A Climatological Estimate of Precipitation for the World Ocean[1]

W. P. ELLIOTT

Air Resources Laboratories, Environmental Research Laboratories, NOAA, Rockville, MD 20852

R. K. REED

Pacific Marine Environmental Laboratory, Environmental Research Laboratories, NOAA, Seattle, WA 98115

(Manuscript received 29 July 1983, in final form 21 December 1983)

ABSTRACT

Climatological estimates of mean annual precipitation over the world ocean are presented and discussed. We obtained a value for mean annual oceanic precipitation (between 65°N and 60°S) of 93 cm, which is smaller than some other estimates. These results are supported by a recent analysis of tropical rainfall based on satellite techniques. Aspects of the need for and utility of climatological information are discussed.

1. Introduction

On a global average, the surface of the earth receives more heat from the combination of solar and longwave radiation than it emits. The excess heat is mainly removed by the evaporation of water, which must be returned to the surface to keep sea level approximately constant. Thus the amount of precipitation is constrained by the earth's heat budget, but this fact does not provide a precise determination of even total oceanic precipitation because of uncertainties in the radiation budget (Budyko, 1974).

Actual measurements of oceanic rainfall were often unreliable and are still quite limited (Reed and Elliott, 1979), and most large-scale maps have been prepared by 1) extension of data from land stations or by 2) various schemes to use some estimate of the intensity of rainfall at sea with ship reports of the frequency of precipitation. The first of these methods has clearly been discredited (see Jacobs, 1968, for example), and variations of the second approach have led to significantly different results. Recently, various satellite-borne sensors have come into vogue; use of microwave radiometers appears to be beset by several problems, but two simple techniques based on visible (Kilonsky and Ramage, 1976) and infrared (Arkin, 1983) radiometry have yielded promising results. As discussed by Arkin (1983), however, their validity appears to be restricted to convective systems in the tropics, and only now can long-term mean (≈ 10 year) estimates be derived.

For many purposes it would be desirable to have *climatological* maps of precipitation over the world ocean. The main concern is that the averages over sizeable areas be free from major, systematic errors. Such estimates should be useful for studying the removal of material from the air, for investigating geochemical cycles and the distribution of substances in the ocean, for examining various effects of evaporation minus precipitation in relation to ocean circulation and heat budgets, and as an aid in the verification of remote sensing techniques. This note extends our previous precipitation estimates to the world ocean.

2. Methods

Our maps (Reed and Elliott, 1979) for the North Atlantic and North Pacific were based on a procedure devised by Reed (1979), which is a variation of the second method noted above. Briefly, the system used the results of Tucker (1961) to derive precipitation amounts from his assessments for the various present weather codes; these amounts were combined with precipitation frequency at the 12 Northern Hemisphere (30–66°N) ocean weather stations to obtain mean monthly and annual precipitation intensity (Reed, 1979). The intensities were then used with the frequency data in the revised series, *U.S. Navy Marine Climatic Atlas of the World* (Meserve, 1974; Director, Naval Oceanography and Meteorology, 1977) to estimate amounts over the midlatitude Northern Hemisphere oceans. This procedure was estimated to yield a random error of ±10% in annual amounts. For the tropical oceans, an intensity value three times that at midlatitudes was used as a result of comparisons of six years of gage measurements from a research vessel (Reed and Elliott, 1977; Reed, 1982). The maps (Reed and Elliott, 1979) were in general agreement with several data sets, which suggested that the large-scale patterns and averaged amounts were realistic.

The *U.S. Navy Marine Climatic Atlas of the World* series now includes volumes for the Indian Ocean,

---

[1] Pacific Marine Environmental Laboratory Contribution No. 628.

South Atlantic Ocean, and South Pacific Ocean (Naval Weather Service Detachment, 1976, 1978, 1979). The frequency data from these volumes were used to extend precipitation estimates to the world ocean. The rates used previously for the tropical and midlatitude Northern Hemisphere were adopted for the Southern Hemisphere; the southern boundary of the "tropical region" was chosen as 10°S, except in the eastern and western Pacific where limits of 0° and 20°S were used respectively. These choices were based mainly on cloud cover distributions from satellite sensors, especially the visible channel data in Miller and Feddes (1971).

The amount of ship data from the Southern Hemisphere was appreciably less than for the Northern Hemisphere, particularly south of 20°S. The number of grids used in the climatic atlases for grouping and averaging the frequency data was small, and their sizes were relatively large. South of about 40°S very few ship data were available. In this latter region we have estimated the rainfall from analogous regions in the Northern Hemisphere, the cloud-cover data from Miller and Feddes (1971), and the few land observations available. In the 20–40°S region, we followed the patterns indicated by the ship data, but the values of the isohyets average about 20% more than would be indicated by the ship data alone. This seems to be a reasonable adjustment because the cloud-cover data, and oceanic/land rainfall ratios, did not support the original low rainfall values at southern latitudes when compared to those in the Northern Hemisphere, where we have more confidence in the values. It seems possible that these sparse data in the southern oceans are more affected by "fair weather bias," as discussed by Quayle (1974), than results in other regions. Finally, some adjustment has been made in our (Reed and Elliott, 1979) previous maps, especially in the western equatorial and subtropical oceans, where the discontinuity between tropical and midlatitude rates used before has been eliminated. This resulted in the emergence of clearer patterns than before, which were supported by the distribution and characteristics of cloud cover, and in somewhat larger amounts in parts of the tropics and subtropics.

Our estimates of the mean annual distribution of precipitation are shown in Figs. 1 and 2. A contour interval of 50 cm was used except in some regions where the results seemed particularly well established or it appeared desirable to emphasize certain features. No attempt was made to show small-scale features or to depict distributions over marginal seas. We feel that preparation of mean seasonal maps would be a marginal undertaking; such data were presented for the Northern Hemisphere (Reed and Elliott, 1979), and Jacobs (1968) gave the seasonal frequency for the world ocean. It is not possible to precisely fix random or systematic errors on these maps, but values of 10–20% may be typical.

3. Results and comparison

The patterns in Figs. 1 and 2 are generally similar to those on most other maps. The equatorial maximum in the Pacific near 7°N is more clearly shown than on some maps (Jacobs, 1951, for example), and the maximum east of New Guinea emerges as a large-scale feature in concurrence with other meteorological ev-

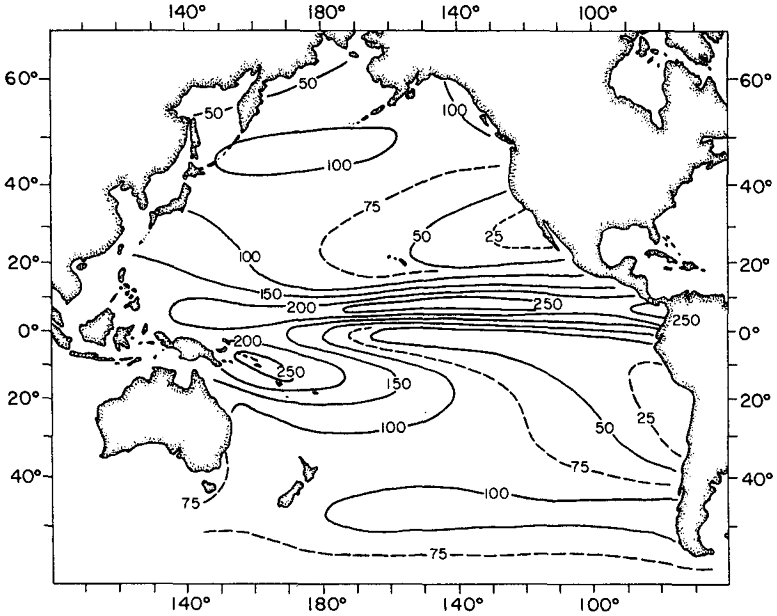

FIG. 1. Annual precipitation (cm) over the Pacific Ocean from 60°S to 65°N.

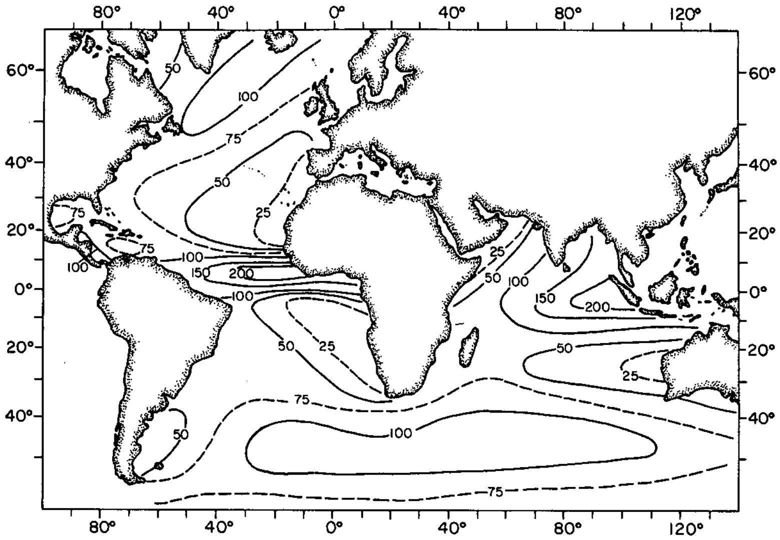

FIG. 2. Annual precipitation (cm) over the Atlantic Ocean and Indian Ocean from 60°S to 65°N.

idence (Hubert *et al.*, 1969). The highest tropical values are in the Pacific; this appears to result from less seasonal migration of the Pacific maximum, however, rather than from less intense rainfall in the other oceans (Reed and Elliott, 1979). The maximum in the Indian Ocean is slightly south of the equator. The other features, such as the subtropical minima and increased precipitation in higher latitudes, are well known and were clearly depicted previously.

The annual amounts shown on our maps and others, especially the maximum isohyets in the tropics, do not agree very well. Where the maximum values in Fig. 1 are about 300 cm, Dorman and Bourke (1979, 1981) showed values over 400 cm, but Jacobs (1951) gave values less than 200 cm. In general, other differences are less extreme. As noted above, our tropical amounts are ultimately tied to our *direct* measurements from a research vessel (Reed and Elliott, 1977; Reed, 1982), and other limited, tropical measurements with gages support them (Seguin and Sabol, 1976). Although no particularly close agreement is expected, Table 1 contains a comparison of Fig. 1 with the rainfall measured at low atolls in the tropical Pacific. Appreciable scatter and somewhat more rain on the islands is apparent, which is not surprising considering the variability of rainfall over any land surface and the general tendency for enhancement of precipitation over land compared to that at sea (Reed and Elliott, 1979). The agreement is rather close, except for the third and fourth groups which are in moderate- to low-rainfall zones, but enough scatter exists that it would be difficult to use rainfall at single atolls to derive oceanic values. It is noted again, however, that our tropical rates are based on direct measurements at sea.

The mean annual precipitation over the oceanic region shown in Figs. 1 and 2 (65°N–60°S) varies in previous assessments from about 115 cm (Baumgartner and Reichel, 1975, and others) to 80 cm (Jacobs, 1951). Figs. 1 and 2 give an average value of 93 cm. This figure may be converted to a global value, using precipitation values for the polar oceans and land from Baumgartner and Reichel (1975), one obtains about 85 cm. The global radiation budgets derived by Hoyt (1976) give values from 90 to 100 cm. The mean of Hoyt's results is about halfway between our estimate and the higher global amounts from Baumgartner and Reichel (1975). Small changes in an estimate of one or more of the radiation components could produce agreement with either estimate.

One recent result does provide additional support for our amounts, however. The Kilonsky and Ramage (1976) technique is in the process of being extended to produce long-term estimates of rainfall over the tropical (20°N–20°S) oceans (O. Garcia, personal communication). We have compared Figs. 1 and 2

TABLE 1. Comparison of annual rainfall amounts (cm) over the tropical Pacific as measured at islands and estimated from Fig. 1. These data are only for low islands (maximum elevation less than 35 m) as given in Reed (1980) and Wright and Reed (1981).

Group	Location	Total sites	Mean ratio $\left(\frac{\text{island}}{\text{ocean}}\right)$	Standard deviation from mean
Line–Gilbert Is.	1°S–6°N, 157°W–173°E	13	1.2	±0.3
Southcentral Is.	1°S–5°S, 155°W–175°E	9	1.1	±0.2
Southern Is.	6°S–11°S, 158°W–176°E	12	1.6	±0.1
Western Is.	1°N–11°N, 140°E–171°E	10	1.5	±0.3
Northern Is.	17°N–28°N, 166°W–154°E	5	1.2	±0.3

TABLE 2. Compilation of annual oceanic precipitation, from Figs. 1 and 2, precipitation over land, from Baumgartner and Reichel (1975), and the combined or global precipitation. The areas used are from Baumgartner and Reichel (1975). Both precipitation height and volume are given.

	Pacific			Atlantic			Indian			Total ocean			Total land			Global		
Latitude band	Ht. (cm)	Area (10^6 km^2)	Vol. (10^3 km^3)	Ht. (cm)	Area (10^6 km^2)	Vol. (10^3 km^3)	Ht. (cm)	Area (10^6 km^2)	Vol. (10^3 km^3)	Ht. (cm)	Area (10^6 km^2)	Vol. (10^3 km^3)	Ht. (cm)	Area (10^6 km^2)	Vol. (10^3 km^3)	Ht. (cm)	Area (10^6 km^2)	Vol. (10^3 km^3)
60–65°N	35	0.75	0.26	82	2.38	1.95				71	3.13	2.21	49	7.20	3.52	55	10.33	5.73
55–60	50	2.53	1.26	91	2.85	2.59				72	5.38	3.85	57	6.63	3.81	64	12.01	7.66
50–55	83	3.25	2.70	85	2.30	1.96				84	5.55	4.66	58	8.05	4.67	69	13.60	9.33
45–50	100	4.06	4.06	71	2.56	1.82				89	6.62	5.88	53	8.46	4.47	69	15.08	10.35
40–45	84	4.51	3.79	68	3.91	2.66				77	8.42	6.45	54	8.01	4.34	66	16.43	10.79
35–40	74	5.42	4.01	54	4.60	2.48				65	10.02	6.49	55	7.63	4.18	60	17.65	10.67
30–35	73	6.22	4.54	53	4.62	2.45				64	10.84	6.99	52	7.92	4.12	59	18.76	11.11
25–30	72	6.86	4.94	54	4.52	2.44	10	0.38	0.04	63	11.76	7.42	61	7.94	4.81	62	19.70	12.23
20–25	78	7.86	6.13	61	4.55	2.78	30	0.95	0.28	69	13.36	9.19	62	7.14	4.40	66	20.50	13.59
15–20	103	8.67	8.93	65	4.18	2.72	82	2.15	1.76	89	15.00	13.41	67	6.16	4.13	83	21.15	17.54
10–15	164	9.82	16.10	85	3.86	3.28	96	2.88	2.76	134	16.55	22.14	102	5.08	5.19	126	21.63	27.33
5–10	233	10.96	25.54	175	2.80	4.90	117	2.86	3.35	203	16.61	33.79	148	5.34	7.93	190	21.95	41.72
0–5°N	144	10.50	15.12	155	3.60	5.58	134	3.27	4.38	144	17.36	25.08	196	4.76	9.34	156	22.12	34.42
0–5°S	90	9.80	8.82	61	3.23	1.97	144	3.75	5.40	96	16.78	16.19	209	5.34	11.18	124	22.12	27.37
5–10	101	8.89	8.98	34	3.03	1.03	135	4.97	6.71	99	16.90	16.72	182	5.06	9.19	118	21.96	25.91
10–15	119	8.38	9.97	38	3.03	1.15	103	5.81	5.98	99	17.22	17.10	143	4.42	6.32	108	21.64	23.42
15–20	101	8.33	8.41	46	2.96	1.36	67	4.86	3.26	81	16.15	13.03	94	5.00	4.68	84	21.15	17.71
20–25	85	7.92	6.73	50	3.30	1.65	46	4.24	1.95	67	15.45	10.33	60	5.05	3.04	65	20.50	13.37
25–30	75	7.44	5.58	50	3.58	1.79	48	4.42	2.12	61	15.45	9.49	52	4.27	2.24	59	19.72	11.73
30–35	72	7.12	5.13	58	3.73	2.16	64	4.90	3.14	66	15.75	10.43	56	3.01	1.68	65	18.76	12.11
35–40	77	6.72	5.17	72	3.87	2.79	75	5.90	4.42	75	16.48	12.38	76	1.17	0.89	75	17.65	13.27
40–45	91	6.28	5.71	87	3.88	3.38	97	5.68	5.51	92	15.83	14.60	107	0.60	0.64	93	16.43	15.24
45–50	103	5.76	5.93	94	3.60	3.38	104	5.34	5.55	101	14.70	14.86	153	0.38	0.58	102	15.08	15.44
50–55	84	5.08	4.27	88	3.38	2.97	86	4.93	4.24	86	13.40	11.48	139	0.20	0.28	86	13.60	11.76
55–60°S	65	4.58	2.98	75	2.85	2.14	65	4.58	2.98	68	12.00	8.10	60	0.01	0.01	68	12.01	8.11
0–65°N	120	81.41	97.38	80	46.73	37.61	101	12.49	12.57	105	140.60	147.56	72	90.32	64.91	92	230.98	212.47
0–60°S	90	86.30	77.68	64	40.44	25.77	86	59.38	51.26	83	186.11	154.71	118	34.51	40.73	89	220.62	195.44
65°N–60°S	104	167.71	175.06	73	87.17	63.38	89	71.87	63.83	93	326.71	302.27	85	124.83	105.64	90	451.60	407.91

with these preliminary maps; the general patterns are quite similar, and our amounts average about 10% less than the satellite-derived estimates near the maxima. Since the tropics have the major impact on world ocean precipitation, this comparison suggests that our large-scale amounts and volumes should be realistic.

Table 2 presents a summary of our annual precipitation estimates for oceanic areas by 5°-latitude bands. The areas within the bands were taken from Baumgartner and Reichel (1975); a summary of their data for land, plus the combined or global values, are also included, and plots of the amounts are presented in Fig. 3. The ocean rainfall estimates in Baumgartner and Reichel (1975) have been widely used of late, although their method employed extrapolation of land data. The average total ocean amount in Table 2 for 0–30°N is 90% of the Baumgartner and Reichel value, whereas our values are only 67 and 80% of their values for 30–60°N and for the Southern Hemisphere respectively. Comparison of our total ocean estimates with the Baumgartner and Reichel estimates for the total land area is also of interest (Fig. 3). The rainfall rate over the oceans exceeds that over the continents north of 5°N, whereas the reverse is generally true to the south. Finally, the peak rainfall over the continents occurs just south of the equator, but it is in the 5–10°N zone over the ocean.

4. Discussion

Satellite sensors appear to be the only technology available to produce daily information needed for forecasting and other services. These techniques are only now providing long-term estimates of tropical precipitation though, and it is unclear if any such system can yield reliable results at higher latitudes. Figs. 1 and 2 provide the type of information needed for many research studies. Atmospheric/oceanic geochemical studies often rely on some estimate of rain rate, and various air trajectory/dispersion models need such information. A recent comparison of the heat budgets and circulation of the subarctic gyres in the North Atlantic and North Pacific used large-scale, climatological precipitation (Warren, 1982), and a study by Georgi and Toole (1982) pointed out that oceanic freshwater fluxes are poorly known and suggested that our relatively low precipitation estimates are more realistic than the higher ones. The maps shown may

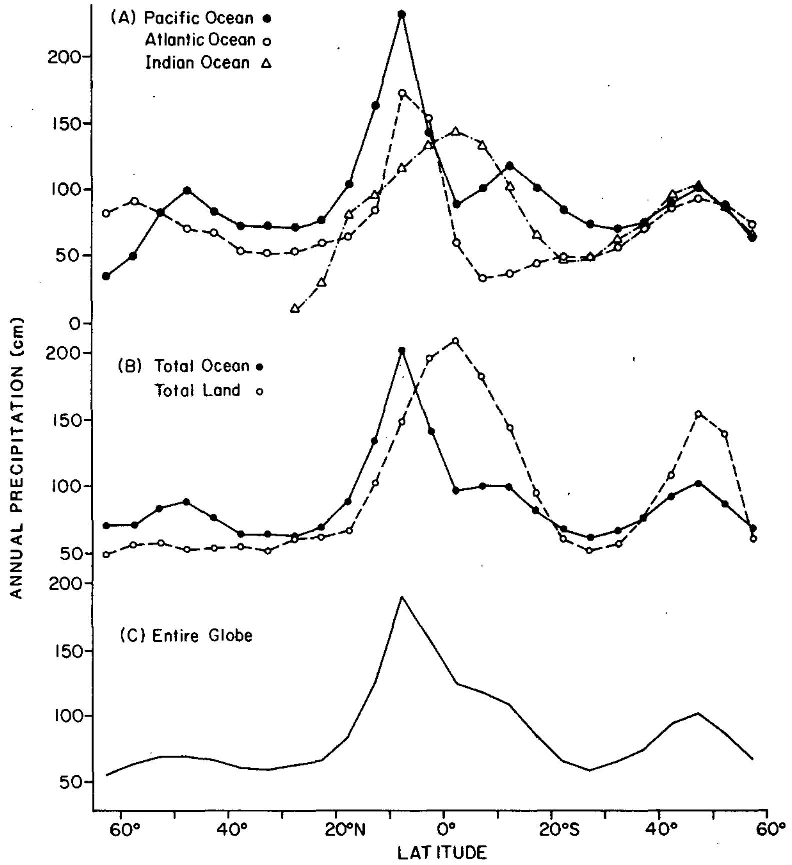

FIG. 3. Average annual precipitation (cm) by 5°-latitude bands for (a) the Pacific, Atlantic and Indian oceans; (b) the total ocean and total land; and (c) the entire globe.

provide an interim solution to the need for information on mean oceanic precipitation.

Acknowledgments. We are indebted to O. Garcia for providing results prior to publication. We also thank J. K. Angell for useful comments and suggestions.

REFERENCES

Arkin, P. A., 1983: A diagnostic precipitation index from infrared satellite imagery. *Trop. Ocean-Atmos. Newsletter,* No. 17, 5-7.

Baumgartner, A., and E. Reichel, 1975: *The World Water Balance.* Elsevier, 179 pp.

Budyko, M. I., 1974: *Climate and Life.* Academic Press, 508 pp.

Director, Naval Oceanography and Meteorology, 1977: *U.S. Navy Marine Climatic Atlas of the World,* Vol. 2, *North Pacific Ocean.* NAVAIR 50-1C-529, Government Printing Office, 388 pp.

Dorman, C. E., and R. H. Bourke, 1979: Precipitation over the Pacific Ocean, 30°S to 60°N. *Mon. Wea. Rev.,* **107,** 896-910.

——, and ——, 1981: Precipitation over the Atlantic Ocean, 30°S to 70°N. *Mon. Wea. Rev.,* **109,** 554-563.

Georgi, D. T., and J. M. Toole, 1982: The Antarctic Circumpolar Current and the oceanic heat and freshwater budgets. *J. Mar. Res.,* **40**(Suppl.), 183-197.

Hoyt, D. V., 1976: The radiation and energy budgets of the earth using both ground-based and satellite-derived values of total cloud cover. NOAA TR ERL 362-ARL-4, 124 pp.

Hubert, L. F., A. F. Krueger and J. S. Winston, 1969: The double intertropical convergence zone—Fact or fiction? *J. Atmos. Sci.,* **26,** 771-773.

Jacobs, W. C., 1951: The energy exchange between sea and atmosphere and some of its consequences. *Bull. Scripps Inst. Oceanogr.,* **6,** 27-122.

——, 1968: The seasonal apportionment of precipitation over the ocean. *Yearbook, Assoc. Pac. Coast Geogr.,* **30,** 63-78.

Kilonsky, B. J., and C. S. Ramage, 1976: A technique for estimating tropical open-ocean rainfall from satellite observations. *J. Appl. Meteor.,* **15,** 972-975.

Meserve, J. M., 1974: *U.S. Navy Marine Climatic Atlas of the World,* Vol. 1, *North Atlantic Ocean.* NAVAIR 50-1C-528, Government Printing Office, 371 pp.

Miller, D. B., and R. C. Feddes, 1971: *Global Atlas of Relative Cloud Cover, 1967-1970.* U.S. Dept. of Commerce and U.S. Air Force, Washington, DC, 237 pp.

Naval Weather Service Detachment, 1976: *U.S. Navy Marine Climatic Atlas of the World,* Vol. 3, *Indian Ocean.* NAVAIR 50-1C-530, Government Printing Office, 348 pp.

——, 1978: *U.S. Navy Marine Climatic Atlas of the World,* Vol. 4, *South Atlantic Ocean.* NAVAIR 50-1C-531, Government Printing Office, 325 pp.

——, 1979: *U.S. Navy Marine Climatic Atlas of the World,* Vol. 5, *South Pacific Ocean.* NAVAIR 50-1C-532, Government Printing Office, 350 pp.

Quayle, R. G., 1974: A climatic comparison of ocean weather station and transient ship records. *Mar. Wea. Log,* **18,** 307-311.

Reed, R. K., 1979: On the relationship between the amount and frequency of precipitation over the ocean. *J. Appl. Meteor.,* **18,** 692-696.

——, 1980: Comparison of ocean and island rainfall in the tropical North Pacific. *J. Appl. Meteor.,* **19,** 877-880.

——, 1982: Reply. *J. Appl. Meteor.,* **21,** 114-115.

——, and W. P. Elliott, 1977: A comparison of oceanic precipitation as measured by gage and assessed from weather reports. *J. Appl. Meteor.,* **16,** 983-986.

——, and ——, 1979: New precipitation maps for the North Atlantic and North Pacific oceans. *J. Geophys. Res.,* **84,** 7839-7846.

Seguin, W. R., and P. Sabol, 1976: GATE convection subprogram data center: shipboard precipitation data. NOAA TR EDS-18, 73 pp.

Tucker, G. B., 1961: Precipitation over the North Atlantic Ocean. *Quart. J. Roy. Meteor. Soc.,* **87,** 147-158.

Warren, B. A., 1982: Why is no deep water formed in the North Pacific? *Trans. Amer. Geophys. Union,* **63,** 985 (abstract).

Wright, C., and R. K. Reed, 1981: Comparison of ocean and island rainfall in the tropical South Pacific, Atlantic, and Indian Oceans. NOAA TM ERL PMEL-25, 17 pp.