Climate Data Record (CDR) Program

Climate Algorithm Theoretical Basis Document (C-ATBD)

Precipitation - Global Precipitation Climatology Project (GPCP) Monthly (01B-34)

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REVISION HISTORY

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1	Robert Adler, Jian-Jian Wang, Mathew Sapiano, University of Maryland College Park	DSR-1083	Initial Delivery	03/22/2016
2	Robert Adler, Jian-Jian Wang, University of Maryland	DSR-1185	Changes necessary to take into account shift in AIRS precipitation product September 2016 and following months.	06/09/2017

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1. Introduction

1.1 Purpose

The purpose of this document is to describe the algorithm submitted to the National Centers for Environmental Information (NCEI) by Dr Robert Adler at the University of Maryland that will be used to create the Global Precipitation Climatology Project (GPCP) Climate Data Record (CDR) Monthly analysis. The GPCP Monthly analysis is a frequently used data set in analyzing global and regional climatologies and variations of precipitation. The data set has been cited over 1500 times in scientific journals and is part of World Climate Research Program (WCRP) and GEWEX activities, including being part of the array of data sets describing the water and energy cycles of the planet. Up to now (2016) the GPCP analysis has been produced by a consortium of individual scientists at various government and university institutions. Incorporating the GPCP Monthly production and distribution into the CDR Program will formalize its production under the auspices of NOAA's commitment for continued production and distribution. The GPCP monthly product blends data from gauges (from the Global Precipitation Climatology Center), precipitation estimates from polar-orbit passive microwave satellites (SSMI, SSMIS) polar orbit IR sounders (TOVS, AIRS) and geostationary infrared satellites (GOES, MeteoSat, GMS, MTSat). The actual algorithm is defined by the computer program (code) that accompanies this document, and thus the intent here is to provide a guide to understanding that algorithm, from both a scientific perspective and in order to assist a software engineer or end-user performing an evaluation of the code.

1.2 Definitions

Symbols are defined where used.

1.3 Referencing this Document

This document should be referenced as follows:

Precipitation – GPCP Monthly - Climate Algorithm Theoretical Basis Document, NOAA Climate Data Record Program CDRP-ATBD-0848 Rev. 2 (2017). Available at https://www.ncdc.noaa.gov/cdr/atmospheric

1.4 Document Maintenance

This document describes the initial submission of the GPCP Monthly CDR.

2. Observing Systems Overview

2.1 Products Generated

This document describes the monthly GPCP CDR. The primary output of this algorithm is monthly precipitation starting in January 1979 on a 2.5°, globally complete grid obtained by merging precipitation from satellites and gauges. The primary output product is an analysis of surface precipitation based on a systematic merger of both surface precipitation gauge information and both polar-orbit and geosynchronous satellite-based precipitation estimates. The GPCP monthly analysis procedures are described in Huffman et al. (1997), Adler et al. (2003) and Huffman et al. (2009). In addition to the monthly precipitation, random errors of the precipitation field are also produced and a number of interim products are also made available as outputs.

2.2 Instrument Characteristics

The monthly GPCP precipitation product is based on data from gauges, and polar orbiting satellites and geostationary satellites. The actual data used is described in section 3.3.1. The following gives information on satellite sensor characteristics that are relevant for this climate data record.

SSM/I

The Special Sensor Microwave/Imager (SSM/I) is a multi-channel passive microwave radiometer that has flown on selected Defense Meteorological Satellite Program (DMSP) platforms since mid-1987. The DMSP is placed in a sun-synchronous polar orbit with a period of about 102 min. The SSMI provides vertical and horizontal polarization values for 19, 22, 37, and 85.5 GHz frequencies (except only vertical at 22) with conical scanning. Pixels and scans are spaced approximately 25 km apart at the suborbital point, except the 85.5-GHz channels are collected at approximately 12.5 km spacing. The channels have resolutions that vary from 12.5x15 km for the 85.5 GHz (oval due to the slanted viewing angle) to 60x75 km for the 19 GHz.

The polar orbit provides nominal coverage over the latitudes 85°N-S, although limitations in retrieval techniques prevent useful precipitation estimates in cases of cold land (scattering), land (emission), or sea ice (both scattering and emission). Further details are available in Hollinger et al. (1990).

SSMIS

The Special Sensor Microwave Imager/Sounder (SSMIS) is a multi-channel passive microwave radiometer that has flown on selected Defense Meteorological Satellite Program (DMSP) platforms since late 2003 as a follow-on to the SSMI instrument. The DMSP is placed in a sun-synchronous polar orbit with a period of about 102 min. The SSMIS provides vertical and horizontal polarization values for the SSMI-like 19, 22, 37, and 91 GHz frequencies (except only vertical at 22) with conical scanning, as well as other channels with a heritage in the Special Sensor Microwave/Temperature 2 (SSMT2) sensor. The SSMI/like frequencies use three separate feed horns: one for the 91 GHz channels, another for the 37 GHz channels and a third for the 19 and 22 GHz channels. This means that there is not a 1:1 co-location of channel values, as there is for SSMI. The SSMI-like channels have the resolutions 46.5x73.6 km (19, 22 GHz) 31.2x45.0 km (37 GHz) 13.2x15.5 km (91 GHz) with the slanted viewing angle and in-line processing determining the oval shape.

The polar orbit provides nominal coverage over the latitudes 85°N-S, although limitations in current retrieval techniques prevent useful precipitation estimates in cases of cold land (scattering), land (emission), or sea ice (both scattering and emission).

The SSMIS is an operational sensor, so the data record suffers some gaps in the record due to processing errors, down time on receivers, etc. Over time the coverage has improved as the operational system has matured.

TOVS

The TIROS Operational Vertical Sounder (TOVS) dataset of surface and atmospheric parameters is derived from analysis of High-Resolution Infrared Sounder 2 (HIRS2) and Microwave Sounding Unit (MSU) data aboard the NOAA series of polar-orbiting operational meteorological satellites. The precipitation estimates from TOVS are derived as a secondary product utilizing various retrieved sounding parameters, including atmospheric temperature and water vapor profiles, cloud-top pressure and radiatively effective fractional cloud cover.

For the period January 1979 - February 1999 (used July 1987 – February 1999), the TOVS estimates are based on two NOAA satellites. Beginning in March 1999, the TOVS estimates are based on a single NOAA satellite. This occurred as the result of the failure of NOAA-11. More information can be found in Susskind et al. (1997)

AIRS

The Atmospheric Infrared Sounder (AIRS) aboard the NASA Aqua polar-orbiting satellite is the source of precipitation estimates to follow-on after TOVS (in 2005). The precipitation estimates from AIRS are derived in a very similar way to those from TOVS as a secondary product utilizing various retrieved sounding parameters, including atmospheric temperature and water vapor profiles, cloud-top pressure and radiatively effective fractional cloud cover.

Outgoing Longwave Radiation (OLR) estimates of broadband outgoing longwave radiation the narrow-band IR channels on the Advanced Very High Resolution Radiometer (AVHRR) aboard the polar-orbiting NOAA series of satellites are used as input to the OLR Precipitation Index (OPI) (Xie and Arkin, 1998) These estimates are used as input before 1986.

IR Data from Geosynchronous Satellites

Precipitation estimates from mainly geosynchronous and some polar-orbit data are made using the Geosynchronous Precipitation Index (Janowiak and Arkin, 1991) for the latitude band 40N-40S. The infrared (IR) data are collected from a variety of sensors. The primary source of IR data is the international constellation of geosynchronous-orbit meteorological satellites – the Geosynchronous Operational Environmental Satellites (GOES, United States); the Geosynchronous Meteorological Satellite (GMS), then the Multifunctional Transport Satellite (MTSat, both Japanese); and the Meteorological Satellite (Meteosat, European Community). . Gaps in geosynchronous coverage (most notably over the Indian Ocean before METEOSAT-5 began imaging there in June 1998) are filled with IR data from the NOAA-series polar-orbiting meteorological satellites. The data are accumulated for processing from full-resolution (roughly 4x8 km) images.

For the period 1986-March 1998 the GPI estimates are accumulated on a 2.5°lat/lon grid for pentads (5-day periods). Starting with October 1996 the GPI data are accumulated on a 1° lat/lon grid for individual 3-hrly images. The boundary is set at January 1997 to avoid placing the boundary during the 1997-1998 ENSO event. The combination of IR satellites provides near-global coverage, but limitations in retrieval techniques prevent useful precipitation estimates poleward of about latitude 40°, higher in the summer hemisphere, and lower in the winter hemisphere.

3. Algorithm Description

3.1 Algorithm Overview

The algorithm to produce the monthly 2.5° GPCP product takes inputs from several different sources and merges them to create the most consistent and accurate monthly precipitation estimates. An overview of the procedures, inputs and outputs of the GPCP Monthly analysis can be found in Adler et al. (2003) and the other GPCP referenced papers. The algorithm as described is Version 2.3. In terms of inputs, some are satellite radiances that need to be converted to precipitation estimates; others are satellite-based precipitation estimates available from sources outside the merger process. The gauge-based analysis from the Global Precipitation Climatology Centre (GPCC) of the Deutscher Wetterdienst (DWD) is also an input. All these data are merged together via a hierarchical analysis procedure meant to produce the most complete analysis with the lowest bias. The analysis procedure systematically uses higher quality estimates to adjust lower quality, but more frequently observed estimates to maximize the sampling, but minimize any bias errors.

3.2 Processing Outline

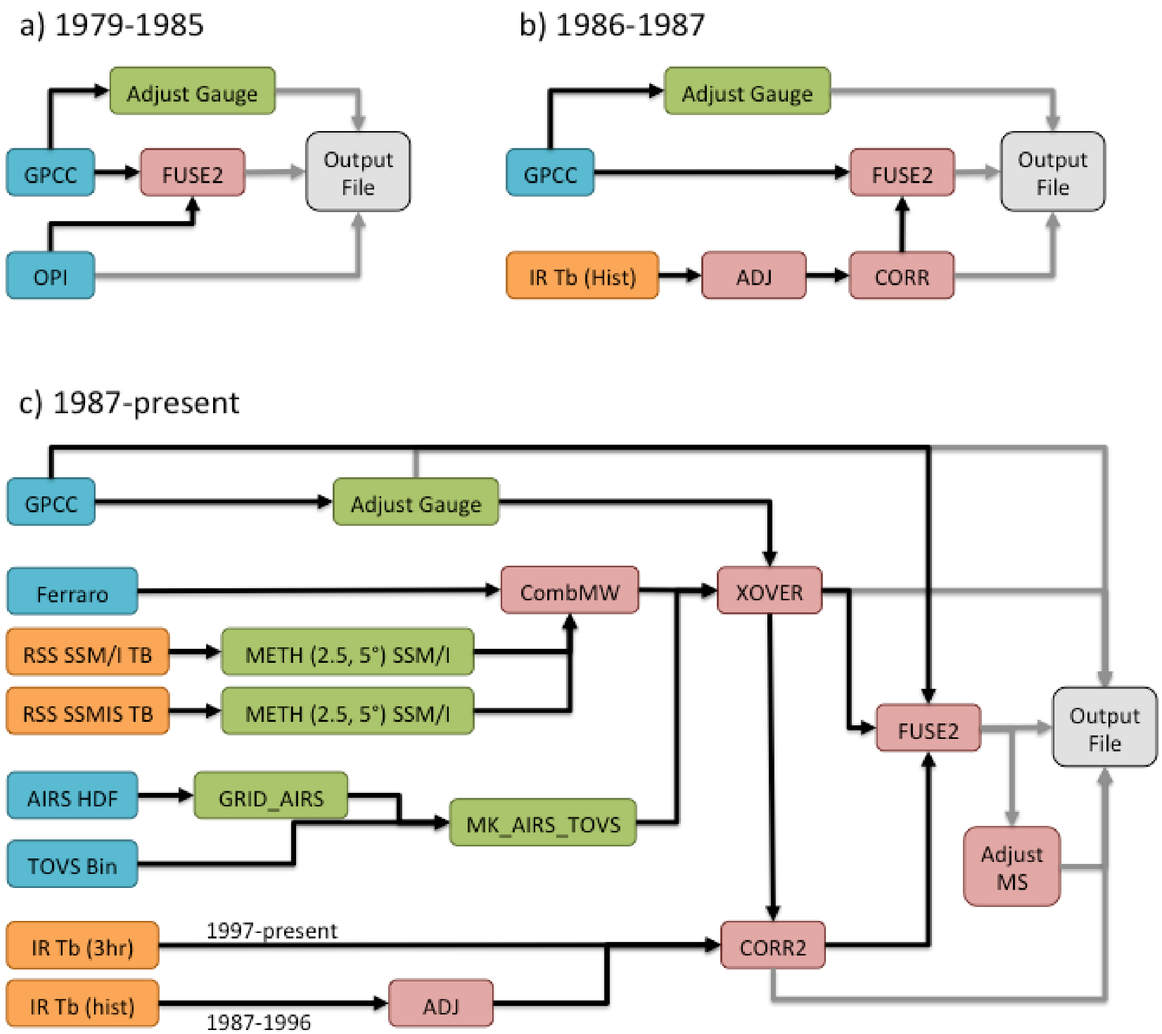

Figure 1: Processing steps required to produce GPCP. Names in boxes approximate names used by code.

The processing for the monthly 2.5° GPCP CDR is split into five different steps referred to as m1-m5.

m1. The first step is a simple diagnostic step where checks of inputs are carried out and listings of input files are made. The details of the inputs (blue and orange boxes) data are described in Section 3.3.1.

m2. The second step (green boxes) involves the processing of raw sensor data to create precipitation estimates (SSMI and SSMIS processing for ocean precipitation) as well as pre-processing of any precipitation datasets to prepare them for ingest into the CDR processing code.

m3. The third step is another diagnostic step; simple checks are performed to ensure that the input precipitation datasets exist.

m4. The fourth step (pink boxes) is the merger step where several interim combination products are generated and the satellite gauge data are produced.

m5. The fifth step (gray box) is the output step where the outputs are checked and the NetCDF file is created.

The strategy and method of calculations in steps m2-m5 are described in section 3.4.4.

Over the period of the GPCP (1979 to present) there have been several major upgrades in the available data that can be used as inputs. These changes in satellite inputs lead to three distinct periods that have some differing inputs and necessarily have different processing requirements. Figure 1 shows the processing steps required for each of the three epochs of GPCP processing. The first epoch stretches from 1979 until 1985 during which time the OPI is the main satellite input to GPCP. The second epoch stretches from 1986 to June 1987 and includes December 1987, during which time the GPI was the main satellite input. The third epoch stretches from July 1987 to present, excluding December 1987, during which time the GPCP includes both the GPI and SSMI or SSMIS data.

3.3 Algorithm Input

3.3.1 Primary Sensor Data

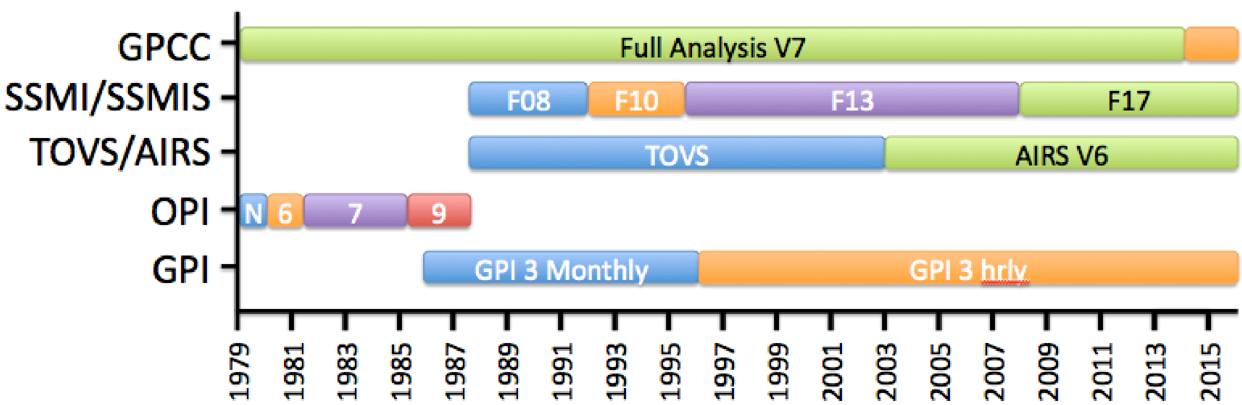

Figure 2: Inputs to GPCP by time.

Table 1: Inputs to GPCP

Name	Data type	GPCP time period	Data source	Notes
GPCC V7 Full Data Reanalysis	Precip	Jan 1979 to Dec 2013	DWD (GPCC)	Climate quality 2.5° gridded gauge data reprocessed regularly
GPCC Monitoring Product V5	Precip	Jan 2014 to present	DWD (GPCC)	Interim version of Full analysis intended to continue record
RSS SSMI Tb CDR	Tb	Aug 1987 to Dec 2008	NCEI	F08: Jul 1987 to Dec 1991 (excl. dec 1987); F11: Jan 1992 to May 1995; F13: June 1995 to Dec 2008
RSS SSMIS Tb CDR	Tb	Jan 2009 to present	NCEI	Replaces SSM/I Tb; data only from F17
Ferraro	Precip	Aug 1987 to present	NESDIS/ STAR	
TOVS	Precip	Aug 1987 to Dec 2002	GPCP/GSFC	No TOVS/AIRS used for Dec 1987
AIRS V6	Precip	Jan 2003 to present	GSFC DISC	Replaces TOVS
OPI	Precip	Jan 1979 to Dec 1985	GPCP/GSFC	Satellites used listed in Table 2.
IR Monthly	Tb	Jan 1986 to Dec 1996	GPCP/GSFC	
IR 3 hourly files	Tb	Jan 1997 to present	CPC	Files include IR histograms and OPI precipitation (see table 2)

Only the precipitation estimates generated from the SSM/I and the SSMIS are produced as part of the processing code and the algorithm to do this is described in section 3.4.

The SSMI/SSMIS era of July 1987 to the present provide a near homogeneous set of input data and analysis technique with the ocean precipitation estimates of the SSMI/SSMIS adjusting the GEO-IR estimates, over both ocean and land, with the gauge analysis adjusting the satellite bias over land and blending with the adjusted satellite analysis. The TOVS/AIRS estimates provide the information at higher latitudes with a smooth transition from the microwave-driven lower latitude estimates and the final blending with the gauge information. For the early period, before 1987, the OPI estimates are the dominant input, along with the Geo-IR for a short period before July 1987. The earlier OPI period is adjusted climatologically by month using the post-1987 years when both analyses are available. Thus the GPCP Monthly period is extended back to 1979 using a cross-calibration overlap.

In addition to the three epochs, there are several other times in which the exact inputs changed (or the version number changed). In order to be exact for the purposes of this section, these different datasets are discussed as separate datasets although they may have a single source data. An example of such a situation is the AIRS data, which includes three different processing versions (V4, V5 and V6).

Table 2: Satellites used for OPI estimate

Satellite	Equator crossing time	Periods used for OPI
TIROS-N	15:30	1 Jan 1979 to 31 Jan 1980
NOAA-6	07:30	1 Feb 1980 to 6 Sep 1981
NOAA-7	14:30	7 Sep 1981 to 4 Feb 1985
NOAA-9	14:30	5 Feb 1985 to 7 Nov 1988

RSS SSM/I Tb

The Special Sensor Microwave/Imager (SSM/I) was a seven channel, conically scanning microwave radiometer that flew aboard the Defense Meteorological Satellite Program polar orbiting satellites. The SSM/I possessed four different frequencies (19, 22, 37 and 85 GHz) three of which had vertical and horizontally polarized channels (there was no 22H channel). GPCP makes use of data from the F08, F11 and F13 satellites. SSM/I Tb is obtained from NCEI form the CDR produced by Remote Sensing Systems (RSS; Santa Clara, CA). GPCP V2.2 uses the consistently processed V6 RSS SSM/I Tb available from NCEI. These data have been extensively quality controlled by RSS and have been intercalibrated using the methods described by Wentz (1997).

RSS SSMIS Tb

The Special Sensor Microwave Imager/Sounder (SSMIS) is a 24 channel, conically scanning microwave radiometer that replaced the SSMI and flies aboard DMSP polar orbiting satellites. Only the 7 SSM/I-like channels are used for GPCP although the 85GHz channel on SSM/I was replaced with a 91GHz channel. At present, only data from F17 is used in GPCP. SSMIS data is also obtained from the NCEI CDR produced by RSS. The RSS SSMIS Tb are produced with the RSS V7 calibration, so a correction is applied in the GPCP CDR software to calibrate these data to the RSS V6 intercalibration standard.

Ferarro precipitation

The primary GPCP-scattering algorithm is an 85-GHz technique described by Ferraro (1997). It has separate components for land and ocean, as well as screening tests for the removal of artifacts caused by various surface types. The algorithm has been calibrated to instantaneous rain rates from ground-based radar measurements (Ferraro and Marks 1995). For the period from June 1990 to late 1991, failure of the 85-GHz channels on the operational SSM/I instrument led to the use of a secondary scattering algorithm using the 37-GHz SI information. While the 85-GHz SI technique can detect rain rates as low as 1 mm/h, the 37-GHz SI is only sensitive to rain rates of 5 mm/h or greater. The monthly scattering-based rainfall field is computed at NCEI using code from NESDIS/STAR of the NOAA National Environmental Satellite, Data, and Information Service (NESDIS). The ocean and land microwave estimates are merged in the near-coastal areas based on relative sampling as described in Huffman et al. (1997)

TOVS precipitation

The Television Infrared Operational Satellite (TIROS) Operational Vertical Sounder (TOVS) instrument flew aboard the NOAA series of polar-orbiting platforms. Susskind and Pfaendtner (1989) and Susskind et al. (1997) described the process for estimating precipitation from TOVS The TOVS precipitation estimates infer precipitation from deep, extensive clouds. The technique uses a climatological multiple regression relationship between collocated FGGE precipitation gauge measurements and several TOVS-based parameters that relate to cloud volume: cloud-top pressure, fractional cloud cover, and relative humidity profile. This relationship is allowed to vary seasonally and latitudinally. Furthermore, separate relationships are developed for ocean and land.

The TOVS data are used for the early SSMI period July 1987 - December 2002 (excluding December 1987) and are provided as monthly 1° gridded estimates. The data covering the span July 1987 - February 1999 are based on information from two satellites. For the period March 1999 - December 2002, the TOVS estimates are based on information from one satellite due to changes in satellite data format. TOVS data were obtained directly from Joel Susskind and are supplied as part of the GPCP CDR source data.

AIRS precipitation (V6)

The Advanced Infrared Sounder (AIRS) instrument flew aboard the Earth Observing System Aqua polar-orbiting satellite along with the Advanced Microwave Sounding Unit (AMSU). The "AIRS data" product for most of the recent era is actually a combined AIRS/AMSU product. This AIRS data were used to replace the earlier TOVS data. The same algorithm applied to TOVS to produce precipitation was also applied to AIRS (Susskind and Pfaendtner, 1989; Susskind et al., 1997). The AIRS data are also obtained in monthly mean 1° gridded format. AIRS data are available from May 2002 and used for the period from January 2003 – present. The AIRS precipitation estimates have been bias-adjusted to the TOVS estimates to minimize the TOVS/AIRS data boundary. Matched histograms of precipitation were computed between the TOVS and AIRS data for the months January, April, July, and October 2004. These seasonal calibrations are applied accordingly to the corresponding seasonal months of data.

The AIRS V6 products are obtained as level 2 gridded data that must be accumulated onto a 1° grid for use in GPCP. The code to grid the AIRS V6 data is included in the GPCP CDR code, so that the Level 2 Gridded files are the direct input to GPCP. The AIRS product using the AIRS/AMSU data continued until September 2016, when the AMSU instrument failed. At the beginning of September 2016 the AIRS/AMSU retrievals are replaced by those from the AIRS instrument alone. This new data is referred to as AIR/IR to distinguish it from the earlier AIRS data using AIRS and AMSU. The precipitation estimates from AIRS IR are adjusted to those of the earlier AIRS, which are used through August 2016 based on an overlap period of January to December 2015. An annual adjustment is calculated as a function of latitude over ocean. From September 2016 onward the adjustment is applied to provide the input estimates to the merged analysis.

OPI precipitation

The Outgoing Longwave Radiation (OLR) Precipitation Index (OPI) (Xie and Arkin 1998) is a technique for retrieving precipitation from OLR measurements taken form the NOAA series of satellites. The data is processed and provided by Pingping Xie at NOAA CPC. Colder OLR radiances are directly related to higher cloud tops, which are related to increased precipitation rates. It is necessary to define "cold" locally, so OLR and precipitation climatologies are computed and a regression relationship is developed for anomalies in OLR and precipitation. The regression approach is used to estimate the anomaly of total precipitation and this is then added to the local climatological value. If the anomaly approach yields unphysical values, a regression based on the actual values is used in place of the anomaly approach. The precipitation climatology used to develop the OLR-derived precipitation estimates was based on the GPCP Version 2.3 satellite-gauge estimates over the time period 1988-2007. The resulting spatially and temporally varying climatological calibration is then applied to the independent OPI data covering the span 1979-1987. The OPI data for the first two satellites (covering January 1979 through August 1981) were given additional adjustments.

GPI precipitation

The GOES Precipitation Index (GPI; Arkin and Meisner, 1987) is a method for estimating precipitation from geostationary satellite infrared information. The data is processed and provided by Pingping Xie at NOAA CPC. The GPI includes inputs from the Geosynchronous Operational Environmental Satellites (GOES, USA), the Geosynchronous Meteorological Satellite (GMS, Japan), the Multifunctional Transport Satellite (MTSat, Japan) and the Meteorological Satellite (Meteosat, European Community). The GPI uses three-hourly channel 4 ~10.7 micron thermal infrared (IR) imagery that is merged and zenith angle corrected at NOAA CPC.

The GPI estimates rainfall by relating cold cloud-top area to precipitation rate. Colder IR brightness temperatures are directly related to higher cloud tops, which are loosely related to increased precipitation rates. From the GATE data, an empirical relationship between brightness temperature and precipitation rate was developed. For a brightness temperature ≤ 235K, a precipitation rate of 3 mm/hour is assigned. For a brightness temperature > 235K, a precipitation rate of 0 mm/hour is assigned. The GPI works best over space and time averages of at least 250 km and 6 hours in oceanic regions with deep convection.

There are two major periods of GPI data used in GPCP. For the period 1986-March 1998 the GPI data were accumulated on a 2.5° grid for pentads (5-day periods), preventing an exact computation of the monthly average. It is assumed that a pentad crossing a month boundary contributes to the statistics in proportion to the fraction of the pentad in the month. Starting with October 1996 the GPI data were accumulated on a 1° grid for individual three hourly images. For this period, the monthly totals are computed as the sum of all available hours in the month. The Version 2.3 GPI product is based on the 2.5° IR data for the period January 1988 to December 1996, and the 1° beginning in January 1997. In both periods, gaps in GPI are filled with low-earth-orbit IR (leo-IR) data from the NOAA series of polar orbiting meteorological satellites. However, the 2.5° only contain the leo-IR used for fill-in, while the 1° data contain the full leo-IR. The latter allows a more accurate Adjusted-GPI. The Indian Ocean sector routinely lacked geo-IR coverage until Meteosat-5 was repositioned to that region starting 06 UTC 16 June 1998.

GPCC Gauge precipitation

The gauge analysis used in GPCP is produced by the Global Precipitation Climatology Centre (GPCC) under the direction of Andreas Becker and Udo Schneider, located in the Deutscher Wetterdienst, Offenbach a.M., Germany (Schneider et al. 2008). Precipitation gauge reports are archived from a time-varying collection of over 70,000 stations around the globe, both from Global Telecommunications System (GTS) reports and from other world-wide or national data collections. An extensive quality-control system is run, featuring an automated screening and then a manual step designed to retain legitimate extreme events that characterize precipitation. This long-term data collection and preparation activity feeds into an analysis that is done in two steps. First, a long-term climatology is assembled from all available gauge data, focusing on the period 1951-2000. For each month, the individual gauge reports are converted to deviations from climatology, and are analyzed into gridded values using a variant of the SPHEREMAP spatial interpolation routine (Willmott et al. 1985). Finally, the analysis is produced by superimposing the monthly anomaly analysis on the climatology for that month. Two GPCC products are used in GPCP; the Full Data Reanalysis (currently Version 7) is a retrospective analysis that covers the period 1901-2013, and it is used in GPCP for the span 1979-2013. Thereafter we use the GPCC Monitoring Product (currently Version 5), 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. When the Full Data Reanalysis is updated to a longer record we expect to reprocess the GPCP datasets to take advantage of the improved data.

3.3.2 Ancillary Data

Not Applicable

3.3.3 Derived Data

Not Applicable

3.3.4 Forward Models

Not Applicable

3.4 Theoretical Description

The bulk of the GPCP CDR code merges the various inputs to obtain the GPCP satellite gauge estimate. Most of the input data are obtained as rain rates having been processed by other groups. The exception to this is the Passive Microwave (PMW) SSM/I and SSMIS estimates used over ocean and the algorithm is briefly outlined in this section. Note that the PMW land estimates are taken from the Ferraro scattering estimates that are processed at NCEI externally to the GPCP CDR code.

3.4.1 Physical and Mathematical Description

METH algorithm for SSMI/SSMIS over ocean

The estimates of precipitation used over the ocean are based on the emission technique that uses the 19 and 22 GHz channels of the SSMI and SSMIS (Chiu et al. 1993; Chiu and Chokngamwong, 2010). The microwave emission technique infers the quantity of liquid water in a column from the increased low-frequency observed microwave brightness temperatures. Greater amounts of liquid water in the column tend to correlate with greater surface precipitation. The algorithm is the Wilheit et al. (1991) iterative histogram approach to retrieving precipitation from emission signals in the 19 GHz SSM/I channel. It assumes a log-normal precipitation histogram and estimates the freezing level from the 19 and 22 GHz channels. The fit is applied to the full month of data. The algorithm is run on a 2.5° grid and a 5° grid with the latter being used to fill the former in the case of the 2.5° version failing to converge.

This technique works well over ocean where the surface emissivity is low and uniform. Over land and ice, however, the emissivity is near one and extremely heterogeneous, making the scattering algorithm the only choice, so the Wilheit et al. (1991) algorithm provides no estimates for land and ice.

The algorithm was retuned for SSMIS to ensure consistency with the SSMI record despite differences in observation strategy and sensor performance. The results show that the F13 precipitation values were slightly higher than the corresponding F17 values for the overlap period October 2008 – September 2009, but these differences weren't large enough to introduce a significant inhomogeneity in the record.

3.4.2 Data Merging Strategy

GPCP is created by merging precipitation estimates in several different stages. Each of these stages leads to the creation of interim products, some of which are given as outputs. Each stage of processing is described below. All the merging of data is done in processing step m4.

SSMI/SSMIS Composite merge

The first step in creating the CDR involves the combination of the estimates of precipitation over land (derived from the scattering technique) and ocean (derived from the emission technique). This is achieved by the GPCPcdr_m4_combMW code.

Since the emission technique eliminates land-contaminated pixels individually, a weighted transition between the two results is computed in the coastal zone. The merger is expressed as

$$R(\text{compos}) = \begin{cases} R(\text{emiss}); & \text{if } N(\text{emiss}) \geq 0.75 \times N(\text{scat}) \\ \dfrac{N(\text{emiss}) \times R(\text{emiss}) + \big(N(\text{scat}) - N(\text{emiss})\big) \times R(\text{scat})}{N(\text{scat})}; & \text{otherwise} \end{cases}$$

where R is the precipitation rate, N is the number of samples and emiss and scat stand for emission technique and scattering technique respectively. The 0.75 threshold allows for fluctuations in the methods of counting samples in the emission and scattering techniques. Note that the second expression reduces to $R(\text{scat})$ when $N(\text{emiss})$ is zero.

A number of quality control measures are included as part of the merger process. The emission and scattering fields are edited before the merger to remove known and suspected artifacts, such as unphysically high values in polar regions.

SSMI/SSMIS merge with TOVS

The coverage of the SSMI/SSMIS precipitation estimates is limited by the orbit of the DMSP satellites as well as shortcomings in the microwave technique over cold land. These gaps in coverage are filled using the globally complete TOVS/AIRS data. The SSMI/SSMIS data are used without any additional TOVS/AIRS data between a latitude range that varies between 40° and 50° north/south depending on the month of the year. If there are holes in coverage as the result of cold land, the TOVS/AIRS data are adjusted to the zonally averaged mean bias of the SSMI/SSMIS data and inserted. Just outside of the zone 40°N-S, the SSMI/SSMIS and TOVS/AIRS data are averaged using equal weighting. Moving further towards the poles, where the SSMI/SSMIS data become less reliable, the average of SSMI/SSMIS and TOVS/AIRS is replaced by TOVS/AIRS data that have been adjusted to a zonally-averaged presumed bias. In the northern hemisphere, this bias adjustment is anchored on the equatorward side by the zonal average of the averaged SSMI/SSMIS and TOVS/AIRS values anywhere from 50°-60°N, depending upon the month of the year. The bias adjustment on the polar side is anchored by the zonal average of the monthly precipitation gauge data at 70°N, with a smooth linear variation in between. The gauge's zonal average only includes grid boxes for which the gauge quality index is greater than zero. From 70°N to the North Pole, TOVS/AIRS data are adjusted to the bias of the same monthly precipitation gauge value average at 70°N. The same procedure is applied in the southern hemisphere, except the annual climatological precipitation gauge values are zonally averaged at 70°S. The monthly values are not used in the Antarctic as the lack of sufficient land coverage there yields unstable results. Furthermore, the current GPCC analysis lacks data over Antarctica, so this climatological adjustment is from a previous GPCC Monitoring Product. All seasonal variations in this description were developed in off-line studies of typical dataset variations, with the driving criterion being choosing a transition that ensures reasonable performance.

Correction of IR precipitation

Before the IR precipitation (GPI) can be merged with the other inputs, it must be corrected to be more consistent with the PMW estimates of precipitation. This is done following the technique of Adler et al. (1994) to create the Adjusted GPI (AGPI). Starting in July 1987, separate monthly averages of approximately coincident GPI and merged PMW precipitation (the merged SSMI/SSMIS/TOVS/AIRS precipitation) are formed by subsets of the three hourly GPI values that correspond most closely in time to the local overpass time of the PMW data. The ratio of merged PMW to GPI averages is computed and quality controlled to prevent unstable answers. In regions of light precipitation an additive adjustment is computed as the difference between smoothed merged PMW and ratio-adjusted GPI values when the merged PMW is greater, and zero otherwise. The spatially varying arrays of adjustment coefficients are then applied to the full set of GPI estimates. In regions lacking geo-IR data, leo-GPI data are calibrated to the merged PMW and these calibrated leo-GPI are calibrated to the geo-AGPI. This two-step process is intended to mimic the information contained in the AGPI, namely the local bias of the SSMI/SSMIS and possible diurnal cycle biases in the geo-AGPI. The second step can be done only in regions with both geo-IR and leo-IR data, and then smooth-filled across the area where leo-IR was used. In the case of the 2.5° IR (which lacks leo-IR in geo-IR regions) the missing calibrated leo-GPI is approximated by smoothed merged PMW for the calibration to geo-AGPI.

During the period January 1986 - June 1987 and December 1987, the OPI data, as calibrated by the GPCP satellite-gauge estimates for part of the PMW period (1988-2007), are used as a proxy for the merged PMW field in the AGPI procedure. Because the overpass times of the calibrated OPI data are not available, a controlled ratio between the full monthly calibrated OPI estimates and the full monthly GPI data is computed. These ratios are then applied to the GPI data to form the AGPI. The additive constant is computed and applied, when necessary, for light-precipitation regions.

Satellite/gauge combination precipitation

The final step of the construction of GPCP is to blend the PMW and IR estimates to create the multi-satellite estimate, which is subsequently merged with the gauge analysis. There are three major periods where the processing flow is different based on the availability of the input data.

From July 1987 (but excluding December 1987), the multi-satellite field consists of a combination of Geo-AGPI estimates where available (latitudes 40° N/S), the weighted combination of the merged PMW estimates and the leo-AGPI elsewhere in the 40° N/S band, and the merged PMW data outside of that zone. The combination weights are the inverse (estimated) error variances of the respective estimates. Such weighted combination of PMW and leo-AGPI is done because the leo-IR lacks the sampling to support the full AGPI adjustment scheme. During this period, the multi-satellite estimate is climatologically adjusted before being output in order to endure its consistency with the earlier OPI data. The climatological adjustment is done after the multi-satellite is merged with gauges and does not affect the final satellite gauge GPCP project, only the interim multi-satellite product that is given as an additional output.

During the period January 1986 to June 1987 and including December 1987, the multi-satellite field consists of a combination of geo-AGPI estimates where available (latitudes 40° N/S) and the calibrated OPI estimates elsewhere. The combination weights are the inverse (estimated) error variances of the respective estimates.

During the period January 1979 to December 1985, there is no geo-IR GPI, and therefore no AGPI. The only satellite input during this period is therefore the OPI data, which is calibrated by the GPCP satellite-gauge estimates over the period (1988-2007).

Finally, the multi satellite product is combined with the gauge data. Prior to combination, the GPCC gauge analysis values are adjusted to remove systematic error due to wind effects, side-wetting, evaporation, etc., following Legates (1987). The process to combine the gauge analysis with the multi-satellite is a two-step process (Huffman *et al.* 1995).

In the first step the multi-satellite is adjusted to have the same bias as the gauges for all pixels with at least 35% land. The adjustment is calculated and applied based on the either a five-by-five or seven-by-seven gridbox average centered on the gridbox of interest. The adjusted multi-satellite is then combined with the gauges using a weighted average where the weights are the inverse (estimated) error variances.

Random errors

The random error of the combined satellite/gauge estimate is based on the technique of Huffman (1997a) and is supplied as an output of the CDR code. The bias error is neglected compared to the random error (both physical and algorithmic) so that the estimated error variance of an average over a finite set of observations, VAR, can be expressed as

$$\mathrm{VAR} = \frac{\mathrm{H}\left(\bar{r} + S\right)\left[24 + 49\sqrt{\bar{r}}\right]}{N_i}$$

where H and S are assumed constant, $\bar{r}$ is the average precipitation rate in mm day^{-1}, N_i is the number of independent samples in the set of observations, and the expression in square brackets is a parameterization of the conditional precipitation rate based on work with the Goddard Scattering Algorithm, Version 2.1 (Adler et al. 1994) and fitting to the Surface Reference Data Center analyses (McNab 1995). The "constants" H and S are set for each of the data sets for which error estimates are required by comparison of the data set against the SRDC and GPCC analyses and tropical Pacific atoll gauge data (Morrissey and Green 1991).

For the independent data sets *rbar* is taken to be the independent estimate of precipitation itself. However, when these errors are used in the combination, theory and tests show that the result is a low bias. *Rbar* needs to have the same value in all the error estimates; so it is estimated as the simple average of all precipitation values contributing to the combination. Note that this scheme is only used in computing errors used in the combination.

The formalism mixes algorithm and sampling error, and should be replaced by a more complete method when additional information is available from the single-source estimates. However, when Krajewski et al. (2000) developed and applied a methodology for assessing the expected random error in a gridded precipitation field, their estimates of expected error agree rather closely with the errors estimated for the multi-satellite and satellite-gauge combinations.

3.4.3 Numerical Strategy

Not applicable.

3.4.4 Calculations

The monthly GPCP code is made up of around 170 individual code files, which are distributed among 10 modules of code plus another 6+ codes to obtain files, create file listings, and perform pre- and post-processing diagnostics.

First, input data must be downloaded using scripts that semi-automate the download process in the directory GPCPcdr_ftp with the main driver code for downloading data being get_GPCPcdr_1month.sh which can be used to download all data for a single month, or it can be used to download a single data item using an optional keyword argument.

Once the data has been downloaded, the GPCP code is run by a single driver code (shell script) in the main directory (GPCPcdr_ECPm_Process1month.sh) that performs a check that all data is present and then calls each of the constituent parts of the processing code.

Once the data is downloaded, GPCPcdr_ECPm_Process1month.sh can be used to produce the monthly GPCP NetCDF file. The code is broken into steps with code stored in the following directories:

a. GPCPcdr_m1
This is the directory for pre-processing steps and tests, including following shell scripts:
GPCPcdr_m1_ChkL1files.sh - checks that all files are in place for given month
GPCPcdr_m1_GetInputFiles.sh - obtains file listings required for processing

b. GPCPcdr_m2
This is the directory containing the algorithms to calculate the precipitation from individual product. The processes prepare the input data for the merged GPCP monthly products.
GPCPcdr_m2_SSMI_Ocean and GPCPcdr_m2_SSMIS_Ocean - run METH algorithm for SSMI and SSMIS, respectively
GPCPcdr_m2_Adjust_Gauge - apply wind-loss correction to Gauge data
GPCPcdr_m2_Grid_AIRS - produce gridded, daily AIRS data at the resolution of 1°
GPCPcdr_m2_Get_AIRS_TOVS - select TOVS or AIRS data and place in interim files

c. GPCPcdr_m4
This is the directory including all codes to merge data for GPCP monthly output.
GPCPcdr_m4_combMW - combine SSMI/SSMIS precipitation estimates
GPCPcdr_m4_CORR2 - produce AGPI from GPI and SSMI/SSMIS

GPCPcdr_m4_XOVER - combine SSMI/SSMIS data with TOVS/AIRS
GPCPcdr_m4_CORR_ADJ - combines SSMI and polar-orbiting IR
GPCPcdr_m4_FUSE2 - combines SSMI/SSMIS/TOVS, AGPI and Gauge data to produce the final satellite/gauge data

d. GPCPcdr_m5
This directory has the codes to produce output files and diagnostics.
GPCPcdr_m5_WriteNC - write CDR (+error) NetCDF file for current month
GPCPcdr_m5_WriteNC_Interim - write all GPCP interim fields to NetCDF file
GPCPcdr_m5_WriteNC_NRT - write ICDR (+error) NetCDF file

3.4.5 Look-Up Table Description

Not applicable.

3.4.6 Parameterization

Not applicable.

3.4.7 Algorithm Output

Fully describe the data products produced by the algorithm. This includes generic names and contents, file formats, specific data, physical units, and estimated sizes.

The GPCP Version 2.3 Combined Precipitation Data Set, covering the period January 1979 through the present (with 2+ months delay). The primary product in the dataset is a combined observation-only dataset, that is, a gridded analysis based on gauge measurements and satellite estimates of precipitation.

The data set archive consists of yearly unformatted REAL*4 binary files with ASCII headers, each of which holds 12 monthly fields. Each file occupies almost 0.5 MB. The grid on which each field of values is presented is a 2.5°x2.5° latitude--longitude (Cylindrical Equal Distance) global array of points. It is size 144x72, with X (longitude) incrementing most rapidly West to East from the Prime Meridian, and then Y (latitude) incrementing North to South. Grid edges are placed on whole- and half-degree values:

First point center = (88.75°N, 1.25°E)
Second point center = (88.75°N, 3.75°E)
Last point center = (88.75°S, 1.25°W)

Missing values are denoted by the value -99999., and the unit of rainfall is mm/day.

In addition to the standard GPCP monthly Climate Data record (CDR) product, an interim product referred to as the GPCP Interim Climate Data Record (ICDR) is also produced. This ICDR is provided for the most recent 2-3 months for which the GPCP CDR is not yet available. The ICDR is constructed in a similar manner to the CDR, except that the GPCC monitoring product (with 2+ months delay) is replaced by the First Guess product. The ICDR is regarded as a provisional product, i.e., users must replace the ICDR data collected with the CDR data once the former becomes available

4. Test Datasets and Outputs

4.1 Test Input Datasets

Initial test input data sets will consist of the next (or last) month of data inputs.

4.2 Test Output Analysis

4.2.1 Reproducibility

Reproducibility will be shown by comparison with results of parallel runs at UMD.

4.2.2 Precision and Accuracy

Precision of monthly rainfall rates is given in units of mm/d.

4.2.3 Error Budget

Not applicable

5. Practical Considerations

5.1 Numerical Computation Considerations

Not applicable

5.2 Programming and Procedural Considerations

Not applicable

5.3 Quality Assessment and Diagnostics

The diagnostic analyses and plots of the output products are performed every month, with the comparison to climatologies. Attention will be paid to any anomalies for further examinations.

5.4 Exception Handling

Not applicable

5.5 Algorithm Validation

Not applicable.

5.6 Processing Environment and Resources

The computer used to process the GPCP monthly product is Red Hat Enterprise Linux Server release 6.7 (version 2.6.32-573.7.1.el6.x86_64). The programming languages and software include: shell scripts to run the processing code; FORTRAN programs to perform most of the calculations; C programs to generate the outputs; MATLAB to make the diagnostic plots.

6. Assumptions and Limitations

There are a number of known data set issues that might be relevant for a CDR. The GPCP team has worked hard to ameliorate the effect of these issues.

a. *The present GPI contains no intersatellite calibration. This is not a serious issue in the AGPI and combination since the data are bias adjusted, although having the intersatellite calibration would provide a better GPI and at second order refine the AGPI at satellite data boundaries. By contrast, the "official" NCEP GPI time series has intersatellite calibration for Jan. 1986 - March 1998, then none thereafter. Tests show that the 40°N-S oceanic average GPI is about 3% higher for the intercalibrated data, compared to the non-intercalibrated data.*

b. *The present GPI has a 3x3-gridbox smoother applied for non-SSMI months (Jan. 1986 - June 1987, Dec. 1987). Locally, values are different than the non-smoothed version, but large- area averages should be accurate.*

c. *Presently the choice of IR satellite source is strictly by the number of images in the 2.5° 3-hrly pentad IR (used to compute adjustment coefficients), but in the 2.5° pentad IR the distance to the satellite is also considered (used to compute the AGPI). So, at some locations nearly equidistant between the two satellites the AGPI is derived for one satellite, but applied to the other. NOTE: In the 1° 3-hrly GPI it is possible for the two satellites to cut in and out on successive hours. As long as the relative contribution of each is in the same proportion for both the SSMI-matched subset and the full data set this is not too important. Using inter- satellite calibrated data would overcome this issue, although it is likely a second-order effect.*

d. *The 1° IR dataset provides comprehensive leo-IR data while the 2.5° IR only provides leo-IR in regions lacking geo-IR. The additional data in the 1° IR allows more accuracy in estimating the calibration of the SSMI-calibrated leo-GPI to the geo-AGPI, causing biases between the 1° and 2.5° AGPI in leo regions (the Indian Ocean being the prime case) of up to 15% in the previous Version 1c. NOTE: Alternatively, a whole different 2.5° pentad low-orbit GPI dataset could be generated, and then integrated into the system. The improvement over the fix should be only second-order.*

e. *The GMS 2.5° histograms were collected with temperature bin boundaries at half- degree values, but the 1° histograms are being collected on whole-degree temperature boundaries; this causes GPI differences in excess of 10% at 30-40° latitude, and everywhere the 1° GPI is smaller. The AGPI largely calibrates out this problem, but if the GPI itself needs to be consistent, the 235K class could be split in the 1° histograms in a future release.*

f. *The SSMIS scattering precipitation estimates use a proxy 85 GHZ channels based on the 91 GHz channels, calibrated to approximately match the zonal* *average TOVS using the months January, April, July, and October 2004 as the seasonal calibration months, but regional differences remain.*

g. *Beginning with January 2009, SSMIS precipitation estimates replaced the SSMI estimates because the F13 SSMI failed in September 2009 and we wanted to both avoid possible degraded performance and to establish a whole-year data boundary to aid in diagnosing possible biases. The SSMIS data have been adjusted to match the large-scale bias of the SSMI to maintain homogeneity across the data boundary.*

h. *The TOVS precipitation estimates for the SSMI period July 1987 – February 1999 are based on two satellites. For February 1999 – April 2005, the TOVS estimates are based on only one satellite.*

i. *TOVS data were partially denied for the period 10-18 September 2001 and cannot be recovered. As well, various operational issues caused partially or completely missing days of TOVS data, particularly in the last few months of NOAA-14's useful life.*

j. *The AIRS precipitation estimates are calibrated to approximately match the zonal average TOVS using the months January, April, July, and October 2004 as the seasonal calibration months, but regional differences remain.*

k. *Beginning with May 2005, AIRS precipitation estimates replaced the TOVS estimates at high latitudes because of TOVS instrument termination. The AIRS data has been adjusted to match the large-scale bias of the TOVS to maintain homogeneity across the data boundary.*

l. *Every effort has been made to preserve the homogeneity of the Version 2.3 data record. However, the regional variances inherent in the OPI data are typically smaller than those encountered in the SSMI data, so the statistical nature of the fields will be different for the pre-SSMI and SSMI.*

m. *The precipitation gauge data used in the Version 2.3 analysis consists of GPCC Full for the period 1979-2014 and GPCC Monitoring for the period 2015 – present. Though there is strong consistency in analysis scheme, quality control, and data sources between the two analyses, there exists a minimal possibility of a discernible change in statistics at the crossover month for the land precipitation.*

n. *Every attempt has been made to create an observation-only based precipitation data set. However, the TOVS estimates (but not AIRS) rely on numerical model data to initialize the estimation technique. It is believed that the impact of the numerical model data is minimal on the final precipitation estimates.*

o. *Some polar-orbiting satellites have experienced significant drifting of the equator-*

crossing time during their period of service. There is no direct effect on the accuracy of the data, but it is possible that the systematic change in sampling time could introduce biases in the resulting precipitation estimates. It is unlikely that this issue affects the SSMI/SSMIS data used for calibration because the sequence of single satellites used have all stayed within ±1 hour of the nominal 6 a.m. / 6 p.m. overpass time.

p. *The new GPCC climatology/anomaly analysis scheme is intended to perform well where data are sparse and/or the terrain is complex. Nonetheless, testing remains to show this everywhere.*

6.1 Algorithm Performance

Not applicable.

6.2 Sensor Performance

Not applicable.

7. Future Enhancements

Describe potential future enhancements to the algorithm, the limitations they will mitigate, and provide all possible and useful related information and links. This subsection should be organized into separate subsections for each potential enhancement, ordered according to a combination of highest operational priority and greatest feasibility.

7.1 Enhancement 1

7.2 Enhancement 2

8. References

Include all references cited in the CATBD. References should be listed in alphabetical order. References that begin with an author list should begin with the last name of the lead author. The following examples indicate the preferred style for three common types of references. Use the CDRReference style to format references.

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Appendix A. Acronyms and Abbreviations

Acronym or Abbreviation	Definition
AGPI	Adjusted GPI
AIRS	Atmospheric Infrared Sounder
AVHRR	Advanced Very High Resolution Radiometer
C-ATBD	Climate Algorithm Theoretical Basis Document
CDR	Climate Data Record
DMSP	Defense Meteorological Satellite Program
DWD	Deutscher Wetterdienst
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GMS	Geosynchronous Meteorological Satellite
GOES	Geosynchronous Operational Environmental Satellites
GPCC	Global Precipitation Climatology Centre
GPCP	Global Precipitation Climatology Project
GPI	GOES Precipitation Index
GTS	Global Telecommunications System
IR	Infrared
HIRS2	High-Resolution Infrared Sounder 2
MeteoSat	Meteorological Satellite
METH	Microwave Emission Brightness Temperature Histograms
MSU	Microwave Sounding Unit
MTSat	Multifunctional Transport Satellite
NCEI	National Centers for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
OLR	Outgoing Longwave Radiation
OPI	OLR Precipitation Index
PMW	Passive Microwave
RSS	Remote Sensing Systems
SSMI	Special Sensor Microwave/Imager
SSMIS	Special Sensor Microwave Imager/Sounder
SSMT2	Special Sensor Microwave/Temperature 2
TIROS	Television Infrared Operational Satellite
TOVS	TIROS Operational Vertical Sounder
WCRP	World Climate Research Program