Implications of a decrease in the precipitation area for the past and the future

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Abstract
The total area with 24 hrs precipitation has shrunk by 7% between 50°S–50°N over the period 1998–2016, according to the satellite-based Tropical Rain Measurement Mission data. A decrease in the daily precipitation area is an indication of profound changes in the hydrological cycle, where the global rate of precipitation is balanced by the global rate of evaporation. This decrease was accompanied by increases in total precipitation, evaporation, and wet-day mean precipitation. If these trends are real, then they suggest increased drought frequencies and more intense rainfall. Satellite records, however, may be inhomogeneous because they are synthesized from a number of individual missions with improved technology over time. A linear dependency was also found between the global mean temperature and the 50°S–50°N daily precipitation area with a slope value of $-17 \times 10^6 \text{km}^2/\circ C$. This dependency was used with climate model simulations to make future projections which suggested a continued decrease that will strengthen in the future. The precipitation area evolves differently when the precipitation is accumulated over short and long time scales, however, and there has been a slight increase in the monthly precipitation area while the daily precipitation area decreased. An increase on monthly scale may indicate more pronounced variations in the rainfall patterns due to migrating rain-producing phenomena.

1. Introduction

The connection between climate change and the hydrological cycle has been discussed in a number of papers [1, 2, 3], and a conclusion from the most recent assessment report by the Intergovernmental Panel on Climate Change (IPCC) is that wet regions get wetter and dry regions get drier with an increased greenhouse effect [4]. Contrasting trends between wet and dry regions complicate the estimation of a simple aggregated index such as the global mean temperature or sea level, although an indicator referred to as the hydroclimatic intensity has been suggested [5] that accounts for the differences between dry and wet regions. The movement of water is related to the flow of energy [6] and the greenhouse effect is entangled with the hydrological cycle [7] where the energy flow involves water vapour to form clouds, and precipitation (e.g. the Hadley cell and the Walker circulation [8]).

The dominant terms in the total water budget of the hydrological cycle include the globally accumulated rate of evaporation $E$ and precipitation $P$, where $E$ is offset by $P$ and $E - P = 0$ in an equilibrium state with constant atmospheric moisture. The conservation of mass implies that the rate of evaporated water integrated over Earth’s surface minus the total precipitation on Earth equal the change in the atmospheric water content: $E - P = \int_A \rho_{\text{H}_2\text{O}} - \int_A \int_P \rho_{\text{H}_2\text{O}}$, where $\rho_{\text{H}_2\text{O}}$ is the density of liquid water and vapour in the atmosphere, $\int_A \rho_{\text{H}_2\text{O}}$ is an areal integral, and $\int_V \rho_{\text{H}_2\text{O}}$ is a volume integral. It is only the area with precipitation ($P > 0$) that contributes to the second integral of the mass balance equation $\int_A P$, and the atmospheric moisture content is constant for an equilibrium state where $\int_A \rho_{\text{H}_2\text{O}} = 0$, implying that $\int_A \rho_{\text{H}_2\text{O}} = A_P \overline{P}$, where $A_P$ is the area of the surface

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with precipitation and $\overline{P}$ is the mean precipitation over this area. This balance can also be expressed as $\overline{E}A_E - \overline{P}A_P = 0$ where $\overline{E}$ is the mean evaporation over area with evaporation, $A_E$. An increase in the mean rate of evaporation is expected to be accompanied with an increase in $\overline{P}$ amplified by $A_E/A_P$ if all else is constant [9], and a reduced area of precipitation and constant or increased rate of evaporation are expected to be associated with increased intensity according to this simple expression. The area of evaporation may vary to some extent, although it is dominated by the oceans which take up approximately 70% of Earth’s surface. $A_P$, on the other hand, is directly related to events producing precipitation and is more limited in terms of size (figure 1), and while $A_E$ can be assumed to be constant, the precipitation area $A_P$ varies from one day to the next depending on rain-producing clouds. The total area $A_P$ at any given time reflects both the global mean precipitation frequency and precipitation intensity. It is a vital index for the hydrological cycle because a long-term change implies more or less frequent precipitation with altered mean intensity if the levels of atmospheric water content and rate of evaporation change to a lesser extent. $\overline{P}$ can be used as an indicator for the rainfall intensity if the 24 hr precipitation amount approximately follows an exponential distribution [10].

2. Methods and data

The precipitation area $A_P$ and area mean precipitation $\overline{P}$ were studied through an analysis based on the Tropical Rainfall Measurement Mission (TRMM) [11, 12] to provide a new picture of the ongoing climate change and the consequence for the hydrological cycle, albeit with a number of caveats. The analysis was based on the daily precipitation product referred to as ‘3B42’ which mainly used two sensors: Infrared Scanner and Microwave Imager. The instruments were carried onboard the missions GMS, GOES-E, GOES-W, Meteosat 7, Meteosat 5, and NOAA 12 on a low altitude (\(~\sim 320\) km) orbit with a low inclination (30–35°) in order to get a high spatial resolution. The orbit and the instrumentation were designed to sample each location in the tropics twice per day at different hour of the day. The TRMM data was calibrated with rain gauge data over land. The TRMM data has a reasonably high spatial resolution (0.25° × 0.25°) and a near-global coverage over both land and ocean (50°S–50°N), and was used here to provide a tentative estimate for $A_P$. The rainfall area $A_P$ was determined by summing up the grid box areas for where the 24 hrs rainfall $p_i$ exceeded a threshold $x_0$ (set to 1 mm day$^{-1}$ for daily TRMM): $A_P = \sum_i a_i H(p_i - x_0)$ where $H(.)$ is the Heaviside function and $a_i$ is the area of grid-box $i$. It was difficult to determine an objective definition of $x_0$ because it was sensitive to the spatial resolution of the gridded data. Furthermore, the grid boxes represent mean area values and it is expected that it only rains over a fraction of the grid-box area and usually for a shorter duration than 24 hrs.

The analysis based on the TRMM was compared with corresponding, but independent, analysis applied to the ERA-Interim reanalysis with spatial resolution of 0.75° × 0.75° [13]. It is important to keep in mind that the reanalysis data are not pure ‘observations’, but are influenced by the underlying assimilation model. In addition, evaporation, moisture, and precipitation are influenced by the underlying assimilation model.
$\frac{L_e}{\pi r_E^2 (1 - A)} S_0$, where $L_e$ is the latent heat of evaporation, $r_E$ is the radius of the earth, and $A$ the planetary albedo (not to be confused with the area). The denominator is the total energy flux, assuming that the incoming equals the outgoing energy flow. This, of course, is a gross simplification, as about half of the heat released by the condensation into cloud drops would be radiated downward if all of it were to be in the form of infrared radiation. On the other hand, the net energy flux associated with the downward emission was expected to be small if most of it subsequently also is returned to space as infrared emission.

An ordinary linear regression analysis was used to estimate the dependency of the precipitation area to the global mean temperature, because coarse spatial resolutions of the models precluded a reliable estimate of $A_p$ and because the projections of the global mean temperature are assumed to be more reliable than the precipitation projections on a grid-box basis. The regression was based on the equation $A_P = \beta_0 + \beta_1 T + \eta$, where $\beta_0$ and $\beta_1$ are regression coefficients, $T$ is the annual global mean temperature from HadCRUT4 [14] (version 4.6), $\hat{A}_P$ is the estimated annual mean precipitation area derived from daily $A_P$, $\eta$ is a noise term, and $\beta_1 = \frac{\partial A_P}{\partial T}$ is the slope value used for scaling the daily precipitation area with the global warming projected with the coupled model intercomparison project phase 5 (CMIP5) global climate models (GCMs) [15].

A supporting material (henceforth referred to as SM) provides further diagnostics, data extracts, and open source code for the analysis. It includes (1) the R-package ‘preciparea’ (available from github.com/brasmus/preciparea) and an R-markdown script with open code for the analysis presented in this paper (for easy replication of the results) and (2) a PDF-document produced with R-markdown which provides the recipe behind the data processing and additional supporting analysis.

3. Results

Figure 2 shows $A_p$ between $50^\circ$S and $50^\circ$N estimated from the daily TRMM data and indicates a decline in $A_p$ from 96 to 89 million km$^2$ over the period 1998–2016, corresponding to 25% and 23% of the total area respectively and a 7% relative change. Most of the trend in $A_p$ was connected to maritime precipitation (See the SM). The decline in $A_p$ was accompanied by an increase in the mean intensity $P$ from 11 mm day$^{-1}$ to 13 mm day$^{-1}$ for the same region and period (table 1), which is consistent with previous analysis of trends in wet-day mean precipitation from rain gauges [16]. There was a reasonable agreement between TRMM and ERA-Interim on the total precipitation amount over $50^\circ$S–$50^\circ$N (table 2), 1100–1300 giga-ton/day, which was of the same order of magnitude as previous estimates [17, 18]. The total atmospheric water content remained approximately constant over 1998–2016 according to the ERA-Interim, whereas the global mean rate of evaporation increased from 1400 to 1500 giga-tons (table 1). The total $50^\circ$S–$50^\circ$N precipitation increased slightly from 1122 giga-ton day$^{-1}$ to
1152 giga-ton day$^{-1}$ according to the TRMM data and 1300–1308 giga-tons according to ERA-Interim (table 1).

To explore dependencies of the daily $A_P$ to the global temperature $T$, a linear regression was used to estimate the linear rate of change based on the annual mean estimates of the daily $A_P$ and the global mean temperature. The global mean temperature was taken from the HadCRUT4 dataset [14], and the regression analysis suggested a reduction in $A_P$ by $-17 \times 10^6 \text{km}^2/\text{m} \cdot \text{C}$ (statistically significant at the 5% level). This scaling factor was then used together with the multi-model ensemble of CMIP5 GCM simulations (108 members) in a naive extrapolation to estimate future changes (assuming emission scenario ‘RCP4.5’ [4]). Based on this simple scaling, the future projections suggest a relative reduction in the daily $A_P$ by 28% in 2100 (More details in the SM).

The area with precipitation accumulated over longer timescales is not expected to show the same characteristic as the daily precipitation area due to migrating phenomena such as cyclones, the Inter-Tropical Convergence Zone (ITCZ), the Madden-Julian oscillation (MJO), and the monsoon. Furthermore, the threshold defining a wet event if affected by the aggregation over longer time scales. Here, the monthly mean $A_P$ estimated from daily estimates for $A_P$, compared with $A_P$ derived from monthly mean precipitation (TRMM and ERA-Interim), shown in figure 3. There was no decline in the monthly $A_P$ from TRMM (thin grey) as seen in the daily index (thick black). Similar difference in trends was found in the ERA-Interim data. One reason for the different curves may be that the threshold $x_0$ for defining wet or dry conditions had to be calibrated for different spatial resolution (TRMM: 0.25° × 0.25°; ERA-Interim: 0.75° × 0.75°), and there was no a priori objective criterion for defining the threshold for different time scales and spatial resolution. In reality, it only rains over a fraction of a grid box and usually for durations shorter than 24 hrs, and migrating precipitation makes the comparison between different time scales and spatial resolutions complicated.

4. Discussion

The study of the precipitation area $A_P$ is both scientifically interesting and important in terms of our understanding of the hydrological cycle and climate change. A 7% decrease in $A_P$ over two decades is dramatic, especially if it reflects a real ongoing long-term change. The precipitation between 50°S–50°N dominates the water budget of the global hydrological cycle both because it represents 77% of the surface area and because the precipitation is most intense in the tropics (table 2). One plausible physical explanation for the observed decline may be that an increased rate of atmospheric overturning [7] may have resulted in more convection and precipitation from cumulonimbus type clouds rather than more spatially extensive stratiform clouds. Such changes will have consequences even...
if they only are due to slow natural variability. These results are consistent with previous analysis of the mean precipitation intensity [16], but the exact picture of $A_P$ depends on whether it was estimated from the TRMM data or reanalysis, as well as the time scale and the choice of threshold value distinguishing between wet and dry conditions. The instantaneous precipitation area is smaller than the area with precipitation accumulated over 24 hrs because it usually only rains for a fraction of the day, and these results are subject to a
number of caveats. It has been noted that the quality of the TRMM is not perfect: Although the TRMM PR responds directly to precipitation size hydrometeors, it operates with a single attenuating frequency (13.8 GHz) that necessitates significant microphysical assumptions regarding drop size distributions for relating reflectivity, signal attenuation and rainfall, and uncertainties in microphysical assumptions for the primary TRMM algorithm (2A25) remain problematic [19]. However, the major source of information for TRMM 3B42 is passive microwave and infrared observations, and not the radar-based observations by TRMM PR. Also, it was assumed that the TRMM suffers less from such shortcomings for rainfall area $A_P$ than for the rainfall intensity $P$.

Inhomogeneities are expected to be present in data products derived over time with occasional introduction of new instruments with better capacities and higher accuracy, and reanalyses should not be trusted for trend analyses in climate change studies, due to inhomogeneities introduced with a changing observational platform [20]. Furthermore, the precipitation in reanalyses are model-simulated quantities and not as reliable as direct observations. However, a clearer picture may emerge by combining independent sources of information and multiple lines of evidence. Other independent studies provide a consistent picture with a decrease in $A_P$ and indicate changes in rainfall patterns and clouds, such as higher cloud tops [21] implying greater precipitation intensities, a widening of the Hadley cell [22, 23], and changes in the ocean salinity [24]. A comparison between $P$ from TRMM, ERA-Interim and similar published statistics suggested a reasonable agreement with independent estimates: There have been a number of attempts to quantify the global rate of precipitation, and Zektser et al. (1993) reported an estimate of $P$ of 834 mm year$^{-1}$ (292 giga-ton day$^{-1}$), but only for Earth’s land surface [25]. Global estimates for both land and ocean are in the range 2.6 mm day$^{-1}$–3.1 mm day$^{-1}$ (1329–1585 gigaton day$^{-1}$) [17] or 2.46–2.90 mm day$^{-1}$ (1258–1482 gigaton day$^{-1}$) [18]. These numbers are similar to corresponding estimates from TRMM and ERA-Interim (tables 1 and 2).

The daily precipitation area $A_P$ has been little discussed in the literature despite its importance. For instance, there is no reference to $A_P$ in the IPCC assessment reports [26, 27, 19, 28, 29, 30]. One reason may be that there has been scarce information about the daily precipitation area on a global scale. The emergence of improved reanalyses and satellite data spanning decades now enables new information which improves our abilities to study $A_P$. The best information presently at hand suggests that the precipitation area is shrinking, but there are still large uncertainties. Further studies based on daily precipitation from high-resolution GCMs are needed to elucidate this further. One important take-home message is that daily and monthly $A_P$ should be included in the list of essential climate variables provided by GCMs, in addition to globally aggregated estimates of total precipitation $P$ and evaporation $E$ to provide a global indicator of the simulated climate. These aspects should also be considered when assessing climate change, as traditional climate sensitivity only includes changes in the temperature and does not provide information about changes to the hydrological cycle and rainfall patterns.

The precipitation area is associated with cloudiness and hence connected to the planetary albedo in addition to the vertical energy flow within the planetary system through evaporation, convection, condensation, and precipitation. It has been suggested that galactic cosmic rays (GCR) affect earth’s climate through clouds [31], but empirical evidence for such a connection have been absent [32] and the correlation between daily $A_P$ and GCR measured by the Climax neutron counter in Colorado [33] was indistinguishable from zero (see the SM for more details).

5. Conclusion

Satellite-based TRMM suggest that the spatial extent of 24 hrs precipitation has declined over the past decades, accompanied by an increase in the precipitation intensity, i.e. falling as more spatially concentrated rain. This trend is still uncertain due to the limitation of the data and the difficulty to calculate the exact value of $A_P$. The estimate of $A_P$ was sensitive to both spatial resolution and temporal scale, but the estimate of the global precipitation rate was consistent in the TRMM-based analysis and the ERA-Interim reanalysis, and of the order 1500 giga-ton/day. A regression analysis suggested that the daily precipitation area diminishes with the global mean temperature, and used with global climate model simulations, crude projections for the future suggested a decrease in daily precipitation area by 28% by 2100. For monthly accumulated precipitation, however, the area appears to experience an increase over...
time, as the area of monthly precipitation is influenced by migratory phenomena and the area is estimated for amounts that are aggregated over longer time scales.

Acknowledgments

I acknowledge the teams at NASA and ECMWF whose efforts have produced the TRMM and ERA-Interim data, CMIP5 and the participating modeling groups, the World Climate Research Programme’s Working Group on Coupled Modeling responsible for CMIP, as well as the means for analysis (R-studio and R). The GCMs were downloaded from the KNMI Climate Explorer (https://climexp.knmi.nl). The HadCRUT4 was developed by the UK MetOffice and the Climate Research Unit at University of East Anglia, UK. This work has been supported by the Norwegian Meteorological Institute. The author has no competing interests, and all data needed to evaluate the conclusions in the paper are present in the paper and/or the supplementary materials available at stacks.iop.org/ERL/13/044022/mmedia. Additional data available from authors upon request.

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