311.16
551.577.3 : 551.526.6
(94-11)

RAINFALL – SEA SURFACE TEMPERATURE ASSOCIATIONS ON THE NEW SOUTH WALES COAST

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(Manuscript received August 1964)

Abstract: There are definite correlations between monthly anomalies in rainfall and sea surface temperatures in inshore waters along the coast of New South Wales. In large part these are considered due to the response of the Ekman current to rain-bearing (onshore) winds, with sea temperature consequently tending to lag behind rainfall. But correlations with rainfall lagging behind sea temperature do occur. Stronger and more definite relations could, it is argued, be established if adequate temperature data a hundred or so miles to sea were also available. Some properties of the sea surface temperature behaviour per se, and its connection with air temperature as well as with rainfall, are also investigated.

1. INTRODUCTION

The influence of the surface temperature of the oceans on the condition of the atmosphere has long been recognized, and for many decades sea temperature data has been collected from ships and deposited in various national archives. Values of monthly normals are now freely available in numerous publications, except over certain ocean regions where shipping is scarce. These data have been further analysed in terms of energy balance, evaporation, etc., for the main oceanic regions of the world.

However, it may be held that a proper understanding of many phenomena such as anomalous periods, trends, and cycles, is not possible without a historical analysis of the same data. This in itself represents quite a substantial task which the World Meteorological Organization has currently under examination. Meanwhile, studies of the implications of non-seasonal variations in sea surface temperature over certain regions, particularly in the North Atlantic, are beginning to emerge (Rodewald, 1963; Bjerknes, 1963).

The need for such investigations in the Australian region is apparent, even though the relative shortage of data subtracts from the expectation of immediate dividends. In a study of Australian rainfall data, O'Mahony (1961) has noted evidence of a correlation between Sydney monthly rainfall and sea temperatures at Port Hacking, together with some indication, from rather slender information, of a similar effect at Coff's Harbour. This is one of the few avenues open for any effective study at the present time, and accordingly we shall go more fully into this and associated effects, making use of more recent data than had been available to O'Mahony.

2. DATA

The sea surface temperatures are taken from the Oceanographical Station Lists (vols. 4 to 52) published by the C. S. I. R. O. Division of Fisheries and Oceanography, brought up to date by direct reference to that Division. The measurements are parts of soundings made at certain fixed points in inshore waters distributed round the coast of Australia, from December 1942 onwards. The soundings were made at varying intervals of time, in most cases about one month apart, sometimes more frequently but sometimes with gaps of several months' duration. From this raw data, a series was drawn up giving the "best" value for each calendar month over the period of the record, adopting the following procedure. Where two or more values were available in any one month, the mid-month value was assessed. Where a single value was available, that value was used. Where a single month was not observed, its value was assessed by interpolation and used as part of the series, provided it was not at the time of the maximum or minimum of the annual cycle. In the latter event, and wherever two or more successive months were not available, a gap was left in the series ("missing" months).

Five stations were finally considered to be sufficiently well spaced and to have records sufficiently long and complete to justify the type of analysis contemplated; the details are given in Table 1. It is seen that all these stations are on the S. E. coast (New South Wales and Tasmania), to which region the ensuing study is therefore limited. Apart from the short length

Table 1. Details of Sea Surface Temperature Records

Station	Coff's Harbour	Port Stephens	Port Hacking	Ulladulla	Maria Island
Latitude (^{o}S)	30^{o}17'	32^{o}43'	34^{o}05'	35^{o}22'	42^{o}36'
Year of first and last month	1948-62	1945-62	1942-63	1944-59	1946-63
Months observed	130	152	247	162	187
Months interpolated	11	35	3	25	8
Months used (total)	141	187	250	187	195
Months missing	21	14	1	0	21

of the series and the appreciable number of missing and interpolated months, it must be added that a considerable element of unrepresentativeness or "noise" is present in the observed months, as judged by the scatter at Port Hacking where more than one measurement per month was frequent. Thus the quality of conclusions, the general level of significance reached in the results, etc., will fall short of what would be expected from longer, complete, and more representative series of monthly values.

Their seasonal variation having first been removed, the series have been correlated with themselves, with each other, and with various rainfall records. A preliminary association analysis, following a method reported elsewhere (Priestley, 1962), had enabled unpromising lines to be largely weeded out. A rainfall station, with a complete series of monthly rainfall values, was chosen in the vicinity of each sounding point: these were Coff's Harbour, Nelson's Head (Port Stephens), Sydney (Port Hacking), Ulladulla, and Hobart (Maria Island). The cube roots of the monthly rainfall values were used in all correlation tests as a normalizing procedure (Stidd, 1953). As a precaution against possible non-representativeness of a single rainfall station, the tests were repeated using the average rainfall of coastal Districts as delineated by the Bureau of Meteorology (1938), substituting District 66 for Sydney and District 69 for Ulladulla. In the event this made no appreciable difference to the results, and the latter tests will not be reported here.

3. SEA SURFACE TEMPERATURE BEHAVIOUR

The general circulation of the surface waters of the region and the accompanying pattern of temperature may be judged from reference atlases, notably that published by Koninglijk Nederlands Met. Inst. (1949). The East Australia Current flows southward from 25^{o}N (further north in summer) in a belt about 100 miles wide adjacent to the coast, reaching a maximum speed of 20 to 30 nautical miles per day about latitude 28^{o}S. Where it decelerates the N-S temperature gradient increases, while some of the water moves westwards to widen the warm tongue as shown in the isotherms of Fig. 1 for December, for which the pattern is typical. The current finally mixes with the water moving eastwards through Bass Strait.

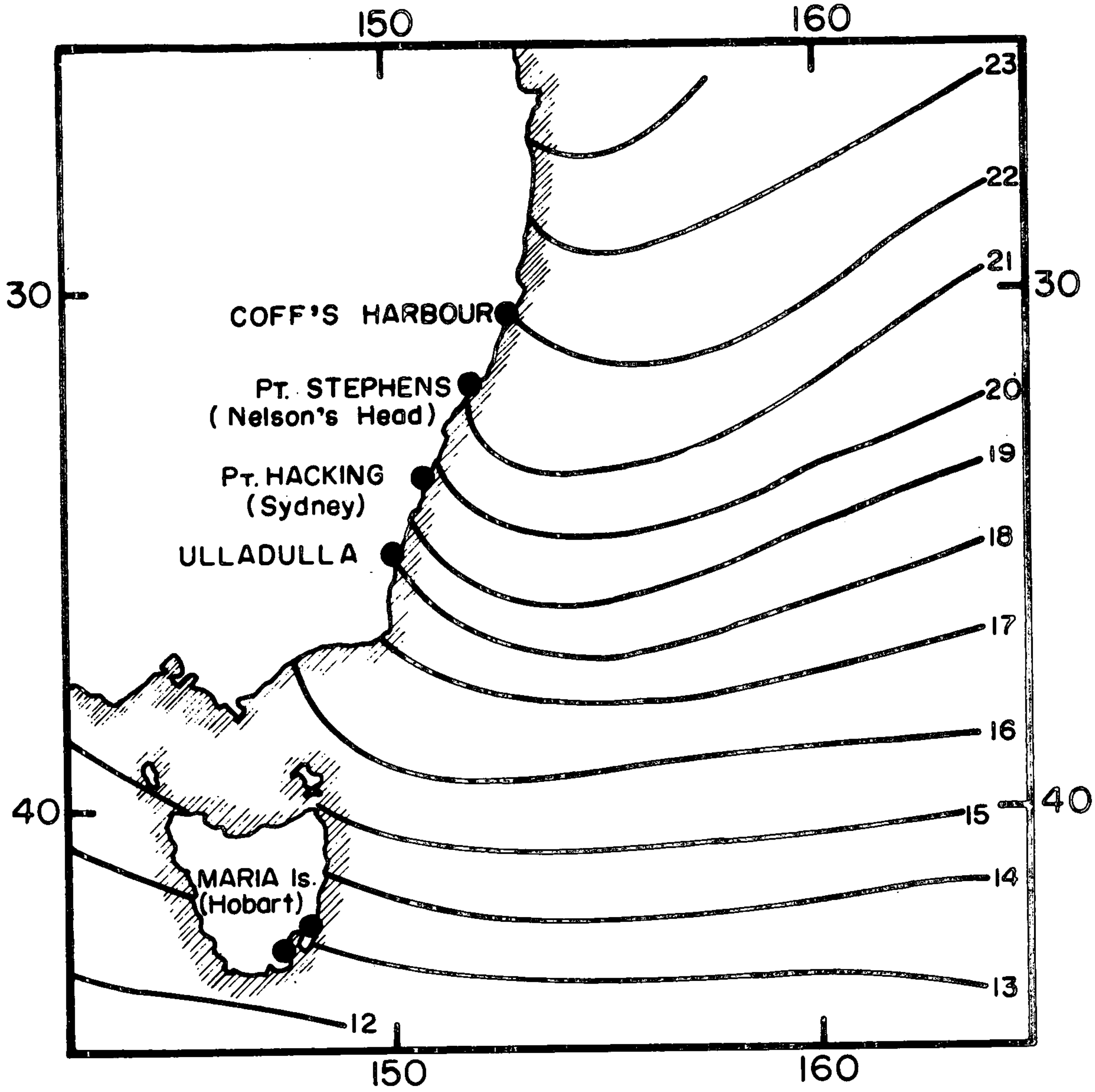

Fig. 1 Location of stations and sea surface temperature (°C) isotherms for December.

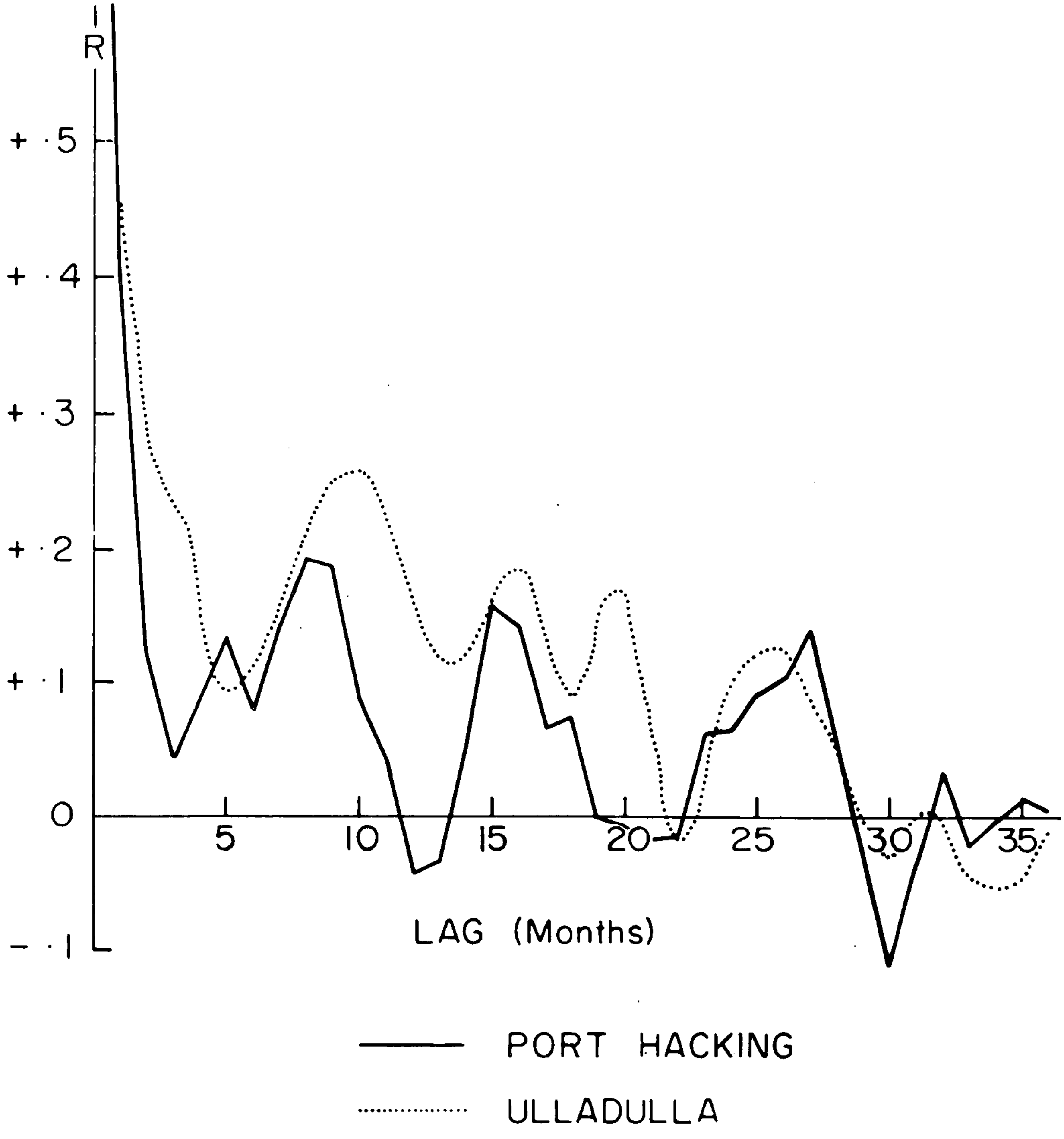

Fig. 2 – Auto-correlation of sea surface temperature at Port Hacking and (smoothed) at Ulladulla.

Close inshore, where the soundings have been made, the warm advection is countered by the effects of upwelling. This is an unfortunate circumstance for the purposes of the present study, for these temperatures will be much more subject to erratic influences, and in any event will not be fully representative of any considerable length of air mass trajectories.

To remove the seasonal variation from the series for each station the average temperature for each month was extracted and all subsequent analyses, except where otherwise stated, are in terms of the anomaly, or departure of the individual monthly value from its mean. Each station showed an average annual range of between 5 and 7°C, with maximum in February or March and minimum in August or September. The root mean square anomaly, at Port Hacking, was 0.91°C, with comparable values elsewhere. The average temperature gradient along the coast was 0.8 to 0.9°C per 100 miles.

To obtain indications of persistence and recurrence tendencies, the autocorrelation at Port Hacking was calculated for lags of 1 to 36 months and is shown in Fig. 2. The values at 2 and 3 months lag are remarkably low for an element which might have been expected to show considerable persistence. Thereafter the main features are the peak at 8 - 9 months and its reappearance at approximately twice and three times this interval. The other stations show higher values at the shorter time lags (spuriously high, at least in part, due to interpolations), and thereafter are less reliable and more erratic than Port Hacking for reasons evident from Table 1. A smoothed curve for Ulladulla is also reproduced in Fig. 2, with a recurrence interval less clearly marked and if anything slightly longer than Port Hacking. Port Stephens indicates narrow peaks at 7 ($r = 0.24$) and 11 ($r = 0.22$) months, and broader ones at 16 ($r = 0.15$) and at 34 months ($r = 0.21$). Coff's Harbour, judged from Table 1 the least reliable, has peaks at 9 ($r = 0.16$) and 16 ($r = 0.14$) months, which correspond with the other stations, and one at 13 months ($r = 0.21$) which does not: the trough at 4 months ($r = 0.04$) is marked. Maria Island shows a steady fall, only slightly interrupted at 8 to 10 months, to its first negative value at 11 months, and thereafter no notable feature except a rise to 0.19 at 32 months. Neither individually nor collectively (since the series are not mutually independent) can any of these results be assigned a high level of statistical significance: but the indications of a recurrence tendency at 8 to 9 months lag at sites in the main current might be worthy of further examination when possible. If it is real it is of considerable interest, being just one-third of the 26 month cycle indicated by a number of upper atmosphere variables.

Correlations between certain pairs of stations have also been calculated at lags of up to ± 6 months. All simultaneous correlations were positive. With the northern station following the southern, all correlations fell off steadily and rather rapidly with increasing lag, but with southern behind northern (i.e. in the sense following the current) the more complicated behaviour of Table 2 was observed. The general picture emerges of a lag correlation following

Table 2. Correlations of Sea Temperature between Stations
(all values positive)

	Distance (miles)	Lag (months)						
		0	1	2	3	4	5	6
Coff's Harbour-Port Hacking	290	.11	.12	.19	.19	.21	.12	.10
Port Stephens-Port Hacking	110	.40	.21	.32	.25	.27	.16	.11
Port Stephens-Ulladulla	210	.17	.21	.33	.34	.29	.21	.16
Port Hacking-Ulladulla	100	.44	.30	.16	.22	.30	.15	.10
Port Hacking-Maria Island	600	.19	.16	.13	.16	.25	.25	.16

the direction of flow much in excess of that observed locally. The times of the main rise in each of the first three rows are consistent in indicating speeds of progression of order 2 to 3 miles per day, as compared with average current speeds in this region of around 12 miles per day (in the more open waters). The fourth and fifth rows would imply rather lower and higher average speeds respectively, but one should be cautious about too detailed an interpretation of the results, particularly the last since it is doubtful whether there could be any direct propagation of the anomaly across Bass Strait.

4. ASSOCIATIONS WITH RAINFALL

Two distinct effects come to mind as likely to cause an association between rainfall and sea surface temperature. The first is the direct effect of air-sea interactions of heat and moisture. Other things being equal, the warmer the water the warmer and moister will be the lower layers of the air on reaching the coast, and the greater the proneness to convection. Eickermann and Flohn (1962) have established very high correlations (0.6 to 0.73) between rainfall for monthly and longer periods at Fernando de Noronha (3.8°S, 32.4°W) and the surface temperature of neighbouring waters. It is clearly desirable that the temperature used should be representative of a substantial length of air trajectory. For this reason it would have been preferable to cast the present study in terms of temperatures one or two hundred miles offshore, had such data been available.

The second effect is an indirect one arising from the operation of the Ekman drift current. Apart from Tasmania, the region considered here derives its main rainfall from easterly winds. An unusually strong or prolonged easterly wind will increase the surface current from the north, and hence the advection of warm water. This would give rise to a relationship in which both anomalies are in reality independent consequences of a third, i.e. wind, but in which the occurrence of a temperature anomaly would tend to lag behind that of the corresponding rainfall anomaly.

With this background we may look at the correlations in Fig. 3 between sea temperature and the rainfall at the adjacent stations. The Maria Island-Hobart relation is not shown since no notable correlation was found: this would have been expected from the fact, confirmed by an independent analysis by D. G. Reid, that the major part of Tasmanian rainfall is of westerly origin. The other correlations are predominantly positive, and the northern pair are approximately symmetrical. However, the two southern stations are strongly biassed towards negative lags, which prompts some more quantitiative discussion of the Ekman effect.

In this it will be supposed that the rainfall is highly correlated with the onshore wind component anomaly in the same month, and that a typical value for the latter is of order 2 m.p.h. The associated anomalous current velocity is then about a mile per day along the coast, as obtained from Ekman's empirical relationship

$$\frac{\text{Current speed}}{\text{Wind speed}} = \frac{0.0127}{\sqrt{\text{sine of latitude}}}$$

With a lag of 1 to 2 months, as indicated from Fig. 3, this corresponds to an anomalous fetch of 50 miles and hence, with a gradient of 0.85°C per 100 miles, to a temperature anomaly of about one-half the root mean square value. The consistency of these magnitudes with the time lag and size of the correlation found supports the view that the Ekman effect is the main cause of the rainfall-sea temperature relationship observed in Port Hacking and Ulladulla.

Following this argument, one may generalise that the Ekman effect should appear most clearly in terms of averages over several months or longer, assuming that wind anomalies over such periods are significant: but that periods much shorter than one month would not be affected by this cause. In some confirmation of the former, Bowen (private communication) has quite independently drawn graphs of 12 month running means of Sydney rainfall and Port Hacking temperature (1943-1960 inclusive). These have been found to give a correlation of +0.59, a value much enhanced from the largest in Fig. 3 presumably due to the reduction of "noise" in the longer-period averages.

As would have been expected from what has gone before, the correlations with rainfall following temperature were somewhat increased by taking the rainfall station downstream of the surface temperature station. This is illustrated in Fig. 4 for Sydney rainfall correlated with Port Stephens temperature. At one month lag, Sydney rainfall also showed a correlation of +0.15 with Coff's Harbour temperature. However, Ulladulla and Maria Island rainfall showed no notable correlations with prior sea temperature at stations to their north.

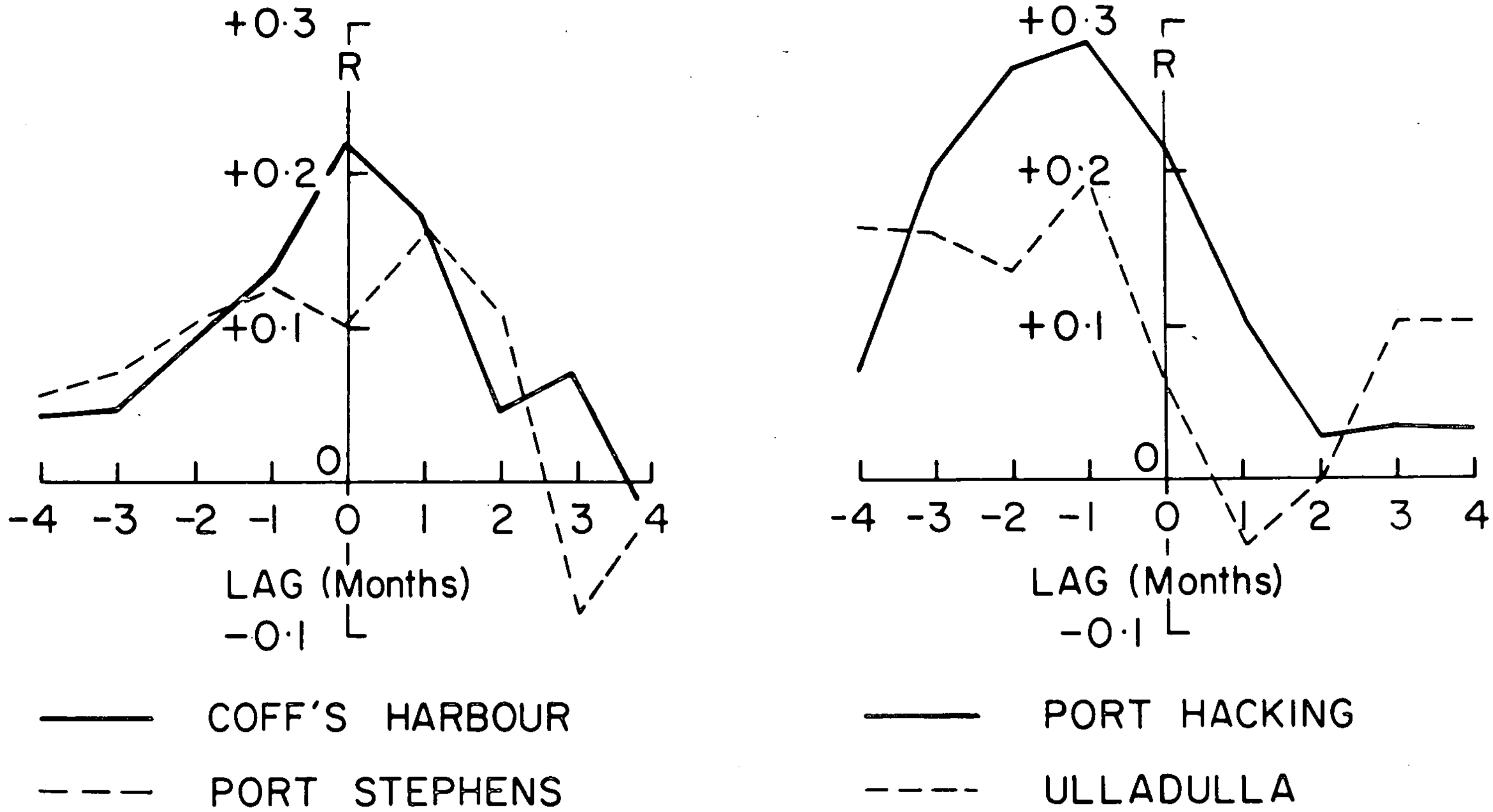

Fig. 3 – Correlation coefficients of station sea surface temperature with adjacent rainfall stations: monthly values at lags up to ±4 months, the positive sign denoting rainfall following temperature.

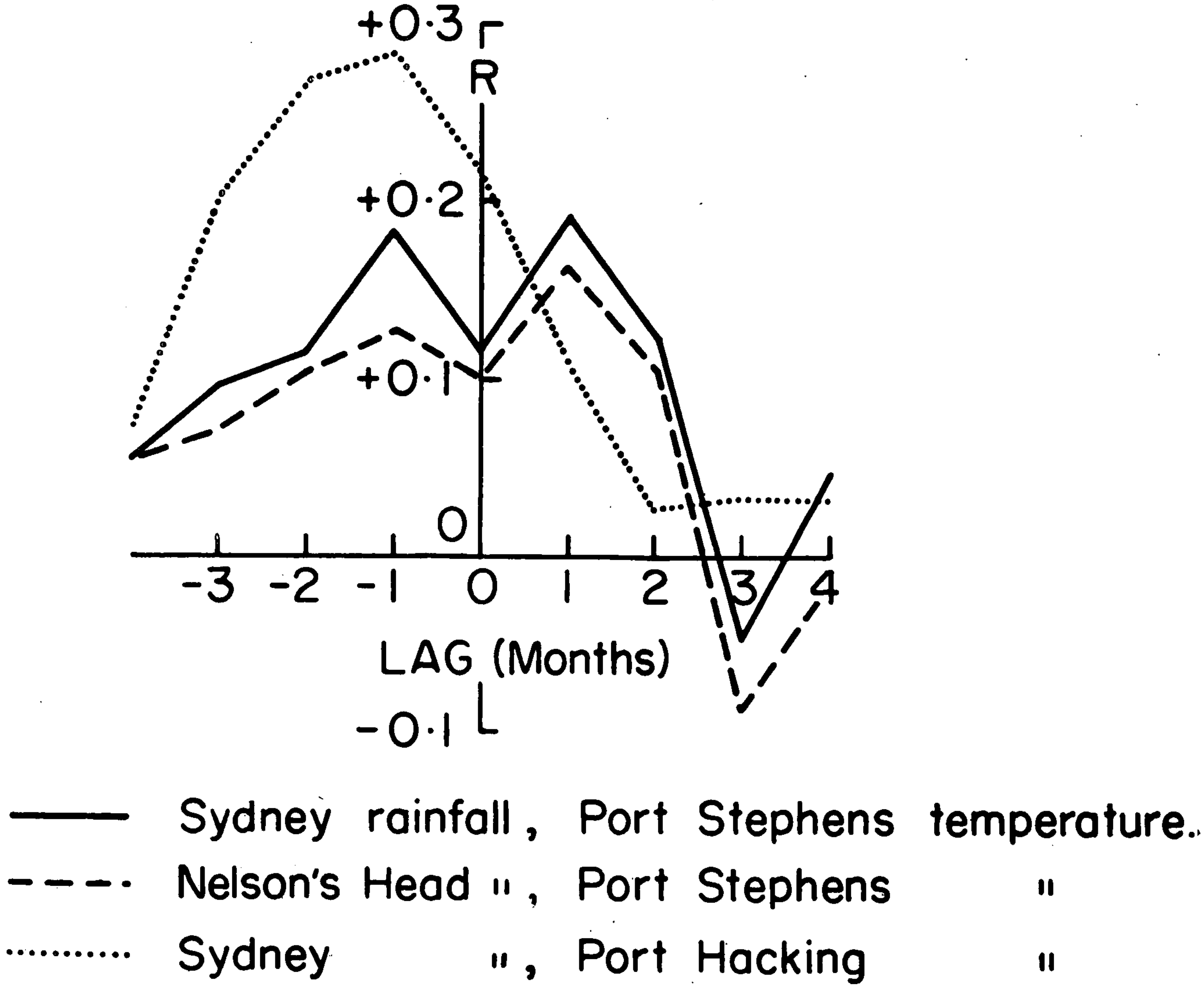

Fig. 4 Correlations downstream (Sydney rainfall vs. Port Stephens temperature) compared with local correlations.

5. DISCUSSION AND CONCLUSIONS

It might be argued that the results presented here are due, not to any real correlation between the shorter-period anomalies, but to an overall trend which is common to both sets of data, rainfall and temperature. That the surface temperatures do indeed show some trend is evident by inspection, and illustrated for Port Hacking in Table 3. The difference between the two decades is most marked for the months November to March inclusive. This non-uniformity

Table 3. Trend in Port Hacking Temperatures (^{o}C)

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Mean 1943-52	20.7	21.6	21.6	20.9	19.6	17.6	16.6	16.3	16.6	17.5	17.8	19.4
Mean 1953-62	21.3	22.0	22.4	21.0	19.4	17.9	17.1	16.3	16.4	17.7	19.2	20.2

throughout the year may have had some effect on the auto-correlation curve of Fig. 2. But there are three factors which indicate that the main findings are largely independent of trend: (i) the small part of the total variance (Port Hacking) accounted for by the trend or, alternatively, the low auto-correlation values at small time lags; (ii) the general enhancement of correlation when taken downstream rather than locally; (iii) an absence of trend in the rainfall values over the same period.

It seems then to have been established, from the overall consistency of the results, that there is a positive association between monthly anomalies in rainfall and sea surface temperature along the New South Wales coast. However, the practical aspiration of using this as a help in predicting monthly rainfall is not greatly furthered by values around +0.15 to +0.20, such as have been observed at one month lag in the appropriate sense. Two factors appear mainly resposible for this disappointment. One is that much of the correlation, at least in the southern half of the region, appears due to the Ekman effect with resultant lags in the opposite sense. The second is that, where evidence exists for a direct effect through heat and moisture exchange, the temperature records are too short and incomplete, and contain too large an element of "noise" and other unrepresentativeness for results of practical application to emerge. One is left with the reasoned argument that the findings would have been considerably more positive and useful if good temperature records had been available a hundred or so miles from the coast.

Two other results may be mentioned in summary. It is not without interest that sea temperature anomalies on the scale studied here may, in the statistical sense of Table 2, be traced downstream for considerable distances, moving with a fraction of the speed of the main current. Secondly, while the quality and quantity of the data was not good enough to justify an elaborate breakdown of the correlation analysis into seasons, in many instances this had been done in the preliminary examination of associations. The indications were that the rainfall-sea temperature correlations were most marked in the June to August quarter, whereas persistence phenomena in sea temperature were strongest from September to November. The latter corresponds to the season at which east coast rainfall exhibits its strongest tendency for persistence (Priestley 1963).

Throughout this study a realisation of the gross inadequacy of the sea surface temperature data, even over this region, has been thrust upon the author. It is hoped that studies such as this and the more elaborate ones cited above will serve to emphasize the need for more sea surface temperature data and for its historical analysis. This includes full exploitation of the possibilities now opening up, through international co-operation, for a much expanded data collecting programme, e.g. by radio buoys and satellite interrogation.

6. SEA AND AIR TEMPERATURE

Whilst the longer-period forecasting of temperature is probably of less importance than that of rainfall, it may be of some interest to append the results of a brief examination of air temperature in the present context. In this the Port Hacking data has been compared with values of monthly mean air temperature at Sydney (one-half of mean daily maximum plus minimum). We shall denote the latter by T and the sea temperatures by θ.

Removing the seasonal variation as before, the correlation between monthly anomalies in T and θ was found to be +0.285. This however was not all due to short-period anomalies, because over the period concerned both T and θ, unlike the Sydney rainfall, indicated a general tend. The linear trend in T was determined as +0.038°C per year, which is of interest in that it is identical with the mean annual trend for θ implied by the figures of Table 3.

After the trend in T was removed, the residual correlation between T and θ was +0.22. With T and θ lagging one month behind each other, the correlations were +0.15 and +0.18 respectively, and there was little correlation at greater lags. Thus the indication, perhaps a little surprising, is that, except in long period trends, air temperature is no better correlated with sea temperature than is the rainfall.

The seasonal variation has also been examined, using the "sympathy" (Priestley 1962) as an association coefficient indicative of the correlation. The results are shown in Table 4, adopting what is an unusual combination of months into seasons, but one which is suggested by the values of θ - T. It is to be expected from knowledge of exchange mechanisms,

Table 4. Air-sea temperature (°F) associations and mean differences

Month	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.
Mean T	71.8	70.1	65.3	59.9	55.9	54.4	55.9	59.4	63.7	67.0	69.8	71.3
Mean θ	71.2	71.6	69.7	67.1	63.9	62.4	61.4	61.7	63.7	65.3	67.6	69.7
θ - T	-0.6	1.5	4.4	7.2	8.0	8.0	5.5	2.3	0	-1.7	-2.2	-1.6
Seasonal sympathy	+.19			+.29			+.32			-.11		

is supported from the seasonal effect alluded to in Section 5, and is borne out again here, that the sea exerts a much stronger influence when it gives heat to the atmosphere than when it receives it. This contrast is much more marked than is immediately apparent from the last row of Table 4, since the most frequent wind directions are from the sea in summer and from the land in winter (K. Nederlands Met. Inst., 1949).

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