



Assimilation of Spaceborne Radar Observations in the Goddard Earth Observing System (GEOS) Model

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Abstract. Spaceborne radar observations provide valuable information on the vertical structure of precipitation and hydrometeors, making them an important resource for numerical weather prediction and model evaluation. The Joint Effort for Data assimilation Integration (JEDI) is the unified and configurable data assimilation system developed and stewarded by the Joint Center for Satellite Data Assimilation (JCSDA) on behalf of its U.S. federal partners being adopted in NASA's Goddard Earth Observing System (GEOS) suite of products. This study describes a new spaceborne radar data assimilation capability developed for use in JEDI, including both the radar forward operator and the associated data assimilation components. This new capability is then demonstrated using observations from the Global Precipitation Measurement (GPM) Dual-frequency Precipitation Radar (DPR). The radar forward operator simulates reflectivities that agree well with observations, with mean differences typically below 2 dB during the August 2023–January 2024 test period. Consequently, a large number of DPR observations can be successfully assimilated into GEOS. Case studies of tropical cyclones show that DPR assimilation can substantially improve the analyzed distribution of precipitation and hydrometeors and, in some cases, improve atmospheric state variables such as wind, pressure, temperature, and water vapor. These results demonstrate the potential of spaceborne radar observations to improve the representation of precipitating systems in GEOS and, ultimately, the quality of future reanalyses and weather forecasts.

1 Introduction

Precipitation plays a central role in Earth's energy and water cycles through latent heat release, intense convective activity in the atmosphere, and its influence on weather and hydrological extremes such as floods and droughts (Stephens et al., 2020; Liu et al., 2015; Council, 2007). Despite its importance, quantitative forecasting of precipitation remains one of the fundamental challenges in numerical weather prediction (NWP) (Cuo et al., 2011; Shrestha et al., 2013). Improving precipitation forecasts in both global and regional models requires high-quality observations that can constrain model microphysics (Köcher et al., 2023). Spaceborne radar measurements, which directly measure the energy backscattered by hydrometeors, are among the most valuable precipitation observations for observing the entire globe (Köcher et al., 2023; Zhang et al., 2013). While passive



microwave and infrared observations provide global measurement of vertically integrated cloud and precipitation (Bauer et al., 2011; Gustafsson et al., 2018), spaceborne radars remain the only observing system capable of delivering detailed, global vertical profiles of precipitation and cloud structure (Kidd and Huffman, 2011; Hou et al., 2014; Skofronick-Jackson et al., 2017; Errico et al., 2007).

Radar instruments measure the returned signal from particles, providing information on hydrometeor content, drop size distributions, and vertical structure (Iguchi et al., 2010). The strong physical relation between radar backscatter and hydrometeors makes radar observations the most direct remote sensing technique for global precipitation measurements (Kidd and Huffman, 2011).

The Tropical Rainfall Measuring Mission (TRMM), a joint effort between NASA and the Japan Aerospace Exploration Agency (JAXA), hosted the first spaceborne precipitation radar. The instrument, known as the Precipitation Radar (PR), operated from 1997 to 2015 and provided the first three-dimensional measurements of rainfall over the tropics and subtropics at Ku-band (13.8 GHz) (Kummerow et al., 1998, 2000). The success of TRMM laid the foundation for the subsequent Global Precipitation Measurement (GPM) mission. Launched in 2014, the GPM Core Observatory, also a NASA–JAXA partnership, represented a major advance in global hydrometeorological observations. Its Dual-frequency Precipitation Radar (DPR) observes the three-dimensional structure of precipitation at Ku-band (13.6 GHz) and Ka-band (35.5 GHz) (Hou et al., 2014; Skofronick-Jackson et al., 2017).

Over the last decade with the advancements in the modelling of cloud and rain scattering, the assimilation of radar observations has gained momentum, particularly for high-impact precipitation events and convective weather systems (Liu et al., 2024; Ikuta, 2022). Numerous studies report positive impacts from assimilation of radar observations, especially in improving the representation of cloud microphysics, storm structures, and short-range precipitation forecasts (Ikuta, 2022; Liu et al., 2024; Pan et al., 2018; Janisková and Fielding, 2020; Fielding and Janisková, 2020). These studies underscore the growing recognition of radar data assimilation as a crucial component of modern data assimilation frameworks, yielding measurable benefits for short-term and convective-scale prediction (Gustafsson et al., 2018).

Historically, the assimilation of radar observations in numerical weather prediction systems has been limited worldwide, with much of the work carried out in research and experimental settings rather than routine operational use, and with direct reflectivity assimilation remaining technically challenging (Fabry and Meunier, 2020; Council, 2002). Early challenges in radar data assimilation arose from the lack of reliable and computationally efficient radar forward operators, inaccuracies in precipitation and cloud water content fields provided by forecast models as the first guess (Gustafsson et al., 2018; Errico et al., 2007), lack of reliable cloud and precipitation scattering databases (Moradi et al., 2023), and the absence of a unified data assimilation framework capable of incorporating active sensor observations.

Recent developments within the Community Radiative Transfer Model (CRTM) enable the assimilation of radar observations (Moradi et al., 2023, 2022). The introduction of a dedicated radar forward operator in CRTM represents a major step forward, providing a robust and computationally efficient tool for simulating radar reflectivities and attenuation across multiple frequencies (Moradi et al., 2023). This forward operator employs a recent hydrometeor scattering database derived using the Discrete Dipole Approximation (DDA) technique to represent non-spherical hydrometeors (Moradi et al., 2022). The per-



formance of the CRTM active module has been extensively evaluated against observations from the DPR onboard the GPM satellite, as well as the Cloud Profiling Radar (CPR) onboard both CloudSat and EarthCARE (Moradi et al., 2023, 2025).

60 The Joint Effort for Data assimilation Integration (JEDI) system, developed through a multi-agency collaboration coordinated by the Joint Center for Satellite Data Assimilation (JCSDA), provides a flexible, modular, and object-oriented infrastructure designed to support the assimilation of diverse observation types across multiple Earth system models (Trémolet and Auligné, 2020).

This work implements the CRTM active radar module, together with its tangent-linear and adjoint counterparts, within
65 the JEDI framework, enabling the assimilation of spaceborne radar observations such as those from the GPM-DPR across the forecast models supported by JEDI. We also extend several JEDI components to support the ingestion, processing, and diagnostics of radar observations. The resulting capability within NASA's GEOS system represents an important step toward the routine assimilation of active spaceborne radar observations in Earth system analyses and numerical weather prediction.

NASA's efforts to incorporate research-quality observations into Earth system reanalyses, through projects such as the
70 Modern-Era Retrospective Analysis for Research and Applications (MERRA) (Rienecker et al., 2008; Gelaro et al., 2017), will also benefit from the assimilation of active spaceborne radar observations. While this study focuses on GPM DPR observations, other spaceborne radar observations provide complementary information for studying precipitation and cloud processes. These include the TRMM PR, which provides Ku-band precipitation measurements similar to GPM DPR, as well as the 94 GHz (W-band) CPR aboard CloudSat (Stephens et al., 2002, 2008) and EarthCARE (Wehr et al., 2023), which provide enhanced
75 sensitivity to clouds and frozen hydrometeors (Ohara and Masunaga, 2025). Together, these active radar observations offer a unique opportunity to improve the representation of precipitation and clouds in future Earth system analyses and reanalyses.

2 Observing System

GEOS assimilates a comprehensive set of conventional and satellite observations, including infrared and microwave radiances, atmospheric motion vectors, Global Positioning System radio occultation, and aircraft data. The satellite observations assim-
80 ilated in the control configuration are listed in Table 1. Additional observations include satellite-derived atmospheric motion vectors, aircraft reports, and conventional surface and upper-air measurements (Gelaro et al., 2017; McCarty et al., 2016).

Because the observation used within the current GEOS framework are primarily archived in BUFR format, which cannot yet be ingested directly by JEDI, we employed the SWELL (Swell Workflow Ecosystem, Layout and Launcher) workflow to convert the BUFR observations into a JEDI-compliant format, conforming to the IODA (Interface for Observational Data
85 Assimilation) data model and conventions for observation processing.

2.1 GPM DPR Observations

The Global Precipitation Measurement (GPM) mission, a joint effort between NASA and the Japan Aerospace Exploration Agency (JAXA), was launched in 2014 as a successor to the Tropical Rainfall Measuring Mission (TRMM) (Hou et al., 2014). The mission's Dual-frequency Precipitation Radar (DPR) was the first spaceborne radar capable of measuring precipitation



Table 1. Satellite observations assimilated in the control experiment.

Acronym	Instrument Name
AIRS	Atmospheric Infrared Sounder
AMSU-A	Advanced Microwave Sounding Unit-A
ATMS	Advanced Technology Microwave Sounder
CrIS	Cross-track Infrared Sounder
IASI	Infrared Atmospheric Sounding Interferometer
MHS	Microwave Humidity Sounder
SSMIS	Special Sensor Microwave Imager/Sounder
AMSR2	Advanced Microwave Scanning Radiometer-2
GMI	Global Precipitation Measurement Microwave Imager

- 90 simultaneously at two frequencies: Ku-band (13.6 GHz) and Ka-band (35.5 GHz). This dual-frequency approach enables detailed profiling of precipitation microphysics and hydrometeor phase discrimination, particularly in mixed-phase and stratiform regions (Skofronick-Jackson et al., 2017). Although the radar remote sensing community commonly refers to these frequencies as the Ku- and Ka-bands, this study alternatively uses Channel 1 and Channel 2, respectively, to maintain consistency with the terminology commonly used for satellite observations in the data assimilation community.
- 95 GPM-DPR has a swath width of 245 km, the Ka-band had a swath width of 120 km before May 2018, therefore provides three-dimensional reflectivity observations with a horizontal resolution of approximately 5 km and vertical sampling of 125 m (Hou et al., 2014; Skofronick-Jackson et al., 2017; Iguchi et al., 2010). These measurements allow for retrieval of crucial variables such as rain rate and drop size distribution (Iguchi et al., 2010). Compared with passive microwave and infrared observations, which rely heavily on retrieval assumptions, the DPR active measurements can be directly related to precipitation
- 100 (Skofronick-Jackson et al., 2017). Moreover, its quasi-global coverage and orbital repeat cycle make it a powerful source of information for global hydrological monitoring, numerical model evaluation, and data assimilation. Because the DPR observations have a much higher spatial resolution than the GEOS model simulations, the observations are first horizontally averaged within 25×25 km bins.

3 The JEDI Framework

- 105 The Joint Effort for Data assimilation Integration (JEDI) is the unified and configurable data assimilation system developed and stewarded by JCSDA on behalf of its U.S. federal partners (NOAA, NASA, the Air Force, and the Navy) to serve their operational and research needs in Earth system analysis and prediction. JEDI provides a flexible, modular, and object-oriented infrastructure designed to support the assimilation of diverse observation types across multiple Earth system models (Trémolet and Auligné, 2020).



JEDI is controlled by the configuration specified in YAML files that define parameters such as time windows, assimilation methods, observation usage and desired outputs. By abstracting these parameters into dynamic configuration files, users can modify observation-specific settings, quality control filters, and observation error models at runtime. This approach eliminates the need to recompile the codebase, allowing a single, unified framework to rapidly execute and test a broad range of consolidated experimental configurations. By placing the focus on agility at runtime, a JEDI-based system can be used to flexibly adapt to different models, observation types, or analysis cycling.

Figure 1 shows a schematic diagram of the JEDI framework, illustrating the relationships between its main components. At the heart of JEDI is the Object-Oriented Prediction System (OOPS), which provides the fundamental data assimilation algorithms. OOPS combines reusable, model-agnostic building blocks, allowing assimilation updates to be computed without requiring knowledge of the specific forecast model or observation data. This abstraction ensures that assimilation logic remains consistent and portable across different applications (Trémolet and Auligné, 2020). The main JEDI components modified to support radar data assimilation include CRTM, UFO, and IODA, which are discussed in more detail in the following sections.

3.1 CRTM

In the context of NWP, the state variables provided by the forecast model (e.g., temperature, water vapor profiles, mixing ratios of hydrometeors) and the observations (e.g. radar reflectivity) are often in different state space, thus forward models are used to convert the model state into the observation space. In the case of radar observations, model variables are related to radar observables through non-trivial physical relationships that require extensive forward model development. The Community Radiative Transfer Model (CRTM) serves as the operational forward model for satellite radiance assimilation across multiple agencies in the United States including NOAA and NASA (Johnson et al., 2023; Liu and Boukabara, 2014).

Moradi et al. (2023) extended the CRTM by adding a module that includes capability to perform forward, tangent linear and adjoint calculations for the radar observations. The CRTM radar module used in this study supports multi-frequency radar simulations and includes non-spherical hydrometeor treatments. It also accounts for attenuation effects due to rain, cloud water, and atmospheric gases. The module also considers the angle dependency of reflectivity simulations through sensor zenith angle. The CRTM active module has been extensively validated for the Ku-, Ka-, and W-bands and has been shown to perform satisfactorily, provided that reliable water content profiles are used as input (Moradi et al., 2025, 2023).

The power received by a radar antenna depends on the transmitted power, target backscattering, and atmospheric attenuation. By normalizing the received signal by the transmitted power, instrument-dependent factors are removed, yielding the radar reflectivity factor. The radar equation can be written as (Petty, 2006):

$$Z_a = \frac{10^{18} \lambda^4}{\pi^5 |k_w|^2} \Gamma \beta_b, \quad (1)$$

where Z_a is attenuated reflectivity factor in $\text{mm}^6 \text{m}^{-3}$, λ is the radar wavelength (m), k_w is the dielectric factor of liquid water, β_b is the volume backscattering coefficient (m^{-1}), and Γ is the two-way transmittance accounting for atmospheric attenuation. The attenuation is derived from the extinction coefficient, which includes absorption and scattering by gases and hydrometeors

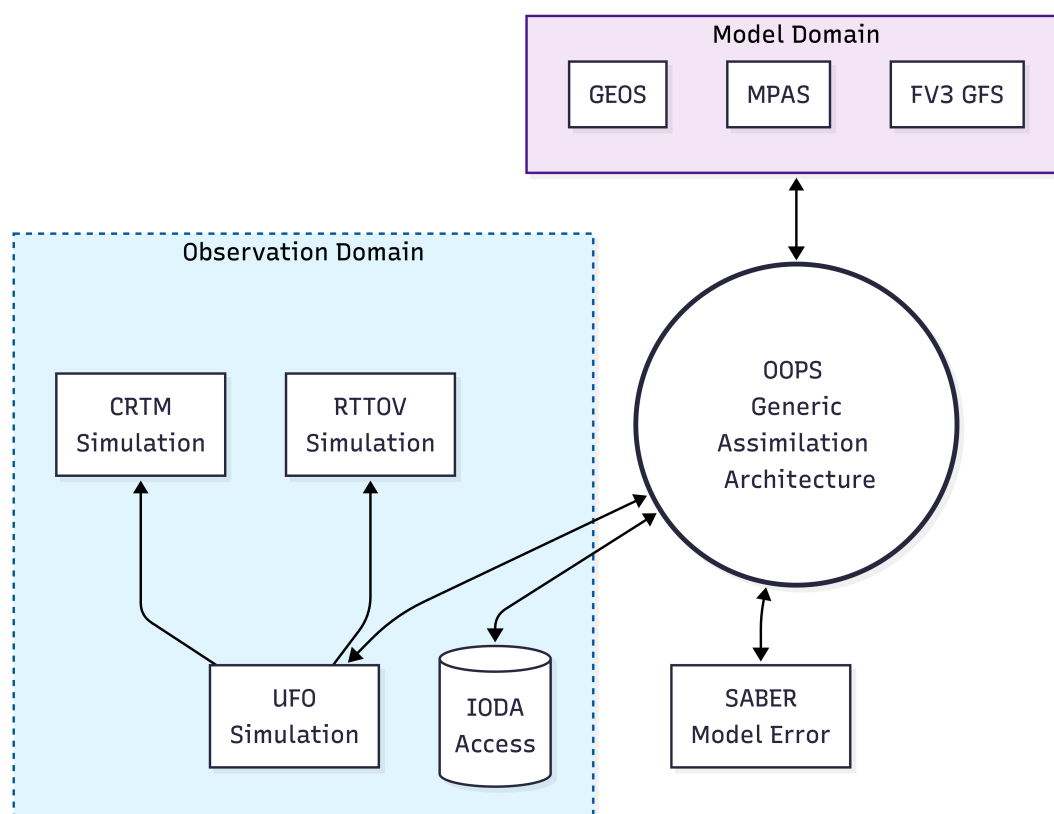


Figure 1. Schematic diagram of the JEDI framework. The Object-Oriented Prediction System (OOPS) provides the core data assimilation algorithms. The Interface for Observation Data Access (IODA) provides the data model and conventions for the various observational data. The System-Agnostic Background Error Representation (SABER) provides background error covariance representations. The Unified Forward Operator (UFO) serves as the computational interface between model variables and observation operators, including radiative transfer models such as the Community Radiative Transfer Model (CRTM) and the Radiative Transfer for TOVS (RTTOV), which simulate satellite observations. JEDI interfaces with multiple forecast models, including the Goddard Earth Observing System (GEOS), the Model for Prediction Across Scales (MPAS), and the Finite-Volume Cubed-Sphere Global Forecast System (FV3-GFS).



(Moradi et al., 2023). Radar reflectivity is commonly expressed in logarithmic units (dBZ) as follows:

$$R_a = 10 \log_{10} (Z_a) . \quad (2)$$

3.2 UFO

145 Within the JEDI architecture, the Unified Forward Operator (UFO) serves as the computational interface between model variables and observation operators such as CRTM. UFO constructs the required CRTM inputs by requesting both the model state variables (e.g., temperature and water vapor) and hydrometeor variables at the observation location. The CRTM performs the forward simulations, and returns the simulated radar reflectivities and their Jacobians to the assimilation algorithm.

While the UFO framework can accommodate new observations through resource (YAML) files when the observation type
150 is already supported, assimilating a new observation type such as radar reflectivity requires substantial software development. This includes preparing the atmospheric and hydrometeor profiles required by CRTM, reconciling the observation and model vertical grids, implementing the tangent-linear (TL) and adjoint (AD) capabilities, generating the required diagnostic outputs, and incorporating a dedicated bias correction scheme (Section 5).

To support active radar observations, the UFO was extended to simulate radar reflectivity and compute observation diag-
155 nostics. Because the radar observations typically have a finer vertical resolution than the model, an averaging operator was developed to map the observations onto the model layers. These layer-averaged quantities, referred to as *derived observations*, are subsequently used throughout the assimilation process.

The CRTM radar interface requires profiles of both frozen and liquid hydrometeors, including snow, cloud ice, graupel, rain, and cloud liquid water. Forward simulations are performed using the complete set of hydrometeor profiles, although the
160 contribution of each species depends strongly on radar frequency. Ku- and Ka-band observations are primarily sensitive to rain, with additional contributions from snow, whereas W-band observations are dominated by scattering from frozen hydrometeors, including snow, graupel, and cloud ice (Turk et al., 2021).

3.3 IODA

IODA is a core component of the JEDI framework responsible for the in-memory management, storage, and retrieval of
165 observational data during the assimilation process. Rather than directly converting raw datasets, IODA defines the standardized data model and conventions—including unified naming and units—that observations must adhere to. Bespoke external utilities (such as those in the *ioda-converter* library) decode raw observation formats and map them onto these IODA conventions, which can then be written to disk through various storage backends like netCDF4. At runtime, IODA reads these standardized observations, populates them into their corresponding memory-resident observation spaces, and exposes the data to quality
170 control filters. This enables the framework to perform the precise thinning, quality control, and data transformations required by the forward operators and the core assimilation algorithm.

In addition to observation conventions, IODA manages metadata consistently, synchronizes observations with the data assimilation cycles, and optimizes input/output performance, which is critical for high-resolution or large-scale experiments. By



separating observation processing from the assimilation algorithms, IODA allows different datasets, from satellite instruments
175 to in situ measurements, to be prepared in a uniform manner. This modularity enhances flexibility, enabling new observation
types to be integrated without need for modifying the core assimilation code, and ensures reliable, consistent data input across
multiple forecast models (Joint Center for Satellite Data Assimilation, 2025).

3.4 SWELL

SWELL is a robust workflow ecosystem developed at GMAO to support the execution and utilization of GEOS and JEDI
180 software and their peripheral dependencies. It is designed to handle outputs from multiple Earth system components, including
atmosphere, ocean, sea ice, and land, and it will support a range of applications such as NWP, reanalysis, and subseasonal-
to-seasonal (S2S) prediction. SWELL also integrates the EVA monitoring package and the R2D2 observation database tool
(Lingerfelt et al., 2024), enabling standardized diagnostics and facilitating collaboration across multiple agencies.

SWELL employs Cylc as its workflow engine, a scheduling system also widely adopted by NWP centers around the world
185 (Oliver et al., 2018, 2019). Cylc manages the inter- and intra-cycle dependencies of the DA workflow by decomposing it into
individual, self-contained tasks. The full replacement of the existing GEOS workflows by SWELL is still underway. In the
present work, the use of SWELL is minimal, with SWELL being responsible only for converting various observational data
inputs into IODA.

4 The GEOS–JEDI Framework

190 Figure 2 illustrates the overall architecture of the GEOS–JEDI data assimilation workflow. To streamline integration, the JEDI
data assimilation components are unified directly within the established GEOS atmospheric processing infrastructure. This
integrated workflow relies on a modular scripting suite that orchestrates the execution sequence between GEOS forward-
processing (NWP) and various GEOS reanalysis applications.

At the start of each cycle, the workflow brings in model initial conditions (so-called restarts), background (first-guess) fields
195 and the observations associated with the current 6-hour cycle. The JEDI analysis involves the steps explicitly detailed in the
green boxes. JEDI begins with the ingestion of observational data, followed by a basic gross quality checks, such as verifying
that observations fall within acceptable physical ranges, observations outside the data assimilation cycle are excluded, and for
regional applications, ensuring that only observations within the model domain are processed. These tasks are handled within
IODA, which instantiates the data as an ObsSpace (Observation Space) object. This object encapsulates the observations in
200 memory, making them directly available to UFO for forward operator simulation and quality control. UFO allows for various
configurable filters and functions that are used to assign errors to the observations and perform different levels of quality
control. Simultaneously, the background states at various times are read into JEDI, providing basic fields such as temperature,
winds, water vapor, ozone, hydrometeor water content, and relevant surface fields.

Each observation operator requires a specific set of state variables interpolated to the observation’s exact spatial coordinates
205 and valid time. While some of these variables can be extracted directly from the background state, others must be derived



through diagnostic conversions or vertical interpolations. Ultimately, these localized background quantities are consolidated into a standardized set of geophysical variables—designated as GeoVals within the JEDI framework—which serve as the required input for the forward operators. For example, to simulate a profile of radio occultation observations with the operator presently used in GEOS–JEDI, UFO requests air temperature, water vapor mixing ratio, three-dimensional pressure and geopotential height information. The profiles of observation-collocated background fields are used to simulate the observations. These are followed by the calculation of corresponding observation and background departures, which are then subjected to various levels of quality control managed by a number of filters and associated functions. It is relevant to point out that satellite radiances and aircraft temperature observations are bias corrected and rely on an extension of the variational produce that accommodates updating the bias correction terms (Dee and Uppala, 2009).

The observation-minus-background departures are ingested by the selected JEDI variational solver to drive the inner-loop minimization algorithm. OOPS provides several solver options, with this work using the Derber–Rosati Preconditioned Conjugate Gradient (DRPCG; (Derber and Rosati, 1989)) algorithm. To minimize differences with the current Gridpoint Statistical Interpolation (GSI)-based GEOS data assimilation system, GEOS–JEDI has been designed to interface with the GSI background error covariance (GSIBEC) through JEDI’s System-Agnostic Background Error Representation (SABER) component. This initial implementation of GEOS–JEDI employs an hourly three-dimensional first guess at the appropriate time (3D-FGAT) variational procedure. The 3D approach used here is intended primarily as an initial testbed for the assimilation of radar observations. Previous all-sky data assimilation studies in GEOS, particularly the introduction of GMI/GPM observations (Kim et al., 2020), demonstrated the importance of ensemble-based methods, such as the Hybrid 4D-EnVar GEOS 12.5 km Forward Processing system (Todling and El Akkraoui, 2013), which provide a better representation of hydrometeor background error covariances.

The resulting JEDI analysis is combined with the background (first-guess) to derive the required tendency for an Incremental Analysis Update procedure (Bloom et al., 1996) that modulates the tendency with a digital filter (Takacs et al., 2018) to enforce stability in IAU. The IAU terms are combined with the model initial conditions (IC) to allow for both short- and extended-range forecasts to be launched, with the short-range forecast being used in the following DA cycle. The assimilation is performed by using the IAU tendencies to force the model toward the data during the first 6 hours of the integration; beyond this, the IAU terms are turned off and the model is set to run freely. The forecasts are performed using the NASA Goddard Earth Observing System (GEOS; (Molod et al., 2015; Rienecker et al., 2008)), which serves as the forecast model within GEOS–JEDI.

In this work, we conduct two sets of experiments at a cubed-sphere horizontal resolution of C360, corresponding roughly to 25 km at the equator, with 72 hybrid vertical levels extending from the surface to the lower mesosphere. The experiments are carried out continuously for the period spanning August 2023 through January 2024. The control experiment assimilates all satellite and conventional observations routinely used in the GEOS system, as discussed in Section 2. The second experiment additionally assimilates GPM-DPR observations from both the Ku-band (Channel 1) and Ka-band (Channel 2) on top of the observations used in the control experiment, enabling evaluation of the impact of GPM-DPR observation assimilation on the analysis and forecast performance.

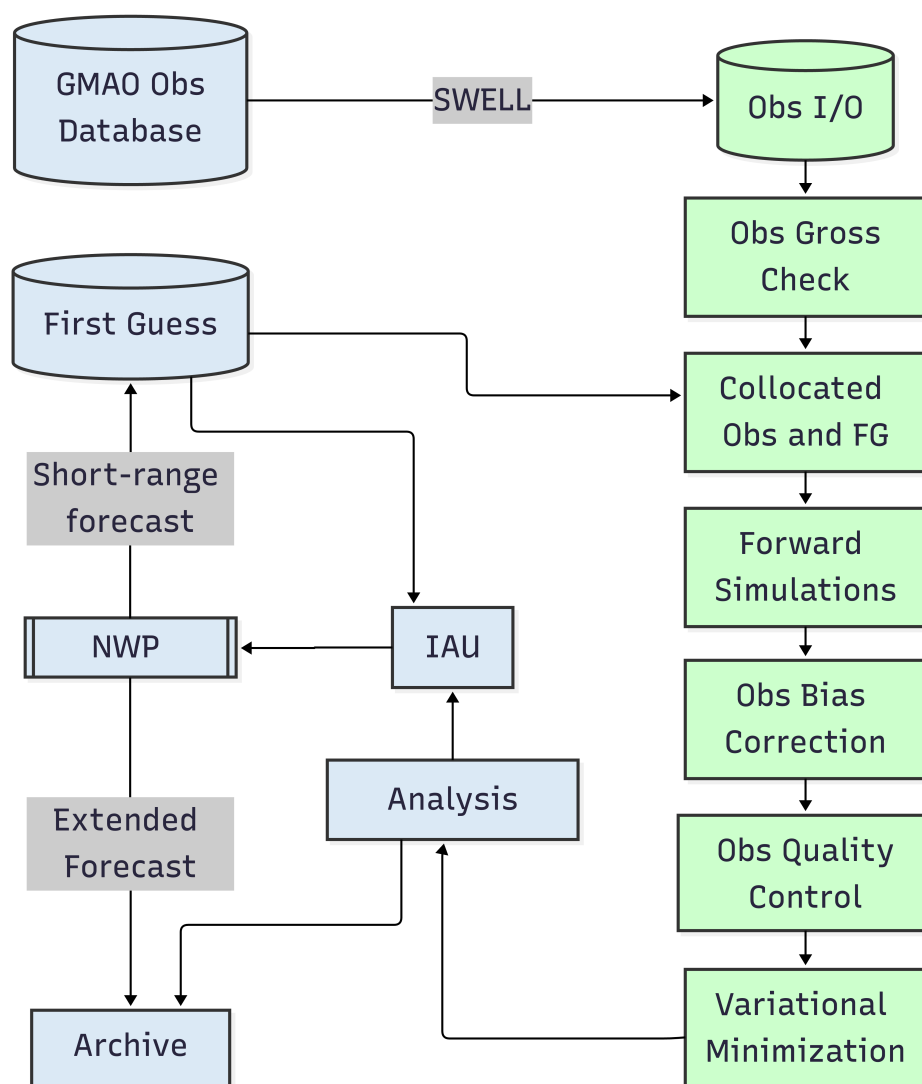


Figure 2. Schematic representation of the GEOS–JEDI data assimilation workflow. The green boxes highlight selected key components of the JEDI workflow. SWELL (Swell Workflow Ecosystem, Layout, and Launcher) converts observations (Obs) from current GMAO binary format to the JEDI-compatible format. The Incremental Analysis Update (IAU) gradually applies the analysis increments to the first guess (background) to produce the initial conditions for the subsequent data assimilation cycle.



240 5 Observation Error and Biases

In data assimilation systems, observation error determines the relative weight assigned to observations with respect to the model background. The observation error variance is represented by the observation error covariance matrix $\mathbf{R}$. For radar reflectivity, the total observation error is assumed to arise from independent sources and can be expressed as

$$\sigma_{obs}^2 = \sigma_{instr}^2 + \sigma_{fm}^2 + \sigma_{rep}^2, \quad (3)$$

245 where σ_{instr} denotes instrumental noise and calibration uncertainty, σ_{fm} represents forward-model error associated with the radar observation operator, and σ_{rep} accounts for representativeness error due to the mismatch between the radar sampling volume and the model grid resolution.

For active sensors such as GPM DPR, systematic calibration errors are generally small because radar reflectivity is derived from the ratio of transmitted and received power using the same antenna and signal chain. However, random measurement
250 errors arising from receiver noise and other measurement uncertainties remain and must be represented in the observation error specification. In addition, numerical models typically show larger errors under intense cloud and precipitation conditions, where radar reflectivities are high. To account for this behavior, a reflectivity-dependent observation error formulation is adopted as follows:

$$\sigma_{obs} = \sigma_0 + \alpha \sigma_{bin} + \beta y + \gamma |y - H(x_b)|, \quad (4)$$

255 where y is the observed reflectivity (dBZ), σ_0 is a baseline error, σ_{bin} is the within-bin standard deviation scaled by α , and β controls the dependence of the error on reflectivity. The innovation-based term accounts for large discrepancies between the observation y and the simulated reflectivity $H(x_b)$.

The reflectivity-dependent term accounts for the increased uncertainty associated with intense precipitation, where nonlinear scattering effects, unresolved hydrometeor variability, and forward-model errors are expected to be larger. To reduce small-scale
260 variability, observations are spatially averaged over approximately 25×25 km regions. The standard deviation of observations within each bin is then added to the observation error to represent unresolved variability and representativeness error; σ_{bin} typically ranges from 1 to 3 dB.

In this study, we ultimately adopt the follow error model for GPM DPR:

$$\sigma_{obs} = \sigma_0 + 0.25 \sigma_{bin} + 0.02 y + 0.1 |y - H(x_b)| \quad (5)$$

265 The term $\sigma_0 + 0.25 \sigma_{bin}$ represents the combined contribution of instrumental and representativeness errors. We originally employed 2.0 dB for the constant error, but because of explicitly including σ_{bin} , we adopted the baseline error to be reduced to $\sigma_0 = 1$ dB in this study. The coefficient $\beta = 0.02$ reflects increasing uncertainty at higher reflectivities due to nonlinear scattering and enhanced subgrid variability, while $\gamma = 0.1$ inflates the error in the presence of large innovations (departures).

Figure 3 shows the distribution of observation errors for GPM DPR Channels 1 and 2. For Channel 1, the observation errors
270 range from approximately 4 to 11 dB, with a peak near 6 dB to 7 dB. Larger observation errors are generally associated with



higher reflectivity values, while smaller errors correspond to lower reflectivities. For Channel 2, the observation errors range from approximately 4 dB to 9 dB and peak near 5–6 dB.

These observation errors can be further tuned to increase the impact of observations in the assimilation system. However, because this study represents the first implementation of radar reflectivity assimilation within the GEOS framework, relatively conservative error values were adopted to limit observation impact, especially in the presence of large discrepancies between the model simulations and the observations. Future work will investigate alternative observation-error models and assess their impact on both analysis and forecast performance.

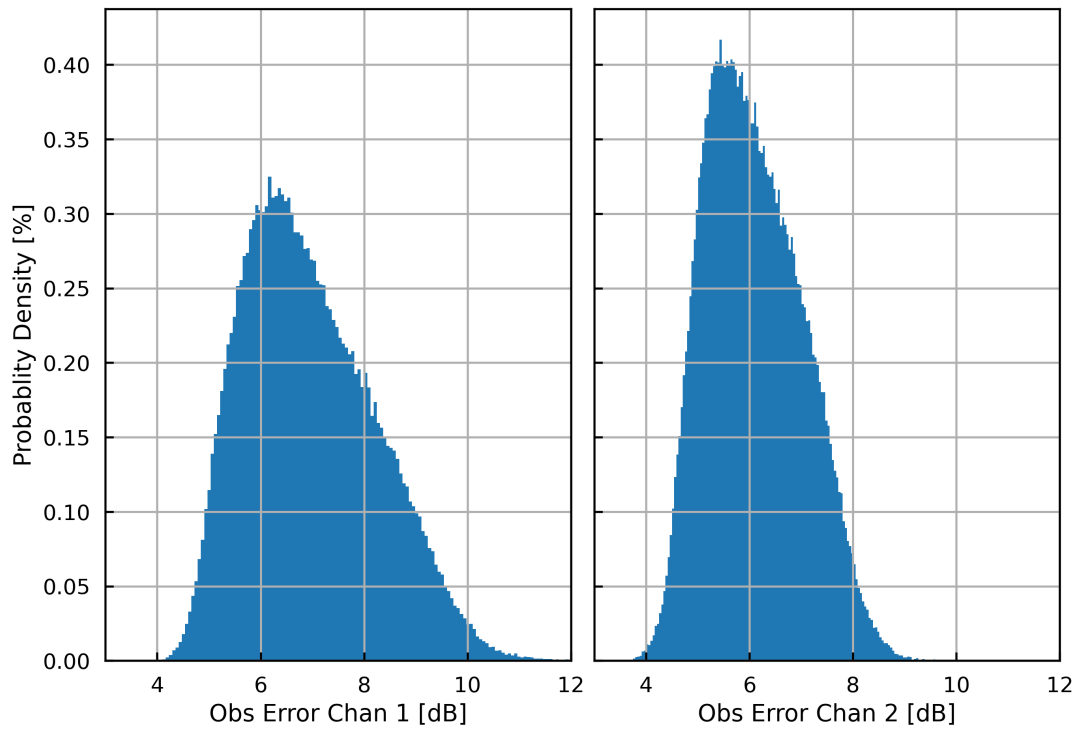


Figure 3. Histogram of observation errors for GPM DPR Channels 1 and 2 used in the assimilation experiments for the period from 15 August to 15 September 2023. Observation errors vary as a function of reflectivity, with larger errors assigned to higher reflectivity values.

The bias in radar reflectivity is specified as a function of radar measurement height and sensor scan angle. It is formulated as:

$$\text{bias}_{\text{init}} = C_1 + C_2 H + C_3 H^2 + C_4 \theta + C_5 \theta^2 \quad [\text{dB}], \quad (6)$$

where C_1 – C_5 are coefficients computed estimated within the variation bias correction (VarBC) procedure, H is the average bin height (m), and θ is the across-track scan angle (degrees).

Figure 4 shows the observation bias and corresponding standard deviation as a function of height and scan position, commonly referred to as field of view (FOV). These biases are estimated using the variational bias correction (VarBC) scheme



285 described by Equation 6, with the bias coefficients dynamically updated throughout successive data assimilation cycles. Both DPR channels show scan-angle-dependent biases, with values ranging from approximately 0 to 2 dB for Channel 1 and from about -3 dB to -1 dB for Channel 2. The standard deviation also varies across the scan, increasing from roughly 0.3 dB on the left side of the swath to about 0.7 dB on the right side.

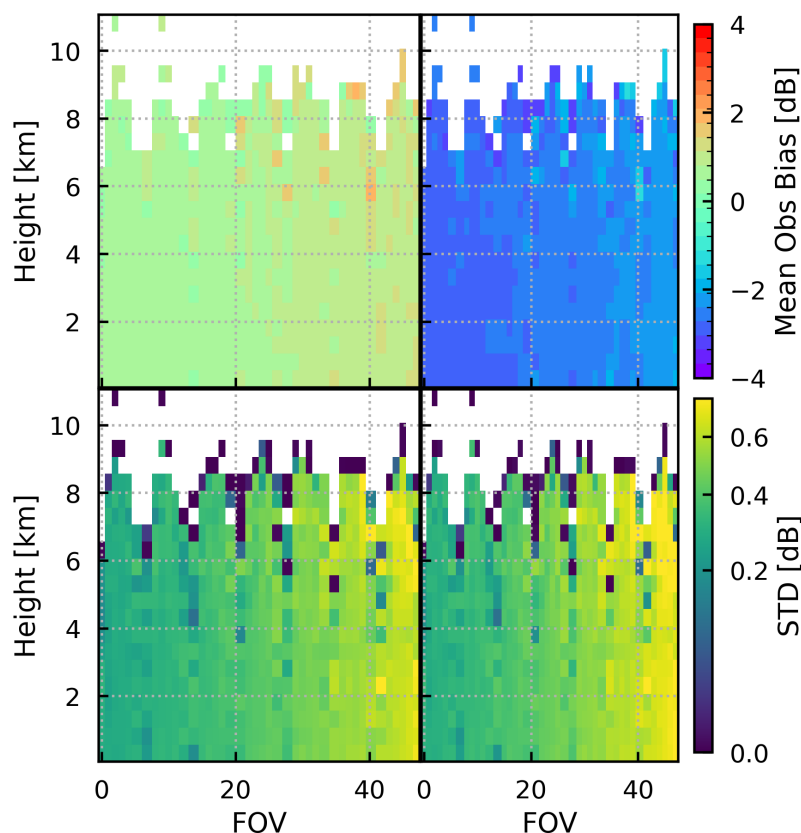


Figure 4. DPR observation biases and their corresponding standard deviations (STD), estimated using the JEDI variational bias correction (VarBC) scheme, as a function of scan position (field of view, FOV) and height for the period from 15 August to 15 September 2023. The left panels show Channel 1 (Ku-band), and the right panels show Channel 2 (Ka-band).



The observations are rejected from the assimilation if they satisfied any of the following criteria, before observation biases
290 were calculated and applied:

$$|y - H(x_b)| > 6 \text{ dB},$$

$$\sigma_{bin} > 6 \text{ dB},$$

$$\text{Height} < 500 \text{ m},$$

$$H(x_b) \notin [15, 70] \text{ dBZ},$$

$$y \notin [15, 70] \text{ dBZ}.$$

(7)

The first criterion removes observations associated with large observation–minus–background values, which may arise from gross errors or deficiencies in the model representation of the observed scene. The second criterion excludes observations characterized by large subgrid variability, as high within-bin standard deviations indicate strong spatial heterogeneity that
295 cannot be adequately represented at the model resolution. The third criterion eliminates observations susceptible to near–surface contamination. The final two criteria reject observations for which either the observed or simulated reflectivities fall outside the effective sensitivity range of the DPR observations.

6 Observations Diagnostics

Figure 5 shows the global distribution of assimilated GPM DPR reflectivity observations for Channel 1 during the period from
300 15 August to 15 September 2023. Reflectivities are averaged between 2 and 15 km altitude. Observation density is highest in the Intertropical Convergence Zone (ITCZ), where frequent deep convection produces strong radar echoes, and along the major midlatitude storm tracks associated with widespread precipitating systems. In contrast, relatively few observations are available over the subtropical oceans and desert regions, where precipitation is infrequent due to persistent large-scale subsidence. Consequently, the assimilated DPR observations are concentrated in regions of active precipitation, with sparse coverage over
305 climatologically dry areas.

Figure 6 shows the mean and standard deviation of the observed-minus-simulated reflectivity differences as a function of FOV and elevation. Overall, both channels show mean differences within approximately -4 to 4 dB; however, the distribution of the observed-minus-simulated reflectivity differences varies between the two channels. Channel 1 differences are generally centered close to zero, whereas Channel 2 shows a broader range of observed-minus-simulated reflectivity differences, mostly
310 between -2 and 0 dB. In contrast, Channel 2 indicates a lower standard deviation compared with Channel 1, with values generally less than 4 dB for Channel 2 compared with larger than 4 dB for Channel 1.

The density plots of observed-minus-simulated reflectivities are shown in Figure 7 for both Channels 1 and 2. Based on the number of observations in each bin, the differences are largely less than 5 dB. The mean difference is less than 1 dB for Channel 1 and around 1.5 dB for Channel 2. The standard deviation is approximately 4.8 dB for Channel 1 and 3.9 dB for
315 Channel 2.

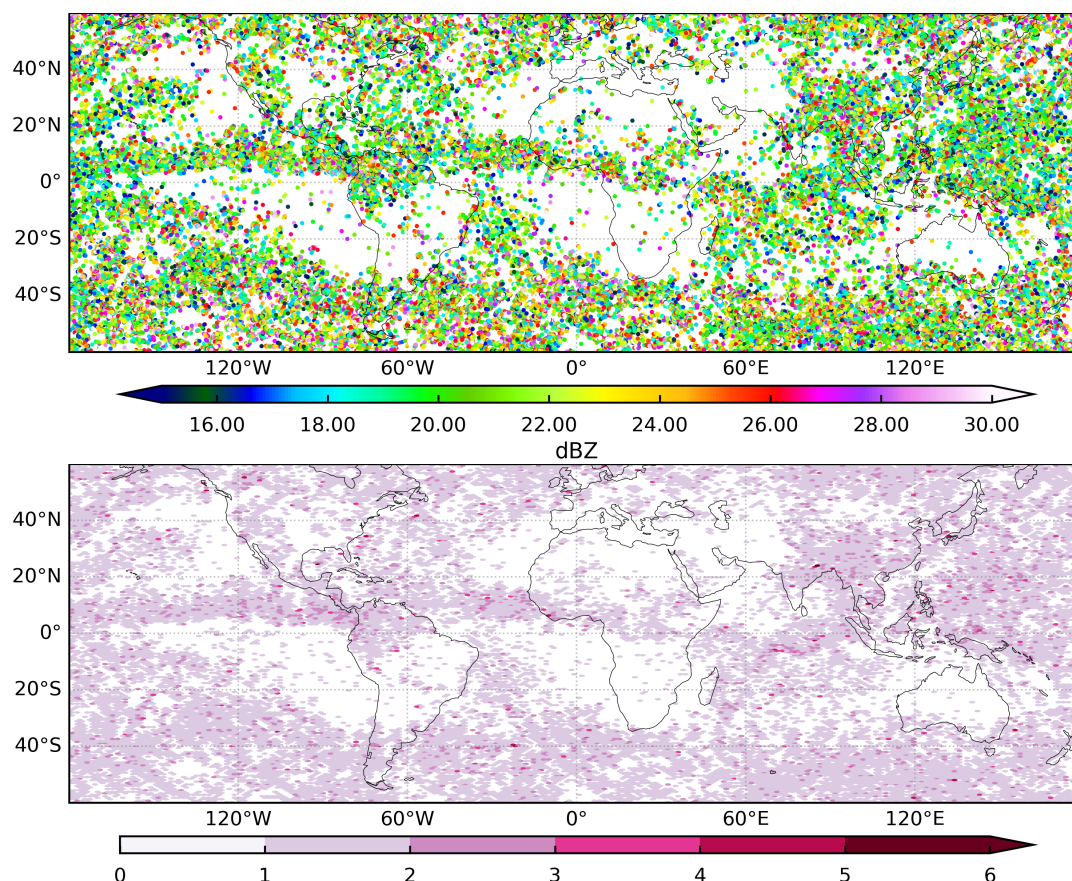


Figure 5. Global distribution of GPM DPR observations (top) and the corresponding observation density (bottom), expressed as the number of observations within 25-km gridded bins, accumulated over the period from 15 August to 15 September 2023.

7 Observations Impact on Analysis

We evaluate the impact of the DPR assimilation on several tropical cyclone fields, including liquid and frozen hydrometeor water content, wind, temperature, and total precipitable water vapor. The impact on analysis varies from neutral to positive across individual cases. To illustrate the range of observation impact, we examine two representative tropical cyclones: Typhoon Khanun, which occurred in August 2023 and reached typhoon intensity in the western North Pacific; and Cyclone Midhili, which formed over the Bay of Bengal in November 2023. Figure 8 shows the Integrated Multi-satellite Retrievals for GPM (IMERG) precipitation rate for the selected tropical cyclones. Although IMERG is itself a retrieval product, it is derived directly from a combination of satellite observations and is therefore expected to represent the overall precipitation structure and spatial distribution of the storms reasonably well (Precipitation Processing System (PPS) At NASA GSFC, 2023). As such, it provides a useful observational reference for evaluating the simulated cyclone precipitation patterns.

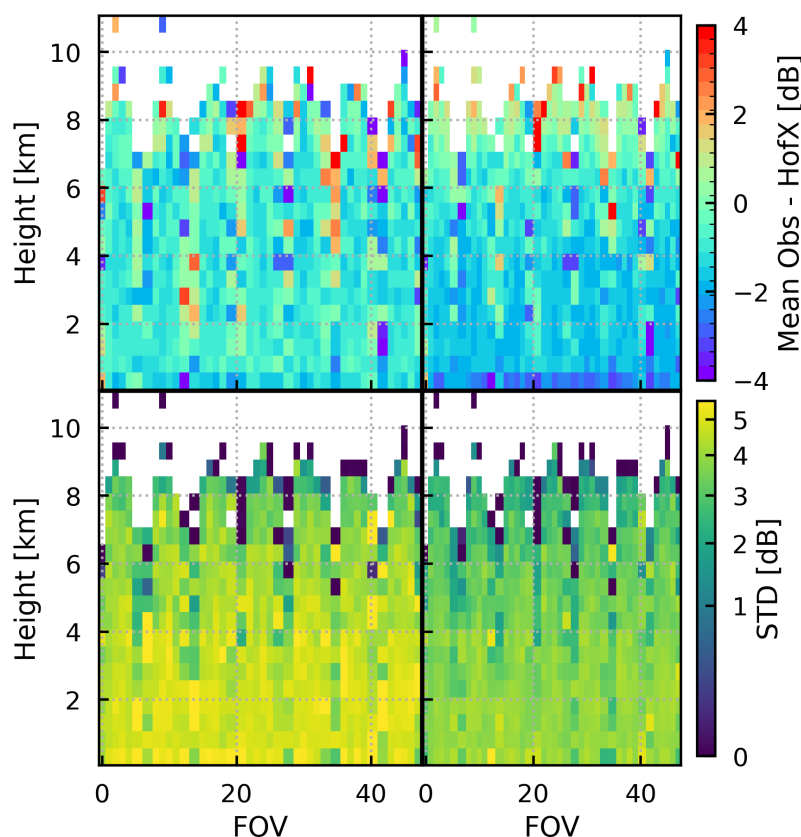


Figure 6. Mean differences (top) and standard deviations (bottom) between observed and simulated values for DPR Channel 1 (left) and Channel 2 (right), shown as a function of FOV and elevation.

We also use ERA5 as a reference for evaluating additional atmospheric and hydrometeor variables, including snow, ice, and cloud liquid water content, as well as temperature, water vapor, pressure, and wind fields. Although ERA5 is itself a reanalysis product rather than a direct observational dataset, it is generated using ECMWF's state-of-the-art 4D-Var data assimilation system and incorporates a comprehensive set of global observations. In contrast, the experiments presented in this study employ a 3D-Var data assimilation framework with a horizontal resolution of approximately 25 km. Given the more advanced assimilation methodology, extensive observational input, and widespread validation of ERA5, it provides a useful benchmark for assessing the realism of the analyzed atmospheric and hydrometeor fields and for identifying improvements resulting from the assimilation of GPM DPR observations.

Figure 9 shows the impact on Typhoon Khanun. In terms of rainwater content integrated between 1000–850 hPa, ERA5 shows a well-defined cyclone structure with peak values reaching approximately 450 g.m^{-2} , and the ERA5 precipitation pattern is broadly consistent with the IMERG precipitation rate. In the control experiment, rainwater content is generally weaker across most of the cyclone domain, except near the storm core. After assimilation of DPR observations, both the

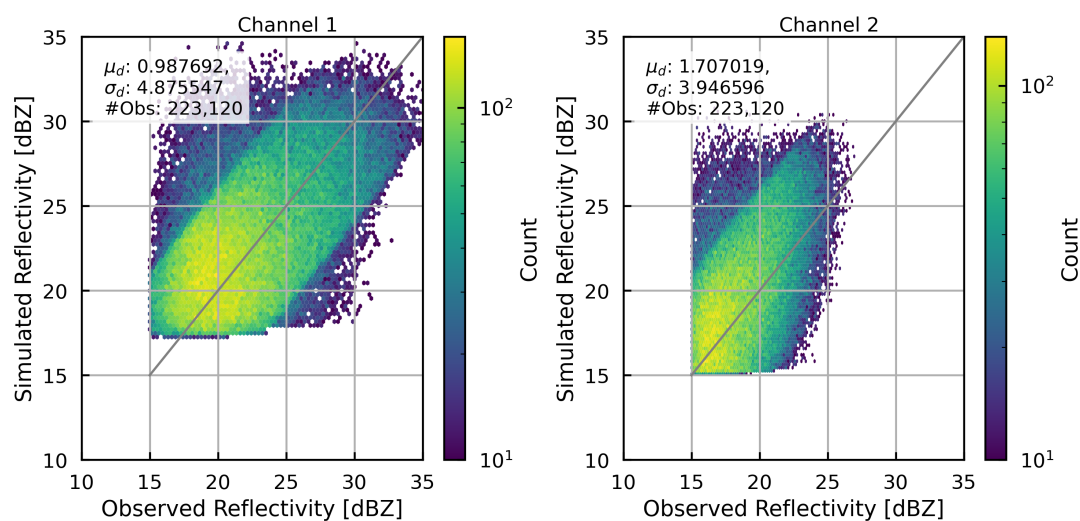


Figure 7. Density plots of simulated versus observed values for DPR Channel 1 (left) and Channel 2 (right). The mean and standard deviation of the differences between observed and simulated values are indicated by μ and σ , respectively.

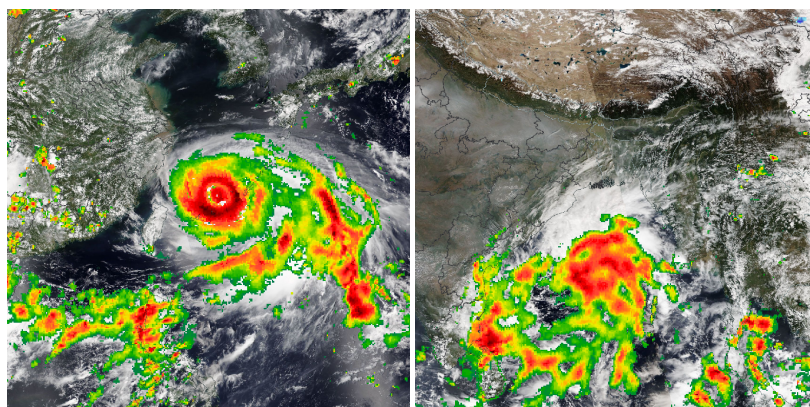


Figure 8. IMERG precipitation rate for the tropical cyclones examined in this study: Typhoon Khanun (August 2023), and Cyclone Midhili (November 2023).



magnitude and spatial distribution of rainwater content become more similar to ERA5 and IMERG. Overall, assimilation of DPR observations leads to a substantial improvement in the representation of rainwater content.

340 In the GEOS control experiment, cloud liquid water content is substantially higher than in the corresponding ERA5 analysis; however, no direct observational product is available for comparison. After assimilation of DPR observations, cloud liquid water content is generally reduced, although the magnitude of the impact is considerably smaller than that observed for rainwater content.

For frozen hydrometeors, the ERA5 reanalysis shows substantial ice and snow water content within both the cyclone core and the surrounding rainband tails. In contrast, the GEOS control experiment significantly underrepresents frozen hydrometeor content in these regions. Assimilation of DPR observations substantially increases the ice and snow water content throughout the cyclone, resulting in a structure that is more consistent with the ERA5 reanalysis.

Figure 10 shows the 850-hPa air temperature. The GEOS control experiment indicates higher temperatures in the cyclone core than the ERA5 analysis, while temperatures along the storm track are generally lower than those in ERA5. Assimilation of GPM DPR observations slightly reduces temperatures within the cyclone core and increases temperatures ahead of the storm. Overall, the impact of DPR assimilation on the temperature field is modest.

For total precipitable water vapor, both the control experiment and the experiment with assimilated DPR observations are generally consistent with the ERA5 analysis. Differences between the two GEOS experiments are relatively small, indicating a limited impact of DPR assimilation on the column-integrated moisture field.

355 Figure 10 also shows cyclone intensity metrics, including mean sea level pressure and wind speed at 850 hPa, together with surface wind vectors. The pressure field in the experiment with assimilated DPR observations is more consistent with the ERA5 analysis than that in the control experiment. At 850 hPa, both ERA5 and the DPR experiment show wind speeds exceeding 35 kt over a relatively broad region surrounding the cyclone, whereas the control experiment confines such winds to a much smaller area. Similarly, the surface wind field indicates wind speeds approaching 50 kt over an extensive region in both ERA5 and the DPR assimilation experiment, while the control experiment shows only a limited area with comparable wind speeds. These results suggest that assimilation of DPR observations improves the representation of cyclone intensity and circulation structure.

We analyzed several additional tropical cyclones; however, to illustrate a case in which assimilation of GPM DPR observations produced only limited changes in most geophysical variables, with the exception of rainwater content, we present the results for Cyclone Midhili. Cyclone Midhili formed over the Bay of Bengal in November 2023 and produced heavy rainfall and significant impacts across Bangladesh.

Figure 11 shows the impact of DPR assimilation on liquid and frozen hydrometeor water contents for Cyclone Midhili. The ERA5 analysis shows a well-defined precipitation core approaching the coastal areas on 15 November 2023, with rainwater content integrated between 1000–850 hPa exceeding 200 g.m^{-2} . A region of relatively low to no rainwater content is evident behind the cyclone core and is surrounded by a relatively organized rainband. This structure is broadly consistent with the precipitation pattern indicated by IMERG in Figure 8. In contrast, the GEOS control experiment produces a much smaller precipitation core and does not clearly reproduce the region of reduced rainwater content behind the storm core. Assimilation

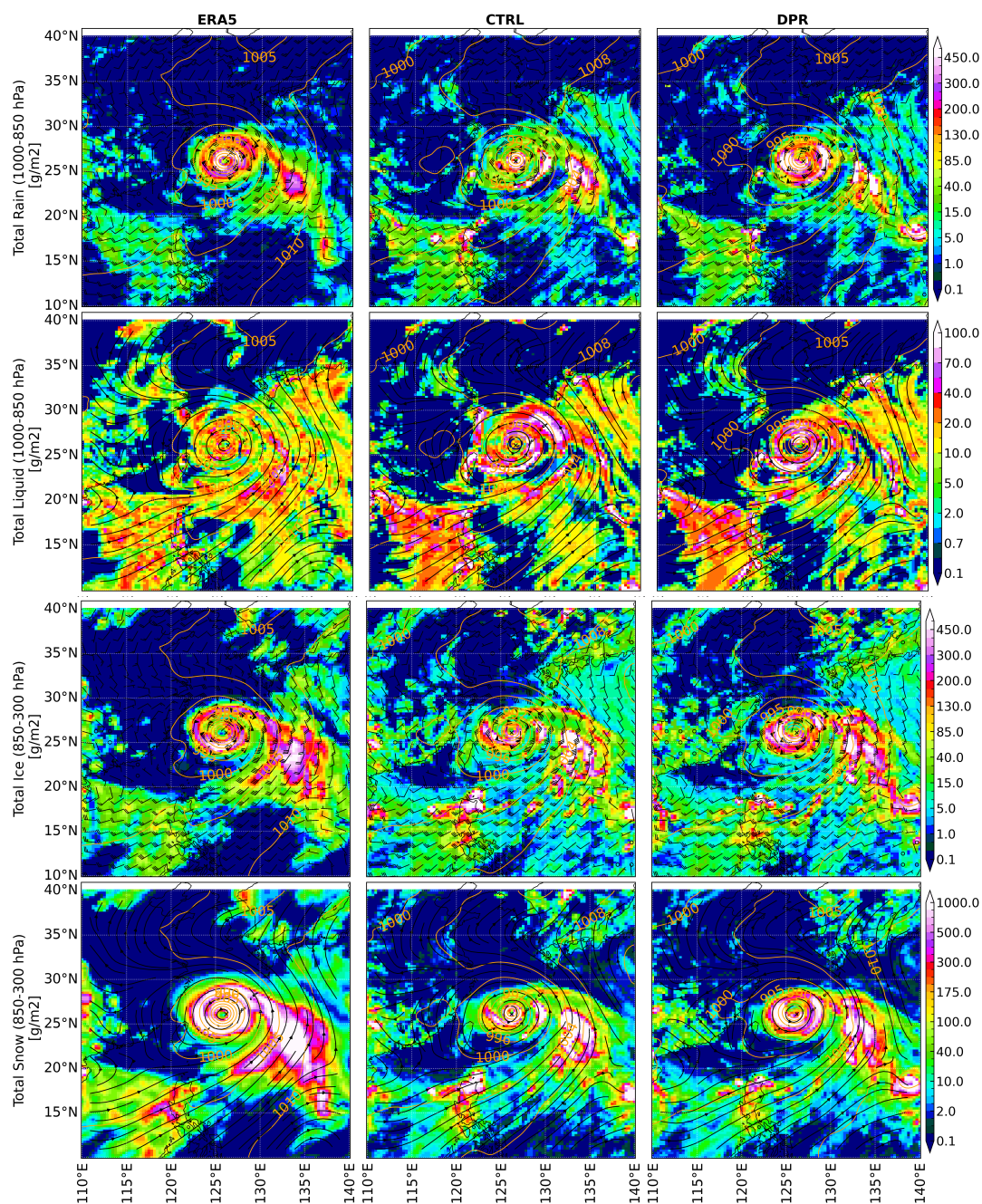


Figure 9. Comparison of GEOS analyses with assimilated GPM DPR observations (DPR), the GEOS-JEDI control analysis (CTRL), and the ERA5 reanalysis for Typhoon Khanun at 0900 UTC on 2 August 2023. In each panel group, the right column shows the GEOS analysis with assimilated GPM DPR observations (DPR), the middle column shows the GEOS-JEDI control experiment (CTRL), and the left column shows the ERA5 reanalysis (ERA5). The fields include from top to bottom, rain water content, liquid water content, snow water content, and ice water content. Mean sea level pressure and 850-hPa wind speed and direction are shown in all panels.

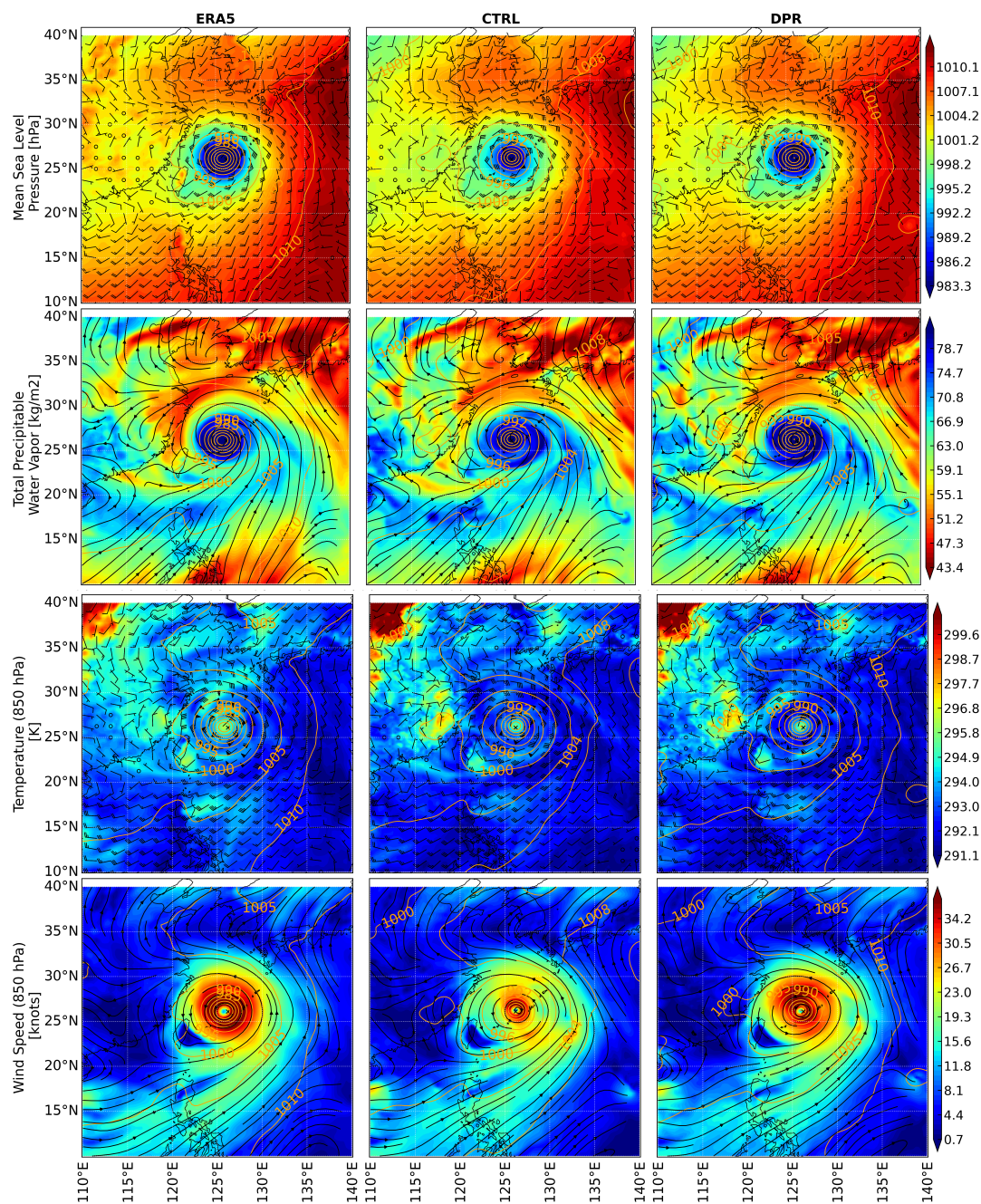


Figure 10. Same as Figure 9, but the fields from top to bottom include: mean sea level pressure, total precipitable water vapor, temperature at 850 hPa, and wind speed at 850 hPa. The mean sea level pressure is also shown in orange contour in all panels. The top two rows show surface wind speed and direction overlaid on the plots, and the bottom two rows show overlaid 850-hPa wind speed and direction.



of DPR observations brings the GEOS analysis into closer agreement with both ERA5 and IMERG. The precipitation core becomes substantially larger, and the region of low rainwater content surrounded by rainbands is more clearly represented.

375 For cloud liquid water content and ice water content, both the control and DPR assimilation experiments are generally consistent with the ERA5 analysis, but the core region with high water content is smaller in both experiments compared with the core in ERA5. In contrast, the snow water content field, which indicates a spatial pattern similar to that of rainwater content, differs more substantially from ERA5 in both experiments. Nevertheless, the experiment with assimilated DPR observations shows improved agreement with the ERA5 analysis relative to the control experiment.

380 Figure 12 shows the mean sea level pressure, total precipitable water content, as well as 850 hPa temperature and wind speed and direction for Cyclone Midhili. The 850-hPa temperature fields over the ocean are similar in both the control and DPR assimilation experiments and are generally consistent with the ERA5 analysis. Over land, however, both GEOS experiments show lower temperatures than ERA5. In terms of total precipitable water vapor, both experiments show good agreement with ERA5. For mean sea level pressure, although differences in the spatial structure are evident between the GEOS simulations
385 and ERA5, the pressure magnitudes are generally comparable. Assimilation of DPR observations has little impact on the mean sea level pressure field. Similarly, the 850-hPa wind field and surface winds are broadly consistent between the GEOS analyses and ERA5, with only minor differences resulting from the assimilation of DPR observations.

8 Impact on Forecast

In the current GEOS modeling system, cloud and precipitation fields are diagnostic variables that are derived from the model
390 state rather than prognostic variables that are directly evolved by the forecast model. Consequently, forecast improvements can only be realized through modifications to the variables used to initialize the model, such as temperature, water vapor, winds, and pressure. Because assimilation of GPM DPR observations primarily improves the representation of cloud and precipitation fields, substantial improvements in forecast skill are not necessarily expected within the current modeling framework.

Efforts are currently underway to enhance the GEOS microphysics representation. These developments are expected to
395 enable more effective utilization of information contained in cloud and precipitation fields, therefore increasing the forecast impact of radar observations as well as all-sky microwave radiances, both of which provide valuable constraints on hydrometeor distributions.

To illustrate how the limited information content transferred to the model initial conditions can nevertheless influence forecasts, we present an example for Typhoon Khanun in Figure 13. As discussed in Figure 10, assimilation of DPR observations
400 improved not only the representation of rainwater content but also the analyzed wind, pressure, and temperature fields. Although differences in forecast rainwater and cloud liquid water content between the control and DPR assimilation experiments are relatively modest, the forecast cyclone position in the DPR experiment is more consistent with the corresponding location in both ERA5 and the tropical cyclone best track data. This result suggests that even relatively small improvements in the analyzed state variables used to initialize the forecast may lead to noticeable improvements in the predicted evolution and track
405 of tropical cyclones.

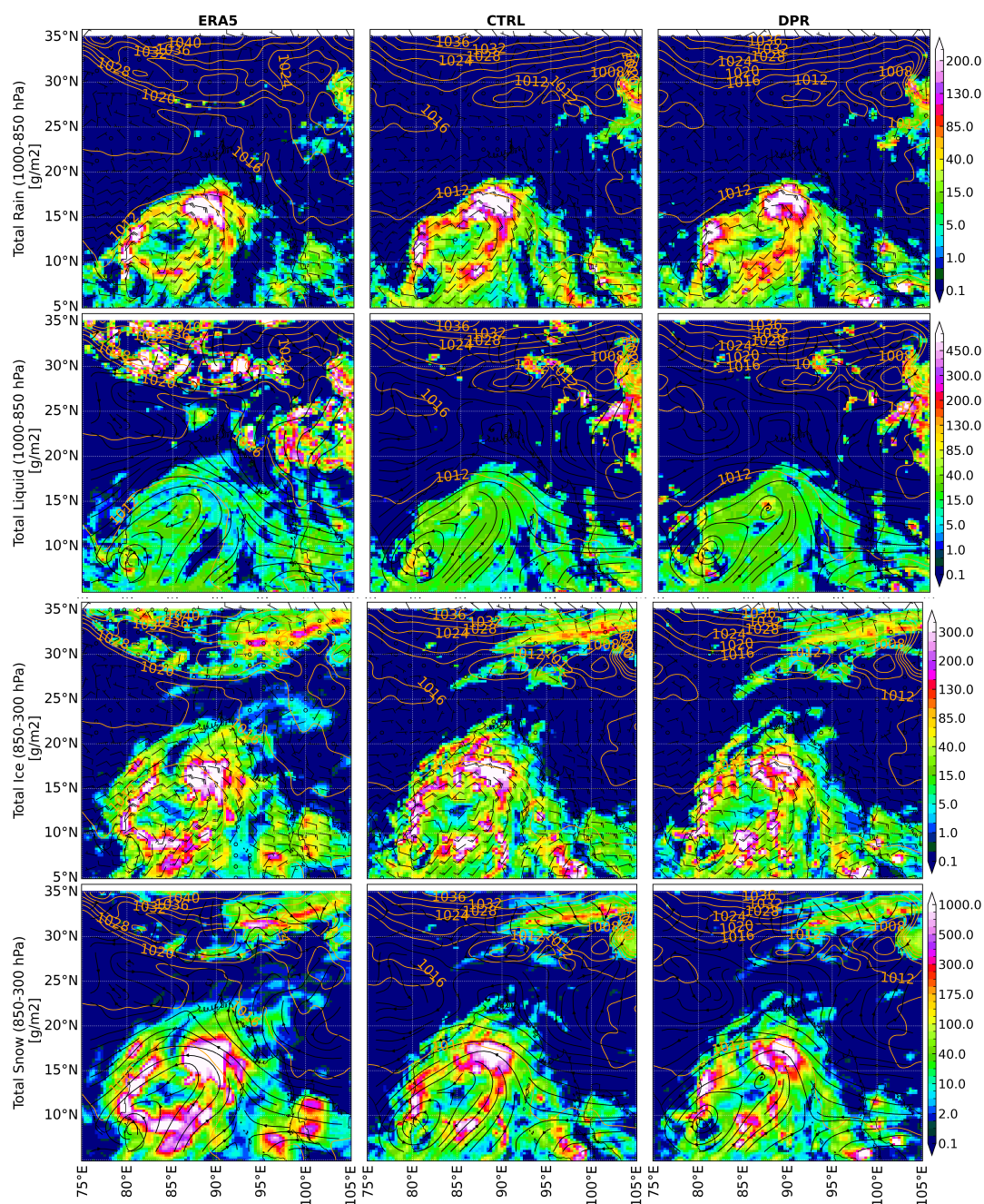


Figure 11. Same as Figure 9, but for Cyclone Midhili at 0000 UTC on 15 November 2023.

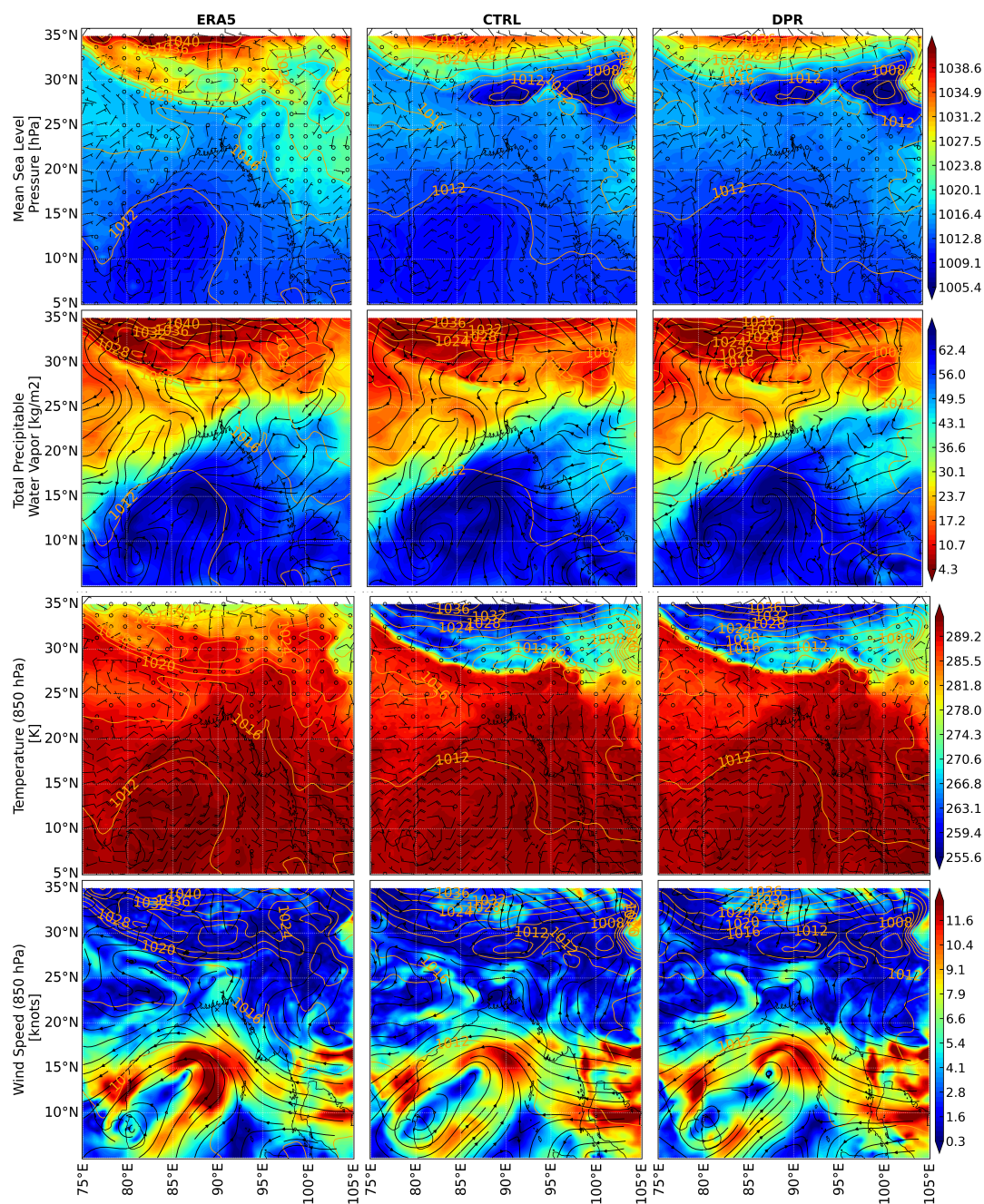


Figure 12. Same as Figure 10, but for Cyclone Midhili at 0000 UTC on 15 November 2023.

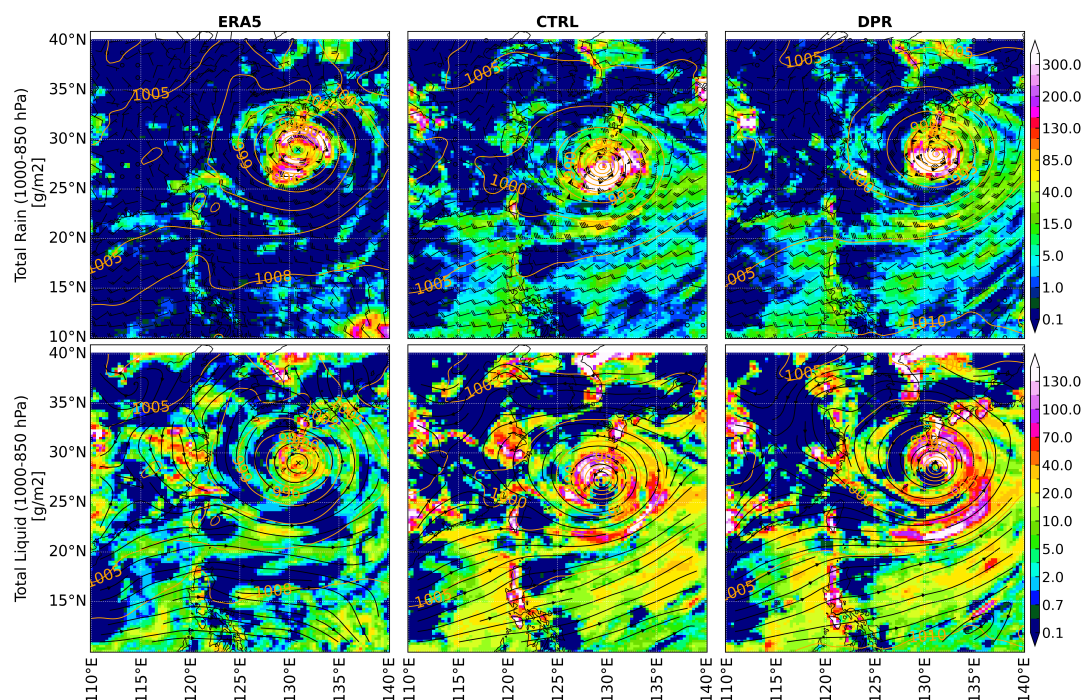


Figure 13. Example GEOS forecast initialized at 2100 UTC 2 August 2023 and valid at 0000 UTC 8 August 2023, showing cloud liquid water content and rainwater content.

9 Conclusions

This study presents a new capability for assimilating spaceborne radar observations within the JEDI data assimilation system. The developed components include the radar forward operator and the associated data assimilation infrastructure required to incorporate observations from the Global Precipitation Measurement (GPM) Dual-frequency Precipitation Radar (DPR). The capability demonstrates benefits when implemented within the GEOS numerical weather prediction system. Although currently a research prototype and not yet implemented in GMAO operational products, this development provides the infrastructure needed to evaluate the impact of assimilating new spaceborne active radar observations not currently used in the GSI-based GEOS system.

Evaluation of the DPR JEDI forward simulations indicates that GEOS backgrounds generally reproduces the observed reflectivity structure, with mean differences between observed and simulated values typically within about 2 dB. The analysis further shows that a large number of DPR observations can be assimilated with this development addressing many of the challenges associated with radar data assimilation, which requires realistic model simulations of hydrometeors that match observations in both three-dimensional space and time.

Assimilation experiments for several tropical cyclones show that DPR observations improve the analyzed distribution of rain water content and, in some cases, frozen hydrometeors. The resulting analyses generally show better agreement with indepen-



dent references, including IMERG precipitation estimates and ERA5 reanalysis fields. Improvements are most evident in the structure and spatial organization of precipitation systems, particularly within tropical cyclone cores and associated rainbands. The impact on thermodynamic and dynamic state variables used to initialize forecasts, such as temperature, moisture, pressure, and wind, is generally smaller than the impact on hydrometeor fields. Nevertheless, the results indicate that assimilation of
425 DPR observations can produce meaningful adjustments to the analyzed atmospheric state and, in some cases, lead to improved forecasts of tropical cyclone position and structure.

The capability presented in this study establishes a foundation for the routine assimilation of spaceborne radar observations within JEDI and GEOS. Although demonstrated using GEOS–JEDI and GPM DPR, the framework is readily extensible to other forecast models and spaceborne radar instruments, including the Precipitation Radar (PR) aboard TRMM, the Cloud
430 Profiling Radar (CPR) aboard CloudSat and EarthCARE, and future missions such as the radar instrument planned for NASA’s Fleet for the Atmosphere Linking Commercial Observations with NASA (FALCON).

Beyond improving analyses and forecasts, this capability provides a new tool for evaluating the representation of clouds and precipitation in forecast models, helping to identify systematic biases in hydrometeor fields and guide model development. It also enables future studies to investigate the use of spaceborne radar data assimilation in global reanalysis systems, including
435 the potential for producing next-generation IMERG-like precipitation products.

Future work will focus on refining observation error specifications, evaluating forecast impacts over longer periods and a wider range of weather systems, and extending the capability to additional spaceborne radar observations. Continued improvements in model microphysics and data assimilation methods is also expected to further enhance the use of cloud- and precipitation-sensitive observations, including spaceborne radars and all-sky microwave radiances, in future numerical weather
440 prediction systems.

Code and data availability. The GEOS Earth System Model source code is publicly available at <https://zenodo.org/doi/10.5281/zenodo.10927491> (Colarco, 2024). The JEDI data assimilation framework, including the OOPS, UFO, SABER, and related components used in this study are available at <https://zenodo.org/records/15501412> (Joint Center for Satellite Data Assimilation, 2020). The GEOS–JEDI configuration and experiment scripts used in this study are available from the corresponding author upon reasonable request.

445 The Global Precipitation Measurement (GPM) Dual-frequency Precipitation Radar (DPR) observations used in this work are publicly available from the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) at <https://gpm.nasa.gov/data/directory/2a-dpr-ges-disc>.

Author contributions. IM led the study, developed the radar observation operator within CRTM, contributed to spaceborne radar data assimilation capability within UFO, designed and performed the experiments, analyzed the results, and wrote the manuscript. RT contributed to the
450 design and implementation of GEOS–JEDI, JEDI development, provided guidance on the data assimilation methodology, and contributed to writing and reviewing the manuscript. YZ contributed to the GEOS model configuration, experiment design, UFO development, observation preparation for JEDI, and manuscript review. BR, BJ, and YT contributed to the development of the JEDI software infrastructure, includ-



ing the integration of CRTM, provided technical support for its implementation in GEOS, and reviewed the manuscript. DA contributed to the development of SWELL and reviewed the manuscript. WG contributed to the GEOS–JEDI development through observation preparation, observation configuration, and testing of the GEOS–JEDI framework at GMAO. SP provided scientific leadership and oversight of the GEOS–JEDI implementation at GMAO and reviewed the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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