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Satellite Clouds and Precipitation Observations for Meteorology and Climate

Vincenzo Levizzani

Abstract Measuring precipitation from space is a long standing issue of meteorology and climatology. Since the launch of the first meteorological satellites in the 60s several visible/infrared/microwave techniques for "inferring", rather than "measuring" rainfall intensity from space were conceived, but seldom reached operational application. Algorithms have greatly evolved and now offer an acceptable quality level when products are averaged over suitable time and space scales. Daily, monthly and yearly products have become important inputs for climate studies, but their quality significantly lowers when the algorithms are applied to estimate instantaneous rainrates. The most recent methods go back to the basic physical principles of precipitation formation and evolution. The re-examination of the physical content of the algorithms is driven by new insights on precipitation formation mechanisms now available together with new observational tools from space and from the ground. New satellite missions, activities and efforts of international organizations are devoted to the generation of high resolution precipitation products for applications in meteorology, hydrology and climate.

Keywords Clouds · Precipitation · Satellite meteorology · Climate

1 Introduction

Satellite rainfall estimation methods have been conceived in time to exploit visible (VIS), infrared (IR), near infrared (NIR), water vapor (WV), passive microwave (PMW), and radar data. A complete review of satellite rainfall estimation methods is beyond the scope of the present paper. The reader will find reviews and comparisons, among others, in the articles by Adler et al. (2001, global products), Kidd (2001, climate), Levizzani et al. (2001, 2002, generic), and Petty (1995, over land methods). A state-of-the-art collection of papers on the advances in the field has been edited by Levizzani et al. (2007). We will here concentrate on the most recent methods,

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i.e. 1) PMW physical-statistical methods, and 2) combined algorithms for global products, having in mind the new observational contributions of cloud processes. A few relevant applications of cloud microphysics observations and rainfall products are briefly described.

2 Passive Microwave Methods

At PMW frequencies precipitation particles are the main source of attenuation of the upwelling radiation and thus PMW-based techniques are physically more direct than those based on VIS/IR radiation. The emission of radiation from atmospheric particles results in an increase of the received signal while at the same time the scattering due to hydrometeors reduces the radiation stream. Type and size of the detected hydrometeors depend upon the frequency of the upwelling radiation. Scattering and emission happen at the same time with radiation undergoing multiple transformations within the cloud column in the sensor's field of view. At different frequencies the radiometers observe different parts of the rain column and this principle is behind the choice of the observing channels.

Precipitation drops strongly interact with MW radiation and are detected by radiometers without the IR strong biases. The biggest disadvantage is the poor spatial and temporal resolution, the first due to diffraction, which limits the ground resolution for a given satellite MW antenna, and the latter to the fact that MW sensors are consequently only mounted on polar orbiters. The matter is further complicated by the different radiative characteristics of sea and land surfaces underneath. While the sea surface has a relatively homogeneous emissivity, land surfaces have a high and variable emissivity, close to that of precipitation, and low polarization. The emissivity depends upon the characteristics of the surface including vegetation and moisture content. Rainfall over land will increase the upwelling radiation stream but at the same time will absorb radiation introducing considerable difficulties in the identification of rain areas. Scattering is thus the key to the PMW rainfall estimation techniques over land.

Several approaches have been developed in time from relatively simple threshold-based algorithms to the most recent and complex physical-statistical techniques. Some of these rather simple threshold methods were used also to produce global estimates such as the one of the National Oceanic and Atmospheric Administration (NOAA) (Ferraro, 1997), which has recently been revisited trying to lower the existing biases (McCollum and Ferraro, 2003).

PMW frequencies have always shown a tendency to perform better for convective precipitation while stratiform rain or, more generally, low rainrates are poorly detected. An example is shown in Fig. 1 where the same precipitation system is simultaneously scanned by three sensors on board the Tropical Rainfall Measuring Mission (TRMM): the Visible and InfraRed Scanner (VIRS), the TRMM Microwave Imager (TMI), and the Precipitation Radar (PR). While the VIS/IR method overestimates by including low-temperature, non-precipitating high clouds,

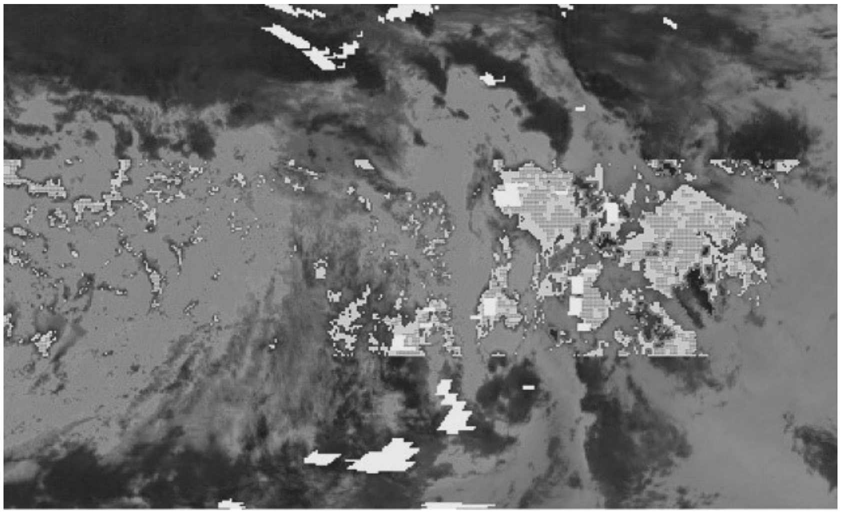

Fig. 1 Rainfall as estimated by the various TRMM sensors over Eastern Mediterranean. The scene is depicted in false colors (Rosenfeld and Lensky, 1998) as seen by VIRS. The central narrow strip is where rainfall is estimated by a VIS/IR method (*gray*) and by the PR (*pink*). The conical scanning of the TMI is in yellow. (courtesy of D. Rosenfeld) (See also Plate 11 in the Colour Plate Section)

its performance in rain area detection is not far from that of the PR. The PMW algorithm based on TMI data, however, is grossly underestimating since it only detects precipitation from cumulonimbus clouds. Low stratiform rainrates go completely undetected.

More complex methods were developed with the aim of tying cloud microphysical profiles and rainrate at the ground. The Goddard Profiling Algorithm (GPROF, Kummerow et al., 2001) retrieves instantaneous rainfall and rainfall vertical structure using the response functions for different channels peaking at different depths within the raining column. However, more independent variables are present within raining clouds than there are channels in the observing system, and thus the solution requires additional assumptions or constraints. Radiative transfer calculations are used to determine a brightness temperature vector, **Tb**, given a vertical distribution of hydrometeors represented by **R**. An inversion procedure is needed to find the hydrometeor profile, **R**, given a vector **Tb**. The GPROF retrieval method is Bayesian and the probability of a particular profile **R**, given **Tb**, can be written as:

$$\Pr(\mathbf{R}|\mathbf{Tb}) = \Pr(\mathbf{R}) \times \Pr(\mathbf{Tb}|\mathbf{R}) \tag{1}$$

where Pr(**R**) is the probability with which a certain profile **R** will be observed and Pr(**Tb**|**R**) is the probability of observing the brightness temperature vector, **Tb**, given a particular rain profile **R**. The first term on the right hand side of Eq. (1) is derived using cloud-resolving models (CRM). The strength of the algorithm is based on the accuracy and number of profiles contained in the dataset. Other authors have proposed analogous approaches and published additional results on cloud-radiation databases (CRD) (e.g., Di Michele et al., 2003, 2005). However, note that the complexity of the 3-D structure of precipitating systems is very high and a certain degree of uncertainty remains on which profile in the CRD is to be attributed to the PMW observational profile linked to a rainrate at the ground. The philosophy behind the recent work on GPROF v.7 (Elsaesser and Kummerow, 2007) is centered around a quantification of the errors associated with the measurement and model assumptions and the a-priori information contained in the retrieval algorithm through an optimal estimation technique. For example, chances are that a better definition of the errors associated with high liquid water path (LWP) non-precipitating clouds will be better defined.

The problem of low rainrates and stratiform rainfall is a serious one and most algorithms perform very poorly under these conditions. The melting layer inclusion in the PMW inversion methods for the generation of adequate CRDs was addressed by Bauer (2001) who was also among the few attempting to tackle the problem of modeling stratiform rainfall in the PMW (Bauer et al., 2000). Kidd (2007) has found that rain retrieval algorithms generally underestimate the rain area (0.6–0.9) and are equally split on rain amount (0.6–1.4), thus overestimating the conditional rainfall. The issue of low rainrate estimates is still under investigation and represents an important topic for future observations using high frequency microwave channels and the new active sensors as mentioned later in this paper.

3 Blended Global Products

Global precipitation products are of the maximum interest for a number of different applications at all scales. Naturally, gridded products find adequate use in meteorology, hydrology and climate for the assimilation in global as well as mesoscale models an for their verification. Adler et al. (2001) have intercompared 25 satellite products, 4 models and 2 climatological products during the 3rd Precipitation Intercomparison Project (PIP-3). The model products do significantly poorer in the Tropics, but are competitive with satellite-based fields in midlatitudes over land. Over ocean, products are compared to frequency of precipitation from ship observations. The evaluation of the observational products points to merged data products (including rain gauge information) as providing the overall best results.

The Global Precipitation Climatology Project (GPCP) offers a number of daily, pentad, monthly and yearly products from a variety of algorithms using VIS/IR and PMW (Huffman et al., 1997, 2001; Adler et al., 2003).

Applications in meteorology, hydrology and civil protection, however, require instantaneous products, which are by far the most affected by errors and biases.

Global products are generally derived using as many sensors as possible in order to ensure the best space-time coverage. One of the first global products is that by Turk et al. (2000) conceived at the Naval Research Laboratory (NRL). The algorithm is a blended technique that uses the NOAA PMW algorithm (Ferraro, 1997) to estimate rainfall upon the passage of a PMW sensor and builds a look-up-table (LUT) linking these rainrates to the IR brightness temperature data of the closest geostationary image. The "calibration" of IR temperatures in terms of rainfall is then used for estimating rainrates from all geostationary IR images until the next PMW sensor overpass when another LUT is built. An example of the NRL global precipitation product is shown in Fig. 2.

The same concept of probability matching between IR temperatures and PMW-derived rainrates has been applied to produce the Microwave/Infrared Rainfall Algorithm (MIRA) (Todd et al., 2001) at high spatial and temporal resolution. The algorithm is also used to produce daily precipitation estimates over Southern Africa for climate applications (Layberry et al., 2006). A similar algorithm that uses a linear relationship between geostationary IR and polar orbiting PMW data is the Microwave/Infrared Rain Rate Algorithm (MIRRA) (Miller et al., 2001), whose tests have indicated low biases and good performances also at daily and monthly scales.

Multispectral data for the identification of raining clouds are applied by the GOES Multispectral Rainfall Algorithm (GMSRA) (Ba and Gruber, 2001). The method uses NIR channels of geostationary sensors to estimate the effective radius of cloud particles at cloud top and dwells on the finding of Rosenfeld and Lensky (1998) that raining clouds are identified by the 15 μm radius threshold in daytime and by a 230 K threshold at nighttime. Rain areas are thus delimited using an empirical cloud microphysical signature at cloud top. The calibration was done using radar data at the ground.

Specific applications were conceived such as the Auto-Estimator (Vicente et al., 2000), which runs in real time for applications in flash flood forecasting, numerical modeling and operational hydrology. The technique uses the IR window of geostationary satellites to compute rainfall amounts based on a power law regression algorithm derived from a statistical analysis between radar-derived rainfall rate at the ground and satellite-derived IR cloud top temperatures collocated in space and time.

A totally novel concept of using PMW and IR was recently introduced by Joyce et al. (2004) with their Climate Prediction Center (CPC) morphing method (CMORPH), which uses motion vectors derived from half-hourly interval geostationary satellite IR imagery to propagate the relatively high quality precipitation

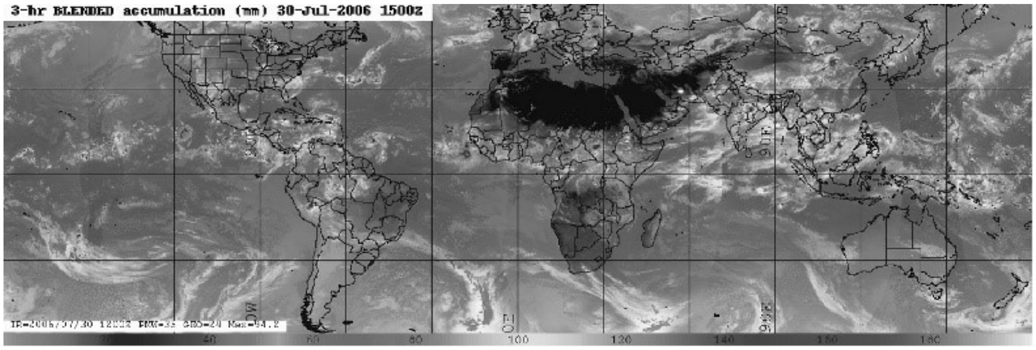

Fig. 2 Global 3-hourly cumulated precipitation (mm) on 30 July 2006, 1500 UTC as derived using the NRL blended PMW/IR algorithm. (courtesy of Naval Research Laboratory) (See also Plate 12 in the Colour Plate Section)

estimates derived from PMW data. The shape and intensity of the precipitation features are morphed during the time between PMW sensor scans by means of a time-weighted linear interpolation. The result are spatially and temporally complete PMW-derived precipitation analyses, independent of the IR temperature field. CMORPH showed substantial improvements over both simple averaging of the PMW estimates and over the above mentioned blended techniques. The technique does not solve the flaws of PMW rain estimation but certainly represent a step forward for global products by eliminating a possible source of errors of blended methods, i.e. the LUT production and its validity in time.

4 Combining Spaceborne Radar and PMW

The advent of TRMM in 1997 and its long lifetime in space have opened up the perspective of using spaceborne radar for estimating precipitation. For the first time algorithms were conceived and products made available on a regular basis for the tropical belt (Haddad et al., 1997; Iguchi et al., 2000). Since then several studies were conducted to compare PMW and PR precipitation estimates and to assess their relative performances. As is easily understood, both techniques of estimating rainrates have their strengths and weaknesses and neither one is completely winning. However, the PR in space has provided an unambiguous tool for cloud structure analysis, which helps considerably while verifying the PMW algorithms' performances.

Ikai and Nakamura (2003) have compared surface rain rates over the ocean derived from the TMI and the PR finding systematic differences due to three main reasons: 1) a problem in the freezing-level assumption in the TMI algorithm for midlatitude regions in the winter, which results in underestimation of TMI-derived rain rates; 2) inadequate $Z-R$ or $k-R$ relationships for convective and stratiform types in the PR algorithm; and 3) the incorrect interpretation of the rain layer when the freezing level is low and the rain type is convective. The strong bright band echo seems to be interpreted as rain and a too strong rain attenuation correction is applied. This results in a too high rain rate by the PR algorithm. Furuzawa and Nakamura (2005) have further investigated the performance of TMI in rain estimation using PR data and found that for low storm heights ($< 5\,\mathrm{km}$) the TMI rainrates are lower than the corresponding ones derived from PR, and this holds for both convective and stratiform rain. Vice versa, for higher storm heights ($> 8\,\mathrm{km}$) the PR estimates are lower. These findings show no dependencies on local time and latitude.

Nesbitt et al. (2004) have compared PR and TMI estimates across the Tropics and found that TMI overestimates rainfall in most of the deep Tropics and midlatitude warm seasons over land with respect to both the Global Precipitation Climatology Center (GPCC) gauge analysis and the PR. The PR is generally higher than the TMI in midlatitude cold seasons over land areas with gauges. The analysis by feature type reveals that the TMI overestimates relative to the PR are due to overestimates in mesoscale convective systems and in most features with 85-GHz polarization-corrected temperature (PCT) of less than 250 K (i.e., with a significant optical depth of precipitation ice).

Berg et al. (2006) relate PR–TMI differences to physical variables that can lead to a better understanding of the mechanisms responsible for the observed differences. For clouds identified as raining by both sensors, differences in rainfall intensity are found to be highly correlated with column water vapor. Adjusting either TMI or PR rain rates based on this simple relationship results in a 65%–75% reduction in the *rms* difference between seasonally averaged climate rainfall estimates. Differences in rainfall detection are most prominent along the midlatitude storm tracks, where widespread, isolated convection trailing frontal systems is often detected only by the higher-resolution PR. Conversely, over the East China Sea clouds below the ~18-dBZ PR rainfall detection threshold are frequently identified as raining by the TMI. Based on calculations using in situ aerosol data collected south of Japan the authors suggest that high concentrations of sulfate aerosols may contribute to abnormally high liquid water contents within non-precipitating clouds in this region.

The combined use of all passive and active instruments can be very instrumental in improving over PMW-based estimates, as for example shown by Grecu et al. (2004). Viltard et al. (2006) have recently used a PR-based database to improve TMI PMW rain estimates. The field is still very much experimental but it appears that perspectives are encouraging in view of the future Global Precipitation Measurement (GPM) Mission.

5 Exploiting Cloud Microphysics

The precipitation community is pursuing a data fusion path between PMW techniques and cloud microphysics as seen from multispectral VIS/NIR/IR measurements now available on geostationary satellites. An excellent perspective on the great potential of using cloud microphysical identification for satellite rainfall estimation is given by Rosenfeld and Woodley (2003). The concept is based on the original findings of Rosenfeld and Lensky (1998) and has significantly evolved considering cloud microstructure all around the world. The necessity of introducing a cloud microstructure identification in PMW estimation algorithms is also supported by the study of Rosenfeld and Ulbrich (2003) who used radar observations to connect raindrop size distributions (RSDS) to radar R-Z (rainfall-reflectivity) relationships from the point of view of rain forming mechanisms. Cloud microstructure which determines maritime and continental cloud masses, cloud dynamics which is behind convective and stratiform cloud classification, and also orographic effects are demonstrated to introduce systematic differences in rainrate estimations. R for a given Z is greater by a factor of more than 3 for rainfall from maritime compared to extremely continental clouds, a factor of 1.5–2 greater R for stratiform compared to maritime convective clouds, and up to a factor of 10 greater R for the same Z in orographic precipitation.

L'Ecuyer et al. (2006), after an investigation on the physical assumptions and information content of the cloud top microphysical retrieval algorithms applied to the MODerate resolution Imaging Spectroradiometer (MODIS) data, have concluded that the combination of the 0.64 and 1.64 μm channels during the daytime and the 3.75 and 11.0 μm channels at night provides the most information for retrieving the properties of the wide variety of liquid clouds modeled over ocean. Building on the analysis techniques of L'Ecuyer et al. (2006), Cooper et al. (2006) have conducted a reexamination of the ice cloud retrieval problem in the context of recent advancements in the understanding of optical properties for a variety of realistic ice crystal shapes. Their results suggest that the channels that maximize retrieval information are strongly dependent upon the state of the atmosphere, meaning that no combination of two or three channels will always ensure an accurate retrieval. Because of this, they suggest a five-channel retrieval approach consisting of a combination of error-weighted VIS, NIR, and IR channels: 0.64, 2.11, 4.05, 11.0, and 13.3 μm. However, the authors note that any of these channels could be replaced by another channel with similar characteristics with little loss in retrieval information.

Lensky and Rosenfeld (2003a) have pushed further the use of microphysical cloud top observations and conceived a nighttime rain delineation algorithm, which seems to perform well even in the case of warm clouds over land for which PMW methods mostly fail. The same technique based on brightness temperature differences (BTD) between the 11 μm and the 3.7 μm channels reveals very instrumental in retrieving the microphysical structure and thus the rain potential of nighttime clouds (Lensky and Rosenfeld, 2003b; see Fig. 3).

Masunaga et al. (2002a) have devised the first physical inversion algorithm for the combined use of VIS/IR and PMW sensors to retrieve the cloud physical quantities such as the LWP and the effective droplet radius using VIRS and TMI. The cloud top temperature obtained from the VIRS analysis is used as an input to the TMI analysis to reduce uncertainties in estimation of LWP. The scatter diagram of the shortwave-retrieved $\mathrm{LWP_{shrt}}$ versus the PMW-retrieved $\mathrm{LWP_{PMW}}$ shows

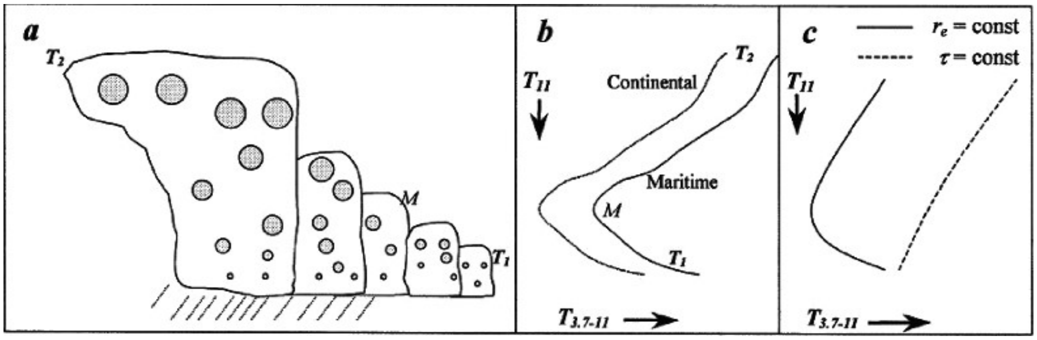

Fig. 3 Nighttime precipitation delineation method of Lensky and Rosenfeld (2003b). (**a**) Clouds of decreasing optical depth and decreasing effective radii from left to right correspond to a decreasing precipitating attitude. (**b**) The $T_{3.7-11}$ curve is drawn schematically as function of the T_{11} temperature. The two $T_{3.7-11}$ curves represent maritime clouds with larger particle sizes and larger $T_{3.7-11}$ (T_1) than those of continental clouds (T_2). (**c**) The effect of the optical depth and particle size on $T_{3.7-11}$. (Lensky and Rosenfeld 2003b; courtesy of the Amer. Meteor. Soc.)

characteristic trends for both precipitating and non-precipitating clouds. Vertical inhomogeneity of the cloud droplet size accounts for small excess of LWP_{shrt} over LWP_{PMW} for non-precipitating clouds, while precipitating clouds produce LWP_{PMW} larger than LWP_{shrt}, owing to the presence of raindrops. These tendencies are reinforced by examination of the global distributions of the shortwave-retrieved droplet radius $Re_{(NV)}$ and the MW counterpart defined by LWP divided by the cloud optical thickness $Re_{(MV)}$. Their results suggest that difference in those effective radii reflects a microphysical mechanism to expedite or suppress the conversion of the cloud water into rainfall.

An application of the above described method to investigate the characteristics of low clouds and warm-rain production in terms of droplet growth based on the effective droplet radii was published by Masunaga et al. (2002b). A categorization was proposed of low clouds into the following groups: (1) non-drizzling, non-raining clouds; (2) non-raining clouds with drizzling near the cloud top; (3) raining clouds; and (4) clouds with no clear interpretation in terms of the effective radii. This categorization is supported by examination of the correlation between static stability and the retrieved results in three "precipitating regions" (Middle Pacific, South Pacific Convergence Zone [SPCZ], and Intertropical Convergence Zone [ITCZ] cumulus regions) and in four "non-precipitating regions" (the Californian, Peruvian, Namibian, and eastern Asian stratus regions). The rainrate derived by the PR provides global characteristics consistent with these results. Californian and Peruvian stratus clouds are found to frequently have the drizzle mode near the cloud top, whereas Namibian strati have fewer chances to drizzle. The drizzle mode almost completely disappears in the eastern Asian region in the winter. The cloud–aerosol interaction is a promising candidate for suppressing the drizzle mode formation in non-precipitating clouds.

The use of lightning detection systems both from ground or spaceborne is being used to enhance the current capabilities in continuous rainfall monitoring over large regions at high spatio-temporal resolutions and in separating precipitation type into its convective and stratiform components (Morales and Anagnostou, 2003). The procedure accounts also for differences in land versus ocean and for various levels of cloud system maturity. Two examples of retrievals are shown in Fig. 4.

An upcoming application with great potential is the use of satellite rainfall estimates for the analysis of human influences on rainfall regimes, such as in the vicinity of major urban areas (Shepherd et al., 2002). Among other things, they found an average increase of about 28% in monthly rainfall rates within 30–60 km downwind of the metropolis, with a modest increase of 5.6% over the metropolis. Portions of the downwind area exhibit increases as high as 51%. The maximum rainfall rates in the downwind impact area exceeded the mean value in the upwind control area by 48–116%.

6 Climate and Global Model Applications

The increasing number of studies and the public concern about presumed climate changes require a clear vision of the necessary integrated observing system for the

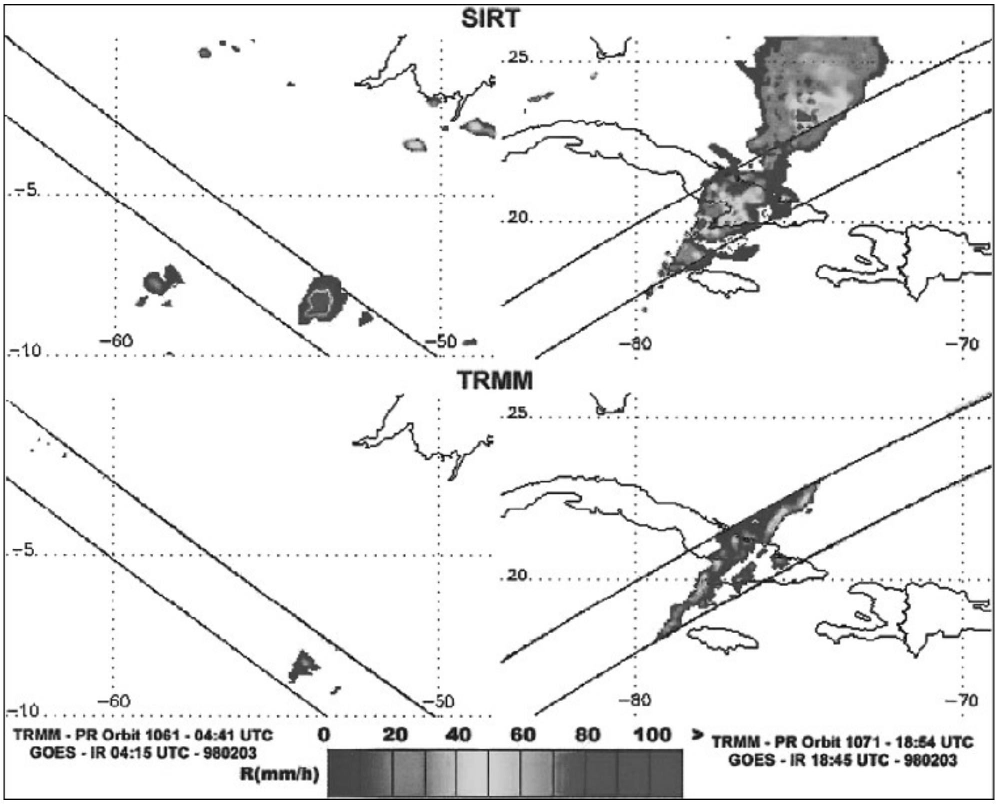

Fig. 4 Instantaneous surface rainfall rates retrieved by the Sferics Infrared Rainfall techniques (SIRT) (*top*) and TRMM PR (*bottom*). Two storm cases are shown in this figure: *left*, 0415 UTC 2 Feb 1998, TRMM orbit 1061; *right*, 1815 UTC 2 Feb 1998, TRMM orbit 1071. (Morales and Anagnostou, 2003; courtesy of the Amer. Meteor. Soc.) (See also Plate 13 in the Colour Plate Section)

identification of how and why the climate is changing globally and at the regional scale. Goody et al. (2002) commented that the societal need for a greater confidence in long-range climate predictions necessarily requires a monitoring program accurate enough to provide the objective verification of climate model capabilities. The key questions that an observing system from space has to address while planning future missions for climate are outlined by Asrar et al. (2001) for the National Aeronautics and Space Administration (NASA) strategy:

- How is the global earth system changing?
- What are the primary forcings of the earth system?
- How does the earth system respond to natural and human-induced changes?
- What are the significant consequences of global change for human civilization?
- What changes in the earth system will take place in the future?

In consequence, a major observation need exists to identify intensifications of the global water cycle as the most significant manifestation of climate change, and leading to increased global precipitation, faster evaporation, and a general exacerbation of hydrological extremes such as floods and droughts.

Trenberth et al. (2002) have identified the importance of transforming our current observing system into a new strategy that goes beyond the single measurement in itself and includes a processing and support system that leads to more reliable and useful data. In particular, the changes in precipitation are more likely in frequency, intensity, duration and type (Trenberth et al., 2003). New et al. (2001) have already pointed out the importance of gauge+satellite precipitation datasets for the identification of the changes in frequency, duration and increasing proportion of precipitation during the heaviest event. All these topics have to be tackled if we want to seriously address the problem of changes in the global water cycle.

In a report of the National Academy of Sciences (NAS) Robinson et al. (2004) have identified a few major points for using satellite precipitation data for long climate records: dependence of retrieval and bias errors on the frequency of high-quality (e.g., PMW) observations, difficulty of measuring solid precipitation, necessity to have in situ validation sites across a variety of climate regimes, and importance to have as many accurate validation sites as possible to maximize the accuracy of the final "best" combination products.

Three different areas are of particular importance for regional and global weather and climate applications: regional studies of the characteristics of precipitating systems, land surface model parameterizations, and model verifications. Three examples in these crucial development areas will now be described.

Reporting the outcomes of a US Weather Research Program (USWRP) workshop held in 2002 on warm season quantitative precipitation forecasts (QPF) Fritsch and Carbone (2004) outline the research strategy to attack the problem of the relatively poor scores of such predictions. One of the key problems is the representation of moist convection in operational models, which is done through parameterization. Improving these parameterizations is believed to be the necessary step towards substantial advances in forecast scores. In particular, the following points are to be considered:

- knowledge of the cloud-scale and mesoscale structure of the environment,
- adequate understanding and representation of cloud-scale and microphysical processes, and
- realistic treatment of certain subcloud-scale processes such as moist turbulence.

Carbone et al. (2002) have set the path towards meeting the first requirement and conducted an extensive study over conterminous US using the Weather Surveillance Radar-88 Doppler (WSR-88D) network. Clusters of heavy precipitation are found to display coherent patterns of propagation across the continental US with propagation speeds for envelopes of precipitation that exceed that of any individual mesoscale convective system (MCS). Their longevity (up to 60 h) suggests an intrinsic predictability of warm season rainfall that significantly exceeds the lifetime of individual convective systems. Wang et al. (2004) developed a similar climatology for warm season precipitation in East Asia using IR brightness temperatures from the Japanese Geostationary Meteorology Satellite (GMS). Their study showed propagation of cold-cloud clusters (or quasi-precipitation episodes) across a zonal span of 3000 km with a duration of 45 h. Regional analysis was successively performed by

Wang et al. (2005) who found latitudinal effects with larger spans, longer durations and stronger propagations in the northern (30–40 N) than in southern (20–30 N) zone. The May–August transition over land (western sector, 95–120 E) was mainly characterized by an increase in diurnal activities, while that over ocean (eastern sector, 120–145 E) was characterized by decreased overall activities instead. Between the two bands, near 107 E, semidiurnal signals were relatively strong and became dominant in June. This double-peaked structure in the diurnal cycle resulted from overlying signals of convection propagating eastward off the Tibetan plateau with those induced locally in late afternoon, and the phenomenon was more evident in May–June. Over the ocean both diurnal and semidiurnal waves had small amplitudes, and the regional variability was much weaker. A similar study was started later over Europe and preliminary results published by Levizzani et al. (2006). Other studies of this worldwide program are being conducted over Africa, Australia and South America.

Note that climate features come out not only as an effect of long term averages, but also from significant deviations from such averages that have a great impact on the society. Zipser et al. (2006) have used the unique capabilities of TRMM PR data in measuring the vertical extent of strong radar echoes and the high-frequency channels of the TMI that give a good indication of the columnar mass and/or density of precipitating ice to investigate a first global climatology of the most intense storms. The diurnal cycle over land and ocean is reported in Fig. 5.

Land surface modeling is becoming increasingly important for climate models as well as for hydrological use. Lee and Anagnostou (2004) have examined the

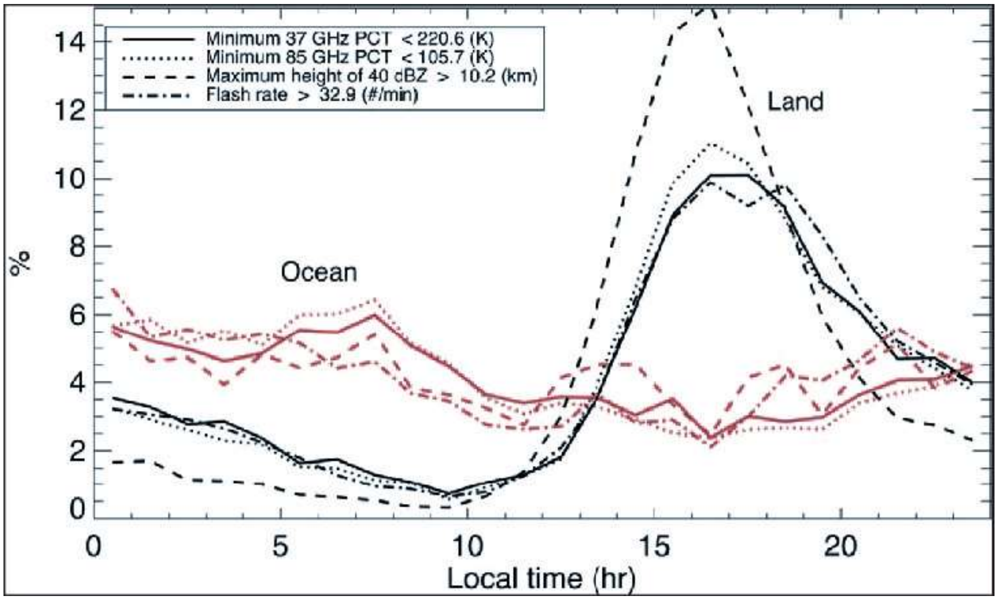

Fig. 5 Diurnal cycle of the three most extreme storm categories (top 0.1%) using 37 and 85 GHz PCT, maximum storm height at 40 dBZ, and lightning flash rate separated by land and ocean precipitation features. There are not enough extreme events over oceans to use only the top two categories. (Zipser et al., 2006; courtesy of Amer. Meteor. Soc.)

effects of precipitation forcing on land surface hydrological variables predicted by a physically based land surface scheme using the Community Land Model (CLM). Results show that the hydrological response is nonlinear and strongly dependent on the error characteristics of the retrieval. Time resolution is shown to have an effect on the error statistics of the hydrologic variables. Coarse time resolutions are associated with errors of lower variance and higher correlation. An important conclusion from this study is that the effects of vegetation and the structural characteristics of rain retrieval error are the primary factors controlling the propagation of errors in the simulation of land surface variables.

Since precipitation exhibits a high spatial variability at very small scales, neglecting subgrid-scale variability in climate models causes unrealistic representation of land–atmosphere flux exchanges, and this is especially severe over densely vegetated areas. Wang et al. (2005) have incorporated satellite-based precipitation observations into the representation of canopy interception processes in land surface models. Their results reveal that incorporation of precipitation subgrid variability significantly alters the partitioning between runoff and total evapotranspiration as well as the partitioning among the three components of evapotranspiration (canopy interception loss, ground evaporation, and plant transpiration). This further influences soil water, surface temperature, and surface heat fluxes. The study demonstrates that land surface and climate models can substantially benefit from the fine-resolution remotely sensed rainfall observations.

Finally, model verification is a topic of utmost relevance and the Global Energy and Water Cycle Experiment (GEWEX) Cloud Systems Study (GCSS) group has undertaken an extensive effort to make use of available observations for cloud and global model evaluation (Randall et al., 2003). The key element of the GCSS work program is the development of improved cloud parameterizations for climate and numerical weather prediction (NWP) models. This is accomplished through the use of cloud-system-resolving models (CSRM). These are models with sufficient spatial and temporal resolution to represent individual cloud elements, and covering a wide enough range of time and space scales to permit statistical analysis of simulated cloud systems.CSRMs can be used as experimental test beds to develop understanding, to produce synthetic four-dimensional datasets, and to test parameterizations. They have in general better performances than simple Single-Column Models (SCM), which represent essentially the column physics of a general circulation model (GCM) considered in isolation from the rest of the model. These latter are the piece that needs to be improved. An example of a case study done by GCSS is shown in Fig. 6 where CSRM and SCM model outputs are compared with cloud radar observations.

7 A Glimpse on International Efforts

International activities concentrate on the improvement of algorithms, especially combined, multisensor algorithms, the calibration and validation of existing products, and the preparation of upcoming satellite missions.

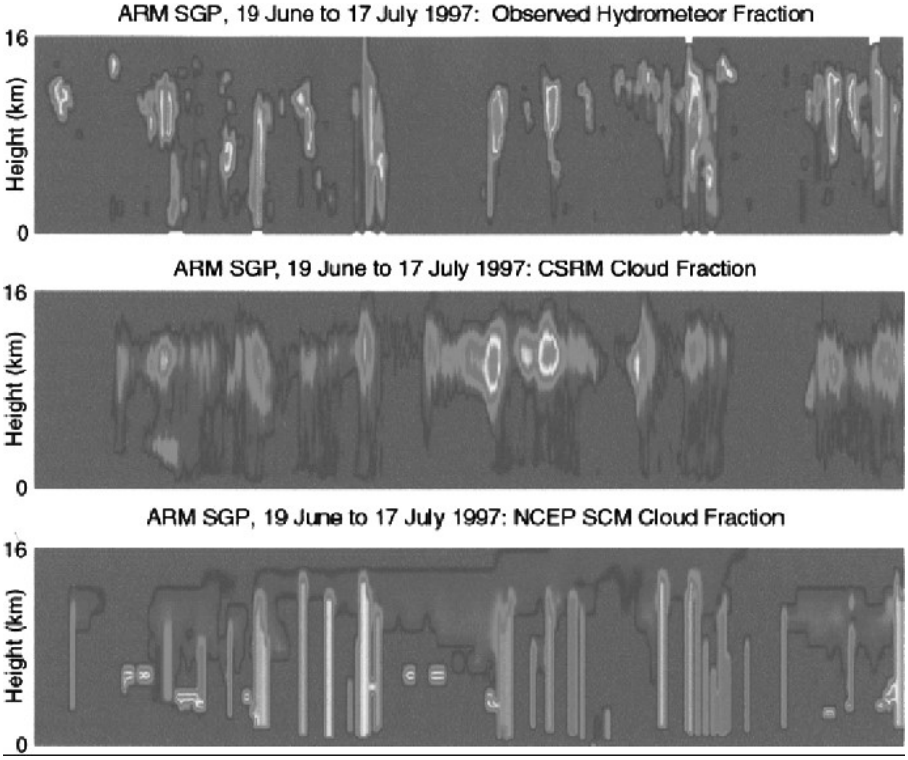

Fig. 6 Time–height cloud fraction for a GCSS case study over the Atmospheric Radiation Measurement (ARM) site in Oklahoma, surface to 16 km: (*top*) observed by the Millimeter wavelength Cloud Radar (MMCR) (3-h averages), (*middle*) simulated by UCLA–CSU CSRM (1-h averages), and (*bottom*) simulated by NCEP SCM (3-h averages). Shades indicates cloud fraction, which ranges from 0 to 1 from outside to the inside of the clouds. (Randall et al., 2003; courtesy of Amer. Meteor. Soc.) (See also Plate 14 in the Colour Plate Section)

The International Precipitation Working Group (IPWG), in particular, was established to organize efforts of the community worldwide. It is active since 2001 and is co-sponsored by the Coordination Group for Meteorological Satellites (CGMS) and the World Meteorological Organization (WMO). The IPWG has launched several activities that are of interest for the overall user community:

- Validation is now being conducted on a routine basis over Australia, Europe and the USA, and data are available on the web site (see Appendix).
- The PMW modeling efforts for the retrieval of snowfall are another important chapter since precipitation estimates up to now have completely disregarded solid precipitation.
- Global products are now available at coarse resolution and this is the reason why IPWG is sponsoring an activity called Program for the Evaluation of High Resolution Precipitation Products (PEHRPP).

New missions are planned that will involve participation from several countries in a combined effort for the best possible space-time coverage and the observation of cloud microphysics. The most important of these plans concerns the GPM mission (Smith et al., 2007; Hou et al., 2008), a constellation of satellites with a main spacecraft hosting a dual-frequency precipitation radar and an advanced PMW radiometer. The constellation will then consist of a large number of smaller satellites boarding PMW radiometers, which will be calibrated against data from the mother ship. It is foreseen that a global coverage of precipitation estimates every 3 h will be reached.

Another important effort focuses on the completion of another constellation, the so-called A-train (Stephens et al., 2002), whose most important component for precipitation studies is CloudSat that flies the first spaceborne millimeter wavelength radar. The unique feature of this radar lies in its ability to observe most of the cloud condensate and precipitation within its nadir field of view and provide profiles of these properties with a vertical resolution of 500 m. CloudSat flies as part of a constellation of satellites that includes the Earth Observing System's (EOS) Aqua and Aura at each end of the constellation, CloudSat, the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) that flies an aerosol lidar, and another small satellite, the Polarization and Directionality of the Earth's Reflectances (PARASOL), carrying the POLDER polarimeter inserted in the formation between the larger EOS spacecraft. CloudSat and CALIPSO have been launched on 28 April 2006 and their products are now available. An example is shown in Fig. 7. Along the line of international partnership is also the Earth Clouds, Aerosol and Radiation Explorer (EarthCARE, ESA, 2001) mission, a joint European-Japanese endeavor being planned.

The idea is to explore what is currently unknown on large scale cloud features from all perspectives and provide new microphysical, radiative and dynamic insights to the rainfall estimation algorithms. The cloud ice content and vertical structure are two of the most important topics to be addressed.

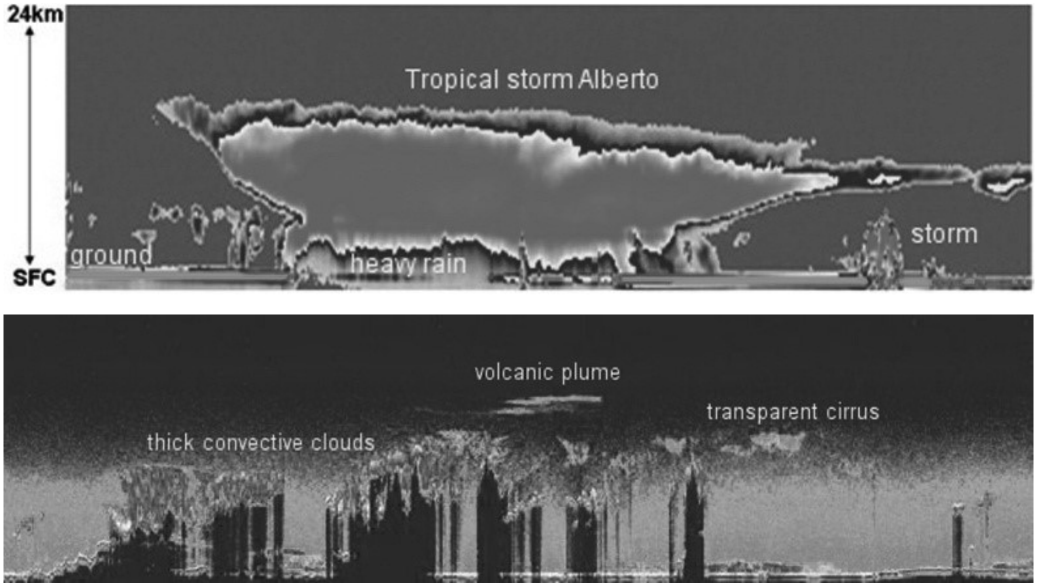

Fig. 7 The *top* image is a vertical cross-section of Tropical Storm Alberto, the first named storm of the 2006 Atlantic Hurricane season, captured by the CloudSat radar on 12 June, 2006. The *bottom* image is a vertical cross-section of the atmosphere from the lidar on CALIPSO northeast from a location near the southwest coast of Australia, across Indonesia and the Pacific Ocean, and over part of Japan on 7 June, 2006. (courtesy of NASA Earth Observatory, http://earthobservatory.nasa.gov/) (See also Plate 15 in the Colour Plate Section)

Appendix: Relevant Web Sites

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO)
http://www-calipso.larc.nasa.gov/
CloudSat
http://cloudsat.atmos.colostate.edu/
Global Energy and Water Cycle Experiment (GEWEX)
http://www.gewex.org/
Global Precipitation Climatology Project (GPCP)
http://cics.umd.edu/ ∼yin/GPCP/
Global Precipitation Measurement (GPM) Mission
http://gpm.gsfc.nasa.gov/
International Precipitation Working Group (IPWG)
http://www.isac.cnr.it/∼ipwg/
MODerate resolution Imaging Spectroradiometer (MODIS)
http://modis.gsfc.nasa.gov/
NASA Earth Observatory
http://earthobservatory.nasa.gov/
NASA Goddard Global Precipitation Analysis
http://precip.gsfc.nasa.gov/
NOAA CPC Morphing products
http://www.cpc.ncep.noaa.gov/products/janowiak/cmorph.html
NOAA Microwave Surface and Precipitation Products System
http://www.orbit.nesdis.noaa.gov/corp/scsb/mspps/
NRL Satellite Meteorology group
http://www.nrlmry.navy.mil/sat_products.html
Program to Evaluate High Resolution Precipitation Products (PEHRPP)
http://essic.umd.edu/∼msapiano/PEHRPP/
Tropical Rainfall Measuring Mission (TRMM)
http://trmm.gsfc.nasa.gov/
TRMM Online Visualization and Analysis System (TOVAS)
http://lake.nascom.nasa.gov/tovas/
TRMM Science Data and Information System (TSDIS)
http://tsdis.gsfc.nasa.gov/

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