NOTES AND CORRESPONDENCE

Air-Sea Interaction and the Quasi-Biennial Oscillation

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13 February 1978 and 12 June 1978

ABSTRACT

Solutions to a set of differential equations representing a system of postulated interactions between the ocean and the atmosphere can reproduce certain hitherto unexplained aspects of atmospheric and oceanic behavior in the Indonesia–North Australia region. These solutions also represent a biennial oscillation and it is concluded that the postulated air-sea interaction could be the source of the tropospheric quasi-biennial oscillation.

1. Introduction

The existence of a quasi-biennial oscillation (QBO) in the troposphere is now fairly well-established. For example, Gordon and Wells (1975) have found a highly significant biennial pulse in central England summer temperatures and Trenberth (1975) found a quasi-biennial cycle in some components of an empirical orthogonal function analysis of monthly pressure anomalies in the Australian region. The conventional explanation of this tropospheric QBO is that it is the result of forcing from the more readily detectable stratospheric QBO through an unspecified troposphere-stratosphere interaction. In turn, the stratospheric QBO has been explained by interaction between the mean flow and large-scale equatorial waves propagating through the stratosphere from below (Plumb, 1977).

However, Brier (1978) has presented a conceptual model which suggests that the tropospheric QBO could arise from a system of air-sea interactions if the sense of either the ocean-to-atmosphere forcing or atmosphere-to-ocean forcing varied seasonally. Thus if the ocean-to-atmosphere feedback was negative throughout the year but the atmosphere-to-ocean feedback was negative for part of the year and positive for the remainder, then a biennial oscillation might be produced in the atmosphere and ocean. Brier (1978) does not suggest a specific form or area of influence for such feedbacks. The purpose of this note is to postulate that air-sea interaction in the Indonesia–North Australia region may provide the required seasonal variation in feedback and could be the source of the tropospheric QBO.

2. Air-sea interaction and the QBO

Over the last decade, several experiments have been performed with numerical models of the atmosphere to estimate the effect that a warm, equatorial, sea surface temperature (SST) anomaly might have on the atmospheric circulation (e.g., Matsuno 1966; Rowntree 1976). In each case, the atmospheric pressure in the tropics and subtropics decreased. It is postulated therefore that an anomalously warm equatorial SST will tend to reduce tropical atmospheric pressure. If, then, an atmosphere-to-ocean forcing mechanism exists such that a positive tropical pressure anomaly produces a decrease in SST during part of the year, and an increase in SST during the remainder of the year, then we will have a pair of feedback relationships of the form proposed by Brier (1978) as a possible cause of the QBO. Strong grounds exist for believing that such a seasonally varying atmosphere-to-ocean interaction occurs in the Indonesia—North Australia region.

An important factor in the production of SST anomalies is the wind speed in the overlying lower troposphere. In general, an increase in wind speed will tend to increase evaporation from the ocean surface and to increase mixing in the upper layers of the ocean, thus causing the SST to decrease. In the Indonesia—North Australia region, lower tropospheric wind speed and atmospheric pressure are correlated, and the sign of the correlation

0027-0644/78/1505-1508$05.00

varies seasonally. For instance, the correlation between monthly mean 850 mb wind speed and surface pressure during July at Darwin is +0.53 (21 years data, significant at 1% level), while the correlation between February monthly mean 950 mb wind speed (more representative than 850 mb of the shallow layer of northwest monsoon winds present during this season) and pressure is −0.49 (significant at 2% level). Thus during the Southern Hemisphere winter a positive pressure anomaly will be accompanied by anomalously high wind speeds which in turn will tend to decrease the SST. However, during summer a positive pressure anomaly will be accompanied by weaker winds than normal allowing the SST to increase.

The seasonal reversal in the pressure-wind speed correlation is the result of the seasonal reversal in the prevailing wind direction in the Indonesia–North Australia region. During winter the prevailing wind direction is approximately easterly. If surface pressure is above normal and if the magnitude of the pressure anomaly is smallest at the equator, then a north-south gradient in pressure will be present and associated with this there will be an easterly geostrophic wind anomaly. This anomalous wind will reinforce the prevailing easterly wind, resulting in above-normal wind speed. During summer, however, the prevailing wind direction is westerly and the easterly geostrophic wind anomaly associated with the same pressure anomaly pattern will result in a weaker than normal wind flow. Thus in summer, wind speed and pressure will be negatively correlated while they will be positively correlated in winter.

This explanation of the seasonal reversal in the sign of the pressure-wind speed correlation rests on the assumption that the pressure anomaly will be smallest at the equator. This assumption is supported by the numerical modeling studies quoted above. For instance, in Matsuno's (1966) model, the largest pressure anomaly produced by the equatorial SST anomaly occurred poleward of the SST anomaly with smaller pressure anomalies at the equator. Similar behaviour is also apparent in Rowntree's (1976) study. Thus the pattern of pressure anomaly produced by the equatorial SST anomaly corresponds to that required to produce the observed seasonal reversal in the sign of the pressure-wind speed correlation.

The air-sea interactions proposed here represent a system similar to that proposed by Brier (1978). Throughout the year, the forcing of tropical atmospheric pressure by SST anomalies will be negative while the sense (positive or negative) of the forcing of SST by tropical pressure anomalies will vary, depending on the direction of the prevailing wind flow, which itself varies seasonally.

A very simple "model" which attempts to simulate these postulated interactions has been developed. Only two variables are included in the model, one being SST anomalies in the Indonesian Archipelego and the other, anomalies of Darwin pressure. The year was divided into two seasons, summer (mid-November–March) and winter (April–mid-November) and a set of the simplest possible differential equations that are capable of representing the postulated interactions between anomalies of pressure (P) and SST (T) were set up. The equations are

$$\left.\begin{aligned} dT/dt &= \alpha P \\ dP/dt &= -\beta T \end{aligned}\right\} \quad \text{(summer)}$$

$$\left.\begin{aligned} dT/dt &= -\gamma P \\ dP/dt &= -\theta T \end{aligned}\right\} \quad \text{(winter)}$$

where t is time and α, β, γ and θ are unspecified positive constants.

Solutions to the above set of equations show varying forms of behavior, depending on the magnitude of the constants, particularly the value assumed for $(\alpha\beta)^{1/2}$. Not all of these solutions will be realistic and some means of rejecting the unrealistic solutions is required. To do this, the observed correlations between SST anomalies in the Indonesian region and pressure anomalies at Darwin, as calculated by Berlage (1957), were used. This correlation varies seasonally, being negative during winter (−0.83, 25 years data) and positive during summer (+0.67). It was therefore assumed that only those solutions of the above set of equations which correctly reproduced this observed relationship between SST and pressure could possibly be realistic. All other solutions were discarded.

While all remaining solutions show qualitatively similar behavior, they are also unstable and the magnitude of P and T generally diverge from the initial values, over 12 or more months. The inclusion of linear damping terms in the equations (i.e., a tendency for anomalies to decay in the absence of the interactions) enables stable solutions to be found. These solutions closely simulate certain aspects of the observed behavior of pressure and SST anomalies in this region.

To demonstrate this, a representative solution of these equations is shown schematically in Fig. 1. A value of 0.0175 days^{-1} is used for $(\alpha\beta)^{1/2}$ and for convenience the magnitudes of α, β, γ and θ are assumed to be equal. This solution reproduces the observed negative (positive) relationship between SST and pressure during winter (summer), and also the observed (Berlage, 1957) positive relationship between SST, averaged from September to February, and the change in pressure (December–May average

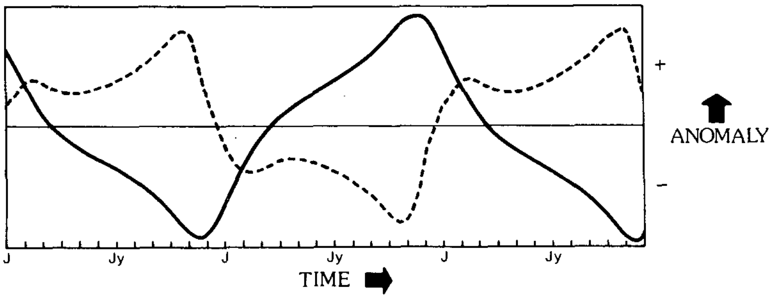

FIG. 1. Monthly averaged pressure (solid) and SST (dashed) anomalies (arbitrary units) produced by model. Marks on horizontal axis indicate each month. January (J) and July (Jy) are indicated.

minus July–November average). Throughout the rest of the year the relationship between SST and the pressure change (in both the model and the real world) is inverse (Berlage, 1957). Also, if we assume that other mechanisms affecting Darwin pressure result in a contribution to the variance that remains relatively constant throughout the year, then Fig. 1 "predicts" a seasonal variation in the persistence of pressure anomalies from one month to the next. Around March, when the magnitude of the anomalies produced by the air-sea interaction is relatively small, persistence should be low compared to later in the year when the interaction produces relatively large anomalies. Such a seasonal variation is observed in persistence of monthly mean pressure at Darwin (Priestley, 1962). Therefore, this conceptual air-sea interaction model apparently can provide a basic framework for understanding important aspects of the behavior of large-scale atmospheric and oceanic anomalies in the Australian region.

Those particular solutions of the above equations which correctly reproduce the observed statistical relationship also produce a biennial oscillation in the atmosphere and ocean (Fig. 1). If one attempts to represent other processes which undoubtedly affect these large-scale anomalies by including random perturbations in the equations, then the features noted previously are still reproduced. However, the random perturbations occasionally cause the changeover in phase of the biennial cycle to be missed. As noted by Brier (1978) this produces a "quasi-biennial" cycle. A QBO has been observed in atmospheric pressure in the Australian region (Trenberth, 1975).

3. Conclusions

Possible air-sea interaction mechanisms relevant to the Indonesia–North Australia region have been discussed. It is proposed that, throughout the year, above-normal equatorial SST will tend to decrease the atmospheric pressure of the tropics and subtropics. It is proposed, that the anomalous pressure pattern thus produced will cause variations in the original SST anomaly. The sense of the variation (increase or decrease) in the SST anomaly will depend on the direction of the prevailing wind which itself varies seasonally. Thus, during part of the year, a positive pressure anomaly will be associated with an increase in SST, while during the remainder of the year the same pressure anomaly would be associated with a decrease in SST.

A mathematical model consisting of the simplest set of differential equations capable of representing these proposed interactions has been developed. Certain solutions to these equations correctly reproduce various aspects of the observed behavior of the ocean and atmosphere in this region, e.g., the seasonal variation in the persistence of pressure anomalies from one month to the next and the seasonal variation in the correlation between SST anomalies and pressure anomalies. These solutions, and only these solutions, also produce a QBO in the atmosphere and ocean. It is concluded that the air-sea interaction represented by the set of equations could be the cause of the observed QBO in atmospheric pressure in the Australian region.

The relationship between pressure anomalies in this region and atmospheric behavior throughout the world is well known (Troup, 1965). It is therefore tentatively suggested that the air-sea interaction discussed here might be the cause of the tropospheric QBO observed in other regions.

It should be noted that the postulated air-sea interaction described here is not suggested as a possible mechanism for the stratospheric QBO.

Acknowledgments. Dr. N. C. Wells, Mr. N. A. Streten, Mr. R. S. Seaman and Dr. D. J. Gauntlett provided stimulating comments and encouragement.

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