14.5 USE OF GRANGER CAUSALITIES TO EXAMINE AIR-SEA FEEDBACKS IN THE TROPICAL PACIFIC OCEAN

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1. INTRODUCTION

Air-sea interactions have been observed to contain a high degree of non-linear feedbacks in the tropical Pacific Ocean region, particularly in relation to sea surface temperature. The coupling of the atmosphere and ocean occurs on spatial scales ranging from less than 1 km to over 10,000 km and on timescales from minutes to years. Changes in sea surface temperature (SST) throughout the tropical Pacific can potentially bring the onset of atmospheric circulatory features that persist from several months to years and influence a significant portion of the global atmosphere. Changes in SSTs have also been shown to be important for such processes as the Madden-Julian Oscillation, varying convective regimes, and westerly wind bursts.

The purpose of this study is to examine potential feedbacks for atmospheric-oceanic processes along the equatorial tropical Pacific, particularly in relation to sea surface temperature regulation. Data was obtained from the TOGA TAO buoys, and then a non-conventional time series analysis technique originally developed for economic applications was adapted. Unlike traditional correlation techniques, this methodology is used to detect feedback relationships within the data between the processes that generated them. In other words, variability in one time series can be better explained by inclusion of data from a second variable time series.

There are several reasons for attempting to understand the feedback mechanisms operating in the tropical Pacific. A determination of the strength of the feedback mechanisms provides understanding of the most important processes acting to regulate sea surface temperature in this region. In addition, understanding of the feedbacks provides greater predictive capabilities given changes in such forcings as surface fluxes. Finally, a quantitative description of feedback mechanisms provides another method for evaluation of a coupled air-sea model's performance.

This study focuses on determining the degree of the feedbacks between variations in sea surface temperature and those atmosphere and ocean parameters affecting it; and on understanding how different areas within the tropical Pacific basin affect the interpretation of these feedback values.

2. DATA

The source of the surface ocean data used for this analysis is the Tropical Atmosphere Ocean (TAO) buoy data array, facilitated by the Pacific Marine Environmental Laboratory (PMEL). The time series method used in this study precludes any use of gap filling. This places a severe constraint on the buoy data sets that can be used. Several buoys in the western, central, and eastern Pacific in the years of 1996 – 1999 maintained continuous data streams. Standard meteorological data was available from each of these buoys, and surface fluxes were calculated using the Clayson et al. (1996) flux algorithm. Each of these buoys also had subsurface temperature measurements. At several of the buoy locations, shortwave radiation was available from mounted pyranometers.

3. GRANGER CAUSALITY

The approach used in this study is based on the time series analysis of Granger (1969). In this approach, a variable (X) is considered to "Granger cause" a second variable (Y) if past values of x contain meaningful information about current values of y that are not already contained in past values of y (Kaufmann and Stern 1997). If Granger causality exists for both x to y and y to x, then there is a feedback relationship between the processes that generated them (Maliekal 1998).

If the data are wide-sense stationary, the unrestricted autoregressive functions used are of the form:

$$X_i = \sum_{i=1}^{M} \alpha_{1i} X_{t-i} + \sum_{i=1}^{M} \beta_{1i} Y_{t-i} + \varepsilon_{1t} \qquad (1)$$

where Y_i is the response variable, α_1 and β_1 are the regressive parameters, X_i is the observational data variable, and e_i is the error term. M is the model order (to be discussed later). As this study is comparing two variables, the second equation required is:

$$Y_i = \sum_{i=1}^{M} \alpha_{2i} Y_{t-i} + \sum_{i=1}^{M} \beta_{2i} X_{t-i} + \varepsilon_{2t} \qquad (2)$$

Equations (1) and (2) are the unrestricted versions of the time series data. Granger causality also requires the restricted autoregressive equations, defined as:

$$X_i = \sum_{i=1}^{M} \alpha_{1i} X_{t-i} + \varepsilon_{1t} \qquad (3)$$

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$$Y_i = \overset{M}{\underset{i=1}{\square}} \square_{2i} Y_{t\square i} + \square_{2t} \tag{4}$$

The measure of linear dependence from Y to X is:

$$F_{y\square x} = \ln \square \frac{\square_1}{\square_1} \square \tag{5}$$

where $\square_1$ is the error variance of the restricted form of the autoregressive equation (3) and $\square_1$ is the error variance of the unrestricted form of the autoregressive equation (1). Similarly, the measure of linear dependence from X to Y is of the form:

$$F_{x\square y} = \ln \square \frac{\square_2}{\square_2} \square \tag{6}$$

based on the error variances from equations (4) and (2). The instantaneous linear feedback is of the form:

$$F_{x \cdot y} = \ln \square \frac{\square_2 \square \square_2}{\det(\square)} \square \tag{7}$$

where $\square$ is the covariance matrix derived from the error variances of the unrestricted equations (1) and (2). The error variance, or residual sum of squares, is calculated from:

$$RSS = \square (e_i)^2 \tag{8}$$

where e_i is the residual, the difference between the measured value and the model fit.

The F values are assumed to follow a $\square^2$ distribution. The degrees of freedom for the F values is the model order, with the degree of freedom for the instantaneous value being 1. This study uses a cutoff of 0.3. The results are robust; significances tend to be either much higher or lower than 0.3. The model order used in this research is based on the Simms criteria, which defines the model order as $(N)^{1/3}$, where N is the size of the dataset.

If $F_{y\text{-}x}$ is statistically significant, then it can be said that X "Granger causes" Y and similarly for $F_{x\text{-}y}$. If both $F_{y\text{-}x}$ and $F_{x\text{-}y}$ are statistically significant, then there is a feedback relationship between the two variables. A statistically significant value of $F_{x.y}$ indicates that feedbacks are occurring on the sub-resolved time scales.

4. SURFACE ENERGY BUDGET

The surface energy budget details the fluxes that control sea surface temperature:

$$F_{net} \square F_{adv} \square F_{ent} = F_{rad} + F_{sh} + F_{lh} + F_{pr} \tag{9}$$

where F_{net} is the net surface heat flux, F_{adv} is the horizontal advection flux, F_{ent} is the entrainment heat flux, F_{rad} is the net surface radiation heat flux, F_{sh} is the sensible heat flux, F_{lh} is the latent heat flux, and F_{pr} is the sensible heat flux due to precipitation. Due to data constraints, only F_{ent}, F_{rad}, F_{sh}, and F_{lh} will be examined, as will the wind stress and mixed layer depth due to their impact on entrainment flux.

5. EXAMPLE: INTERANNUAL VARIABILITY IN THE CENTRAL PACIFIC

An analysis of the data from the buoy located at 0°N 140°W for the months of November through February (1996-1997 and 1997-1998) is presented. The statistically significant results of causality values of various fluxes on sea surface temperature are shown (where a statistically significant causality between sea surface temperature and the variable is also found, a feedback mechanism is noted). A higher F value implies stronger causality.

Nov 1996 – Feb 1997		Nov 1997 – Feb 1998	
$F_{sol\text{-}sst}$ *(feedback)*	12.2	$F_{sol\text{-}sst}$ *(no feedback)*	46.6
$F_{sol\text{-}sst}$ *(no feedback)*	---	$F_{sol\text{-}sst}$ *(feedback)*	8.1
$F_{sol\text{-}sst}$ *(feedback)*	11.3	$F_{sol\text{-}sst}$ *(no feedback)*	---
$F_{sol\text{-}sst}$ *(feedback)*	14.1	$F_{sol\text{-}sst}$ *(no feedback)*	14.8
$F_{sol\text{-}sst}$ *(feedback)*	8.9	$F_{sol\text{-}sst}$ *(no feedback)*	---

In the 1996/1997 time series, solar radiation, latent and sensible heat flux, and mixed layer depths were all causers of variability in sea surface temperature, in roughly equal amounts. There was also a feedback mechanism for each of these forcings. In contrast, the 1997/1998 time series (an El Niño period) showed that solar radiation was much more important in forcing the sea surface temperature variability than any other factor evaluated. However, no feedback mechanism was found. In other words, non-local effects were much more important in determining solar variability (and thus sea surface temperature variability). This can also be noted by the lack of feedbacks between the local entrainment and latent heat fluxes and mixed layer depth. Further results will be shown in the presentation.

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6. REFERENCES

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