THE WORTH OF LONG-RANGE LIGHTNING OBSERVATIONS ON OVERLAND SATELLITE RAINFALL ESTIMATION

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1. INTRODUCTION

Lightning is a physical phenomenon that was excessively deified and feared for centuries. Even in the progressive minds of the ancient Greek society lightning was considered as the inescapable wrath of Zeus, seeking to punish mankind. It was in the dawn of the 1750's when Benjamin Franklin, the American philosopher and inventor, brought the lightning phenomenon to human proportions by relating it with atmospheric electricity. Years later, in the beginning of the 20^{th} century C.T.R. Wilson (inventor of the Cloud Chamber) first used electric field measurements to estimate the structure of thunderstorm charges involved in lightning discharges (Krider 1996). Besides studies related to thunderstorm evolution, other aspects of lightning were addressed. For example, the propagation of electromagnetic waves excited by lightning strokes in the Very Low Frequency band (VLF or sferics) stimulated the interest of many researchers such as Bremmer (1949), Budden (1951) and Schumann (1954). Along the same lines, Pierce (1977) described the physics of sferics based upon work conducted after World War II. Lightning has strong relevance to numerous scientific fields ranging from atmospheric physics/chemistry to water and energy cycle. In the 1990's, NASA prioritized particular interest on lightning research giving it a hydrological applications dimension (Goodman 1988). This effort was further supported by the launch of the Tropical Rainfall Measuring Mission (TRMM) satellite (Simpson et al. 1988)—the first of its kind to carry on the same platform precipitation radar (PR), a multi-frequency radiometer, and a Lightning Imagine Sensor (LIS) (Christian et al., 1999).

In this paper we will discuss the connection of lightning with convective precipitation processes, and present the advancements that lightning data can offer on the precipitation estimation. In the subsequent paragraphs we will discuss the physical properties of lightning formation, and the microphysics of electrified convective systems. We will highlight the current state-of-the-art on continuous lightning monitoring from ground-based radio receivers and illustrate the physical consistency of lightning with passive microwave observations. We will conclude by describing current techniques on combining satellite and lightning data aiming at the improvement of high-frequency precipitation estimation over large regions.

2. PHYSICS OF ELECTRIFIED CLOUDS

Lightning is an electrical manifestation of thermodynamic and mechanical work performed by storm updrafts. Updrafts determine the supply, growth and transport of water condensate to the upper regions of storms, and directly control the dynamics of charge separation that lead to lightning. Lightning is related to the cloud microphysics with the presence of separated (positive and negative) electrical charges inside a thundercloud (Williams et al., 1989). A regular lightning charge occurs when the potential built-up inside a cloud has exceeded the breakdown threshold of the surrounding air, which value varies around 200 kV/m as a function of atmospheric humidity. The fact that clouds can develop electrical fields is far from surprising. Inside the clouds, the density of suspended material is increased to a significantly higher level than the surrounding environment so eventually any dielectric material available can receive charge trough common turboelectric effects (piezo-electric, thermoelectric etc.). This is also stated as the convective hypothesis, according to which there is a discontinuity of electrical conductivity between the dry surrounding air and the saturated cloud, where free moving ions are captured (Ziegler et al 1991). Laboratory studies have identified originally uncharged ice particles that acquired substantial electrical charge without the aid of an external electrical force (Takahasi et al., 1999). One of the key mechanisms proposed is the so-called charge transfer and its thermodynamic implications during collision between vapor-grown ice particles and hail at the presence of super-cooled droplets. Regarding the polarity of the charge, this is dependent on the temperature and liquid water content. Solomon and Baker (1998) portrayed an interesting representation of the charge that hail receives during these collisions and its dependence on liquid water content (hail is charged positively or negatively depending upon the environment in which it grows). A non-conductive charge separation has also been proposed based on a thermo-electric process. In this case the charge is transferred while for instance the outer surface of a hail droplet melts while the interior is still frozen. According to Simpson and Scarse (1937) who conducted pioneering research on thunderstorm electrification by examining numerous in-cloud electric field profiles, a typical thundercloud has three distinctive charged regions: an upper positive charged region at about -30^0 C, a middle negative at about -10^0 C and a mixed positive and negative at around 0^0 C isotherm.

There are two major categories of electrical discharges: a lightning type that discharges via two opposite charges inside the same or different cloud, is the so-called Intra Cloud (IC) strikes, a group that represents almost 80% of the world-wide lightning activity. Conversely discharges that are channeled from a point inside the cloud to the ground are called cloud-to-ground (CG) and represent the minority of such electrical activity yet they can release energy, several orders of magnitude higher that the IC discharges (up to 10^{15} joules). A typical CG would be channeled from a negatively charged lower cloud part to a positive ground. In the same manner, depending upon the structure and physical location of the charges inside the cloud, one may well encounter the formation of a positive lightning strike (positive cloud base to negative earth). A general consideration regarding the ratio of IC to CG lightning strikes, as Boccipio et al. (2001) states, shows a seasonal variation across the continental U.S., yet having an average value of 0.9. There are other lightning categories that fall outside the scope of this chapter; nevertheless, the interested reader can browse through other impressive expressions of atmospheric electricity as the “elves”, sprites, “blue-jets” etc. (Lyons et al., 2003).

3. LONG-RANGE LIGHTNING DETECTION

Lightning over larger areas (continental to global scale) can be also detected on a continuous basis from ground radio receivers operating at the Very Low Frequency (VLF else known as atmospherics or sferics) (Chronis and Anagnostou 2003; Anagnostou et al. 2002; Lee 1986a,b). Lee (1986a,b) was first to show that sferics receiver networks could achieve large regional coverage due to the relatively low attenuation of the lightning-excited electromagnetic signal. He developed such a system with receivers deployed originally in UK, Cyprus and Gibraltar. The University of Connecticut and National Observatory of Athens recently deployed a second-generation sferics network (named Zeus) covering Europe and African continents, and to a lesser accuracy West Asia and the Atlantic and Indian oceans. Zeus system, built by Resolution Displays Inc., makes use of advanced computing technology, signal processing algorithms, GPS and satellite communications networking to improve the state of the art in receiver design at long-range frequencies. Details about the system and its long-range locating error characteristics are provided in Chronis and Anagnostou (2003) and in Zeus web page (http://sifnos.engr.uconn.edu). The authors have demonstrated a mean locating error of about 15 km within the network periphery, while at very long ranges (>5,000 km) the locating error exhibited a larger variability with a mean at around 150 km.

4. PHYSICAL CONSISTENCY OF LIGHTNING AND MICROWAVE OBSERVATIONS

A number of studies have targeted the relation between microwave properties of precipitating particles and electrification. The majority of these investigations have resulted in empirical relationships between lightning intensity (e.g., flash rate) and convective parameters (such as updraft velocity, precipitation, ice water content). Toricinta et al. (2001) for example used lightning frequency information to classify reflectivity profiles from TRMM PR. Along the same lines, Cecil and Zipser (1999) studied the radiometric and electrification properties of well-formed hurricane eye walls while Chang et al. (2001) combined synoptic meteorological observations with passive microwave and lightning observations to study the 1998 Groundhog Day storm over Florida.

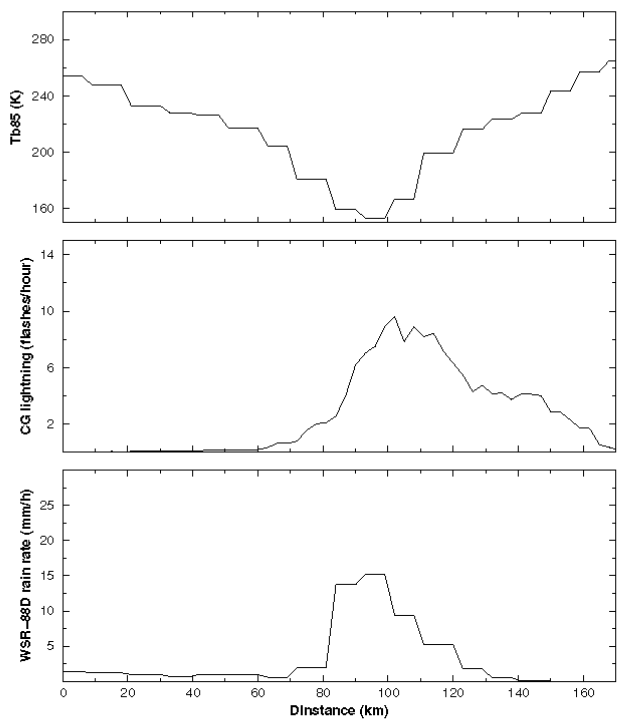

Figure 1: Rays of Tb85, CG flash rate and rainfall rate along a cross section of an MCS in Oklahoma.

As already stressed out, lightning formation is a strong indication of convective activity and the presence of ice particles. In this section we will draw a parallel between these physical properties and microwave observations of rainfall. In particular, we will use a number of independent observations to show the correlation between lightning activity and convective structure. Our analysis is based on four months of data (May through August, 2002) originating from a large area in the US Southern Planes [103^0 W to 93^0 W and 33^0 N to 37^0 N]. The data include (a) high frequency (85 and 37 GHz) passive microwave brightness temperatures from three Special Sensor Microwave/Imager (SSM/I) sensors onboard F13, F14, and F15 defense meteorological satellites, (b) CG lightning location obtained from the U.S. National Lightning Detection Network (NLDN), and (c) hourly rain-rate fields from stage III (i.e., rain gauge calibrated) WSR-88D precipitation products. The SSM/I overpass represents a time window of ~3 minutes, while the corresponding flash density corresponds to ±½-hourly accumulations of CG flashes around the SSM/I overpass time, and the hourly WSR-88D rain rates are selected from the hour that contains the SSM/I overpass time. The common spatial scale of the collocated data is that of the 85 GHz frequency having the coarser resolution (15km×17km). Initially the WSR-88D rain rate fields were available at 4-km resolution, while NLDN lightning data are associated with a location error below 1 km in the above area (Cummins et al. 1998).

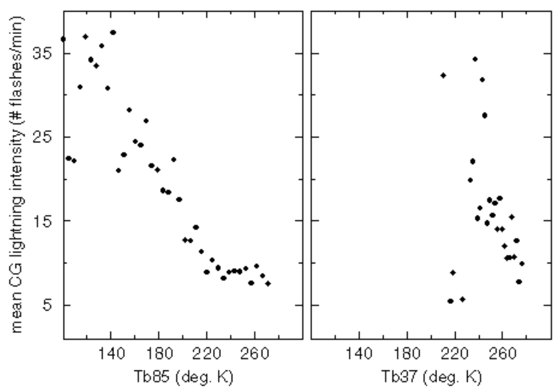

Figure 2: Scatter plot of mean CG flash rate for different categories of 85 GHz (left panel) and 37 GHz (right panel) brightness temperatures.

The collocated data were classified into two main categories, pixels having (or neighboring to pixels with) non-zero flash density (electrified pixels) and those associated with zero flash density (non-electrified). We make use of this distinction in order to examine the passive microwave scattering properties of electrified versus the non-electrified areas in a precipitation regime. The data analysis resulted in about 30,000 (9,000) non-electrified (electrified) SSM/I pixels associated with precipitation.

Our analysis based on the above data exhibits a tight relation between flash rate and the depression in the passive microwave signal at 85 GHz (Tb85), which is the channel mostly sensitive to ice scattering (Mohr et.al 1999). Figure 1 presents a characteristic example of this relation. It displays corresponding plots of Tb85, CG flash rate, and WSR-88D rain rate profiles taken across a Mesoscale Convective System in Oklahoma. The figure shows a very good spatial correlation between Tb85 and CG lightning frequency patterns, while there is a minor shift (<15 km) between radar rainfall patterns and those of Tb85 and CG flash rates. This is likely related to spatial displacements between precipitation ice processes concentrated in regions with strong updrafts and surface precipitation beneath. Figure 2 (left panel) highlights a mean non-linear (nearly exponential) relationship of flash rate to Tb85. In Figure 3 (left panel) we show that Tb85 values from electrified pixels have a tendency to “shift” towards colder temperatures, comparatively to Tb85 values from rainy pixels that reside outside the electrified areas.

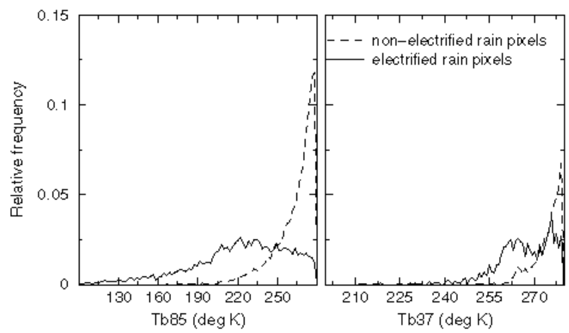

Figure 3: Relative frequency histograms of Tb85 and Tb37 in cases of electrified and non-electrified passive microwave observations in rainfall.

A mixture of emission and scattering is depicted by the lower wavelength of 37 GHz (Tb37), which is directly influenced by the presence of super-cooled hydrometeors. The strong relationship exhibited between flash rate and Tb85 is not apparent in the case of Tb37 channel (Figure 2-right panel). It is shown that Tb37 has low sensitivity to the intensity of electrification. An explanation to this is that the existence of super-cooled cloud water does not require a convective regime, something compelling at the presence of graupel and intense lightning activity. According to Smith et al. (1992) there may be counteraction between the 85 and 37 GHz signatures since emission by super-cooled water droplets may increase Tb85 (smoothing out abrupt brightness temperature changes). Compensation of this warming effect can be provided by the existence of a thicker ice layer above the super-cooled water layer, fact argued here to be the dominant case of intense electrification. To support our argument we use the polarization corrected temperature difference of 37GHz versus 85GHz (Tb37-Tb85), which quantifies the warming effect mentioned above. In Figure 4 we plot the probability distribution of Tb37-Tb85 for electrified and non-electrified pixels. The histogram of non-electrified pixels shows a mean around zero, expressing an equal impact by emission and ice scattering, which is a typical characteristic of the stratiform mixed phase. On the other hand, in electrified/convective areas, the difference shows an apparent shift to positive values, fact explained by the faster decrease of the Tb85 due to scattering compared to the Tb37.

Finally, in Figure 5 we show the relationship of mean rain rate to Tb85 (Tb37) for electrified and non-electrified pixels. We note differentiation in the Tb85-rain rate relationships of electrified and non-electrified rain areas, which demonstrate the significance of lightning information in passive microwave rain estimation. First, the relationship of electrified pixels gives almost twice as much rain the non-electrified relationship does. Second, in the non-electrified pixels the relationship “breaks apart” as Tb85 reduces to colder than 200 K temperatures, while in the electrified pixels, it sustains the monotonic character throughout the whole range of brightness temperatures. These distinct differences in the Tb85-rain relationships between electrified and non-electrified clouds indicate that lightning information can have a positive impact on the overland passive microwave rain estimation, which is primarily based on Tb85 observations. Having established the quantitative connection of lightning to convection and precipitating ice processes, we will now demonstrate the potential improvements in quantitative precipitation estimation coming from combining lightning information with the lesser definitive but quasi-continuous satellite Infrared (IR) observations.

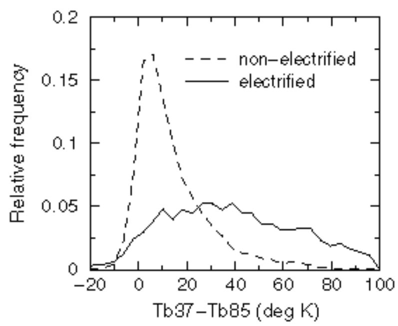

Figure 4: Frequency histogram of the Tb37-Tb85 difference for electrified and non-electrified passive microwave observations in rainfall.

5. HIGH-RESOLUTION LARGE-REGIONAL RAINFALL ESTIMATION FROM COMBINING SATELLITE IR AND LIGHTNING DATA

Geo-stationary Infrared (IR) imagery has been a useful tool to rainfall monitoring due to its advantage of providing global coverage and high frequency (15-30 min) of observations. There has been significant research on developing rain retrieval algorithms from IR data. Among the first algorithms is the development of a simple threshold technique named GOES Precipitation Index (GPI) (Arkin and Meinser 1987). The technique implemented an IR threshold to delineate areas of mean rainfall value, based on which Arkin and Xie (1994) produced precipitation products over tropical and subtropical regions. Further improvement of geo-synchronous satellite precipitation retrievals through regional calibration by the use of microwave observations (which have a more direct physical link to precipitation rate) is currently approached in a number of studies with the most recent including Hsu et al. (1999), Todd et al. (2001) and Huffman et al. (2003). Other studies have tried to calibrate an IR algorithm, on the basis of high-resolution passive microwave retrievals, in deriving convective and stratiform precipitation, but with moderate success (Negri et al. 2002; Anagnostou et al. 1999). A generality to be drawn from these studies is the weakness of satellite IR measurements to sufficiently characterize the convective precipitation variability. The incorporation of regional lightning information from long-range network data would offer the additional information needed to bring convective rain area and rate estimation at accuracy levels suitable for studying the water cycle at high spatial-temporal frequency.

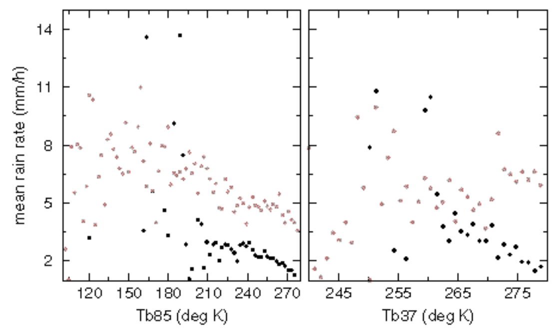

Figure 5: Scatter plot of mean rain rate for different categories of Tb85 and Tb37 in electrified and non-electrified passive microwave rainfall observations.

Relatively few studies have related lightning information with precipitating regimes observed by geo-stationary satellites. Grandt (1992) studied thunderstorm evolution by combining Meteosat images and sferics location retrievals, during different seasons over Africa and Europe and classified convective clouds using indexes related to cloud-top brightness temperatures. Grecu et al. (2000) used a combination of lightning and IR brightness temperature observations to retrieve rainfall. In this study it is showed that the aforesaid combination could reduce by 15% the error variance of rain volume estimates compared to an IR only scheme for clouds associated with lightning. The authors also demonstrated that lightning information could improve the overall rainfall estimation accuracy compared to an IR only approach. The above study although targeted the significance of lightning information in rainfall estimation its result is limited by sample size and regional extent (15-days over Southern United States) as well as an increased uncertainty in the overland passive microwave rainfall fields used as reference for calibration/validation. The most comprehensive studies on the use of lightning data jointly with IR as a mean for advancing our capabilities on continuous precipitation monitoring over large regions are those of Morales and Anagnostou (2003) (hereafter MA03) and Chronis et al. (2004) (hereafter CH04). Below we describe the main findings from those studies.

MA03 developed a technique to retrieve rainfall rates by combining satellite IR observations with data from a long-range lightning network of sferics receivers in US East Coast and the Caribbean (see Figure 1 of MA03). The study used TRMM Precipitation Radar (PR) rainfall products to calibrate and evaluate the combined IR/lightning rain retrieval. The hypothesis made in formulating the methodology is that precipitation from electrified clouds has distinct ice microphysical properties compared to non-electrified clouds; consequently, developing different rain retrieval parameterizations for clouds with and without lightning would contribute to improving precipitation estimation, while a better evaluation of convective rainfall may be achieved by combining flash rate and IR brightness temperature variables compared to using sole IR data. The authors developed parameterizations for the estimation of total rain area and the convective rain area portion that are distinct for lightning and lightning free precipitating clouds. The parameterizations were developed using bulk variables evaluated on the basis of cloud systems delineated by the 258 K isotherm in the IR array. Those variables are the cloud area defined by the 258 K isotherm, the area contained within the isotherm of the most frequent IR temperature in the cloud system, and the lightning area in the case of electrified clouds. The rainfall rate relationships were developed in a probabilistic way by matching the cumulative distributions of IR brightness temperatures and lightning rates with the corresponding PR precipitation estimates. These rain relations were evaluated separately for convective/stratiform rain types, lightning/lightning-free clouds, and land/ocean surfaces exhibiting distinct functional forms as shown in MA03.

Three months (December 1997 to February 1998) of coincident data over a large region (i.e., 125W-45W in longitude and 40N-10S in latitude) were used to evaluate the algorithm parameters and assess its performance. Additional validation was performed based on rain gauge observations from a network in Florida. As shown in MA03 (see Figure 7 of MA03) the estimated rain areas are well determined when compared against rain areas observed by TRMM-PR. Overall, the technique underestimates both lightning (21%) and lightning-free (29%) rain areas. The standard error and correlation coefficients for lightning (lightning-free) areas are 36% (43%) and 0.97 (0.96), respectively. Retrievals in lightning clouds are shown to have lower error (higher correlation) on the definition of convective and stratiform rain areas compared to the lightning-free clouds, this effect is more pronounced in the estimation of convective precipitation (we note a correlation increase of 0.15). Comparisons with a validation rain gauge network in Florida revealed that the combined technique is able to represent the observed precipitation distribution at scales ranging from 100 km^2 to 4 $degree^2$ with low overall bias (6%) at 100 km^2, which increases at coarse resolution (~35% at 4 $degree^2$).

The authors investigated the significance of lightning information on rainfall estimation accuracy. In that respect, the same technique was set to run without lightning information: namely, all clouds were set as non-electrified. Comparisons with TRMM-PR showed that lightning information improves rainfall estimation accuracy when compared to the non-lightning scenario. In rain area determination there was an overall bias reduction of

31%. In rain volume the lightning information was shown to introduce bias reduction of 10%. In rain gauge comparisons, the bias reduction from incorporating lightning data was more pronounced. It ranged from 80% to about 38% (9%) for the 0.1-degree and 1-degree (2-degree) spatial scale, respectively. The increase in correlation coefficient was 0.13 for the hourly gauge data. For more details on the above findings the interested reader is referred to MA03.

A subsequent study by CH04 came to confirm and strengthen the findings by MA03. The authors developed a technique (named OMVRIOS) somewhat different in terms of algorithmic structure, but based on the same principles. Two main differences are the use of overland passive microwave retrievals from SSM/I observations as reference rainfall dataset and the simplifications introduced in the algorithm by reducing the number of parameterizations. OMVRIOS technique was demonstrated on a different geographic regime, the European continent, based on Zeus sferics network. The sferics data in this study exhibited better locating error and detection efficiency characteristics compared to the US network data. This was mainly due to improvements in the new system (lower noise floor at each receiver location, improved signal frequency and noise reduction, improvements in the locating algorithm by incorporating a more accurate model for the sferics signal velocity) and the larger number and better configuration of receivers deployed in Europe. The basic commonalities of the two techniques is the use of bulk cloud cluster variables, and that lightning information is used to first differentiate between electrified versus non-electrified cloud cluster parameterizations and second as a variable for the electrified clouds in the estimation of convective rain area and rain rate. Below we discuss some of the key aspects of OMVRIOS, while more details can be found in CH04.

The technique was assessed and compared against two existing microwave-calibrated IR retrievals (the PERSIAN of Hsu et al. 1997 and VAR of Huffman et al. 2003) as well as the same technique but without the lightning information (OMVRIOS no-lightning) on the basis of independent six-hourly rain accumulation measurements from ECMWF gauge network spread across Europe (see Figure 1 of CH04). The error statistics of OMVRIOS estimates against gauges exhibited scale dependence: the bias decreased from 30% at 0.1-degree resolution to ~5% at 5-degree resolution. The root mean square difference decreased from 93% (0.1 degree) to 78% (5 degrees), while the corresponding correlation increased from 0.78 to 0.95. The retrieval would detect about 50% of the total rainfall, and over 80% (95%) of rainfall accumulations exceeding 20 mm (25 mm) in a six hourly interval. Its overall false rain detection rate was 10%, which was shown to drop to zero for rain accumulations exceeding 8 mm in a 6-hourly interval. A main conclusion derived from the comparison of the technique against IR-only rain retrievals was that lightning information helps reduce IR retrieval uncertainty. In terms of rain detection the combined lightning/IR retrieval was shown to have significantly highest critical success index score (in the order of 40% to 100% increase) compared to the IR-only techniques. In terms of rainfall rates it was shown to have lower (25%-40%) root mean square differences compared to the other IR retrievals, and a nearly 0.3 increase in correlation with 6-hourly rain gauges. Improvements are also apparent in the cumulative distributions of 6-hourly rainfall accumulations derived from the different techniques and rain gauge rainfall measurements. As shown in Figure 12 of CH04, OMVRIOS exhibits a much closest agreement with rain gauges compared to the other techniques.

The demonstrated positive impact of continuous long-range lightning measurements on high-frequency precipitation estimation from satellites will help advance water and energy cycle understanding at both regional and climate scale. With the increasing availability of regional lightning data over the major convective chimneys of earth (e.g., Africa, South America, South Asia) algorithms like OMVRIOS can now provide improved rainfall fields (in terms of both resolution and accuracy) to what is currently available from sole IR techniques. This would advance our ability to study in more detail convective system dynamics and microphysics, as well as the role of surface conditions (e.g. soil moisture) on the water cycle variability.

7. CLOSING REMARKS

The main focus of this chapter has been on the use of lightning information as a mean of advancing precipitation estimation from satellite observations. The key aspect of lightning is its tight physical connection to convection in a cloud, which is one of the weak points of satellite IR observations. It was shown that lightning information could help improve both overland passive microwave and IR based precipitation estimation. In terms of an overland passive microwave retrieval the advancement comes from the demonstrated microphysical differences of lightning vs. lightning-free clouds resulting in distinct Tb85-rain rate relationships. In terms of an IR rain retrieval the improvement is more pronounced as it was demonstrated in the associated studies. The approach of incorporating lightning data in an IR retrieval is through classification of cloud systems in electrified vs. non-electrified, and consequently using the flash rate and IR temperature variables jointly in estimating the convective rain area and rain rate. Validation studies in U.S. and Europe have shown that the combined IR/lightning approach is superior to other techniques that are based solely on IR observations. Research is now underway to expand those combined algorithms in other continental convective regimes such as Africa, South Asia and the Amazon basin.

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