HOW OFTEN DOES IT REALLY RAIN?

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Hourly precipitation observations at 0.25° allow much improved estimates of the frequency of rain or snow. Precipitation occurs 11% of the time, but only 8% of the time over land.

The perceptions about whether a place is a nice place to live often depend on how sunny it is or how often it rains (or snows). The latter relates to how dreary the weather appears, and it is the duration much more than the amount that clouds perceptions. For instance, in Seattle in winter it rains a lot, but much of the rainfall is quite light. It has given Seattle a reputation for being a rainy city. In fact, a friend who grew up in Seattle had a joke that asks "How can you tell that it is summer in Seattle?" The answer: "The rain is warmer." Now this is quite unfair, as summer in Seattle can be quite dry and sunny, but it illustrates the point. Of course, the precipitation amount matters a lot more for vegetation and farming than frequency or duration of precipitation and is certainly a vital metric of climate. Nevertheless, the intermittent nature of precipitation means that it is important to quantify not just the amount, but also the frequency and duration of events, and the intensity of precipitation when it occurs. The intensity likely relates most strongly to risk of flooding, especially when sustained over many hours. Further, it is the amount that relates mostly to changes in energy availability, while frequency and intensity change mostly with temperature (via Clausius–Clapeyron). Changes in frequency and intensity are larger and more robust aspects of climate change (Trenberth et al. 2003).

The main statistics available for precipitation are for amount. This is because rain gauges are easy to deploy in many places. These are really fancy buckets, designed to catch the precipitation over the past day, and produce a single value once per day. Most farmers keep track of such information as it is vital for their management of irrigation and fertilizer. But these data do not tell us much about the real frequency of precipitation, because it seldom rains all day, and even if it does, the rate varies. In a consummate study, Dai (2001) used synoptic reports to determine daily frequencies of precipitation and its character, while Sun et al. (2006) analyzed precipitation frequency and intensity and number of rainy days, but using only daily data. Herold et al. (2016) examined precipitation amount and number of wet days over major land areas of the globe based on several observational, reanalysis, and model daily products and demonstrated a large disparity among the products. Hourly values of precipitation are increasingly becoming available,

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and these are much more in step with the needs to assess the lifetime and frequency of storms and rain or snow events.

One of the great myths is Noah's flood. The tale of this flood occupies chapters 6–8 of the Book of Genesis in the Bible (Silverman 2013). Noah, of course, built an ark to save certain animals and his family. Is it possible to have rain for 40 days and 40 nights? Can it rain everywhere at the same time? Certainly, the answer to these two questions together is no. Where does the moisture come from? From a science perspective, we have to deal with the hydrological cycle. The evaporation of moisture from especially the oceans provides the main source of the moisture for storms that produce the precipitation. Typical evaporation rates are 1–5 mm day^{-1}, and hence it might be possible to have continuous rain at those same rates: what goes up must come down, except that the phenomena that produce precipitation do not work that way (Trenberth et al. 2003). Instead, storms reach out and gather in moisture from surrounding areas, concentrate it, and dump it down, typically at much higher rates that can easily exceed 3 in. day^{-1} (75 mm day^{-1}). This 3-in. threshold is our rule of thumb for when local flooding occurs.

Of course, the odds of obtaining precipitation in a grid square increase as the time is extended, and daily values are quite inadequate to analyze the true frequency of precipitation, while 3-hourly values are not bad. In other words, the duration of precipitation events often exceeds 3 h but not a day (see Trenberth et al. 2017). Recently, a new dataset of precipitation (see "Datasets and methods" section) has become available at hourly resolution that allows us to better answer these kinds of questions: How often does it precipitate? How often does it precipitate above a certain threshold? The dataset is for 60°N–60°S, which we refer to as near global.

As we show here, globally at 0.25° resolution, it does not perceptibly rain or precipitate 89% of the time, or equivalently, it is precipitating on average over 11% of the global area. Actually, these are not true global numbers as they pertain to the region 60°N–60°S, and they depend on the threshold used for detectable precipitation. Here we use 0.02 mm h^{-1} for the moment (discussed below). Hence, the average precipitation rate, when it occurs, is about 9 times the average evaporation rate. In other words, in order to supply the moisture to the weather system, each system has to reach out to embrace an area 9 times the area of the precipitation in order to sustain the precipitation. This simple calculation assumes precipitation at the lowest threshold, whereas if a more typical value for moderate rain of 0.2 mm h^{-1} is used, the factor is about 15.

Moreover, these numbers include both land and ocean, and since we may be more interested in land, where we live, the values are 8% and an area 12 times as big as the precipitating area, or for the moderate rain, 5% and 20 times the area. Alternatively, we can take the square root of the areal dimension and convert it to a linear average radius of the supply area versus the precipitation area: in general, the radius of the supply area ranges from a factor of 3 globally to 3.5 for land, or for moderate rates the factors are 4 globally and 4.5 for land. All of these aspects are detailed below, following the description of the datasets and methods in the next section.

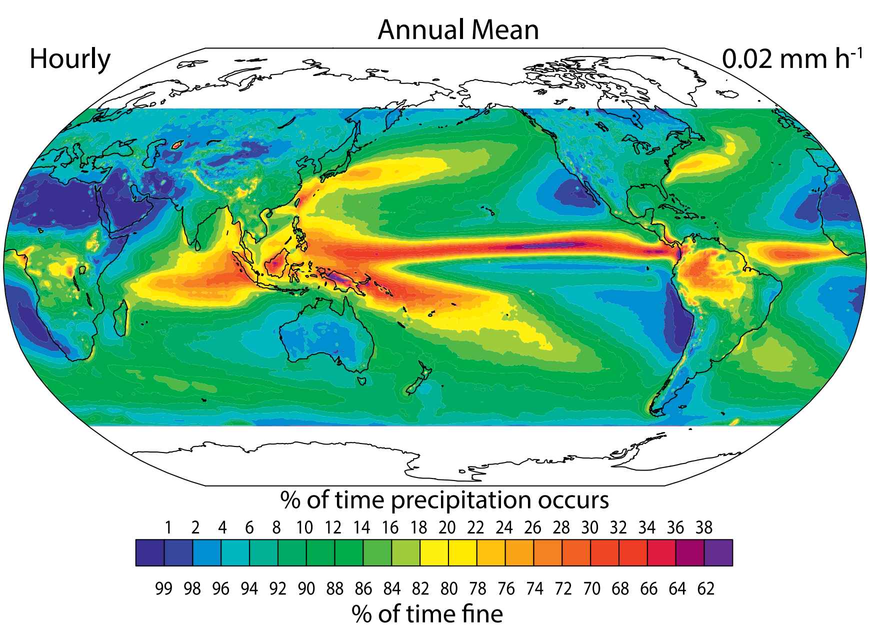

Fig. 1. Annual mean of the percentage time precipitation occurs above or below a given threshold of 0.02 mm h^{-1} for hourly data.

DATASETS AND METHODS. Observational datasets have evolved, and the latest generations of Climate Prediction Center morphing technique (CMORPH) version 1.0 bias corrected (CRT) and Tropical Rainfall Measuring Mission (TRMM) 3B42v7 have all been bias corrected using ground-based stations or Global

Precipitation Climatology Project (GPCP; Huffman et al. 2009) products, generally with great improvements (Maggioni et al. 2016; Gehne et al. 2016; Xie et al. 2017). The new and much improved CMORPH global high-resolution precipitation estimates (Xie et al. 2017) begin in 1998, and we use them at hourly resolution for 60°N–60°S. Issues remain in winter over land because of snow, but careful evaluations show a consistently superior performance over the TRMM-3B42 dataset (Xie et al. 2017). There may also be issues related to fewer observations being available in the earlier part of the record. TRMM values (Huffman et al. 2007) are available only 3-hourly and for a more limited region of 50°N–50°S. We also consider daily amounts, as these are most widely available and have been used in many studies.

Trenberth et al. (2017) have used these datasets to compare results with the National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM) and therefore provide useful validation and commentary on how good the model is and document many aspects of intermittency of precipitation. We considered using the model to infill the high latitudes, but we found that matches across midlatitudes were not satisfactory to provide confidence in the outcome.

The issue of how to compare instantaneous rainfall rates from sensors on satellite instruments, such as those on TRMM, with ground data were addressed by Wolff and Fisher (2008). Sampling errors relate to the 1–3 estimates per day from satellites, and these can explain on the order of 10% of variance of the differences. Substantial issues occur over coastal regions where land versus ocean effects come into play. Saturation of channels brings in biases at high rain rates, making for large differences during heavy rain events. Over ocean, the TRMM Microwave Imager (TMI) can only resolve rates of greater than 0.02 mm h^{-1}, while saturating at greater than 20 mm h^{-1} rates. Hence, very light rain rates are not well known.

So how do we define whether or not it is raining? In reality, a trace is defined as less than 0.01 in. (0.25 mm), and values less than this are not measured in rain gauges. From space, as discussed above, a practical limit for detection of precipitation has proven to be 0.02 mm h^{-1} from instantaneous rates, which would be up to 0.5 mm day^{-1} if continuous at just below that threshold. We therefore use this rate as the lower threshold to determine whether it rains (or, more generally, precipitates) or not. As an aside, many places, like Australia and New Zealand, consider a "wet day" to be one with more than 1 mm, while a "rain day" is one with more than 0.2 mm. Here,

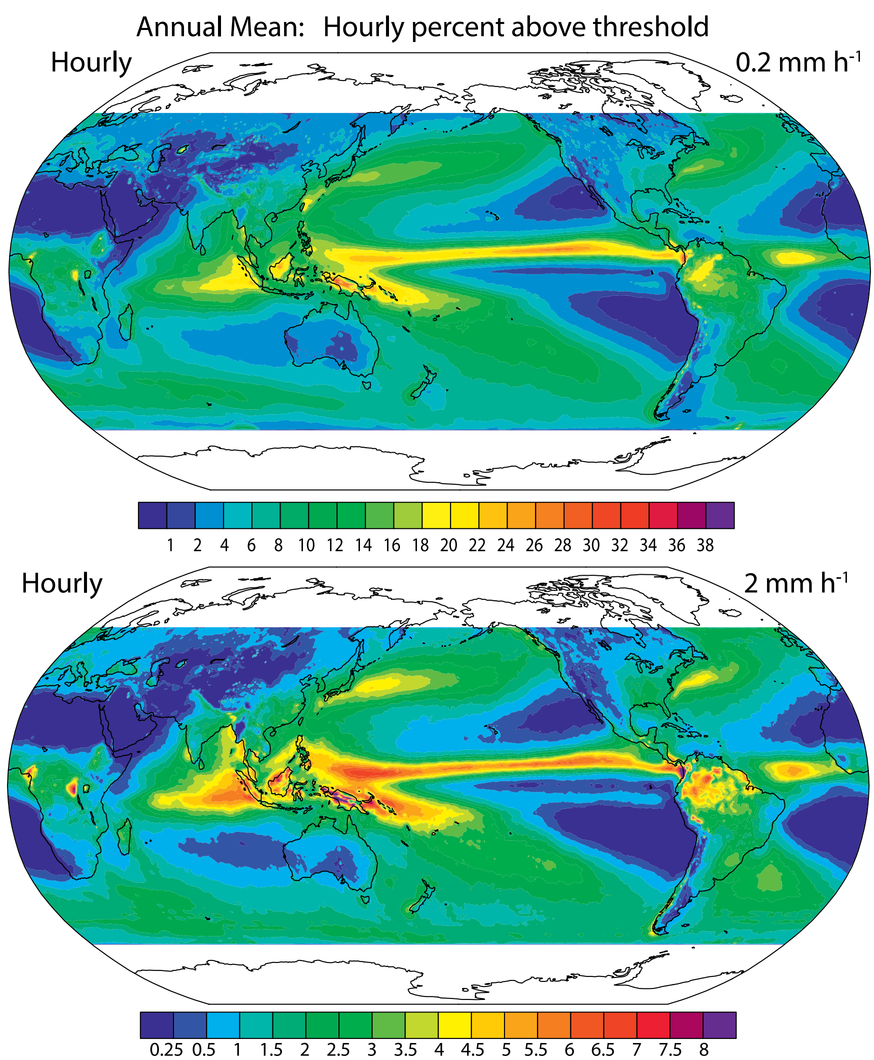

Fig. 2. Annual mean of the percentage time precipitation occurs above a given threshold of (top) 0.2 and (bottom) 2 mm h^{-1} for hourly data.

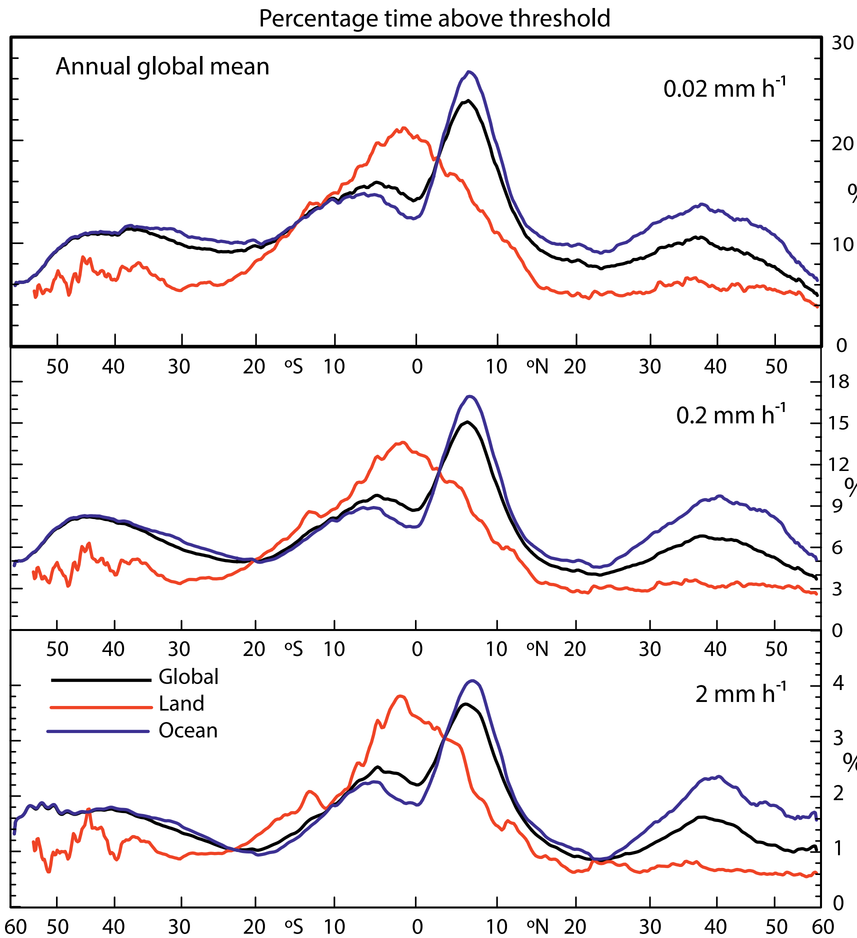

Fig. 3. Zonal mean percentage of time precipitation falls above a given threshold 0.02, 0.2, and 2 mm h^{-1} for the global (black), land (red), and ocean (blue) domains. The axis is sin(latitude) to provide a measure of the area covered by the values.

we focus on three thresholds: 0.02 mm h^{-1} as a light drizzle rate; 0.2 mm h^{-1} as an intermediate rate; and 2 mm h^{-1} as a heavy rate, but not so heavy that it excludes many regions.

The same issue applies to spatial averages. The odds of precipitation at a point are inevitably less than over an area, and the larger the area, the greater the odds are. It is always raining somewhere on the globe, and hence the global frequency is 100%. Here we have chosen to perform most statistics at 0.25° resolution, although we also have values at about 1° resolution, as in Trenberth et al. (2017).

Table 1. The 60°S–60°N global, land-only, and ocean-only fractions of area (mean, SD, and 95th percentile) with CMORPH hourly precipitation rate greater than or equal to 0.02, 0.2, and 2.0 mm h^{-1} during 1998–2013.

Rate		Globe	Land	Ocean
0.02 mm h^{-1}	Mean	11.0	8.2	12.1
	SD	1.1	1.4	1.3
	95th (%)	12.8	10.6	14.1
0.2 mm h^{-1}	Mean	6.9	5.0	7.6
	SD	0.6	0.9	0.8
	95th (%)	7.9	6.5	8.8
2.0 mm h^{-1}	Mean	1.6	1.2	1.8
	SD	0.16	0.24	0.21
	95th (%)	1.9	1.6	2.1

FREQUENCY OF PRECIPITATION OR DRY CONDITIONS.

Figure 1 is the main result and shows the frequency of precipitation above a light drizzle threshold. Therefore, we can also reverse the color bar, and instead of contours of 1%, 2%, 4%, 6%, …, 40% giving the frequency of precipitation, these can also be interpreted as 99%, 98%, 96%, 94%, …, 60% of the time for no precipitation, that is, "fine" weather. In many places, this result is also related to the incidence of sunshine, such as documented for the United States as a solar power resource (Haupt et al. 2016). However, that obviously also depends on latitude and season, and whether it is daytime.

The total amount of precipitation is mostly determined by the frequency rather than the intensity (e.g., Dai 2001), and therefore the geographic patterns of the frequency at different thresholds (Figs. 1, 2) match each other and the total amount (not shown; see Trenberth et al. 2017) quite well. Hence, the highest frequency of precipitation occurs where the highest amounts are recorded, in the tropical convergence zones [intertropical convergence zone (ITCZ) and South Pacific convergence zone (SPCZ)] and monsoon rains, where precipitation occurs more than a quarter of the time at the lowest threshold (Fig. 1). Globally averaged, frequencies are higher over ocean than over land by about 2.5%–4% at light to moderate rates (Table 1, Fig. 3). In Table 1, the assessment is of the percentage of area covered for the given threshold as hourly values, along with a standard deviation (SD) and the 95th percentile, which closely matches that expected for a normal distribution (1.64 × SD). Hence, the SD can be used as an error bar for the mean value to indicate effects of sampling: the global value at the lowest threshold is 11.0% ± 2.2% at the 2-SD level. Figure 3 presents the zonal averages of Figs. 1 and 2 for the total, land, and ocean domains.

The above numbers, computed on an areal basis, also apply to the temporal frequency, and Table 2 gives the global, land, and ocean values for the annual mean as well as each season for not only the hourly data, but also for 3-hourly and daily data, which are mapped in Fig. 4. Seasonal variations (Fig. 5) are small over the global oceans, as increases in one region compensate for losses elsewhere when monsoon rains shift location. There is a more distinctive annual cycle over global land, not surprisingly, since most land is in the Northern Hemisphere. The peak occurs in northern summer when the atmosphere can hold more moisture for all thresholds.

Table 2. Global (60°S–60°N, 0°–360°E) averaged fraction of time (%) during which the CMORPH 0.25° × 0.25° precipitation rate is equal to or greater than the specified threshold for annual (ANN), Dec–Feb (DJF), Mar–May (MAM), Jun–Aug (JJA), and Sep–Nov (SON) of 1998–2013 for hourly, 3-hourly, and daily data.

		ANN	DJF	MAM	JJA	SON
Hourly						
$0.02\ mm\ h^{-1}$	Globe	11.0	10.9	11.0	11.3	11.0
	Land	8.2	7.1	8.1	9.3	8.2
	Ocean	12.1	12.3	12.1	12.0	12.1
$0.2\ mm\ h^{-1}$	Globe	6.9	6.9	6.9	7.0	7.0
	Land	5.0	4.5	4.9	5.6	5.0
	Ocean	7.6	7.7	7.6	7.5	7.6
$2.0\ mm\ h^{-1}$	Globe	1.6	1.6	1.6	1.6	1.6
	Land	1.2	1.1	1.2	1.3	1.2
	Ocean	1.8	1.8	1.8	1.7	1.8
3 hourly						
$0.02\ mm\ h^{-1}$	Globe	13.8	13.5	13.7	14.2	13.8
	Land	10.7	9.1	10.6	12.3	10.7
	Ocean	15.0	15.1	14.9	14.9	14.9
$0.2\ mm\ h^{-1}$	Globe	7.7	7.6	7.7	7.9	7.8
	Land	5.8	5.2	5.7	6.6	5.8
	Ocean	8.4	8.5	8.4	8.3	8.5
$2.0\ mm\ h^{-1}$	Globe	1.6	1.6	1.6	1.6	1.6
	Land	1.2	1.1	1.1	1.3	1.2
	Ocean	1.7	1.8	1.7	1.7	1.7
Daily						
$0.02\ mm\ h^{-1}$	Globe	27.7	26.6	27.7	28.7	27.7
	Land	23.4	19.2	23.1	27.4	23.8
	Ocean	29.2	29.4	29.4	29.1	29.1
$0.2\ mm\ h^{-1}$	Globe	12.8	12.5	12.8	13.1	12.8
	Land	10.4	9.3	10.1	11.8	10.4
	Ocean	13.7	13.7	13.7	13.6	13.7
$2.0\ mm\ h^{-1}$	Globe	0.8	0.8	0.8	0.8	0.8
	Land	0.5	0.6	0.5	0.6	0.5
	Ocean	0.9	0.9	0.9	0.8	0.9

Overall, precipitation occurs 11.0% ± 1.1% (1 SD) of the time—at the threshold of 0.02 mm h^{-1}—or alternatively, 89.0% of the time it is not precipitating (Table 1, Fig. 1). But outside of the ITCZ and SPCZ, where values exceed 30%, the rates are more like 10% or so, and over land where most people live, values are closer to about 8% (Table 1). There are huge areas of deserts, both over land and over the oceans where semipermanent subtropical anticyclones reside, where values are less than 4% (Fig. 1). The dry zone along the equator is mitigated by occasional El Niño events. For the moderate rates of precipitation with a threshold of 0.2 mm h^{-1}, the near-global annual mean is 6.9% and 5.0% over land. For the heavy rains (>2 mm h^{-1}), the near-global mean is 1.6%.

The frequency change in going from hourly to 3-hourly data (Table 2) is modest (11.0%–13.8% global annual mean), but it changes dramatically as daily data are used (27.7%; Table 2, Fig. 4). However, the heavy rain frequency drops from 1.6% of the time for hourly to 0.8% for daily, showing that it is difficult to sustain high rates for more than about 3 h (also 1.6%). Using 3-hourly data we can also compute results for the TRMM dataset, although for a more limited domain (50°N–50°S) and, for the same domain, the CMORPH has 14.4% versus 10.8% for TRMM as the annual near-global mean frequency of precipitation exceeding the light drizzle threshold. Differences are biggest over land. For the moderate-rain threshold, the differences are much smaller, 7.9% versus 6.9% (CMORPH versus

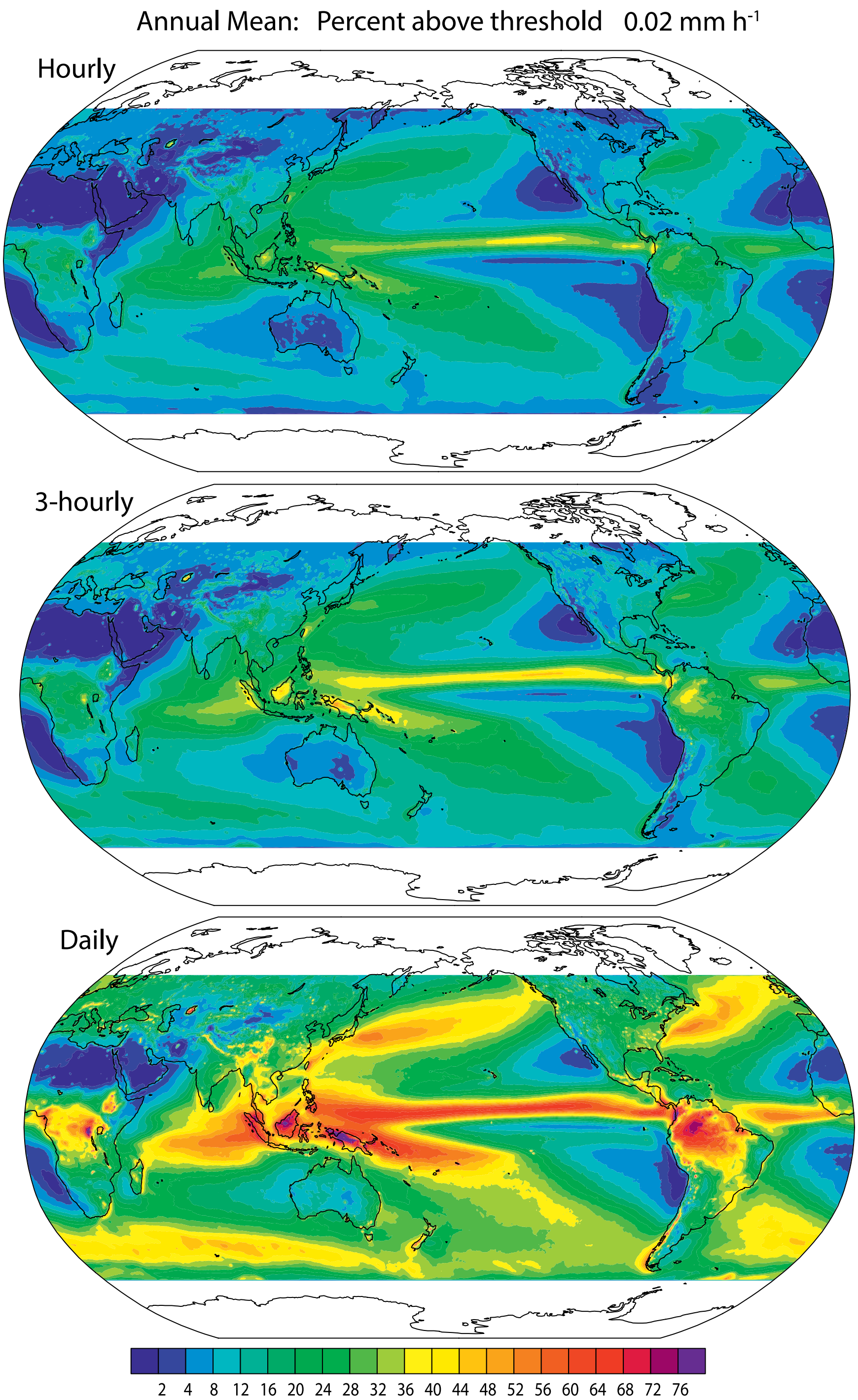

Fig. 4. Annual mean of the percentage time precipitation occurs above a given threshold of 0.02 mm h^{-1} for (top) hourly, (middle) 3-hourly, and (bottom) daily data.

TRMM), and TRMM values are slightly higher for the heavy rain category, 1.7% versus 1.6%. TRMM values are also slightly higher when daily frequency is considered. Although these differences indicate uncertainty, the nature of how the CMORPH versus TRMM retrievals are performed, and the evaluations done so far, lead us to place a lot more weight on the CMORPH values, although uncertainty is large in winter over continents where and when snow occurs. CMORPH uses a tracking of cloud clusters technique at 30-min resolution from geostationary satellites to provide improved continuity in space and time.

When the spatial resolution is increased from 0.25° to about 1° (as used in Trenberth et al. 2017), the CMORPH frequency (50°N–50°S) increases from 14.4% to 19.5% for the light precipitation threshold and from 11.2% to 18.4% over land. For moderate rates, the increase is from 7.9% to 9.3%. This highlights the need to be very explicit in dealing with rain frequency in specifying the resolution in both space and time. Presumably, the true frequency at points is slightly less again, but not by much, owing to the spatial scales and movements of most rain producers.

For major land areas, the annual percentage time it precipitates above the light drizzle threshold (Fig. 6) reveals the huge annual cycles in the tropical monsoon regions and the much lower rates in winter nearly everywhere (some of which may be artificial owing to the snow detection issue). Africa is large enough to include both of the summer monsoons and winter dry periods in each hemisphere. For these regions, precipitation occurs most frequently at 25% of the time annually over Maritime Continent, followed by South America at 13.6%, and least frequently over northern Asia and Australia at around 5.3%–5.4% (Fig. 6). Annual

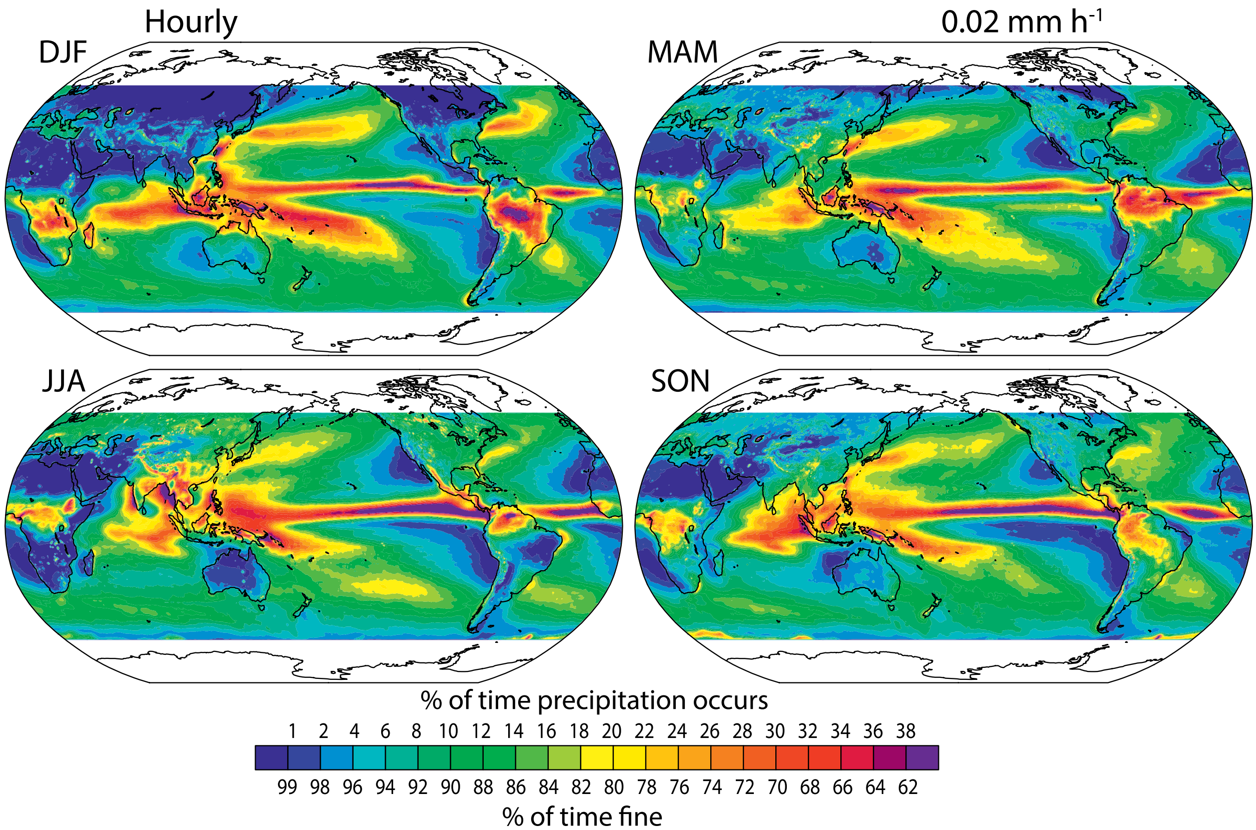

Fig. 5. Seasonal mean of the percentage time precipitation occurs above (or below) a given threshold of 0.02 mm h^{-1} for hourly data.

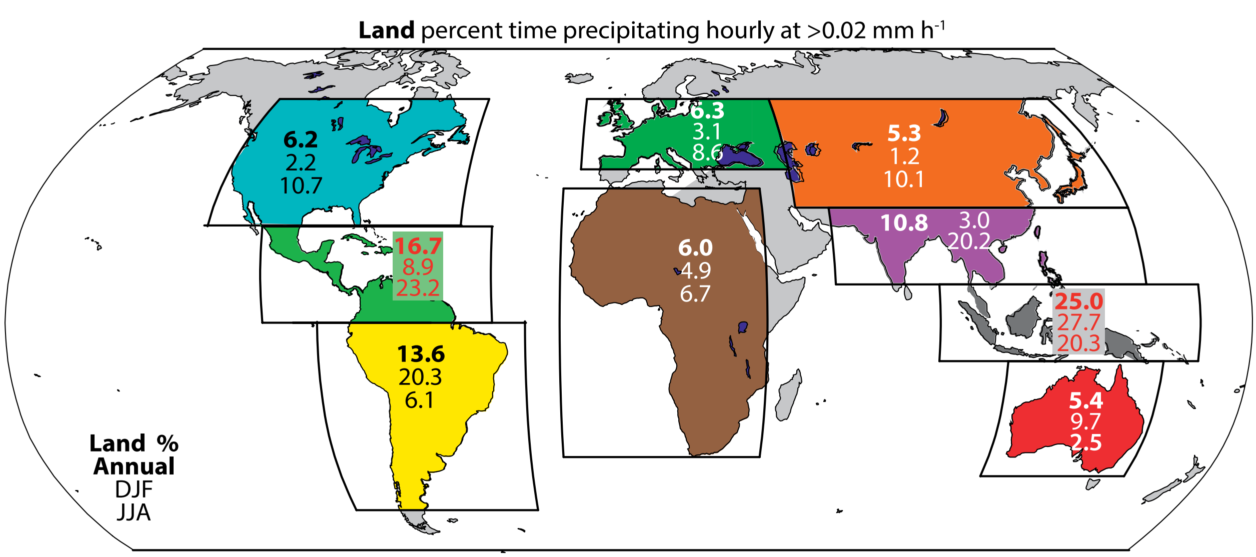

Fig. 6. Land-only averaged fraction of time (%) during which the CMORPH 0.25° × 0.25° hourly precipitation rate is equal to or greater than 0.02 mm h^{-1} for ANN (bold), DJF, and JJA of 1998–2013. The regions are North America: 25°–59°N, 125°–50°W; Central America: 0°–25°N, 110°–40°W; South America: 49°S–0°, 90°–30°W; Europe: 40°–59°N, 15°W–50°E; Africa: 35°S–35°N, 20°W–40°E; South Asia: 10°–30°N, 60°–150°E; north Asia: 30°–59°N, 50°–150°E; Maritime Continent: 10°S–10°N, 90°–165°E; and Australia: 40°–10°S, 110°–155°E.

Table 3. Land-only averaged fraction of time (%) during which the CMORPH and TRMM 0.25° × 0.25° 3-hourly precipitation rate is equal to or greater than 0.06 mm h^{-1} for ANN, DJF, and JJA of 1998–2013. Blue columns are summer in the Northern Hemisphere (JJA), and pink columns are summer in the Southern Hemisphere (DJF). North America (NA): 25°–49°N, 125°–50°W; Europe: 40°–49°N, 15°W–50°E; South Asia (S Asia): 10°–30°N, 60°–150°E; North Asia (N Asia): 30°–49°N, 50°–150°E; Central America (CA): 0°–25°N, 110°–40°W; Maritime Continent (MC): 10°S–10°N, 90°–165°E; Africa: 35°S–35°N, 20°W–40°E; Australia (AU): 40°–10°S, 110°–155°E; South America (SA): 49°S–0°, 90°–30°W.

		NA	Europe	S Asia	N Asia	CA	MC	Africa	AU	SA
ANN	CMORPH	7.6	7.9	11.3	5.7	17.4	26.1	5.9	5.8	14.1
	TRMM	5.5	5.7	7.6	4.3	11.8	16.7	4.8	3.7	9.3
DJF	CMORPH	3.9	5.0	3.2	1.8	9.4	28.9	4.7	10.2	20.9
	TRMM	4.2	3.6	1.7	2.1	6.1	18.3	4.9	6.6	14.0
JJA	CMORPH	10.8	8.0	21.4	9.5	24.6	21.5	6.8	3.1	6.6
	TRMM	7.3	7.1	14.9	7.1	16.4	13.3	4.5	1.7	4.0

precipitation frequency is quite similar in the Maritime Continent region over the ocean areas (24.6%).

To some colleagues, the results in Fig. 6 run counter to expectations, although information even from local studies is hard to find for validation. Kursinski and Mullen (2008) analyzed hourly precipitation using Stage IV (radar) data for the eastern United States, but provided results only for 1 and 5 mm h^{-1} thresholds. Results are very similar at 4-, 16-, and 32-km resolution, and values are greater in summer in general, especially west of the Great Lakes to 105°W. These confirm our earlier results for gridded hourly observations at 2° latitude × 2.5° longitude and 0.1 mm threshold in Trenberth (1998, their Fig. 6) that for most of the United States, except for the far West, there is more frequent precipitation in summer. Paulat et al. (2008) analyzed hourly radar data in Germany with a detection limit at 0.1 mm h^{-1} at 7-km resolution. The frequency of events was higher in winter (10%–20%) than in summer (7%–14%).

As a check on Fig. 6, we performed similar analyses with 3-hourly data from TRMM and CMORPH, but we had to restrict the poleward latitude to 50°. Results for 0.06 mm h^{-1} (as we use 3-hourly, we triple the threshold) are given in Table 3. The CMORPH values are mostly higher than for TRMM, but the pattern is the same: higher values in summer than in winter. The differences indicate substantial uncertainties, and the agreement on the seasonal differences does not mean they are right; remote sensing of snow and precipitation in winter remains a challenge. So here all we can do is report the results and challenge others to improve them.

We also considered various ways to estimate the values poleward of 60° and thus obtain a true global value. However, results have not proven satisfactory. If we simply take the 60° zonal mean values and assume that they apply, then the global mean drops about 1%, from 11% to 10%. However, there is no good reason to expect values over Antarctica and Greenland, where snow is the predominant precipitation, to match those at 60°. Moreover, the precipitation frequency may well be higher (Dai 2001).

CONCLUSIONS. The information provided here as maps and tables gives estimates of how often it perceptibly rains or precipitates, or, turning this around, how often it does not rain. The results certainly depend upon the thresholds used, and there are uncertainties related to whether the sensors and observing system properly measure the rates used. Nevertheless, these results provide a preliminary cut at the topic in hand.

Trenberth (1998) introduced the concepts dealt with here and presented hourly frequencies for a threshold of 0.1 mm, but for a grid size of 2° latitude × 2.5° longitude for the United States based upon gridded station data. The frequency maps relate strongly to amounts in most, but not all, places. The estimates are based upon satellite observations calibrated with ground-based estimates, but these suffer from lack of adequate detection of precipitation in snowy winter conditions, thereby biasing the continental winter estimates low. Not unexpectedly, it rains more often over oceans where water supply is not limited, but even then, there are large subtropical ocean deserts.

The results are quite sensitive to both the spatial scales of the data and its temporal resolution, and it is important to get down to hourly values to gain a proper appreciation of the frequency. Here we used 0.25° gridded data, which likely overestimates values at a point slightly, but not by much, and it provides a realistic way to assess the dreariness of the weather at any location. At 1° resolution values are about 35% higher. At 3-hourly resolution they are about 25% higher, and at daily resolution they are more like 150% higher on average.

The results may also be surprising to some people. The frequency of precipitation over the United States is generally higher in the Southeast, where it exceeds 10% in all seasons. While it gets up to perhaps 15% in the Seattle region in the winter, spring, and fall, it is less than 10% in summer. In between these regions, there are many spots where the frequency is less than 8%, and at times less than 5%. The maps reveal the great arid regions, including the Sahara, Gobi, Syrian, and Australian Deserts, but also with extremely rare precipitation over parts of the ocean off of the west coasts of continents in the subtropics.

The fact that it precipitates only over 11% of the globe at any time demonstrates that the rates of precipitation on average when and where it occurs are 9 times the evaporation rates, or in other words, the area required to feed a precipitating weather system is 9 times the precipitation area through the convergence of moisture. This also highlights the importance of the environmental moisture content, which is largely governed by temperature via the Clausius–Clapeyron equation (see Trenberth et al. 2003). As temperatures rise by 1°C with global warming, the average near-surface moisture holding capacity goes up by about 7%. Thus, in most places where moisture availability is not an issue, such as the oceans and coastal regions, the actual moisture is apt to also go up by this amount, thereby feeding 7% more moisture into any storms or weather systems. Hence, it rains harder, as is observed, or it snows harder, provided that temperatures are cold enough. In reality, other effects modify these expectations somewhat (Trenberth 2011). Temperature increases from human-induced climate change are larger over land than oceans, and thus the relative humidity is likely to drop a bit, reducing somewhat the moisture transport onto land. On the other hand, the extra moisture adds latent heat to the weather system as it is condensed, and often this invigorates storms and can easily double the extra rainfall amounts. Whether this happens or not depends a lot on where the main latent heating and precipitation occurs relative to the storm center, and in hurricanes it directly intensifies storms, while in extratropical storms the influence on intensification is less and it contributes more to changes in motion and development direction of the storm. For thunderstorms, the effect can also be one of adding to intensity.

Therefore, by determining good estimates of the frequency of precipitation with climate variability and change, it is perhaps surprising that we can deduce some consequences for expectations of precipitation extremes. Although the above arguments are heuristic, because the frequencies obviously differ considerably with location and event, and most weather systems are not circular, they provide an excellent rule of thumb and conceptual basis for understanding how often rain falls and how it may change in the future.

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REFERENCES

Dai, A., 2001: Global precipitation and thunderstorm frequencies. Part I: Seasonal and interannual variations. *J. Climate*, **14**, 1092–1111, https://doi.org/10.1175/1520-0442(2001)014<1092:GPATFP>2.0.CO;2.

Gehne, M., T. M. Hamill, G. N. Kiladis, and K. E. Trenberth, 2016: Comparison of global precipitation estimates across a range of temporal and spatial scales. *J. Climate*, **29**, 7773–7795, https://doi.org/10.1175/JCLI-D-15-0618.1.

Haupt, S. E., J. Copeland, W. Y. Y. Cheng, C. Amman, Y. Zhang, and P. Sullivan, 2016: Quantifying the wind and solar power resource and their interannual variability over the United States under current and projected future climate. *J. Appl. Meteor. Climatol.*, **55**, 345–363, https://doi.org/10.1175/JAMC-D-15-0011.1.

Herold, N., L. V. Alexander, M. G. Donat, S. Contractor, and A. Becker, 2016: How much does it rain over land? *Geophys. Res. Lett.*, **43**, 341–348, https://doi.org/10.1002/2015GL066615.

Huffman, G. J., and Coauthors, 2007: The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *J. Hydrometeor.*, **8**, 38–55, https://doi.org/10.1175/JHM560.1.

——, R. F. Adler, D. T. Bolvin, and G. Gu, 2009: Improving the global precipitation record: GPCP version 2.1. *Geophys. Res. Lett.*, **36**, L17808, https://doi.org/10.1029/2009GL040000.

Kursinski, A. L., and S. L. Mullen, 2008: Spatiotemporal variability of hourly precipitation over the eastern contiguous Unites States from Stage IV multisensory analyses. *J. Hydrometeor.*, **9**, 3–21, https://doi.org/10.1175/2007JHM856.1.

Maggioni, V., P. C. Meyers, and M. D. Robinson, 2016: A review of merged high-resolution satellite precipitation product accuracy during the Tropical Rainfall Measuring Mission (TRMM) era. *J. Hydrometeor.*, **17**, 1101–1117, https://doi.org/10.1175/JHM-D-15-0190.1.

Paulat, M., C. Frei, M. Hagen, and H. Wernli, 2008: A gridded dataset of hourly precipitation in Germany: Its construction, climatology and application. *Meteor. Z.*, **17** (6), 719–732, http://elib.dlr.de/57270/1/s3.pdf.

Silverman, J., Ed., 2013: *Opening Heaven's Floodgates: The Genesis Flood Narrative, Its Context, and Reception*. Gorgias Press. 548 pp.

Sun, Y., S. Solomon, A. Dai, and R. W. Portmann, 2006: How often does it rain? *J. Climate*, **19**, 916–934, https://doi.org/10.1175/JCLI3672.1.

Trenberth, K. E., 1998: Atmospheric moisture residence times and cycling: Implications for rainfall rates with climate change. *Climatic Change*, **39**, 667–694, https://doi.org/10.1023/A:1005319109110.

——, 2011: Changes in precipitation with climate change. *Climate Res.*, **47**, 123–138, https://doi.org/10.3354/cr00953.

——, A. Dai, R. M. Rasmussen, and D. B. Parsons, 2003: The changing character of precipitation. *Bull. Amer. Meteor. Soc.*, **84**, 1205–1217, https://doi.org/10.1175/BAMS-84-9-1205.

——, Y. Zhang, and M. Gehne, 2017: Intermittency in precipitation: Duration, frequency, intensity, and amounts using hourly data. *J. Hydrometeor.*, **18**, 1393–1412, https://doi.org/10.1175/JHM-D-16-0263.1.

Wolff, D. B., and B. L. Fisher, 2008: Comparisons of instantaneous TRMM ground validation and satellite rain-rate estimates at different spatial scales. *J. Appl. Meteor. Climatol.*, **47**, 2215–2237, https://doi.org/10.1175/2008JAMC1875.1.

Xie, P., R. Joyce, S. Wu, S.-H. Yoo, Y. Yaroah, F. Sun, and R. Lin, 2017: Reprocessed, bias-corrected CMORPH global high-resolution precipitation estimates from 1998. *J. Hydrometeor.*, **18**, 1617–1641, https://doi.org/10.1175/JHM-D-16-0168.1.