OUR WET WORLD

Cameron Oliver, XRain (https://xrain.info)

ABSTRACT

Rainfall—or a lack of it—defines so much about life on this earth. From arid deserts to tropical rainforests, from swampy marshlands to raging rivers, from parched meadows to luscious crops, water is central to the diverse environments of our world.

People have observed rainfall for many thousands of years, learning what to expect and how to take advantage of the different seasons. In time this observation became more sophisticated, with various forms of rain gauges enabling a scientific study of precipitation. Kidd et al. (2017) estimates there are now 100,000 “official” rain gauges installed across the world; of course this does not include many personal or informal gauges.

Yet, despite their potential accuracy, rain gauges can only tell us about a single location. Rain radar systems improve the situation significantly, providing a spatial view of the surrounding area. But the addition of satellite-based measurements in more recent years allows us to ‘plug the gaps’ in our understanding, offering data where rain gauge or rain radar measurements are not available. Satellites offer us a truly global perspective on rainfall around our world.

This paper is a visual tour of precipitation patterns across continents and oceans, from several perspectives.

We’ll see the tropical rain belt, a manifestation of the inter-tropical convergence zone (ITCZ) near the equator where warm, moist air from northeast and the southeast trade winds converge. Air is forced upwards, generating heavy precipitation in the process. As it moves up, the air loses its ability to hold moisture, and this falls as precipitation, often heavy.

We’ll examine how rainfall varies over the course of the day; known as ‘diurnal’ variation. This is driven by the cycle of solar heating throughout the day, causing changes in evaporation, wind and other processes. Afternoon rain is common in the tropics and night time rain is common over oceans. We’ll look at examples from Southeast Asia and the Americas.

And finally, we’ll look at how extreme rainfall varies across the globe, on land and over oceans. Where are the biggest storms—both at short durations and long durations? Are these also the wettest places overall?

Satellite data allows us to ‘plug the gaps’ in our understanding, offering data where rain gauge or rain radar measurements are not available. It has potential to provide seasonal and flood data for a wide variety of endeavours, from agriculture to infrastructure.

KEYWORDS

Rainfall, precipitation, satellite, tropical rain belt, tropical cyclones, diurnal cycles, extreme precipitation

PRESENTER PROFILE

Dr Cameron Oliver is a hydrologic, hydraulic and software engineer who has over ten years of experience in hydrological and hydraulic modelling for a variety of clients across New Zealand, Australia, Papua New Guinea and the Pacific Islands, including public sector, food and beverage, irrigation, and mining. He has been involved in flood modelling, flood risk assessments, water balance modelling and erosion protection design. Cameron has developed XRain, a tool to understand seasonal and extreme precipitation across the world based on satellite measurements over a 20 year period.

1 INTRODUCTION

Rainfall is vital for life on earth. Rain and its subsequent runoff and infiltration sustains plants and animals alike, and its abundance or lack thereof can have significant consequences. Traditionally rainfall has been measured at discrete locations using physical rain gauges, but rain radar and more recently satellite observations have allowed us to observe rainfall spatially.

The Global Precipitation Measurement (GPM) mission is a joint initiative between NASA and JAXA to measure rain and other forms of precipitation across the globe from satellites. GPM is centred around the "Core Observatory" satellite that combines both active and passive sensors and enables consistent precipitation estimates to be computed across other 8 other satellites in the constellation. GPM is the successor to the Tropical Rainfall Measuring Mission (TRMM), also a joint NASA-JAXA project.

This paper describes interesting observations from the GPM IMERG v6b Final dataset (Huffman et al. 2019) between 2001 and 2020. The dataset covers between 60° N and 60° S, including many places without any physical rain gauges.

2 TROPICAL RAIN BELT

Mean precipitation depth is one of the most helpful ways to characterise and compare the rainfall of a location. Figure 1 plots this parameter across the globe for the June solstice[1], averaged across 20 years of observations (2001 to 2020) and including the prior and following 2 weeks (i.e. 7 June to 5 July) to improve smoothing.

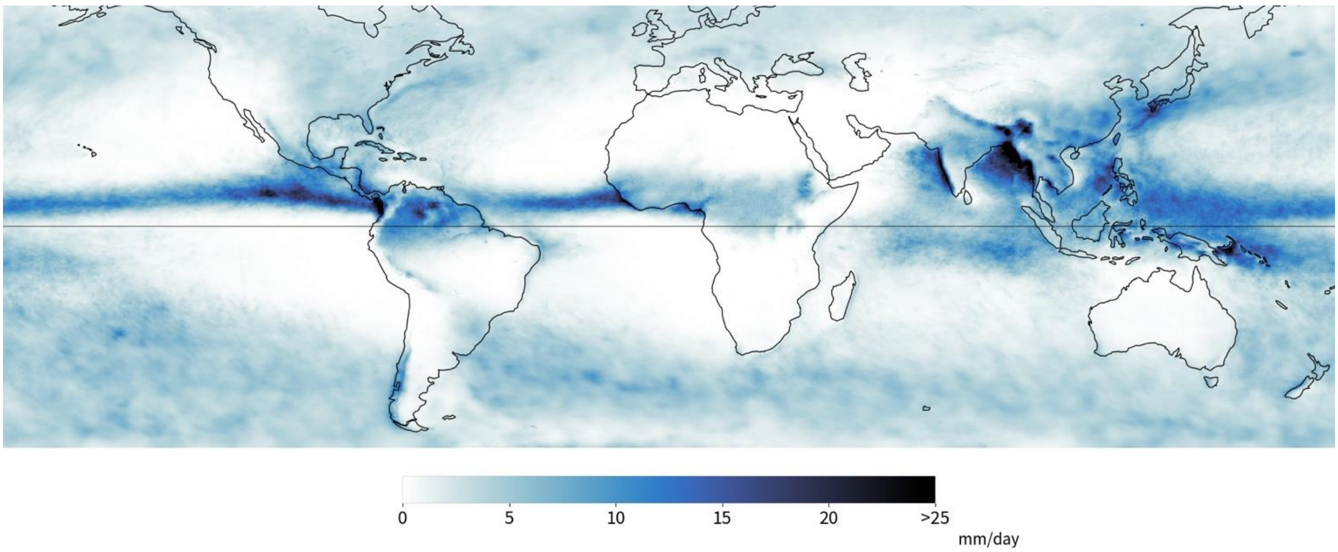

Figure 1: June solstice average rainfall

The most distinct feature in Figure 1 is a band of especially heavy rainfall near the equator (marked in this image as a grey line). Although clearest on the left-hand side of the image—

[1] At this date the sun is at its northern-most declination (latitude) with respect to the earth.

to the west of Africa and the Americas—it wraps around to Southeast Asia on the right. This band is known as the tropical rain belt and is caused by the intertropical convergence zone (ITCZ), where northeast and the southeast trade winds converge and force warm, moist air upwards. This moisture in turn condenses, generating precipitation.

Generally speaking, the most intense rainfall across the globe is within the ITCZ, but over continents a variety of meteorological features—such as high terrain—mean this is not always the case (Nicholson, 2018).

To the east of Papua New Guinea, the tropical rain belt appears to split into two parts, one north of the equator and the other south. Between this so-called "double ITCZ" is a ridge of high pressure (Kerkmann, 2008). The southern portion has less intense rainfall than the north, and eventually becomes indistinguishable.

The tropical rain belt and the ITCZ move throughout the year as prevailing winds change, however at a global scale this movement is relatively subtle. Figure 2 plots average rainfall at the December solstice, when the southern hemisphere is experiencing its summer. To the west of Africa and the Americas, the tropical rain belt remains north of the equator. Differences between June and December include:

- The northern parts of South America are extremely wet in June, while in December precipitation is spread more evenly across the continent.
- In June the African continent is wet across a band extending north of the equator (roughly up to 12° N; corresponding with the edge of the Sahara Desert), while in December the area south of the equator is wet.
- India through to southern China are wet in June but dry in December.

Climate change is projected to cause the tropical rain belt to move northwards (Mamalakis et al., 2021) because the Northern Hemisphere is warming faster than the Southern Hemisphere.

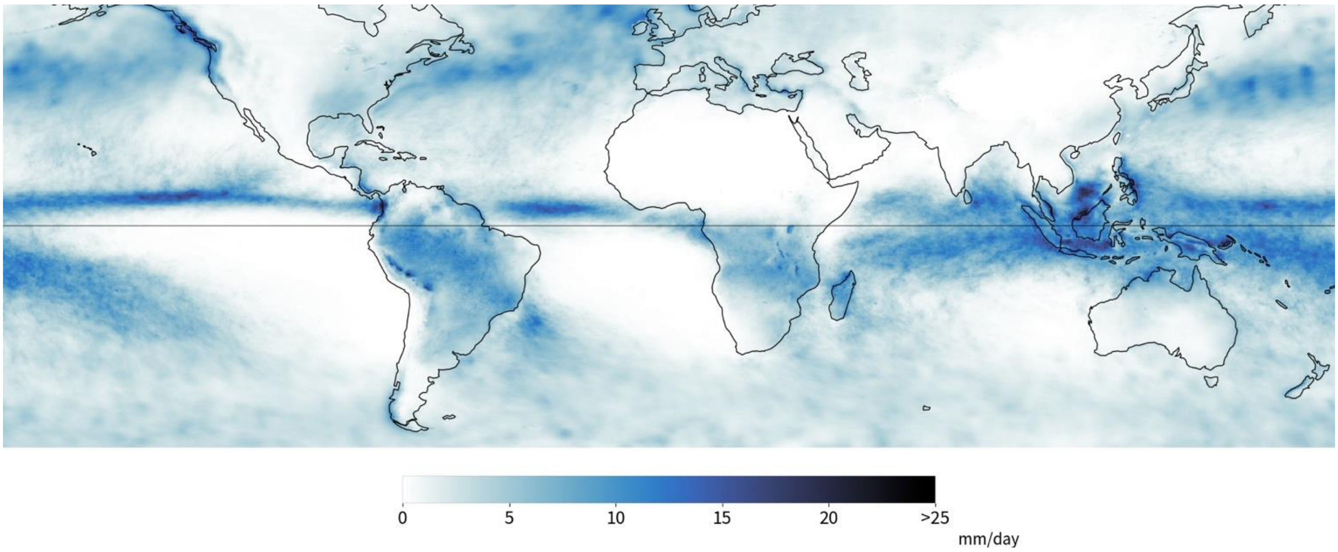

Figure 2: December solstice average rainfall

3 DIURNAL CYCLES

In many parts of the world, rainfall is more likely to occur at a certain time of the day. At its heart, this "diurnal cycle" is caused by the daily cycle of solar heating. As the sun heats the surface of the earth, the air is warmed and rises, bringing with it evaporated moisture.

Solar heating causes the land to warm up faster than adjacent water bodies, creating a pressure gradient that drives onshore breezes and brings in further moisture. At night winds tend to reverse and the ocean is the greatest source of evaporation.

In general, precipitation peaks from mid-afternoon to evening over land and overnight or early morning over the ocean. Dai (2001) states:

> *"Showery precipitation and thunderstorms occur much more frequently in the late afternoon than other times over most land areas in all seasons, with a diurnal amplitude exceeding 50% of the daily mean frequencies. Over the North Pacific, the North Atlantic, and many other oceanic areas adjacent to continents, showery precipitation is most frequent in the morning around 0600 LST [local solar time], which is out of phase with land areas. Over the tropical and southern oceans, showery precipitation tends to peak from midnight to 0400 LST. Maritime thunderstorms occur most frequently around midnight."*

The amplitudes of fluctuations are stronger over land than over the ocean and are stronger in summer than in winter (Watters et al., 2021).

Figure 3 plots early morning precipitation over Southeast Asia, while Figure 4 plots afternoon precipitation for the same region. Of note:

- Across the region the heaviest rainfall over land masses is generally in the afternoon.
- In the Philippines, precipitation is minimal in the morning (8am) but heavy in the late afternoon (5pm), particularly over the islands of Luzon, Panay and Mindanao.
- There is heavy precipitation off the western coast of Myanmar (Bay of Bengal and Andaman Sea) in the morning (6:30am), while in the afternoon (3:30pm) the heaviest precipitation is seen onshore, over the states of Rakhine and Ayeyarwady.

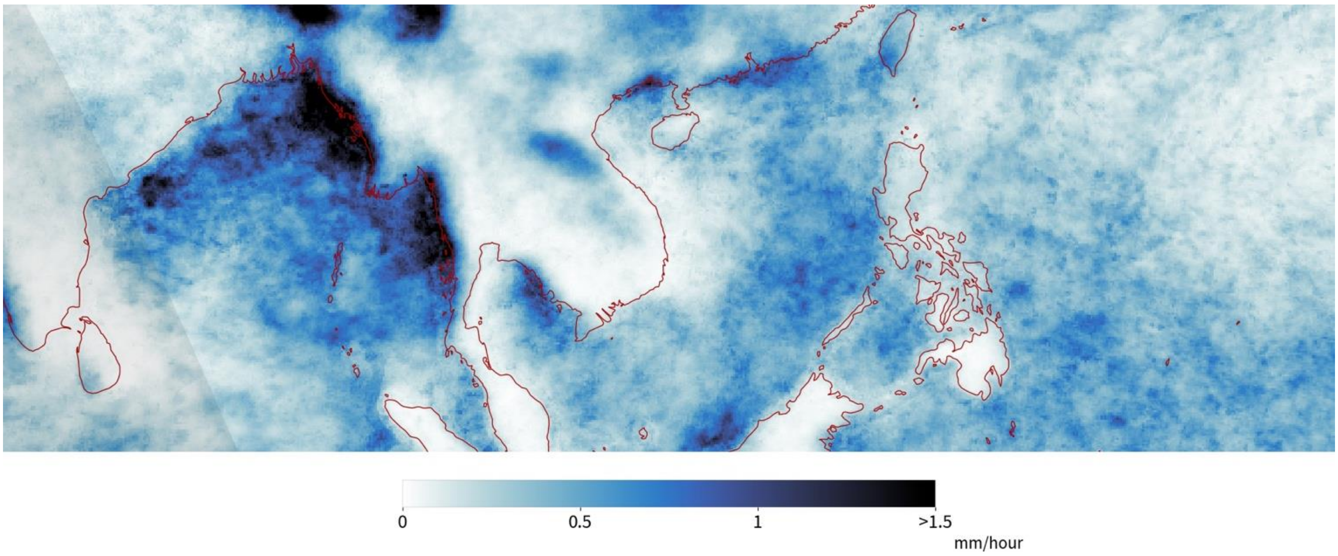

Figure 3: Average June precipitation at 6:30am Myanmar and 8am Manila

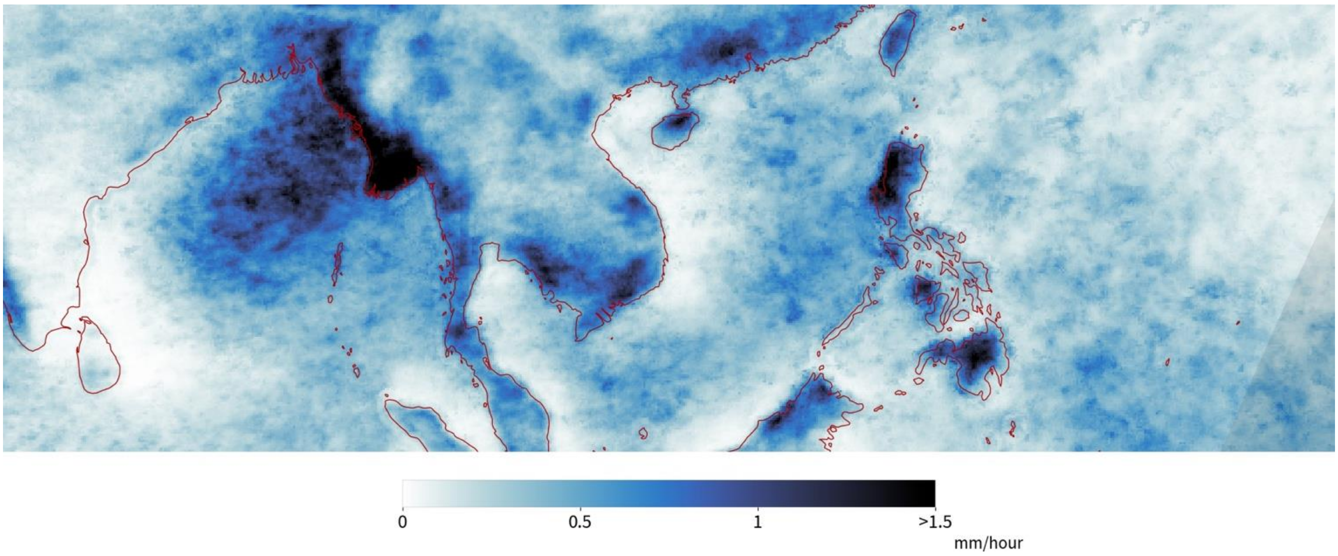

Figure 4: Average June precipitation at 3:30pm Myanmar and 5pm Manila

Figure 5 plots morning precipitation over the Americas, between the equator and 31° N, and Figure 6 plots afternoon precipitation for the same region. Of note:

- In the morning, there is a large zone of heavy precipitation directly to the west of Colombia, over the Pacific Ocean. There is also a band of heavy precipitation to the north of Panama and Costa Rica. Land masses are comparatively dry, particularly over Mexico, Guatemala, Belize, El Salvador and Honduras.
- In the afternoon there is significantly more rainfall over all land masses. Directly to the west of Colombia there is very little precipitation over the ocean; this has been pushed further westwards.

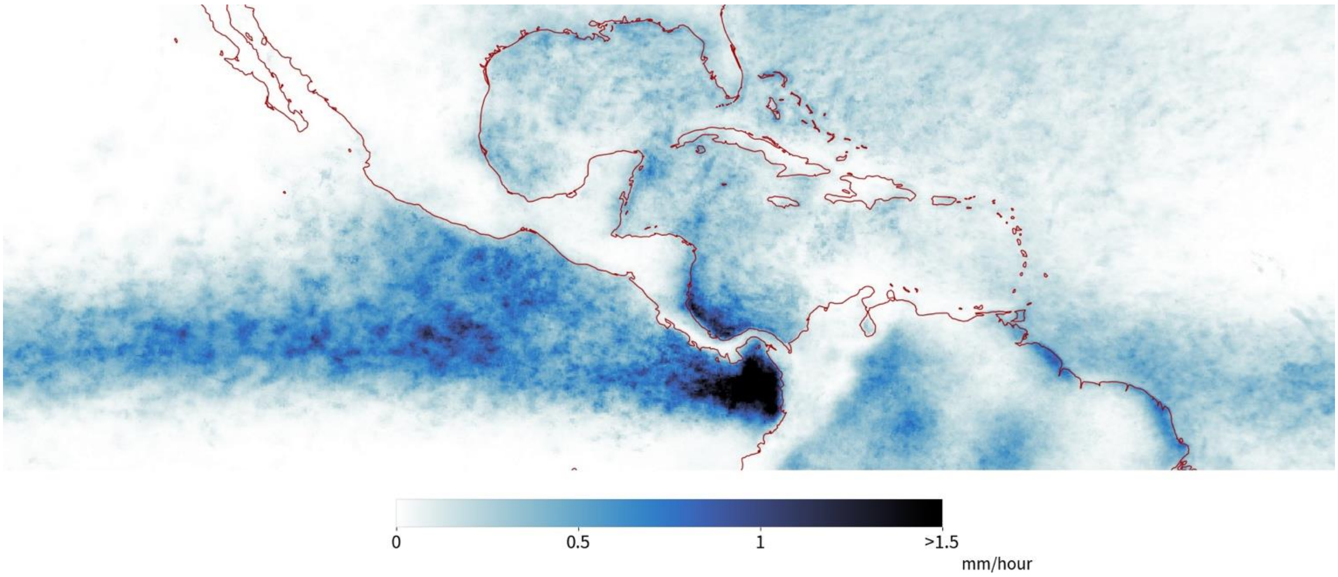

Figure 5: Average June precipitation at 9am Central Standard Time

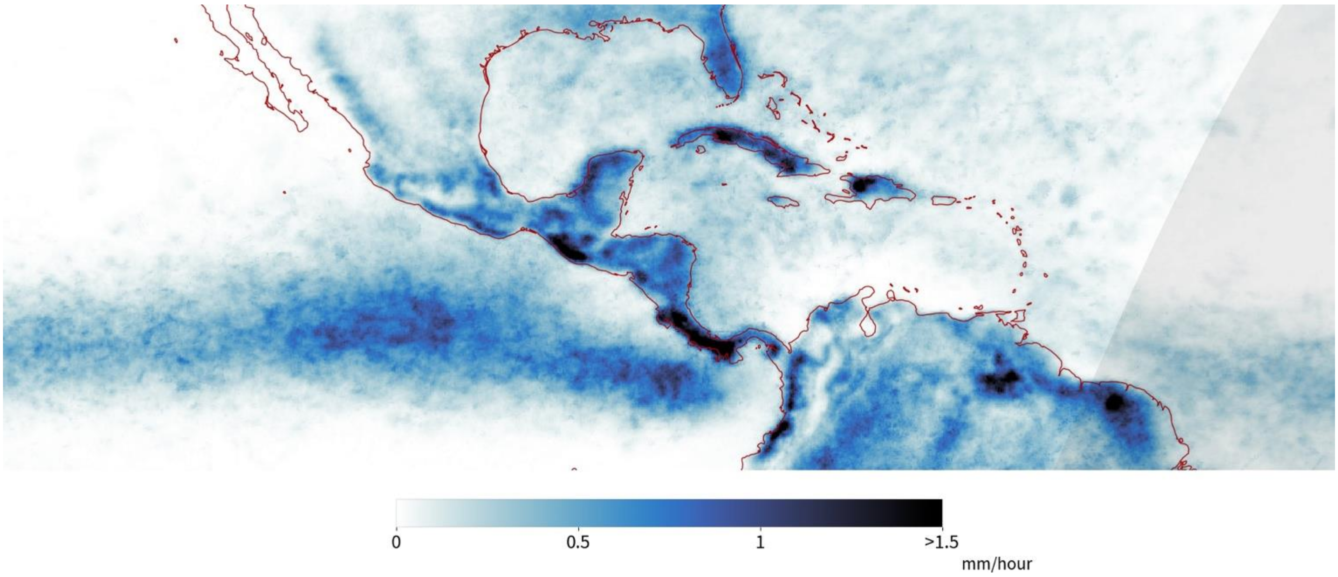

Figure 6: Average June precipitation at 4pm Central Standard Time

4 EXTREME RAINFALL

XRain has derived estimates of extreme precipitation across the globe from the GPM IMERG v6b dataset, as described in Oliver (2022). Also known as *design rainfall*, *precipitation frequency*, *intensity-duration-frequency*, *depth-duration-frequency* or *high intensity precipitation*, this data is available for purchase from the XRain website.

Figures 7, 8 and 9 plot 1% annual exceedance probability (AEP) depths at the 1 hour, 24 hour and 18 week durations.

Across all event durations, the largest depths are generally seen over the oceans, where evaporation is greatest. However the areas with the smallest depths are to the west of South America, over the Pacific Ocean, and to the west of Southern Africa, over the Atlantic Ocean.

At the 1 hour duration (Figure 7), there is a large zone of similar-intensity rainfall over oceans on the right of the image; i.e. the Indian Ocean and Pacific Ocean between latitudes of 25° S and 25° N and longitudes of 35° E and 180° E. On land, particularly high depths are seen along or adjacent to mountain ranges such as the Himalayas (Nepal) and the Andes (South America) due to orographic effects.

At 24 hours (Figure 8), two bands of especially high depths are seen on the right of the image, between 5° and 25° N and between 5° and 25° S, where tropical cyclones are commonly found[2].

At 18 weeks (approx. 4 months; Figure 9) the plot represents long-term weather patterns and as such is “smoother” than the 1 hour and 24 hour plots. The effect of the tropical rain band is particularly clear to the west of Africa and the Americas.

---

[2] Internet: https://en.wikipedia.org/wiki/File:Global_tropical_cyclone_tracks-edit2.jpg Accessed 5 April 2020

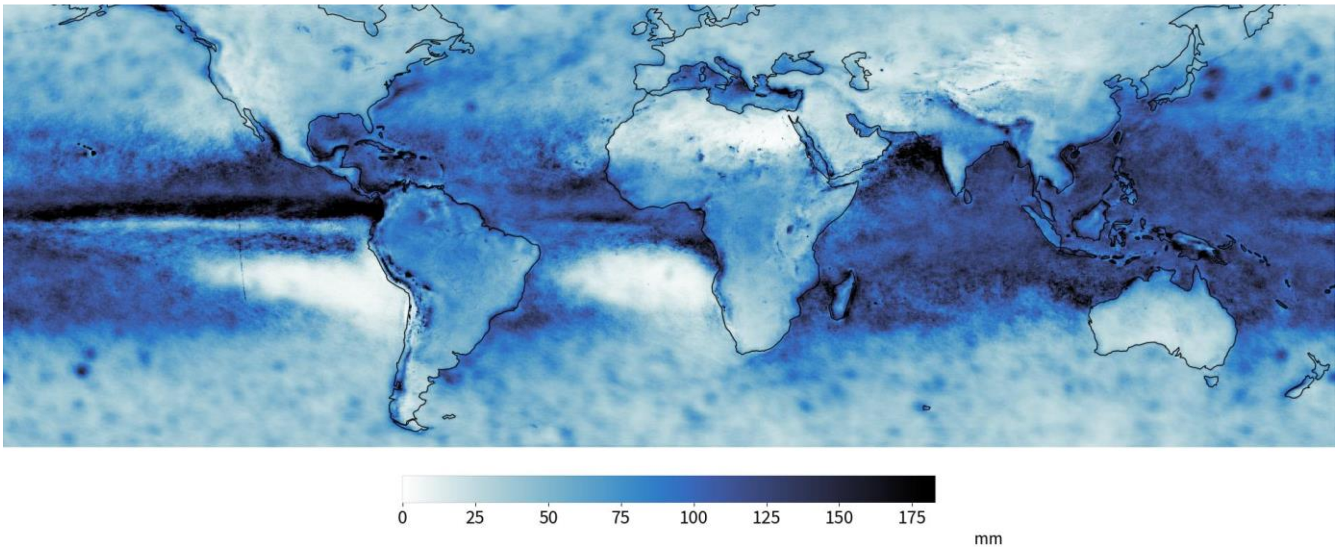

Figure 7: 1 hour duration 1% AEP extreme precipitation depth

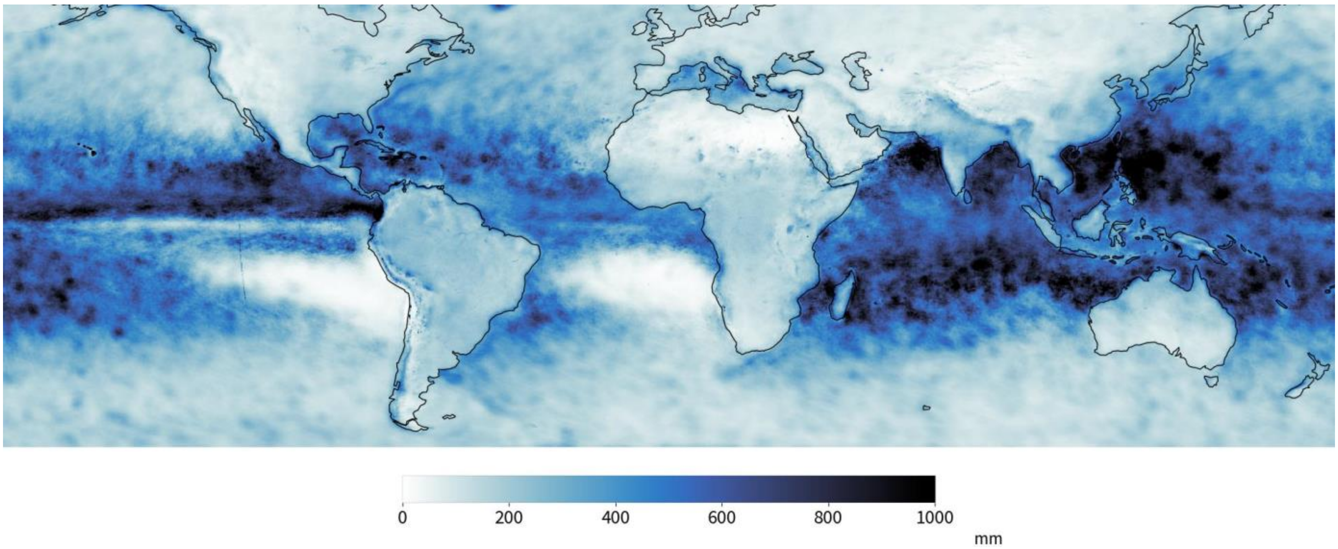

Figure 8: 24 hour duration 1% AEP extreme precipitation depth

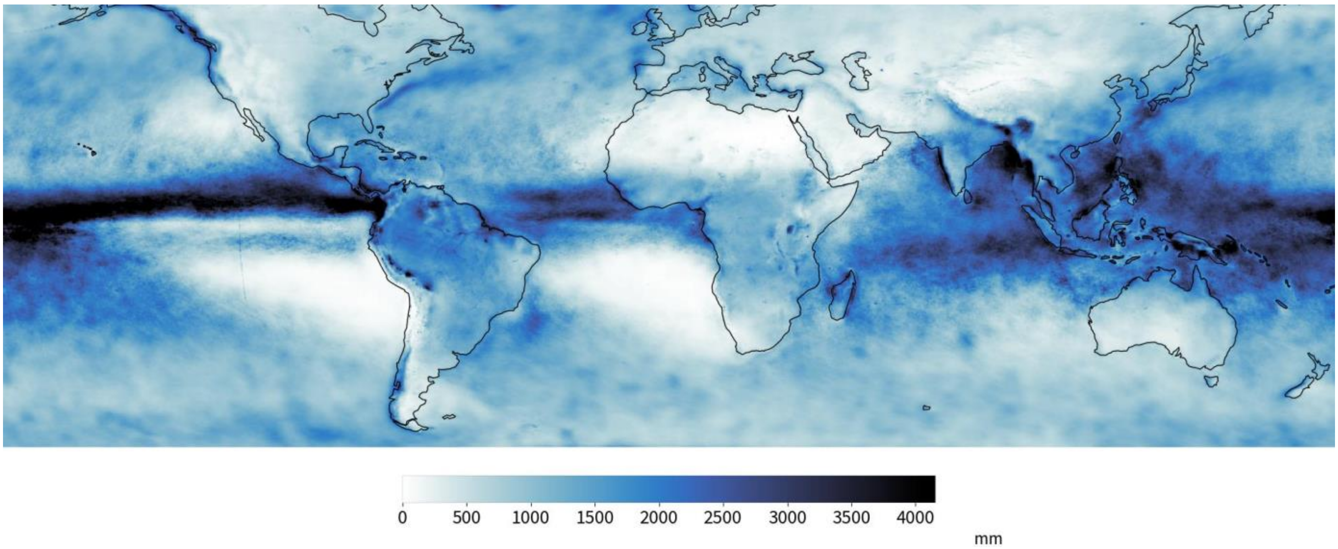

Figure 9: 18 week duration 1% AEP extreme precipitation depth

5 CONCLUSIONS

While a long-term rain gauge record can tell us many things about the rainfall patterns at a location, it is measured at a discrete location and cannot itself describe how rainfall varies spatially in that area. The deployment of weather radar systems from the 1950s introduced the concept of spatial measurements of rainfall, but the more recent introduction of satellite-based precipitation monitoring has allowed us a much wider-scale understanding of rainfall patterns across the world.

This paper has visually examined global patterns of rainfall across seasons, noting the tropical rain belt and its interplay with the intertropical convergence zone (ITCZ). Changes in rainfall across the course of the day have been illustrated in the context of Southeast Asia and the Americas. And finally extreme rainfall depths have been examined at a range of event durations.

At a global scale, the water cycle is the interplay of many meteorological processes, including solar heating and wind circulation. Rainfall is a worldwide phenomenon, but not a uniform one in space or in time. This has many impacts on life for plants and animals alike.

REFERENCES

Dai, A., 2001. Global Precipitation and Thunderstorm Frequencies. Part II: Diurnal Variations. Journal of Climate, Volume 14, Issue 6, Pages 1112–1128, https://doi.org/10.1175/1520-0442(2001)014<1112:GPATFP>2.0.CO;2.

Huffman, G.J., Stocker, E.F., Bolvin, D.T., Nelkin, E.J., and Tan, J., 2019. GPM IMERG Final Precipitation L3 Half Hourly 0.1 degree x 0.1 degree V06. https://doi.org/10.5067/GPM/IMERG/3B-HH/06.

Kerkmann, J., 2008. The Inter-tropical Convergence Zone (ITCZ) seen in ASCAT wind measurements in June 2008. EUMETSAT publication, 19 June 2008. Internet: https://www.eumetsat.int/inter-tropical-convergence-zone-itcz

Kidd, C., Becker, A., Huffman, G.J., Muller, C.L., Joe, P., Skofronick-Jackson, G., Kirschbaum, D.B., 2017. So, How Much of the Earth's Surface Is Covered by Rain Gauges? Bulletin of the American Meteorological Society, Volume 98, Issue 1, Pages 69–78, https://doi.org/10.1175/BAMS-D-14-00283.1

Mamalakis, A., Randerson, J.T., Yu, JY., Pritchard, M. S., Magnusdottir, G., Smyth, P., Levine, P.A., Yu, S., Foufoula-Georgiou, E., 2021. Zonally contrasting shifts of the tropical rain belt in response to climate change. Nature Climate Change, Volume 11, Pages 143–151, https://doi.org/10.1038/s41558-020-00963-x

Nicholson, Sharon E., 2018. The ITCZ and the Seasonal Cycle over Equatorial Africa. Bulletin of the American Meteorological Society, Volume 99, Issue 2, Pages 337–348, https://doi.org/10.1175/bams-d-16-0287.1.

Oliver, C. J., 2022. Extreme Precipitation Statistics on a Global Scale. XRain Report EH1. Revision 5, November 2022.

Watters, D., A. Battaglia, and R. P. Allan, 2021. The Diurnal Cycle of Precipitation according to Multiple Decades of Global Satellite Observations, Three CMIP6 Models, and the ECMWF Reanalysis. Journal of Climate, Volume 34, Issue 12, Pages 5063–5080, https://doi.org/10.1175/JCLI-D-20-0966.1.