NOTES AND CORRESPONDENCE

Life Span of Subseasonal Coupled Anomalies

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ABSTRACT

The impact of the local phase relationship between the low-level atmospheric circulation and the sea surface temperature (SST) on the duration of atmospheric anomalies is statistically evaluated. Using 5-day-average data from the NCEP–NCAR reanalysis, it is found that most of the long-lasting atmospheric anomalies are locally coupled with SST anomalies, with their number decreasing from the equator to the extratropics. The longer-lasting anomalies tend to have relationships of cyclonic-over-cold or anticyclonic-over-warm phase in the extratropics, and cyclonic-over-warm or anticyclonic-over-cold in the Tropics. This preferential phase relationship of the long-lasting anomalies is consistent with a predominant ''atmosphere-driving'' situation in the extratropics and an ''ocean-driving'' one in the Tropics.

A similar analysis using data from a one-way interaction model, with the ocean always forcing the atmosphere is carried out to compare the results with those from the reanalysis. The results show that the one-way interaction produces fewer (more) long-lasting anomalies in the extratropics (Tropics). These differences arise mostly in atmosphere-driving situations, namely, the cyclonic-over-cold or anticyclonic-over-warm phase relation. This suggests that ignoring the atmosphere's feedback effect on the ocean can lead to erroneous damping (lengthening) of atmospheric anomalies in the extratropics (Tropics).

1. Introduction

Atmospheric anomalies over the ocean have a different character depending on how they interact with the underlying surface conditions. Interactions can be either one-way (either ocean driving the atmosphere or vice versa) or two-way. When the interaction is predominantly one-way with the ocean driving the atmosphere, the larger thermal inertia of the ocean provides a persistent forcing that can modify the duration of the coupled atmospheric anomalies. This is often the case in the Tropics, where the atmosphere tends to respond to the SST variations through changes in the large-scale surface convergence and upper-tropospheric divergence. In the extratropics, on the other hand, the atmosphere usually forces the ocean (Davis 1976). Because the atmosphere responds so quickly to external forcing, the nearly simultaneous relationships observed in the cross-correlation analysis may also include oceanic forcing or two-way interactions (Wallace and Jiang 1987). The consensus gathered from observational studies and GCM experiments is that there is forcing by the extratropical ocean to the atmosphere, but it is weaker than the atmosphere's internal variability (Kushnir et al. 2002).

Mechanisms for air–sea interaction that influence the persistence of atmospheric anomalies have been suggested for the large scales (e.g., Namias 1959; Palmer and Sun 1985; Barsugli and Battisti 1998) and for local scales (e.g., van den Dool 1984; Ronca and Battisti 1997). They include anomalous turbulent heat fluxes, Ekman advection, and local feedback mechanisms. These mechanisms vary in importance depending on factors such as the geographical location, the season, and the conditions of both the ocean and the atmosphere. The effect of a particular mechanism could, in principle, be quantified from numerical experiments using coupled GCMs but the analysis of sophisticated fully coupled models can be as difficult as analyzing the atmosphere itself. The impact of the coupling on the characteristics of atmospheric anomalies has been addressed using simplified coupled models. The thermal damping theory proposed by Barsugli and Battisti (1998) indicates that

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in the extratropics, coupling decreases the energy flux between the two media. This adjustment results in a reduction of the effective thermal damping of the ocean on the atmosphere, lengthening the persistence of the anomalies. The impact of coupling is perceived as less relevant for shorter time scales because the change of SST within these intervals is not significant. Several experiments show, however, that in regions characterized by rapidly changing sea surface conditions (e.g., near the coast or in shallow enclosed seas) the coupling of an ocean model with high-resolution atmospheric models has a positive impact on the skill of weather predictions (e.g., Gustaffson et al. 1998).

The objective of the present study is to statistically evaluate from observations, the effect of *locally coupled SST anomalies* on the duration of subseasonal atmospheric anomalies. By ''local coupling'' we mean that anomalies in the ocean and the atmosphere overlap in time in the same grid box. Our hypothesis is that large departures of SST from its annual cycle affect the duration of concurrent atmospheric anomalies and that this effect depends on the local phase relationship between the two media. We use the atmospheric and SST anomalies derived from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data [henceforth Reanalysis; Kalnay et al. (1996); Kistler et al. (2001)], considering that the Reanalysis contains the natural (two-way) interaction that exists within the observed coupled ocean–atmosphere system. In addition, we study a one-way interaction model with prescribed SST, to investigate how forcing the coupling interaction to be one-way affects the duration of atmospheric anomalies. The model is part of the Atmospheric Model International Project (AMIP; Gates 1992). A comparison of the duration in one-way and two-way interaction scenarios will provide suggestions on the relevant processes that take place in the coupled anomalies.

2. Data and method

We use three global fields: SST, 850-hPa relative vorticity (RV; derived from the wind data) from the Reanalysis, and 850-hPa relative vorticity from an AMIP run from the same model as the Reanalysis but without data assimilation. The data span 19 yr (1980–98) starting at the time when the SST data became most reliable. The data are daily and gridded with a spatial resolution of 2.5° in latitude and longitude. The AMIP model is the same model used in the Reanalysis without atmospheric data assimilation. The prescribed SST is also the same used in the Reanalysis (details are provided at the PCMDI's Web site: http://www-pcmdi.llnl.gov/amip). We have deliberately reversed the sign of the relative vorticity field in the Southern Hemisphere. Thus positive vorticity anomalies are cyclonic, and negative anomalies anticyclonic in both hemispheres. Because the sign of vorticity anomalies are undefined at the equator, we performed a linear interpolation at the equator from the closest latitude points to avoid sharp contrasts in the results. A 5-day average was then computed from the daily vorticity and SST data to filter out synoptic-scale transient anomalies. Note that in the Reanalysis both the wind field, from which the relative vorticity is derived, and the SST are obtained from independent analyses based on observations, so that it contains the coupling continually generated by nature.

To identify the anomalies we first subtract the annual cycle from the time series of the vorticity and SST fields at each grid point. The annual cycle is represented by the first two annual modes of the Fourier series. Then, we consider the anomalies whose departure from the annual cycle exceeds one-quarter of the local standard deviation. The duration of a local anomaly is defined as the time interval in which it continuously exceeds this threshold. This method is used to estimate the duration of quasi-stationary anomalies, which dominate the 5-day-average data. Once the anomalies are detected, we compute the number of cases when the atmospheric and oceanic anomalies are spatially and temporally coincident in each grid box. The coupled anomalies are further stratified according to the phase relationship between the two media.

Following Mo and Kalnay (1991), an empirical rule is employed to classify locally coupled anomalies into ''atmosphere-driving'' versus ''ocean-driving'' cases without considering atmospheric advection. As illustrated in Fig. 1, atmosphere-driving anomalies (left panel) are characterized by a low-level atmospheric cyclonic vorticity over cold SST, (or anticyclonic vorticity over warm SST). The cyclonic vorticity anomaly produces Ekman upwelling and colder temperatures in the ocean, and is associated with cloudiness, reducing solar radiation. Conversely, for an anticyclonic anomaly driving the ocean, both clear skies and Ekman downwelling would cause SST to increase. By contrast, the rule suggests that ocean-driving anomalies (right panel) are characterized by low-level atmospheric cyclonic vorticity over warm SST (or anticyclonic vorticity over cold SST). In these cases the warm SST anomaly induces upward motion, resulting in low-level cyclonic vorticity (cold anomalies induce low-level anticyclonic vorticity).

Peña et al. (2003) applied this rule to classify the locally coupled anomalies in the 5-day-average data and found that the geographical regions depicted as mostly atmosphere-driving and mostly ocean-driving agreed well with those obtained with the lag-correlation technique, in which the atmosphere is considered to be mostly driving if the atmospheric anomalies precede the ocean anomalies and vice versa. Although this rule may not optimally separate the atmosphere-driving from ocean-driving anomalies, it provides a simple means to classify the locally coupled anomalies in terms of the local phase relationship and enables us to investigate

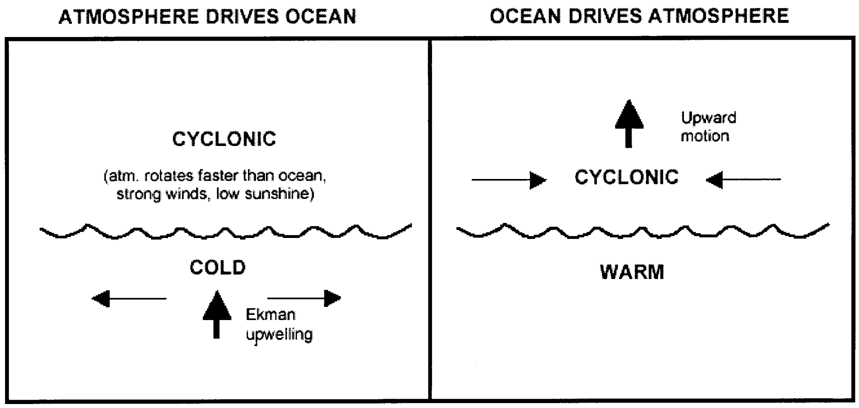

Fig. 1. Schematic of the characteristics of coupled ocean–atmosphere anomalies for (left) atmosphere-driving and (right) ocean-driving situations. See text for explanation. Adapted from Mo and Kalnay (1991).

fundamental characteristics of the locally coupled anomalies.

3. Life span of coupled anomalies

In this section we present the statistical effect of coupling on the duration of atmospheric anomalies. The geographic distribution of the number of atmospheric anomalies has a strong latitudinal dependence but a modest zonal variation (not shown). The latitudinal dependence can be seen by computing the zonal average number of cases per grid point over the oceans, that is, the number of vorticity anomalies in a given latitude divided by the number of grid points. The total number of anomalies zonally averaged and classified according to their duration, is plotted in Fig. 2a. The figure shows that as duration increases there are fewer anomalies, and that there are more long-lasting anomalies occurring near the equator. The classification of the zonal mean distribution of anomalies according to whether they are locally coupled (Fig. 2b) or uncoupled (Fig. 2c) shows that the former account for essentially *all* the long-lasting anomalies, whereas uncoupled atmospheric anomalies have a very short life span with no latitudinal dependence. Therefore, we can conclude that the atmospheric anomalies overlaying large-amplitude SST anomalies tend to last longer than otherwise. This is particularly true in the Tropics. However, the time scale of SST anomalies cannot explain the shorter duration of subseasonal atmospheric anomalies in extratropics because the duration of subseasonal SST anomalies themselves have little latitudinal variation (not shown here). In other word, given the same life span of the SST anomalies, the atmospheric anomalies in the Tropics tend to last longer than those in extratropics. We argue that this is another indicator that ocean driving is more dominant in Tropics. The results above also indicate that the effect of coupling is important even at the subseasonal time scales, which are much shorter than the interannual time scales where the effect of the thermal coupling is strongest (Bladé 1997; Barsugli and Battisti 1998).

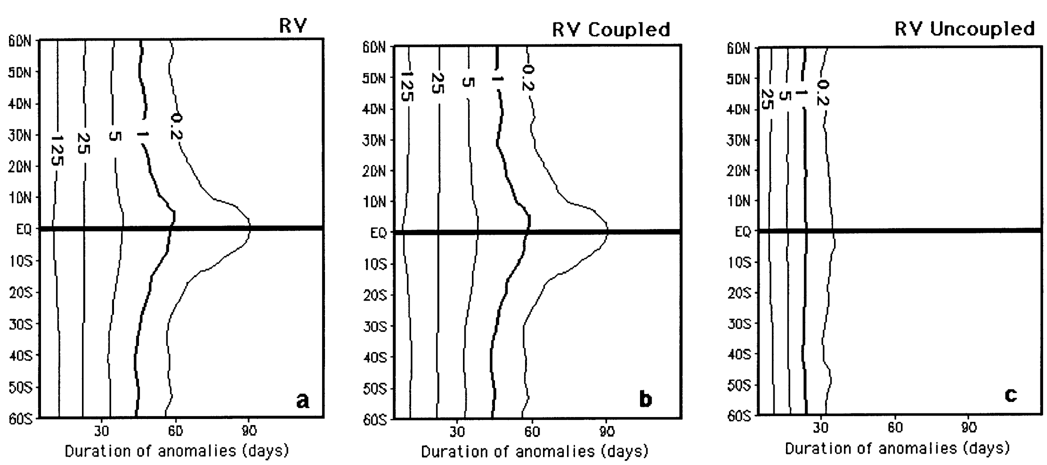

Fig. 2. Zonally averaged number of 850-hPa RV anomalies over the ocean vs duration of anomalies (a) total over 19 yr, (b) locally coupled with SST anomalies, and (c) locally uncoupled.

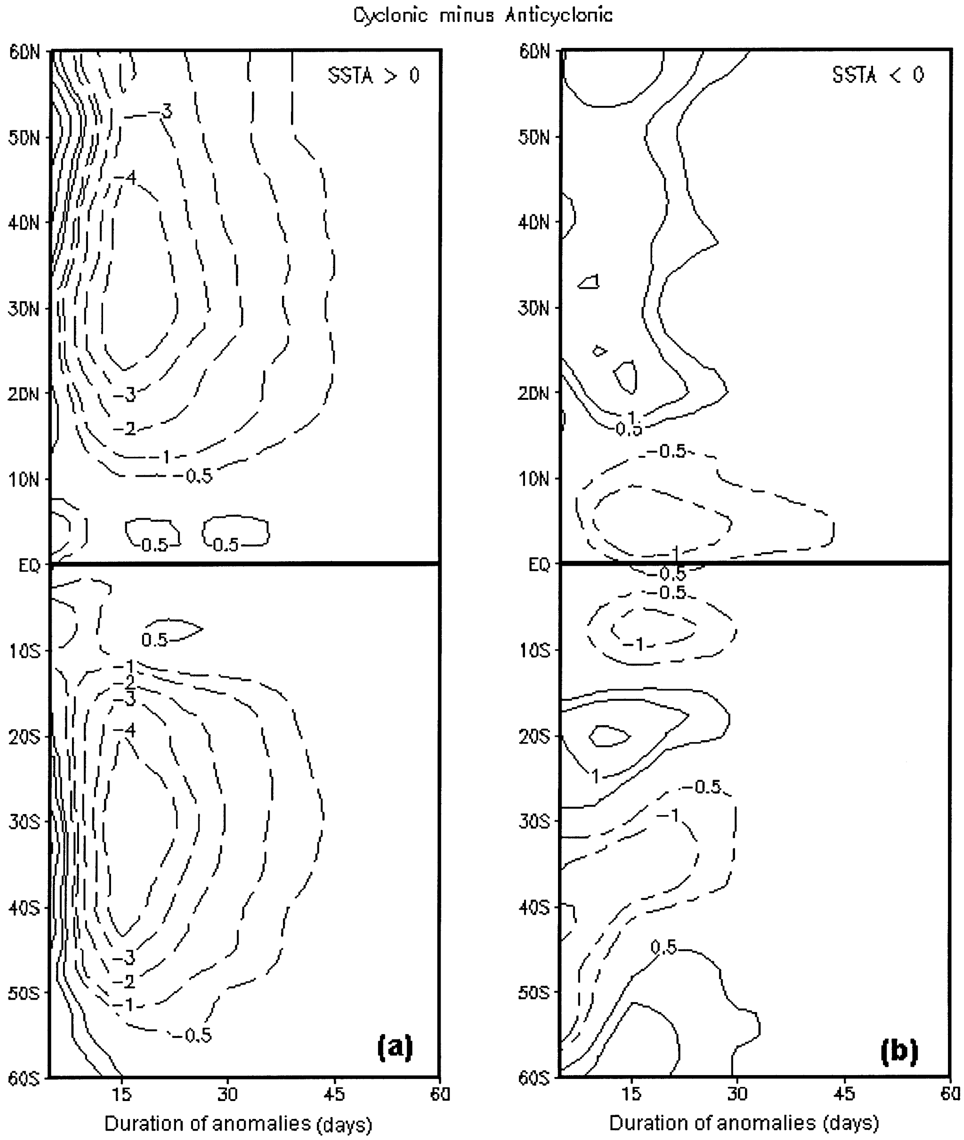

FIG. 3. Number of cases of cyclonic minus anticyclonic anomalies, zonally averaged, over the ocean for (a) positive and (b) negative SST anomalies, as a function of anomaly duration and lat.

4. Impact of the local phase relationship

Using the zonally averaged number of anomalies versus duration of anomalies introduced in the previous section can help distinguish the effect of the local phase relationship of the atmosphere with the underlying SST. Intuitively, one should not expect coupled anomalies to have similar characteristics for positive as for negative SST anomalies because certain processes, such as convection, are nonlinear with respect to the sign of the SST anomalies. In Fig. 3, the number of cyclonic minus anticyclonic anomalies for both positive and negative SST anomalies shows that the distribution of subseasonal atmospheric anomalies is not symmetric with respect to the sign of the local SST anomaly. In the deep Tropics, cyclonic anomalies last longer when the underlying SST anomaly is warm (as indicated by the positive contours in Fig. 3a for latitudes from 10°S to 10°N), whereas anticyclonic anomalies are more likely to last longer when they are coupled with cold SST anomalies (negative contours in Fig. 3b for latitudes from 10°S to 10°N). The region outside the deep Tropics shows the opposite situation. The two figures suggest that, in general, ‘‘same sign’’ (cyclonic-over-warm or anticyclonic-over-cold) coupled anomalies are longer lasting in the deep Tropics whereas ‘‘opposite sign’’ (cyclonic-over-cold or anticyclonic-over-warm) anomalies last longer in the extratropics. This result is consistent with the cross-correlation analysis between low-level circulation (or geopotential height) and the SST (e.g., Peña et al. 2003), which is positive in the Tropics and negative in the extratropics. Another characteristic of the distribution of anomalies in Fig. 3 is that anticyclonic-over-warm anomalies in the extratropics and anticyclonic-over-cold anomalies in the Tropics are the two longer-lasting configurations. This suggests that anticyclonic anomalies' time scales are more sensitive to the existence of large-amplitude SST anomalies underneath in all latitude bands. An intriguing feature of the distribution of atmospheric anomalies in Fig. 3 for the cases of negative SST anomalies (right panel) is the alternating signs pattern in the Southern Hemisphere. Computing the number of cases of 15-day or longer-lasting anomalies without the zonal average (not shown) reveals that the alternating signs pattern arises from the pronounced number of same sign cases associated with the Southern intertropcial convergence zone (SICZ).

A physical interpretation of the differences between the Tropics and extratropics shown in Fig. 3 can be drawn from Mo and Kalnay's dynamical rule (section 2), which states that same sign anomalies indicate ocean driving the atmosphere, while opposite sign indicates atmosphere driving the ocean. Figure 4 shows the difference of ocean driving minus atmosphere driving according to this rule. From this view, the longer-lasting anomalies in the extratropics are predominantly atmosphere-driving whereas in the Tropics they are predominantly ocean-driving, which confirms past studies suggesting that the atmosphere drives the ocean in the Tropics and the opposite in the extratropics. Figure 4 also shows that ocean-driving anomalies in the extratropics, do exist but they tend to decay faster. It remains to be answered whether it is local or remote forcing that makes the atmosphere-driving anomalies in the extratropics live longer despite the shorter memory of the atmosphere compared to that of the ocean.

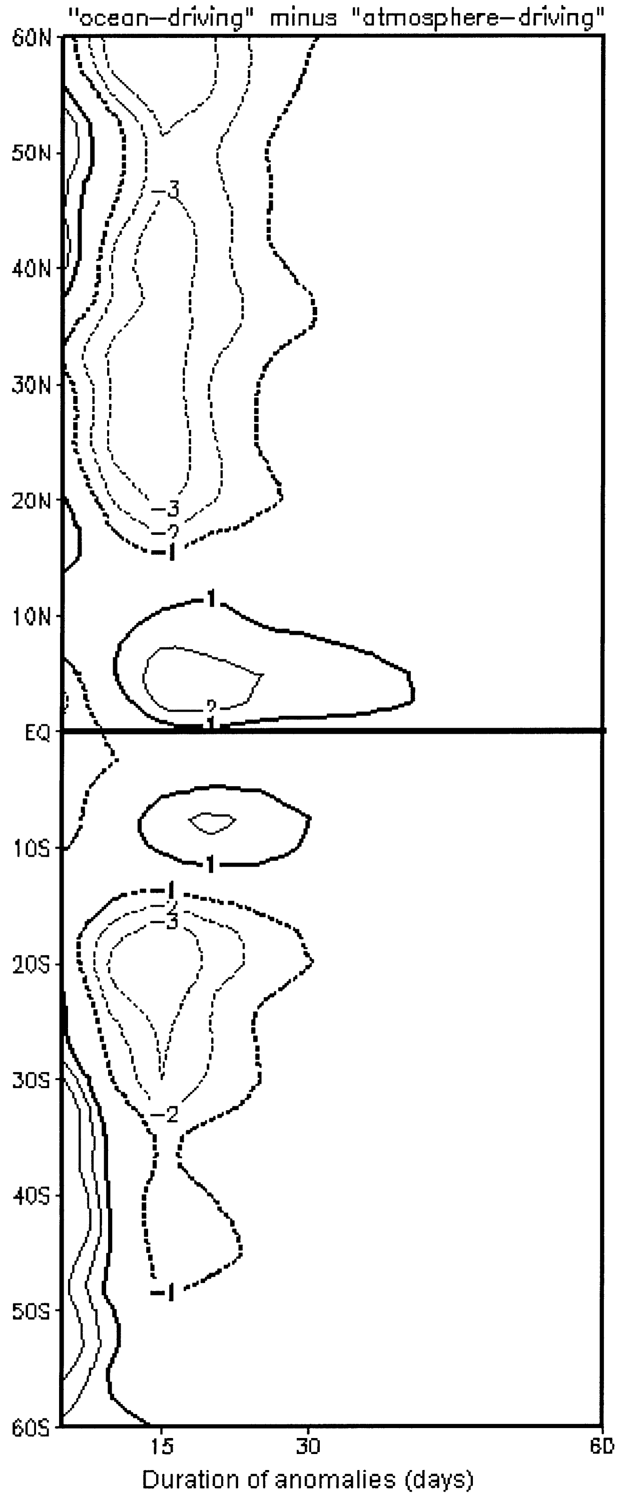

Fig. 4. Number of cases of ocean-driving minus atmosphere-driving anomalies, zonally averaged, over the ocean.

5. Anomaly duration in one-way and two-way interactions

The impact of neglecting the feedback of the atmosphere upon the ocean can be quantified by comparing the statistics generated in data that contains the two-way ocean–atmosphere interactions, such as the Reanalysis, with model data with prescribed SST where the ocean always drives the atmosphere. The distribution of duration of atmospheric anomalies calculated with the same procedure using the NCEP AMIP run (not shown) can be compared with the results from the Reanalysis shown in Fig. 2b. The difference between these two distributions, given in Fig. 5a, indicates that the one-way interaction scenario tends to produce more longer-lasting anomalies in the Tropics and more shorter-living anomalies in the extratropics than observed in the Reanalysis. Since the ocean has a longer memory and thus provides a longer-lasting forcing to the atmosphere, one might expect that simulated anomalies

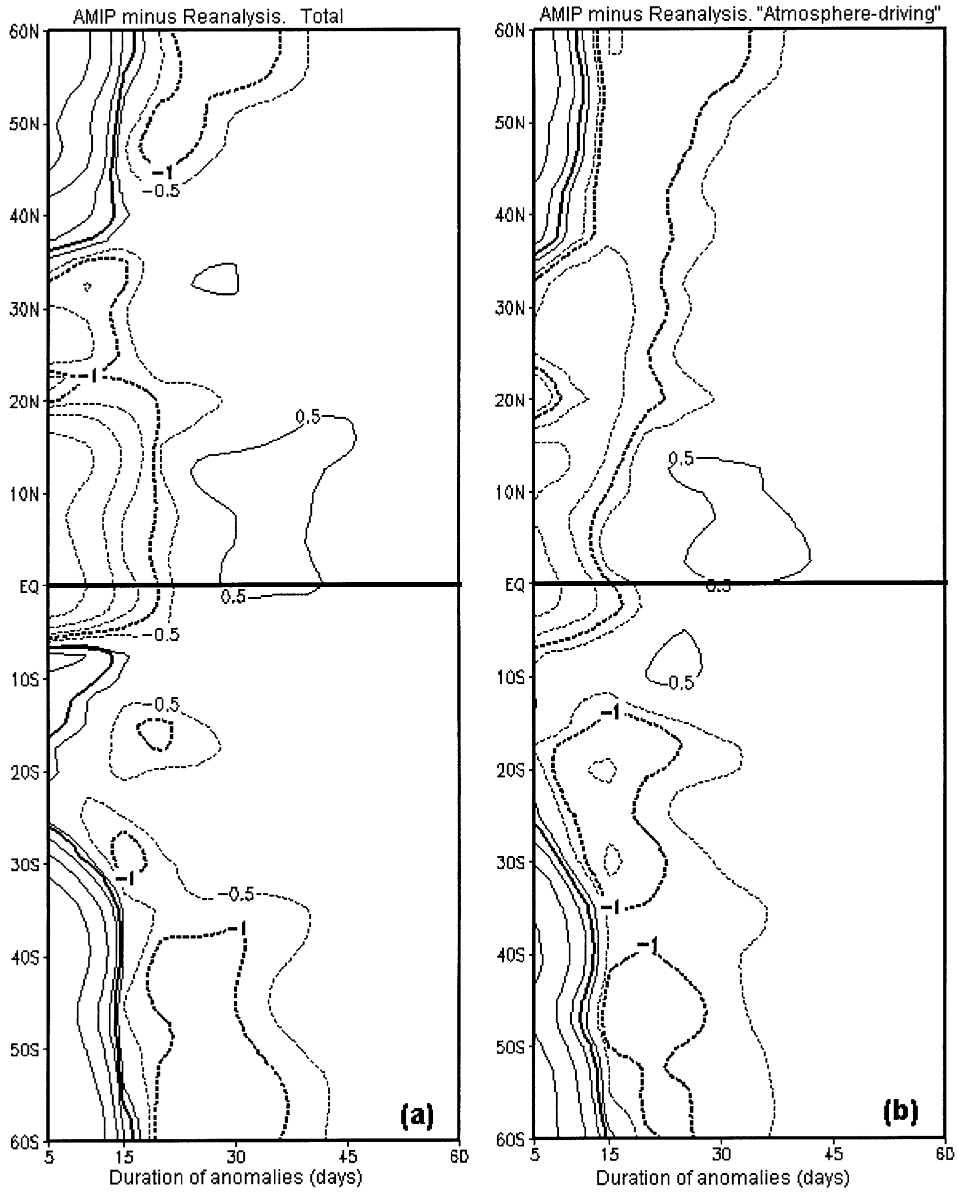

FIG. 5. Distribution of anomalies in AMIP minus anomalies in Reanalysis for (a) the total number of coupled anomalies and (b) the number of atmosphere-driving cases.

would be more persistent than observed anomalies. However, this only happens in the Tropics, where the dominance of the ocean-driving scenario in the AMIP run is correct. In extratropics, the artificially longer-lasting forcing from the prescribed SST actually damps out the atmospheric anomalies much faster than the reality when atmospheric feedback is inhibited as the cases of AMIP-type model integrations.

Using the diagnostic rule of Mo and Kalnay (1991) to select the coupled anomalies that are predominantly atmosphere driving, Fig. 5b provides the difference in the number of these anomalies between the Reanalysis and the AMIP run. A comparison of this result with Fig. 5a indicates, as could be expected, that the mismatch in the number of long-lasting anomalies in both the Tropics and extratropics is mostly due to ignoring the atmosphere-driving anomalies. Studies based on the cross-correlation statistics between SST and rainfall (Masutani 1997; Hurrell and Trenberth 1999) have shown that AMIP runs contain an incorrect feedback relation in the extratropics. Our results suggest that the incorrect feedback of the atmosphere to the ocean leads to erroneously damping the extratropical anomalies and extending the tropical ones. It should be pointed out that although the same model was used in the AMIP run as in the reanalysis, there may be additional biases between the two results due to assimilation of data in the reanalysis, so that additional research is needed to confirm our results.

6. Summary and discussion

We developed an empirical procedure to detect locally coupled ocean–atmosphere anomalies in the 5-day-average data. We applied it to both the NCEP–NCAR reanalysis (which contains the real two-way coupling that takes place in nature) and to an AMIP model run in which the observed SST forces that the atmosphere, and there is no atmospheric feedback to the ocean. Using this method we describe the geographic frequency distribution and the average life span of both coupled and uncoupled anomalies. The statistics generated with this procedure show that the duration of locally coupled anomalies is influenced by the local phase relationship between the ocean and atmosphere.

The main results of our study are the following:

- Locally coupled atmosphere anomalies last longer than uncoupled anomalies.
- The longest-lasting anomalies in the extratropics tend to be anticyclonic-over-warm, in agreement with the notion that in the extratropics atmospheric anomalies tend to drive ocean anomalies.
- The longest-lasting anomalies in the deep Tropics tend to be cyclonic-over-warm or anticyclonic-over-cold, in agreement with the notion that the ocean tends to drive the atmosphere in the Tropics.
- An AMIP run, where the ocean always drives the atmosphere, tends to produce an excess of long-lasting anomalies in the Tropics and a deficit in the midlatitudes.

Our results suggest that climate experiments with prescribed SST can be misleading in identifying extratropical patterns of predictability.

Although no attempt was made to isolate local from remote forcings, when we carried out the same analysis for only El Niño and non–El Niño years, we found no significant difference in the distribution of the number of anomalies (not shown). Perhaps, the reason why ‘‘atmosphere-driving’’ anomalies in the extratropics live longer, despite the shorter memory of the atmosphere compared to that of the ocean, may be related to global quasi-stationary wave variability that may or may not be related to the global-scale ocean–atmosphere coupling. Another explanation is that atmosphere-driving cases result not only from a one-way interaction mechanism with the atmosphere forcing the ocean, but also from a positive feedback mechanism between oceanic and atmospheric processes. For example, Goodman and Marshall (1999), found that coupled anomalies with a configuration anticyclonic-over-warm or cyclonic-over-cold, which resembles the atmosphere-driving phase relationship described in this paper, has the fastest growing mode in their ideal ocean–atmosphere model. Consideration of other vertical levels, besides 850 hPa, and subsurface ocean temperatures and currents may provide a more complete knowledge of the characteristics and processes involved in the generation of locally coupled subseasonal anomalies and why they tend to have a preferential phase relationship. A key remaining question is whether ‘‘ocean-driving’’ anomalies, identified with the present methodology, are more predictable than atmosphere driving as is often anticipated in extended-range atmospheric prediction.

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