NOTES AND CORRESPONDENCE

**Influence of Sea Surface Temperature Anomalies
over the Indian Ocean and Pacific Ocean
on the Tropical Atmospheric Circulation
— A Numerical Experiment —**

By Koji Yamazaki

Meteorological Research Institute,

1-1 Nagamine, Tsukuba, Ibaraki 305 Japan

(Manuscript received 17 May 1988, in revised form 19 August 1988)

1. Introduction

During the warm phase of the El Niño/Southern Oscillation (ENSO), the sea surface temperature (SST) over the central and eastern tropical Pacific becomes warm and a global atmospheric response of wavenumber 1 is observed in the tropics. Many GCM sensitivity studies of SST anomalies (SSTA) over the equatorial Pacific have been performed under northern winter conditions (*i.e.*, Rowntree, 1972; Blackmon *et al.*, 1983; Tokioka *et al.*, 1986, and many others). Relatively few studies have been made for northern summer conditions (Keshavamurty, 1982; Tokioka *et al.*, 1985, 1987).

Tokioka *et al.* (1985) studied the atmospheric response to the SSTA observed in the early summer of 1983 when the 1982/83 El Niño was still active. The SSTA over the Indian Ocean was not included in their experiment. Comparison of the simulated atmospheric anomalies with the observed atmospheric anomalies showed that the agreement was fairly good except over the Indian Ocean and the maritime continent (Tokioka *et al.*, 1987). The discrepancy is large during the second month (June) when the SSTA over the tropical Pacific became smaller than that in the

first month (May). This suggests that the SSTA over the Indian Ocean has a non-negligible impact on the tropical circulation, at least for the region over the Indian Ocean. This possibility is one of the motivations for this study.

Another motivation is as follows. The climatological SST over the central Indian Ocean is as warm as that over the central Pacific. However, the basic flows are different between the two regions, particularly in the summer. The simulated response to the SSTA over the Pacific is similar to the Gill (1980)/Matsuno (1966) pattern found in many GCM studies (*e.g.*, Tokioka *et al.*, 1985; Keshavamurty, 1982). The question arises as to what will happen if the SSTA is placed over the Indian Ocean. Does the Gill/Matsuno pattern, which is a linear response to an equatorial heat source under the condition of no basic flow, develop? How different are the linear response and the response of a non-linear GCM? Does the tropical response have a global scale? This paper will attempt to answer the above questions.

2. Model and experiment

The model used is the 15 layer version of the Meteorological Research Institute's (MRI) GCM with a horizontal resolution of 4° in latitude by 5° in longitude with a top at 10 mb. A

comprehensive description of the model is given in Tokioka *et al.* (1984). The standard physical processes are included in the model. In the present experiment, the standard Arakawa-Schubert cumulus parameterization is used.

The control run (or C-run) was started on May 1 and integrated to September 1 using the climatological SST. The climatological SST used was the 15-year mean for 1970-1984 compiled by the National Oceanic and Atmospheric Administration (NOAA) and it is shown in Fig. 1 for July. On the model date of July 1, a SSTA was inserted over the equatorial Indian Ocean (8°N - 8°S , 57.5°E - 82.5°E) and the model was integrated through September 1. The given SSTA is symmetric about the equator and consists of; the addition of a positive 2°C anomaly to the central 6 grid points and the addition of a 1°C anomaly to the surrounding 14 grid points. Hereafter, this integration is called the Indian Ocean run (or I-run). For comparison, another run was performed. The same SSTA as in the I-run was inserted on July 1, but over the equatorial central Pacific (8°N - 8°S , 177.5°E - 157.5°W). Hereafter, this run is called the Pacific run or the P-run.

The shapes and magnitudes of the SSTA for the I-run and P-run are exactly the same and are shown as rectangles along the equator over the Indian and central Pacific Oceans in Fig. 1. The normal SSTs are also similar in both regions, having temperatures of approximately 28°C . The atmospheric flows near the SSTA regions are, however, quite different for the two regions. Figure 2 shows the July through August mean

wind fields at 200 mb (upper) and 900 mb (lower) simulated by the C-run. Over the Indian Ocean, the summer monsoon circulation is established and strong easterlies at the 200 mb level are dominant. Over the central Pacific, the easterly trade wind is dominant in the lower troposphere and the upper level wind is weak. Upper level westerlies exist over the SSTA region used for the P-run.

3. Time-mean anomaly fields

3.1 Precipitation

Figure 3 shows the 2-month mean precipitation anomalies for the I-run (upper) and the P-run (lower). The maximum precipitation anomaly appears over the SSTA region and its value exceeds 8 mm/day for both the I and P runs. Table 1 gives the time and spatial mean precipitation and evaporation anomalies over the SSTA regions. The table indicates that the local precipitation and evaporation changes are similar in both cases. Note that the precipitation anomalies are about 3 times larger than the evaporation anomalies, which implies that about two-thirds of the precipitation anomalies are caused by moisture convergence into the SSTA regions.

In the I-run, strong negative anomalies are seen over the regions around the SSTA. The minimum value over India is less than -3 mm/day. In general, rainfalls over India and Indochina are suppressed. Also, the rainfalls over north Africa decrease except for the area of northeast Africa, where a narrow positive band extends north-westward from the SSTA region. Over the equatorial western Pacific, a slight enhancement of precipitation occurs. In the tropical western hemisphere, no large precipitation anomalies are found. In the P-run, negative anomalies spread over a much broader region, *i.e.*, over the western Pacific, Indian Ocean and northeast Africa.

3.2 Flow fields

The two-month mean 900 mb wind anomaly field is shown in Fig. 4 for the I-run (upper) and the P-run (lower). There is a convergent flow over the SSTA region in both cases. The convergent flow, induced by convective heating brings

Fig. 1. Climatological mean sea surface temperature for July (1970-84). Contour interval is 2°C . The double rectangles over the Indian Ocean and the Pacific denote the specified SSTA regions.

Fig. 2. July-August mean wind vector and zonal wind velocity at 200 mb (top) and at 900 mb (bottom) simulated in the control run (C-run). For the top (bottom) figure, the contour interval is 10 m s^{-1} (5 m s^{-1}). Easterly regions are shaded.

moisture into the SSTA regions which further enhances the convective heating. In the I-run, there is a significant anomalous flow from the northeast into the SSTA region. Also, an anomalous westerly in flow can be seen west of the SSTA region. The low-level convergence over the SSTA region is caused by these flows. To the north of the SSTA region, anomalous easterlies extend from the Arabian Sea to the South China Sea, where the normal monsoon westerlies would

prevail (Fig. 2). In other words, the summer monsoon westerly is weakened and deflected to the south in the I-run. It can also be noted that this anomalous flow is divergent over India and the Bay of Bengal. This low-level divergent flow causes the reduction in precipitation in the area as was pointed out in Fig. 3. Weakening of the summer monsoon circulation is easily understood. Placing the positive SSTAs over the equatorial Indian Ocean reduces the north-south

Fig. 3. July-August mean precipitation anomaly for the I-run (top) and the P-run (bottom). The contour interval is 1 mm day^{-1} . Negative values are shaded.

Table 1

	I-C	P-C	
Precip	5.28	5.97	mm/day
Evap	1.51	2.02	mm/day
Precip-Evap	3.77	3.95	mm/day
Precip/Evap	3.50	2.96	

July through August mean precipitation (first line) and evaporation (second line) anomalies over the SSTA regions for the I run (left column) and the P run (right column). The third line shows the differences and the last line shows the ratio of precipitation and evaporation.

(land-ocean) low-level temperature gradient that generates the monsoon circulation.

In the P-run, on the other hand, the most significant wind anomaly near the SSTA region is the anomalous westerlies found west of the SSTA region along the equator. Much weaker anomalous easterlies are found east of the SSTA region. The convergent flow over the SSTA region is caused predominantly by the zonal wind component, which differs from that in the I-run.

At 200 mb, a divergent flow can be found

above the SSTA region in both cases (Fig. 5). Again, the response patterns for the two cases are quite different. In the I-run (upper), the westerly anomaly lies over the SSTA region and extends to the maritime continent along the equator. With the exception of the anticyclone over Egypt, which is a possible response to the positive precipitation anomaly over northeast Africa, there is no clear anticyclonic vortex near the SSTA region. The anomalous westerly flow over the equatorial Indian Ocean means a weakening of the tropical easterly jet. Thus the monsoon flow is weakened, although the strength of the Tibetan high itself does not change. In this case it may be explained by the fact that the land-sea contrast is reduced only by increasing the SST over the Indian Ocean.

In the P-run (lower), anomalous westerlies extend from the SSTA region to Brazil along the equator and anomalous easterlies exist to the west of the SSTA region. An intense anticyclonic vortex is clearly seen to the south of the SSTA region. This simulated response does not differ much from the linear response to a tropical heat source with no wind or uniform zonal wind studied by Gill (1980) and Lau and Lim (1982).

Fig. 4. July-August mean wind vector anomaly at 900 mb for the I-run (top) and the P-run (bottom). The solid boxes along the equator denote the SSTA regions.

It is intriguing that the long band of anomalous westerlies is found near the dateline along the equator (Fig. 5, upper). At 900 mb (Fig. 4, upper), a weak easterly anomaly is discernible along the equator, but the east-west extent is small. This flow anomaly can be partly explained by the positive precipitation anomaly over the western Pacific (150°E – 180°E) shown in the upper section of Fig. 3. However, the magnitude of this positive precipitation anomaly is small and the cause of the anomaly can not be explained fully. Inspection of Hovmöller diagrams for the u and v wind fields at several latitudes and the daily 200 mb map (not shown) reveals that this anomaly is not stationary and is related to eastward moving cyclonic disturbances in the Southern Hemisphere. Since the upper westerly extends to the equator near the date line (Fig. 2), the extratropical wave can propagate easily to the equator in this region. The westerly anomaly at the equator is the northern extension of the cyclonic anomaly just south of the equator. Unlike the anomalous westerlies over the Indian Ocean, the westerly anomaly near the date line has only a small divergent component (Fig. 6). Therefore, the westerly

anomaly near the date line is probably due to the influence of the extratropical disturbance in the Southern Hemisphere and is not a direct response to the SSTA.

3.3 Velocity potential at 200 mb

To examine the large-scale response in the divergent wind fields, the two month mean velocity potential anomaly at 200 mb is shown in Fig. 6. Negative regions (shaded) correspond to divergent regions. In the I-run (upper), the divergent center is found over the Indian Ocean and a weak convergent center is situated over central America. The large negative anomaly is mostly confined within the Indian Ocean region and the global-scale response is not strong.

On the other hand, in the P-run, both the negative and positive anomalies are large and exhibit a strong weavenumber one response on the global-scale. This response resembles the low index phase of the Southern Oscillation Index (SOI). Although the local heating anomalies in both cases are similar, as shown in Fig. 3 and Table 1, the global responses in the divergent fields are quite different. In the I-run, the negative heating anomaly that surrounds the

Fig. 5. July-August mean wind vector anomaly at 200 mb for the I-run (top) and the P-run (bottom).

positive anomaly over the SSTA region, contributes, in part, to shield the remote influence of the heating anomaly directly induced by the SSTA.

Keshavamurty (1982), using a GFDL GCM, conducted similar numerical experiments with warm SSTAs over different parts of the equatorial Pacific under summer conditions. The experimental design of his central Pacific case is similar to the present P-run, with the prescribed SSTA as large as 3°C and its horizontal extent broader than the current SSTA. The peak in the precipitation anomaly in his central Pacific case is located on the Northern Hemisphere side of the equator and the anticyclonic vortex in the

Northern Hemisphere is stronger. Even with such differences, his results and the present results agree rather well in the tropics. Both results show a global response in the divergent wind anomaly to the tropical heat source and display strong westerly anomalies along the equator over Africa at 200 mb.

4. Transient behavior in the tropics

Figure 7 shows Hovmöller diagrams of velocity potential anomalies at 200 mb averaged over 6°N through 6°S . All values in Fig. 7 are the deviations from the time means of the C-run. In this figure, the temporal variation of the SSTA impact on the tropical atmosphere can be seen.

Fig. 6. July-August mean velocity potential anomaly and divergent wind anomaly at 200 mb for the I-run (top) and the P-run (bottom). The contour interval is $5 \times 10^5 \text{ m}^2 \text{ s}^{-1}$. Shaded regions denote negative values.

Since the atmospheric initial conditions are the same for all three cases (with the exception of the location of the SSTA), the three runs are quite similar for the initial 10 days or so. Eastward-traveling disturbances having periods of about 10 days, can be seen in all three runs. In particular, the traveling disturbance is seen clearly during the first 10 days. In the standard MRI GCM the traveling 10-15 day wave, which is interpreted as an unstable Kelvin wave, is dominant in the tropics (Kitoh and Tokioka, 1987; Tokioka *et al.*, 1988).

In the I-run, the activity of the transient wave is somewhat more intense and the source of the

wave appears, as expected, to be located over the Indian Ocean. Even in the C-run, the wave seems to be initiated over the Indian Ocean. At about 60°E , where the time mean negative anomaly lies (Fig. 6, upper), the anomaly varies and changes its sign with time, especially during the last month. In the I-run, the divergence associated with the traveling wave is enhanced over the central Pacific and a stationary response can not be seen. The intense activity of the eastward-traveling wave seems to prevent the global response seen in time-mean field. On the other hand, in the P-run, the transient wave activity is rather weak after 10 days, and later stages, a

Fig. 7. Longitude-time sections of the velocity potential anomaly at 200 mb, averaged over 6°N – 6°S . All values are deviations from the time mean values of the C-run at each latitude. The I-run (left), C-run (center) and P-run (right). Negative values are shaded. The contour interval is $2 \times 10^6 \text{ m}^2 \text{ s}^{-1}$.

quasi-stationary response is seen.

It is of interest to attempt to explain the difference in transient behavior between the I and P runs. A possible mechanism is as follows. In the I-run, the eastward-traveling wave can be easily excited over the Indian Ocean owing to the positive SSTA there. During eastward propagation, the wave may be enhanced over the warm SST region (warm SST pool) covering the central Indian Ocean to the central Pacific (see Fig. 1) through the supply of heat due to convective activity. In the P-run, the excited traveling wave over the SSTA region (the central Pacific), passes over the relatively cold SST regions, *i.e.*, the eastern Pacific and the Atlantic. Therefore, the wave decays to the east of the SSTA region. At the same time the compensating downward motion to the west of the SSTA region suppresses convective activity over the Indian Ocean and the western Pacific. This, in turn, reduces the excitation of the wave. The difference in the SSTA location in relation to the warm SST pool may well determine the different transient behavior.

An important factor that controls the activity of unstable Kelvin waves is the vertical profile of convective heating (*e.g.*, Takahashi, 1987; Tokioka *et al.*, 1988). When there is deep heating

(above 500 mb), the phase speed of the unstable Kelvin wave is fast and close to that of a free mode. By a linear analysis, Chang and Lim (1986) showed that the growth rate of the fast traveling wave was decreased when the heating peak was lowered, but still above 500 mb. From Fig. 8, it can be seen that the heating peak in the I-run is located at higher levels than that in the P-run and is in accord with the linear analysis of wave-CISK theory.

5. Discussion and summary

The influence of the SSTA over the equatorial Indian Ocean and the central Pacific was studied by numerical experiments. The prescribed SSTA is symmetric about the equator and is the same (except for location) in both cases. The local heating anomalies are similar in both cases. In the P-run, the response over and near the SSTA region (Pacific) is similar to that of the symmetric heat source case in Gill (1980), although the northern anticyclone is weak and the location of the southern anticyclone shifts eastward compared with that in Gill (1980). Lau and Lim (1982) studied the effect of the zonal mean flow in the response to a symmetric tropical heating. When the mean flow was

Fig. 8. Vertical profiles of total diabatic heating due to precipitation processes (penetrative cumulus convection, middle-level convection and large-scale condensation) for the I-run (solid lines) and the P-run (dashed lines). Those averaged over the SSTA regions are the right two lines and the zonal means at the equator are on the left.

westerly, the anticyclone off the equator intensified and shifted eastward. For an easterly mean flow the anticyclone is weakened. The mean flow effects seem to be able to explain the simulated response in the P-run.

In the I-run, the response over and near the SSTA region does not resemble the theoretical results of Gill (1980). To the east of the SSTA region where the Kelvin wave response is dominant, some resemblance can be found to the easterly basic flow case in Lau and Lim (1982). However, in the I-run, the easterly flow along the equator to the west of the SSTA region is completely missing. The negative anomaly over India, which is an asymmetric forcing about the equator, might be responsible for the absence of the easterly flow response (Fig. 6 of Lau and Lim, 1982). However, a simple linear combination of the linear responses to the heat sources

and sinks does not seem to be able to fully explain the simulated response, particularly in the Southern Hemisphere. Further theoretical study of the atmospheric response to a heat source with vertical wind shear and/or horizontal wind shear will be needed. The use of a GCM to study such atmospheric responses to these heat sources is also useful.

The results obtained in the present study are summarized as follows;

(1) Although the local heating anomalies are similar, the distribution of the heating and cooling anomalies around the SSTA regions are quite sensitive to the location of the SSTA.

(2) When the SSTA is placed over the Indian Ocean (I-run), the global scale response, centered at the SSTA is weak, particularly in the divergent wind fields. On the other hand, a strong global scale response of wavenumber 1 is obtained when the SSTA is placed over the central Pacific (P-run).

(3) Eastward traveling wave activity is enhanced in the I-run, while it is weakened in the P-run.

The present study has demonstrated the sensitivity of the tropical atmospheric response to the location of the SSTA. There are two main factors which cause this sensitivity. One is the difference in the ambient basic flow and the other is the difference in the location of the SSTA in relation to the warm SST pool.

Acknowledgments

The author would like to thank Dr. Tatsushi Tokioka for his continuous encouragement and discussion throughout this work. Also, thanks are extended to Prof. H. Lim, Messrs. Akio Kitoh and Tomoaki Ose for many useful discussions. He also thanks the reviewers for their comments on the original manuscript.

Computations were made with the HITAC 810 at the MRI.

References

- Blackmon, M.L., J.E. Geisler and E.J. Pitcher, 1983: A general circulation study of January climate anomaly patterns associated with interannual variation of equatorial Pacific sea surface temperatures. *J. Atmos. Sci.*, **40**, 1410-1425.

- Chang, C.-P. and H. Lim, 1986: *Kelvin Wave-CISK: A possible mechanism for the 30-50 day oscillations*. Preprint volume, International Conference on Monsoon and Mesoscale Meteorology with MSROC, 4-7 November 1986, Taipei, Taiwan. (see also *J. Atmos. Sci.*, **45**, 1709-1720)
- Gill, A.E., 1980: Some simple solutions for heat-induced tropical circulation. *Quart. J. Roy. Meteor. Soc.*, **106**, 447-462.
- Keshavamurty, R.N., 1982: Response of the atmosphere to sea surface temperature anomalies over the equatorial Pacific and the teleconnections of the Southern Oscillation. *J. Atmos. Sci.*, **39**, 1241-1259.
- Kitoh, A. and T. Tokioka, 1987: A simulation of the tropospheric general circulation with the MRI atmospheric general circulation model. Part III: The Asian summer monsoon. *J. Meteor. Soc. Japan*, **65**, 167-187.
- Lau, K.-M. and H. Lim, 1982: Thermally driven motions in an equatorial plane: Hadley and Walker circulations during the winter monsoon. *Mon. Wea. Rev.*, **110**, 336-353.
- Matsumo, T., 1966: Quasi-geostrophic motions in the equatorial area. *J. Meteor. Soc. Japan*, **44**, 25-43.
- Rowntree, P.R., 1972: The influence of tropical east Pacific Ocean temperatures on the atmosphere. *Quart. J. Roy. Meteor. Soc.*, **98**, 290-321.
- Takahashi, M., 1987: A theory of the slow phase speed of the intraseasonal oscillation using the wave-CISK. *J. Meteor. Soc. Japan*, **65**, 43-49.
- Tokioka, T., K. Yamazaki, I. Yagai and A. Kitoh, 1984: *A description of the Meteorological Research Institute atmospheric general circulation model (MRI-GCM-I)*. Technical Reports of the Meteorological Research Institute, No. 13, MRI, 249pp.
- , K. Yamazaki and M. Chiba, 1985: Atmospheric response to the sea-surface temperature anomalies observed in early summer of 1983: A numerical experiment. *J. Meteor. Soc. Japan*, **63**, 565-588.
- , A. Kitoh and A. Katayama, 1986: Atmospheric response to the sea surface temperature anomalies in the mature phase of El Nino: Numerical experiment under the perpetual January condition. *J. Meteor. Soc. Japan*, **64**, 347-362.
- , K. Yamazaki and M. Chiba, 1987: A case study of the impact of sea-surface temperature anomalies and initial conditions on dynamical forecast up to two months in the early summer of 1983. *Pap. Meteor. Geophys.*, **38**, 265-277.
- , ———, A. Kitoh and T. Ose, 1988: Equatorial 30-60 day oscillation and the Arakawa-Schubert penetrative cumulus parameterization. (submitted to *J. Meteor. Soc. Japan*)

インド洋と太平洋の海面水温偏差が熱帯大気に及ぼす影響に関する数値実験

山 崎 孝 治

(気象研究所)