Global Precipitation Observations to Advance
Water/Energy Cycle, Climate, Model, and Disaster Science

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Executive Summary

Quantified Earth Science Objective: Provide a 30-year record of high-quality daily and sub-daily precipitation for water/energy cycle closure, global change detection, climate and numerical weather forecast model evaluations, and flood and landslide analysis.

Importance and Utility: The unifying theme is the geophysical variable *precipitation*, a key parameter across many Earth Science topics, and designated as an Essential Climate Variable. Critical science and application targets within the ESS themes for which precipitation is a determinant factor include: In the global energy and water cycles [Theme I] precipitation is one of the direct links in the water cycle, and a strong constraint on the energy cycle. In global change studies [Themes I, IV] it is important to complement numerical models with observation-based metrics of long-term change. For numerical models [Themes I, II, IV] detailed, long-term observations of precipitation are required to guide and constrain model development. For floods and landslides [Theme II] precipitation is the primary time-varying driver, and observations are still the data source of choice.

Quality: Passive microwave observations are needed no more than three hours apart, and preferably hourly, over climate (30+-year) timescales, at 5-10 km resolution globally. The constellation should be a mix of conically-scanning and cross-track-scanning sensors with SSMIS- and ATMS-class channel selections, respectively, with a precessing radar providing consistent calibration for all sensors.

Affordability: GPM initially satisfied the 3-hour observation interval for passive microwave sensors globally better than 90% of the time using the domestic and international constellation. The impending shortfall in conically-scanning microwave sensors is primarily due to the end of DMSP. In the short term, GMI2 could be completed and launched (likely with a partner); DoD should revisit launching the completed DMSP-F20 (with an SSMIS); nations who have microwave sensor satellites whose data is not now generally available in the U.S. could be included; and Japan should build the JAXA GCOM-W2 satellite (carrying an AMSR2). On the new technology side, next-generation developments (COWVR, TEMPEST, TROPICS) and concepts such as GeoSTAR and a large deployable reflector have promise. The key fact is that the precipitation constellation already exists, already exploits a diverse instrument base, and already leverages domestic and international partners. The critical need is to ensure that the erosion of the constellation is corrected to include conically-scanning passive microwave sensors that are adept at precipitation retrieval.

Introduction: The unifying theme in this concept paper is the geophysical variable *precipitation*, which is widely recognized as a key parameter across many Earth Science topics (e.g., in the GEO [2012, 2014] user surveys, and designation as an Essential Climate Variable in Bojinski et al. 2014).

Importance and Utility: Critical science and application targets within the Earth System Science themes for which precipitation is a determinant factor include:

A deep understanding of the global energy and water cycles is necessary to explicate how and why energy flows through the Earth System. Integrated studies of all the parameters provide assessments of our knowledge of each energy and water cycle parameter and point to remaining areas of uncertainty (L'Ecuyer et al. 2015, Rodell et al. 2015). [Theme I] Precipitation is one direct link in the water cycle, returning water to the Earth's surface, and a strong constraint on the energy cycle in latent heating. Only by long-term, global observations of all components, including precipitation, can researchers achieve a more accurate, mutually consistent accounting of the energy and water cycles, improving on current estimates (Trenberth et al. 2009).

Global change studies trace the past and future trajectory of the Earth System. Numerical models are the main tool, but it is important to complement this work with observation-based metrics. [Themes I, IV] From a climate-scale perspective, the satellite record is short, particularly for the high quality needed for extremes. Gu et al. (2016) used the more-approximate Global Precipitation Climatology Project (GPCP) precipitation product to evaluate global variation over the period 1979-2012, showing the Pacific Decadal Oscillation and, to a lesser extent, Atlantic Multidecadal Oscillation patterns to estimate the global precipitation trend.

Numerical models of the atmosphere (on "weather" timescales) and the coupled Earth System (particularly at climate timescales) codify our understanding of how the systems function, and provide predictions for both weather and climate (Eyring et al. 2015). Continued model development is necessary to improve predictions and provide finer-scale detail. [Themes I, II, IV] One particularly contentious aspect continues to be models' representation of precipitation. They poorly represent the diurnal cycle of precipitation, and convective rainfall in general. Climate models necessarily operate at coarser scales to conserve execution time, but when regional climate models "downscale" precipitation, significant shifts in patterns raise doubts about the models' correctness. Extensive, well-calibrated precipitation observations provide a strong validation that constrains the models. An example is that precipitation observations for the Madden-Julian Oscillation provide a severe test for numerical models (Jones et al. 2004).

Floods and landslides severely impact human activity, from loss of life to losses of infrastructure and economic activity. Floods rank very high among geophysical disasters in total loss of life and economic destruction (CRED 2016). Numerical models of these destructive events provide an evolving capability to provide forecasts and real-time analyses. [Theme II] Precipitation is the dominant mechanism for pre-conditioning the region's susceptibility, and then drives runoff (floods), or pushes soil saturation past a critical point (landslides). In the case of mainstream flooding, a forecast can be based on the prior observed precipitation and a short-range numerical forecast of precipitation. Such modeling is already having important societal benefits, but issues remain, particularly for landslides (Hossain 2014, Wu et al. 2014, Kirschbaum et al. 2015).

Quality: Observation interval: Precipitation arises in discrete patches that are sub-cloud-scale in space and time; the intrinsic statistics are highly skewed and feature a large number of exact zeros. Accordingly, accumulations can be dominated by the few largest events, and these events necessarily require a relatively fine space/time scale of observations. Even for climate studies, the necessary evaluation of extreme events, frequently defined on a daily basis, means the observations have to take place at sub-daily intervals. What is the appropriate time interval? Reed et al. (2015) analyzed the observation interval that is needed for accurate hydrological responses to extreme precipitation events. They determined that the maximum observation interval was less than 4 hours for regions where an estimate could be made, and in many places it was less than 3, down to 1 (Fig. 1). Recently, C. Kidd conducted a sampling study using European radar data provided by the U.K. Met Office at 5 km, 15 min resolution. Considering the summation of native-resolution data to 3, 6, 12, and 24 hr periods as the "correct" answer, the data were uniformly subsampled around the day. Four metrics were computed for 2014-15 and plotted versus the number of (uniformly spaced) samples around the day (Fig. 2). [Statistics are undefined once the sampling drops below at least one in each period.] While there are ripples, likely due to the 15 min data interval, the overall structure is as we expect – longer accumulations have better statistics, and a single estimate in a 3 hr period is not satisfactory. Once again, a 1-hour observation interval is needed to reliably resolve these critical fine details. A third study (Joyce and Xie 2011) correlated "displaced" microwave precipitation estimates against precipitation estimates from the U.S. radar network (Fig. 3). Overpasses of microwave estimates were moved forward and backward in time according to an estimate of motion from geosynchronous infrared (GEO-IR) data, and then these time-displaced fields were correlated against radar estimates. In about ±90 min the correlation drops to the e-folding value, again pointing to the need for hourly observations. On the other hand, this study supports the concept that the current 3 hr observation interval can be made useful for fine-scale estimates. To do this, the algorithm is cast as an analysis following the motion (i.e., Lagrangian). Although the concept is approximate and requires continued work, several "morphing" algorithms are currently being produced routinely (CMORPH, GSMaP, and IMERG).

Period of record: The entire range of precipitation events must be adequately sampled. Climate averages – not even extremes – are usually computed from 30-year records. Fu et al. (2010) analyzed gauge data in Australia spanning nearly a century for a range of "extreme" precipitation definitions. The results clearly show large interdecadal variations, making it unlikely that "long" satellite records of 5, 10, or even 20 years can truly represent the global precipitation record that is so desperately needed. Additionally, a long record is required to provide a continuous record of data specifically for the period over which climate fluctuations and change occur. The Fu et al. (2010) study would not have been possible without a century of precipitation gauge observations, and the same applies for global satellite observations in the current epoch of global change.

Spatial resolution: User surveys such as GEO (2012, 2014) elicit a wide range of requirements, but the median across user groups is 5-10 km. More importantly, there is a heavy penalty for sensors with larger footprints, namely the uncertainties introduced by non-uniform beam filling (NUBF), in which strongly differing precipitation amounts in the same scene combine non-linearly. Kirstetter et al. (2015) show that NUBF can be severe in the case of small, strongly convective precipitation on the 5x5 km footprints of the TRMM Precipitation Radar (PR). Taken together, these facts argue that 5-10 km resolution is a necessary standard.

Sensors: What sensors can provide the necessary accuracy in precipitation? Active sensors, such as the DPR, provide excellent accuracy, but looking ahead to **Affordability**, it is considered wholly impractical to expect complete coverage by radars. Rather, TRMM and GPM have clearly demonstrated the key role that a radar in a precessing orbit has in calibrating precipitation estimates produced by all the passive sensors. Although GEO-IR are very fine scale, the Joyce and Xie (2011) study demonstrates that snapshot precipitation estimates based on GEO-IR data have low accuracy (Fig. 3). Conically-scanning microwave sensors (CSMW) typically provide channels covering 10-183 GHz with linear polarization at many of the window frequencies. The utility of these channels for precipitation estimation depends on surface type: all channels are useful over ocean; only frequencies above ~37 GHz are quantitatively useful over land (due to the warm, time/space-varying background); and surface snow/ice complicate retrievals. Footprints are constant size for a given channel. In addition, note well that these channels support many other Earth Science parameters. Cross-track-scanning microwave sensors (XTMW) typically provide channels covering 23-183 GHz. Their channel information is similar to CSMW for estimating precipitation over land, but footprints vary in size with scan position, and the channel selection is not optimized for precipitation. Over ocean, CSMW provide better precipitation information than XTMW. One important caution in this discussion is that these retrievals are highly under-constrained; it is possible that current algorithm results do not yet fully exploit the information content available from the various sensors.

Finally, incorporating surface precipitation gauge data, in places where they're available, improves satellite-based precipitation estimates significantly, mostly by reducing bias. Interestingly, this improves random error down to the few-day time scale.

Affordability: The necessary ingredients were assembled by about 2005: CSWM and XTMW instruments flying on the domestic/international constellation of satellites of opportunity, an active (radar) sensor in a precessing orbit, the constellation of GEO-IR sensors, and available surface gauge data. The observation interval for passive microwave sensors at the start of GPM (Fig. 4a) satisfied the 3 hr standard at all latitudes better than 90% of the time using satellites from European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), French Centre National d'Etudes Spatiales (CNES), Indian Space Research Organisation (ISRO), Japan Aerospace Exploration Agency (JAXA), U.S. Department of Defense (DoD), U.S. National Aeronautics and Space Administration (NASA), and U.S. National Oceanic and Atmospheric Administration (NOAA). The demise of TRMM on April 8, 2015 (Fig. 4b), and DMSP-F19 on February 11, 2016 (Fig. 4c) reduced the coverage. The impact of losing yet another satellite from the March 1, 2016 constellation depends on how much the satellite overlaps others (Fig. 5). [Note: in April 2016 the DMSP F17 37V channel started failing.]

Looking ahead, the most serious problem with the constellation is that the planned launches of CSMW (Fig. 6) are not sufficient to maintain the required sampling. This shortfall is primarily due to the termination of the U.S. DoD Defense Meteorological Satellite Program without a replacement system being planned. The Compact Ocean Wind Vector Radiometer (COWVR; Brown et al. 2014) is being developed by the U.S. Air Force and Jet Propulsion Laboratory for wind vectors, but it has limited utility in its initial form for precipitation. The supply of XTMW has strong advocates in the modeling community, so the shortfall is in the CSMW. Note in Fig. 6 that the next currently scheduled CSMW launches in about 2019. However, it is not necessary for any single agency to make up the shortfall.

An additional argument in favor of these CSMW is that they present a critical, cross-cutting advantage: a judicious choice of channels can support a wide variety of Earth Science parameters, including sea ice, snowpack, soil moisture, sea surface temperature, and ocean surface wind speed. The administrative burden in negotiating such a multi-disciplinary satellite is real, but there are excellent precedents, including AMSR2 and SSMIS. The payoff is a reliable supply of data for a vast array of Earth Science studies with no single study bearing the entire expense.

This discussion has focused on requirements and needs, not particular instruments, although the AMSR2, GMI, and SSMIS instruments certainly provide the class of measurements that are required. In the short term, there are several opportunities for enhancing the constellation. First, a second, partially assembled GMI (GMI2) is in storage. It currently lacks funding to complete and launch, either by NASA or another agency, but the initial investment has already been made. Second, the DMSP-F20 (carrying an SSMIS imager) is completely configured and sitting in storage. While its launch was cancelled, and DoD is not part of the Decadal Survey, the recent demise of DMSP-F19 creates increased risk of a data gap for DoD, as well as the civilian community; DoD should revisit launching DMSP-F20 to alleviate this issue in the near term. A third short-term action, which could impact the long-term plan as well, would be to work with nations whose microwave sensor data are not now available in the U.S., specifically Russia and China (the upcoming WCOM, in particular). The administrative challenges to this path are severe, but exploring this concept in a multi-national context might prove fruitful. Finally, plans for the JAXA GCOM-W2 satellite (carrying an AMSR2 CSMW) were put on hold a few years ago, but could provide a key resource as older CSMWs fail and deplete the constellation.

On the new technology side, next-generation developments, such as COWVR and the CubeSat-based Temporal Experiment for Storms and Tropical systems (TEMPEST; Reising et al. 2015) and Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS; Blackwell 2016), will provide opportunities to advance the Technical Readiness of new technologies. The next key advance would be to set missions based on these technologies that satisfy precipitation's channel/resolution needs, ensuring the long-term record at reduced cost. One important recommendation by the recent ESTO workshop on microwave radiometers is that a large deployable reflector is a priority. This advance would free passive microwave radiometers from launch costs driven by large, fixed reflectors. One technology approaching space qualification is the Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR; Tanner et al. 2007). This instrument is targeted for GEO satellites, as opposed to the low Earth orbit (LEO) in which all of the current passive microwave instruments fly. As such, it could provide high-time-resolution precipitation estimates if the resolution and channel selections are correctly chosen. Clearly, a global solution would require multiple GeoSTAR instruments, but a synergistic LEO-GEO solution can be sketched that would reduce the expense of the GeoSTAR(s) by limiting its use to active weather areas. The new-generation, less-expensive instruments are badly needed to get the observation interval down to 1 hour by enabling a larger population of precipitation-relevant CSMW (and XTMW) satellites.

The key fact is that a version of the precipitation constellation already exists, already exploits a diverse instrument base, and already leverages domestic and international partners. The critical need is to ensure that the constellation continues to include enough CSMWs that are particularly attuned to the needs of precipitation retrieval. Stocker and Furukawa (2011) raise a similar concern about the availability of CSMWs, The GEOSS Water Strategy Report (GEOSS 2013) contains a specific recommendation to maintain the constellation, and International Precipitation Working Group (IPWG) has consistently recommended the same to its parent organization, Coordinating Group for Meteorological Satellites (CGMS).

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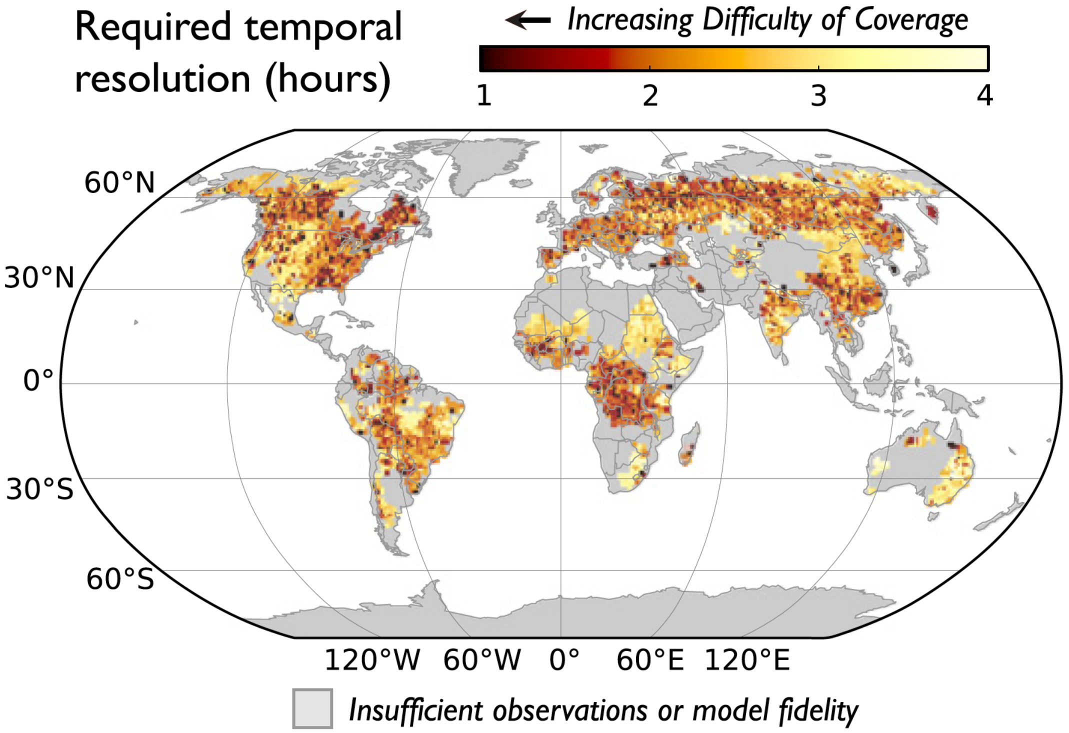

Fig. 1. Hydrological model-based estimate of the temporal resolution of satellite-based precipitation observations (in hours) required to maintain acceptable flood predictions. Grayed-out areas denote locations where either the hydrologic model lacked acceptable performance relative to historical streamflow observations or historical data was insufficient to make an assessment. [Reed et al. 2015, Fig. 2]

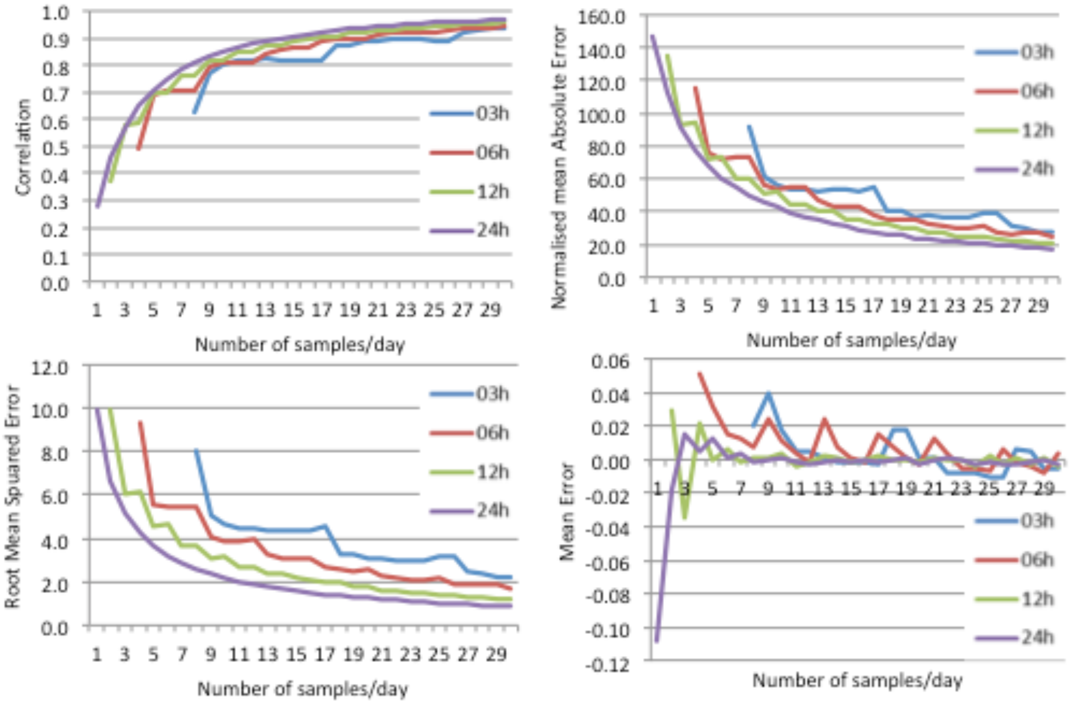

Fig. 2. Error metrics that result from subsampling the 5 km, 15 min European radar data (U.K. Met Office) over the period 2014-15 to the specified number of (evenly spaced) samples per day for four different accumulation intervals: 3 hr, 6 hr, 12 hr, and 24 hr. [C. Kidd, unpublished]

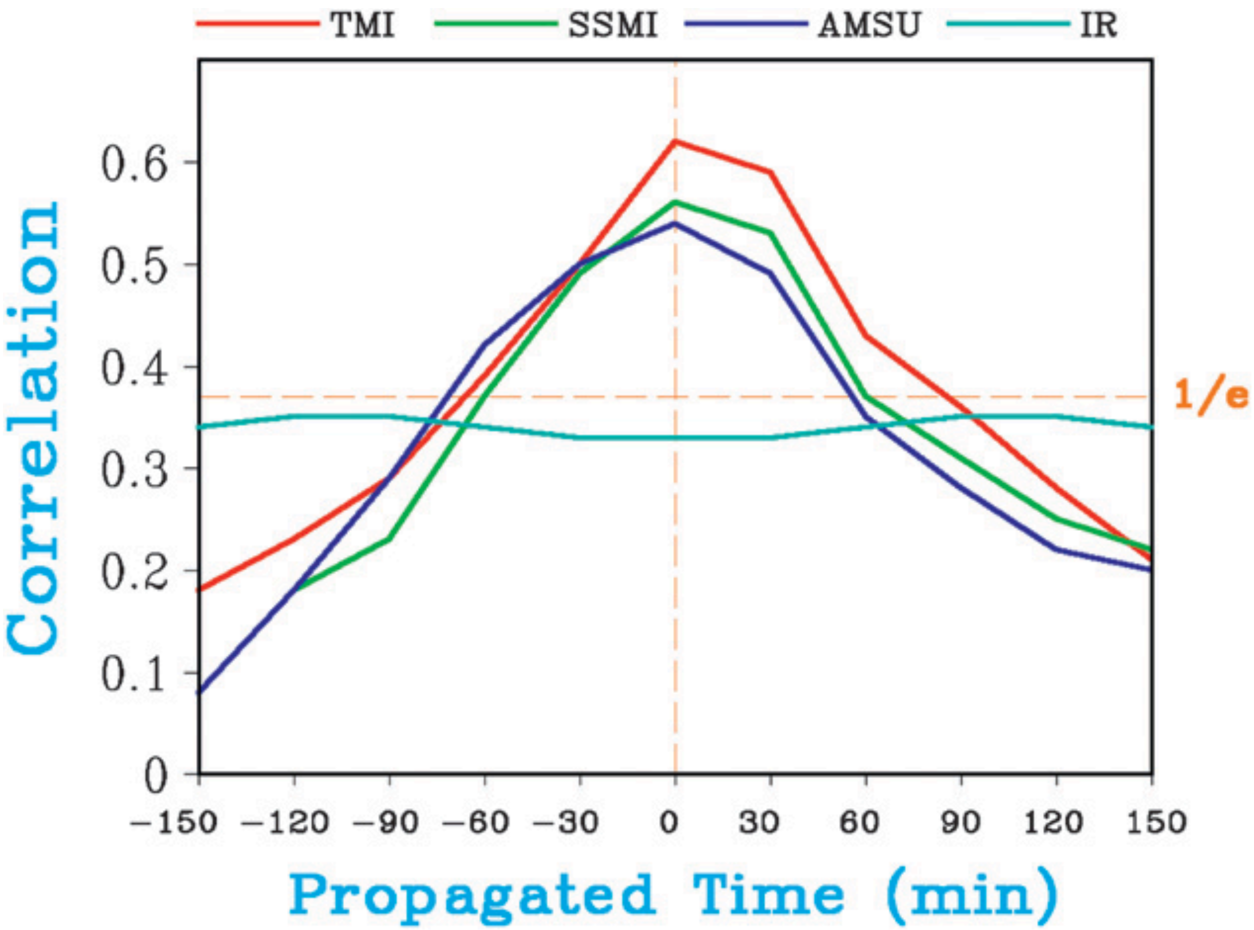

Fig. 3. Correlation between NOAA Stage II radar-based precipitation estimates and satellite-based estimates CONUS for June–September (JJAS) 2007. Positive and negative propagation times indicate forward and backward propagation, respectively, for the passive microwave sensors (TMI, SSMI, AMSU), but the IR observations are at the shifted time. [Joyce and Xie 2011, Fig. 3]

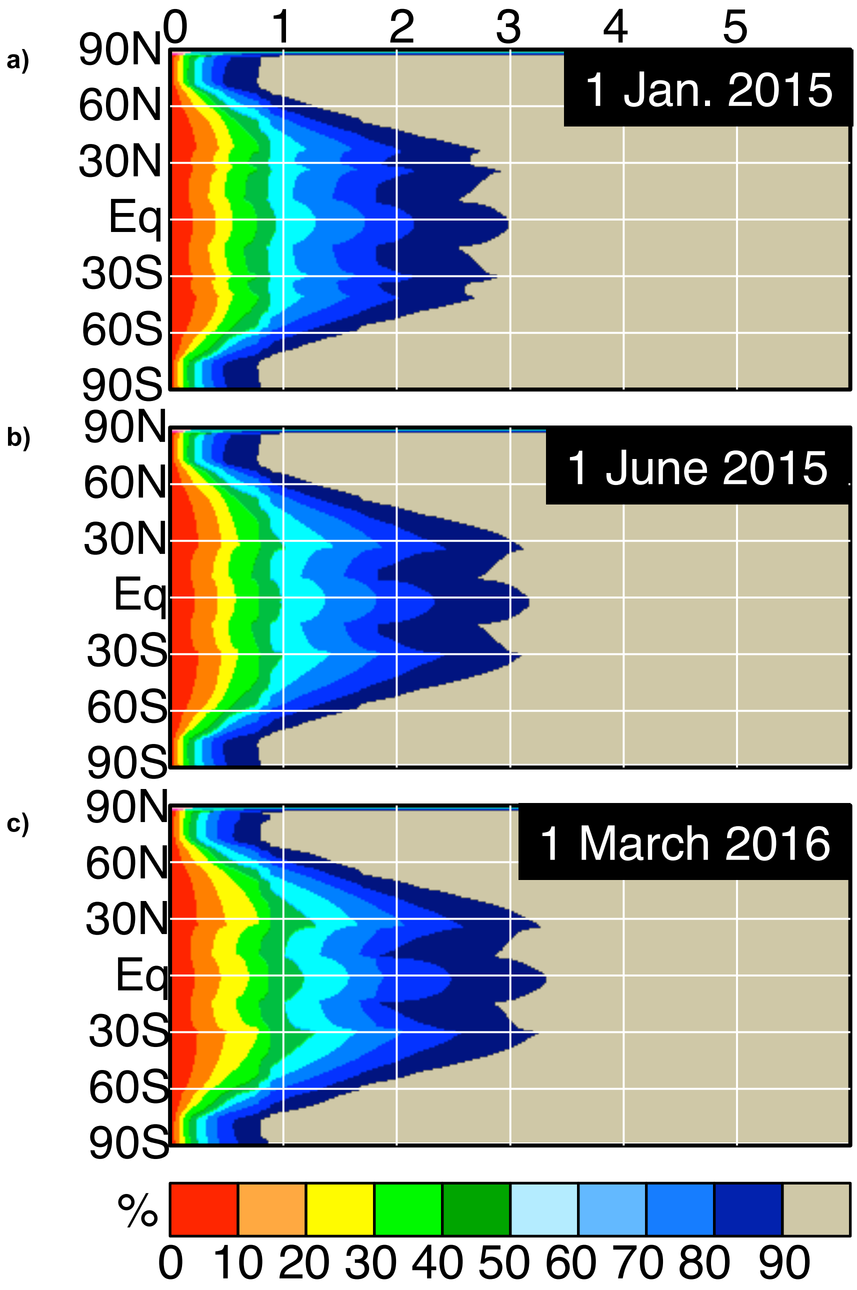

Fig. 4. Overpass interval, expressed as the percent of the day that is less than the X axis values (hrs) as a function of latitude. (a) The full constellation early in GPM consisted of CSMWs (DMSP-F16 SSMIS, DMSP-F17 SSMIS, DMSP-F18 SSMIS, DMSP-F19 SSMIS, GCOMW-1 AMSR2, GPM GMI, TRMM TMI) and XTMWs (Megha-Tropiques SAPHIR, METOP-A MHS, METOP-B MHS, NOAA-18 MHS, NOAA-19 MHS). (b) TRMM TMI ended April 8, 2015, reducing coverage 40°N-S. (c) DMSP-F19 ended February 11, 2016, affecting all latitudes. [C. Kidd, unpublished]

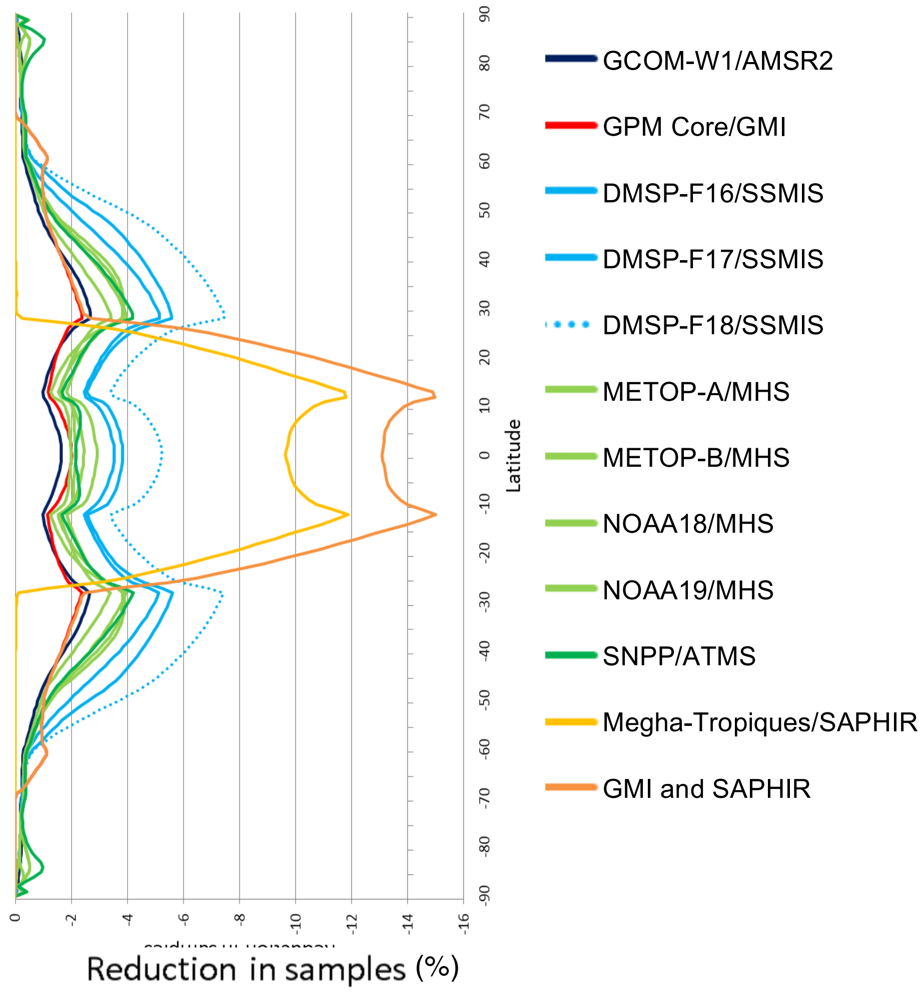

Fig. 5. Additional reduction in sampling (in %) for loss of the indicated satellite/sensor from the March 1, 2016 constellation. The satellite/sensor combinations are abbreviated as The two-satellite case (GMI and SAPHIR) demonstrates that successive losses are not simply additive. [C. Kidd, unpublished]

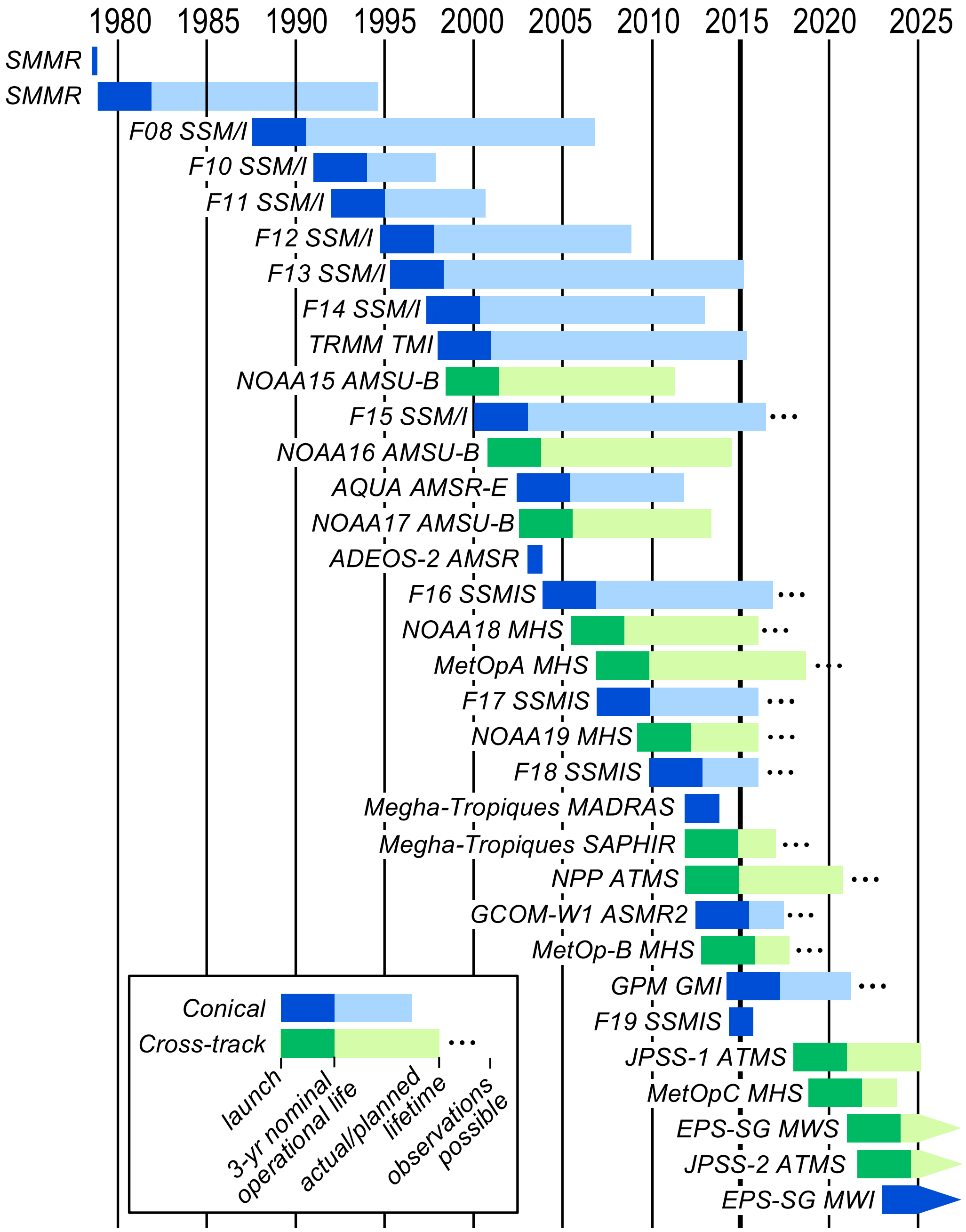

Fig. 6. Time history of passive microwave sensors. CSMWs (XTMWs) are shown in blue (green), with shading indicating mission stages, as shown in the key. Note that SMMR data are not currently used in the precipitation community due to channel, sampling, and calibration issues. [C. Kidd, unpublished, based on CEOS database]