SATELLITE RAINFALL ESTIMATES: A LOOK BACK AND A PERSPECTIVE

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ABSTRACT

Quantitative satellite rainfall estimates have always suffered from substantial limitations due to their VIS/IR brightness temperature mapping confined only to cloud top. MW data, though more responsive to cloud microphysics, are confined to polar orbits and suffer from spatial resolution drawbacks. A new chapter has started with the launch of the new generation of geostationary satellites (GOES and future MSG), their new spectral channels and shorter image repetition time, the very successful development of TRMM, and the concept of the proposed Global Precipitation Missions (GPM). It is thus worthwhile re-examining the overall satellite rainfall estimation strategies. A review of the existing scenario is briefly conducted as a baseline for the application of the new methodologies. The new methods have several aspects worth mentioning: 1) the exploitation of the new channels of instruments like SEVIRI at the geostationary orbit and MODIS at polar altitude deserves special attention for the increasing amount of physical information on cloud top microphysics and structural features; 2) the multi-instrument approach is considered as the ultimate strategy for more accurate instantaneous rainfall estimations at all latitudes via the synergy of a wide range of passive and active instruments (SEVIRI, SSM/I, TMI, PR, VIRS, MODIS and others); 3) very promising operational developments are foreseen from rapid-update IR/MW estimation cycles; 4) applications of satellite rainfall products to NWP model assimilation represent a way to significantly contribute to the future of mesoscale and large scale meteorology.

1. INTRODUCTION

The objectives of satellite rainfall estimates are manifolds and touch sensitive problems such as rainfall occurrence, amount and distribution at all scales for a number of applications in meteorology, climatology, hydrology, and environmental sciences. The uneven distribution of raingauges, yet the most precise instruments, and their limited sampling area represent a substantial problem when dealing with effective spatial coverage. Weather radars ensure a wider coverage whereas their quantitative accuracy is often not very high due to calibration problems. Finally, the lack of rainfall data over the oceans has always introduced biases in data assimilation for weather forecasting at all temporal and spatial scales. As a consequence, satellite rainfall monitoring needs to address the key questions of spatial and temporal coverage, which cannot be achieved by other observing systems. At the same time the improvement of the overall quantitative accuracy still represents an open problem.

Levizzani (1998a) has covered results and future perspectives from the geostationary orbit and Levizzani *et al*. (2000) introduce the new research and operational scenarios that stem out of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) of METEOSAT Second Generation (MSG). Up to the present it has

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been difficult to consider satellite precipitation estimates from a unified perspective encompassing all possible applications. Technical limitations constrain the launch of microwave (MW) sensors to Low Earth Orbits (LEO). The most recent technological developments mostly refer to MW instruments, imagers and sounders, on board polar orbiters, but the use of visible (VIS), infrared (IR) and water vapor (WV) channels of geostationary satellites is by no means over. The launch of the newest generation of geostationary satellites, the Geostationary Operational Environmental Satellite GOES-I series (Menzel and Purdom, 1994) and the upcoming MSG (Schmetz *et al.*, 1998), add new channels to the traditional VIS/IR/WV triplet. The challenges deriving from the exploitation of these new channels are unprecedented and the science community is at work to be ready at the launch time.

New techniques have been developed that make use of geostationary and polar orbiting observations of all kinds for combined estimations over the whole globe with enhanced accuracy and timeliness (e.g. Turk *et al.*, 1998; Vicente *et al*, 1998). A vision of the next future of rainfall estimations is presented in view of their quantitative amelioration and the very important applications in weather analysis and forecasting. In particular, assimilation of rainfall data into global circulation and local area models deserves special attention and has already been demonstrated to be one of the most promising use of satellite data.

2. THE PRESENT OF SATELLITE RAINFALL ALGORITHMS

An overview of existing algorithms has been given in some detail by several authors (Barrett and Martin, 1981; Kidder and Vonder Haar, 1995; Levizzani, 1999; Levizzani *et al.*, 2000; Petty, 1995). The reader is referred to these reviews for a rather complete introduction to the field. Here it is worth to just give a brief overview of the present capabilities of instruments and associated algorithms.

Algorithms that make use of VIS/IR imagery fall under one of the following major categories depending on their approach to rainfall physical and dynamic features:

- Cloud indexing (Arkin, 1979; Arkin and Meisner, 1987; Arkin and Ardanuy, 1989; Arkin and Janowiak, 1991; Huffman *et al.*, 1997; Kerrache and Schmetz, 1988; Todd *et al.*, 1999).
- Bispectral (Bellon *et al.*, 1980; Cheng *et al.*, 1993, Cheng and Brown, 1995; Lovejoy and Austin, 1979; Tsonis, 1987; Tsonis and Isaac, 1985).
- Life-history (Griffith *et al.*, 1978; Negri et al., 1984; Robinson and Scofield, 1994; Scofield and Oliver, 1977; Scofield, 1987; Scofield and Naimeng, 1994; Vicente and Scofield, 1996).
- Cloud model (Gruber, 1973; Wylie, 1979; Adler and Negri, 1988).
- Use of other IR and near IR channels (Inoue, 1987, 1997; Kurino, 1997; Vicente, 1996).

Several inter-comparisons were conducted: for example Negri and Adler (1993) document the results of the one over Japan.

Passive MW-based methods have been mainly developed for the Special Sensor Microwave/ Imager (SSM/I). They range from relatively simple polarization techniques (e.g. Spencer *et al.*, 1989; Kidd, 1998) to much more complex approaches based on cloud models and microphysical response of the different cloud layers (e.g. Smith *et al.*, 1992; Mugnai *et al.*, 1993). These latter try to identify as closely as possible the contributions to rainfall of the different cloud processes that vary very much from cloud to cloud; as an example, Mugnai *et al.*, (1990) provide a clear-cut analysis of a hailstorm. Panegrossi *et al.* (1998) have recently demonstrated the importance of identifying the typology of the observed cloud system and associate it to an appropriate cloud-model simulation because the estimation of precipitation and cloud structures from profile-based retrieval algorithms is closely linked to the cloud–radiation database. The description of a collection of several MW algorithms can be found in Wilheit *et al.* (1994). Intercomparison exercises have been conducted to verify the performance level of each algorithm; results from NASA's WetNet PIP-2 intercomparison are given by Smith *et al.* (1998).

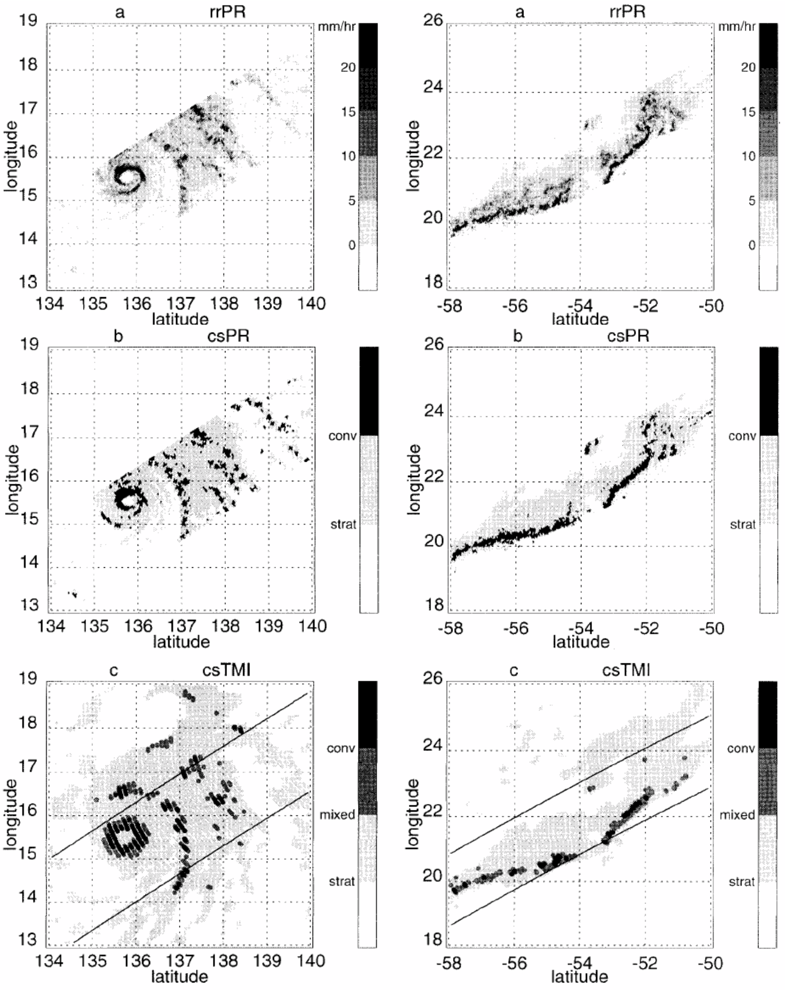


Figure 1. *Left: Supertyphoon Paka, 19 Dec 1997. Right: Squall line, 7 Apr 1998. Top: Precipitation rates derived from TRMM Precipitation Radar (PR). Middle: PR-derived Convective/Stratiform (C/S) index. Bottom: C/S map from actual TRMM MW Imager (TMI) data (from Hong et al. (1999), courtesy of American Meteorological Society).*

Methods that combine the deeper physical insights of the MW on polar orbiting satellites and the space-time coverage of the IR at the geostationary orbit have been explored by several scientists. Adler *et al.* (1994) were among the first to work on a global scale and concentrated on tropical rainfall analysis. The methods mostly concentrate on cumulative rainfall analysis (e.g. Adler *et al.*, 1993), although attempts have been made to tackle the problem of instantaneous estimates (e.g. Levizzani *et al.*, 1996).

New perspectives were opened with the advent of the Advanced Microwave Sounding Unit (AMSU-A and B) on board the NOAA series spacecrafts. AMSU-A has 15 channels and enhanced scanning capabilities for the derivation of products such as total precipitable water, cloud liquid water, sea ice and precipitation. Algorithms were produced by NOAA-Office of Research and Applications (ORA) and are now running in experimental version. The precipitation derivation algorithm, derived from the work of Ferraro (1997) and Grody *et al.* (1999), is described by Zhao *et al.* (1999) together with the current product validation efforts.

The Tropical Rainfall Measuring Mission (TRMM) (Kummerow *et al.*, 1998) since its launch in late 1997 has represented a major step towards the future of MW combination with VIS/IR sensors. Its newly-designed Precipitation Radar (PR) opens up the horizon of active rainfall sensing from space platforms. Two examples of multi-instrument rainfall derivation are given in Fig. 1 where convective and stratiform rain sectors are delimited and the synergistic use of active and passive instruments is clearly explained. One of the most important objectives of TRMM is the identification of latent heat release in the tropics as a major question mark for general circulation and climate models (Olson *et al.*, 1999). In particular, it is important to verify that large-scale heating and cooling can be attributed primarily to the fraction of convective and stratiform precipitation rather than details of the cloud environment (Tao *et al.*, 1993). Thus, classifying convective and stratiform regions is necessary for retrieving latent heating release (Houze, 1997) and understanding the contribution of the different systems to the total rainfall amount (e.g. Anagnostou and Kummerow, 1997; Mohr *et al.*, 1999).

Simple VIS/IR techniques still maintain a certain level of climatological value although new MW products are being conceived and distributed (see the Global Precipitation Climatology Project, GPCP, http://orbit-net.nesdis.noaa.gov/arad/gpcp/). Verification of the algorithm's performance is constantly being conducted against ground-based rainfall measurements (McCollum *et al.*, 2000). At the same time MW data have been

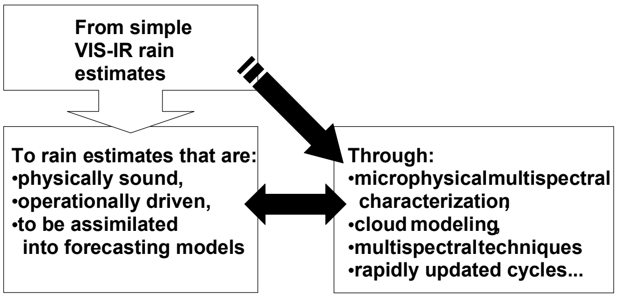


Figure 2. *Schematic diagram of the strategy for the development of satellite rainfall algorithms using the new multispectral sensors. Note the synergy between satellite data and cloud modeling. Operational requirements including assimilation into numerical weather prediction models will have an impact on the new techniques together with nowcasting and disaster management needs. Climatology will also greatly benefit from the available space and time coverage.*

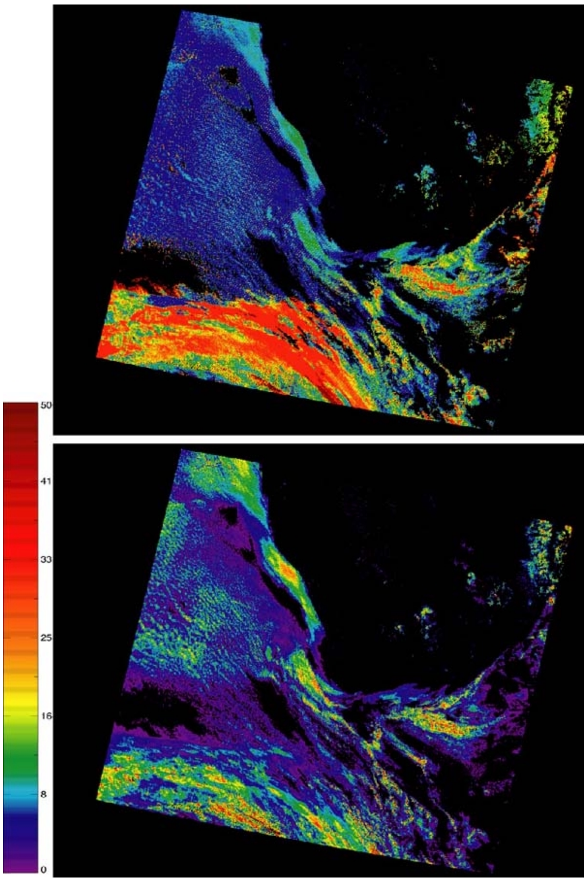
used to improve the GOES precipitation index (GPI) (Xu *et al*., 1999) for the improvement of monthly rainfall measurements at various spatial scales.

3. THE FUTURE BETWEEN PLANS AND PERSPECTIVES

There is a great urge towards the use of the new sensors and the synergic use of MW and model data for satellite rainfall estimates that have a better physical basis and meet the operational needs of weather forecasting. Fig. 2 depicts a possible strategy for making proper use of the new generation of multispectral sensors in the VIS/IR together with MW sensors and model data.

Rosenfeld and Gutman (1994) were among the first to concentrate on cloud top microphysical properties in view of a remote sensing of potential rain clouds. Lensky and Rosenfeld (1997) have successively conceived a new multispectral rainfall estimation technique based on this original idea. Precipitation areas and rainfall amounts are quantitatively determined taking into account the significant microphysical and dynamical differences behind rain formation processes in convective and stratiform clouds that lead to large differences between cloud top properties and rain intensities. Rosenfeld and Lensky (1998) have used imagery from the Advanced Very High Resolution Radiometer (AVHRR) and applied the technique to continental and maritime convective clouds calculating the evolution of the effective radius (r_e) with temperature and inferring from it information on precipitation forming processes. In-cloud microphysical processes such as diffusional growth, rainout, mixed-phase precipitation, and glaciation are linked to the particular cloud system under observation since not all processes appear in a single cloud system. Differences are observed between clouds forming from different air masses: this is related to the modification that the pristine air mass (e.g. maritime) is undergoing while moving (e.g. inland). Other transformations are documented for those air masses moving towards areas affected by massive aerosol loads (biomass burning, urban air pollution,…) (Rosenfeld, 2000a). A recent application of this method to the detection of highly supercooled water down to -38° C in deep convective clouds was substantiated by aircraft penetrations and is changing the current understanding of cloud processes and precipitation formation (Rosenfeld and Woodley, 2000). For further details the reader is directed to the article of Rosenfeld (2000b) in the present volume. These techniques are in line with the potential of the new MSG channels as indicated by the study of Watts *et al.* (1998) on the response of the SEVIRI instrument and its potential for the retrieval of cloud properties. Two examples of cloud top microphysical characterization using the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra (EOS-AM-1) spacecraft is shown in Fig. 3. Such capabilities will be available at the geostationary scale using SEVIRI on board MSG.

The SEVIRI instrument (Woick *et al*., 1997; Schmetz *et al*., 1998) will add substantial multispectral capabilities to the geostationary coverage of cloud systems. Perspectives on rainfall retrievals have been examined in detail by Levizzani *et al*. (2000). The nominal repeat cycle of SEVIRI foresees to scan a full disk image every 15 minutes. Shorter repeat cycles will be possible by scanning only a reduced number of scan lines with expected beneficial impact on nowcasting applications including the real time monitoring of severe rainfall (Levizzani, 1998b) and hazardous situations such as flood episodes (Barrett and Michell, 1991). Real-time applications of multispectral image data will be greatly enhanced because of the better co-registration of images. This is essential when observing mesoscale and small scale features of the order of a



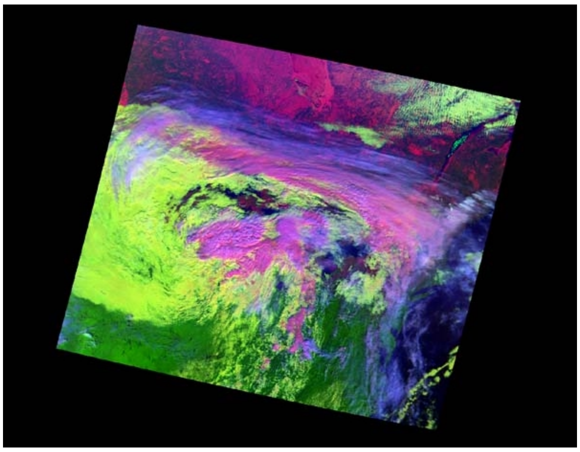


Figure 3. *Left* - *Cloud particle effective radius and cloud optical thickness near South Africa from MODIS. Retrievals of cloud effective droplet size (top image) and optical thickness (bottom image) off South Africa. In the top image, larger particle sizes (red) correspond to ice clouds, while smaller sizes off Namibia correspond to liquid water stratocumulus. The color bar is scaled to μm for the top image and is dimensionless for the bottom image.*
Right - *Great Lakes, North America. Clouds at top, colored pink, are cold, high-level snow and ice clouds, while the neon green clouds are lower-level water clouds. The image is a RGB composite of bands 1, 6, and 31 (0.66, 1.6, and 11.0 μm, respectively) (courtesy of NASA, http://ltpwww.gsfc.nasa.gov/MODIS/).*

few pixels. Novel MSG features for IR rainfall methods will be the use of multi-channel approaches to determine cloud phase and the separation of optical thin clouds from opaque possible rain bearing clouds.

Multispectral techniques were normally applied to AVHRR polar data since geostationary satellites provided only broadband VIS, thermal IR and WV channels. With the advent of the newest geostationary satellites new channels were added to the existing VIS/IR/WV triplet: the GOES-I series imager and the GMS-5 Visible and Infrared Spin Scan Radiometer (VISSR) include the traditional VIS and WV channels and the split-window channels (11 and 12 μm). GOES-I has also the near infrared 3.9 μm channel. AVHRR-based techniques such as the split-window method (Inoue, 1987, 1997; Kurino, 1997) can be directly applied to geostationary data. Kurino (1997) has also used the WV channel based on observations of "warm water vapor pixels" (Tjemkes *et al.*, 1997) over deep convective clouds. The brightness temperature in the water vapor (T_{WV}) over such clouds is often higher than that in the IR (T_{IR}) and is related to the presence of stratospheric water vapor and its amount. Amorati *et al.* (2000) have found a qualitative correspondence between such positive temperature differences T_{WV}-T_{IR} and rainfall amount above deep convective storms in Northern Italy.

The 15 minute operational image repetition time provides one more significant advantage. Cumulonimbus cloud genesis and evolution times are very rapid and the 30 minute repeat cycle of traditional geostationary sensors is comparatively a very long time period. Moreover, the normal scanning mode of operational weather radars is around 10-15 minutes. Calibration and comparisons with ground radar data has always represented a problem for the time matching between successive satellite images. Unequivocal needs for rapid updates of rainfall estimates over land and ocean exist for quantitative precipitation forecasting, numerical weather prediction, hydrology, and Earth-space Ka-band communications (Turk *et al.*, 1998, 2000a, b; Marzano *et al.*, 2000). Satellites are the key platform to maintain routine observations near coasts and over the oceans. Existing SSM/I radiometers on board the Defense Meteorological Satellite Program (DMSP) satellites and the TRMM Microwave Imager (TMI) allow for a limited coverage of precipitation systems along polar or tropical orbits.

An important research task concerns the refinement of MW rainfall algorithms. An effective MW-based strategy has necessarily to be based on a precise identification of the cloud and precipitation systems. Panegrossi *et al.* (1998) have found that an agreement with measurement manifolds can be achieved using model manifolds generated from different simulations. A good overlapping of measurement and model manifolds, though, does not guarantee the adequacy of a cloud–radiation database to represent an observed event. It is just as important to identify the typology of the observed cloud system and to associate it to an appropriate cloud-model simulation because the estimation of precipitation and cloud structures from profile-based retrieval algorithms is closely linked to the cloud–radiation database. Ba *et al.* (1998) followed an original approach to link multispectral cloud top information to MW scattering signatures. The stratiform rain structure has recently been examined from cloud and radiation modeling by Bauer *et al.* (2000). Statistical approaches are also been followed for adjusting the MW-based precipitation levels (Anagnostou *et al*, 1999).

The ultimate step towards effective satellite rainfall estimates is the development of combined MW and IR strategies. Such a need has long since been recognized as a way of combining MW-based precision and IR geostationary time repetition and coverage (e.g. Jobard and Desbois, 1994; Levizzani *et al.*, 1996; Bauer *et al.*, 1998). An attempt to calibrate IR geosynchronous data using SSM/I retrievals over the Pacific Ocean was made by Vicente and Anderson (1994): their approach involves multilinear regressions allowing for two daily calibrations between MW rainfall rate and IR cloud top temperature. Laing *et al.* (1999) studied mesoscale convective systems (MCS) in Africa deriving a relationship between SSM/I-derived precipitation characteristics and METEOSAT IR data. The technique of Turk *et al.* (1998, 2000a) is used on the operational time frame with emphasis on the identification and tracking of rapidly developing rain storms particularly those that form over the ocean and head inland. Absolute rainfall amounts are secondary with respect to relative values. The other major goal of the method is to develop a 3-hour global rainfall analysis devoid of spatial and temporal gaps, which are a characteristic of LEO satellites; these analyses are meant for assimilation into numerical weather prediction models. The technique statistically blends together SSM/I and TMI data with 11 μm IR data from any geostationary instrument in a near real time fashion for retrieving instantaneous rainfall rates and accumulations at the geostationary update cycle. The concept is to adjust IR data in near real time using co-localized MW-derived rain rates (see also Turk *et al.*, 2000b, present volume).

The auto-estimator technique proposed by Vicente *et al.* (1998) follows another concept making use of IR 11 μm GOES and radar data from the US network with applications to flash flood forecasting, numerical modeling, and operational hydrology. The rainfall retrieval is performed through a statistical analysis between surface radar-derived instantaneous rainfall estimates and IR cloud top temperatures collocated in space and time. Rainfall estimates are adjusted for different moisture regimes using precipitable water and relative humidity fields from a numerical model and SSM/I measurements. The technique is now operational for the GOES system and is run at NOAA-NESDIS ORA. The microphysical method based on the work of Ba *et al.* (1998) is also operationally used.

4. IMPACTS ON NUMERICAL WEATHER PREDICTION MODELS

Numerical model initialization through sparse surface and upper air observations has always suffered from the consequent inadequate description of the initial state of the atmosphere. The description of the four-dimensional atmospheric continuum lacks both space and time resolution over land and is very deficient, when non-existent, over the oceans. The assimilation of satellite data into numerical models is operationally done via three/four-dimensional variational assimilation of clear-sky radiances (e.g. Anderson *et al.*, 1994) and water vapor fields (Matricardi *et al.*, 1996). Initialization of numerical models with physical variables that are not primary variables of the model is very complex and can produce instabilities and poor model performances depending on many factors and the type of model.

Manobianco *et al.* (1994) have dynamically assimilated satellite-derived precipitation into a regional scale model by scaling the internally generated model profiles of latent heating for the simulation of tropical cyclones. Simulations showed that (1) satellite precipitation does not induce noise during or after the assimilation period, (2) forces the model to reproduce the magnitude and distribution of satellite rainfall patterns, and (3) improves the simulated mean sea level pressure (MSLP) minima, frontal positions and the low-level vertical motion patterns. The model retains information from the assimilation up to 8.5 hours after the end of the assimilation itself. SSM/I-retrieved rainfall rates were assimilated into a limited area model (LAM) by Peng and Chang (1996). For the test cases the assimilation reduced the average 48-h forecast distance error of 239 km in the control runs down to 81 km in the assimilation experiments.

A multivariate optimal interpolation analysis was applied by Turk *et al.* (1997, 2000c) to the physical initialization of the Naval Operational Global Atmospheric Prediction System (NOGAPS) for the nowcasting of tropical precipitation. SSM/I-derived rainrates were incorporated into files at 6 h intervals and the initialization was done while the model integrated to produce the 6 h forecast (first guess). SSM/I oceanic rainrates were also used to calibrate a 30-km resolution geostationary-based rainrate retrieval algorithm and the results assimilated as well. Added accuracy, better location and intensity of convective precipitation were found to lead to an improvement in the NOGAPS assimilation rainrates as verified against satellite observations. Turk *et al.* (2000a), in particular, have shown a positive impact in the 24- and 36-h forecast positioning of hurricane Georges (28 September 1998) by 12 to 16 %, while virtually no impact (3.5 %) was found at the 72-h forecast level.

The assimilation of satellite rainrates during the initialization of the numerical simulation of an extra-tropical cyclone was conducted by Alexander *et al.* (1999). Data were used from passive MW, IR and lightning detectors to produce a continuous time series of rainrates suitable to be assimilated into the mesoscale model. A significant improvement in the forecasts of precipitation patterns, MSLP fields, and geopotential height fields was found also in this extra-tropical case.

Results generally indicate that a positive impact of non-conventional satellite data, precipitation above all, into numerical weather prediction models exists especially via physical initialization (Krishnamurti *et al.*, 1994). Other approaches exist involving assimilation of visible satellite data in the analysis for adjusting the humidity field and radiative parameterization (Lipton and Modica, 1999). A great deal of work remains to be done involving satellite meteorologists and numerical modelers.

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