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Invited review article

Global precipitation measurements for validating climate models

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ABSTRACT

The advent of global precipitation data sets with increasing temporal span has made it possible to use them for validating climate models. In order to fulfill the requirement of global coverage, existing products integrate satellite-derived retrievals from many sensors with direct ground observations (gauges, disdrometers, radars), which are used as reference for the satellites. While the resulting product can be deemed as the best-available source of quality validation data, awareness of the limitations of such data sets is important to avoid extracting wrong or unsubstantiated conclusions when assessing climate model abilities. This paper provides guidance on the use of precipitation data sets for climate research, including model validation and verification for improving physical parameterizations. The strengths and limitations of the data sets for climate modeling applications are presented, and a protocol for quality assurance of both observational databases and models is discussed. The

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Abbreviations: 4D, Four-dimensional; 1DD, GPCP One-Degree Daily; AIRS, Atmospheric Infrared Sounder; ANN, Artificial neural networks; APHRODITE, Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation; AR5, IPCC Fifth Assessment Report; ARM, Atmospheric Radiation Measurement; ATBD, Algorithm Theoretical Basis Document; BIAS, Bristol-NOAA InterActive Scheme; C3VP, Canadian CloudSat/CALIPSO Validation Program; CaPPM, Cloud and Precipitation Processes Mission; CDR, Climate Data Records; CESM, Community Earth System Model; CFAD, Contoured-Frequency-by-Altitude Diagram; CFSR, Climate Forecast System Reanalysis; CHIRPS, Climate Hazards group Infrared Precipitation with Station; CMAP, CPC Merged Analysis of Precipitation; CMORPH, CPC MORPHing technique; CORDEX, Coordinated Regional Climate Downscaling Experiment; COSMO, Consortium for Small-scale Modeling; CPC, Climate Prediction Center; CRM, Cloud Resolving Model; CRU, Climate Research Unit; CSH, Convective-Stratiform Heating; CST, Convective-Stratiform Technique; DPR, Dual-frequency Precipitation Radar; DSD, Drop Size Distribution; ECA, European Climate Assessment; ENSO, El Nino-Southern Oscillation; ERA-I, European Centre for Medium-Range Weather Forecast (ECMWF) interim reanalysis; GCE, Goddard Cumulus Ensemble; GCM, General Circulation Model/Global Climate Model; G-CRM, Global Cloud Resolving Model; GHCN, Global Historical Climatology Network; GMI, GPM Microwave Imager; GPCC, Global Precipitation Climatology Centre; GPCP, Global Precipitation Climatology Project; GPI, Global Precipitation Index; GPM, Global Precipitation Measurement mission; GPROF, Goddard profiling algorithm; G-SDSU, Goddard Satellite Data Simulator Unit; GSMAP, Global Satellite Map Product; GV, Ground validation; HH, Hydrometeor Heating; HR-GCM, High Resolution General Circulation Model; HRPP, High-Resolution Precipitation Products; iFloodS, Iowa Flood Studies; IMERG, Integrated Multi-satellitE Retrievals for GPM; IPCC, Intergovernmental Panel on Climate Change; ipHex, Integrated Precipitation and Hydrology Experiment; IPSL, Institut Pierre Simon Laplace; IR, Infrared radiation; ITCZ, Intertropical Convergence Zone; JCR, Journal Citation Reports; JRA25, Japanese 25-year Reanalysis; LH, Latent Heat; LMDZ, Laboratoire de Météorologie Dynamique Zoom; MERRA, Modern-Era Retrospective analysis for Research and Applications; MP, Microphysics; NRL, Naval Research Laboratory; NU-WRF, NASA-Unified Weather Research and Forecasting; OLYMPEX, Olympic Mountain Experiment; PBL, Planetary Boundary Layer; PDF, Probability distribution function; PERSIANN, Precipitation Estimation from Remote-Sensed Information using ANN; PMIR, Passive Microwave-InfraRed; PMW, Passive Microwave; PR, Precipitation Radar; PRESTORM, Preliminary Regional Experiment for STORM-Central; PRH, Precipitation Radar Heating; QA, Quality Assurance; QC, Quality Control; RAMS, Regional Atmospheric Modeling System; RCM, Regional Climate Model; REFAME, Rain Estimation using Forward Adjusted-advection of Microwave Estimates; RSS, Remote Sensing Systems; SBM, Spectral bin microphysics; SG, Satellite-Gauge; SLH, Spectral Latent Heating; SSM/I, Special Sensor Microwave Imager; SSMIS, Special Sensor Microwave Imager/Sounder; TAMSAT, Tropical Applications of Meteorology using SATellite data and ground-based observations; TMI, TRMM Microwave Imager; TMPA, TRMM Multi-Satellite Precipitation Analysis; TMPI, Threshold-Matched Precipitation Index; TOVS, TIROS Operational Vertical Sounder; TRMM, Tropical Rainfall Measuring Mission; VIS, Visible; WRF-SBM, Weather Research and Forecasting – Spectral Bin Microphysics

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paper helps elaborating the recent IPCC AR5 acknowledgment of large observational uncertainties in precipitation observations for climate model validation.

1. Introduction

Precipitation is a major element in the Earth's hydrological cycle and at the same time is tied dynamically to the atmospheric circulation by redistributing the latent heating through the troposphere. Precipitation thus serves as a critical linkage between the global water and energy cycles.

Among the key questions in this outstanding research topic is how much global precipitation has been changing over time in association with global warming. It is known that precipitable water has increased with temperature nearly as rapidly as predicted from the Clausius-Clapeyron eq. (6–7% K^{-1}), while the rate of global precipitation change is expected to be only a few % K^{-1} at best (e.g., Allen and Ingram, 2002). The lower amplitude increase in precipitation may be understood in terms of the energy budget constraint that latent heating must be balanced primarily by the atmospheric radiative cooling (Mitchell et al., 1987).

The fact that water vapor increases faster than precipitation on a global scale suggests that as a whole the Earth's hydrological cycle slows down in the warming climate. On the other hand, future climate projections also imply that on a regional scale precipitation intensifies where it is already moist in the present climate (IPCC, 2014). As such, a full understanding of the nature of precipitation under delicate balance (or short-term imbalance) in the global water and energy budget remains a major challenge. We are therefore in urgent need of long term, continuous and accurate measurements of global precipitation to better document how the climate system behaves and better prepare for the future climate change (cfr. Michaelides et al., 2009; Michaelides, 2013a, 2013b, 2014, 2016).

However, although precipitation measurements are often considered as the "truth" to validate models against, it is important to be aware that measurements have their own uncertainties of different kinds. Rain gauge analyses such as the Global Precipitation Climatology Centre (GPCC) product (Becker et al., 2013; Schneider et al., 2014, 2017), for example, have spatial representativeness issues since the ground stations are highly inhomogeneously distributed over land and are totally absent over oceans (Kidd et al., 2017).

Satellite data products are superior to gauge products in spatial coverage over the globe but are subject to retrieval errors and biases. Merged data products such as Global Precipitation Climatology Project (GPCP; Adler et al., 2016; Huffman et al., 2009) and Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin, 1997) have been among the most extensively used products for model validation purposes. Their use in climatological studies is in constant growth as the temporal coverage of the data sets increases (Kidd, 2001). In those products, multiple satellite and gauge measurements are combined so as to maximize the spatial and temporal sampling, but retrieval errors are generally even more difficult to track down in the merged products owing to the complexity of the algorithm.

The purpose of this paper is to discuss how currently available precipitation data sets may be used to validate climate models, to illustrate the uncertainties and limitations of the products and simulations, and to propose a common set of standards for both reference data sets and climate models in order to avoid pitfalls and issues arising from different practices between the observational and modeling communities.

2. Data sets of global precipitation

For climate-scale comparisons of the precipitation component of the hydrological cycle, complete, global precipitation data sets are required and much effort is spent on providing climatologically-sound data sets, with particular attention paid to avoid possible inconsistencies in such products. However, note that at present no single-source of global precipitation measurements exists (Michaelides et al., 2009). Many single-source data sets exist that provide climate-scale precipitation products, some of which are combined to provide multi-sourced global precipitation products.

In terms of coverage, surface data per se essentially refers to land-only measurements (including islands). Even over the land areas there is great variation in the availability and density of the observations (Kidd et al., 2017), which affects the representativeness of the measurements. Over the oceans, the few islands that provide measurements do not adequately represent the precipitation over the surrounding oceans or even accurately represent the immediate oceanic surroundings. Some land areas are now covered by surface-based radar networks; these regions tend to have also adequate gauge measurements, but gauges don't adequately capture the spatial variability of rainfall that radar can provide. Satellite data sets, although touted as 'global' are usually *nearly* global, typically being limited to 60°S to 60°N due to the extent of the available satellite observations, or to the limitations in the retrieval schemes.

2.1. Surface-based data sets

2.1.1. Rain gauge-based products

A great number of instruments are designed to provide in situ measurements of precipitation. The most common and longest-serving is the rain gauge. Gauges designed for measuring precipitation (rainfall and snowfall) represent the fundamental, de facto standard of precipitation measurements across the globe. Sevruk and Klemm (1989) and New et al. (2001) put the number of gauges worldwide at more than 150,000, while Groisman and Legates (1995) estimated the number of 'different' gauges to be as many as 250,000. While it is certain that many gauges exist, these numbers depend largely upon their construction principles (i.e., what is considered as a *valid* gauge), their density and or gauge record; in particular, not all gauges have operated continuously or simultaneously. Indeed, the number of gauges available at a particular temporal resolution, for a specific period, or with a certain temporal latency depends greatly upon regional/national data policies. The reader can find an up-to-date appraisal of gauge coverage and distribution in Kidd et al. (2017).

Despite the impressive number of gauges, their availability and therefore representativeness across the Earth's surface is highly variable (see Kidd et al., 2017). The vast majority of gauges over the Earth's surface are concentrated in populated regions. Over the oceans very few gauges exist with most being 'coastal' and not necessarily representative of the open ocean. Furthermore, while the number of gauges that report daily accumulations of precipitation might be considered adequate, gauges that report sub-daily precipitation (critical for extreme pluvial events) are very limited in number (Kidd et al., 2017).

The basic rain gauge has a number of limitations. Sevruk and Klemm (1989) noted more than 50 different types of gauge design (whether aerodynamic or not) with different orifice size and heights above ground. At the gauge-scale, the 'capture' of precipitation by a rain gauge is affected by the wind flow around the orifice (Duchon and Essenberg, 2001). Turbulence induced by the wind-gauge interaction interrupts the flow across the gauge orifice affecting light precipitation the most but to some extent also heavy rainfall (Duchon and Biddle, 2010), resulting in an under-catch at low intensities and higher wind