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# Precipitation Measurement and the Advancement Toward Global Observations

Josh Durkee*
*Department of Geography and Geology, Western Kentucky University*


## Abstract

Precipitation is an important variable in the global hydrologic cycle that helps to sustain life, influences a variety of daily activities, and plays a critical role in the Earth's energy balance. Our understanding of precipitation, especially in forecast applications, hazards mitigation, and water resources are among the leading challenges in the scientific community. Over the last 50 years, the science of precipitation observation and measurement, particularly at global scales, has advanced quite rapidly since the age of basic precipitation collection at the surface. Scientists have developed numerous techniques to estimate precipitation at the surface and from space, but not without their drawbacks. This article presents an overview of the advantages and limitations of some of the more mainstream techniques of precipitation measurement, and the march toward a relatively high quality, full global precipitation observation network.


## *Introduction*

The Earth's hydrologic cycle is a delicate, yet very powerful process that is largely driven by precipitation. Precipitation provides much of the necessary fresh water transported from the atmosphere to the surface in order to help sustain life forms and socioeconomic activities (e.g. agriculture, hydroelectricity, transportation, etc.) on Earth. However, it is well known that prodigious precipitation or the lack thereof can also lead to disastrous outcomes. According to the Emergency Management Database International Disaster Database (EM-DAT 2009), floods (particularly freshwater flash floods; Jonkman 2005) and droughts are among the leading global hazards in terms of total affected people (Figures 1 and 2). Undoubtedly, as the global population increases, the already limited water supplies in many global regions (notwithstanding quality concerns) will likely become more problematic.

From a physical perspective, water vapor condenses and precipitates where it can remain frozen or liquid and later melt, evaporate, or freeze. These phase-change processes exchange sizeable quantities of latent heat energy in the atmosphere, which plays a considerable role in the global wind circulation. The relationship between precipitation and atmospheric circulation ultimately feeds back as a key component in the development, maintenance, frequency, magnitude, and distribution of precipitating events. Consequently, these precipitation characteristics have a pronounced affect on the global energy balance. For example, clouds and ice are effective at reflecting shortwave solar energy and absorbing longwave terrestrial energy. Hence, precipitation is also an essential constituent in the science of climate change. Studies have shown that natural (e.g. El Niño Southern Oscillation) and anthropogenic (e.g. urbanization) forcing have the ability to alter the characteristics of various weather systems and resultant precipitation patterns on

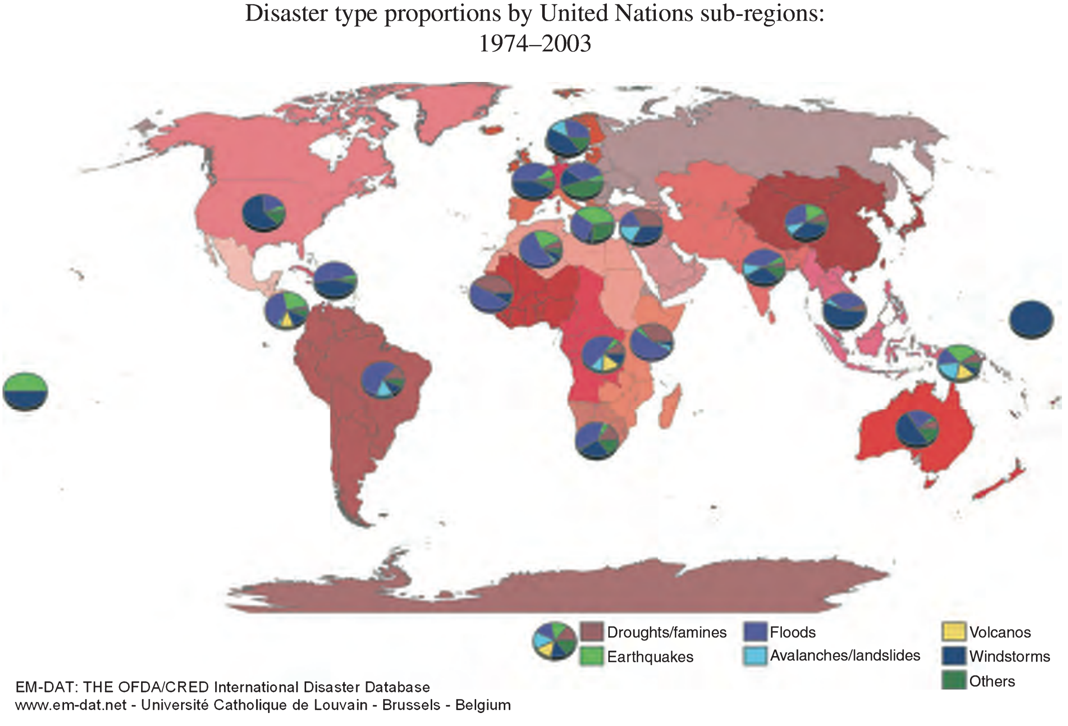


Fig. 1. EM-DAT International Disaster Database global hazards map illustrating proportions of each hazard type by region during 1974–2003.

local, regional, and global scales (Curtis 2008; IPCC 2007; Ramanathan et al. 2001; Ropelewski and Halpert 1989, 1987; Shepherd et al. 2002).

It is quite clear that precipitation is a critical component in the Earth's water and energy cycles, weather and climate variability, and life on Earth. This reflects the utmost importance of improving our knowledge and understanding of the science of precipitation. To get at the heart of understanding the physical nature of precipitation, many scientists have devoted their efforts toward developing a variety of methods for precipitation observation and measurement, and advancing these techniques toward global coverage. As one might expect, great challenges are presented when attempting to accurately describe various attributes of precipitation on a variety of space and time scales. The issue of scale is derived in part, by the land/water ratio across the planet. That is, *direct* observation of precipitation over our water-dominated planet is rarely achieved. The spatial distribution of precipitation is also often highly irregular, particularly away from the point of direct observation. Aware of these concerns, scientists have adopted remote sensing approaches with the help of satellites and radar to estimate precipitation in areas that cannot sufficiently be directly measured with traditional precipitation capture approaches such as precipitation gauges. Today, the increased coverage and accuracy in global precipitation observation and measurement is afforded by a combination of these techniques.

The overarching goal for precipitation observation methods is to be able to accurately and precisely quantify all forms of precipitation at all locations on Earth. Reliable global measures of precipitation can be used in a variety of important applications including (but not limited to) numerical weather prediction and quantitative precipitation forecasting

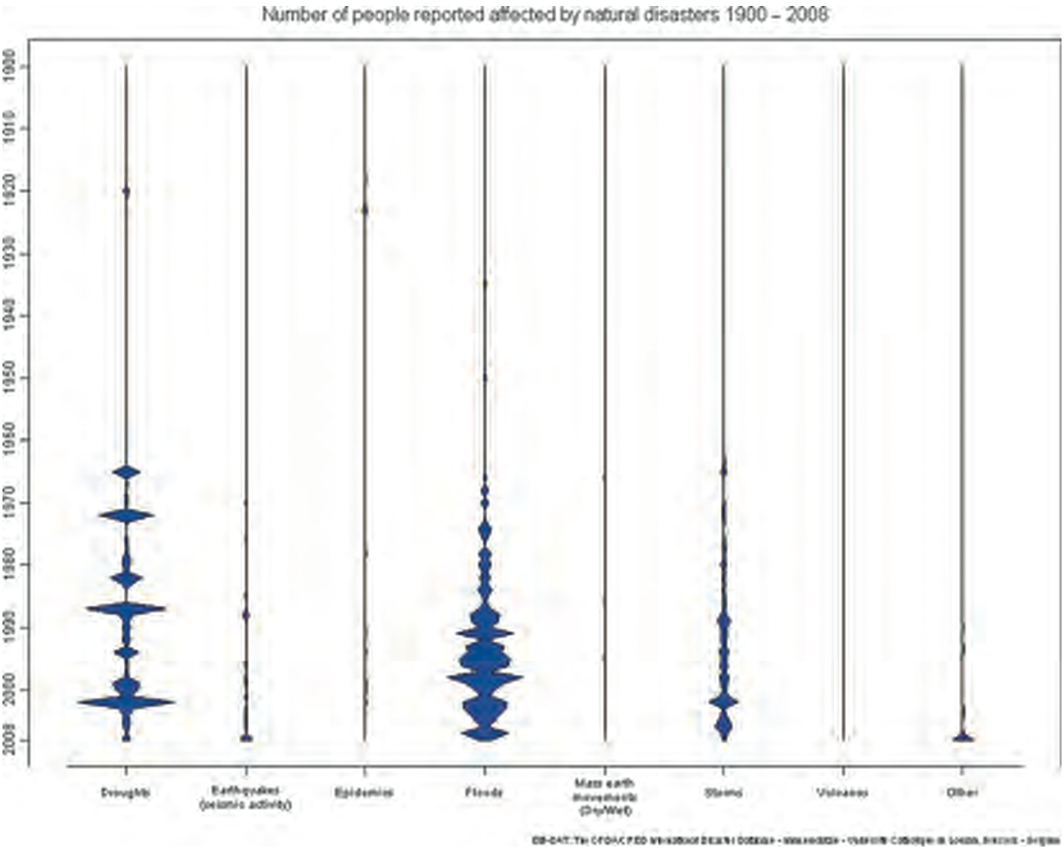


Fig. 2. EM-DAT International Disaster Database graph showing the number of people reportedly affected by various hazard types from around the world during 1900–2008.

(one of the foremost challenging aspects in weather forecasting), hazards (floods and drought), and water resource management (Chandrasekar et al. 2003). The purpose of this article is to highlight recent and contemporary conventional methodologies for assessing precipitation, and to provide insight into the advantages and limitations of these approaches, particularly at global scales. The intention of this review is not to provide detailed descriptions or comprehensive histories about various instrument types, algorithm development, regulations, etc., that have been set forth in the history of [global] precipitation observation and measurement (e.g. Michaelides 2008; Levizzani et al. 2007). Rather, this article provides a general evaluation of the fundamental principles that underlie various approaches for observing and quantifying [global] precipitation, including an overview of current developments and the future of global precipitation assessment.

### *In Situ Measurements (Precipitation Gauges)*

Precipitation is often a rapidly evolving and stochastic process on various space and time scales, which presents quite a challenge for point measurements such as the current nominal rain gauge. Regardless, rain gauges are advantageous with respect to continuous sampling and the robust physical collection of precipitation, which many other instruments (e.g. satellites and radar) are incapable of sampling. It is worth noting too that the classical recording rain gauge is the oldest of all precipitation measuring technologies; however there is no agreement in the literature of the date and person or group to which the rain gauge can be solely attributed to. The point here is that another advantage of rain gauges is that the data records often date back much further in time compared to other instruments and techniques. Most meteorological agencies around the world continue to use surface gauges as the primary *in situ* precipitation quantification method of choice. These gauges are largely considered suitable for, albeit limited to, precipitation measures at local, and regional scales and are valuable calibrators for precipitation estimates for other instruments (e.g. satellites and radar) (Levizzani et al. 2007; Sevruk 1994). Despite the usefulness of the rain-gauge approach, this method of precipitation collection does have its limitations, particularly for deployment on a global scale.

The primary flaw in assessing global precipitation with surface rain gauges is given by the limited capability to sufficiently record precipitation over water surfaces (e.g. buoys and ships), of which the Earth is covered proportionally by 71%. The remaining 29% of global terrestrial surface is comprised of various topographic landscapes that are either not suitable locations for rain-gauge deployment or are remotely inaccessible (e.g. dense forests, vast polar or subtropical deserts, rough terrain, etc.). Another limiting factor of the terrestrial surface includes developing nations, which often lack suitable funds and personnel necessary to properly maintain surface gauge networks. Therefore, precipitation gauges can only be placed on less than a quarter of the Earth's surface, which clearly inhibits any possibility of a global rain gauge precipitation observation network (Chen et al. 2008).

The concern over poor spatial sampling is often exacerbated by insufficient gauge network densities in many regions (Wilson and Brandes 1979) (Figure 3). According to Schneider et al. (2008) and the Global Precipitation Climatology Center (1992), at least 8–16 gauges are necessary for every 2.5°×2.5° cell (i.e. nearly 40,000 evenly distributed gauges) to maintain a sampling error less than 10% for aerially averaged monthly precipitation. Statistical analyses of relatively dense gauge networks show that the sampling error can range between 7 and 40% (Rudolf and Schneider 2005; Rudolf et al. 1994; World Meteorological Organization 1990). In fact, quite often does precipitation fall in the absence of a surface gauge, thereby raising the error to 100%.

In addition to the spatial limitations of surface gauges, there is a host of instrument design [e.g. tipping bucket gauge (Alena et al. 1990; Habib et al. 2001; Nystuen et al. 1996) and weighing gauge (Chvíla et al. 2005; Higgins et al. 1996)] and regulation differences (e.g. manual versus automated operation) among each user that can lead to considerable discrepancies in the accuracy of the end product of the precipitation measurement. Notwithstanding, there are a variety of other potential systematic errors inherent with the use of surface gauges, including wind (Alter 1937; Kuligowski 1997; Larson 1985; Legates 2000; Nespor and Sevruk 1999; Rodda 1967; Sevruk 1993) wetting, evaporation (Kidd 2001; Kuligowski 1997; Legates 2000; Nespor and Sevruk 1999; Rodda 1967; Sevruk 1985), and instrument calibration, which all lead to underestimated precipitation amounts. In contrast, overestimated precipitation may be attributed to poor gauge installment (e.g. too close to the ground), which can lead to 'splash-in', drifting and/or blowing snow, false sensor triggers from high wind, and condensation (Sevruk 2005).

Ultimately, surface gauges alone cannot adequately represent global precipitation due to the spatial heterogeneity (even at local scales) on the limited available surface around the world. In light of the advantages and inadequacies discussed above, these instruments do remain quite valuable in other precipitation measurement methodologies.

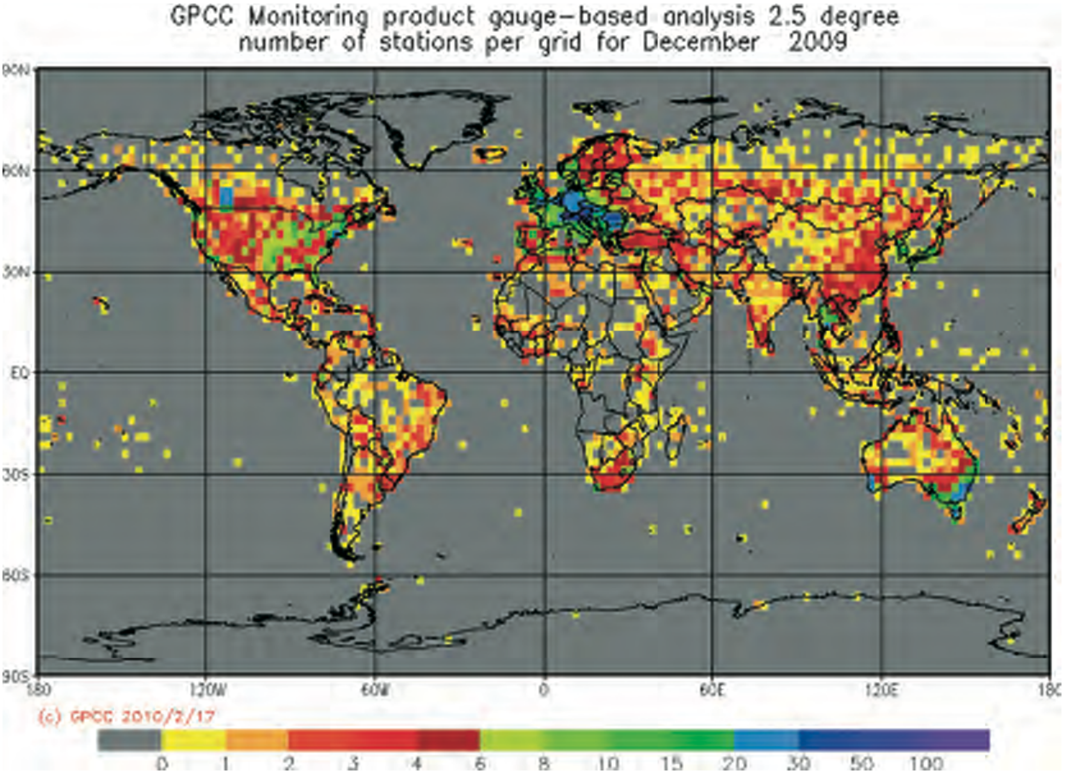


Fig. 3. Number of *in situ* stations per 2.5° grid box for December 2009. Image generated online via Deutscher Wetterdienst at http://www.dwd.de.

## *Remote Sensing Techniques*

With the advent and implementation of radar and satellite technologies in the mid-to-late 20th century, atmospheric scientists have sought unique methodologies for measuring precipitation that addresses the shortcomings of surface point measurements. The use of active and passive remote sensing enables superior spatial sampling that is nearly impractical to achieve with most gauge networks. In addition to sharing some similar limitations of the *in situ* precipitation measurements described above, there are a number of tradeoffs among the advantages and disadvantages between gauge and remotely sensed based precipitation. The main drawback of remotely sensed precipitation is the restricted ability to only *infer* the occurrence of precipitation. That is, remote sensing platforms are only capable of algorithmically estimating precipitation based on the radiometric properties of clouds (e.g. cloud height and type) and precipitation particles (emission and scattering of liquid and frozen water, respectively).

### ACTIVE MICROWAVE (RADAR)

Active microwave remote sensing is generally described as an instrument [e.g. Weather Surveillance Radar – 1988 Doppler (WSR-88D)] that sends a signal that is intercepted by an object and measures the portion of that signal that returns back to the instrument. Specifically, weather radars actively transmit electromagnetic microwaves [typically 10 cm

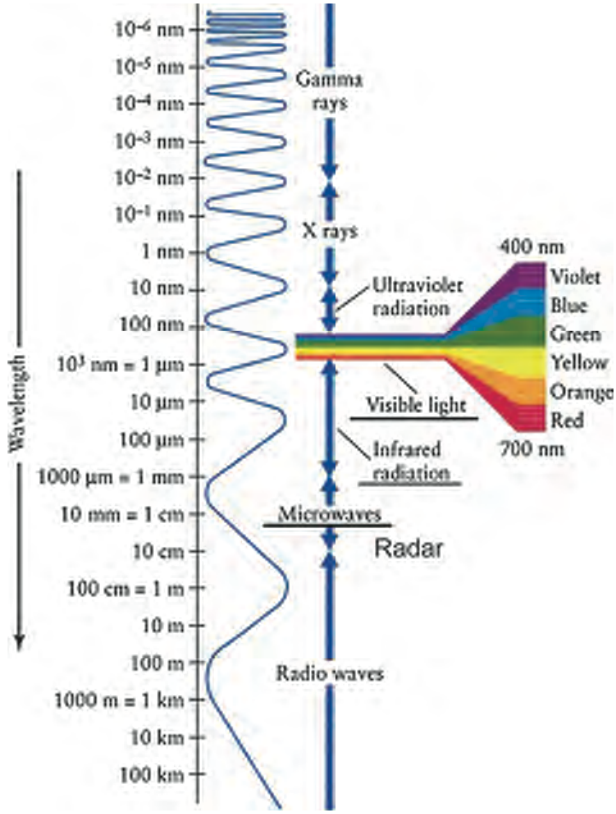


Fig. 4. The electromagnetic spectrum, highlighting the active microwave region. Image provided by NASA.

wavelengths (Figure 4); S-band] at a variety of elevation angles that interact with various hydrometeor targets (among other objects including birds!) and propagate in wave-form through the atmosphere. These targets may absorb or scatter the incident energy, of which a small fraction is received by the radar's antenna in the form of backscattered energy. Radar-based precipitation estimates (or precipitation rates; $R$) are often related to the logarithmically determined reflectivity factor ($Z$). Unfortunately, indirect precipitation estimates stemming from $Z$–$R$ methods are subject to considerable error due to the poor physical relationship between $Z$ and $R$. The rate of precipitation is proportional to drop volume and density, while the reflectivity is related the surface area of the drop (Legates 2000). Therefore, the drop-size distribution is often estimated from techniques originally developed by Marshall and Palmer (1948). Consequently, the error associated with the assumed $Z$–$R$ relationship has been shown to reach 100% (Yin et al. 2001), depending for instance on heavy versus light precipitation (Waldvogel 1974) and/or liquid versus frozen precipitation (Hunter 1996), among other variables (e.g. signal calibration maintenance, anomalous propagation, ground clutter, surface estimation, attenuation, and beam filling) (Austin 1987; Doviak 1983; Fulton et al. 1998; Joss and Waldvogel 1990; Sauvageot 1994; Smith 1990; Wilson and Brandes 1979).

In addition to the concerns over the assumptions and inadequacies of radar-estimated precipitation and the potential resultant error, radar instruments, similar to surface precipitation gauges, are also constrained to a variety of other limiting factors that ultimately does not allow for a global network of radar-based precipitation. Again, there is less than a quarter of viable land surface sufficient for radar use. This includes the limited use in proximity to shorelines (because of the inability or impracticality of radar installation over water bodies, particularly oceans) (Figure 5), and remote and developing regions around the world. Additionally, areas with rough terrain can create beam-blocking barriers that prevent the full sampling swath (Figure 6). Currently, surface weather radar instruments

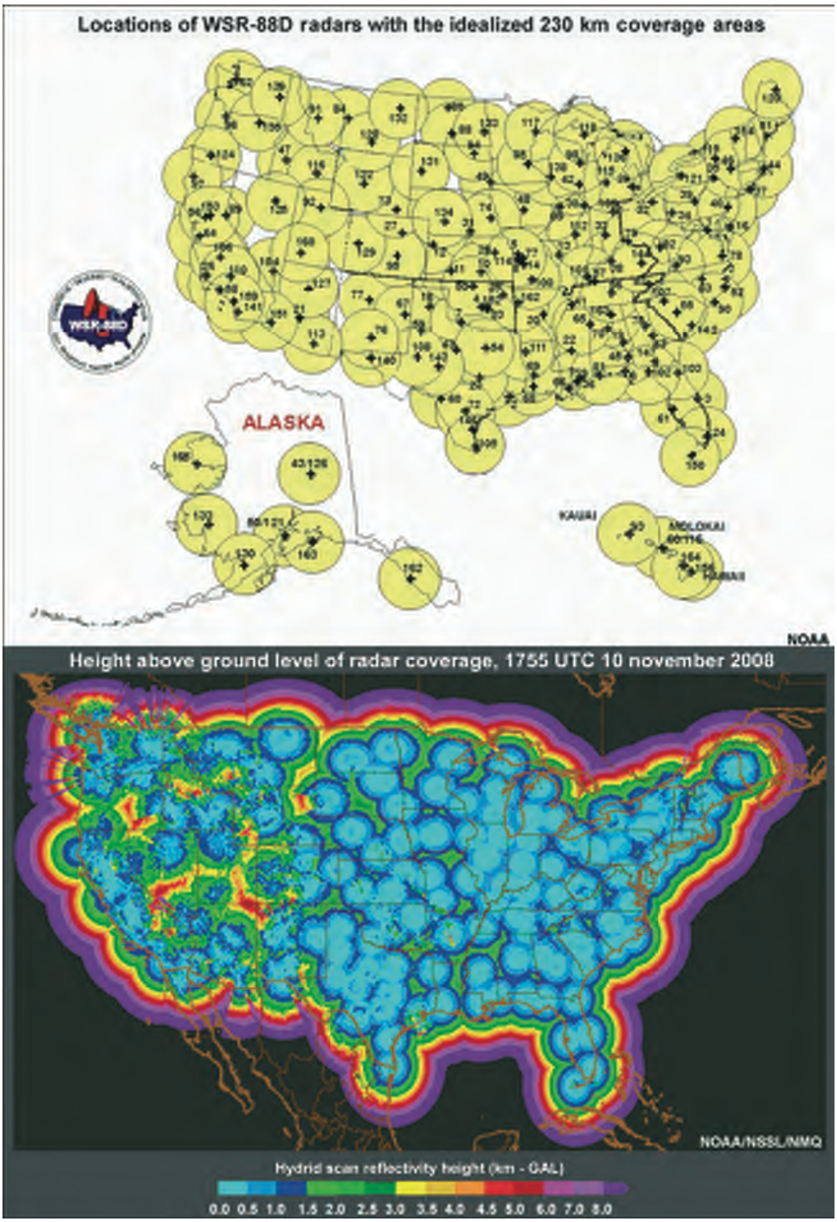


Fig. 5. The coverage mosaic of the WSR-88D radar systems in the United States. Source: National Oceanic Atmospheric Administration and The COMET Program.

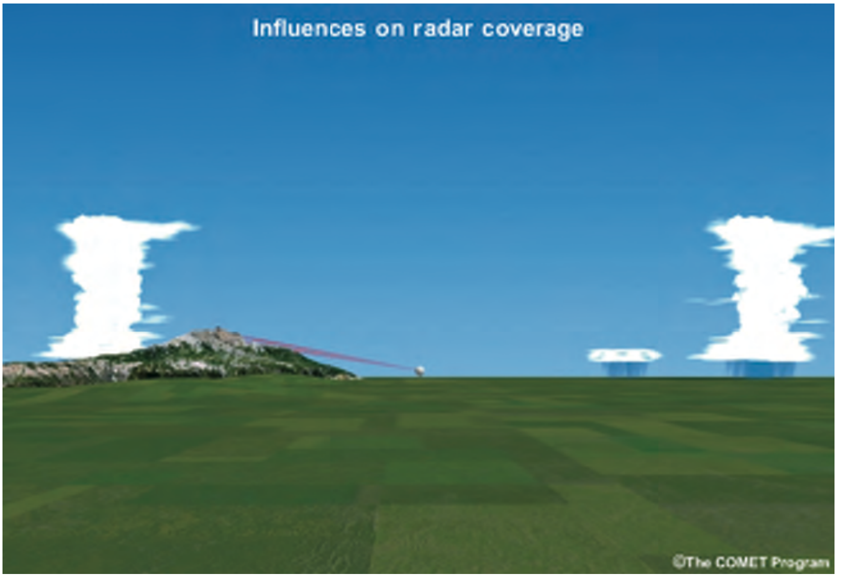


Fig. 6. Schematic diagram of terrain beam-blocking features that inhibit precipitation target detection. Image provided by The COMET program.

such as the WSR-88D contain relatively high temporal sampling (on the order of minutes) and spatial sampling capabilities of 0.25 km by 0.5° at a spectra range of 300 km (referred to as *super resolution*), based only from a horizontal active sensing scheme through the precipitation. (i.e. single polarization) (Chandrasekar et al. 2008). It is expected that over the next decade, these systems will upgrade to a dual-polarization system, which is capable of both horizontal and vertical backscattered pulse sensing. As result, dual-polarized radar systems will have the ability to provide enhanced information on precipitating systems and precipitation characteristics (e.g. rain drop shape, size, and distribution) (Chandrasekar et al. 2008). Markowski and Richardson (2010) and Burgess and Ray (1986) provide excellent, in-depth summaries of the fundamentals of radar design and application described above. Overall, radar-based precipitation estimates are excellent alternatives to other traditional surface-based measures such as precipitation gauges, particularly with vastly improved spatial resolutions. Nevertheless, much of the world's precipitation remains left unsampled by these instruments due to their fixed position, limited sampling range, and relatively high operation and maintenance costs. With this in mind, the scientific community has moved toward the development of space-based approaches in order to observe and measure precipitation in many un-sampled regions around the world.

## VISIBLE AND/OR INFRARED SENSING

Given that surface-based techniques of precipitation measurement are quite limited in spatial scope, the only way to gain a global perspective of precipitation is with the use of geosynchronous and polar-orbiting satellites (Figure 7). Together, these satellites operate under a variety of orbital paths, spatial and temporal resolutions, and radiometric sensing capabilities that are able to observe precipitation in most of the poorly sampled regions around the world (mainly over the oceans, vast desert and polar regions, and developing

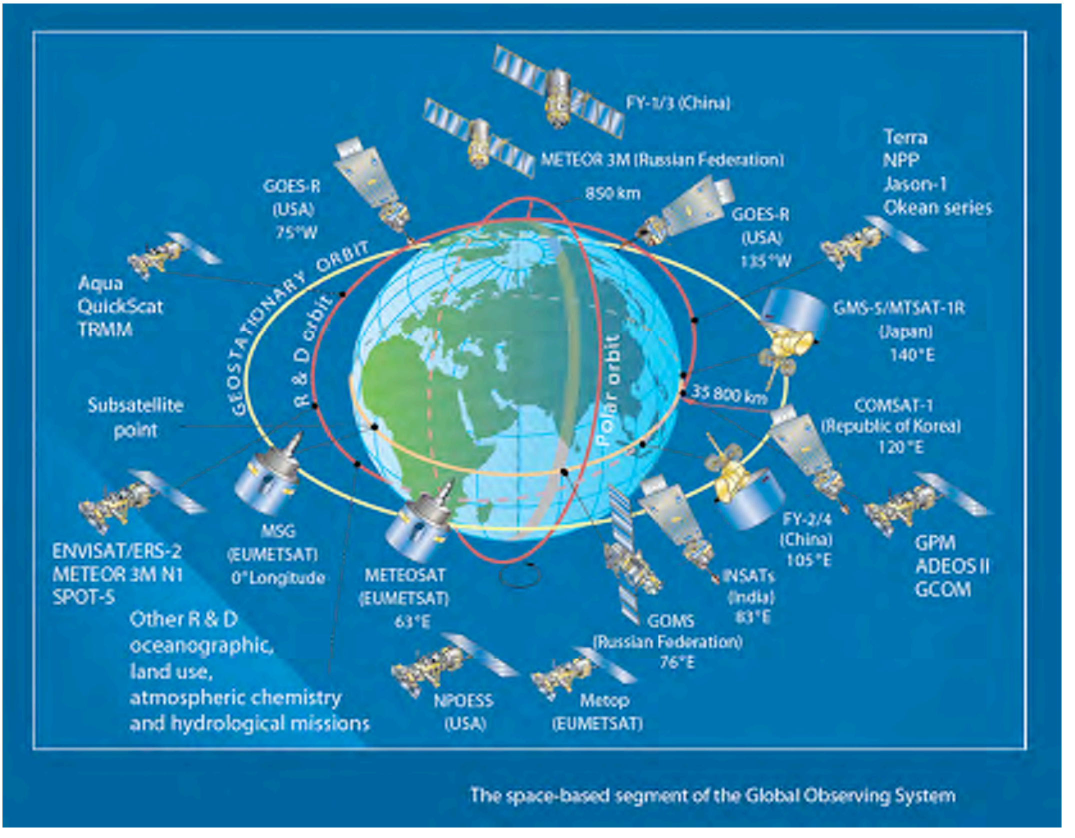


Fig. 7. Space-based global observation satellite network. Image courtesy of the World Meteorological Organization.

regions). There have been a number of space-based methodologies developed for a variety of satellites, each benefiting from advancing technology, as well as owing detriment to a host of assumptions and systematic limitations.

To begin, visible (0.65 $\mu$m) and thermal infrared (IR; 10–12 $\mu$m) (VISIR) (see Figure 4) imagers on board geosynchronous satellites (e.g. Geostationary Operational Environmental Satellite, GOES) are used to detect cloud attributes as a way to indirectly infer the occurrence of precipitation. Visible radiometers detect the brightness of clouds (i.e. cloud thickness) through reflected and/or backscattered solar energy with respect to water droplet and ice crystal density. IR radiometers help us examine the temperature characteristics of clouds and therefore are not dependent on the sun (i.e. IR sensing is independent of the time of day). Typically, cooler (warmer) clouds appear whiter (darker) and are *assumed* to be located higher (lower) in the troposphere. Since clouds are generally opaque to VISIR radiation, VISIR algorithms relate cloud-top reflectivity and brightness temperatures (a thermal metric of radiation of a blackbody object with equal emittance of radiation at a particular wavelength) to cloud height and depth, and precipitation rates. The assumption follows that the occurrence of little or no precipitation is indirectly determined from warm, dark clouds, whereas heavy precipitation is related to cool, bright clouds (Kidd 2001).

The VISIR approach takes advantage of continuous and consistent full-disc (hemispheric) observations, with relatively good spatial (1 and 4 km) and temporal resolutions

(15 min). However, the fundamental flaw with this approach is the observation of cloud-top properties, rather than actual precipitation reaching the surface (Gruber and Levizzani 2008; Kidd et al. 2003; see Figure 3 in Kidd 2001). Specifically, VISIR radiometers often experience trouble discriminating between the physics of relatively low, warm precipitating clouds (stratus) and cold precipitation-free clouds (cirrus) (Rogers 1981).

There have been a variety VISIR techniques that attempt to address the assumptive relationship between cloud attributes and the occurrence of precipitation. One widely used operational technique involves the idea of cloud indexing (Arkin 1979; Barrett 1970). This approach derives a GOES precipitation index (GPI), which is based on the probability and intensity of precipitation from different classes of clouds that stems from an IR temperature threshold (235 K) over a 2.5°×2.5° area (Arkin et al. 1994; Arkin and Meisner 1987). Overall, the GPI technique is considered best-suited for climatological precipitation applications, rather than individual events (Adler et al. 1994; Arkin and Janowak 1991; Arkin and Meisner 1987; Kidd 2001).

In another method, Scofield and Kuligowski (2003) followed up on the Auto-Estimator technique discussed in Vicente et al. (1998) with the Hydro-Estimator. Here precipitation is related to GOES IR brightness temperatures and local rainfall averages. If the inferred precipitation is above the local average, the pixels are not selected (i.e. no precipitation). Additionally, adjustments to the Hydro-Estimator data are derived from numerical weather prediction data depending on the relative humidity, evaporation effects, wind, and topography.

Another algorithm includes the bispectral approach, which are discussed in the studies conducted by Tsonis and Isaac (1985), Lovejoy and Austin (1979a,b), and Dittberner and Vonder Haar (1973). In this technique, cold/bright and warm/dark cloud radiances are cross-analyzed in order to determine the probability of precipitation. Tsonis and Isaac (1985) found the bispectral approach works best for relatively heavier precipitation events when compared to stratiform precipitation. The life history method considers precipitation-rate variability during the life cycle of a cloud-precipitating system. The problem here is that the cirrus canopy of one convective storm may mask the on-going life cycles of other nearby storms (Griffith et al. 1980, 1978; Negri et al. 1984; Stout et al. 1979). Ba and Gruber (2001) discuss the GOES Multispectral Rainfall Algorithm, which utilizes the visible, near-IR, water vapor, and thermal IR channels to effectively determine precipitating clouds at various heights based on cloud-top temperatures. Additionally, there have been numerous cloud-model techniques (Adler and Mack 1984; Adler and Negri 1988; Martin and Howland 1986; Scofield and Oliver 1977; Wylie 1979) that have been developed in an attempt to differentiate between heavy and stratiform precipitation by replicating cloud microphysics. While this method has been shown to improve the overall performance of the basic VISIR approach, the cloud-model approach is sensitive to the prevailing weather and climate patterns of a given location (Marrocu et al. 1993).

In summary, VISIR techniques have been shown to work relatively well at larger space and time scales, particularly for heavier precipitation events, despite the governing limitation that precipitation processes are indirectly inferred from cloud-top attributes. A widely used alternative in space-based approaches involves the use of passive microwave (PMW) sensors, which provide a more direct inference of the occurrence of precipitation.

### PASSIVE MICROWAVE

In contrast to active remote sensing, PMW sensing simply measures the radiation that is emitted from an object. Some of the earlier studies on precipitation estimation using

PMW sensors dates back to the work of Rao et al. (1976) and Wilheit et al. (1977). These studies revealed the initial advantages and limitations of PMW precipitation data. The most important consideration is that PMW precipitation estimates are more physically robust, when compared to VISIR metrics. Within clouds, liquid and frozen precipitation-sized particles are sensitive to microwave radiation, which therefore provides a more direct link to precipitation processes and does not rely on cloud properties.

The physics of liquid and frozen hydrometeors is an important element of PMW precipitation estimates. Liquid particles are effective absorbers of microwave energy, while ice is more effective at scattering energy. Scattering and absorption properties are segregated into three frequency channels in the microwave spectrum. Specifically, between 10 and 37 GHz (low frequency) PMW sensors detect the thermal emission of liquid droplets. The relationship here is that warmer (cooler) microwave brightness temperatures are linked to heavier (lighter) precipitation. At higher frequencies (e.g. 85 GHz) these sensors primarily detect the scattering of outgoing terrestrial energy due to ice particles. As a result, high-frequency ice scattering signatures are less directly related to rainfall, but do remain more physically linked to precipitation and perform with greater accuracy compared to VISIR techniques (Ebert et al. 1996; Joyce et al. 2004; Smith et al. 1998). In contrast to low frequency detection, cooler (warmer) microwave brightness temperatures are associated with heavier (lighter) precipitation. Between these low and high frequency channels, both scattering and absorption processes dominate (Joyce et al. 2004; Kidd et al. 2003).

Consequently, PMW radiometers suffer from their own set of draw backs, some of which are discussed in detail in Robertson (2005), Kidd et al. 2003, Kidd 2001, Kidd and Barrett (1990), Lovejoy and Austin (1980), among others. First, the detection of the emission and scattering properties of precipitation particles is dependent on whether these processes reside over oceans or terrestrial surfaces, as well as the surface cover (e.g. snow-covered land surface). The difference between the polarized emissivity of the ocean surface ($\epsilon$=0.4–0.6) and non-polarized emission of liquid precipitation droplets ($\epsilon$=0.8–0.9) allows PMW radiometers to discriminate the appearance of 'warm' rainfall over a backdrop of a 'cool' ocean surface. Terrestrial surfaces void of ice/snow have similar emissivity values of liquid droplets, which can create an indistinguishable mask that unifies the appearance of both the precipitation and land surface. Moreover, PMW instruments often experience difficulty sensing the difference between cloud droplets and precipitation-sized drops (Lovejoy and Austin 1980).

Aside from cloud-microphysical issues, PMW instruments are currently restricted to sun-synchronous, low-Earth orbiting satellites and therefore are not capable of the spatial and temporal sampling of VISIR sensors. These satellites are not fixed in position with respect to the viewing angle of the Earth as geosynchronous satellites are. The result is that PMW instruments are only capable of creating snapshots (one or two views per day) of instantaneous precipitation (Lettenmaier 2005; Smith et al. 1998) (Figure 8). This exemplifies the tradeoff between PMW and VISIR techniques; improved accuracy at the expense of lower sampling frequency and poorer spatial resolution (~4 km to 40+ km). Lastly, PMW sensors commonly suffer from beam filling errors, which result in underestimation error of observation (Figure 9) (Lovejoy and Austin 1980).

Overall, low frequency PMW channels generally fail at detecting precipitation processes over land, but are suitable over the oceans. While less direct than low-frequency detection, high-frequency ice scattering signatures are independent of the background surface type and perform generally well over land and the oceans. However, as previously mentioned, if the surface contains a backdrop of ice or snow, this cool background can

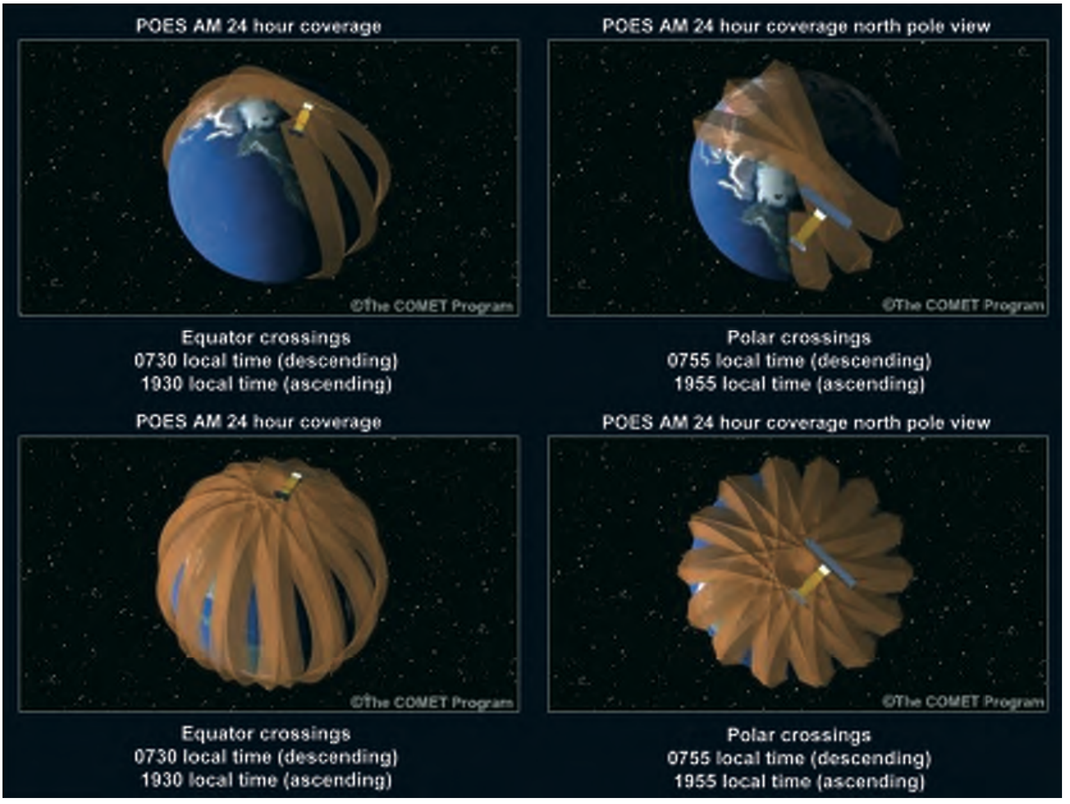


Fig. 8. Temporal sampling swath of polar satellite orbits. Image provided by The COMET Program.

mask out the ice-scattering signature. Since most warm-cloud precipitation processes are void of ice scattering, the use of high frequency detection of precipitation is also restricted mainly to deep convective systems in the tropics and cold-cloud precipitation processes at middle and higher latitudes (Ferraro et al. 1998–2000). PMW imagers such as the Special Sensor Microwave Imager (SSM/I; Ferraro 1997), Advanced Microwave Sounder Unit (AMSU; Ferraro et al. 2000; Weng et al. 2003), Advanced Microwave Scanning Radiometer (AMSR-E; Tachi et al. 1989; Turk and Miller 2005), and the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI; Kummerow et al. 1998, 2000, 2001) remain as the key microwave sensors used in contemporary algorithm development for precipitation estimation (Gruber and Levizzani 2008; Scofield and Kuligowski 2003). An excellent intercomparitive analysis of many of these algorithms is summarized in Smith et al. (1998) and Levizzani et al. (2007).

*Merged Approaches*

By now it is clear that the various methods designed for precipitation observation and measurement each present a unique set of advantages and limitations. The overall performance of each method is highly dependent on the assumptions and/or algorithms that underlie each technique, the type of microphysical precipitation processes at hand, and the (horizontal and vertical) location of the precipitating system. This is especially

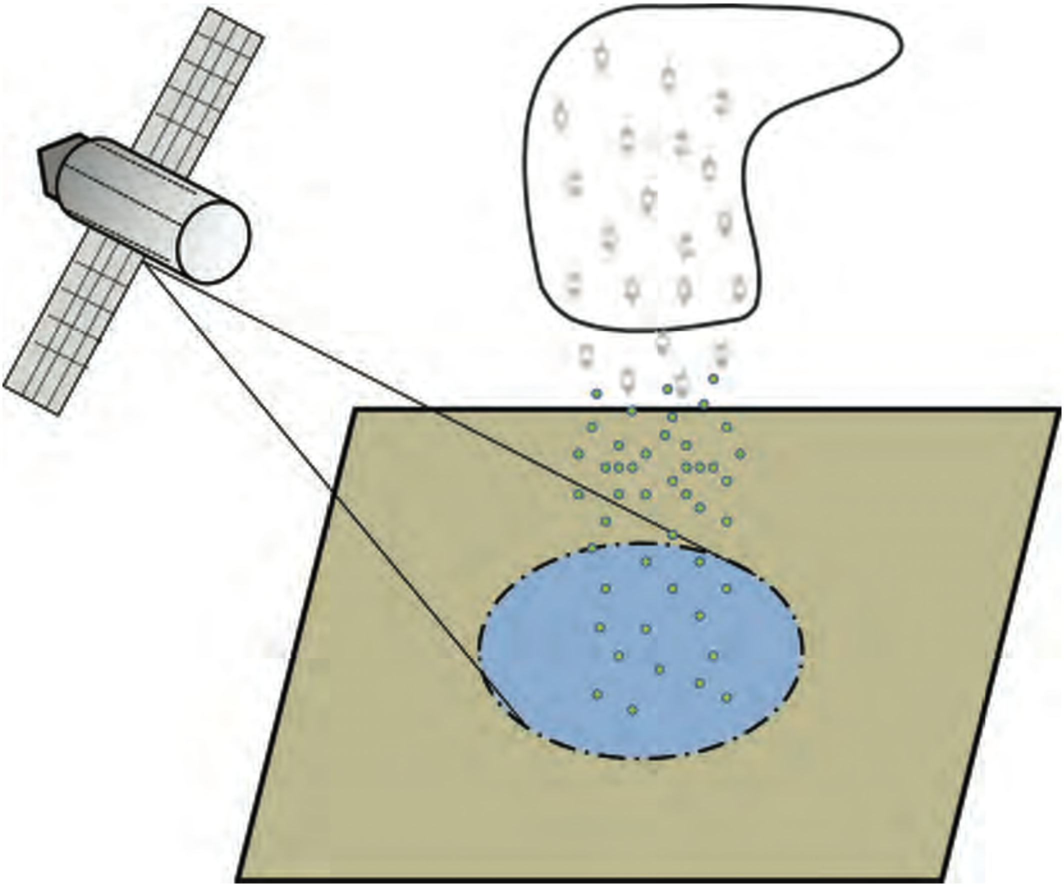

Fig. 9. Schematic diagram illustrating beam-filling errors and resultant underestimation of precipitation.

problematic when attempting to comprehensively and accurately observe and measure precipitation at global scales. As a result, contemporary methods have been focused on blending the techniques from various sensors and instruments in order to develop relatively high quality global precipitation estimates. This hybrid approach is conducted with the goal to create the optimal precipitation end product by utilizing the advantages of various techniques and minimizing the error or bias inherent from each approach. Such precipitation products take advantage of the relatively high space and time resolution of IR sensors, improved accuracy of PMW data, and the direct collection of precipitation from surface gauges (Adler et al. 2003; Kidd et al. 2003).

Blended, merged, or hybrid methods of precipitation estimation as they are often referred to as, includes a wide variety of approaches. In terms of IR/PMW combined estimates, Sorooshin et al. (2000) discussed the use of artificial neural networks to relate IR brightness temperatures to PMW rainfall rates. This precipitation estimation from remotely sensed information using artificial neural networks, or PERSSIAN precipitation product provides global precipitation estimates every six hours at 0.25° resolution. At the Naval Research Laboratory, Turk and Miller (2005) developed a (NRL blended) method that determines the relationship between IR brightness temperatures and PMW rain rates by statistically matching histograms between the two sources, and is available at three-hourly intervals at 0.10° resolution. Joyce et al. (2004) developed the Climate Prediction Center Morphing Method (CMORPH) that uses IR data to linearly interpolate and evolve the PMW rain rate data during times when the PMW data is unavailable. The result is a relatively higher temporal (30-min intervals) and spatial resolution (0.7°) between 60°N/S.

Other multi-source precipitation estimates involves a blend of *in situ* and remote sensing data. The final product often includes an average precipitation estimate that is weighted by the technique with the least error bias (Huffman et al. 1997). The Global Precipitation Climatology Project (GPCP) is under the Global Energy and Water Cycle Experiment in association with the World Climate Research Program that is devoted to these types of hybrid precipitation estimates on a global scale. Currently the GPCP produces three nominal (Version 2.1) global precipitation products (Huffman et al. 2009). First, the satellite-gauge product is a global monthly merged dataset at 2.5° resolution from 1979 to near present, derived from surface gauges, and IR and PMW satellite data (Adler et al. 2003).

A similar technique, the Climate Prediction Center Analysis of Precipitation (CMAP) provides monthly and 5-day intervals, or pentad global precipitation estimates at 2.5° resolution from 1979 to near present, which too are derived from (albeit different sources) surface information, and polar-orbiting and geosynchronous satellites (Xie and Arkin 1995, 1997). Following up on the GPCP and CMAP monthly products, Xie et al. (2003) developed a GPCP pentad dataset that is consistent with the monthly data by adjusting the CMAP pentad against the GPCP monthly product. The final GPCP product is the one-degree daily (1DD) global dataset, which is available from October 1996 to near present (Huffman et al. 2001). Each of the GPCP datasets are consistent with one another in that the sum of the pentad and 1DD datasets are equivalent to the monthly estimates.

Realizing the advantages of hybrid techniques of global precipitation estimation, the National Aeronautics and Space Administration (NASA) and Japan's National Space Development Agency (now known as the Japan Aerospace Exploration Agency or JAXA) collaborated on a joint program known as the TRMM. The TRMM satellite was launched in late 1997 with the aim of estimating rainfall and latent heat energy over much of the poorly sampled areas over the tropical and subtropical oceans and terrestrial surfaces (Kummerow et al. 1998, 2000).

The single TRMM platform is comprised of a suite of sensors including the TRMM microwave imager (TMI), a visible and IR Radiometer Scanner (VIRS), the Clouds and Earth Radiant Energy System, a Lightning Imaging Sensor, and the first space-borne Precipitation Radar (PR) (Figure 10, Table 1). The TRMM sensor suite offers a variety of precipitation products at varying space and time resolutions from 1998 to near present (Table 2). While many of the products are derived from combined sensors on board, the TRMM 3B42 and 3B43 datasets also include data from other satellites (e.g. SSM/I, AMSU-B, AMSR-E, and geosynchronous platforms) and surface gauges, which provide three-hourly, daily, and monthly global merged 0.25° precipitation estimates between 50°N/S (Figure 11) (Huffman and Bolvin 2007; Huffman et al. 2007). It is worth noting that the CMORPH, NRL blended, and PERSIANN datasets all incorporate TRMM data into each precipitation product.

The TRMM program has proven to be quite successful by offering a variety of relatively high quality precipitation datasets that have been used in a wide range of applications in precipitation science research. However, the multi-source TRMM data remain limited by the latitudinal distribution and the inability to fully sample the entire world.

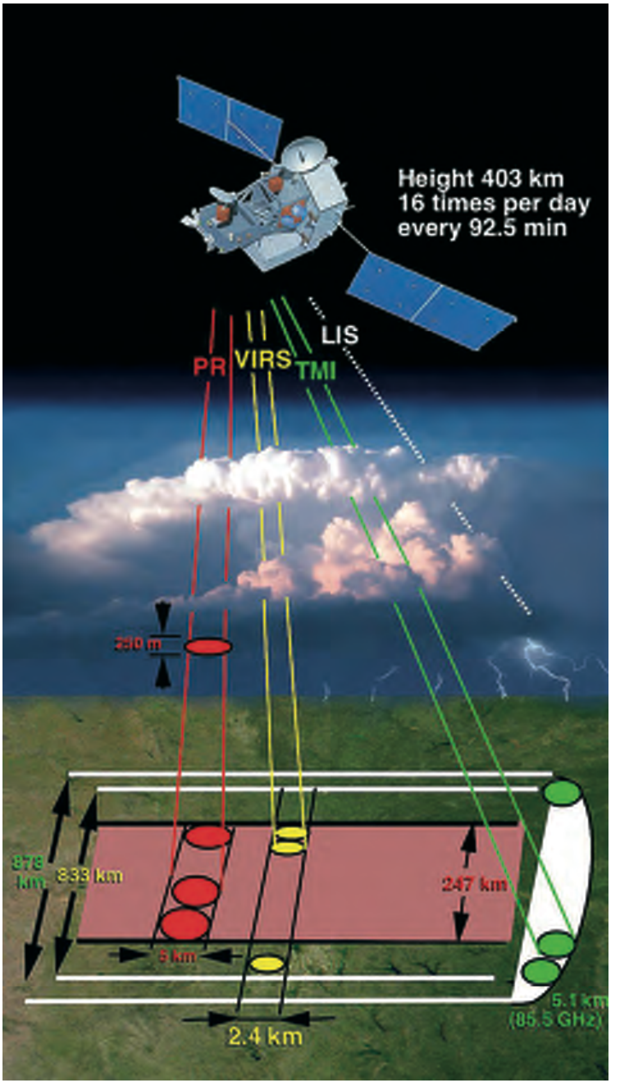


Fig. 10. Schematic illustration of the sensors on board the TRMM platform. Image courtesy of NASA.

Both the success and the short comings of TRMM have paved the way for the future of global precipitation observation and measurement.

## *Looking Ahead at Global Precipitation Approaches*

One of the goals for blended or merged global precipitation measurements (GPMs) is to eliminate IR-inferred precipitation in place of the more physically robust PMW data. The challenge of course is to increase the temporal sampling of PMW, and to also move to a full global observation system. There are two ways to increase the temporal sampling; increase the number of polar-orbiting satellites or place PMW sensors on board geosynchronous platforms. The latter of these two options is becoming more plausible with the advent of high frequency channels and better handling of poor surface resolution (Lensky

**Table 1. Summary of the TRMM rainfall sensor suite. After Kummerow et al. (2000).**

| | TMI | VIRS | PR |
|---|---|---|---|
| Channel(s) | 10.7, 19.3, 21.3, 37.0, and 85.5 GHz (dual-polarized except for 21.3: vertical only) | 0.63, 1.61, 3.75 and 12 $\mu$m | 13.8 GHz |
| Resolution | 10 km×7 km field of view at 37 GHz | 2.2 km | 4.3 km foot print/250 m vertical resolution |
| Scan strategy | Conical (53° inclination) | Cross-track | Cross-track |
| Swath (km) | 760 | 720 | 215 |

**Table 2. Summary of TRMM precipitation products. After Kummerow et al. (2000).**

| | Name | ID | Product |
|---|---|---|---|
| Level-2 | Surface rain x-section | 2A21 | Radar surface scattering x-section/total path attenuation. |
| | PR rain type | 2A23 | Rain type (convective/stratiform) and height of bright band. |
| | TMI profiles | 2A12 | Surface rainfall and 3D structure of hydrometeors and heating over TMI swath. |
| | PR profiles | 2A25 | Surface rainfall and 3D structure of hydrometeors and heating over PR swath. |
| | PR-TMI combined | 2A31 | Surface rainfall and 3D structure of hydrometeors derived from TMI and PR simultaneously. |
| Level-3 | TMI monthly rain | 3A11 | Monthly 5° rainfall; oceans only. |
| | PR monthly average | 3A25 | Monthly 5° rainfall and structure statistics from PR. |
| | PR statistical | 3A26 | PR monthly rain accumulations; statistical method. |
| | PR-TMI monthly average | 3B31 | Monthly 2B31 accumulation and ratio of this product with accumulation of 2A12 in overlap region. |
| | TRMM and other satellites | 3B42 | Geostationary precipitation data calibrated by TRMM, daily, 1° resolution. |
| | TRMM and other data | 3B43 | TRMM, calibrated IR, and gauge products; data merged into single rain product, monthly, 1° resolution. |

and Levizzani 2008). Such a system would likely lead to considerable increased accuracy in precipitation measures over the entire planet. Proposed solutions to help bring PMW sensors to geosynchronous platforms have been described in Bizzarri et al. (2007).

The NASA/JAXA collaboration plans to continue to follow up on the framework and success of TRMM by deploying the next-generation suite of satellites that together will comprise the GPM mission (Figure 12). The primary instruments onboard the core GPM spacecraft will include the GPM microwave imager (GMI) (Table 3) and the first space-based Dual-frequency PR. Together, these instruments will serve as the nominal

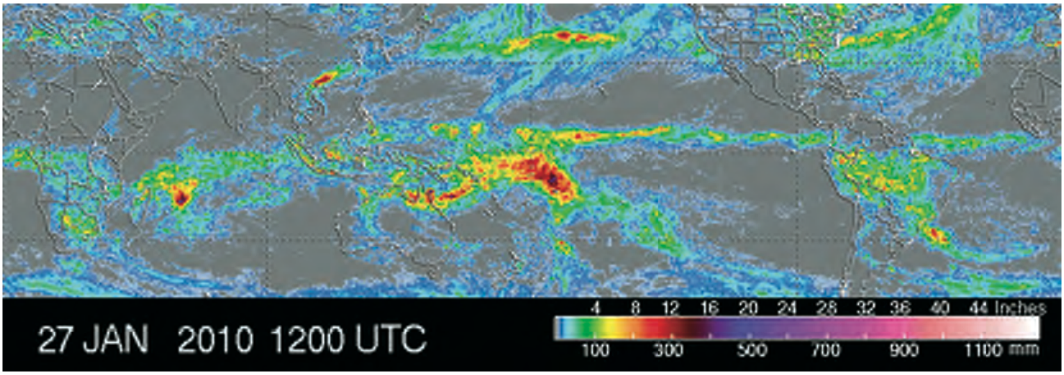


Fig. 11. TRMM 3B42 three-hourly global rain accumulation for 27 January 2010 at 1200 UTC. Image courtesy of NASA.

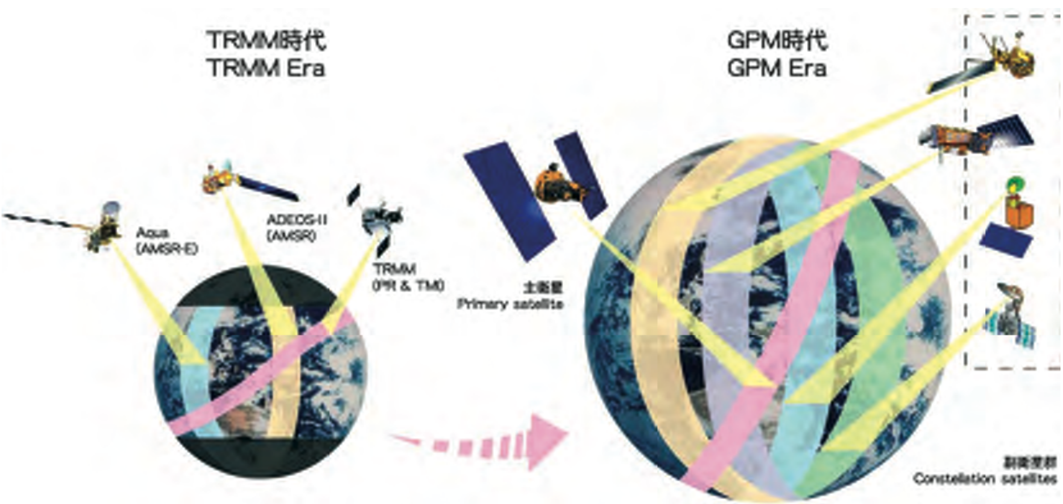


Fig. 12. Graphical representation of the transition between TRMM to GPM. Image courtesy of JAXA.

calibrator for space-based precipitation estimation. Full global coverage will be sampled by a constellation of PMW radiometers that will accompany the core GPM satellite (Figure 13). In addition to increased spatial and temporal sampling, the improved accuracy of GPM data will provide additional information on frozen and relatively light precipitation (Hou et al. 2008). The launch of the core GPM satellite is currently slated for 2013–2014. More information regarding the GPM mission is currently available online at http://gpm.gsfc.nasa.gov/.

## *Concluding Remarks*

This article highlights the advantages and short comings of various precipitation measuring methods and the march toward an accurate global precipitation observation system. The advancement of precipitation observation and measurement, particularly at global scales, has progressed rapidly over the last 50 years. While improved technologies, new

**Table 3. Summary of the GMI sensor. Adapted from Hou et al. (2008).**

| Frequency (GHz) | Vertical (V) and Horizontal (H) Polarization | Core footprint (km) at 405 km altitude | Constellation footprint (km) at 650 km altitude |
|---|---|---|---|
| 10.65 | V/H | 19.4 × 32.2 | 30.8 × 51.7 |
| 18.7 | V/H | 11.2 × 18.3 | 18.0 × 29.4 |
| 23.8 | V | 9.2 × 15.0 | 14.8 × 24.1 |
| 36.5 | V/H | 8.6 × 14.4 | 13.8 × 23.1 |
| 89.0 | V/H | 4.4 × 7.3 | 7.1 × 11.7 |
| 165.5 | V/H | 4.4 × 7.3 | 7.1 × 11.7 |
| 183.31 ± 3 | V | 4.4 × 7.3 | 7.1 × 11.7 |
| 183.31 ± 8 | V | 4.4 × 7.3 | 7.1 × 11.7 |

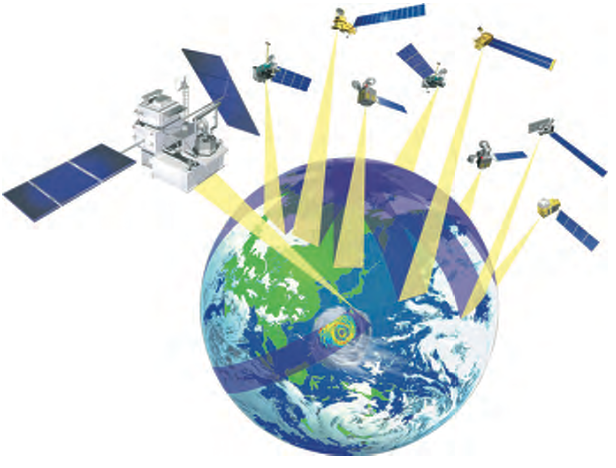

Fig. 13. Conceptual diagram illustrating the core satellite platform and attendant constellation satellites used in the GPM mission. Image courtesy of JAXA.

instruments and designs, various algorithm developments, and technique enhancements have provided a variety of approaches for observing precipitation, no single instrument or method can provide the answer to all of the applications and problems in measuring this stochastic quantity. The current push in precipitation science is to utilize multi-source, hybrid approaches in an attempt to reduce the error in precipitation measurement. It is worth mentioning that model-based precipitation estimates are another important technique that is widely used in forecasting and reanalysis applications. Model-based approached rely heavily on the accuracy of the instruments and other techniques described in this article. Thus a tangential and important research area includes validation work.

A concern over the use of multiple precipitation observation sources is that operational and/or systematic errors from a single data source can greatly hinder the accuracy of the overall precipitation product. Moreover, some methods provide greater accuracy for observing and measuring precipitating systems of various magnitudes and over different regions. The scope of the current article does not include detailed descriptions of these efforts. For an inventory of regional inter-comparisons and validation studies of multi-sensor/instrument approaches and algorithms (including those not mentioned here), the reader is encouraged to consult the International Precipitation Working Group, which is currently located online at http://www.isac.cnr.it/~ipwg/. Other inter-comparison projects include the Program to Evaluate High Resolution Precipitation Products (Sapiano and Arkin 2009; Turk et al. 2008), which is available online at http://essic.umd.edu/~msapiano/PEHRPP/data.html. Other seminal inter-comparison and validation studies include the work by Ebert et al. (2007, 1996), Ebert and Manton (1998), and Adler et al. (2001). Lastly, recent books by Michaelides (2008) and Levizzani et al. (2007), among other summaries (e.g. Kidd 2001; Kidder and Vonder Harr 1995; Krajewski et al. 2000; Kuligowski 1997) are excellent resources that provide in-depth descriptions of precipitation observation and measurement.

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### *Short Biography*

Dr Josh Durkee is an Assistant Professor of Meteorology and Climatology in the Department of Geography and Geology at Western Kentucky University in Bowling Green, Kentucky, USA. His research has focused on the climatology and rainfall produced from particularly large, long-lived thunderstorm systems called mesoscale convective complexes (MCCs). In a recent study, Dr Durkee utilized TRMM satellite data to quantify MCC rainfall contributions across subtropical South America and determined the overall impact of MCC rainfall across the region. Dr Durkee also conducts research on the climatology and dynamical framework of high-wind events that take place away from thunderstorm environments (also referred to as nonconvective high-wind events). His work has been published in the *Journal of Climate*, *Monthly Weather Review*, *International Journal of Climatology*, and *Theoretical and Applied Climatology*, including contributions to the upcoming book, *Encyclopedia of Geography*. He also serves as the administrator to CLIMLIST, an international listserv of nearly 3000 meteorologists and climatologists from around the world. Dr Durkee received his BS degree in Geography from Western Kentucky University, and his MS and PhD degrees in Geography from the University of Georgia, where he specialized in synoptic and mesoscale meteorology and climatology, remote sensing, and hydrology.

### *Note*

* Correspondence address: Josh Durkee, Western Kentucky University–Geography and Geology, 1906 College Hights Blvd., Bowling Green, Kentucky 42101, USA, E-mail: joshua.durkee@wku.edu

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