NOTES

On the Relationship between the Amount and Frequency of Precipitation over the Ocean[1]

R. K. REED

Pacific Marine Environmental Laboratory, Environmental Research Laboratories, NOAA, Seattle, WA 98105

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ABSTRACT

Data at 12 ocean weather stations were used to determine the amount of precipitation by a method devised by Tucker (1961), and precipitation frequency at each site was taken from recent climatic atlases. By combining the above data, monthly and annual estimates of precipitation intensity were calculated. The monthly intensities were then corrected for a suspected bias in Tucker's assessments. Precipitation can be calculated from these intensities and climatological maps of frequency; monthly and annual values have standard deviations of 12 and 9% of the means, respectively. The results are believed to have general applicability to extratropical regions. Furthermore, in data-sparse areas, use of intensities with frequencies can provide a more reliable estimate of oceanic rainfall amounts than Tucker's method.

1. Background

The difficulties in deriving reliable climatological values of precipitation at sea are well known. Tucker (1961) devised a method for computing precipitation which did not rely on extrapolation of amounts from land stations. Briefly, his method assigned quantitative values to each rainfall category in the present weather code; hence one can apply the method directly to ships' weather reports archived at data centers. Tucker (1961) used his assessments at the Atlantic ocean weather stations, and Reed and Elliott (1973) drew a map from the data at lightship and ocean weather stations in the North Pacific. These maps showed appreciably less rainfall at sea than most earlier ones, and patterns for the North Atlantic and North Pacific were quite similar.

Recently, evidence has been presented (Reed and Elliott, 1977) which indicates that Tucker's method gives reliable results over extratropical oceans, provided that there are large amounts of data over areas of reasonable size. In the tropics, however, estimates with Tucker's assessments appear unreliable, presumably because rainfall there is often considerably more intense than in Great Britain, where his coefficients were derived. Even though Tucker's assessments could be reevaluated for tropical regions and the method applied to the World Ocean, there is evidence that this would not be an entirely satisfactory procedure.

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The ocean weather stations were all located between 28 and 66°N. The spatial coverage, however, is only adequate to permit the preparation of crude rainfall maps. Hence one must use ship-of-opportunity reports to derive more reliable distributions and to extend the coverage south of 28°N. This creates a problem in that a large number of observations are needed to provide statistical significance to the amounts by Tucker's method, which is mainly caused by the extreme variability of rainfall intensity and duration. Tucker (1961) investigated the variability inherent in his method by determining the standard deviations from the means (in percent of the means) for both monthly and annual values at individual stations. He estimated that data for a five-year period at ocean weather stations are needed to yield a standard deviation of 13% for monthly means (1200 observations) and 4% for annual means (14 400 observations). Maps of the distribution of ship reports (provided by R. Quayle, National Climatic Center, 1976, personal correspondence), however, show that very few areas of reasonable size (e.g., 2°×2°) have a sufficient number of reports to enable one to compute annual or monthly amounts by Tucker's method with deviations as small as at ocean weather stations. This inadequate data base exists even along major shipping lanes, and the situation is far worse over vast regions of the tropics.

Thus application of Tucker's method to the World Ocean would appear to be a dubious undertaking based on an evaluation of data quantity, but aspects of data quality also need to be considered. As shown by Quayle

(1974), ship-of-opportunity reports are influenced by "fair-weather bias"; that is, mariners may avoid bad weather or take fewer observations than normal. By comparison of ship-of-opportunity reports with data at fixed sites (ocean weather stations or lightships), one may assess systematic differences and approximately correct the errors in frequency, but it is uncertain how to correct the probable errors in the distribution of weather codes on which Tucker's method depends. Another problem results from the fact that weather codes have changed several times, and some of the earlier codes had categories that only described precipitation in a very general way (e.g., drizzle). It was sometimes difficult to tell which code was used, and conversions into the current code were of necessity subjective and uncertain. Ship-of-opportunity reports prior to 1955 are most seriously affected by problems with code conversions (R. Quayle, personal communication); elimination of observations before 1955, however, would seriously erode an already limited data base. It should be stressed that efforts were made to ensure high-quality data at ocean weather stations, and we cannot expect comparable results from all ships-of-opportunity.

This note examines the relationship between oceanic precipitation frequency and amount in an effort to determine if frequency data can be satisfactorily used as the primary input in preparing rainfall maps. Direct use of frequency data (with rainfall rate or intensity values) might eliminate some of the problems that result from using present weather codes in Tucker's method. One advantage is that frequency data do not depend on an observer's subjective estimate of general precipitation type, intensity and duration. Second, frequency data can be approximately corrected for "fair-weather bias" by comparison with data at ocean weather stations. Finally, there is some evidence (to be discussed) that the variance in frequency data is not as highly dependent on data quantity as are estimates from Tucker's method.

2. Data and methods

Precipitation frequency data for the North Atlantic and North Pacific are contained in the recently revised series entitled, *U. S. Navy Marine Climatic Atlas of the World* (Meserve, 1974; Director, Naval Oceanography and Meteorology, 1977). The data were presented as monthly maps, and frequencies at the ocean weather stations and other select areas were tabulated. (The frequency data from ship-of-opportunity reports have been corrected approximately for "fair-weather bias" and other sources of error.) Frequency data at the ocean weather stations were taken directly from these publications. Mean monthly computed rainfall amounts at nine North Atlantic weather stations were taken from Tucker (1961). These data were for the five-year period 1953–57. Rainfall amounts for the North Pacific stations N, P and V were computed by Tucker's method from the taped data (archived at NOAA's National Climatic Center) for the periods 1955–68, 1955–59 and 1956–68, respectively. The short-data period at station P was used because of possible improper use of categories for drizzle and rain since 1959 (Capt. G. P. Britton, University of Reading, personal communication). Thus precipitation amounts and frequencies are available for a total of 12 stations which should represent a variety of conditions in extratropical ocean regions.

The amounts (cm) computed by Tucker's method and the frequencies (%) from the atlases can be used to compute precipitation intensity on both a monthly and annual basis; i.e., $I=A/F$, where I is intensity, A amount, and F frequency. For practical reasons, the intensity units used are cm/(month %) or cm/(year %); hence one can apply these factors directly to monthly or annual frequency maps to derive amounts. Table 1

TABLE 1. Monthly and annual intensity [cm/(month %) and cm/(year %), respectively] of precipitation at 12 ocean weather stations. The amounts were computed for periods as listed in the text, and the frequency data were obtained mainly during the period 1950–70. The monthly intensities may be converted to mm h^{-1} by the relation 1 cm/(month %) = 0.27 mm h^{-1}.

Station	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
A	62°N, 33°W	0.41	0.59	0.28	0.29	0.24	0.32	0.45	0.55	0.43	0.53	0.36	0.47	4.9
B	56°N, 51°W	0.28	0.33	0.27	0.29	0.30	0.31	0.31	0.44	0.46	0.36	0.28	0.37	3.9
C	52°N, 36°W	0.36	0.30	0.24	0.22	0.31	0.33	0.33	0.45	0.37	0.35	0.32	0.38	3.9
D	44°N, 41°W	0.27	0.27	0.29	0.27	0.33	0.36	0.29	0.41	0.43	0.41	0.30	0.44	3.9
E	35°N, 48°W	0.41	0.29	0.32	0.18	0.33	0.40	0.38	0.38	0.47	0.36	0.24	0.24	3.8
I	59°N, 19°W	0.39	0.36	0.22	0.19	0.29	0.31	0.29	0.36	0.42	0.38	0.32	0.41	4.0
J	53°N, 20°W	0.32	0.29	0.26	0.24	0.31	0.34	0.29	0.41	0.36	0.34	0.30	0.42	3.9
K	45°N, 16°W	0.25	0.36	0.40	0.24	0.35	0.24	0.25	0.32	0.31	0.27	0.26	0.24	3.5
M	66°N, 2°E	0.44	0.47	0.29	0.34	0.34	0.35	0.28	0.24	0.46	0.48	0.43	0.43	4.6
N	30°N, 140°W	0.30	0.38	0.23	0.26	0.30	0.24	0.31	0.32	0.32	0.37	0.28	0.36	3.9
P	50°N, 145°W	0.40	0.31	0.29	0.27	0.27	0.29	0.30	0.39	0.40	0.39	0.38	0.43	4.1
V	34°N, 164°E	0.40	0.40	0.33	0.31	0.35	0.38	0.44	0.56	0.37	0.48	0.37	0.49	4.8
Mean		0.35	0.36	0.28	0.26	0.31	0.32	0.33	0.40	0.40	0.39	0.32	0.39	4.1
Standard deviation from mean (in % of mean)		19	25	17	18	11	15	19	23	14	18	17	20	10

TABLE 2. Monthly factors used by Tucker (1961) to adjust monthly mean precipitation.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.98	1.06	0.79	0.78	0.92	1.01	1.08	1.21	1.15	1.18	0.92	1.08

lists the intensity values that were computed from these data sets, and the means and standard deviations are also given. The monthly means indicate a tendency toward low values in spring and high values in late summer-early fall. The mean annual intensity is 4.1 cm/(year %). Obvious areal differences in annual intensity are present; high values seem to occur near low-pressure center tracks (Marine Climatic Atlases), although the value at station B is an exception.

3. Variability of the intensity estimates

The data in Table 1 form the basis for the determination of the variability in rainfall intensity over the ocean. Given reliable frequency data, we wish to be able to say how "good" the derived amounts are. Intensity may vary on both temporal and spatial scales, but examination of spatial variability is not attempted here because of limited data.

The standard deviations (σ_I) in Table 1 do not reflect the error that would result from applying intensity values to climatological frequency data. This is due to the fact that the amounts, except at two stations, were computed from the data for five-year periods, and the monthly and annual mean amounts have standard deviations of 13 and 4%, respectively, as determined by Tucker (1961). The deviations in Table 1 are composed of the variability resulting from the computation of amounts by Tucker's method (σ_T) and the uncertainty that arises from the true variability (in time or space) in the ratio of amounts to frequencies (σ_v); hence $\sigma_I^2=\sigma_T^2+\sigma_v^2$. This expression was used with the values in Table 1 and the standard deviations in Tucker's method to compute σ_v or the variability in intensity. The annual data gave a σ_v of 9%, and the mean monthly σ_v was 12%. If data have a normal distribution, these values need to be approximately doubled to give random errors at 95% confidence intervals; even without normally distributed data, however, the worst case confidence interval for two standard deviations is 75% (Mendenhall, 1967).

So far the discussion has dealt with random errors, or the uncertainty that would result from combining monthly or annual intensities with precipitation frequency to estimate amount. It should be stressed that the values given apply only to extratropical, not tropical, ocean rainfall. In addition to random errors, it is believed that a bias or systematic error may exist in Tucker's estimates of amount, which in turn affects the calculated intensities. Tucker (1961) derived his coefficients from data at British land stations; he found best agreement between measured and estimated precipitation when the monthly means were further modified by multiplication by varying monthly factors as given in Table 2. These factors have no significant effect on annual means but strongly influence some monthly values. Plots of monthly frequencies and measured amounts at several stations in Britain showed a skewed relation to each other; measured amounts in spring were relatively low compared with frequencies, but in late summer and fall the amounts were anomalously high. This behavior led to the seasonally varying factors shown in Table 2, where the lowest factors occur in spring and the highest in the August–October period. Should these factors have been applied to data at all of the North Atlantic ocean weather stations as Tucker has done? The question cannot be answered with certainty because of the lack of reliable measurements of rainfall at these sites; a number of arguments against the practice will be advanced, however.

What is the cause of the low rainfall (compared to frequency) in spring and large amounts in fall that were observed in Great Britain? The disparity may result from seasonal variations in either intensity or duration. If intensity were the major factor, one would expect that amounts estimated by Tucker's method would match measured amounts, unless there were some unusual bias in the coding practice of observers. It seems that a more likely cause would be seasonal variations in duration; thus if rain in spring were generally of short duration, estimates could be larger than measured amounts (which would show an anomalous relation to frequency) and one would need to reduce the estimates as Tucker did. However, Elliott and Reed (1973) used Tucker's (1961) assessments without the monthly factors because better agreement of frequency and amount was obtained and, more importantly, because computed amounts at lightships a few kilometers off northern California, Oregon and Washington would not have shown the highly distinct midsummer minimum that is present at all near-by land stations. Finally, elimination of the monthly factors results in a summer minimum in rainfall intensity (as will be demonstrated), which is in agreement with a summer maximum in drizzle—with low incidence of other types—at stations N, P and V (taped data) and at I, J and K (Capt. G. P. Britton, personal communication).

Consequently, the mean monthly intensities shown in Table 1, which had all been multiplied by the factors, were divided by the factors in Table 2 to produce values of mean monthly intensity not in-

TABLE 3. Mean monthly intensity [cm/(month %)] of precipitation as determined from the dashed curve in Fig. 1.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.36	0.36	0.35	0.34	0.33	0.32	0.31	0.31	0.33	0.34	0.35	0.36

fluenced by them (Fig. 1). The data modified by the factors (solid lines) show low intensities in spring and high values during August–October. Removal of the factors (open circles) indicates minimum intensities in summer. The new values have presumably eliminated the systematic error resulting from the factors, and the intensity listed for each month (Table 3) can be used directly with frequency data to compute amount.

4. Discussion

The methods suggested provide an alternate means of estimating precipitation; one needs only to use maps of precipitation frequency rather than the present weather codes used by Tucker (1961). (Furthermore, these methods differ from earlier attempts to use oceanic frequency data with mean intensities over land.) Monthly mean estimates of precipitation would have a random error comparable to the results from Tucker's method when 1200 observations were available. As noted, however, there are few areas of reasonable size with that many observations and the frequency method generally would provide a better estimate than Tucker's method. In areas with relatively abundant data, the random error in annual mean data from using intensity is probably comparable to that from using Tucker's method. Elsewhere, the frequency method should be superior.

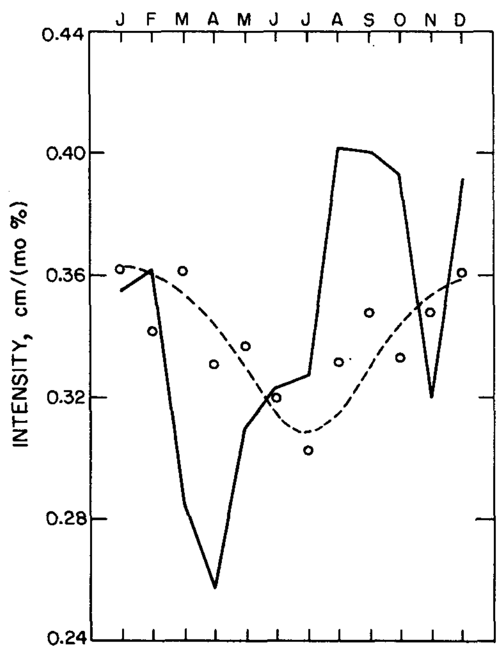

FIG. 1. Mean monthly intensity [cm/(month %)] of precipitation based on data at the 12 ocean weather stations. The solid line is for data modified by Tucker's monthly factors, and the open circles are intensities where the effects of the factors have been eliminated. The dashed curve is a subjective estimate of the seasonal cycle of intensity.

An interesting finding here is that, in contrast to Tucker's method, there is not a large difference in the monthly or annual random errors using intensities. This suggests that estimates based on frequencies are not highly sensitive to data quantity.

The intensity values given here are for extratropical regions. How may one convert frequencies to amount in the tropics? Reed and Elliott (1977) found that about three times as much rain was caught in a small gage as was estimated from weather reports. Hence it is suggested that as a crude approximation one could use an annual value of 12 cm/(year %) or a monthly value of 1 cm/(month %). The most serious problems are 1) knowing where to change from extratropical to tropical rates and 2) determining the extent of possible intertropical variations. The problems could be resolved with additional direct measurements or by reevaluation of Tucker's assessments at tropical stations.

Other possible approaches to specification of oceanic precipitation should be investigated. Dorman and Bourke (1978) recently have suggested a relation between rainfall rate and temperature. Rao and Theon (1977) described results from the Electrically Scanning Microwave Radiometer on the Nimbus 5 satellite. Such a method would seem to offer the only practical solution for the need for oceanwide data in real time.

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