

Equatorial Atlantic Rain Frequency: An Intercentennial Comparison

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(Manuscript received 17 May 2002, in final form 23 January 2003)

ABSTRACT

Analyses of the frequency of rain occurrence over the equatorial Atlantic Ocean from two sources are compared: a nineteenth-century journal publication based on ship's logbook entries, and a 3-yr average, 1998–2000, of observations from the precipitation radar aboard the Tropical Rainfall Measuring Mission satellite observatory. The sources agree remarkably well on the position and shape of the equatorial maximum, with a correlation coefficient of 0.99. However, the magnitudes differ by about a factor of 2, with the modern estimate being lower. This disparity is likely to be attributable to characteristics of the observing systems. The radar sensitivity and scanning characteristics combine to underestimate rain occurrence. The precise nature of the nineteenth-century sources are not documented; however, they almost certainly have been incorporated into the Comprehensive Ocean–Atmosphere Data Set (COADS).

1. Introduction

The collection and analysis of weather data over the oceans has progressed steadily over the centuries, the primary sources of information evolving from descriptive observations recorded by humans aboard merchant and military ships to measurements of visible, infrared, and microwave radiation from sensors aboard meteorological satellites. An overview of the vast international body of scientific literature on the subject is far beyond the scope of this paper. However, the remainder of this section touches briefly on a limited number of contributions that track the historical progress of rain observations over the oceans, especially those that are relevant to the Atlantic intercentennial comparison presented below.

The maritime nations of the world have held a long interest in mapping and understanding weather patterns over the global oceans to benefit their commercial interests and national security. From the scientific point of view, mid-nineteenth-century investigators clearly understood the fundamental role of latent heating of the atmosphere during the formation of equatorial rains in the maintenance of tropical wind systems (e.g., Maury 1861). The contributions of Maury, his contemporaries, and predecessors, were remarkable, as they synthesized sparse and irregular data from ship's logbooks into coherent descriptions of the trade wind systems of the world's oceans. Maury, superintendent of the U.S. Naval Observatory and Hydrographic Office, also commented

extensively on the equatorial doldrums, where the observed heavy rain and persistent cloudiness gave rise to the term “equatorial cloud ring” (cf. Maury 1861, paragraph 514, p. 276). He was an important contributor to the Conference of Maritime Nations at Brussels, Belgium, in 1853, where discussions on the subject of international cooperation in marine meteorology led to the development of a uniform system for recording meteorological observations at sea. Although observations of rain recorded aboard ships remained qualitative, nineteenth-century scientists made quick use of these improved records to refine knowledge of oceanic precipitation patterns and to develop theories for the observed distributions (e.g., Loomis 1882).

Elias Loomis, professor of natural history and astronomy at Yale University from 1860 to 1889, made perhaps the earliest published estimate of the climatological pattern of rain over the world's oceans (Loomis 1882). As part of his study, Loomis listed a survey of precipitation observations at 713 stations worldwide and noted that Ascension Island in the South Atlantic reported an annual rainfall of less than 100 mm. In an effort to understand whether the cause for this low amount was due to local orographic effects or to large-scale atmospheric circulation patterns, he acquired records of rain occurrence observations recorded in ship's logs as they journeyed across the equatorial Atlantic Ocean. Loomis's tabulated result from the ship's log information is one source in the intercentennial comparison presented below.

By the late twentieth century the qualitative shipboard weather observations of rain occurrence had been utilized to develop several quantitative estimates of ocean

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rainfall patterns (Tucker 1961; Dorman and Bourke 1981; Jaeger 1983; Legates and Wilmott 1990). The most extensive long-term marine database currently available, the Comprehensive Ocean–Atmosphere Data Set (COADS; Woodruff et al. 1987), has been developed from weather observations from voluntary observing ships, providing an invaluable record for studies of climate and its variability (e.g., Pan and Oort 1990; Petty 1995; Dai 2001).

The most recent half-century has seen rapid technological advances in remote sensing and satellite meteorology, providing meteorologists with unprecedented details in patterns of cloudiness and precipitation over the previously sparsely sampled oceans. Kornfield and Hasler (1969) composited global maps of high-resolution visible imagery for the calendar year of 1967, showing detailed information on cloudiness and the inter-tropical convergence zones of the world's oceans. Rao and Theon (1977) utilized data from the Electrically Scanning Microwave Radiometer (ESMR) aboard the *Nimbus-5* satellite to discriminate between precipitating and nonprecipitating clouds and to derive oceanic rainfall maps, revealing new patterns of oceanic rainfall.

Weather satellites in geostationary orbit, such as the Geostationary Operational Environmental Satellites (GOES), now monitor oceanic cloudiness patterns around the clock and around the world. Perhaps the most widely used estimator of oceanic rainfall in use today is the GOES Precipitation Index (GPI; Arkin and Meisner 1987). The GPI was originally derived from a comparison of cloud-top temperatures observed by satellite infrared sensors to rainfall-rate estimates based on surface-based radar observations during the Global Atmospheric Research Program's (GARP) Atlantic Tropical Experiment (GATE; Richards and Arkin 1981). GATE was conducted over the equatorial Atlantic Ocean during 1974.

The first spaceborne precipitation radar (PR) was launched into a low earth orbit aboard the Tropical Rainfall Measuring Mission (TRMM) satellite in November 1997. The TRMM orbit was designed to sample rain over the tropical regions with a special emphasis on tropical oceans (Simpson et al. 1988). The TRMM PR was designed to distinguish between precipitating and nonprecipitating clouds, to measure the vertical structure of precipitating hydrometeors within cloud systems, and to provide quantitative estimates of rainfall rate (Kozu et al. 2001). The TRMM program is providing weather and climate analysts and modelers with a wealth of new information on oceanic rainfall (Kummerow et al. 2000). The TRMM PR is now into its sixth year of successful operations, having completed its design life of 3 yr near the end of the year 2000.

This paper presents a comparison of climatological patterns of rain occurrence over the equatorial Atlantic Ocean from two sources: the TRMM PR during the years 1998–2000, and ship's logbook reports as tabulated by Loomis in his 1882 publication.

2. Data

In 1882 Elias Loomis published his sixteenth paper in a series of 23 "Contributions to Meteorology" in the *American Journal of Science*. The 1882 paper includes a table titled "Rains on the Atlantic Ocean from 20° to 30° West Longitude." The table columns are for each of the 12 months of the year and the rows are for 2° intervals of latitude from 20°N to 10°S, except for 10°N to the equator where the intervals are 1° in latitude. There is precious little information on the source of Loomis's data except for the following statement: "This table is derived from a work entitled 'Meteorological Data,' published by authority of the Meteorological Committee of the Royal Society of London, and the figures represent the number of rains corresponding to a hundred observations of the wind reported in the logbooks examined." Thus, the table entries can be interpreted as the percent occurrence of rain over the equatorial Atlantic Ocean. This sector of the equatorial Atlantic Ocean, just west of Ascension Island, has been well traveled for many centuries (see, e.g., Pan and Oort 1990, their Fig 1). The data that was used to construct the table has almost surely been incorporated into the COADS database.

The PR aboard the TRMM observatory is the first radar in earth orbit designed to measure rainfall rate (Kozu et al. 2001). With a minimum detectable signal of about 17 dBZ, the PR can detect rainfall rates as low as 0.42 mm h⁻¹ assuming a first-guess *Z–R* relation of $Z = 200R^{1.6}$. The PR has a horizontal resolution of 4.3 km at nadir, a cross-track scan that is about 220 km wide with 49 fields of view (FOVs), and a vertical resolution of 250 m. Operating at a frequency of 13.8 GHz, the PR has the capability to detect isolated rain showers, such as precipitating trade wind cumulus (Short and Nakamura 2000) and to map large-scale precipitation systems.

The TRMM Science Data Information System (TSDIS) produced the PR data analyzed in the present study, using standard TRMM algorithms (e.g., Iguchi et al. 2000). Product 3A25 contains monthly summaries of PR statistics within latitude–longitude boxes that are 0.5° × 0.5°. The statistics include the total number of PR FOVs, the number of PR FOVs with rain indicated in the near-surface range bin, and the average rainfall rate when raining. These statistics were used to compute the percent occurrence of rain and total annual rainfall across the equatorial Atlantic Ocean for the years 1998–2000 and for the same latitude–longitude sectors tabulated by Loomis (1882).

3. Results

Figure 1 shows the annually averaged probability of rainfall occurrence observed by the TRMM PR for the 3-yr period from 1998 to 2000 over a domain from 30°S to 30°N and 90°W to 30°E. A maximum of just over

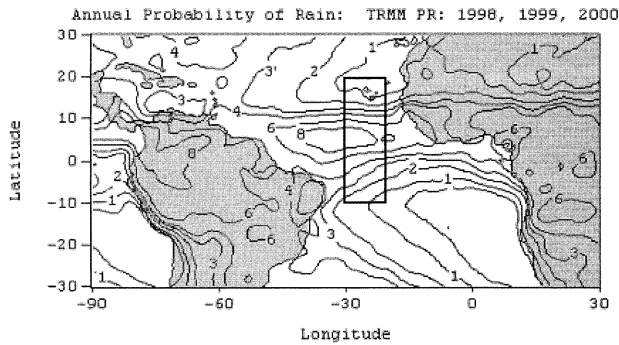


FIG. 1. Annual probability of rain occurrence observed by the TRMM PR for the 3-yr period of 1998, 1999, and 2000. A rectangle bounds the region from 20°N to 10°S, between 20° and 30°W.

8% occurs over the equatorial Atlantic Ocean at about 5°N, with minima of less than 1% to the north and south. The maximum is associated with the intertropical convergence zone (ITCZ), where the northeasterly trade winds of the Northern Hemisphere clash with the southern trade winds of the Southern Hemisphere. The minima are associated with regions of large-scale descent in the atmosphere, which suppresses atmospheric convection and rainfall. A rectangle bounds the region from 20°N to 10°S, between 20° and 30°W, the region of special interest below.

Figure 2 shows north–south profiles of annual rain occurrence as observed by the TRMM PR and as tabulated by Loomis (1882) for the equatorial Atlantic sector from 20°N to 10°S and 20° to 30°W. Data points from both sources are at intervals of 1° of latitude from 10°N to the equator and 2° elsewhere. The ship observations show rain occurrences that are twice as large as those observed by the TRMM PR. A discussion of probable causes for the discrepancy will be presented in the next section.

Figure 3 shows the data from Fig. 2 replotted with double y axes. By rescaling the data it becomes readily apparent that the shape and location of the near-equatorial maximum in rainfall occurrence is virtually identical for the two data sources. Note that the scale for the modern source (TRMM PR) is exactly 0.5 that for the ship observations.

The latitudinal profiles of rainfall probability shown in Fig. 3 have similar asymmetries, although their magnitudes differ by a factor near 2. From the maxima near 5°N they both show lower minima to the north than to the south. The asymmetry is related to the large-scale pattern of rain occurrence seen in Fig. 1. The northern end of the analysis domain (see rectangle) is directly within the minimum just west of northern Africa. The southern end of the domain is west of the minimum near the west coast of southern Africa. The equatorial maximum broadens southward toward South America, contributing to the asymmetry.

Figure 4 shows a scatter diagram of the Loomis and TRMM PR rainfall probabilities versus each other and

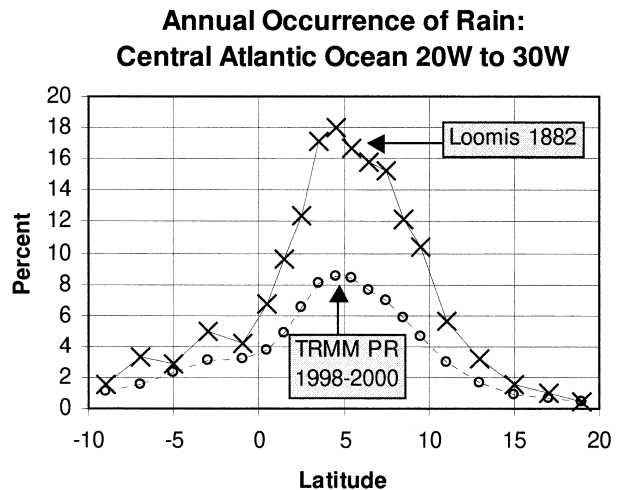


FIG. 2. South–north profile of rain probability (%) over the equatorial Atlantic Ocean (20°–30°W) as tabulated from ship observations by Loomis (1882) and as measured by the TRMM PR for the years 1998–2000.

the best-fit linear regression line. More than 98% of the variance of Loomis's results are explained by the TRMM PR data with an intercept of less than 1% and a slope near 2. The high correlation is surprising, and may be fortuitous, given the vast separation of the data sources, both in time and observing technology. Such a finding warrants further investigations of the correspondence between TRMM PR observations of rain and those recorded by shipboard observers.

Loomis (1882) tabulated his data at monthly intervals, charting the annual migration of the near-equatorial

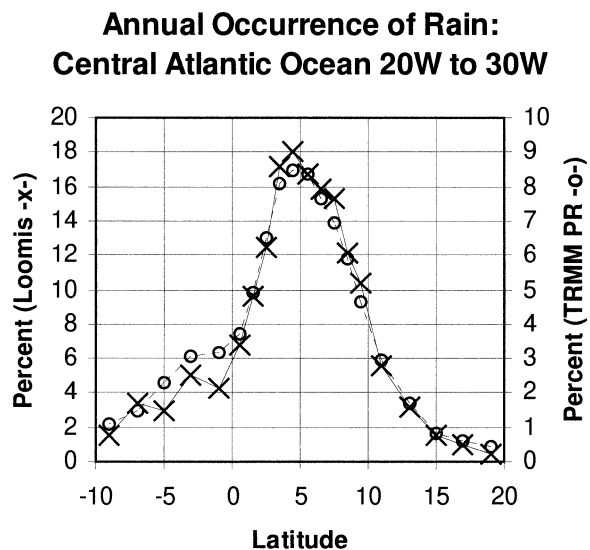


FIG. 3. Annual probability of rain occurrence observed by the TRMM PR within the rectangle in Fig. 1 for the 3-yr period of 1998, 1999, and 2000, vs data for the same region tabulated by Loomis (1882). Note the separate y-axis scales for the radar and ship observations.

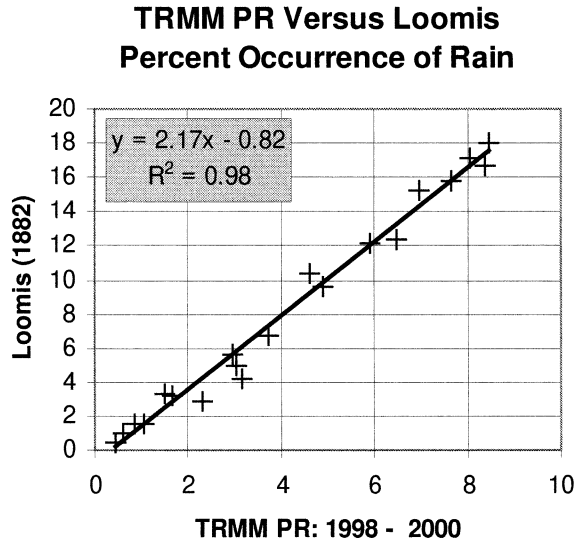


FIG. 4. Scatter diagram of the annual probability of rainfall measured by the TRMM PR (for the years 1998, 1999, and 2000) and estimated by Loomis (1882). Data points are the same as in Figs. 2 and 3; 20 lat intervals from 20°N to 10°S within the 10° lon sector between 20° and 30°W.

maximum of rain occurrence through the course of the year. Table 1 gives the square of the monthly correlation coefficients between rain occurrence probabilities from the TRMM PR and those tabulated by Loomis (1882), indicating that the agreement between the two climatologies over the course of the annual cycle is also quite high. The correlation with the annual average latitudinal profile is higher than any of the individual months because random, uncorrelated sampling fluctuations from month to month are smoothed over in both data sources.

A measure of the statistical significance of the correlations indicated in Table 1 can be calculated by using an analysis of variance method (Panofsky and Brier 1968). The F statistic, $r^2(N - 2)/(1 - r^2)$, where r is the correlation and N is the number of independent data points, for $r^2 = 0.72$ and $N = 20$ yields 46.3, a value that is significant beyond the 99% level for the lowest correlation in Table 1. Even if the number of independent samples is assumed to be much lower due to the spatial structure and persistence of the ITCZ, the statistical significance in the correlations still appears to be quite high.

4. Discussion

The high correlation shown in Fig. 4 between latitudinal profiles of rain occurrence over the equatorial

Atlantic Ocean from two disparate sources is somewhat surprising. Nevertheless, the magnitudes of rain occurrence differ by a factor of 2, with the modern estimate being lower. The discrepancy in magnitude could be due to a number of factors. Among these are (i) ship-reporting procedures, (ii) PR characteristics, (iii) a climatic change in rainfall occurrence. Brief discussions of the potential effects of these factors are given below along with quantitative estimates, when possible.

a. Ship-reporting procedures

It is likely that the rain data tabulated by Loomis represents prevailing conditions over the interval of time between observations. The sources cited by Loomis could have been hourly or perhaps every 4 h, the standard duration of a “watch” aboard ships. His lack of specificity in describing the data suggests a mixture of reporting frequencies. The uncertainty in the nature of the observations is one type of problem discussed by Wright (1986) as affecting detection of climatic variations from ship observations. Furthermore, standardization of weather-reporting procedures aboard ships had only just begun in the mid-nineteenth century. Petty (1995) cites climatologies of ocean precipitation frequency that include past precipitation reports (precipitation during the past hour but not at the time of observation) to offset a perceived under reporting of precipitation (U.S. Navy 1974). Loomis’s documentation of his data source refers to the number of observations of rain per 100 observations of the wind. If each ship observation of rain occurrence indicates prevailing conditions over some interval of time, the reporting of rain occurrence relative to an instantaneous measure would be increased. On the other hand, Houze and Cheng (1977) found that large-scale systems dominated the areal coverage by precipitation over the Atlantic ITCZ during GATE. The ship-reporting procedures would be less effective in increasing rainfall occurrence statistics in the ITCZ where large-scale systems predominate.

b. PR characteristics

The PR operates at a frequency of 13.8 GHz, suffering from substantial attenuation in heavy tropical rains. However, the rain-profiling algorithm automatically corrects for attenuation (Iguchi et al. 2000). Furthermore, complete attenuation of the radar signal is very rare, requiring a 5-km path of rainfall rate exceeding 80 mm h^{-1} . The PR does have several characteristics that are likely to affect its estimate of rain occurrence. These

TABLE 1. Square of the monthly correlation between TRMM PR and Loomis precipitation probabilities for the same lat–lon points indicated in Figs. 2 and 3.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
r^2	0.84	0.86	0.72	0.89	0.92	0.95	0.95	0.87	0.87	0.94	0.95	0.73

are (i) spatial resolution, (ii) sensitivity, and (iii) surface clutter.

1) SPATIAL RESOLUTION

With a horizontal resolution of 4.3 km, the PR FOV has the potential for overestimating the occurrence of rain, depending on the typical size of rain cells. For comparison with rain occurrence observations from moving ships, the PR FOV represents an effective time-scale, dependent of the ship's speeds. These factors would tend to increase the PR estimates relative to the ships. However, the predominance of large-scale systems reported in the ITCZ by Houze and Cheng (1977) would tend to mitigate PR FOV effects in increasing rainfall occurrence statistics.

2) SENSITIVITY

The PR sensitivity of 17 dBZ corresponds to a rainfall rate of about 0.4 mm hr^{-1} , just above the threshold of light rain and in the range of heavy drizzle. The degree to which this sensitivity threshold will result in an undersampling of rain occurrence depends on the relative frequency of rainfall rates below the threshold. For example, in a study of rainfall occurrence in the United Kingdom by human observers and rain gauges it was found that the observers reported a 63% higher incidence than the gauges when the gauge measurements were truncated at 0.5 mm hr^{-1} (Adler et al. 2001), even though drizzle was omitted from the observer's records. However, the rainfall rate climatology over the equatorial Atlantic is likely to differ substantially from that over the United Kingdom, as Loomis's analysis domain straddles the heavy rainfall regime of the ITCZ with trade wind cumulus and marine stratocumulus regimes both north and south.

Nevertheless, Schumacher and Houze (2000) reported that the PR missed 46% of near-surface rainfall occurrences over a Pacific ITCZ site due to the 17-dBZ cutoff. Also, Cheng and Houze (1979) reported that approximately 40% of GATE precipitation fell from mesoscale regions where the radar echoes were nearly horizontally uniform and varied slowly with intensities significantly less and areas much larger than the convective regions. This suggests that the PR may have missed a substantial fraction of rainfall occurrences in large-scale ITCZ systems due to its lack of sensitivity.

3) SURFACE CLUTTER

The PR is most effective in detecting rain in the nadir-viewing position, where the radar pulse volume is nearly parallel to the surface. Detection of precipitation echoes can be made within one range gate of the surface. However, as the beam scans from side to side the off-nadir FOVs are affected by interactions between the edge of the main beam and the surface, contaminating several

range gates above the surface, and limiting the PR's ability to detect shallow precipitation. Short and Nakamura (2000) have estimated that the overall occurrence of rain is underrepresented by about 25%, because the rainfall retrieval algorithms are designed to avoid surface contamination effects (Iguchi et al. 2000). As a result, shallow rain cells are less likely to be detected as the radar scan angle progresses from nadir to a maximum of 17° . Rainfall accumulation is much less sensitive to this problem because the missing shallow rain cells tend to have relatively low rainfall rates (Short and Nakamura 2000).

c. A climatic change in rain occurrence

A recent study of COADS data has shown that the Atlantic ITCZ undergoes only slight interannual variation in position, pressure minimum, and convergence maximum (Machel et al. 1998). Dai (2001) has also documented the frequency of rainfall occurrence over the world's oceans from the COADS dataset for the last half of the twentieth century, with images showing Atlantic ITCZ patterns that are consistent with Loomis's results. The high correlation shown in Fig. 4 and the latitudinal profiles shown in Figs. 2 and 3 indicate that the position of the Atlantic ITCZ was virtually the same in the late nineteenth century as it was at the end of the twentieth century, consistent with the comprehensive studies cited above. The difference in rainfall occurrence between the two sources utilized in the present study is not likely to be accounted for by climatic change.

5. Summary and conclusions

A correlation of 0.99 has been found between latitudinal profiles of annual rain occurrence over the equatorial Atlantic Ocean from two vastly different sources: a climatological analysis of ship's logbook entries published in the late nineteenth century (Loomis 1882) and TRMM spaceborne radar observations for the years 1998–2000. The location and shape of the rainfall maximum associated with the Atlantic ITCZ is virtually identical in the two sources despite the disparities in time and technology.

However, the magnitude of rain occurrence differs by about a factor of 2, with the modern estimate being lower. A qualitative consideration of potential factors affecting the magnitudes suggests that they would tend to contribute to the disparity. Among the factors considered were the ship's reporting procedures, radar characteristics such as resolution, sensitivity and surface clutter, and last, climatic variability. The major factors appear to be the PR surface clutter filter, resulting in an underreporting of rain occurrence that may be as high as 25% and the PR sensitivity cutoff of 17 dBZ that may miss 40% or more of surface rainfall occurrences. These two factors would increase the PR rainfall re-

porting by a factor of 1.75. The difference in rain occurrence remains an outstanding unresolved issue; although the majority of relevant factors would tend to decrease the radar-based estimates and increase those recorded in ship's logbooks.

Nevertheless, the fidelity demonstrated in this comparison lends further credence to the utility of historical records from ship's logbooks in depicting climatological features over the sparsely sampled oceans (e.g., Garcia et al. 2001). Further investigations may allow a calibration of the historical sources with the modern record.

Acknowledgments. Dr. Benjamin Kedem generously provided the historic reference to Prof. E. Loomis's work. This study is supported through the TRMM Science Team under the NASA Headquarters TRMM Program Scientist Dr. Ramesh Kakar.

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