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Pacific sea-surface temperature related to rain in California

CALIFORNIA is experiencing the worst drought in modern history, and there is much concern and speculation about future rainfall prospects. We recently succeeded in relating South Atlantic sea surface temperatures (SST) to rain in northeastern Brazil[1], and here we use similar methods to relate sea surface temperatures over the North Pacific Ocean to rainfall in California. We found December SST in the north-east Pacific off Washington to have a limited but definite predictive value, and to account for about 45% of the variation in California rainfall for the period February–April.

Namias has published several papers relating SST in the Pacific to atmospheric circulation[2]. In our approach, aimed at obtaining a useful forecasting tool, we go directly from a contributory cause (SST) to an ultimate effect (rainfall), bypassing intervening physical processes. We justify this by the belief that rainfall is an integrator of the multitude of ocean–atmospheric interactions and processes that occur simultaneously on several scales of space and time.

We divided the rainy season into two parts, early rains (November–January), and the late rains (February–April). The months May–October are usually dry in California, and when rains do occur they are influenced by factors apart from the normal November–April rains. We did not investigate the effect of SST on rains in May–October, although SST off Baja California is almost certainly related to the occurrence of September and October rains originating from decaying *chubascos*, or west coast Mexican hurricanes.

First, we established rainfall indices (RFI) for California. Rainfall is quite highly correlated among stations over most of the state. We chose three stations: Sacramento, Fresno and Los Angeles. All have long records, and are about equally spaced along the length of California. All three stations respond only to synoptic situations that are definitely wet, and receive little moisture from marginal situations. For November–April all three stations have high correlation with the November–April RFI, r being 0.90, 0.92 and 0.89, for Sacramento, Fresno and Los Angeles, respectively. To give each station equal weight in the index, multipliers of 0.86, 1.26 and 0.96, derived from 1930–60 mean annual rainfall values, were used for Sacramento, Fresno and Los Angeles, respectively. The RFI for a given period is the sum of weighted rainfall for that period, in millimetres.

Interestingly, for the period 1889–1972 there is no correlation between early and late rainfall indices. Kendall's parameter τ equal to -0.07 and r to -0.02, are not significant. Thus failure of early rains does not indicate that late rains will also be deficient.

Our SST values were mean temperatures developed by NMFS Pacific Environmental Group from ship observations assembled by the National Climatic Center. These values are means of all observations taken in a given 5° quadrant in a Marsden Square, during a given month and year. They have not been corrected for space or time bias, and it would be expected that correlations obtained from them would be improved if corrections could be made. We used monthly averages of available ship observations of SST in 5° quadrants, 1931–72, for the Pacific Ocean north of 15°N latitude. Ship reports for three Marsden Squares (90, 128, 130) were not conveniently available, so these areas were not considered. The area to the south-east of Hawaii and equatorwards of 15° is probably influential in California rainfall, but SST data there are too sparse for analysis. Elsewhere, data exist in most quadrants for most years, except 1941–46. In preparing our correlation maps, we used all values that were averages of four or more observations in a given month and quadrant, except a few extreme coldest and warmest values based on less than 10 observations were excluded.

In our work relating rain in Brazil to SST in the South Atlantic Ocean we found a slight warming trend of 0.0078 °C per yr for the period 1907–72, and had assumed that this warming was due to instrumental error resulting from evaporative cooling from bucket samples in early years, and heating by ships' engines in injection temperatures in later years. Removal of this trend improved correlations with rainfall. We had originally intended to adjust the North Pacific SST data for the same reason, but soon found that the trend was generally much larger and more variable in space and time than could be accounted for by instrumental factors. We therefore added an arbitrary 0.01 °C per yr before 1972, to compensate partially for the warming trend. Corelations obtained when temperatures are so adjusted are higher than when the raw data are used, which suggests that some degree of instrumental warming may be real.

We found little significant or useful correlation between Pacific SST and November–April rainfall, although there is a tendency towards negative correlation extending from the central Pacific to the region south-east of Japan. In general, the cold water there tends to make California rainy.

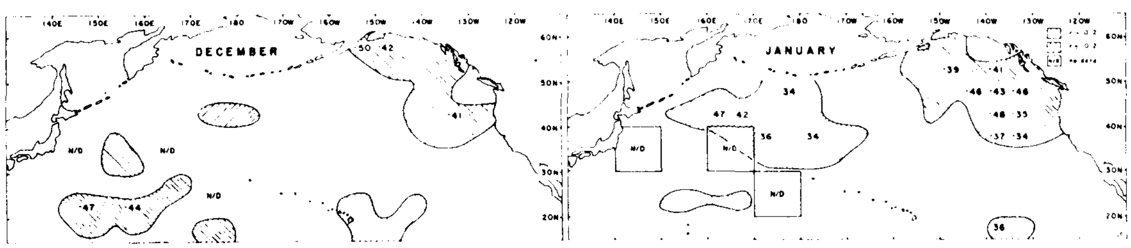

Fig. 1 Correlation between SST and November–January rainfall in California. Correlation coefficients plotted when significant above the 0.05 level.

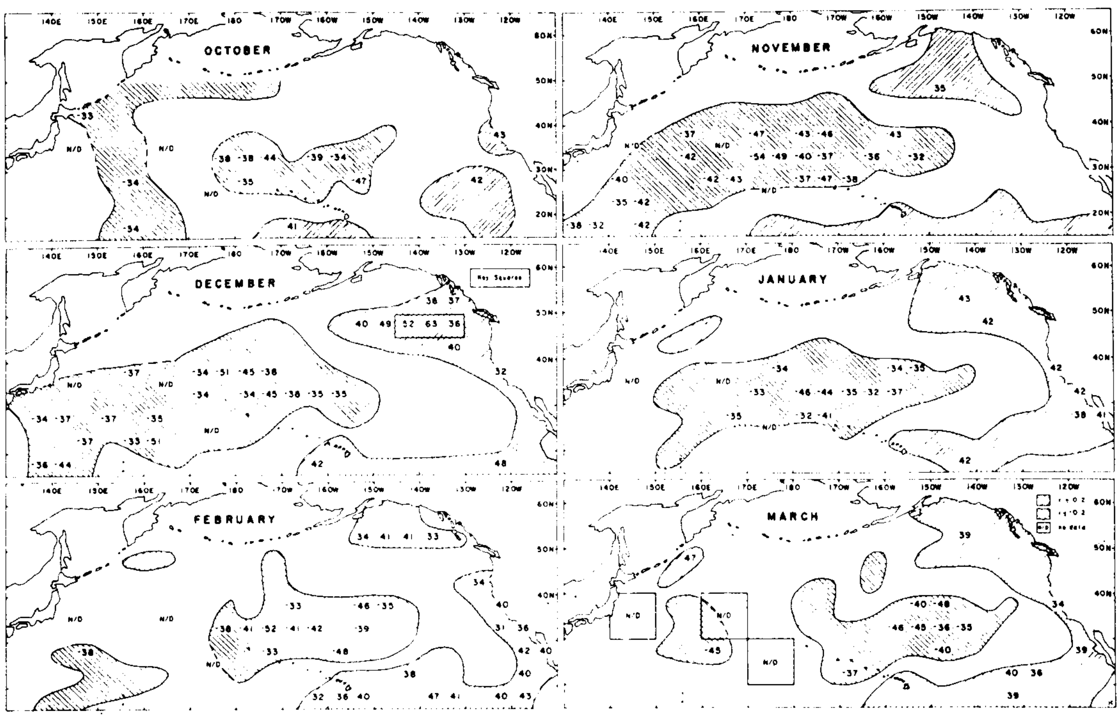

Fig. 2 Correlation between SST and February–April rainfall in California. Correlation coefficients plotted when significant above the 0.05 level.

We found no useful forecasting relation between Pacific SST and November–January rainfall, however, these rains are accompanied by negative correlation—cold water off the coast (Fig. 1). This substantiates Namias' view that warm water off the coast was involved in the 1976–77 winter drought in California[3].

A useful forecasting relation seems to exist between SST and February–April rainfall. The situation begins with negative correlation (cold water) in the western and central parts of the Pacific in October. Later in November, December and January, positive correlation (warm water) appears in the Gulf of Alaska. This progresses southwards in February and March, while cold water remains a short distance out to sea (Fig. 2). The area of positive correlation in the north-east Pacific off Washington in December seems to offer the most promise in forecasting February–April rains. In this area MS 158-4 has a correlation coefficient (r) of 0.63 between December SST and February–April rainfall, significant above the 0.001 level. It seems that processes induced by cold water in the central and western Pacific in October, November and December, when followed by warm water west of Washington in

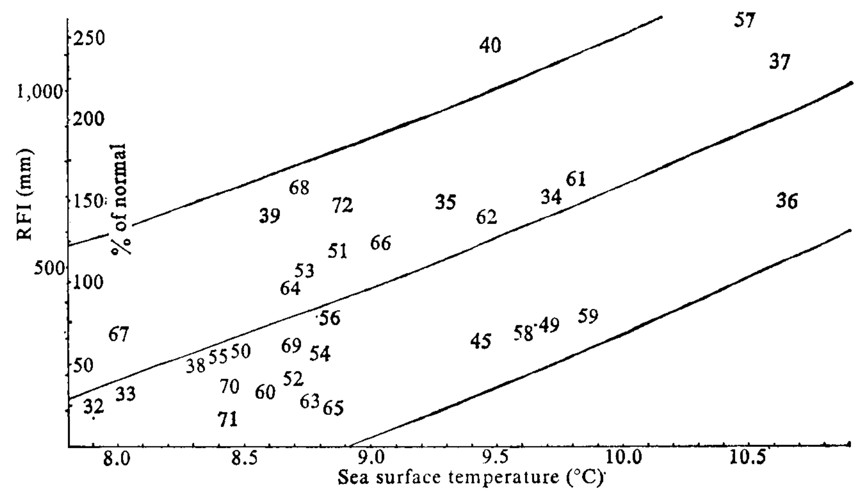

Fig. 3 February–April California rainfall indices (RFI) plotted against corrected December SST in Marsden Square 158–4. Normal SST is 9.04 °C and RFI is 459 mm. Years indicated are for SST. Second degree regression line with 95% confidence limits is shown.

December, are favourable to February–April rains in California. This implies that SST gradient between the two areas is important although we found that this gradient does not yield correlation coefficients as high as using SST at MS 158-4 directly.

Mean SST values for a given month and quadrant contain real SST variations, as well as considerable noise due to non-random distribution of observations in space and time and to various instrumental errors. This noise can be reduced by using a median anomaly from three adjacent quadrants, using those quadrants most nearly aligned with the isotherms of SST. The median is a better measure than the mean because of the effect of extreme values on the mean. The three-quadrant median deviation is taken as the corrected deviation from normal for the central quadrant. Table 1 illustrates the derivation of corrected SST values for MS 158-4.

When monthly SST values in MS 158-4 are refined as stated above, by introducing data from adjacent quadrants, $r=0.68$ and $\tau=0.50$, both with massive significance. This provides the basis for a February–April rainfall forecast using December SST (Fig. 3). Normal is defined as the mean for the 34 yr during the period 1931–72 when data exist in all three quadrants. When SST is normal, the rainfall forecast will be for 100% of normal, with 95% confidence limits between 10% and 190% of normal. If SST is 1 °C above normal, the rainfall forecast is for 160% of normal, with 95% confidence limits between 65% and 250%. If SST is 1 °C below normal the rainfall forecast is for 40% of normal, with 95% confidence limits between 0% and 135% of normal. The confidence limits are unfortunately wide, but probably reflect with reasonable accuracy the limits set by SST upon rainfall. Although imprecise, it is an improvement over a forecast based on

Table 1 Derivation of corrected SST for MS 158–4 (°C × 100)

Year	SST for MS 158–4		Deviation	Deviation	Deviation		Corrected SST
	Raw value	Adjusted*	MS 159–3	MS 158–4	MS 158–3	Correction†	MS 158–4
1931	824	865		−48	22		
32	750	790	−126	*−123*	−7	0	790
33	736	775	*−80*	−138	*−110*	28	803
34	900	938	94	25	*62*	37	975
35	894	931	14	*18*	95	0	931
1936	1018	1054	158	141	*154*	13	1067
37	1029	1064	212	*151*	−42	0	1064
38	797	831	116	*−82*	−154	0	831
39	829	862	58	*−51*	−76	0	862
40	900	932	*35*	19	43	16	948
1941	—	—	—	—	—	—	—
42	—	—	—	—	—	—	—
43	—	—	—	—	150	—	—
44	—	—	—	—	190	—	—
45	916	943	116	*30*	−28	0	943
1946	—	—	165	—	—	—	—
47	—	—	—	—	—	—	—
48	—	—	−93	—	−209	—	—
49	947	970	8	*57*	94	0	970
50	897	919	*−65*	6	−91	−71	848
1951	906	927	*−24*	14	−38	−38	889
52	843	863	*−44*	−52	7	6	869
53	831	850	*−39*	−63	−27	24	874
54	877	895	−46	−18	*−32*	−14	881
55	823	840	2	*−73*	−90	0	840
1956	844	860	29	−53	*−32*	21	881
57	1034	1049	209	136	*137*	1	1050
58	953	967	−3	54	*51*	−3	964
59	1012	1025	33	112	*75*	−37	988
60	848	860	−120	*−53*	104	0	860
1961	1078	1089	12	176	*70*	−106	983
62	1079	1089	−22	176	*35*	−141	948
63	787	796	*−35*	−117	−21	82	878
64	958	966	−93	53	*−41*	−94	872
65	878	885	−44	*−28*	10	0	885
1966	901	907	8	*−6*	−11	0	907
67	798	803	−125	*−110*	−78	0	803
68	871	875	−105	*−38*	−22	0	875
69	867	870	−63	*−43*	−8	0	870
70	878	880	−70	−33	*−67*	−34	846
1971	845	846	−52	*−67*	−93	0	846
72	948	948	*−21*	35	−22	−56	892
n	35	35	36	35	38		34
Mean SST	894	913	862	913	996		904
r	0.593	0.628					0.668
t	4.23	4.63					5.07
α''	< 0.001	< 0.001					< 0.001
φ	0.441	0.482					0.509
z	3.73	4.07					4.24
α''	< 0.001	< 0.001					< 0.001

Median values are italicised.
*0.21 °C added for each year before 1972.
†Difference between MS 158–4 deviation from normal and three square median deviation from normal.

climatic normals, which would be for 100% of normal with 95% confidence limits between 10% and 190% of normal, regardless of SST.

The τ value of 0.50 implies that the odds are three to one that a change in rainfall will match the sign change in SST.

We believe that, early in the season, cold water in the central Pacific induces greater-than-normal troughing in the overlying atmosphere. This induces an increased frequency of south-westerly winds that push the SST isotherms northwards in the Gulf of Alaska. As winter advances the cold anomaly in the central Pacific is advected slowly eastward. Troughing in the atmosphere may likewise move eastward, and act to decrease the intensity of the surface subtropical high pressure cell off the California coast. The resultant decreased north-westerly winds along the coast allows a warm SST anomaly to form by decreased upwelling and by reduced southward flow of the California Current. The warm water moves southward, and then westward with the North Equatorial Current as the season advances, to create a positive anomaly of SST near Hawaii. Namias has shown that warm water in this area is important for California moisture[4]. Our speculation is tenuous, but we hope that other researchers will study the cause and effect relationships underlying what seems to be real correlation between SST and California rainfall.

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