Remote Sensing of Precipitation from Space over Land Surfaces

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1. Introduction

Rainfall estimation from satellite data over land surfaces still represents a challenge because neither at visible/infrared (VIS/IR) nor at microwave wavelengths (MW) do raindrops provide significant contributions to the total signal to allow a direct estimation of rain rate near the surface. In VIS/IR methods, cloud top temperature and reflectivity are usually related to time-space averages of surface rainfall (Arkin and Meisner 1978, Adler and Negri 1988, Barrett et al. 1995, Ba and Gruber 2001). Therefore, VIS/IR methods show some skill on aggregated scales suitable for climatology but little accuracy for instantaneous estimates generally required for process studies and numerical weather prediction (NWP). The advantage of VIS/IR observations, mainly from geostationary satellites, is the high temporal sampling frequency (15-30 minutes) and rather high spatial resolution (5 km) that is useful for monitoring cloud evolution. With at least 5 operational geostationary satellites, global coverage is achieved over a latitude range of 0-60 degrees.

At microwave wavelengths (*mm* to *cm* or frequencies of ~10-200 *GHz*), clouds and precipitation are radiometrically more transparent so that the observed radiances (usually expressed in blackbody equivalent brightness temperatures, *TB*) respond to changes in hydrometeor profiles but also to surface emission. At these wavelengths, land surface emissivity is high and spatially quite variable so that the land surface contribution to observable radiance is difficult to separate from that of rain and therefore greatly affects rainfall retrieval accuracy (e.g. Petty 1995). For instantaneous applications, rain rate retrieval accuracy ranges from 50-200*%* at a spatial resolution of 5-15 *km*. At present, three satellites of the Defense Meteorological Satellite Program (DMSP) and one AQUA satellite provide passive microwave observations that are well suited for rainfall retrievals. This set produces a near-global coverage every 12 hours.

With the launch of the Tropical Rainfall Measuring Mission in November 1997, the first spaceborne precipitation radar (PR) became available (Kummerow et al. 1998). It is a single-frequency (13.8 *GHz*), electronically scanning radar with nominal resolutions of 4.3 *km* and 0.25 *km* in the horizontal and vertical dimensions, respectively. The cross-track scan pattern covers a 215 *km* swath. Its sensitivity is specified with 0.5 *mm/h*. The TRMM orbit is non sun-synchronous and covers latitudes between 38°N and 38°S. Even though the spatial sampling is limited, this observation tool provides the most accurate rain retrievals with an estimated accuracy of 15-25*%*. Ideally, a global spaceborne rainfall observing system would comprise a sufficient number of precipitation radars of the TRMM type to fulfill the general requirements of accuracy and spatial/temporal sampling. However, the cost of such a system is prohibiting so that passive visible/infrared and microwave radiometers will provide the bulk of such observations in the future.

In terms of data interpretation, the single-sensor retrieval methodology is well established. However, the synergetic use of passive visible/infrared and microwave as well as active microwave data has been studied only in the very recent past due to the increasing demand of regional and global users for rapid-update, near real-time and high spatial resolution products. Also, the assimilation of rainfall observations in NWP models has been initiated at various forecasting agencies and is likely to improve forecasts in cases where only a few other observations are available. NWP model output serves a large variety of communities and accurately predicted precipitation distributions therefore have a large impact on many applications. The next section illustrates the passive microwave signatures of precipitation. The state of rainfall retrieval from space over land surfaces is briefly summarized and validation examples are given. The paper also provides an outlook to future developments with regard to satellite instrument and retrieval algorithm development.

2. Passive microwaves

Visible reflectance and infrared emission measurements at the top of the atmosphere have been used for cloud observation and cloud development tracking since their availability in the 1970's. In recent years and with the development of more sophisticated sensors, more physical information on cloud type, development stage and precipitation processes could be inferred (e.g. Levizzani et al. 2002). The instantaneous retrieval of actual near-surface rain rates, however, is rather inaccurate due to the loose physical connection between near-cloud top cloud physics and surface rain rate. For this reason, passive microwave observations have always been preferred for instantaneous applications due to the better relation between precipitating water and microwave radiation.

Figure 1 shows an example of passive microwave signatures of clouds and precipitation at microwaves over land. The figure was generated from combined cloud-radiative transfer simulations of top-of-the-atmosphere microwave radiances at 22, 53, 89, 183±7 *GHz*, respectively. These frequencies correspond to channel 1 of the Special Sensor Microwave/Imager (SSM/I), channel 4 of the Advanced Microwave Sounding Unit (AMSU-A), and channels 1 and 5 of AMSU-B. The simulation represents the storm responsible for the Piemonte flood in October 2000 and was carried out with the non-hydrostatic mesoscale model of the University of Wisconsin-Madison (Tripoli 1992) and a multiple-scattering radiative transfer code (Bauer 2001). Land surface emissivity was assumed to be constant over the entire frequency range and for nadir incidence while sea surface emissivity increases with frequency.

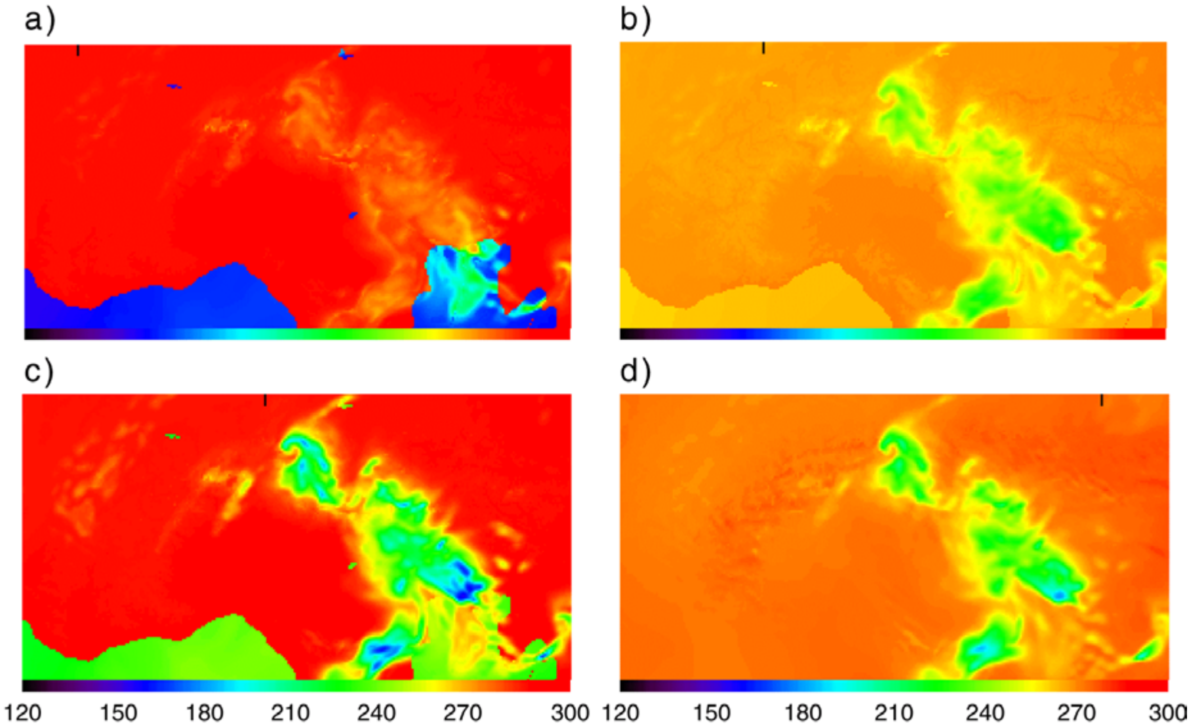

Figure 1: Simulated top-of-the-atmosphere brightness temperatures (in degrees K) at 22 (a), 53 (b), 89 (c), 183±7 (d) GHz of the storm system the caused the Piedmonte flood October 13-16, 2000.

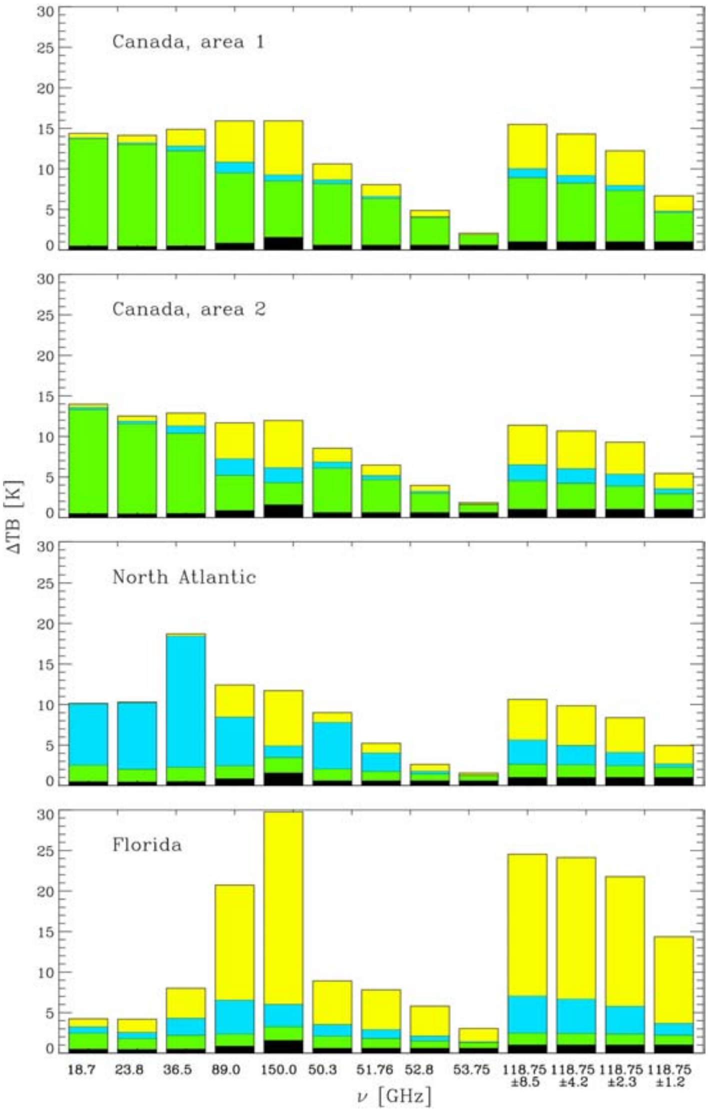

Figure 2: Passive microwave radiometric signal from liquid (blue) and frozen (yellow) precipitation, surface(green) and radiometer noise (black) for Canadian snowstorm (a, b), Atlantic front (c) and Florida convection. Simulations performed at window channels (18.7, 23.8, 36.5, 89.0, 150 GHz) and near oxygen absorption lines (50+, 118.75± GHz).

The simulation shows the radiometric contrast between rain, clouds and the surface. Generally, the higher the frequency the more scattering occurs inside the cloud and the lower the brightness temperatures (TB) become. At 22 *GHz* (Figure 1a), the surface contribution is dominant and the cloud is almost transparent. At 53 *GHz* (Figure 1b), cloud water emission is stronger and the bulk of the signal originates from mid to upper layers therefore the TB's are reduced with regard to surface emission. However, the vicinity of this frequency to strong oxygen absorption lines also increases the clear-sky emission and reduces the contrast between land and ocean. At 89 *GHz* (Figure 1c), clear-sky emission is weaker again and scattering of radiation at precipitating hydrometeors occurs. TB's < 200 *K* indicate areas with highest precipitation intensity. At 183±7 *GHz* (Figure 1d), scattering should be even stronger but becomes attenuated by the strong water vapor absorption at this frequency. In summary, (1) higher frequencies respond stronger to precipitation, (2) window frequencies have significant surface contributions, (3) frequencies near absorption lines provide compromise between response to precipitation and reduction of surface signal.

The trade-off between maximizing the cloud signal and minimizing surface contributions becomes critical for less intense rain and light snowfall. For a quantitative estimation, Bauer and Moreau (2005) simulated signal variability from clouds, surface and radiometer noise for three different synoptic situations (Canadian snowstorm, North Atlantic front, scattered Florida convection). The simulations were carried out at common window frequencies (18.7, 23.8, 36.5, 89.0, 150.0 *GHz*) as well as frequencies near strong oxygen absorption lines (sounding channel frequencies, 50-60, 118.75 *GHz*). The latter have less sensitivity to surface effects due to the stronger contribution of clear atmospheric absorption. Figure 2 compares the radiometric standard deviation (in degrees *K*) for four cases; the first two being from the same precipitation system but with less intensity and no liquid precipitation (Figure 2a) and with higher intensity and moderate liquid precipitation amounts (Figure 2b). As a reference, an oceanic case has been included as well (Figure 2c). The comparison indicates that at lower frequencies the surface contribution dominates the signal so that these frequencies provide little information on precipitation. Only at higher frequency window and sounding channel frequencies the signal to noise relationship suggests that rainfall/snowfall retrieval is possible. Studies of this kind are crucial for estimating the benefit of various channel combinations when future satellite sensors are developed.

3. Retrieval algorithms

Retrieval techniques that are based on VIS/IR observations may have reached the limits of sophistication simply because of the loose connection of near cloud-top cloud physics and near-surface rainfall. From the more climatologically oriented algorithms developed 20 years ago (e.g. Arkin and Meisner 1987, Scofield 1987), the current developments point towards more ‘physical’ techniques that attempt to infer certain microphysical key parameters (e.g. effective droplet radius) to identify cloud development stage and cloud type for constraining the inversion (e.g. Levizzani et al. 2002). This approach is nurtured by the improvement of VIS/IR sensors that have more channels with narrower spectral widths, for example Meteosat’s Spinning Enhanced Visible & InfraRed Imager (SEVIRI).

Algorithms that use passive microwave observations mainly employ the available higher frequencies (85-150 GHz from SSM/I, Advanced Microwave Scanning Radiometer (AMSR), AMSU, TRMM Microwave Imager (TMI)) to maximize the precipitation signal (Grody 1991, Ferraro and Marks 1995, Ferraro et al. 2000, Kidd et al. 2003). As outlined above, surface effects are problematic at these frequencies so that algorithms emerged recently that include sounding channels in the retrievals (Bauer and Mugnai 2004).

Merging/blending techniques have gained importance from the demand for high spatial/temporal resolution products. These techniques combine infrared and microwave observations such that the infrared observations produce a high-frequency preliminary rain estimate that is calibrated by less frequent but more accurate microwave observations. There are two basically different approaches: (1) the calibration techniques (Huffman et al. 1997, Turk et al. 2000) and (2) the ‘morphing’ techniques (Joyce et al. 2004). All these are run operationally at NASA/Goddard Space Flight Center (GSFC), Naval Research Laboratory (NRL) and NOAA/Climate Prediction Center (CPC), respectively. The former calibrate a rainfall retrieval obtained from geostationary infrared observations by regional and temporally varying weighting factors (Huffman et al. 1997, Adler et al. 2003) or through *TB*-rainfall histogram matching (Turk et al. 2000, Levizzani et al. 2000). The involved single-sensor algorithms may employ ancillary information on surface or atmospheric condition (Hsu et al. 1997). The morphing techniques retrieve advection dynamics from subsequent infrared cloud imagery and produce synthetic microwave rain retrievals with high temporal resolution by applying the dynamics to two real subsequent observations. Obviously, the merging techniques become more accurate the more accurate and frequently available the microwave estimates are.

There are only a few techniques for combining passive and active microwave observations. This is because the observation geometry is quite different and the information obtained from the radar must be largely degraded to match the specifications of the radiometer. The first-order impact of the radar observations on the combined retrieval is the removal of retrieval biases from the radiometer estimates. For satellite applications, these methods were mainly developed in the framework of TRMM (Haddad et al. 1997, Connor and Petty 1998, Bauer et al. 2001, Bauer et al. 2002).

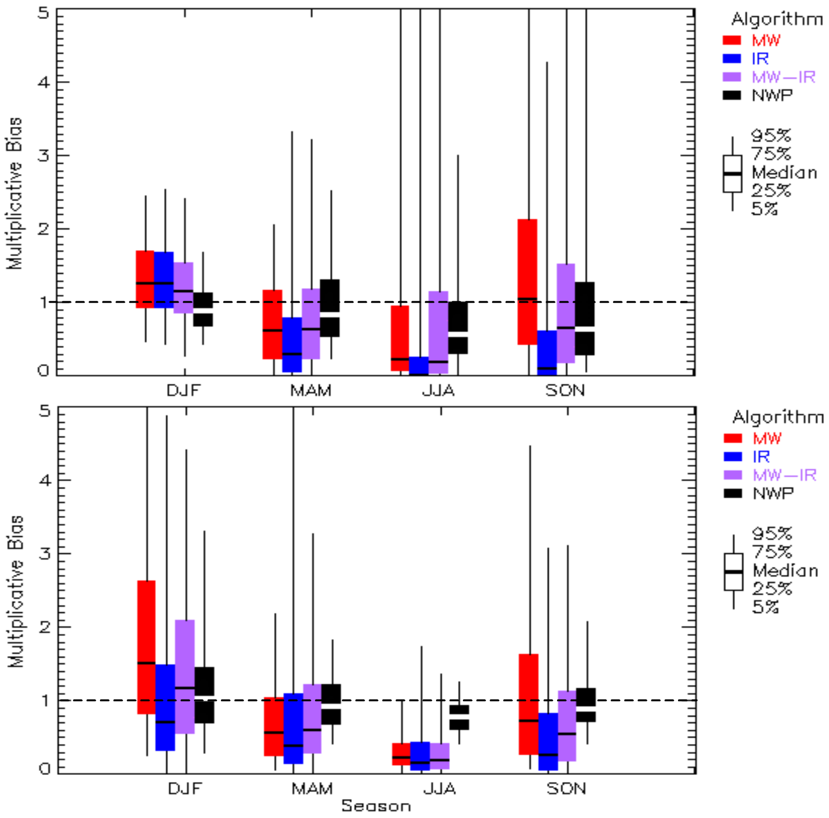

Figure 3: Summary of algorithm validation over 22 months (December 2002 - September 2004) on a 1°x1° grid over Australia (Ebert 2002) for passive microwave (MW), infrared (IR) and merged (MW-IR) satellite products as well as numerical weather prediction (NWP) model output. Top panel refers to Australian tropics bottom panel to Australian mid-latitudes (Courtesy Beth Ebert, BMRC).

4. Validation

The validation of space-based precipitation retrieval products is a major undertaking because the validation data itself is vulnerable to large uncertainties. Surface rain gauge and radar networks are only densely populated in industrialized areas. Therefore the representativeness of rain observations at the surface greatly depends on the applied quality control and the final product's temporal and spatial resolution (e.g Krajewski et al. 2000).

In the past, algorithm evaluation projects over land surfaces have been carried out under the auspices of the World Meteorological Organization (WMO) and within NASA's WetNet program. Ground validation represented a substantial part of the TRMM program and initiated several field campaigns. Dedicated and continuously operating ground validation sites (so called super-sites) are already planned in preparation of the Global Precipitation Measurement (GPM) mission that is foreseen for the 2010+ timeframe.

Continuous regional and global validation efforts are maintained, among others, by the Global Precipitation Climatology Centre (GPCC[1]), the Bureau of Meteorology Research Centre (BMRC[2]), NOAA's Climate Prediction Center (CPC[3]), and the University of Birmingham[4]. Daily and monthly validation statistics are produced and regularly updated.

Figure 3 shows an example of a summary of algorithm validation over 22 months (December 2002 - September 2004) on a 1°x1° grid over Australia (Ebert 2002). The figure summarizes the performance of a collection of passive microwave, infrared and merged satellite estimates and NWP model forecasts in terms

[1] http://www.dwd.de/de/FundE/Klima/KLIS/int/GPCC/GPCC.htm

[2] http://www.bom.gov.au/bmrc/wefor/staff/eee/SatRainVal/sat_val_aus.html

[3] http://www.cpc.ncep.noaa.gov/products/janowiak/us_web.shtml

[4] http://kermit.bham.ac.uk/~kidd/ipwg_eu/ipwg_eu.html

of multiplicative biases. The discrepancy between generic estimates is generally quite large. Between autumn and spring, the infrared retrievals perform worse than the other sources. Interestingly, the forecast models seem to outperform the direct observations in most situations with less biased estimates and more narrow departure distributions. The results in Figure 3 certainly depend on the selection of algorithms and NWP models as well as the validation area and time scales so that no global conclusions may be drawn from this example. However, the example indicates that merged satellite products generally perform equally or better that the individual single-sensor algorithms and that NWP models perform equally well. This points at the fact that future developments will focus on algorithm merging and data assimilation for improving satellite-only or satellite-model estimates of precipitation.

5. Outlook

In preparation of GPM, many algorithm developers have realized the requirement for a globally concerted and flexibly designed algorithm framework (Kummerow et al. 2005). This framework requires an open architecture that will allow the international community to participate in the algorithm development, its refinement, and its error characterization. Algorithms designed for the future should also be able to fully characterize uncertainties at any space and time scale being considered by the users. This ranges from instantaneous estimates needed for many hydrologic and weather forecasting applications to large space and time averages required for climate model verification and climate trend monitoring. While such a requirement is perhaps self-evident, such a complete error characterization does not currently exist and is undoubtedly the greatest challenge facing the community. Currently, instantaneous retrieval errors over land surfaces reach from 50 to several hundred percent depending on the surface and atmospheric characteristics as well as the employed observation instruments. While this seems excessive it must be admitted that ground validation data itself lacks both representativeness and coverage in many cases and that it may be inaccurate to a similar degree as the satellite estimates.

Several rainfall product intercomparison studies have indicated that numerical forecasting model output shows similar skill as space-based observations. This can only be explained by the increasingly accurate model physical parameterizations and better data assimilation schemes that have been developed in recent years. The assimilation of rainfall observations itself in large-scale model analyses is established at several forecasting centers (e.g. NCEP, JMA, ECMWF; Mahfouf et al. 2004) and can be expected to produce impact in situations where cloud and rain dynamics can not be significantly constrained by other observations that are currently only available in cloud-free areas.

Recently, WMO has established an International Precipitation Working Group (IPWG, http://www.isac.cnr.it/~ipwg) that provides a platform for many international activities regarding satellite missions and instruments, algorithm development efforts, validation issues and operational product generation. Apart from the references mentioned in this paper, Levizzani et al. (2005) provides an up-to-date overview of rainfall observation from space.

6. References

Adler, R.F., and A.J. Negri. 1988: A Satellite Infrared Technique to Estimate Tropical Convective and Stratiform Rainfall. *J. Appl. Meteor.*, **27**, 30-51.

Adler, R.F., C. Kidd, G. Petty, M. Morrisey, and M.H.Goodman, 2001: Intercomparison of global precipitation products: The Third Precipitation Intercomparison Project (PIP-3). *Bull. Amer. Meteor. Soc.*, **82**, 1377-1396.

Adler, R.F., G.J. Huffman, A. Chang, R. Ferraro, P. Xie, J. Janowiak, B. Rudolf, U. Schneider, S. Curtis, D. Bolvin, A. Gruber, J. Susskind, and P. Arkin, 2003: The Version 2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979-Present). *J. Hydrometeor.*, **4**, 1147-1167.

Arkin, P.A., and B.N. Meisner, 1987: The Relationship Between Large-Scale Convective Rainfall And Cold Cloud Over The Western Hemisphere During 1982-1984. *Mon. Wea. Rev.*, **115**, 51-74.

Ba, M.B. and A. Gruber, 2001: GOES multiple spectral rainfall algorithm (GMSRA). *J. Appl. Meteor.*, **40**, 1500-1541.

Barrett, E.C. and co-authors, 1995: The first WetNet Precipitation Intercompariosn Project (PIP-1): Interpretation of results. *Remote Sens. Rev.*, **11**, 303-373.

Bauer, P., 2001: Microwave radiative transfer simulation in clouds: Including a melting layer in cloud model bulk hydrometeor distributions. *Atmos. Res.*, **57**, 9-30.

Bauer, P., D. Burose, and J. Schulz, 2002: Rainfall detection over land surfaces using passive microwave satellite data. *Meteor. Z.*, **11**, 37-48.

Bauer, P., P. Amayenc, C. D. Kummerow, E. A. Smith, 2001: Over ocean rainfall retrieval from multi-sensor data of the Tropical Rainfall Measuring Mission. Part II: algorithm implementation, *J. Atmos. Oceanic Technol.*, **18**, 1838-1855.

Bauer, P. and A. Mugnai, 2004: Precipitation profile retrievals using temperature--sounding microwave observations. *J. Geophys. Res.*, **108**, doi:10.1029/2003JD003572.

Bauer, P. and E. Moreau, 2005: Hydrometeor retrieval accuracy from microwave window and sounding channel observations. *J. Appl. Meteor.*, in press.

Conner, M.D. and G.W. Petty, 1998: Validation and intercomparison of SSM/I rain-rate retrieval methods over the continental United States. *J. Appl. Meteor.*, **37**, 679-700.

Ebert, E.E., 2002: Verifying satellite precipitation estimates for weather and hydrological applications. *1st Intl. Precipitation Working Group (IPWG) Workshop*, Madrid, Spain, 23-27 September 2002.

Ferraro, R.R. and G.F. Marks, 1995: The development of SSM/I rain-rate retrieval algorithms using ground-based radar measurements. *J. Atmos. Oceanic Technol.*, **12**, 755-770.

Ferraro, R.R., F. Weng, N.C. Grody and L. Zhao, 2000: Precipitation characteristics over land from the NOAA-15 AMSU sensor. *Geophys. Res. Let.*, **27**, 269-2672.

Grody, N.C., 1991: Classification of snowcover and precipitation using the Special Sensor Microwave Imager. *J. Geophys. Res.*, **96**, 7423-7435.

Haddad, Z.S., E.A. Smith, C.D. Kummerow, T. Iguchi, M.R. Farrar, S.L. Durden, M. Alves, and W.S. Olson, 1997a: The TRMM "Day-1" Radar/Radiometer Combined Rain-Profiling Algorithm. *J. Meteor. Soc. Japan*, **75**, 799-809.

Hsu, K, X. Gan, S. Sorooshian and H.V. Gupta, 1997: Precipitation estimation from remotely sensed information using artificial neural networks. *J. Appl. Meteor.*, **36**, 1176-1190 .

Huffman, G.J., R.F. Adler, P. Arkin, A. Chang, R. Ferraro, A. Gruber, J. Janowiak, A. McNab, B. Rudolf, and U. Schneider, 1997: The Global Precipitation Climatology Project (GPCP) Combined Precipitation Data Set. *Bull. Amer. Meteor. Soc*., **78**, 5-20.

Joyce, R.J., J.E. Janowiak, P.A. Arkin, and P. Xie, 2004: CMORPH: A Method that Produces Global Precipitation Estimates from Passive Microwave and Infrared Date at High Spatial and Temporal Resolution. *J. Hydrometeor*. (accepted).

Kidd, C., D.R. Kniveton, M.C. Todd and T.J. Bellerby, 2003: Satellite Rainfall Estimation Using Combined Passive Microwave and Infrared Algorithms. *J. Hydrometeor.*, **4**, 1088-1104.

Krajewski, W.F., G.J. Ciach, J.R. McCollum and C. Bacotiu, 2000: Initial validation of the Global Precipitation Climatology Project over the United States. *J. Appl. Meteor.*, **39**, 1071-1086.

Kummerow, C., W. Barnes, T. Kozu, J. Shiue, and J. Simpson, 1998: The Tropical Rainfall Measuring Mission (TRMM) sensor package. *J. Atmos. Oceanic Technol.*, **15**, 808-816.

Levizzani, V., and Co-authors, 2000: Use of MSG SEVIRI Channels in a Combined SSM/I, TRMM, and Geostationary IR Method for Rapid Updates of Rainfall. *Proc. First MSG RAO Workshop*, Bologna. 17-19 May 2000. ESA SP-452 October 2000.

Levizzani, V., D. Rosenfeld, E. Cattani. S. Melani, F. Torricella, and I. Lensky, Madrid, 23-27 September 2002: Multispectral observations of cloud top as a powerful tool for rainfall estimations. *1st Intl. Precipitation Working Group (IPWG) Workshop*, Madrid, Spain, 23-27 September 2002.

Levizani, V., P. Bauer, and J. Turk (Eds.), 2005: Measuring precipitation from space - Eurainsat and the future. Springer Berlin, in press.

Mahfouf, J.-F., P. Bauer, and V. Marécal, 2003: The comparative impact of the assimilation of SSM/I and TMI rainfall rates in the ECMWF 4D-Var system. *Mon. Wea. Rev*., in press.

Petty, G.W., 1995: The status of satellite-based rainfall estimation over land. *Remote Sens. Environ*., **51**, 125-137.

Scofield, R.A., 1987: The NESDIS operational convective precipitation estimation technique. *Mon. Wea. Rev*., **115**, 1773-1792.

Tripoli, G.J., 1992: A nonhydrostatic mesoscale model designed to simulate scale interaction. *Mon. Wea. Rev.*, **120**, 1342-1359.

Turk, F.J., J. Hawkins, E.A. Smith, F.S. Marzano, A. Mugnai, and V. Levizzani, 2000: Combining SSM/I, TRMM and infrared geostationary satellite data in a near-real time fashion for rapid precipitation updates: advantages and limitations. *Proc. 2000 EUMETSAT Meteorological Satellite Data Users' Conference*, Bologna, Italy, 29 May-2 June 2000.