

# SST ANOMALIES AND BLOCKING

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## 1. INTRODUCTION

There is a large body of published literature on the possible role of sea surface temperature (SST) anomalies in producing quasi-stationary circulation anomalies in midlatitudes, to be referred to, loosely, as blocking. We present here only a summary of what we consider to be important physical concepts that have appeared during the past decade in connection with the problem of the influence of SST anomalies on extratropical circulation anomalies.

Let us first ask a basic question. How does a SST anomaly influence the atmospheric circulation? The immediate effect of a SST anomaly is to alter the sensible heat flux and evaporation over the region of the SST anomaly. This will alter the temperature and humidity of the overlying air. If that was all the SST anomaly did, there would be little change in the atmospheric circulation. However, if the sensible heating of the air produces gradients of surface pressure, then it can change the convergence of the moist air and precipitation in the region of the SST anomaly. The magnitude and the structure of the convergence pattern will depend upon the magnitude and structure of the SST pattern itself. Warmer and moister surface air might lead to deeper moist convection and heating of the atmospheric column. This might lead to further enhancement of the surface pressure gradients, an increase in moisture convergence in the boundary layer, and an increase in precipitation. This Convective Instability of the Second Kind, or CISK-type positive feedback, among heating of the vertical column, convergence in the boundary layer, and precipitation can transform the initial surface heat flux anomaly into a three-dimensional heating anomaly which can produce changes in large-scale atmospheric circulation. Based on these arguments it is possible to present the following simple conceptual framework to understand the effects of SST anomalies on atmospheric circulation.

$$\partial T \rightarrow \partial Q \rightarrow \partial C$$

The SST anomaly ( $\partial T$ ) produces a deep heating anomaly ( $\partial Q$ ), which in turn produces a circulation anomaly ( $\partial C$ ). For longer periods,  $\partial C$  in turn can affect  $\partial T$ , however, the discussion in this paper will be confined to those time scales for which  $\partial T$  is quasi-steady (about a month or a season). It is now simple to state, at least in this conceptual framework, that whether a SST anomaly will produce a circulation anomaly will depend upon two things: the SST anomaly should produce a heating anomaly, and the heating anomaly should produce a circulation anomaly. We shall examine the two factors separately.

Let us first examine the factors which will determine whether a given SST anomaly will produce a heating anomaly or not. These factors are as follows:

1. The magnitude and structure of the SST anomaly.
2. The magnitude and structure of the climatological SST on which the anomaly is superimposed.

These two factors together determine the modified SST field due to presence of an anomaly. Since the atmosphere is influenced by the total SST, not just the SST anomaly, the anomaly alone is not of any special significance except as a convenient descriptor of the SST field. The basic SST field is of utmost importance because a change in saturation vapor pressure for a  $1^\circ$  change from  $29^\circ$  to  $30^\circ\text{C}$  is much larger than that for a similar change from  $20^\circ$  to  $21^\circ\text{C}$ . Moreover, the structure of the actual SST field determines the magnitude and the pattern of convergence which is crucial for the establishment of a deep heat source.

There are additional factors which determine the transformation of a SST anomaly into a deep-heating anomaly and which suggest that the tropical SST anomalies are more effective than the midlatitude SST anomalies in producing deep-heat sources.

3. The latitude of the SST anomaly. Changes in the thermal wind produced by the changes in SST depend upon the rotation rate. Even weaker SST gradients in the tropics can produce large changes in thermal wind and convergence of moisture in the boundary layer.

4. The location of the SST anomaly with respect to the large scale flow. If a warm SST anomaly occurs under the ascending branches of the Hadley and/or Walker cells in the tropics, it can increase the moisture convergence and heating, whereas a similar warm anomaly under the descending branch will not be able to produce moisture convergence and rainfall because even the additional moisture due to enhanced evaporation will be diverged away.

5. The dominant instability mechanism. Warm SST anomalies in the tropics might enhance the moist convection quickly and produce a deep heat source due to moist convective instability. If the effect of the SST anomaly

were only to change the shear of the flow and thereby to change the dynamical instability properties of the flow, that may involve a relatively longer time scale.

A similar consideration of the factors which determine the influence of a given heating anomaly on the circulation anomaly also suggests that there are distinctly different processes that determine the response due to tropical and midlatitude heating anomalies. It is therefore appropriate to divide the remaining discussion into four broad topics covering the influence of tropical and extratropical SST anomalies on the tropics and extratropics.

There is a vast amount of literature covering these topics and we cannot present a comprehensive review of the previous works for each topic. We shall confine our discussion mainly to the topics in Sections 2 and 3, and we shall summarize the results of only a few representative investigations.

## 2. INFLUENCE OF TROPICAL SST ANOMALIES ON EXTRATROPICAL CIRCULATION

The question of the influence of the tropical heating on midlatitude circulation has been investigated using past atmospheric observations and models of varying degrees of complexity ranging from linear and simple nonlinear models to global general circulation models (GCMs). The most significant difference between the simple models and the GCMs lies in the treatment of the heating anomaly  $\partial\dot{Q}$ . In GCMs,  $\partial T$  is explicitly used to calculate  $\partial\dot{Q}$  from model physics and dynamics, whereas in simple models  $\partial\dot{Q}$  is prescribed. The GCMs enable us to examine the effects of all the processes involved in  $\partial T \rightarrow \partial\dot{Q} \rightarrow \partial C$ , whereas the simple models examine the processes involved in  $\partial\dot{Q} \rightarrow \partial C$  only. Simple models also prescribe the large-scale mean flow which can be either zonally symmetric or have simple asymmetries. In spite of these limitations of the simple models, they are useful tools for carrying out a large number of experiments and for helping to understand the mechanisms for the remote response to tropical heating anomalies.

The mechanisms suggested so far to explain the midlatitude effects of tropical heating anomalies can be summarized under the following broad categories.

1. *Rossby wave propagation.* Forced (steady) Rossby wave solutions of the linearized barotropic vorticity equation show remarkable similarity to some of the observed patterns of circulation anomalies associated with tropical heating. However, this mechanism is not adequate to explain the amplitudes of the observed circulation anomalies. Moreover, the tropical and the

midlatitude flows are not necessarily steady for the time scales that are required to set up stationary Rossby waves.

2. *Instability of the horizontally and vertically sheared zonal flows.* The horizontal and vertical shears of observed flows can allow a variety of perturbations to grow by barotropic and/or baroclinic instability mechanisms. The tropical heating, depending upon its magnitude and location, can act as a trigger for the growth of some preferred normal modes.

3. *Modification of the Hadley circulation.* Tropical heat sources can modify the intensity of the Hadley circulation, which in turn can change the zonal flow in the midlatitudes. The modified zonal flow, interacting with the preexisting quasi-stationary heat sources (and mountains), can produce quasi-stationary circulation anomalies. Circulation anomalies can also be produced by growth and decay of perturbations unstable with respect to the modified zonal flow. There have been no systematic modeling or diagnostic studies to determine the role of modified zonal flows.

If one examines the results of numerical experiments with multilevel global primitive-equation models, one can find partial support for each of the mechanisms described above. It is found that the differences in the model simulations with and without tropical heating show, especially for the first 5–15 days, well-defined Rossby wave trains with very small amplitudes ( $\sim 10$  m) emanating from the heat source. However, after about 2 weeks or less, the differences due to a tropical heat source are indistinguishable from the differences that could arise due to instabilities and nonlinear interactions in the midlatitude flow itself, irrespective of the tropical heat sources.

A spatially coherent pattern of significant correlations between equatorial Pacific SST anomalies and the circulation over North America has been found by several investigators (Horel and Wallace, 1981). This pattern of significant correlations is also reproduced by a long integration (15 years) of a GCM using the observed SST over the equatorial Pacific (Lau and Oort, 1985).

Linear model calculations have shown that the midlatitude response due to tropical heating anomalies depends upon the amplitude and vertical structure of heating, the structure of the prescribed zonal flow (especially the presence/absence of a zero wind line), vertical resolution and the upper boundary of the model, and the parameterization of dissipation. If one chooses a suitable value of dissipation for producing a reasonable tropical response, there is no guarantee that the midlatitude response will also be equally reasonable.

We have chosen to describe the results of Nigam (1985) because he does not make arbitrary assumptions about the heating and the zonally averaged zonal flow. These fields are taken from a GCM integration, and the linear

model has been constructed by linearizing the same GCM equations. The horizontal and vertical resolutions as well as the vertical spacing of the model levels are identical for the GCM and the linear model. The GCM solution is used to verify the results of the linear model. It is found that after a suitable tuning of the dissipation term, the stationary solution produced by the linear model is remarkably similar to the GCM simulation. The dissipation term in the linear model can be assumed to mimic, at least partially, the effects of nonlinearity and transients. Separation of the linear solutions forced by tropical heating and orography shows that the stationary-wave amplitude in middle latitudes due to tropical heating is only about 50 m, whereas the orographically forced solution is about 300 m. Results of this and several other linear model studies suggest that the tropical heating is not an important forcing for the midlatitude stationary waves. However, the limitations of the linear models, and especially the prescription of damping, should be thoroughly examined before accepting these results.

Sardeshmukh and Hoskins (1985) have carried out diagnostic studies using atmospheric observations and shown that the regions of deep tropical heating and large upper level divergence occur in conjunction with very small absolute vorticity, and therefore a linear balance between the  $\beta$  term and the divergence term, which describes the dominant balance in the linear models, is not valid. They find that nonlinear advection is quite important to get a reasonable vorticity balance at the upper levels. They also find the transients to be important to describe the observed flow. Schneider (1985) has shown that the essential features of the large-scale tropical flow can be simulated by a steady nonlinear vorticity equation with prescribed divergence sources.

It should be noted, however, that most of these studies are concerned with the explanation of climatological mean, stationary waves and not that of the interannual variability of quasi-stationary anomalies. The role of SST anomalies in producing interannual variability of monthly or seasonal means and the relative importance of the prescribed zonal flow and the prescribed heating have not been fully examined using multilevel linear models.

Sensitivity experiments to determine the influence of tropical SST anomalies on midlatitude circulation using GCMs have also produced a variety of results which are too ambiguous to fit any conceptual framework for the physical mechanisms involved. For example, the transient response (change in circulation for the first few weeks after the SST anomaly is introduced) can be quite different from the equilibrium response (change in circulation after a long-term integration of the model with and without the SST anomaly). In a series of short integrations ( $\sim 75$  days) with the Goddard Laboratory for Atmospheric Sciences (GLAS) model, Shukla and Wallace (1983) found that the simulated response due to composite El Niño SST anomalies was

very similar to the observed circulation anomaly during the El Niño years. However, the observed midlatitude circulation anomaly during the winter of 1982/1983 could not be simulated well using a similar model with the observed SST anomaly during 1982/1983 (Fennessy *et al.*, 1985).

Several GCMs have been used to simulate the effects of the observed 1982/1983 SST anomaly in the equatorial Pacific, and there are considerable differences among the midlatitude responses simulated by different GCMs. The following impressions emerge from a large number of GCM sensitivity studies:

1. The tropical response (change in location of maximum precipitation and accompanying changes in wind flow, surface pressure, and vertically integrated temperature) is well simulated by most of the models.
2. The initial spin-up time (the time taken by a GCM to produce a well-defined large-scale precipitation anomaly after the SST anomaly is introduced) strongly depends upon the parameterizations of boundary layer and moist convection.
3. The midlatitude response is different for different GCMs. In particular, the transient response depends on the structure of the initial conditions, and the equilibrium response depends upon the model climatology.

Since the transient midlatitude response depends strongly on the initial conditions, it can be conjectured that the interactions between the perturbations forced by the tropical heating and the preexisting stationary and transient waves in the midlatitude could be an important factor in determining the "final" midlatitude response. The location of the tropical heating and the location of the corresponding forced wave trains with respect to the amplitudes and phases of the midlatitude planetary waves could be an important factor in determining the evolution of the midlatitude flow. Direct interactions between the forced wave trains and the mountains can also influence the subsequent evolution of the flow.

A long-term integration ( $\sim 15$  yr) by the Geophysical Fluid Dynamics Laboratory (GFDL) model by Lau and Oort (1985) using the observed SST anomalies in the tropical Pacific has shown that the tropical as well as the midlatitude circulation anomalies were well simulated. In particular, the pattern of correlation between the tropical SST anomaly and midlatitude circulation anomaly is remarkably similar to that of the observations. This suggests that the high-frequency transient disturbances in the tropics are not large enough to alter the large-scale, low frequency tropical variability due to the influence of the boundary conditions.

There have been only a few experiments which have examined the predictability of the midlatitude flow with and without the tropical SST anomaly. Such experiments should provide direct confirmation of the effect of tropical

SST anomalies on midlatitude flow. There is some evidence of an improvement in the midlatitude forecasts for 30-day averages using the observed SST compared to the climatological SST; however, such studies are only few in number, and a large number of such controlled experiments are required to establish the robustness of this result.

### 3. INFLUENCE OF EXTRATROPICAL SST ANOMALIES ON EXTRATROPICAL CIRCULATION

The earlier discussion on the factors that determine the transformation of a SST anomaly into a deep-heating anomaly ( $\partial T \rightarrow \partial Q$ ) suggests that it is relatively more difficult to transform a SST anomaly into a heating anomaly in the extratropics, compared to the tropics. The most important reasons are (1) the mean SST in midlatitudes is considerably lower than that in the tropics; (2) the pressure and wind fields are in quasi-geostrophic balance and therefore it is not possible to produce large convergence or divergence; (3) there are already large asymmetries in surface heating due to land-ocean contrast; and finally (4) the midlatitude flow is highly variable due to dynamical instabilities. However, there have been numerous observational studies [see the collected papers by Namias (1975)] which suggest a significant relationship between the SST anomalies and circulation anomalies in the midlatitudes. Also, there have been several modeling studies (using simple models and complex GCMs) to investigate the effects of midlatitude SST anomalies on midlatitude circulation but the results are inconclusive. Some meteorologists have expressed the opinion that the tropical SST anomalies might be more effective than the mid-latitude SST anomalies in producing quasi-stationary circulation anomalies in the midlatitudes. Most of the early investigations (Charney and Eliassen, 1949; Smagorinsky, 1953) were primarily concerned with explaining the observed climatological stationary waves in the atmosphere as responses to orographic forcing or forcing due to stationary heat sources. It is now generally accepted that the mountains provide the most important forcing for the stationary waves. It is further argued that if the climatological heat sources are not effective in producing stationary anomalies, it is inconceivable that the SST anomalies and the associated weak heat sources can produce changes in the circulation sufficiently large to be distinguished from the natural variability of otherwise active midlatitude flow.

The results of the sensitivity experiments with GCMs are also ambiguous, and at times contradictory. For example, Kutzbach *et al.* (1977) and Chervin *et al.* (1980) reported that for the National Center for Atmospheric Research (NCAR) model, even an unrealistically large SST anomaly (about four times

larger than the observed) over the northern Pacific could not produce a statistically significant change in the circulation away from the anomaly. Shukla and Bangaru (1978) found that a SST anomaly about twice as large as the observed SST anomaly could produce large changes in the planetary-scale circulation, giving rise to significant changes away from the SST anomaly. A similar result has also been reported by Pitcher *et al.* (1984) using a new version of the NCAR model. They found significant changes in circulation away from the anomaly using a SST anomaly twice the observed SST anomaly. However, they did not find any significant changes in circulation for the observed anomaly itself. It appears that these results are largely model dependent. It has been pointed out by Blackmon and Lau (1980) that the version of the NCAR model used by Chervin *et al.* (1980) had serious deficiencies in simulating the transient variability, and therefore results of sensitivity studies with that model should not be considered a sufficient evidence for the inability of midlatitude SST anomalies to produce circulation anomalies. In fact it is not unconceivable that even the present models, which show a significant response to a SST anomaly twice the observed anomaly, can be further improved, and then it may not be necessary to artificially increase the anomaly.

Heuristically, it can be argued that it would be more difficult to detect the influence of midlatitude SST anomalies on midlatitude flow because the flow already contains preexisting wave patterns due to stationary forcings and dynamical instabilities. The response of the flow is going to be very different depending upon the location of the SST-induced heat source with respect to the structure of the preexisting wave patterns. Moreover, the steady and the transient components are equally important in describing the dynamics of the midlatitude flow, and therefore the effects of SST-induced heat sources have to be significantly larger than the transient variability which is naturally present at the midlatitudes.

For this reason, it will also be difficult to detect the impact of SST anomalies on deterministic prediction using GCMs. If the model physics and boundary-layer parameterizations do not generate a strong heat source within about 2 weeks of the introduction of the SST anomaly, the midlatitude flow can change significantly before being influenced by the SST anomaly.

We do not wish to discuss here the influence of tropical SST anomalies on tropical circulation nor the influence of extratropical SST anomalies on tropical circulation. It would suffice to state that it has been clearly established, from observational as well as modeling studies, that the tropical SST anomalies exert profound influence on the tropical circulation. The most notable examples are the El Niño – Southern Oscillation – monsoon interactions, and the role of SST anomalies in droughts over northeast Brazil and



tropical Africa. As regards the influence of extratropical SST anomalies on tropical circulation, the results are as ambiguous as those discussed in Section 3; however, there have been several suggestions that even the small circulation anomalies produced by the midlatitude SST anomalies can trigger changes in convection in the tropical regions which can further amplify to produce large heating anomalies in the tropics.

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