TRMM Multi-satellite Precipitation Analysis (TMPA)
3-Hourly Precipitation

1. Intent of This Document and POC

1a) This document is intended for users who wish to compare satellite-derived precipitation estimates with climate model output in the context of the CMIP5/IPCC historical experiments. Users are not expected to be experts in satellite-derived Earth system observational data. This document summarizes essential information needed for comparing this dataset to climate model output. References are provided at the end of this document to additional information.

This NASA dataset is provided as part of an experimental activity to increase the usability of NASA satellite observational data for the modeling and model analysis communities. This particular archive of data is not a standard NASA satellite instrument product, but does represent an effort on behalf of data experts to repackage a standard product that is appropriate for routine model evaluation. The data may have been reprocessed, reformatted, or created solely for comparisons with climate model output. Community feedback to improve and validate the dataset for modeling usage is appreciated. Email comments to HQ-CLIMATE-OBS@mail.nasa.gov .

Dataset File Names (as they appear on the ESG), depending on processing epoch:

pr_TRMM-L3_v7_*YYYYMMD1h1m1-YYYYMMD2h2m2*.nc
pr_TRMM-L3_v7A_*YYYYMMD1h1m1-YYYYMMD2h2m2*.nc

where *YYYY* = year
MM = month
D1 = first day (of the month)
D2 = last day (of the month)
h1m1 = ending hour and minute of the first 3h period (of the day, UTC)
h2m2 = ending hour and minute of the last 3h period (of the day, UTC)

1b) Technical point of contact for this dataset:

George J. Huffman, george.j.huffman@nasa.gov

2. Data Field Description

CF variable name, units:	pr (precipitation_flux), units of kg / m^2 / s
CF variable name, units:	prSterr (precipitation_flux_standard_error), units of kg / m^2 / s
Spatial resolution:	0.25°x0.25° latitude/longitude
Temporal resolution and extent:	3-hourly snapshot fields, January 1998 – December 2013 (and extended for following years as they become available) contained in monthly files
Coverage:	latitudes 50°N – 50°S

3. Data Origin

The TMPA algorithm is used to compute the “TRMM and Other Sources” 3-hourly and monthly products, which have the identifiers “3B42” and “3B43” within the TRMM project. Within the ESG these datasets are posted with file names of the form

pr_TRMM-L3_v7_*YYYYMMD1h1m1-YYYYMMD2h2m2*.nc.
pr_TRMM-L3_v7A_*YYYYMMD1h1m1-YYYYMMD2h2m2*.nc.
pr_TRMM-L3_v7-7A_*YYY1M1-YYY1M2*.nc
prStderr_TRMM-L3_v7-7A_*YYY1M1-YYY1M2*.nc

This algorithm is designed to provide spatially-complete, consistently-calibrated 3-hourly fields of precipitation estimates for the latitude band 50°N-50°S. Data are drawn from four sources, namely TRMM precipitation radar (PR) data, passive microwave (PMW) radiances at multiple frequencies and polarizations (observed from a mixed constellation of operational and research low-earth-orbit [LEO] satellites), thermal infrared brightness temperatures (IR Tb; observed by the international constellation of geosynchronous-Earth-orbit [GEO] satellites), and surface precipitation gauge measurements. The monthly estimates contained in this data set are an optimal combination of the monthly satellite precipitation estimates and the precipitation gauge analysis (see below).

Each of the PMW data streams is processed into precipitation estimates using sensor-specific algorithms. As well, the TRMM Microwave Imager (TMI) is combined with the PR data to produce TRMM Combined Algorithm (TCI) precipitation estimates, which are then used to calibrate all the PMW estimates. The calibration is accomplished in two steps; first, climatological histogram matching is applied to each sensor type to make its precipitation record more consistent with the TMI’s, with regional and seasonal dependence that varies from sensor to sensor. Then a TCI-TMI histogram matching that varies by 1°x1° gridbox and month is applied to the individual TMI-adjusted PMW precipitation estimates. The TCI is only available in the latitude band 37°N-S, but the various PW precipitation estimates are valid at higher latitudes. As a first approximation, the calibration at the limits of TCI coverage are simply used at the higher latitudes.

All of these TCI-calibrated PMW precipitation estimates are grouped into 3-hourly maps, each covering ±90 minutes from the nominal synoptic observation times (00, 03, …, 21 UTC). Where overlaps of satellite swaths occur, the TCI has the highest priority for providing the grid value, conical-scan imagers are next, and cross-track sounders have the lowest priority. For each calendar month histogram-matched calibrations of coincident IR Tb’s to these merged calibrated PMW precipitation fields are computed and used to generate IR precipitation estimates for each 3-hour period. The complete 3-hourly multi-satellite precipitation estimate is composed of the calibrated PMW estimates, where available, and the IR estimates otherwise.

At the monthly time scale, all available 3-hour estimates in the month are averaged in each gridbox to generate a monthly multi-satellite field. Meanwhile, monthly accumulations for the available precipitation gauge data are analyzed and gridded by other organizations – see “surface precipitation gauges” in Section 6. Each month, the gauge analysis is used to remove large-area biases in the satellite data, then combined with the (debiased) multi-satellite data using optimal weighting by the inverse (estimated) error variances to form the TMPA monthly satellite-gauge combination, which has the TRMM product number

3B43 (ESG dataset name of the form pr_TRMM-L3_v7-7A_*YYY1M1-YYY2M2*.nc). After that, the 3-hourly fields in a month are linearly scaled gridbox-by-gridbox so that they (approximately) sum to the gridbox's monthly value. This adjusted 3-hourly field is TRMM product number 3B42 (ESG dataset names of the form pr_TRMM-L3_v7_*YYYYMMD1h1m1-YYYYMMD2h2m2*.nc or pr_TRMM-L3_v7A_ *YYYYMMD1h1m1-YYYYMMD2h2m2*.nc, depending on processing epoch). In the CMIP5 collection the precipitation is referred to as field pr (precipitation_flux). The formal reference for 3B42/3B43 is Huffman et al. (2007), while the detailed technical documentation (Huffman and Bolvin 2012) is posted at *ftp://precip.gsfc.nasa.gov/pub/trmmdocs/ 3B42_3B43_doc.pdf*.

The TRMM version number for this series of 3B42 is Version 7. A summary of the upgrades from Version 6 to Version 7 is provided in the technical document. Updates are planned to the CMIP collection of 3B42 after each additional month of the data is computed. After the Version 7 processing, it was discovered that AMSU-based precipitation estimates had been neglected as input. Subsequently, Version 7 was again reprocessed during the AMSU period to incorporate those data, and in the original archive these months were given the version number 7A. The TMPA system is very robust to data dropouts, so it is believed that the differences between the original and revised Version 7 should be small in most cases. The most noticeable differences should occur in the sequence of precipitation events and amounts at fine time/space scales.

In the monthly data file, the latest field (V7 or V7A) is included, based on the processing epochs

199801-199912	V7
200001-201009	V7A
201010-ongoing	V7

In the daily data files, each month is either V7 or V7A alone, for the same processing epochs, and is denoted as such in the file names.

For most of the period of record essentially every grid box has a value, so sampling is not typically an issue. However, the quality of the estimates varies widely due to the heterogeneous sources of data, both for individual data sets and across years as the available constellation of sensors varies. The primary sampling issue is that the Indian Ocean sector lacked a publicly available GEO-IR sensor before July 1998. This is largely offset by using the data from the adjacent GEO-IR imagers. These data are somewhat less accurate because they must be corrected for the high zenith angle at which they are observed.

The precipitation research group in the NASA/GSFC Mesoscale Atmospheric Processes Laboratory is responsible for technical development and maintenance for the TMPA. Data set processing and reprocessing are the responsibility of the Precipitation Processing System (PPS) at NASA/GSFC, while archival activities are supplied by the Goddard Earth Sciences Data and Information Services Center. Gerald L. Potter developed the conversion routines to CMIP-standard files.

4. Validation and Uncertainty Estimate

The TMPA has been subjected to a number of validation studies, primarily focusing on the fine scales. Generally, the full-resolution (3-hourly 0.25°) validation results show low skill, while averaging improves the results. The fine-scale, somewhat uncertain data are released as such to allow the user flexibility in determining how best to average the data for their particular application. It is a major result of the validations that the TMPA's use of gauge analyses is key to controlling the bias that tends to typify satellite estimates over land, and other dataset producers are starting to adopt this practice. This result extends well beyond the accidental inclusion of the same gauges in both the TMPA and the validation, but rather reflects the fact that on the monthly time scale adjacent gauges tend to be sufficiently correlated that after the first few relatively well-distributed gauges are incorporated, additional gauges will tend to simply confirm the analysis (Rudolf and Schneider 2005; Bolvin et al. 2009). Furthermore, hydrological modeling tends to show that the influence of the gauge data extends well down into the sub-monthly time scales, even while the satellite estimates completely determine the sequence of precipitation events and their relative sizes.

Over ocean there is no such gauge control, and indeed validation studies with gauge data from isolated atolls and the ATLAS II buoys tend to show a low bias in the TMPA (see, e.g., Table 1 in Huffman et al. 2007; Adler et al. 2009). This is less true in the current Version 7 products. Within the framework of the TMPA, we expect the monthly average to track rather closely with the final calibrator, which is the TCI over ocean and the gauge analysis over land. Looking at the global ocean average over the latitude band 30°N-30°S, we see in Fig. 1 that the 3B43 product does track with TCI, but is higher by about 5%. The basis for this difference is under investigation, but it seems consistent enough and minor enough to warrant release of the dataset. The offsets tend to be positive in most places, and larger in regions of larger precipitation, as should be expected. However, differences are not necessarily the largest in the highest precipitation regions. The GPCP monthly analysis is included in Fig. 1 as a fairly independent measure of the average, and it appears highly correlated, although the GPCP interannual variations are somewhat larger. As well, there is a slight phase lag in the smoothed interannual variations between TMPA and GPCP.

The debiased month-to-month fluctuations about the true mean are termed "random error" in the TMPA and computed for each grid box for each month following Huffman (1997). This field in 3B43 is posted as field prSterr (precipitation_flux_standard_error) in separate ESG datasets of the form prStderr_TRMM-L3_v7-7A_*YYY1M1-YYY2M2*.nc. [One anomaly in the original TMPA data set is that the random error field has the misleading variable name "relativeError" for historical reasons.] It is awkward to quote bulk error statistics because the random error behaves roughly like the square root of the monthly rain rate, so neither it nor the random error normalized by the mean (which approximately varies as the inverse square root of the mean) yields a nice linear statement. The sensor type also enters the picture, primarily (in the monthly) providing more accurate estimates over land than ocean. Inspecting Table 1 in Huffman et al. (2007), one seems RMS differences on the order of 32 to 75 % of the mean, depending on mean rainrate and location. It is still a matter for research to characterize the random (and bias) errors in a more complete way. Recently, Tian et al. (2013) argue that the error statement should be in a log-transformed space to better separate random and systematic error, while Maggione et al. (2014) have developed a promising scheme for computing probability quantiles for short-interval precipitation estimates. Pending this work, the experimental random error estimates in the original 3-hourly files are not posted in the CMIP5 collection.

As stated above, the most noticeable differences between the original Version 7 and revised Version 7A data will be at the fine scales, where substitution of AMSU estimates in the revision will typically yield different values than the original estimates that had to use IR input. However, the larger-scale statistical behavior of the two data sets should not be too different.

It is worth mentioning that users should expect to see relatively large local excursions in precipitation from month to month. Larger time/space averages will usually be more stable, but ENSO fluctuations in the tropical Pacific can cause large variations in regional, or even basin-wide zonal averages over ocean. The 1997-1998 El Niño event is a particular example. Note well that the ENSO precipitation variations over ocean tend to cancel with variations over land, so the results are somewhat sensitive to the definition of "ocean" and "land", and the net fluctuations over the combination of land and ocean tends to be smaller than the fluctuations over each individually.

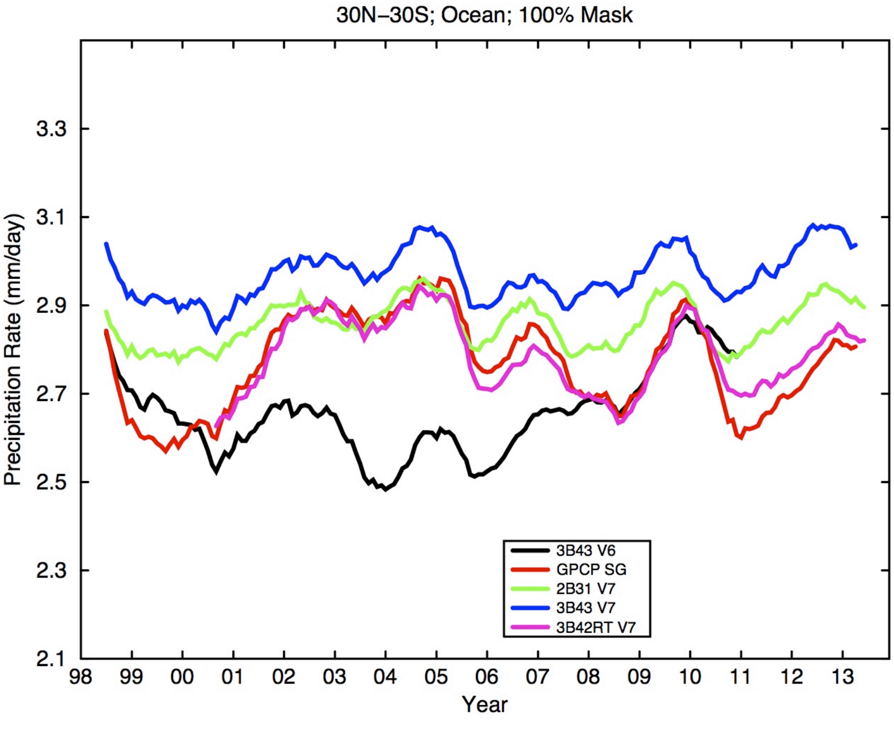

Fig. 1. Time series of precipitation averaged over ocean regions in the latitude band 30°N-30°S with a 13-month running boxcar filter for 3B43 V7 (blue), TCI (green), and GPCP monthly SG Version 2.2 (red). The real-time 3B42RT (magenta) and previous 3B43 V6 (black) are shown for comparison. Units are mm/d (which differs from the CMIP units).

The diurnal cycle depicted in the 3-hourly 3B42 V7 (and all other versions) is affected by the particular mix of satellite sensors at any given time and place, in common with all other such satellite-based precipitation estimation systems. The diurnal cycle phase produced by IR estimates, which respond to cloud tops, is known to lag the phase of surface observations in many locations. The lag is highly variable, but frequently reported as up to 3 hours. The passive microwave estimates over land depend on the solid hydrometeors, which typically are confined to the upper reaches of clouds. This dependence also leads to lags compared to surface observations, up to about 1.5 hours. Over ocean the passive microwave estimates are driven by the full vertical profile of precipitation for imagers, but primarily by solid hydrometeors for sounders. Thus, there is a mix of typical lags, minimal for imagers and up to 1.5 hours for sounders. When you consider the regional variability in the lags of the individual sensor types and the variable mix of sensors contributing to the diurnal cycle during different epochs of satellite coverage, the general statement is that lags are more likely early in the dataset, before many passive microwave satellites were available, and are more likely over land. The TRMM PR, being a radar, gives relatively unbiased estimates of the diurnal cycle, but its sampling is so sparse that it takes several years of data to allow a reasonable estimate to appear out of the sampling noise. See Kikuchi and Wang (2008), although their study with Version 6 will have larger lags due to concentrating early in the record and with fewer passive microwave satellites than Version 7 has for the bulk of their study period.

5. Considerations for Model-Observation Comparisons

Collecting the issues raised in other parts of this document:

- TCI calibrations for the PMW precipitation estimates at latitudes outside the latitude band 37°N-S are approximated as the value at the north or south boundary, as appropriate.
- The TMPA estimates consistently run about 5% above the calibrator (TCI). Differences are mostly positive, with larger values in regions of larger precipitation, but not necessarily with highest values coincident.
- There tends to be higher uncertainty at the finest resolutions, which is improved by averaging, either implicitly or explicitly.
- The diurnal cycle inferred from 3B42 has lags that depend on region and sampling by the various sensors.

As well, a few additional factors should be noted:

- Coastal zones present special challenges for retrievals due to the heterogeneity of the surface scene. GPROF, in particular, seems to have trouble detecting precipitation in near-coastal waters for certain weather/surface configurations, and sometimes generates artifacts in near-coastal deserts (both within about 50 km of the coastline). In a few cases where the land/ocean contrast in precipitation is strong (such as Jamaica), the gauge values tend to bleed into the surrounding coastal waters on 1°x1° blocks related to the gauge analysis resolution.

- Orographic enhancement of precipitation is sometimes a challenge for the satellite schemes. The issue arises when the enhancement takes place (mostly) in the liquid phase, which current PMW algorithms cannot "see" over land. On the other hand, in a few places the orography provokes very inefficient storms that create large amounts of ice near cloud top relative to the precipitation reaching the ground. The satellites consequently overestimate the rainfall in these cases.
- Current PMW schemes cannot make retrievals over snowy or frozen surfaces, which yield signals similar to frozen precipitation. This is a problem both because it denies direct use of PMW estimates in the dataset and because it denies use of the PMW estimates in the IR calibration. The TMPA contains work-arounds for such situations, but the dataset will contain many fewer PMW estimates and the resulting IR estimates are of lower quality, even while they comprise the bulk of the estimates. As a result, statistics over cold-season land situations should be examined for possible degradation by these snow effects.
- The current version differs from the previous release of CMIP5-format data as follows:
    1. The conversion from the native mm/hr units to the CMIP5 units of $kg/m^2/s$ was previously computed by multiplying by 1/3600, but in this release it is computed by dividing by 3600. The differences are unimportant, but users will see ubiquitous changes.
    2. Erroneous treatment of zero values in the monthly data as missing has been corrected. A few legitimate missing values exist during 2006.
    3. The most current monthly data are assembled into a single file, rather than being segregated by processing epoch (V7 or V7A), as was done in earlier releases.
- The original data files have additional fields that researchers might find useful, including the relative weighting of the gauge in the monthly data and the satellite source for the 3-hourly data, but they are not included in this CMIP5 archive.

6. Instrument Overview

The TMPA is a standard product of the TRMM project, which is a joint activity of NASA and the Japanese Aerospace Exploration Agency (JAXA). TRMM was launched in late 1997 to study tropical rainfall. The instrument complement includes three instruments focused specifically on retrieving rainfall: the Precipitation Radar (PR), the first precipitation radar in space; the TRMM Microwave Imager (TMI), a conically scanning multi-channel dual-polarization PMW radiometer; and the Visible and InfraRed Scanner (VIRS), an optical sensor providing visible and infrared imagery. Two related instruments round out TRMM's instrumentation: a Cloud and Earth Radiant Energy Sensor (CERES), an Earth radiation budget sensor that failed about six months after launch; and the Lightning Imaging Sensor (LIS), a staring imager that locates and detects lightning within individual storms.

The goal of the TMPA dataset is to use "all" available quasi-global precipitation estimates from the international constellation of precipitation-relevant satellites to create a High-Resolution Precipitation Product with complete coverage over the chosen domain and period of record (50°N-50°S, 1998-present). Fig. 2 summarizes the periods of record for the various inputs:

- PR, a phased-array Ku-band (13.8 GHz, 2.2 cm) radar on the TRMM satellite, which originally flew at 350 km, but was boosted to 401.5 km in 2001 with an orbital inclination of 35°. Primarily as a result of the inclination, TRMM precesses through the diurnal cycle in about 46 days.
- PMW radiometers in two different flavors: conical-scan imagers and cross-track-scan sounders. The former include TMI, Advanced Microwave Scanning Radiometer for Earth Observations (AMSR-E; on Aqua), Special Sensor Microwave/Imager (SSMI; on the Defense Meteorological Satellite Program [DMSP] series), Special Sensor Microwave Imager/Sounder (SSMIS; on the DMSP series); feature multiple channels and dual polarization well-suited to estimating precipitation; provide constant footprint sizes, although these sizes differ for different channels; and are processed with sensor-specific versions of the Goddard Profiling algorithm (GPROF; Kummerow et al. 1996, Olson et al. 1999). The latter includes Advanced Microwave Sounding Unit (AMSU; on the National Oceanic and Atmospheric Administration [NOAA] series) and Microwave Humidity Sounder (MHS; on the NOAA series and Operational Meteorological Satellite A [MetOp-A]); features multiple channels relevant to precipitation; provides footprints that vary from circular at nadir to highly elliptical at the limb; and are processed with the NOAA ice water path algorithm (Zhao and Weng 2002, Weng et al. 2003). All of the PMW satellites except TRMM fly in sun-synchronous orbits at about 800 km. The periods of record used in the TMPA are sometimes shorter than the full record of the sensor, reflecting the TRMM period of record and sensor degradation (F15 SSMI, NOAA16 AMSU).
- GEO-IR imagers, whose data are ingested as analyses from two different sources. The first 25.5 months are provided by NOAA as GridSat-B1 files, which are a regridding of geostationary IR (and other) data subsampled (not interpolated) to ~10-km resolution at 3-hourly intervals. In mid-February 2000 CPC began providing Global Merged 4-km IR datasets on a 4-km-equivalent latitude/longitude grid every half hour over the latitude band 60°N-60°S. Recalling that the minimum international agreement for data exchange is a full-disk image every three hours, the images on the major synoptic hours (00, 03, …, 21 UTC) usually have nearly complete coverage, and these are the images used in the TMPA. The remaining images not used by the TMPA have highly variable coverage. In both datasets the data are recalibrated to optimize homogeneity over time, and corrected for biases due to varying zenith view angles.
- Surface precipitation gauges, whose measurements are ingested as monthly analyses from the Global Precipitation Climatology Centre (GPCC; Schneider et al. 2008). Precipitation gauge reports from a time-varying collection of over 70,000 stations around the globe are quality-controlled, expressed as deviations from a local climatology, and analyzed into gridded values. Finally, the month's analysis is produced by superimposing the anomaly analysis on the month's climatology. The GPCC creates multiple products, and two are used in the TMPA. The Full Data Reanalysis (currently Version 6) is a retrospective analysis that covers the period 1901-2010, and it is used in the TMPA for the span 1998-2010. Thereafter we use the GPCC Monitoring Product (currently Version 4), which has a similar quality control

and the same analysis scheme as the Full Data Reanalysis, but whose data source is limited to GTS reports. We continue our long-standing practice of correcting all gauge analysis values for climatological estimates of systematic error due to wind effects, side-wetting, evaporation, etc., following Legates (1987).

The TMPA technical document (Huffman and Bolvin 2014) provides expanded summaries for each sensor and references to relevant documentation.

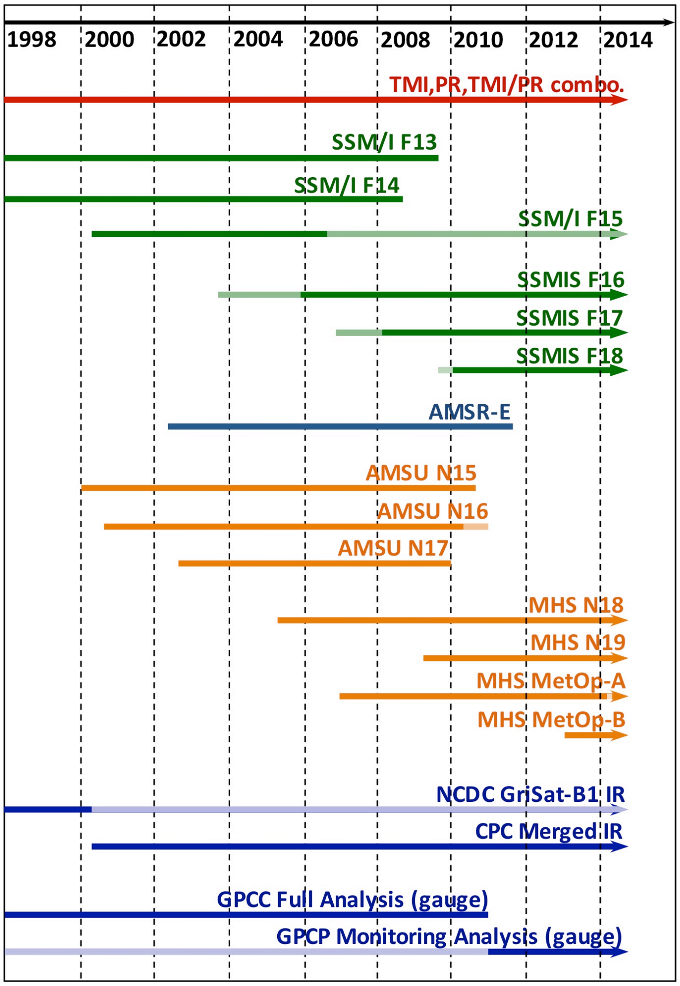

Fig. 2. Periods of record for the various data sets used in computing the TMPA (solid lines). Some of these sensors' periods of record extend beyond these periods of use, shown in light colors.

7. References

The TMPA has not been registered with a DOI. The International Polar Year (IPY) Data policy guidelines (http://.ipydis.org/data/citations.html) suggest a formal reference for data sets of the form

Huffman, G.J., R.F. Adler, D.T. Bolvin, E.J. Nelkin, 2014: *TRMM Version 7 3B42 and 3B43 Data Sets*. NASA/GSFC, Greenbelt, MD. Data set accessed <date> at http://mirador.gsfc.nasa.gov/cgi-bin/mirador/presentNavigation.pl?tree=project&dataset=3B43:%20Monthly%200.25%20x%200.25%20degree%20merged%20TRMM%20and%20other%20sources%20estimates&project=TRMM&dataGroup=Gridded&version=006&CGISESSID=d12193016851737673840d0848b43592.

As an “Acknowledgment”, one possible wording is: "The TMPA data were provided by the NASA/Goddard Space Flight Center's Mesoscale Atmospheric Processes Laboratory and PPS, which develop and compute the TMPA as a contribution to TRMM."

Additional details: At frequencies below about 37 GHz the radiative transfer signal in PMW sensor channels is primarily a combination of emission from the surface and then from the overlying atmosphere, including cloud and precipitation liquid water. At higher frequencies the useful signal results from scattering of the upwelling radiant energy out of the line of sight. Unfortunately, the land surface is radiometrically emissive and heterogeneous, so current-generation algorithms, including GPROF, can only use the emission channels over ocean. The restriction to frozen hydrometeors alone over land is an issue because they only represent the upper reaches of clouds, while the liquid phase tells about precipitation nearer the surface. Thus, conical-scan radiometers, which span both radiometric regimes, provide better answers over ocean than land. This is also the basis for the issues with retrievals over snowy/frozen surfaces and when orographic enhancement is in the liquid phase. Cross-track scanners largely depend on the scattering channels over both land and ocean, so they are less accurate than conical-scan imagers over ocean. As well, the priority for populating the PMW data field is also affected by resolution; typically the imagers have resolutions at or below 12 km, uniformly across the entire swath, while the sounders tend to start at circular footprints of size 16 km at nadir, but then stretching to 25x50 km at the limb.

Data source:

http://mirador.gsfc.nasa.gov/cgi-bin/mirador/presentNavigation.pl?tree=project&dataset=3B42:%203-Hour%200.25%20x%200.25%20degree%20merged%20TRMM%20and%20other%20satellite%20estimates&project=TRMM&dataGroup=Gridded&version=007&CGISESSID=f45a3d18a53b33549dac853d2401c500

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8. Revision History

Rev 0 – 12/16/2011 – This is a new document/dataset [G.J. Huffman]

Rev 1 – 8/2/2012 – Upgrade to TRMM Version 7 [G.J. Huffman]

Rev 2 – 1/22/2013 – Upgrade to TRMM Version 7A [G.J. Huffman]

Rev 3 – 10/21/2013 – Add text about variation due to ENSO, update dataset period of record [G.J. Huffman]

Rev 4 – 0701/2014 – Update graphics, IR in Indian Ocean prior to mid-1998; add error computation developments, diurnal cycle comments, changes from previous posting for CMIP5 archive; correct CMIP5 file name templates [G.J. Huffman]