Correlations between Rainfall and Sea Surface Temperature during GATE

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ABSTRACT

Lead and lag correlation coefficients are obtained between sea surface temperature and rainfall in the B-scale region during GATE. Significant negative correlation is found for 1-day lag and positive correlation for 1-day lead of sea surface temperature, implying negative feedback with a response delay of about 1 day. Mechanisms that may contribute to the correlations are discussed.

In this note, we discuss the correlation coefficients between sea surface temperature and rainfall as a function of lead and lag time between these two parameters. The data were taken in the B-scale region of the eastern tropical Atlantic Ocean during the GARP Atlantic Tropical Experiment (GATE). Significant correlations are found for both 1-day lead and 1-day lag between sea surface temperature and rainfall. This indicates that the sea surface temperature tends to affect, as well as respond to, rainfall over a time interval of approximately 1 day. In the case of 1-day lead for sea surface temperature, the correlation is positive as expected, since higher surface temperatures increase convection leading to subsequent increase in rainfall. The correlation is negative for 1-day lag in surface temperature indicating a decrease in sea surface temperature after significant rainfall. This is presumably due to the deposition of a layer of cooler rainwater on the ocean surface, and possibly to the existence of cool downdrafts and increased cloud cover during the rain episodes.

The sea surface temperatures, averaged over the B-scale domain, for the 100 days of GATE have been tabulated by Krishnamurti (1976) and are shown in Fig. 1. There is a tendency for the sea surface temperature to increase during the GATE period (the first day of GATE is 16 June 1974) and in order to detrend the data, a least-squares linear fit was made which is also shown in the figure. The linear fit is

$$T_0 = (26.53 \pm 0.06) + (8.43 \pm 0.96) \times 10^{-3}d, \quad (1)$$

where T_0 is the sea surface temperature (°C) and d is the day of GATE.

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The three phases of GATE occurred during the periods 28 June–15 July 1974, 28 July–15 August 1974 and 30 August–19 September 1974. The average daily rainfall values for the B-scale domain for these periods have been archived at the National Center for Atmospheric Research, and are shown in the lower histogram for each phase in Fig. 2. Also shown in this figure, in the upper histogram for each phase, are the values of ΔT, the deviation of the sea surface temperature from the linear fit of Eq. (1). Correlation coefficients r between rainfall and ΔT were obtained for sea surface temperature lag values from -3 to $+4$ days. (A negative value of lag corresponds to a positive number of lead days.) The results for all phases of GATE combined are shown in Fig. 3a and for each of the phases separately in Fig. 3b. The total number of data points is 57, with 18, 18 and 21 data points in phases I, II and III, respectively. We define significant correlation as those values of r for which $P \leqslant 0.05$, where P is the probability that the correlation has occurred by chance. The values of r for which $P = 0.05$ are shown by dashed lines in Fig. 3. Significant values of r are those for which $|r|$ is greater than or approximately equal to the dashed line value.

Significant correlations occur for all phases combined (Fig. 3a) for sea surface temperature lags of ± 1 day, with $+1$ day lag being very significant ($P \approx 0.002$). The data for all phases are shown in Fig. 4. In Fig. 4a, the 1-day lag data are given as well as the linear regression line

$$\Delta T = (0.137 \pm 0.033) - (7.7 \pm 2.5) \times 10^{-3}RR, \quad (2)$$

where RR is the average rainfall (mm day^{-1}). The data for a 1-day lead are shown in Fig. 4b along with the linear regression

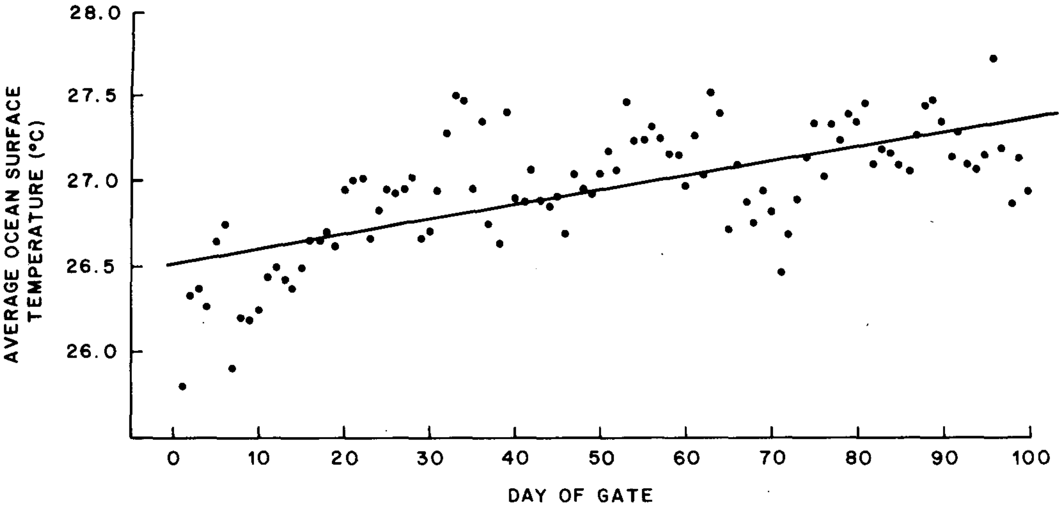

FIG. 1. The B-scale average sea surface temperature for each day of GATE as tabulated by Krishnamurti (1976). The line is a least-squares fit to the data.

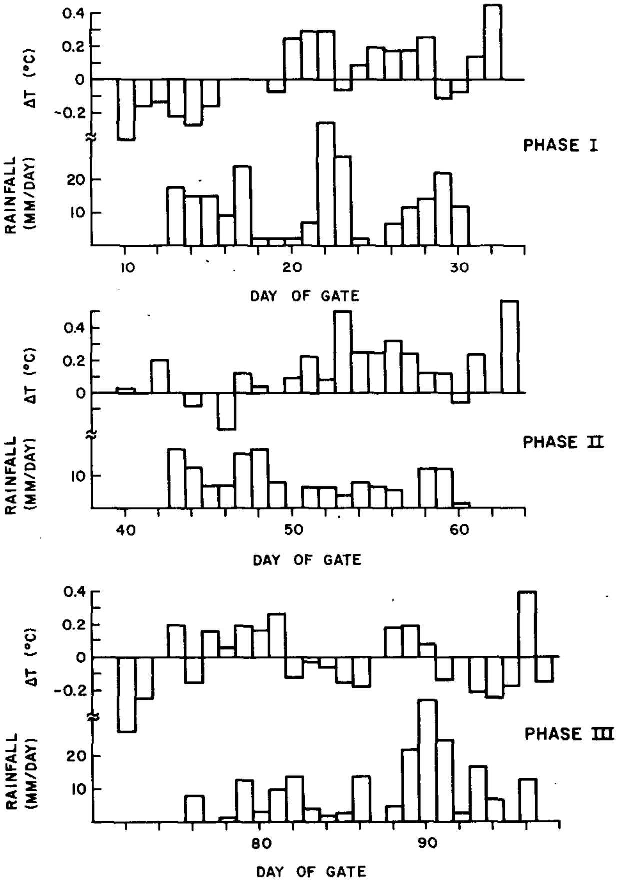

FIG. 2. The daily averaged rainfall for the B-scale domain and the deviation ΔT of the daily averaged sea surface temperature from the linear fit in Fig. 1 for the three phases of GATE.

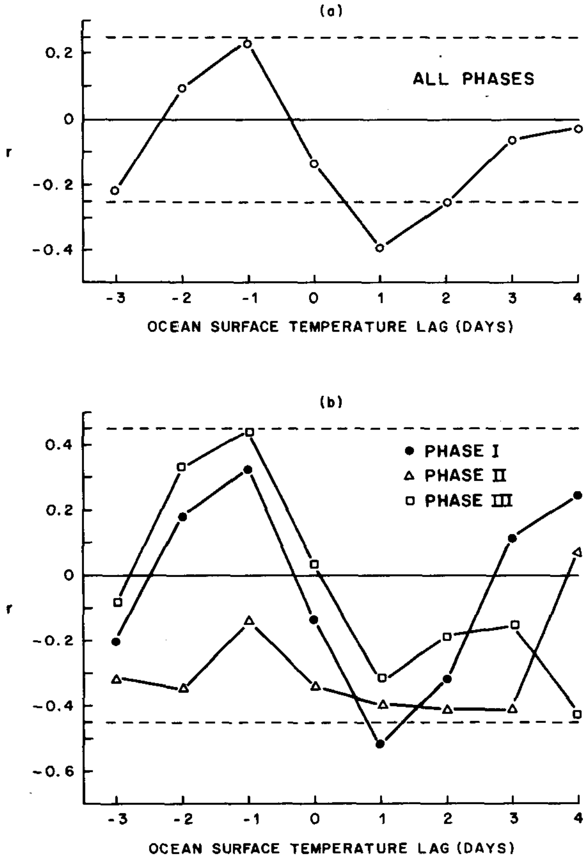

FIG. 3. The correlation between rainfall for the B-scale domain and ΔT as a function of sea surface temperature lag: (a) all phases of GATE combined, (b) each phase separately. The dashed lines are values of r which correspond to $P = 0.05$, where P is the probability that the correlation occurs by chance.

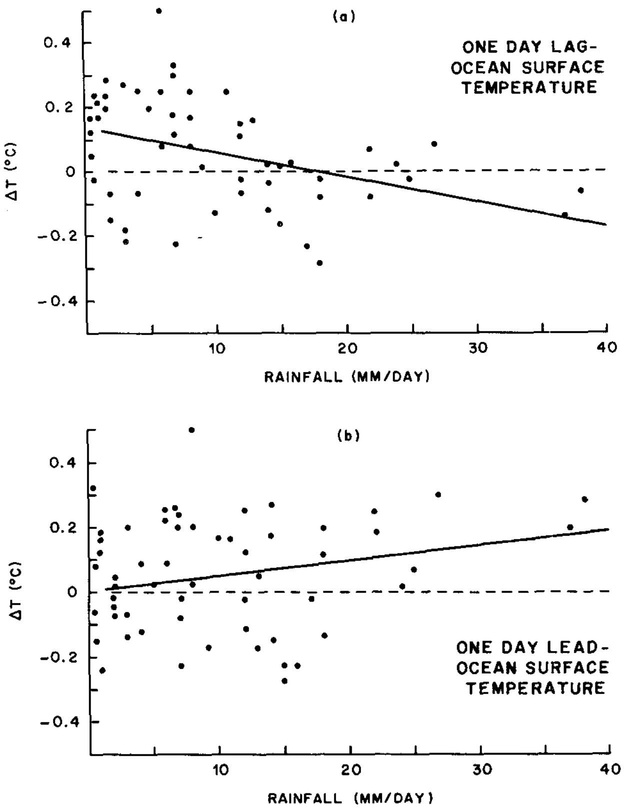

FIG. 4. ΔT versus rainfall for all phase of GATE: (a) surface temperature lags rainfall by 1 day, (b) surface temperature leads rainfall by 1 day.

$$\Delta T = (0.61 \pm 3.5) \times 10^{-2} + (4.5 \pm 2.6) \times 10^{-3} RR. \quad (3)$$

The correlations are -0.39 ($P \approx 0.002$) and $+0.23$ ($P \approx 0.07$) for the regressions in Eqs. (2) and (3), respectively. The linear regression for the data in Fig. 4b with the sea surface temperature as the dependent variable is

$$RR = (9.6 \pm 1.2) + (11.4 \pm 6.6)\Delta T \quad (4)$$

with the correlation again being $+0.23$.

The correlations obtained from these data indicate that a negative feedback mechanism exists between rainfall and sea surface temperature. Increased surface temperature increases subsequent rainfall presumably through the mechanism of increased convection. The increased rainfall, in turn, will tend to decrease the sea surface temperature. In both cases, there is a delay time of about 1 day with somewhat less significant correlations for lead and lag times of up to 2 days apparent in the data of Fig. 3. It is shown in the Appendix that the period of oscillation of the rainfall and sea surface temperature data should be equal to twice the sum of the lead and lag times when the lag correlation is negative and the lead correlation is positive. Since the resolution of the measurements of lead and lag time is about ± 0.5 days, periods of oscillation of from about 2 to 10 days are expected in the data. The power spectra for the rainfall data from the three phases are shown in Fig. 5, and significant peaks are seen for periods between 2 and 6 days. Fig. 6 is the power spectrum for the ΔT data. Again, significant peaks occur for periods of about 3, 5–6, 7 and 9 days. The peak at about 14 days cannot be explained by the feedback mechanism. Oscillations with this period have also been observed in the upwelling data in the Gulf of Guinea (Hisard and Merle, 1978) and in the meridional stress and wind speed data during GATE (Krishnamurti, 1978). Longer period contributions to ΔT not shown in Fig. 6 may be due to the use of a linear detrending curve in Fig. 1 which does not take into account possible curvature in the overall shape of the data.

The decrease in sea surface temperature due to prior rainfall may be due to increased downdrafts and reduced solar radiation. Higher wind velocities

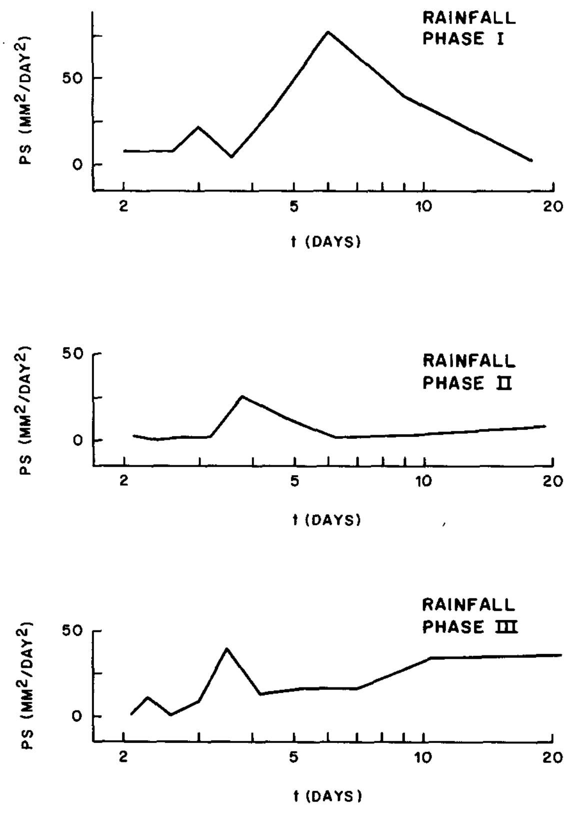

FIG. 5. Power spectra for the rainfall data of the three phases of GATE (see Fig. 2) as a function of period t.

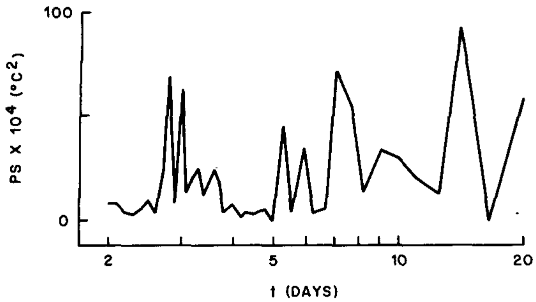

FIG. 6. Power spectrum for the sea surface temperature data ΔT for the 100 days of GATE as a function of period t.

are definitely correlated with increased rainfall in the GATE data (Riehl *et al.*, 1977). Presumably, these mechanisms tend to operate over periods of time shorter than the 1-day lag seen in the correlation results. We conjecture that the strong negative correlation for 1-day lag in sea surface temperature is due to the deposition of a fairly deep layer of cool rainwater which tends to remain stratified on the ocean surface for a period of the order of a day. Such a layer of relatively low temperature, low salinity and low density water to a depth of ~10 m has been observed to persist for at least 18 h by Ostapoff *et al.* (1973). The observations were made during GATE (days 34 and 35) aboard the *Professor Zubov* which was located at the edge of the B-scale region. The sea surface temperatures reported by Krishnamurti, and shown in Fig. 1, were obtained from samples taken somewhat below the immediate surface of the ocean. The 1-day lag correlation can be understood on the basis of a cool layer of water deposited by rainfall which persists at depths of at least a few meters for a period of the order of 1 day. The existence of such a layer has been verified by observation.

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APPENDIX

Relation between Lead and Lag Time and Period of Oscillation

Let t_1 be the lag time between ΔT and RR with negative correlation and t_2 be the lead time between ΔT and RR with positive correlation. The relationships between ΔT and RR are then

$$\Delta T(t + t_1) = -b\,RR(t), \quad \text{(A1)}$$

$$\Delta T(t - t_2) = b\,RR(t). \quad \text{(A2)}$$

These equations correspond to Eqs. (2) and (3). The slope parameters are taken to be equal, which is consistent with the parameters in (2) and (3) to within a standard deviation. The constants on the right-hand sides of (2) and (3) are ignored since ΔT is a deviation from a linear fit and not an absolute quantity. Taking the time dependence of ΔT and RR for a given frequency of oscillation to be

$$\Delta T = A_T \cos\omega t, \quad \text{(A3)}$$

$$RR = A_R \cos(\omega t + \phi), \quad \text{(A4)}$$

which allows for a possible phase difference ϕ between RR and ΔT, and substituting into (A1) and (A2), we have

$$A_T \cos[\omega(t + t_1)] = -bA_R \cos(\omega t + \phi), \quad \text{(A5)}$$

$$A_T \cos[\omega(t - t_2)] = bA_R \cos(\omega t + \phi). \quad \text{(A6)}$$

These equations reduce to

$$\cos[\omega(t + t_1)] + \cos[\omega(t - t_2)] = 0,$$

or

$$\cos[\tfrac{1}{2}\omega(t_1 + t_2)] \cos[\tfrac{1}{2}\omega(2t + t_1 - t_2)] = 0, \quad \text{(A7)}$$

which must be satisfied for all t. Thus,

$$\tfrac{1}{2}\omega(t_1 + t_2) = \pi(t_1 + t_2)/T = \pi/2, \quad \text{(A8)}$$

$$T = 2(t_1 + t_2). \quad \text{(A9)}$$

Therefore, for a given frequency of oscillation, the period is twice the sum of the lag and lead times when the lag correlation is negative and the lead correlation is positive.

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