RAINFALL MEASUREMENTS FROM SPACE: WHERE ARE WE?

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1. INTRODUCTION

Measuring precipitation from space is a long standing need of operational meteorology, hydrology and climate. Since the launch of the first meteorological satellites in the 60s methods for “inferring”, rather than “measuring” rainfall intensity from space were conceived and calibrated from time to time. Since then the products have greatly evolved in time and always offered a sufficient quality when averaged over suitable time and space scales, but generally suffered from contradictory performances when coming down to instantaneous rainrates. New methods try to incorporate the physical basics of precipitation formation and evolution: the cloud physics content of the algorithms is re-examined and better observational and modeling tools are now available.

International efforts in the field of precipitation measurements from space focus on:

- Cloud microphysics and cloud modeling for advanced rain retrieval algorithms;
- Cooperative missions including the Global Precipitation Measurement (GPM), the European contribution to GPM (EGPM), the Earth Clouds Aerosol and Radiation Explorer (EarthCARE), CloudSat, Calypso, Megha-Tropiques;
- International teams such as the International Precipitation Working Group (IPWG) and the Global Precipitation Climatology Project (GPCP).

Currently open problems are, among others:

- Quantitative measurements for all kinds of applications;
- Measurement of solid precipitation at high latitudes;
- Improvements required to measure light rain and sustained low rainrates during stratiform events;
- Synergy between active and passive sensors;
- Validation strategies that need to be upgraded to match the modified sensor performances and the enhanced physical content of the algorithms.

Synergies between satellite meteorology, cloud physics, cloud modeling, numerical weather prediction (NWP), hydrology, and climate change studies are necessary to advance performances of algorithms at all scales, regional to global (Levizzani et al. 2004).

2. THE PRECIPITATION PROBLEM

Knowledge of precipitation amount and precipitation processes is directly related to the understanding of the global energy and water cycle through climate diagnostics and modeling, NWP, nowcasting, hydrological applications, oceanography, flood forecasting, transportation, agro-meteorology, and water resource management (ESA 2004).

Precipitation is a major source of energy for driving the atmospheric circulation through the storage, transport and release of latent heat associated to the precipitation formation processes. It constitutes about 75% of the heat energy of the atmosphere. The energy equivalent of precipitation at the surface is estimated to be of the order of 85 W m^{-2}: this is about one third of the solar radiative energy available to the Earth’s system, and 80% of the net radiative energy at the surface. Therefore, accurate knowledge of precipitation is crucial for understanding weather and climate at all scales. Cloud-aerosol interactions are also crucial in precipitation formation and play a key role in global climate changes.

Clouds are the source of all precipitation, but details of precipitation formation processes are poorly understood. Understanding them is crucial for quantitative precipitation forecasting (QPF). The societal benefits in providing warning of flash flooding would be immense. Global observations of the probability distribution function of vertical motions within the grid box to constrain convective parameterization schemes are also needed. Measurements of precipitation amount from space are therefore very much needed for local as well for global weather and climate applications considering the necessarily sparse distribution and scarce amount of raingauges, which are obviously limited to the continents. Science and technology are advancing fast and considerable efforts are being devoted to the task.

3. MEASURING PRECIPITATION FROM SPACE: HOW?

It is difficult to look at satellite precipitation estimates from a unified perspective encompassing all possible applications and considering all instrument-related aspects (e.g. Levizzani et al. 2002). Rainfall estimation methods have been conceived using data from sensors in the visible/infrared (VIS/IR) and passive microwave (PMW), and from precipitation radar (PR). It has been clearly demonstrated that PMW and PR data are more linked to the physical structure of the cloud and therefore more responsive to precipitation formation processes.

Technical limitations presently limit the launch of PMW sensors to Low Earth Orbits (LEO) though advancements are in view leading to the first PMW sensor at the geostationary level (Bizzarri et al. 2003). Technological developments of PMW instruments and radar on board LEO orbiters at the end of the 90s culminated in the launch of the Tropical Rainfall Measuring Mission (TRMM) (Kummerow et al. 2000), which marked a breakthrough in our observational capabilities of the atmosphere-ocean system.

However, the use of VIS, IR and water vapor (WV) channels of geostationary satellites is by no means over considering the need for truly global and instantaneous coverage. Rainfall estimation methods that work in this spectral range attribute precipitation levels based on cloud top brightness temperature. Ancillary quantities such as water vapor vertical content, wind field, cloud classification, and radar rainfall data sets may play a role from time to time, but the assignment of rainrates is in general very indirect and regardless of the actual cloud structure.

“Blended” methods that combine rainrates as retrieved by PMW sensors at LEO orbits with brightness temperatures in the IR from GEO sensors have recently come out (e.g. Turk et al. 2000; Kidd et al. 2003). The idea is to dwell upon the superior performances of PMW sensors that overpass scarcely a given area and “calibrate” the IR temperatures of the GEO imagery that is available at 15-30 min intervals. Frequently upgraded rain maps are thus produced with the necessary space-time coverage for a number of different applications that range from assimilation into NWP models to hydrology and climate change.

The specific application of satellite-retrieved rainrates obviously determines the space-time accuracy and the monitoring strategy. From very frequent instantaneous measurements for hydrology and water management to 6-hourly data for NWP assimilation up to daily and monthly values for climatological applications, a wide range of algorithms is available. In particular, satellite retrievals (e.g. Huffman et al. 2001) have revealed instrumental to an increased understanding of global change trends as the GPCP group has demonstrated.

4. CHALLENGES POSED BY GPM AND APPLICATIONS

The GPM mission will further advance the current capabilities of measuring precipitation from space widening the scope to global measurements with its advanced radar and radiometer systems and constellation concept (Shepherd et al. 2002). The GPM, while trying to fill in a gap of global data and space-time coverage, poses clear problems and challenges that were already hidden between the lines of past missions and algorithms.

Kummerow et al. (2004) point out that it is “of utmost importance the need for a transparent, parametric algorithm that insures uniform rainfall products across all sensors”. The key requirements for the new algorithm(s) are:

1. Based on an open architecture that will allow the international community to participate in the algorithm development, its refinement, and its error characterization.
2. Parametric structure given the fact that GPM is a cooperative mission between many agencies and algorithms cannot be designed for specific radiometers with defined frequencies, viewing geometry, spatial resolutions or noise characteristics.
3. Robustness in such a way that differences between sensors can be confidently interpreted as physical differences between observed scenes rather than artifacts of the algorithm.

One of the top challenges is represented by the full characterization of uncertainties at any space-time scale from instantaneous estimates needed for hydrologic and weather forecasting applications (e.g. Ebert 2003) to large space and time averages required for climate model verification and climate trend monitoring (e.g. Gebremichael et al. 2003). Such a complete error characterization does not currently exist and is undoubtedly the greatest challenge facing the community. Ongoing efforts are being sponsored by the IPWG (http://www.isac.cnr.it/~ipwg/) and the GPCP (http://cics.umd.edu/~yin/GPCP/) as part of their institutional activities.

5. UPFRONT RESEARCH TOPICS

In order to meet the operational GPM requirements and, more generally, to improve the quantitative standard of rainfall measurements, several key research topics are identified. We will briefly examine a few of them that are directly related to cloud physics:

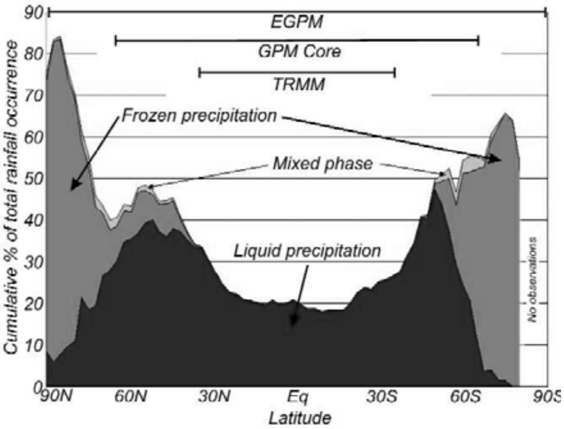

Figure 1. Mean zonal occurrence of oceanic light precipitation (% of total rainfall occurrence) derived from the Comprehensive Ocean-Atmosphere Data Set using ship-borne meteorological observations (1958-1991). The bars indicate the latitudinal coverage of TRMM and those foreseen for GPM and EGPM. (courtesy of C. Kidd, Univ. of Birmingham, and European Space Agency, ESA 2004)

- Snowfall and light rain measurement.
- Cloud-aerosol interactions and physics of precipitation formation.
- Verification of model output.

When referring to precipitation measurements it is rarely considered that in reality we are dealing with liquid precipitation. However, at latitudes above about 60 N-S frozen precipitation becomes predominant for large part of the year as is clear from Fig. 1 where data from the Comprehensive Ocean-Atmosphere Data Set (COADS) are shown. For instance, while the typical annual average precipitation total in Canada is 535 mm, with 36% falling as snow, in northern Canada the proportion of snowfall to total precipitation ramps up to approximately 90%, almost all of which is produced in the form light snowfall (Mugnai et al. 2004). The latitudinal dependence of the snow to total precipitation ratio is shown in Fig. 2 for three locations from south to north Canada. Therefore, light snowfall, and a smaller component of light rainfall, are key drivers to the water cycle in mid to northern latitudes. This issue is manifest in seeking to understand how snow accumulation is changing in the context of the current global warming trends, for example the presumed growth of the Greenland ice sheet, which seems very small to represent a real response to a warmer polar climate (Davis et al. 1998).

The EGPM mission is specifically designed to detect and measure snowfall, light rain, and warm rain – both over land and ocean – particularly in mid and northern latitude climates (Mugnai et al. 2004). The payload consists of: (1) an innovative conically scanning PMW radiometer combining the conventional rain-measuring window channels at 18, 23, 37, and 85 GHz, a high-frequency window channel at 150 GHz, and four cross-paired temperature-sounding channels near 52 and 118 GHz (four channels in each O_2 absorption region); and (2) a Ka-band (35.6 GHz) 3-beam nadir-pointing precipitation radar having a sensitivity of ~5 dBZ.

The sounding channels respond to scattering by snow and are less sensitive to surface emission than the window channels. Additionally, coupled radiometric observations within the strong oxygen absorption band between 50-54 GHz and near the strong O_2 absorption line at 118.75 GHz, permit the accurate retrieval of precipitation information by exploiting differential atmospheric absorption within each band and differential hydrometeor scattering between the two bands. Choosing pairs of frequencies in the two O_2 absorption regions that have similar weighting functions for clear skies over precipitating clouds, enables vertical partitioning (slicing) of the frozen cloud constituents.

Cloud physics research aspects are key to another important area of rainfall measurements from space, the aerosol-cloud interactions. Satellite observations have shown direct evidence that aerosols from forest fires (Rosenfeld 1999) and urban and industrial pollution (Rosenfeld 2000) inhibit precipitation formation. Ramanathan et al. (2001) argue that aerosols can lead to an increase in solar heating of the atmosphere, changes in the atmospheric temperature structure, suppression of rainfall, and less efficient removal of pollutants. These effects can contribute to weaken the hydrological cycle.

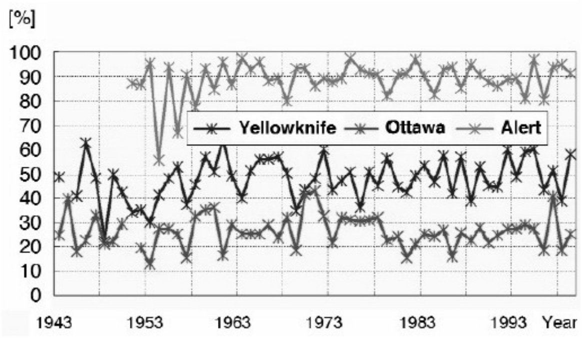

Figure 2. Snow to total precipitation ratio for selected latitudinal locations in Canada. Bottom to top curves: Ottawa (~48˚N), Yellowknife (~63˚N), and Alert (~84˚N). (courtesy of P. Joe, Meteorological Service Canada, and European Space Agency, ESA 2004)

In particular, recent studies were carried out in the Amazon rainforest area to find out more about the aerosol influence on cumulus cloud formation and the net climate forcing actions. Koren et al. (2004) have used satellite data over the Amazon region during the biomass burning season to show that scattered cumulus cloud cover was reduced from 38% in clean conditions to 0% for heavy smoke (optical depth of 1.3). At the same time Andreae et al. (2004) have demonstrated that heavy smoke from forest fires in the Amazon reduces cloud droplet size insofar delaying the onset of precipitation from 1.5 kilometers above cloud base in pristine clouds to more than 5 kilometers in polluted clouds and more than 7 kilometers in pyro-clouds. Suppression of low-level rainout and aerosol washout allows transport of water and smoke to upper levels. Elevating the onset of precipitation allows invigoration of the updrafts, causing intense thunderstorms, large hail, and greater likelihood for overshooting cloud tops into the stratosphere. There, detrained pollutants and water vapor would have profound radiative impacts on the climate system.

Finally, let us mention the issue of cloud structure and model verification that will see clouds and precipitation physics from space play a crucial role for the improvement of precipitation measurements. Three major points need to be addressed first:

- It has been demonstrated that radar and lidar can distinguish liquid and ice phases in clouds (e.g. Hogan et al. 2003) thus helping rainfall measurements based on physical algorithms.

- Calculations show the presence of supercooled liquid water to be fundamental to for the radiative properties of cloud.
- Yet, cloud representation in models is very crude and unevaluated.

An adequate synergy of ground based and satellite borne instruments is required to address open cloud structure issues. Missions such as EarthCARE and CloudSat, in synergy with GPM and EGPM, offer the appropriate suite of instruments and observing strategies that are needed to link together the cloud physics and the precipitation communities in a combined effort. This will also be the target of international projects that are now being conceived and will be launched in the next future.

Model verification is a compelling issue at all scales and it is clear that precipitation measurements from space must attain a higher quality level to be effective in this direction. This will proceed in parallel with the improvement of clouds and precipitation parameterization in the models.

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