largest negative OLR anomaly (indicative of enhanced convection) is centered on the equator between 160°E and 150°W, coincident with a broad 850 mb convergence anomaly. The warm SST and $\nabla\cdot v_s$ anomalies, in the lower two panels, are also coincident but they extend between the date line and the South American coast, distinctly to the east of the OLR and $\nabla\cdot v_{850}$ anomalies. The impression given by the plots in figure 1 is that, at least for this particular month, the near-equatorial surface convergence anomaly is coupled to the SST anomaly, whereas the convergence anomaly at 850 mb is more closely associated with the OLR anomaly.

4. Variance and cross-correlation of SST, OLR, and convergence

Figure 2 shows plots of the local variance of monthly anomalies of OLR, SST, $\nabla\cdot v_{850}$ and $\nabla\cdot v_s$ about monthly climatological averages (the annual cycle has been removed). Variance maxima in OLR and 850 mb divergence are nearly coincident across the near-equatorial Pacific to the west of about 120°W. SST and $\nabla\cdot v_s$ variance maxima are located east of the dateline extending to the South American coast. Note that the variance of $\nabla\cdot v_s$ is generally much greater than the variance of $\nabla\cdot v_{850}$ but the spatial distributions of these variances are very different. We divide the near-equatorial Pacific into three longitudinal zones based on these anomaly variance calculations : in the west (from the maritime continent to the dateline) OLR and $\nabla\cdot v_{850}$ variances are large and SST and $\nabla\cdot v_s$ variances are small; in the east (120°W to South America) OLR and $\nabla\cdot v_{850}$ variances are small and SST and $\nabla\cdot v_s$ variances are large; in the mid-Pacific (between the dateline and 120°W) the variances of all these fields are large.

Geographical variations of pointwise correlations between monthly anomalies of OLR and $\nabla\cdot v_{850}$ or $\nabla\cdot v_s$ (Fig.3) underscore the distinctions implied by the previous two figures. The only region of significant local correlation (exceeding 0.4) of SST and OLR anomalies lies along the equator between the dateline and the South American coast, nearly coincident with the region of maximum variance of SST anomalies. The OLR-$\nabla\cdot v_{850}$ correlation exceeds 0.4 in a band across the western and central Pacific as far east as about 120°W. In contrast, significant OLR-$\nabla\cdot v_s$ correlations are located along the equator from the South American coast westward only to the dateline. Hence surface

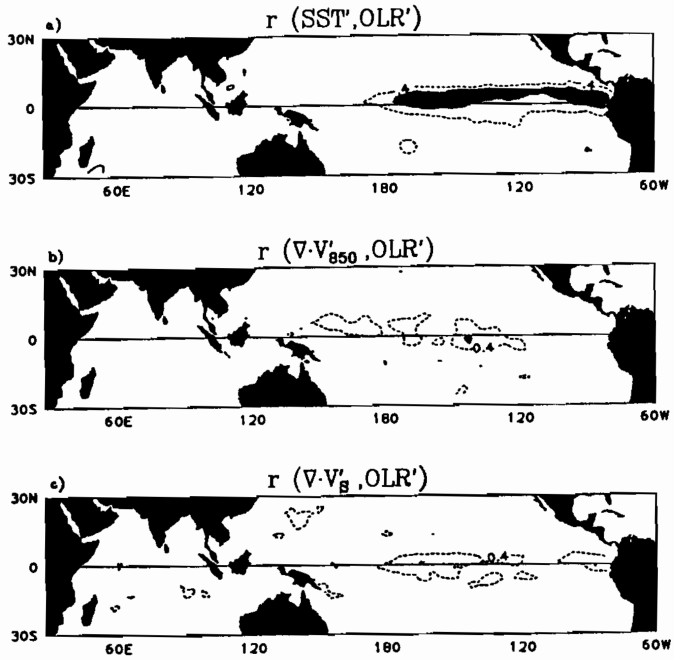

FIG.3. Pointwise correlation between monthly anomalies of OLR and monthly anomalies of (a) SST, (b) $\nabla \cdot v_{850}$, (c) $\nabla \cdot v_s$. In (a), -0.4 contours are dashed and correlations less than -0.6 are stippled; +0.4 contours are solid and correlations greater than +0.6 are hatched. Sign convention is reversed in (b) and (c).

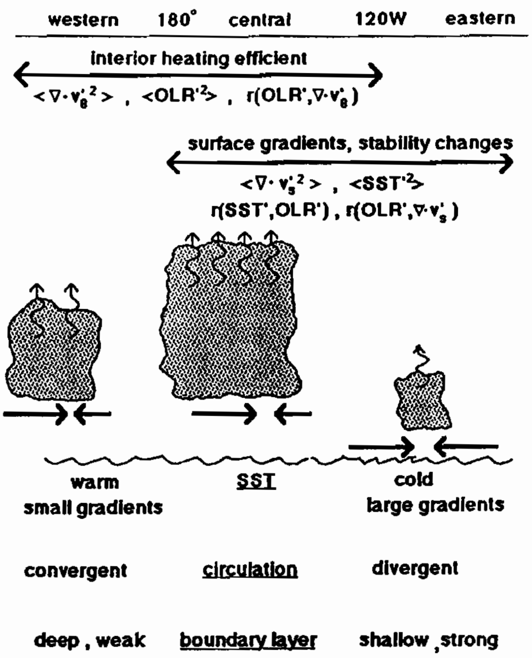

FIG.4. Schematic depiction of longitudinal variations of SST-OLR-wind relationships across the near-equatorial Pacific.

convergence and OLR anomalies are highly correlated over the eastern Pacific despite the low variance of OLR anomalies there; conversely the correlation is nearly zero over the western Pacific despite the high OLR variance there.

5. Discussion and recommendations for COARE

Our results and interpretation are summarized in figure 4 by a schematic depiction of longitudinal variations in the relationships among monthly anomalies of SST, convection and low-level wind convergence across the near-equatorial Pacific.

. *West of the dateline* (Including the proposed COARE domain), where the mean SST field features warm temperatures and small temperature gradients and the mean low-level atmospheric circulation is convergent, monthly anomalies of SST and $\nabla \cdot v_s$ are small and anomalies of OLR and $\nabla \cdot v_{850}$ are large (as determined by the variances of the anomaly time series). OLR anomalies are better correlated with $\nabla \cdot v_{850}$ anomalies than with $\nabla \cdot v_s$ anomalies. SST and OLR anomalies are not significantly correlated.
. *From 120°W eastward to the South American coast,* in contrast, the mean SST field is cold with large temperature gradients and the mean low-level atmospheric circulation is divergent. Monthly anomalies of SST and $\nabla \cdot v_s$ are large and anomalies of OLR and $\nabla \cdot v_{850}$ are small. OLR anomalies are better correlated with $\nabla \cdot v_s$ anomalies than with $\nabla \cdot v_{850}$ anomalies, and the correlation between OLR and SST is high.
. *In the central Pacific between the dateline and 120°W,* anomaly variances of all these quantities are relatively large. Anomalies of SST and convergence at both the surface and 850 mb are significantly correlated with OLR anomalies.

Taken together these results support the following comparison of the coupling mechanisms discussed in the introduction: forcing of the low-level wind field (particularly at 850 mb) by *interior heating* is relatively effective over the western Pacific (the proposed COARE domain), whereas forcings by *stability changes* and *surface gradients* are relatively more effective over the *eastern* Pacific. It seems likely that the central Pacific is a regime in which all of these forcing mechanisms are effective.

Several additional conclusions follow from the results. First, it must be emphasized that the convergence of the surface wind field is significantly different from the convergence at 850 mb, reinforcing the results of a previous comparison of u and v winds derived from individual station data (Harrison and Gutzler, 1986). Winds from these two levels should therefore not be used interchangeably, particularly for purposes of vertically extrapolating the horizontal wind convergence. Second, our results imply that *none* of the forcing mechanisms considered can individually provide a satisfactory parameterization of large-scale ocean-atmosphere coupling over the entire Pacific. Furthermore it appears that vertical structure beyond a single layer is required to simulate correctly the low-level convergence field.

The results confirm that the proposed COARE domain is well-situated to examine interior heat-forced circulations - as it was designed to be, of course. Perhaps not so obvious is the suggestion made here that the other coupling mechanisms considered may be much more effective across the central Pacific. The variances of monthly-mean SST and OLR anomalies increase eastward across the dateline, so extending the COARE domain eastward (even by just 10° or so) would capture more of the low-frequency variability of these fields and might allow an examination of other ocean-atmosphere coupling mechanisms as well. The interaction and feedbacks among different mechanisms at the eastern edge of the warm pool would be extremely interesting to study.

Intensive examination of the near-surface vertical structure of convergence (and more generally, the vertical structure of the boundary layer) should be an important component of COARE data collection and analysis efforts. SST and OLR fluctuations across the COARE domain are not well-correlated and 850 mb convergence is better correlated with OLR than surface convergence. We interpret this to mean that the 850 mb convergence is a better indicator of vertical motion that the larger convergence at the surface, i.e. the 850 mb circulation is representative of a thicker layer of convergence (more mass convergence) than the surface wind. Alternative interpretations could be made, including the possibility that significant tilts exist in the upward motion associated with large-scale, deep convection. The local pointwise statistics calculated here would not capture such tilts; this study is now being generalized to examine questions like this.

Other uncertainties in this study will require special data sets to address. For example, in Zebiak's (1986) model the initial forcing for convection comes from enhanced latent flux associated with a warm SST anomaly, yet SST-OLR correlations are nearly zero over the western Pacific. Perhaps the SST anomalies in the western Pacific are too subtle to be depicted properly in the data, or perhaps some other mechanism (such as destabilization of the tropospheric column from cold-air incursions in the upper troposphere) provides the initial convective trigger. It is hoped that COARE can provide sufficiently accurate and dense three-dimensional circulation and thermodynamic data to provide some definitive answers to these questions.

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TABLE OF CONTENTS

MEETING COLLECTED PAPERS

WATER MASSES, SEA SURFACE TOPOGRAPHY, AND CIRCULATION

EL NINO/SOUTHERN OSCILLATION 1986-87

THEORETICAL AND MODELING STUDIES OF ENSO AND RELATED PROCESSES

MOMENTUM, HEAT, AND MOISTURE FLUXES BETWEEN ATMOSPHERE AND OCEAN

EMPIRICAL STUDIES OF ENSO AND SHORT-TERM CLIMATE VARIABILITY

MISCELLANEOUS