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Randal D. Koster, Editor

Observation-Corrected Precipitation Estimates in GEOS-5

Rolf H. Reichle and Qing Liu

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

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Rolf H. Reichle
NASA's Goddard Space Flight Center, Greenbelt, Maryland

Qing Liu
NASA's Goddard Space Flight Center, Greenbelt, Maryland

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

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Abstract

Several GEOS-5 applications, including the GEOS-5 seasonal forecasting system and the MERRA-Land data product, rely on global precipitation data that have been corrected with satellite and/or gauge-based precipitation observations. This document describes the methodology used to generate the corrected precipitation estimates and their use in GEOS-5 applications. The corrected precipitation estimates are derived by disaggregating publicly available, observationally based, global precipitation products from daily or pentad totals to hourly accumulations using background precipitation estimates from the GEOS-5 atmospheric data assimilation system. Depending on the specific combination of the observational precipitation product and the GEOS-5 background estimates, the observational product may also be downscaled in space. The resulting corrected precipitation data product is at the finer temporal and spatial resolution of the GEOS-5 background and matches the observed precipitation at the coarser scale of the observational product, separately for each day (or pentad) and each grid cell.
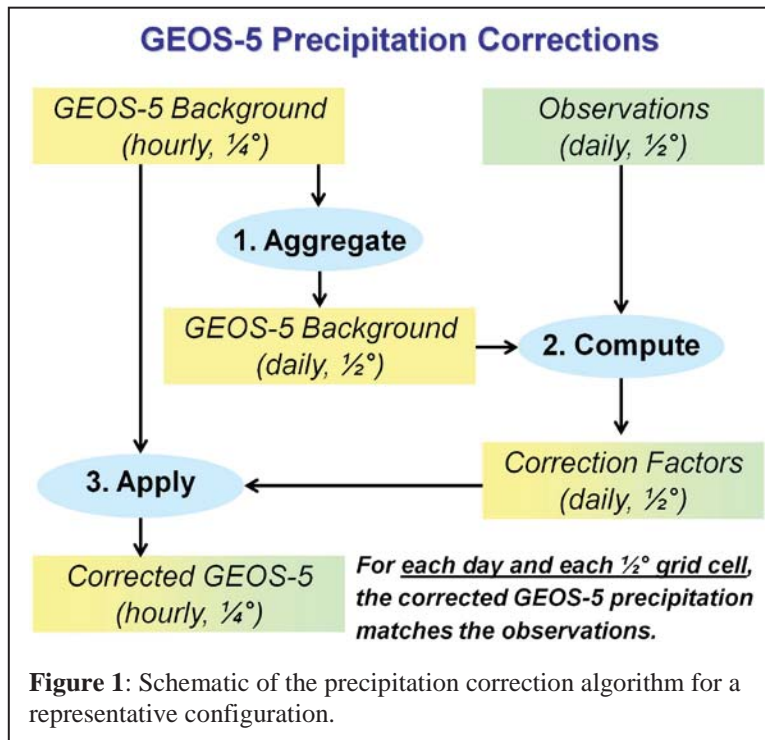
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1. Introduction

Since the release in 2011 of the Modern-Era Retrospective analysis for Research and Applications (MERRA; *Rienecker* et al. 2011, *Lucchesi* 2012), observation-corrected precipitation estimates have been used in a variety of applications of the Goddard Earth Observing System Model, version 5 (GEOS-5). Such applications include the GEOS-5 seasonal forecasting system (*Ham* et al. 2014), the MERRA-Land data product (*Reichle* et al. 2011, *Reichle* 2012), and the MERRA Aerosol reanalysis (MERRAero; *Da Silva* et al. 2011, 2012). Precipitation corrections are also used in the forthcoming MERRA-2 data product and in the planned SMAP L4_SM data product (*Entekhabi* et al. 2014, *Reichle* et al. 2014a,b).

The present document describes the generation and use of the observation-corrected precipitation estimates. These estimates are derived by disaggregating publicly available, observationally based, global precipitation products from daily (or pentad) totals to hourly accumulations using precipitation estimates from the GEOS-5 atmospheric data assimilation system. Depending on the specific combination of the observational precipitation product and the GEOS-5 background estimates, the observational product may also be downscaled in space.

The observationally based precipitation data products used here are from the Global Precipitation Climatology (GPCP) project and the NOAA Climate Prediction Center (CPC). These data products combine observations from a variety of satellites and/or gauges into global fields. In this document, we refer to these products simply as "observations". The GEOS-5 data products that are used as background in the precipitation corrections process include MERRA, the GEOS-5 Forward Processing (FP) system and the GEOS-5 Forward Processing system for Instrument Teams (FP-IT).

Figure 1 shows a schematic of the key elements of the precipitation corrections algorithm for a representative configuration. In the graphic, the hourly GEOS-5 background is on a ¼° grid and the

Figure 1: Schematic of the precipitation correction algorithm for a representative configuration.

observed precipitation is available in daily totals on a ½º grid. First, the GEOS-5 background precipitation is aggregated from its finer spatial and temporal scales to the coarser scales of the observations. Second, correction factors are computed at the coarser scale of the observations, separately for each day and each grid cell. Finally, these correction factors are applied to the GEOS-5 background at its native resolution. The result is a corrected GEOS-5 precipitation data product at the finer temporal and spatial resolution of the GEOS-5 background that matches the observed precipitation at the coarser scale, separately for each day and each grid cell.

This document is structured as follows. Section 2 provides an overview of the observational and GEOS-5 data products that are used in the precipitation corrections. Section 3 offers a detailed discussion of the precipitation corrections algorithm. It also summarizes the corrected GEOS-5 precipitation products and their use in a variety of GEOS-5 applications.

2. *Input Data Products*

2.1 Observationally Based Precipitation Data Products

This section provides details about the observational precipitation data products on which the precipitation corrections are based. Key attributes are listed in Table 1 and discussed below. Additional information can be found in the references.

Data Product	Region	Period	Time Step	Grid	Observations
GPCPv2.1 pentad	Global	1979 – Sep 2009	Pentad	2.5 deg	Satellites, Gauges
CMAP	Global	1979 – present	Pentad	2.5 deg	Satellites, Gauges
CPCU	Global land	1979 – present	Daily	0.5 deg	Gauges

Table 1: Overview of observational precipitation data products. "Global land" includes large lakes and land areas that are permanently frozen.

2.1.1 Precipitation Data Products for Global Land and Ocean

The CPC Merged Analysis of Precipitation (CMAP) product and the GPCP version 2.1 pentad product provide global estimates of total precipitation for each pentad (5-day period) at 2.5 degree spatial resolution. Both products are based on gauge observations and satellite estimates (Xie et al. 2007; Adler et al. 2003).

The CMAP product is available from the NOAA-ESRL Physical Sciences Division: `ftp://ftp.cpc.ncep.noaa.gov/precip/cmap/`. The dataset spans 1979-present with a latency of about 6 days. The CMAP version "v0905" standard product was used for the period 1979-2006 and the CMAP version "v0011" "real-time" ("RT") product is used for the period 2007-present.

The GPCP version 2.1 *pentad* product is a temporal disaggregation of the GPCP version 2.1 *monthly* product using the CMAP pentad product from the NOAA Climate Prediction Center. The GPCPv2.1 pentad product was provided by Pingping Xie from NOAA CPC for the period of January 1979 to August 2009. The monthly totals of the GPCPv2.1 pentad product are designed to match those of the GPCPv2.1 monthly product, separately for each month in the time series and for each grid cell.

The CMAP and GPCPv2.1 pentad products have the same spatial and temporal resolution: 2.5 degree latitude by 2.5 degree longitude global (144x72) with grid cell centers at 88.75S, 1.25E

(bottom left corner) and 88.75N, 358.75E (top right corner). The datasets consist of 73 pentads per year, with the first pentad covering 1 January to 5 January. The 12th pentad always covers 25 February to 1 March, that is, in a leap year the 12th pentad includes 6 days.

To ensure consistency between the precipitation corrections based on CMAP and GPCPv2.1 data to the extent possible we created a rescaled version of the CMAP pentad data product ("CMAP/GPCPv2.1-clim") that matches the 1979-2008 monthly *climatology* of the GPCPv2.1 pentad product as follows:

(i)   For the purpose of computing the climatologies in the subsequent step, missing data points in CMAP or GPCPv2.1 for 1979-2008 are masked out in *both* datasets.

(ii)   For each grid cell and each of the 73 pentads, compute the long-term mean value of the 30-year data record (separately for CMAP and GPCPv2.1).

(iii) For each grid cell, smooth the CMAP and GPCPv2.1 pentad climatologies by computing the 5-pentad mean climatology (that is, for each pentad, average the current pentad and the two pentads immediately before and after the current pentad).

(iv)   For each grid cell and each of the 73 pentads of the year, compute a climatological rescaling factor by dividing the smoothed GPCPv2.1 climatology by the smoothed CMAP climatology. The climatological rescaling factor is limited to [0.1,10] and is set to 1 (no rescaling) if the (non-smoothed) climatological value of CMAP or GPCPv2.1 is less than 1e-4 mm/d.

(v)   Rescale the CMAP precipitation by multiplying the CMAP estimate for a given pentad and grid cell with the corresponding climatological rescaling factor. The resulting dataset is referred to as "CMAP/GPCPv2.1-clim".

Note that this rescaling of the CMAP data product is just a pre-processing step that merges two observationally based products and should not be confused with the precipitation correction methods that merge an observationally based product with a model-based background (as detailed section 3.1).

2.1.2   *Precipitation Data Products for Global Land*

The CPC Unified Gauge-Based Analysis of Global Daily Precipitation (CPCU) provides estimates of daily total precipitation over global land areas. The data are on a 0.5 degree grid with grid cell centers at 89.75S, 0.25E (bottom left corner) and 89.75N, 359.75E (top right

corner) and are available for the period from 1979 to present from:
`ftp://ftp.cpc.ncep.noaa.gov/precip/CPC_UNI_PRCP/GAUGE_GLB/.`

The exact definition of the 24-hour time period that contributes to the daily CPCU values varies across the global grid. An ancillary data file provides this information in the form of End of Day (EOD) time (which is constant for the time period of the data record). Furthermore, the CPCU data product includes information about the spatial density of the precipitation gauges that were used in the construction of each estimate.

The CPCU "V1.0" product was used for the period 1979-2005 and the CPCU "real-time" ("RT") is used for the period 2006-present.

2.2   Background GEOS-5 Data Products

This section provides a brief overview of the GEOS-5 data products that are used as background estimates for the precipitation corrections. Key attributes are listed in Table 2 and discussed below. Additional details about GEOS-5 products can be found at
`http://gmao.gsfc.nasa.gov/products.`

Data Product	Period	Grid	Version
MERRA	01/01/1979 – present	0.50 deg by 0.6667 deg	GEOS-5.2.0
FP-IT (and RP-IT)	01/01/2000 – present	0.50 deg by 0.6250 deg	GEOS-5.9.1
FP (incl. G5.7.2)	08/18/2011 – present	0.25 deg by 0.3125 deg	variable

Table 2: Overview of GEOS-5 background data products. All products provide hourly, global precipitation estimates.

MERRA provides global, hourly precipitation data from 1979 to present. The spatial resolution is 0.5 degree latitude by 2/3 degree longitude (540x361) with grid cell centers at 90S, 180W (bottom left corner) and 90N, 179.333E (top right corner). MERRA data are available for internal use at the NASA Global Modeling and Assimilation Office (GMAO) with a latency of approximately 3 weeks and are published at the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC) with a latency of approximately 6 weeks.

Hourly precipitation data are also available from the GEOS-5 Forward Processing (FP) system from 18 August 2011 to present in near-real time (Table 2; *Lucchesi* 2011, *Lucchesi* 2013b). Unlike reanalysis data, the data from the FP system are generated with evolving versions of the GEOS-5 system: GEOS-5.7.2 (08/01/2011 – 06/11/2013), GEOS-5.11.0 (06/11/2013 –

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08/20/2014), and GEOS-5.13.0 (since 08/20/2014). Since its inception, the output from the FP system has been available on a global grid with a 1/4 degree spacing in latitude and a 5/16 degree spacing in longitude (1152x721), with grid cell centers at 90S, 180W (bottom left corner) and 90N, 179.6875E (top right corner). Plans for future upgrades of the FP data stream include an increase in resolution.

Moreover, hourly precipitation data are available from the GEOS-5 Forward Processing for Instrument Teams (FP-IT; *Lucchesi* 2013a) system and its associated reprocessing (RP-IT) streams. While the version of the GEOS-5 system that is used to generate this data stream is not strictly frozen, the objective is to limit the upgrades to the system and consult with NASA instrument teams prior to any version changes. To date, only GEOS-5.9.1 has been used to generate the FP-IT and associated RP-IT streams.

Including reprocessing streams, FP-IT data are available from 2000 to present and are updated in near-real time. The data are available on a global grid with a 1/2 degree latitude spacing and a 5/8 degree longitude spacing (576x361), with grid cell centers at 90S, 180W (bottom left corner) and 90N, 179.375E (top right corner).

The MERRA, FP, and FP-IT data streams include three separate precipitation fields in the hourly, time-average, 2d "flx" (flux) file Collection:

- PRECTOT (total precipitation flux at the surface = total rainfall + total snowfall),
- PRECCON (total convective precipitation flux at the surface = convective rainfall + convective snowfall), and
- PRECSNO (total snowfall flux at the surface).

Note that the sum of PRECCON and PRECSNO is *not* equal to PRECTOT. Moreover, the FP and FP-IT data streams additionally include three separate precipitation fields in the hourly, time-average, 2d "lfo" (land forcing) file Collection:

- PRECCU (liquid precipitation flux from convection at the surface),
- PRECLS (liquid precipitation flux from large scale processes at the surface), and
- PRECSNO (frozen precipitation flux at the surface).

These latter three fields sum up to the total precipitation flux at the surface (PRECTOT).

3. Corrected Precipitation Data for GEOS-5 Applications

Table 3 provides an overview of the observational and GEOS-5 background data products used to generate the corrected precipitation datasets for various GEOS-5 applications. The methods used to generate the corrected precipitation data are discussed in detail in section 3.1. Additional remarks on some of the applications are given in section 3.2.

Application	Region	Period	Observations	Background	Method
GEOS-5 Seasonal Forecast Initialization (V2 in *Ham* et al. 2014)	Global	1979 – Aug 2009	GPCPv2.1	MERRA	A
		Sep 2009 – present	CMAP/GPCPv2.1-clim	MERRA	A
		[after MERRA ends]	*CMAP/GPCPv2.1-clim*	*FP-IT*	*A*
		Most recent 2-4 weeks	CMAP/GPCPv2.1-clim	FP	A
MERRAero	Global	Jul 2002 – present	CMAP/GPCPv2.1-clim	MERRA	A
MERRA-Land	Global land	1979 – present	CPCU	MERRA	BM
SMAP Nature Run v3	Global land	2000 – 2013	CPCU	FP-IT	BMTX
		2014 – present	CPCU	FP	AMTX
SMAP L4_SM (initial version)	Global land	2015 – present	CPCU	FP	AMTX
MERRA-2	Global ocean, Africa	1979 – Sep 2009	GPCPv2.1	MERRA	A
		Sep 2009 – present	CMAP/GPCPv2.1-clim	MERRA	A
		[after MERRA ends]	*CMAP/GPCPv2.1-clim*	*FP-IT*	*A*
	Global land (excl. Africa)	1979 – present	CPCU	MERRA	BM
		[after MERRA ends]	*CPCU*	*FP-IT*	*BM*

Table 3: Overview of precipitation corrections in GEOS-5 applications and their use of observations (section 2.1), GEOS-5 background data (section 2.2) and correction methods (section 3.1). The final column identifies the two main correction methods by letter (A and B). Additionally, T implies latitude tapering, X implies that Africa is excluded from corrections, and M implies that observed precipitation that is "missing" in the GEOS-5 background is

added in the correction process. See section 3.1 for details. "Global land" includes large lakes and land areas that are permanently frozen. The SMAP Nature Run v3 is an internal data product of the SMAP project.

Note that the final MERRA-Land data product that is available from the GES DISC (Reichle et al. 2012) uses corrected precipitation based on the CPCU data product as shown in Table 3. The preliminary version of the MERRA-Land data product that is discussed in Reichle et al. (2011) used corrected precipitation based on the GPCPv2.1 and CMAP/GPCPv2.1-clim data products.

3.1   Precipitation Correction Methods

This section describes the methods used for correcting the model-based background estimates with the observationally based precipitation data products.

There are two main methods, A and B, that are very similar. The key elements of the algorithm are shown in the schematic of Figure 1. In a nutshell, the GEOS-5 background estimates are aggregated to the time step and (if applicable) the spatial grid for which the observations are available. Correction factors are then derived, separately for each (observational) time step and grid cell, such that the corrected precipitation matches the observed precipitation as closely as possible for each (observational) time step and grid cell. The two methods differ only in one aspect – in method A, the correction factors are computed on the grid of the observations whereas in method B, the correction factors are computed on the grid of the background GEOS-5 data. Additional algorithmic steps address latitude-dependent and location-dependent correction procedures (options T and X) as well as the handling of the special case where precipitation was observed but is absent from the GEOS-5 background estimates (option M).

3.1.1   Method A

Separately for each day or pentad for which precipitation observations are available, the GEOS-5 background precipitation estimates are corrected as follows:

(i)   Aggregate the hourly GEOS-5 background total precipitation (PRECTOT) to the pentad (or daily) accumulation period of the observations. For corrections using the CPCU product, this involves identifying for each grid cell the 24-hour period that contributes to the given "day" according to the CPCU EOD ancillary information and assigning the EOD times to the grid of the GEOS background data using the nearest neighbor method. (The latter step is the same for each day of CPCU data.)

(ii) Aggregate/interpolate the pentad (or daily) accumulations of the GEOS-5 background precipitation to the spatial grid of the observationally based product. The spatial aggregation/interpolation is mass conservative and carried out via a fine resolution exchange grid that nests into the original grid as well as into the target grid. After identifying the coarsest possible exchange grid with the desired nesting property, the precipitation is first remapped from the original grid to the exchange grid. Thereafter, the precipitation is aggregated to the target grid by simple averaging from the exchange grid to the target grid.

(iii) For each grid cell of the observational product, compute a correction factor by dividing the observational precipitation estimate by the corresponding GEOS-5 background estimate of total precipitation (PRECTOT). (Note that this is done separately for each grid cell and each pentad or day.) If the GEOS-5 background value is zero and/or observational estimate is a no-data-value, the correction factor is set to 1 (that is, no correction).

(iv) Interpolate the gridded correction factors to the native GEOS-5 background grid using the approach described in step (ii).

(v) For each grid cell of the native GEOS-5 background grid, multiply the GEOS-5 background hourly values of total precipitation (PRECTOT) with the interpolated correction factor for that grid cell. Apply the same multiplication to all available precipitation components, including total convective precipitation (PRECCON), total snowfall (PRECSNO), etc.

3.1.2 Method B

This method is used when the grid spacing of the observations is similar to that of the GEOS-5 background data, which occurs typically when the 0.5 degree CPCU observations are used with "one-half degree" GEOS-5 background data from MERRA or FP-IT. For each day of CPCU data, the correction steps are as follows:

(i) Same as step (i) of method A (section 3.1.1).

(ii) Interpolate the daily observations to the GEOS-5 background grid using the mass conservative approach described in step (ii) of method A.

(iii) Same as step (iii) of method A except that for method B correction factors are computed on the grid of the GEOS-5 background data.

(iv)   Does not apply in method B.

(v)   Same as step (v) of method A.

3.1.3   Option M: Add "Missing" Precipitation

If for a given GEOS-5 background grid cell the correction factor was set to 1 because the GEOS-5 background accumulated (pentad or daily) precipitation was zero but the observational estimate was non-zero, the observed precipitation that is "missing" from the GEOS-5 background is added evenly to the three corrected GEOS-5 hourly estimates of total precipitation (PRECTOT) between midnight and 3am local time. Local nighttime is chosen to avoid inconsistencies with GEOS-5 background estimates of downward radiation at the surface. If for a given hour between midnight and 3am local time the GEOS-5 background air temperature at the lowest model level (TLML, which is also in the "flx" data Collection) is below 273.15 K, the precipitation is designated as snowfall and also added to PRECSNO.

3.1.4   Option T: High-latitude Tapering

At high latitudes the precipitation gauge network is extremely sparse and measuring (often solid) precipitation is in any case difficult. Therefore, the quality of gauge-based observational products at high latitudes is typically poor. In some cases the precipitation corrections are therefore tapered with latitude such that at low latitudes the observations corrections are applied as usual but at high latitudes the "corrected" precipitation is identical to the GEOS-5 background data. Specifically, after step (iv) of methods A and B (sections 3.1.1 and 3.1.2) adjusted (tapered) correction factors c' are computed from the original correction factors c as follows:

$$c' = w * c + (1 - w) * 1 \tag{1}$$

where w is a latitude-dependent weight such that w=1 for abs(latitude)≤42.5°, w=0 for abs(latitude)≥62.5°, and 0<w<1 in between (linearly interpolated). The tapered correction factors c' are then used in step (v).

3.1.5   Option X: Exclude Africa from Precipitation Corrections

In Africa the precipitation gauge network is extremely sparse and the quality of gauge-based observational products is therefore poor. In some cases the precipitation corrections are

therefore not applied in Africa. Formally, this can be achieved by resetting the corrections factor to 1 prior to step (v) in methods A and B above.

3.2   Use of Corrected Precipitation in GEOS-5 Applications

The corrected precipitation datasets of Table 3 are used in land-only GEOS-5 applications as well as in coupled land-atmosphere models. Land-only applications include, for example, MERRA-Land and the SMAP L4_SM data product. In this case, the precipitation forcing is applied directly as part of the land surface forcing. For the SMAP application, the land is thus forced with precipitation from the background FP system at high latitudes and over Africa, with the CPCU-corrected precipitation over low latitudes, and with a linear combination of the background and observed precipitation between 42.5º and 62.5º latitude (section 3.1).

Applications of the corrected precipitation datasets with the Atmospheric General Circulation Model (AGCM) include MERRA-2 and the generation of the initial conditions for the GEOS-5 seasonal forecast system. In this case the corrected precipitation data are read into the coupled modeling system and then used to adjust the model-generated precipitation from the atmospheric moist physics module of the AGCM.   This merger includes the latitude-dependent tapering of the corrected precipitation (section 3.1.4) *within* the AGCM, that is, the land surface in MERRA-2 is forced with its own, model-generated precipitation at high latitudes, with the corrected precipitation data over low latitudes, and with a combination of the two between 42.5º and 62.5º latitude. Note that atmospheric water and energy prognostic variables associated with the creation of precipitation are not directly modified but can be indirectly modified through subsequent feedback with the land surface. Furthermore, in the case of MERRA-2 the corrected precipitation is based on the 2.5 degree, pentad CMAP product over Africa and on the 0.5 degree, daily CPCU product over low-latitude land elsewhere. Moreover, in MERRA-2 as well as the MERRA-driven aerosol reanalysis (MERRAero) the corrected precipitation data are also used to modulate aerosol wet removal processes over land and ocean.

Initial conditions for the GEOS-5 seasonal forecasting system are needed routinely and close to real time (`http://gmao.gsfc.nasa.gov/products/climateforecasts/GEOS5/DESC/`). The system that generates the initial conditions thus uses corrected precipitation based on the MERRA background as close to real time as MERRA is available and then fills in the most recent weeks with corrected precipitation based on the FP background. To generate the subsequent set of initial conditions, the system is rewound to the point in time at which corrected precipitation based on the MERRA background ended and is then run forward with newly available corrected precipitation based on the MERRA background for as long as possible. In

the long-term, the initial conditions are therefore always based on corrected precipitation using the MERRA background for as long as possible.

At the time of writing, the production of MERRA-2 is underway. Its most recent stream will overtake that of MERRA soon. Moreover, it is expected that MERRA (and MERRA-Land) will end within the next year or so. Once MERRA ends, the corrected precipitation that will be used for MERRA-2 and the GEOS-5 seasonal forecasting system will use the FP-IT data as background instead of MERRA data.

Finally, the version of the GEOS-5 land-only or coupled modeling system determines the triplet of corrected precipitation variables that is read into the system (section 2.2). Currently, GEOS-5 applications that use corrected precipitation data typically read PRECTOT, PRECCON, and PRECSNO. Only the SMAP applications read PRECCU, PRECLS, and PRECSNO.

Acknowledgments

References

Adler, R. F., and Coauthors (2003), The Version 2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979-Present), *J. Hydrometeor.*, 4, 1147-1167.

Da Silva, A., P. R. Colarco, A. S. Damenov, V. Buchard-Marchant, C. A. Randles, and P. Gupta (2011), An Overview of the GEOS-5 Aerosol Reanalysis, American Geophysical Union Fall Meeting, 5-9 December 2011, San Francisco, CA, USA.

Da Silva, A., P. Colarco, A. Darmenov, V. Buchard-Marchant, C. Randles, and R. Govinaradju (2012), Overview of the MERRA Aerosol Reanalysis: Toward an Integrated Earth System Analysis, 4th World Climate Research Programme International Conference on Reanalyses, 7-11 May 2012, Silver Spring, MD, USA.

Entekhabi, D., and Coauthors (2014), SMAP Handbook, *JPL Publication, JPL 400-1567*, NASA Jet Propulsion Laboratory, Pasadena, California, USA, 192 pp.

Ham, Y.-G., S. Schubert, Y. Vikhliaev, and M. J. Suarez (2014), An assessment of the ENSO forecast skill of GEOS-5 system, *Climate Dynamics*, doi: 10.1007/s00382-014-2063-2.

Lucchesi, R. (2011), File Specification for GEOS-5.7.2 (version 1.6, released 26 Nov 2012), NASA Global Modeling and Assimilation Office, Greenbelt, MD, USA, 57 pp. Available at http://gmao.gsfc.nasa.gov/documents/GEOS-5.7.2_File_Specification.pdf.

Lucchesi, R. (2012), File Specification for MERRA Products (version 2.3, released 3 Aug 2012), *GMAO Office Note No. 1*, NASA Global Modeling and Assimilation Office, Greenbelt, MD, USA, 87 pp. Available at http://gmao.gsfc.nasa.gov/pubs/office_notes.

Lucchesi, R. (2013a), File Specification for GEOS-5 FP-IT (Forward Processing for Instrument Teams) (version 1.2, released 15 Jan 2013), *GMAO Office Note No. 2*, NASA Global Modeling and Assimilation Office, Greenbelt, MD, USA, 63 pp. Available at http://gmao.gsfc.nasa.gov/pubs/office_notes.

Lucchesi, R. (2013b), File Specification for GEOS-5 FP (Forward Processing) (version 1.0, released 11 Jun 2013), *GMAO Office Note No. 4*, NASA Global Modeling and Assimilation Office, Greenbelt, MD, USA, 63 pp. Available at http://gmao.gsfc.nasa.gov/pubs/office_notes.

Reichle, R. H. (2012), The MERRA-Land Data Product (Version 1.2), *GMAO Office Note No. 3*, NASA Global Modeling and Assimilation Office, Greenbelt, MD, USA, 43 pp. Available at http://gmao.gsfc.nasa.gov/pubs/office_notes.

Reichle, R. H., and Coauthors (2011), Assessment and enhancement of MERRA land surface hydrology estimates, *Journal of Climate*, 24, 6322-6338, doi:10.1175/JCLI-D-10-05033.1

Reichle, R. H., J. V. Ardizzone, G.-K. Kim, R. A. Lucchesi, and B. Weiss (2014a), Soil Moisture Active Passive Mission Level 4 Surface and Root Zone Soil Moisture Product Specification Document (Initial Version 1.3, 17 Jun 2014), *GMAO Office Note No. 6*, NASA Global Modeling and Assimilation Office, Greenbelt, MD, USA, 63 pp.

Reichle, R. H., R. D. Koster, G. J. M. De Lannoy, W. T. Crow, and J. S. Kimball (2014b), Soil Moisture Active Passive Project Algorithm Theoretical Basis Document: SMAP Level 4 Surface and Root Zone Soil Moisture Data Product, *NASA Jet Propulsion Laboratory Publication*, JPL D-66483, DRR No: SMAP-11-013, NASA Jet Propulsion Laboratory, Pasadena, California, USA, 66 pp.

Rienecker, M. M., and Coauthors (2011), MERRA - NASA's Modern-Era Retrospective Analysis for Research and Applications, *Journal of Climate*, 24, 3624-3648, doi:10.1175/JCLI-D-11-00015.1.

Xie, P., A. Yatagai, M. Chen, T. Hayasaka, Y. Fukushima, C. Liu, and S. Yang (2007), A gauge-based analysis of daily precipitation over East Asia, *J. Hydrometeorol.*, 8, 607-626.