On Ocean-Atmosphere Coupling in the North Atlantic Ocean

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Abstract

Using summaries drawn from the Comprehensive Ocean Atmosphere Data Set (COADS) for the period 1947-1990 in the North Atlantic Ocean, we explore the geographical variability of the structure of the cross correlation function between anomalies of sea surface temperature (SSTA) and anomalies of the sum of the latent and sensible heat fluxes (LSHFA). Two distinct cross correlation structures emerge, one of which dominates in the open ocean at midlatitudes and the other of which dominates near the western boundary current and in the tropics. The former is characterized by a strong antisymmetry, while the latter is one-sided with a peak at zero-lag. A discrete stochastic model (vector first-order auto-regressive model) is proposed to account for the observed structure. The model, which reproduces these structures with fidelity, implies that the SSTA and LSHFA must be mutually coupled in order to reproduce the characteristics of the observations, especially in the open ocean at midlatitudes. The low-frequency, decadal-scale propagating signals that have been the subject of several recent studies are not captured by this model as seen in the residuals that remain from a fit of the model to the observed anomalies. This suggests that the development of SSTA has a significant contribution from processes that cannot be characterized as an integral response to atmospheric white-noise forcing.

I. Introduction

A. Ocean/Atmosphere Interactions in the North Atlantic

Many authors have suggested that coupled interactions between the ocean and atmosphere may influence climate variability on seasonal to decadal timescales [Bjerknes, 1964; Frankignoul, 1985; Deser and Blackmon, 1993; Kushnir, 1994; Frankignoul, 1995]. One fundamental coupling between these fluids is through the transfer of heat across the air-sea interface. This consideration has motivated a number of observational and numerical studies to support the hypothesis that anomalies of the atmospheric circulation are mainly responsible for the appearance of anomalous wintertime SST [see Delworth (1996) for an overview]. In these studies, the atmospheric circulation is often parameterized and the choice of the parameter used to characterize the atmosphere varies. Davis (1976) chose sea level pressure to represent the atmospheric circulation for a study of seasonal to annual variability over the North Pacific. He found that a significant correlation between sea level pressure anomalies (SLPA) and SSTA occurs only when SLPA leads SSTA by a month or so. He pointed out that this suggests the ocean is being driven by the atmosphere. Davis (1978) also found that a seasonal stratification of the data indicates that autumn and winter SLPA are predictable from prior observations of either SLPA or SSTA.

Frankignoul and Hasselmann (1977) explored a stochastic model (univariate first-order auto-regressive model) of climate variability in which the SST tendency is driven by random fluxes of latent plus sensible heat. They recognized that the form of the cross correlation function between the SSTA tendency and the chosen atmospheric parameter provides a critical test of the basic premise of the model. To facilitate a comparison with the results of Davis (1976), they parameterized the atmospheric circulation using anomalous surface pressure to represent the anomalous surface heat flux. They found that the cross correlation between SLPA and SST tendency anomalies is zero for negative lags, and is a decaying exponential for positive lags with its maximum at zero lag. They attribute the observed peak at a one-month lag to the 1-month averaging performed on the observed time series prior to performing the correlation and they conclude that the stochastic model explains most of the features of mid-latitude SST anomalies. As they explicitly state: "We suggest here that the development of SST anomalies can be understood..., without invoking feedback mechanisms, as the integral response of the ocean to random short-time-scale forcing by the atmosphere."

Frankignoul and Reynolds (1983) recognized that cross-correlations between dominant empirical orthogonal functions of SST variability and the variability of net surface heat flux have an “antisymmetric aspect” (Frankignoul, 1985) that cannot be successfully modeled by the development proposed by Frankignoul and Hasselmann (1977). They hypothesized an atmospheric feedback, which implies that the atmospheric parameter (net surface heat flux in this case) consists of both the random fluxes of heat and a term proportional to SSTA. No feedback from the ocean to the atmosphere is included. Although purely antisymmetric cross correlations cannot be obtained via this model, significant antisymmetric character can be introduced this way. Again, the peak values tend to occur at zero lag, but two factors contribute to moving the peaks away from zero: (1) the introduction of colored noise and (2) the 1-month averaging performed on the observed time series prior to calculating the correlation.

B. Geographical Variability

Using a simple thermodynamic model to relate the flux anomalies to the tendency of the SST anomalies, Cayan (1992) sought to test the hypothesis that the atmosphere forces the ocean. In this model, the upper-ocean heat balance is driven by the latent and sensible heat flux. The signature of this process is expected to be a negative correlation between anomalies of latent plus sensible heat flux and anomalies of SST tendency. This signature was found nearly everywhere in the extratropics, where the flux and the tendency are well correlated. In the tropics, however, Cayan found that the correlations are smaller and the flux anomalies tend to be in phase with the SST (not tendency) anomalies. This suggested to him that the flux anomalies are driven by the ocean thermal field. Although he did not directly comment about this, Figure 2 of Cayan (1992) reveals a small, positive correlation between flux and tendency anomalies in both the tropics and a region centered around 40•N off the coast of North America.

Battisti *et al.* (1995) conducted some numerical experiments to test the hypothesis that North Atlantic SST variability is due to the variability in the surface heat flux (which is dominated by latent plus sensible heat flux). They found the hypothesis to be significantly in error only along the U.S. coast, in a small region extending from Cape Hatteras to Nova Scotia. Here the observed flux anomalies are anticorrelated with the SSTA, which they suggested implicates ocean advection in generating SSTA. They did not examine relationships in the tropics.

As noted above, the nature of the cross correlations between the SSTA and LSHFA can provide a critical test of the nature of air-sea coupling, especially in midlatitude regions. Evidence for geographical variability of the cross correlations between SSTA and LSHFA suggest that this property could delineate regions where the nature of air-sea interactions are significantly different. In this paper, we will explore this hypothesis, using an analysis of observations from the North Atlantic Ocean.

II. Data Processing

The data set for this study was drawn from the Comprehensive Ocean-Atmosphere Data Set (COADS) trimmed file, for which individual observations were averaged both temporally and geographically into monthly means for 2• x 2• bins (Woodruff *et al.*, 1987). Our study region covers the North Atlantic Ocean from 8•N to 60•N and from 94•W to 6•W. We eliminate from further consideration all bins which have more than 9 years of missing data for any given month. Our analysis uses the remaining 737 2• x 2• bins (gray, red and blue squares in Figure 1a), each with a time series of 528 monthly values for the period from January 1947 to December 1990. In this study, we concentrate on three variables: sea-surface temperature (SST), latent heat flux (LHF) and sensible heat flux (SHF). Flux estimates in COADS were calculated via bulk formulae from measurements of SST, air temperature, surface winds and humidity. See Cayan (1992) for both a discussion of the methods used by COADS and an analysis of the errors in that database. Anomalous values of SST, LHF and SHF were calculated as departures from the monthly means of the detrended time series at each location; missing values were replaced with climatology. LHFA and SHFA were summed to provide a time series of LSHFA at each location. Our sign convention has positive flux anomalies leaving the ocean.

<u>III. Results</u>

A. Observations

At each of the 737 locations, we computed the cross correlation between SSTA and LSHFA. Figure 1a shows the locations of the bins associated with the lowest (red) and highest (blue) deciles based on the value of the cross correlation at zero lag. Notice that the lowest decile (red) corresponds to the midlatitude region away from the Gulf Stream, which has been characterized as a place where "...wintertime interannual to subdecadal variability in SST is mainly due to local anomalies in the air-sea flux of sensible and latent heat" (Battisti *et al.,* 1995). The highest decile (blue) corresponds to the regions noticed by Cayan (1992) and Battisti *et al.* (1995) as being exceptions to this characterization. Henceforth, we will refer to these as the red and blue regions, respectively. The median cross correlation functions (CCF) for these two regions (solid lines in Figure 1b,c) emphasize the difference inherent in the relationship between SSTA and LSHFA. The CCF in the blue region is virtually zero for negative lags, peaks at zero lag and decays for positive lags. For the red region, however, the CCF has a strong antisymmetric component. The difference between the two regions is further emphasized by the cross spectrum and phase spectrum between SSTA and LSHFA (Figure 2a,b respectively). Both regions have cross spectral densities which decrease with increasing frequency. More importantly, the nearly constant phase spectra are at distinctly different phases for the two regions with SSTA leading LSHFA by about 90• and 20• in the red and blue regions, respectively. Of course, this is equivalent to saying that LSHFA leads SSTA by 270• and 340•, respectively.

We considered another approach for choosing locations of the highest and lowest deciles, based on the frequency with which the SSTA and the LSHFA had the same or opposite signs. This approach changed some details, but the conclusion that two distinct regions can be defined is still correct, and the new regions are substantially the same as those found previously (Figure 1d). Note the similarity of the median cross correlations (Figure 1e,f) to those already presented (Figure 1b,c).

B. Modeling

Inspired by the success of local linear stochastic theory in explaining the character of climate variations (Hasselmann, 1976; Frankignoul, 1995), we sought the simplest stochastic model that would unify our results. We particularly wanted the model to be able reproduce the forms of the cross correlation functions derived from the data, including the antisymmetric shape of the cross correlation function in the red region. Hasselmann's model, as extended by Frankignoul and Reynolds (1983), is unable to produce an antisymmetric cross correlation function (although it can produce an "antisymmetric aspect" [Frankignoul, 1985]), primarily because no feedback from ocean to atmosphere is included. Accordingly, we turn our attention to a first order vector auto-regressive model (Wei, 1993), which includes feedbacks in both directions.

We consider the model

$$\mathbf{Z_t} = \Phi\mathbf{Z_{t-1}} + \mathbf{a_t} \tag{1}$$

where $\mathbf{Z}_t$ is a two dimensional column vector, Φ is a 2 x 2 matrix of coefficients and $\mathbf{a}_t$ is a two dimensional column vector of innovations (random noise), with the property

$$< \mathbf{a_t a_{t+k}^T} >= \begin{cases} \Sigma & \text{if } k=0 \\ \mathbf{0} & \text{if } k \neq 0 \end{cases} \tag{2}$$

where Σ is a 2 x 2 symmetric positive definite matrix. Following Frankignoul and Reynolds (1983), we associate the ocean state, $Z_{1,t}$ with standardized SSTA and the atmospheric state, $Z_{2,t}$ with standardized LSHFA, where the time series are standardized by subtracting the monthly means and dividing by the monthly standard deviations.

It is instructive to consider the impact that the parameters in this model have on the character of the resultant CCF. There are seven parameters required to fully specify Φ and Σ**.** We define the elements of Φ and Σ by ϕ_{ij} and σ_{ij}, respectively. The diagonal elements of Σ represent the variances of the random noise that directly forces the ocean and atmosphere, respectively, while the off-diagonal term represents the correlation between the two noise processes. The diagonal elements of Φ represent the memory or persistence of the ocean and atmosphere states. The off-diagonal terms represent the feedback or coupling whereby the ocean directly influences the atmosphere and visa versa. We confine ourselves to the range $1 > \phi_{11}, \phi_{22} \bullet 0$.

If Φ is identically zero, then correlations between the ocean and atmosphere arise solely because of correlations between the two noise processes. The CCF is zero everywhere except at zero lag where it takes the value σ_{12}, which may be positive or negative. Similarly, when the diagonal elements of Φ are nonzero (memory), and the off-diagonal elements of Φ are zero (no feedback), there is no correlation between the ocean and atmosphere, unless the two noise processes are correlated ($\sigma_{12} \bullet 0$). When correlations exist, the extreme value of the CCF (positive or negative) is at zero lag and the magnitude of the correlation decays exponentially on either side of the origin. The decay rates depend on the values of ϕ_{11} and ϕ_{22}. In general, these rates are different on either side of the origin, but the CCF never crosses zero. In summary, if there is no feedback, nonzero CCF can arise only via correlations in the noise. If there is memory in addition to the noise correlation, then the correlations are extended to nonzero lags, but the CCF never crosses zero.

Provided that the system has memory ($\phi_{11} \bullet 0$ or $\phi_{22} \bullet 0$), correlations at zero lag (and all other lags, too) may be introduced by feedback; correlated noise is no longer necessary. If the noise processes are uncorrelated ($\sigma_{12} = 0$) and there is only partial feedback ($\phi_{12} \bullet 0$), then the CCF never crosses zero. With the combination of partial feedback ($\phi_{12} \bullet 0$) and correlated noise ($\sigma_{12} \bullet 0$), it becomes possible for the CCF to cross zero. This corresponds to the "antisymmetric aspect" mentioned by Frankignoul (1985). In this case the CCF can exhibit extrema for at most two lags, one at zero and another at ± 1. When both feedback terms are nonzero, a great variety of behaviors for the CCF become possible. In particular, only with full feedback ($\phi_{12} \bullet 0$, $\phi_{21} \bullet 0$) is it possible to obtain a CCF that simultaneously exhibits extrema at both +1 and -1 lag and is small or zero at zero lag.

How do these considerations relate to the observations? We seek estimates for Φ and Σ, using a least-squares fit of the model to the observations at each location (Ljung, 1987; Wei, 1993). Figure 3 depicts the distribution functions of the parameters ϕ_{ij}, along with the formal uncertainties derived by the fit. ϕ_{11} (Figure 3a), which represents the persistence of the SSTA, is clearly larger than the other terms and has a median value of about 0.5. ϕ_{22} (Figure 3d), on the other hand, indicates that the persistence of the LSHFA is relatively short, with a median value of about 0.05. Median values of ϕ_{12} (Figure 3b) and ϕ_{21} (Figure 3c) are approximately of equal magnitude (about 0.15) and of opposite sign. Figure 3 (e,f,g) show the distributions for σ_{11}, σ_{12} and σ_{22} respectively. Clearly the noise input to the LSHFA is more uniform and generally stronger than that for the SSTA and a wide range of noise correlations of both signs exists.

A dramatic example of the organization of the observations by the fitted parameters of the model is shown in Figure 4, where red/blue represents the regions where the fitted values of σ_{12} are less/greater than zero. Figure 4 captures very clearly the distinction between the two regions discussed in the last section. The lowest and highest deciles of fitted values for σ_{12} produce Figure 5. Comparison of Figure 5 with Figures 1a-c and 2 reveal that the extreme deciles based on the distribution of fitted values for σ_{12} (Figure 5) are substantially the same as those based on the distribution of the values of the CCF at zero lag (Figures 1a-c and 2). Using the former deciles (based on the sign of σ_{12}), we extract parameter values for the red/blue regions from the distributions in Figure 3 to produce Figure 6. We see that the red region has significantly higher SSTA persistence and that the feedback coefficient ϕ_{21} is strongest in the red region. The blue region, on the other hand, has a substantially reduced SSTA persistence and a small value for ϕ_{21}. Regional differences for ϕ_{22} and ϕ_{12} are much less pronounced. ϕ_{22} is considerably smaller than ϕ_{11} in both regions, as expected from the curves shown in Figure 3. This supports the idea that the atmosphere has much less persistence (memory) the does the ocean. Notice that the noise input into the SSTA in the blue region (σ_{11}) is considerably stronger than that for the red region.

We ran an ensemble (200) of realizations of the model using the median values of Φ and Σ obtained from the two regions to produce model-based estimates of the CCF, power spectra, cross spectrum and phase spectrum. We find good agreement with the observed cross correlation functions (compare Figure 7c,d with Figure 5d,e). We also recover the basic structure of the phase spectra as well (compare Figure 7f with Figure 5g). The observations suggest that the cross spectral amplitudes of the SSTA and the LSHFA are the same in the red and blue regions (Figure 5f), while the model simulations indicate that the red region has slightly lower cross spectral amplitudes at high frequencies. Many realizations of the model were required to make these regional distinctions apparent, so it may be that the uncertainty (noise) in the observations is simply too large to allow the emergence of this subtle feature. The model cross-spectra also have a distinct knee near a frequency of about 1 cycle/year and are flat out to lower frequencies. The observational cross-spectra, on the other hand, increase as the frequency decreases. The autospectra are also well-modeled (compare Figure 7a,b with Figure 5b,c) except at low-frequencies. These discrepancies are related to the low-frequency structure in the residuals (observations minus model fit).

Autocorrelations and autospectra of the residuals suggest that the model is successful in capturing the organized temporal structure at each location in the observations. Autocorrelation values are less than 0.2 and autospectra are approximately constant at all frequencies. Recall, however, that we obtained the model fit at each location independently. Spatial correlations in the observations are known to exist and residuals from the fit display large scale spatial and temporal structure. Figure 8a shows the annual-mean, zonally-averaged residuals of SSTA and LSHFA together with an identically-processed field of uncorrelated white noise. We see that the SSTA residuals contain the large propagating features that have been the focus of recent studies (Hansen and Bezdek, 1996; Sutton and Allen 1997). The LSHFA residuals, although not as well-defined as in the SSTA residuals, also show propagating features on scales much larger than those seen in the white noise panel.

One characterization of the consequences of the spatial correlations can be seen in power spectra of the basin-wide median time-series of the residual SSTA and LSHFA (Figure 8b,c). The residual SSTA spectrum is clearly dominated by low frequency energy, while that for the LSHFA residuals is less evident.

In summary, the discrete first-order vector autoregressive model captures the structure of the cross correlation functions, cross spectra and phase spectra of the observations, including the geographical variability of these functions. It does not, however, capture the behavior of the observations at low frequencies and large space scales.

IV. Discussion

A precise description of the interaction between the ocean and atmosphere is bound to be a complicated matter. The development and interpretation of the mixed-layer heat budget, from which SST may be inferred, is complex (Frankignoul, 1985). This budget contains at least 5 important terms that are not directly a function of local air-sea heat flux. A similar description for the coupled system (heat budget of the oceanic mixed-layer/atmospheric surface boundary layer system) would be even more complex. There is no hope of accurately measuring all of the processes well enough to assess the nature of air-sea coupling on climate time scales any time soon. In the face of these difficulties, it is clear that progress on this critical issue will be possible only in small steps. We propose here one such step by seeking to describe and model statistical relationships that characterize the low-order behavior of this intricate system.

In that spirit, we seek a simple parameterization of the ocean and atmosphere that can be associated with observations. Of the oceanic fields available, SST appears to be the one that most influences the atmosphere; it is a natural choice. For the atmosphere, we choose the local surface heat flux, derived from measurements of wind and ocean/atmosphere differences of temperature and humidity, because it has a direct link to the SST. The local surface heat flux is a forcing term in the SST tendency equation. In other studies, some have chosen to parameterize the atmosphere with sea-level pressure (SLP), or some other measure of atmospheric mass distribution. The nature of the apparent statistical connection between the ocean and the atmosphere can be quite different depending on the choice of parameterization and further consideration of the relationship between SLP and surface heat flux is needed to properly interpret such studies.

For example, the antisymmetric character of the CCF between SSTA and LSHFA is not apparent in the CCF between SLPA and SSTA. In the red region of the North Atlantic, the CCF for SLP and SSTA is very similar to that of Davis (1976). In this region, however, our model fits suggest that both mutual feedback and correlated noise are required to explain the observed structure. This is not be true for the CCF between SLPA and SST because only partial feedback between SLPA and SSTA is required to obtain the observed shape. This difference, which leads to a substantial difference in interpretation, arises from the difference between surface heat flux and surface pressure. Our result appears to be more basic because the relationship between SSTA and LSHFA is more direct.

We propose a coupled model driven by two sets of random impulses correlated only at zero lag. Nontrivial coupling (or feedback) is essential for reproducing the observed CCF structure, so it appears inappropriate to interpret the results as one medium forcing the other. If either ϕ_{12} or ϕ_{21} are zero (partial feedback), one of the variables does not have a direct dependence on the value of the other. In this case, it is appropriate to say that one variable forces the other. This might be thought of as the causal limit of the coupled system. The success of the fully coupled model suggests that it is better to think of SSTA and LSHFA as being mutually coupled, with the nature of the coupling being different in different times and places. Depending on the signs of the feedback terms, this means that the two systems work together to reinforce or to oppose each other, but they always work together. One of the systems never simply forces the other in a causal sense.

The noise correlation σ_{12} may be interpreted as zero lag correlation between SSTA and LSHFA due to unobserved physical mechanisms. For the blue region, the noise correlation, σ_{12} (Figure 6f), is positive. With our sign convention, this means that the random component of the forcing of SSTA tends to be positive (negative) when the LSHFA are upward (downward). Thus, the most important coupling between SSTA and LSHFA is contemporaneous. ϕ_{21} is close to zero (Figure 6c), so the LSHFA is only weakly affected by the previous month's SSTA. The significant, but small, negative values for ϕ_{12} (Figure 6b) in this region indicate that the LSHFA provides a negative feedback to the SSTA.

The contemporaneous coupling in the red region has the opposite sign, with the random component of the forcing of SSTA tending to be positive (negative) when the LSHFA are downward (upward). Furthermore, Φ tends to be antisymmetric in the red region. This means that the coupling is essential in the red region and it accounts for the antisymmetric shape of the CCF in this region with extreme values at lags of 1 and -1. The previous month's SSTA and LSHFA both provide feedback to influence the results of both fields the following month. This conclusion differs from those found in previous studies where the atmosphere is found to drive the ocean (Delworth, 1996; Battisti *et al.*, 1995).

A comparison with the results of Frankignoul (1995, 1985) are in order. A rigorous transformation between the development of Frankignoul (1995), which uses a continuous model, and our development of the discrete model is not transparent. Nonetheless, the spirit of the two models is very much the same and the basic mechanisms of white noise forcing, persistence and feedbacks are identical. Basically, the Frankignoul (1995) approach is equivalent to our approach with partial feedback ($\phi_{21} = 0$). This produces SSTA spectra that are similar to those observed and is able to produce CCF that have an "antisymmetric aspect" (Frankignoul, 1985). This forms the basis of the success of the

Frankignoul approach, but colored noise and explicit inclusion of the effect of using monthly-averaged data are required to move the extrema in the CCF away from zero. In our model, ocean feedback to the atmospheric state is explicitly included and shown to be nontrivial. This added mechanism allows the possibility of a CCF with extrema at lags of both ±1 with the value at zero lag small or zero, in accordance with the observations. The model (with fitted parameters) produces faithful estimates of the CCF, cross spectra and phase spectra. Frankignoul (1995) did not explicitly consider the comparison of their model cross and phase spectra with the observations, but we find that we cannot get a good match with observations if we neglect the ocean to atmosphere feedback ($\phi_{21} = 0$).

The primary importance of these results is probably the guidance they provide for the development of coupled general circulation models. Such models must be able to reproduce the observed cross correlation structure between LSHFA and SSTA before conclusions based on their output can be made with confidence. These models, once verified, will provide the best tool for exploring the potential connections between the propagating low-frequency structures in SSTA and variability of the earth's climate.

V. Conclusions

Based on an analysis of COADS summaries from 1947-1990, we show that the form of the cross-correlation between SSTA and LSHFA provides a clear distinction between an open-ocean midlatitude region (red) and another which dominates near the western boundary current and in the tropics (blue). The red region is characterized by CCF which are strongly antisymmetric and by phase spectra that are about 75° over a broad frequency range. The blue region, on the other hand, has CCF which peak at zero lag, are one sided, and have phase spectra that are about 25° over a broad frequency range.

A discrete first-order vector auto-regressive model is used to interpret and unify our findings . Correlations in such a model potentially arise from two sources: (1) Noise that is correlated at zero lag only and represents unobserved physical mechanisms and (2) Feedbacks between the ocean and atmosphere. Fits of the observed time series show that the red and blue regions have several distinctions: (1) The sign of the noise correlation is positive in the red region and negative in the blue region. (2) The persistence of SSTA is smaller in the blue region. (3) The feedback of ocean to atmosphere is small in the blue region. (4) The persistence of LSHFA is very small in the red region. The CCF in the red region requires that the noise be correlated, the ocean have significant persistence and the feedback between ocean and atmosphere be significant in both directions. This is different than the model of Frankignoul and Reynolds (1983) which included only feedback from atmosphere to ocean. In the blue region, the CCF can be well-modeled with only correlated noise and ocean persistence.

The model fits are performed on each location separately and the residuals from each location do not show any remaining temporal structure. Spatial-temporal correlations, however, are evident in the residuals which propagate on decadal time scales. It appears that these features cannot be modeled by local linear stochastic models. Some method of incorporating spatial correlations must be developed to account for these features. It therefore appears that it is premature to conclude that “...the development of SST anomalies can be understood..., without invoking feedback mechanisms, as the integral response of the ocean to random short-time-scale forcing by the atmosphere" as suggested by Frankignoul and Hasselmann (1977) for two reasons: (1) Full feedback is required to model the observations with a linear, local stochastic model and (2) The residuals that remain after fitting such a model to the observations contain important low-frequency propagating signals that the model cannot account for.

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VIII. Figure Captions

Figure 1. Locations and structure of cross correlation functions between observed values of SSTA and LSHFA in the red and blue regions (see text). Locations are chosen from lowest (red) and highest (blue) deciles of two distributions formed by: (1) Sorting the zero-lag value of the cross correlation function (a-c), (2) Sorting the frequency with which SSTA and LSHFA have the same sign (d-f). Red and blue in panel a (d) show locations from which cross correlations shown in panels b and c (e and f) were chosen. Black represents land, white depicts locations that are considered data-poor and gray depicts the locations used in this study that are not in the lowest or highest decile. Solid lines in (b,c,e,f) are the medians of the individual cross correlation functions shown in light gray. Solid lines are color coded to conform to locations shown in (a,d). Positive/negative lags mean that SSTA leads/lags LSHFA.

Figure 2. Magnitude (a) and phase angle (b) of cross spectra between SSTA and LSHFA observations for the red and blue regions as determined in Figure 1a-c. Units of phase angle are degrees and negative angles mean that SSTA leads LSHFA.

Figure 3. Distribution functions of fits for elements of Φ and Σ. Dark line is the value and light lines show one standard error derived from the fitting process.

Figure 4. Locations of bins with sign of the innovation (noise) cross correlation (σ_{12}) greater than (blue) or less than (red) zero.

Figure 5. (a) Locations, (b,c) auto spectra, (d,e) cross correlation functions, (f) cross spectra and (g) phase spectra for observed values of SSTA and LSHFA in the red and blue regions (see text). Locations are chosen from lowest (red) and highest (blue) deciles of the distribution of σ_{12}. In (a), black represents land, white depicts locations that are considered data-poor and gray depicts the locations used in this study that are not in the lowest or highest decile. Solid lines in (b,c,d,e,f,g) are the medians of the various individual functions. Individual cross correlation functions (d,e) are shown in light gray. Solid lines are color coded to conform to locations shown in (a). Positive/negative lags mean that SSTA leads/lags LSHFA.

Figure 6. Distribution functions of fits for elements of Φ and Σ based on the least and greatest deciles of the distribution of σ_{12}. Red/blue lines show values of the parameter and are color coded to the red/blue regions. Light gray/dark gray denote one standard error for values of Φ shown by red/blue curves.

Figure 7. Statistics derived from 200 realizations of the model using median parameters from fits shown in Figure 6. All panels depict median values derived from the 200 realizations. (a,b) Auto spectra of SSTA and LSHFA for red and blue regions, (c,d) Cross correlation function of SSTA and LSHFA, (e,f) Cross and phase spectra of SSTA and LSHFA. Figures are color coded to denote appropriate regions.

Figure 8. (a) Latitude-time plots showing residuals remaining after the fit to observations. Top: SSTA residuals, Middle: LSHFA residuals, Bottom: white noise. Monthly SSTA and LSHFA were used to form annual means and then averaged longitudinally over 2° latitude bands. Each of the three data arrays were smoothed by a Hanning-weighted 3x3 window. Values are coded in 10 gray scales (linear from -0.6 to 0.6), with white/black being positive/negative, respectively. (b) Power spectrum of median of SSTA residuals. (c) Power spectrum of median of LSHFA residuals.