2.5. Extreme and intense precipitation

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2.5.1. Introduction

Extreme and intense precipitation is at the core of many scientific and societal concerns, both from a meteorological and a climate change perspective. In recognition of this central role and the need to enhance research efforts, WCRP established a Grand Challenge on Weather and Climate Extremes, a core research focus of which was on heavy precipitation (Alexander et al., 2016). The maturity of new precipitation observational datasets has triggered interest in their ability to help document extreme precipitation. In this chapter, we summarize our current assessment and we focus on intense precipitation, the wet end of extreme precipitation, leaving the dry end of the spectrum (droughts) for a later time.

The recent emergence of multiple satellite-based datasets, reanalyses from multiple centers and a new set of ground-based gridded datasets indeed prompts the need to assess how extreme intense situations are described by these renewed observational-based capabilities (Roca et al., 2019). This is even more urgent, as none of these efforts have been purposely constructed for very intense rainfall conditions. We note that the following condensed review is not a guidance document and we do not address the technicalities here (order of operation, selection of an extreme index; the requirement for length of the record, etc). Rather, we focus on what our current ability is to document extreme precipitation.

Intense precipitation can arise from either a short burst of very precipitating deep convection and/or a long spell of moderately raining systems, or both. The definition of "extreme" precipitation therefore remains scale-dependent, and here we put the emphasis on daily precipitation at ~100 km scale.

The chapter is organized by first exploring global land and ocean. Then a limited regional investigation is proposed along with a process-oriented assessment of the products' capability. A third section is dedicated to showcasing a few subjectively-selected studies where the data are actually used for a scientific application. Finally, a list of recommendations is offered.

2.5.2. Global land

Owing to the conventional networks of rain gauges, the documentation of precipitation over global land benefits from a large number of datasets including in situ gridded, satellite-based on atmospheric reanalysis. Alexander et al. (2020) used many extreme indices based on those recommended by ETCCDI (Zhang et al., 2011). Figure 2.5.1 shows the large discrepancies across observationally-based products characterized by a factor of 2 in magnitude. The figure also shows how the various sub-ensemble of products (in situ, satellite uncorrected, satellite gauge corrected and reanalyses) contribute to the overall spread. This intercomparison generally emphasizes that global space-based precipitation products show the potential for

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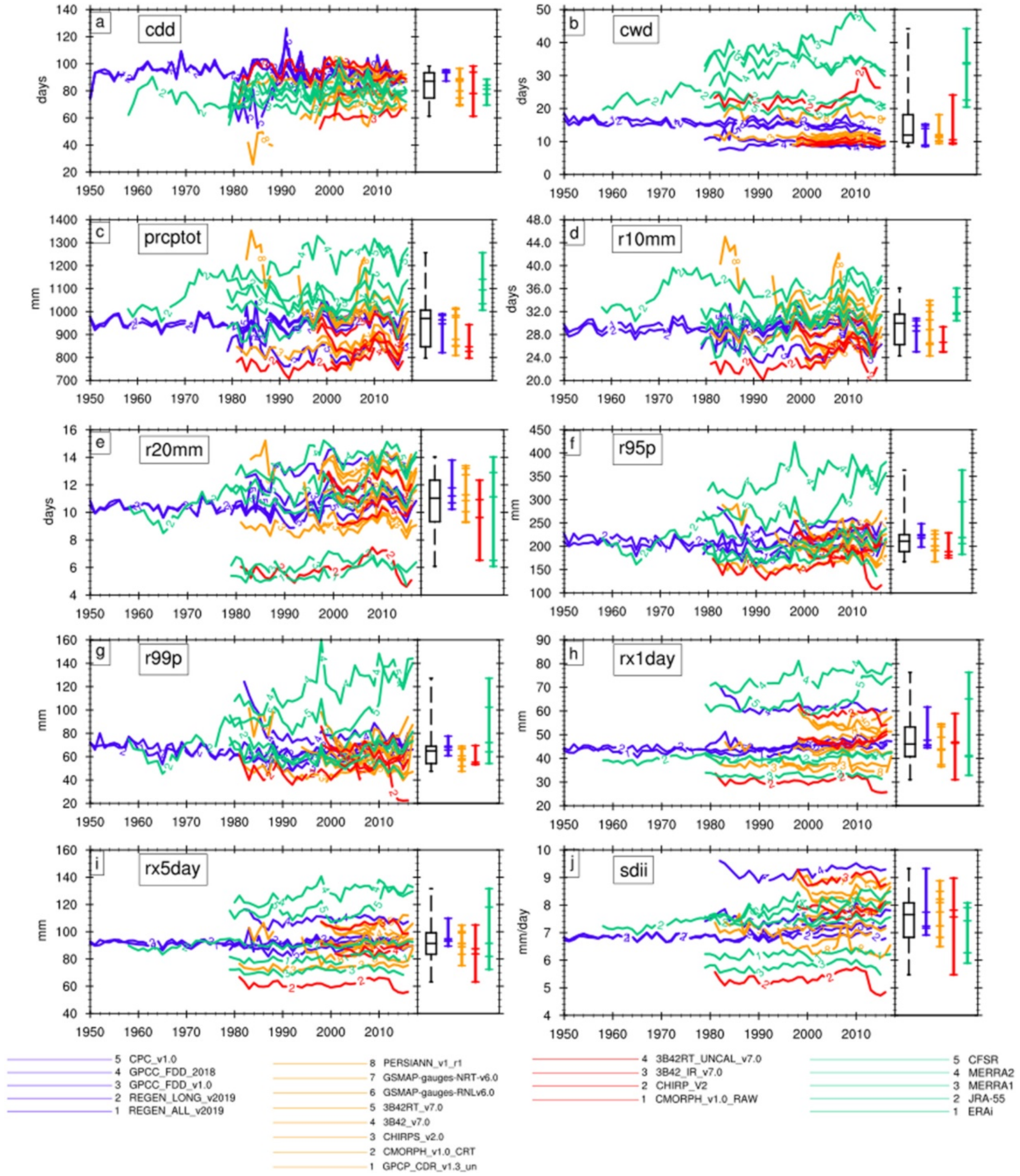

Figure 2.5.1. The time series of quasi-global land (50°S–50°N) averaged wettest day (Rx1day) for various gridded datasets. The spread of the various sub-ensemble of products is also shown on the right panel using a boxplot including all products (black boxplot). Adapted from Alexander et al., 2020

climate scale analyses of extremes as a complementary source to in situ gridded data while reanalysis should be used with caution.

Bador et al. (2020a) further indicates that better agreement on the space/time location of extremes is found among the products rather than on the actual magnitude of the extreme metrics. Donat et al. (2019) looked at the trends in extreme precipitation to reveal that precipitation totals and extremes have increased in humid regions since the mid-twentieth century. Conversely, despite showing tendencies to increase, no robust changes can be detected in the drier regions. Masunaga et al. (2019) performed a large number of product intercomparison and suggested that, for many of the satellite-based products, the uncertainty of the climatology is shown to be a poor predictor of the uncertainty in the extreme of the distribution. Origins of the systematic bias depend qualitatively on precipitation regimes (climatology versus extremes, for instance) and may be traced back to uncertainties at fundamental levels of the satellite microwave algorithms (Sekaranom and Masunaga 2017, 2019). This underscores the need to focus on extreme and intense precipitation in the assessment and the intrinsic difficulty in exploring both totals and extreme precipitation. Focusing on a subset of products [PERSIANN-CDR, ERA-I, Water and global Change (WATCH) Forcing Data methodology applied to ERA-Interim data (WFDEI), National Centers for Environmental Prediction-Department of Energy Reanalysis 2 (NCEP2), and the Multi-Source Weighted-Ensemble Precipitation (MSWEP)] over the 1979–2017 period and GPCC as a reference, Chen et al. (2020) confirms the large discrepancies in the absolute magnitude of extremes intensity. The study further shows nuanced performances from the reanalysis and PERSIANN-CDR, highlighting a regional and seasonal variability in their capability to represent extremes compared to the reference. It is furthermore shown that performance can vary along the temporal record, adding uncertainty to trend analyses.

The previous generation of products were not well nor systematically assessed, but for the satellite-based products, studies revealed large spread among products (Herold et al. 2017; Aghakouchak et al. 2011, Sun et al., 2018). The current assessment suggests that the situation might have improved somewhat.

2.5.3. Global ocean

Conventional in situ data from networks of buoys (Wu and Wang, 2019), rain gauges over atolls in the tropics (Greene et al., 2008), radar measurements from islands (Henderson et al., 2017) or ship-based disdrometer observations (Klepp et al., 2018) are tentatively used to evaluate and characterize reanalyses and the satellite-based products. However, due to the scarcity of in situ precipitation observations (Serra, 2018), the assessment of the capabilities is usually very weak. It is even worse in the case of the extreme precipitation.

Figure 2.5.2 shows the probability of exceedance over the tropical ocean for various satellite-based products (De Meyer and Roca, 2021), exhibiting the large spread for threshold above ~75 mm/day. The analysis further reveals the disparity between the microwave constellation-based products and the IR or single microwave platform products (PERSIANN and GPCP). It also shows that two clusters of products emerge, one with a larger occurrence of “extreme” extremes (IMERG, GSMaP and HOAPS) than the other [CMORPH, Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA)]. MSWEP, as a simple combination of the two later products, is close to this cluster as well.

Burdanowitz et al. (2019) explore the scaling of ERA-5 extreme instantaneous precipitation at 30 km with SST over the global ocean and show significant departures from the OceanRAIN dataset. Masunaga et al. (2019) generally find a larger spread among the extremes of various products over the ocean compared to land (Masunaga et al., 2019).

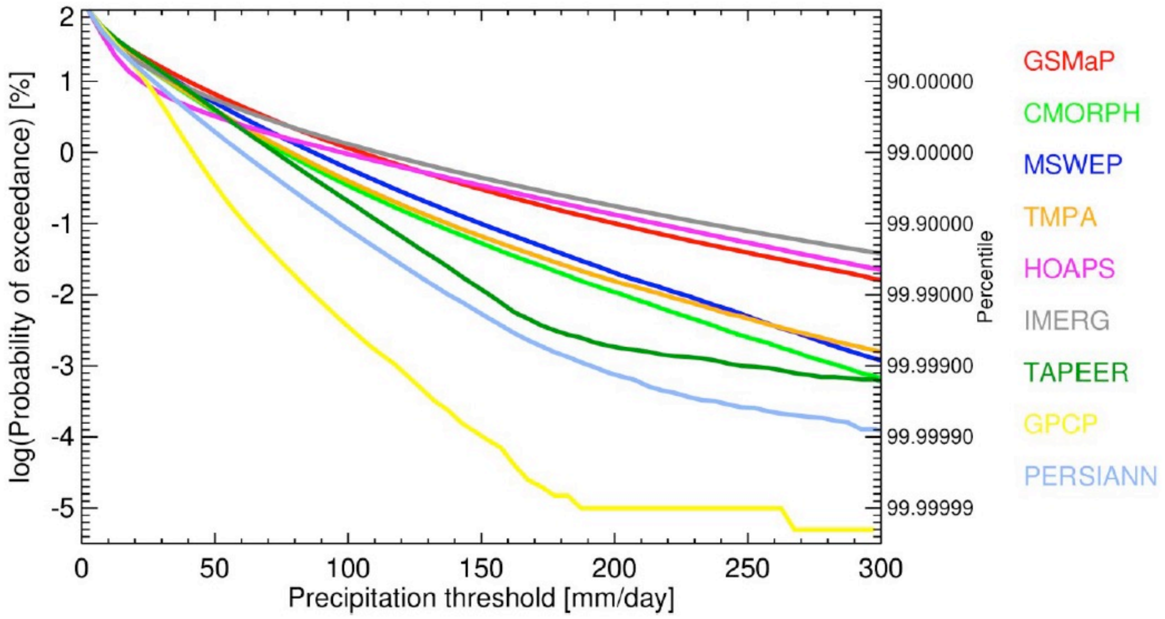

Figure 2.5.2. Probability of exceedance of daily 1°x1° accumulated precipitation over the tropical ocean (30°S–30°N) for the period 2017–2017 except for the TAPEER product where it is restricted to the 2012–2016 period.

2.5.4. Regional and process-oriented investigations

While a systematic exploration of all ongoing regional studies about precipitation extreme is out of the scope of the present chapter, we have selected only a few references that convey the main messages. These references can serve at a starting point for the interested reader.

2.5.4.1. Regional

2.5.4.1.1. *Asia*

Over the Tibetan Plateau, Wu et al. (2019) show that TRMM and CHIRPS overestimate extreme high precipitation. He et al. (2019) intercompared in situ, satellite and reanalysis gridded products over East mainland China (105°–140°E, 15°–35°N). Figure 2.5.3 shows the daily precipitation distribution for boreal summer together with the references rain-gauge network data.

The intercomparison confirms global results with reanalysis strongly underestimating the “extreme” extreme cases. The in situ gridded observations also seem to suffer from the same issue. PERSIANN, as already pointed out, is truncated and does not exhibit values above 120 mm/d. Only the 3B42 (TRMM) product seems to approach the reference datasets. In this region, extreme precipitation is distributed around two maximum centers, over the lower-middle reach of the Yangtze River basin and in South China. ERA-Interim, MERRA, and CFSR do not represent these regional features. The moist-season extreme precipitation in the Korean peninsula and Japan is often brought about by warm rain processes and hence may be difficult to properly capture in the satellite-based products relying partly on the microwave scattering by ice particles (Sohn et al., 2013). The same difficulty may be encountered for extremes in other regions beyond east Asia as well (Hamada et al., 2015).

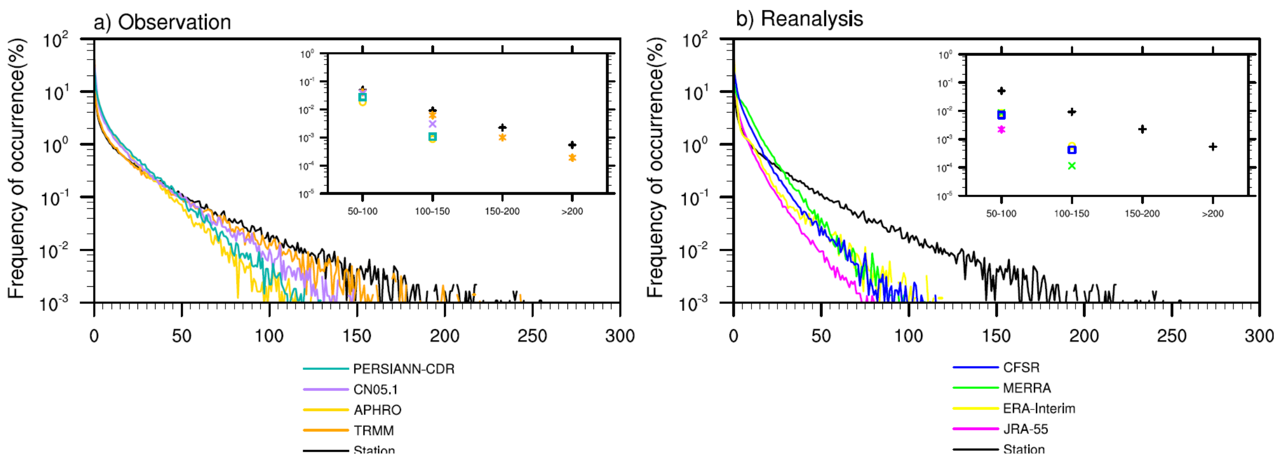

Figure 2.5.3. Frequency of occurrence of daily precipitation in mm/d for boreal summer. From Wu et al (2019). CN05.1 is based on the interpolation of data from 2400 observational stations in China (Wu and Gao, 2013). The Asian Precipitation–Highly Resolved Observational Data Integration Toward Evaluation of Water Resources (APHRODITE) dataset is based on rain gauge observation records over Asia.

2.5.4.1.2. *Western and central Europe*

Using the European daily high-resolution Observational Gridded Dataset (E-OBS) as a reference, seven gridded products (one gauge-based, three satellite-based and two reanalysis-based products) were analyzed using temporally and spatially matched pairs of precipitation estimates with a focus on the detection of extreme events (Lockhoff et al., 2019). The occurrence of wet-day intensities is generally well reproduced by all products and deficiencies are noted in coastal regions and dry areas in the region. The performances show substantial scale dependence with skills showing up 3-day and 1.25° and above scale. This is confirming earlier results for GPCP daily that exhibits better performances at 3°/5 days (Lockhoff et al., 2014).

2.5.4.1.3. *Over the continuous U.S.*

In an effort to identify robustness among various products, five in situ-based gridded products, three satellite-based datasets, two regional reanalyses and one regional climate model simulation have been intercompared in pairs using a Generalized Extreme Value (GEV) framework (Timmermans et al., 2019). The products are used at the 25 km, 5-day resolution. The results are in line with the European-based investigations with a strong scale dependence revealed by this consistency exploration. The inconsistency appears stronger over complex terrain in all products, and satellite-based products are characterized by seasonally varying performances.

2.5.4.1.4. *Africa*

Harrison et al. (2019) investigate changing precipitation in Sub-Saharan Africa using rain gauge and satellite products. They show that satellite products struggle to correlate with the REGEN reference for the R1xday (wettest day) and Rx5day (consecutive 5-day maxima) extreme precipitation indices over the 1983–2013 period. They further compare a set of 12 satellite products and various rain gauge-based gridded products over a limited time span with a focus on the wet season (Figure 2.5.4). Their analysis concludes that sparse data indicates a positive trend in African rainfall extremes and that the satellite products were found useful to fill some space/time gaps in the conventional observational record.

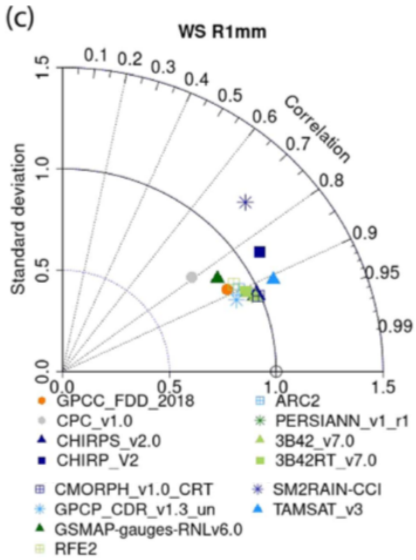

Figure 2.5.4. Taylor diagram for wet season indices, 1998–2013. Number of rain days (R1 mm). Diagrams show how gauge and satellite products compare to REGEN 1998–2013 data in terms of Pearson's correlation (azimuth angle), ratio of standard deviations (distance from black curve) and mean square error (distance from black circle on x-axis). Adapted from Harrison et al., 2019

While not directly an intercomparison or an assessment, the recent work of Le Coz and Van De Giesen (2020) offers some guidance for end-users about what satellite products to use for floods and extreme applications among others tailored for Africa, and is worth being mentioned as a useful entry point for this region.

2.5.4.1.5. *Australia*

Australia, like some other regions, has a very good ground-based network and associated gridded products [for example, the Australian Water Availability Project (AWAP, Jones et al., 2009) daily gridded 5 km x 5 km resolution dataset]. However, even then, in sparsely populated regions like the central and western parts of the country, very few in situ gauges exist and estimating extreme rainfall and/or trends in these regions is problematic (King et al., 2013). Contractor et al. (2015) intercompared daily precipitation values from AWAP with GPCP 1DD version 1.2 and TRMM 3B42 V7 over the period 1998–2013 and found that correlations were reasonably good, although were not better than 0.6 for Australia as a whole. The satellite products generally underestimated the most "extreme" extremes across the range of cities that Contractor et al. (2015) considered. It is worth noting, though, that an in-depth intercomparison of extreme precipitation in all products across whole the region has yet to be performed.

2.5.4.2. Process-oriented

2.5.4.2.1. *Atmospheric rivers*

Atmospheric rivers are associated with extreme precipitation. Focusing on the winter of 2017 on the Californian coast, Wen et al. (2018) showed that six major satellite estimates were able to report heavy precipitation during the atmospheric rivers. Yet while the ensemble mean was close to the rain gauge references, there was considerable spread characterized in the individual products. None of the products or the operational radar network accurately documented the peak extreme rain rate during the sequence of the events. Ramos et al. (2020) compared two cases of atmospheric rivers over California and Portugal in winter 2016 and evaluated more than 20 satellite, in situ and reanalysis gridded precipitation products. Similar results were obtained for the satellite products. But unlike at the global scale, the reanalysis datasets were shown to outperform the satellite and gridded in situ products slightly with respect to this region and processes when compared with reference rain gauges (Wen et al., 2018).

2.5.4.2.2. *Scaling of extreme precipitation with surface temperature*

The sensitivity of extreme precipitation to surface conditions (water vapor and temperature) has received considerable interest, and over the tropical land, earlier analysis raised questions about an otherwise physically-based theory based on thermodynamics that stipulates a ~6–7% K increase of the extreme with each surface degree of warming. By pooling data over land using a 10+ suite of satellite products, Roca et al. (2019) showed that the most recent, constellation-based, gridded daily products support the theory and do indeed exhibit a robust (low spread) Clausius-Clapeyron sensitivity. Over tropical oceans, the sensitivity of extremes for this generation of products is also in line with the theory and characterized by a small spread (De Meyer and Roca, 2021). The investigation further reveals that while the constellation-based products show robust scaling behavior, considerable uncertainty remains on the absolute magnitude of extreme precipitation as shown in Figure 2.5.5. It is not possible to identify which clusters might be the closest to truth.

In summary, the community has produced an extensive evaluation effort over various regions. The results are generally in line with the global studies. Yet we ought to take better advantage

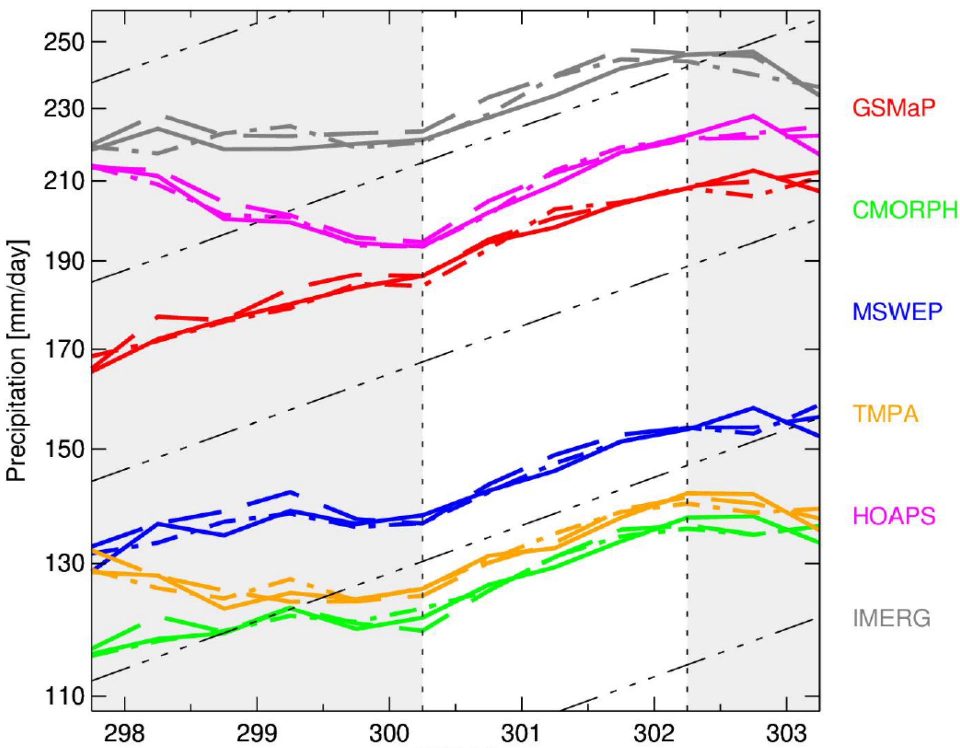

Figure 2.5.5. The value of the 99.9th percentile of the 1°x1° daily accumulated precipitation as a function of the SST lagged by 2 days. Each color corresponds to a precipitation product. Solid line for Operational SST and Sea Ice Analysis (OSTIA), dashed line for Optimally Interpolated Sea Surface Temperature (OISST) and dash-dotted lines for Optimally Interpolated Remote Sensing Systems Sea Surface Temperature (OIRSS). For the period 2007–2017. Regimes are separated by vertical dashed lines. Thegrey shaded areas indicate the non-robust cold regime between precipitation products (left) and the non-robust warm regime between SST products (right). Black dash-dotted lines correspond to the Clausius-Clapeyron 6%/K rate. From De Meyer and Roca, 2021

of these valuable studies in the assessment through new mechanisms to be proposed. The emergence of process-oriented multi-product assessments is encouraging to help end-users to navigate products.

2.5.5. Example applications

While assessment exercises tend to highlight the non-robust features of the assessed data, as it fuels dataset improvements, we have also highlighted some robust features that permit further scientific analysis. Indeed, the balance of evidence suggests we are now in an interesting position where some datasets are fit for some scientific applications while clearly not all the datasets are fit for all scientific investigations. While a guidance document would help navigate the situation, in the following paragraphs we showcase a sub-selection of studies that actually make use of the datasets to further advance our understanding of extremes within the water cycle.

2.5.5.1. Atmospheric physics

Using constellation-based satellite precipitation estimates from FROGS and the recent mesoscale convective system database Tracking Of Organized Convection Algorithm through a 3-DsegmentatioN (TOOCAN), based on homogeneous infrared observations from geostationary satellites (Fiolleau et al., 2020), the role of organized convection on the occurrence of extreme precipitation in the tropics has been investigated. The study shows that the long-lived systems are disproportionally responsible for extreme precipitation relative to their occurrence (Roca and Fiolleau, 2020).

2.5.5.2. Climate model evaluation of extremes

The sensitivity of climate model extremes to model resolution was investigated and assessed against the spread in the observational record (Bador et al., 2020b). It was shown that an increase in resolution, while improving the model's representation of intense precipitation, is unlikely to be enough to improve model performance significantly. This indicates that, in tandem to higher resolution, improvements in model physics and/or tuning is required to better improve model scores at simulating extremes. The use of the observational record for model evaluation of extremes is further considered in the framework of the emerging Department of Defense (DoD)-based and precipitation-centric model evaluation project (Pendergrass et al., 2020).

2.5.6. Summary

The observational estimation of extreme precipitation has benefited from the recent emergence of many new datasets, from in situ, reanalysis and satellite data. The current assessment effort falls short of addressing all of the concerns related to extreme precipitation. Among the identified gaps are extreme snowfall events over land and ocean and orographic intense precipitation. Nevertheless, this first assessment effort points towards a few sound conclusions.

Generally speaking, the new generation of satellite products can be used in support of scientific investigations along with the in situ-based gridded datasets. The current reanalysis datasets appear to suffer from larger uncertainties, making their fitness-for-purpose in extreme precipitation analysis more arguable.

More specifically, in the case of the satellite-based observations over land, the situation appears to have improved from the last decade and a number of salient features have emerged. The new generation of satellite-based global datasets now appear to have the potential for climate scale analyses of extremes. For these products, uncertainties in climatology have been shown to be a poor predictor of the uncertainty in the extremes of the distribution. A very large number of regional investigations have been performed over various land areas, generally in line with the global assessment results, although such a number of studies is difficult to integrate.

Over the oceans, while a number of features are robust among the last generation of satellite constellation-based products, the large spread in the absolute magnitude of the extreme value remains to be addressed. Process-oriented evaluation has started to emerge in the literature and shows good promise to formulate further assessments.

As a consequence, a number of scientific investigations related to extreme precipitation have been supported by the datasets (scaling with SST, climate model evaluation, and so on), which is encouraging. Yet the various datasets may not all meet the requirements for some of the scientific investigations needed, prompting recommendations from agencies and product developers.

2.5.7. Recommendations

Based on this first and partial attempt to assess the ability of observational gridded precipitation products to document extreme precipitation, we are in a position to formulate some recommendations for the agencies and the community.

2.5.7.1. General considerations

i. Consolidate present findings; elaborate and refine the current set of diagnostics
ii. Improve the products, as the assessment has identified some non-robust features that deserve further attention. Feedback to dataset providers with specific details could be formulated in targeted workshops.
iii. Fill the gaps in the assessment
iv. Communicate the robust dataset features to support further research using the datasets

2.5.7.2. Specific considerations

i. Explore further the process-oriented assessment
ii. A community effort is needed to clarify the magnitude of extreme precipitation over the ocean.
iii. Better benefit from the scattered myriad of local and regional evaluation studies, possibly through an extensive regionally-oriented assessment with a common set of scores and metrics. GEWEX Regional Hydroclimate Projects and WCRP/Regional offices could play a role.
iv. The fact that some products are better fit for purpose than others requires a guidance document to help navigate the large suite of available datasets.
v. The products need to be assessed for the dry precipitation extremes (droughts) too.

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2.5.9. References

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