

REVIEW ARTICLE

Comparative Analysis of Modern Reanalysis Products for Climate and Weather Studies: Global and Indian Perspectives

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Abstract. Reanalysis datasets are essential to modern climate and weather research, providing spatially and temporally consistent reconstructions of atmospheric, land, and ocean conditions. They are produced by assimilating historical observations into numerical weather prediction models using fixed physical parameterizations and data assimilation schemes, creating long-term homogeneous datasets crucial for climate diagnostics, extreme event analysis, and impact assessments. Advances in computing power, satellite observations, and assimilation techniques have enabled the development of high-resolution global and regional reanalysis products. This review presents a comparative evaluation of major global reanalysis datasets, including ERA5, MERRA-2, JRA-55, and NCEP/NCAR, alongside Indian climate datasets such as India Meteorological Department (IMD) gridded observations and regional reanalysis efforts by the Indian Institute of Tropical Meteorology (IITM) and the Ministry of Earth Sciences (MoES). Key features—including spatial and temporal resolution, assimilation frameworks, variable availability, strengths, and limitations—are assessed with emphasis on applications over the Indian subcontinent. The analysis shows that global reanalysis products provide dynamically consistent multi-variable datasets suitable for large-scale circulation studies, climate variability assessment, and boundary condition generation. However, their representation of regional processes, particularly the Indian Summer Monsoon, localized extreme rainfall, and temperature extremes, remains limited. In contrast, Indian gridded and regional datasets better capture monsoon rainfall patterns, surface temperature variability, and extreme events due to dense observational networks and regionally optimized methods. The review highlights the need for careful dataset selection based on research objectives and advocates integrated global–regional reanalysis frameworks to improve weather forecasting, climate resilience planning, and climate change impact assessments in India.

Keywords: Reanalysis data, climate studies, weather analysis, ERA5, MERRA-2, IMD Gridded data, Indian monsoon

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1. Introduction

Reanalysis products have become indispensable tools in modern climate and atmospheric research due to their ability to provide spatially and temporally continuous reconstructions of the Earth system over extended historical periods. By assimilating diverse observational datasets—such as surface station records, radiosondes, satellite measurements, aircraft observations, and oceanic data—into numerical weather prediction (NWP) models using fixed data assimilation frameworks, reanalysis datasets offer physically consistent and homogeneous representations of atmospheric, land, and oceanic variables [1,2]. These attributes make reanalysis products particularly valuable for long-term climate diagnostics, trend detection, variability assessment, and evaluation of extreme weather events.

Over the past few decades, several international meteorological agencies have developed successive generations of global reanalysis systems with substantial improvements in spatial resolution, temporal frequency, data assimilation techniques, and uncertainty quantification. Prominent examples include ERA5 developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), MERRA-2 from the National Aeronautics and Space Administration (NASA), JRA-55 produced by the Japan Meteorological Agency (JMA), and the NCEP/NCAR reanalysis jointly developed by the National Centers for Environmental Prediction and the National Center for Atmospheric Research [3–6]. These global datasets have been widely applied in studies of large-scale atmospheric circulation, climate variability, land–atmosphere interactions, and global energy and water cycles.

Despite their widespread utility, global reanalysis products often face limitations in representing regional climatic features, particularly over monsoon-dominated and topographically complex regions such as the Indian subcontinent. The Indian Summer Monsoon system is

characterized by strong land–ocean thermal contrasts, mesoscale convective processes, and sharp spatial gradients in rainfall and temperature, which are not always adequately captured by coarse-resolution global models or sparse observational inputs [7,8]. These deficiencies can lead to biases in precipitation, temperature extremes, and surface fluxes, limiting the applicability of global reanalysis datasets for regional climate impact studies and operational decision-making in India.

To overcome these limitations, India has developed high-resolution gridded observational datasets and regionally optimized reanalysis initiatives through national agencies such as the India Meteorological Department (IMD), the Indian Institute of Tropical Meteorology (IITM), the Ministry of Earth Sciences (MoES), and the Indian Space Research Organisation (ISRO). IMD gridded datasets, derived from dense station networks, provide reliable representations of rainfall and temperature variability, while regional reanalysis efforts aim to better capture monsoon dynamics and extreme weather events [9–11].

In this context, the present review systematically compares widely used international reanalysis products with Indian-standard datasets, focusing on their data characteristics, strengths, limitations, and suitability for climate and weather-related studies over India. The review emphasizes the importance of dataset selection based on research objectives and advocates for integrated global–regional reanalysis approaches to enhance climate resilience, weather forecasting, and climate change impact assessments.

2. Concept of Reanalysis Data

Reanalysis data represent a systematic reconstruction of historical atmospheric, land, and oceanic states through the retrospective assimilation of past observations into a fixed numerical weather prediction (NWP) model coupled with a consistent data assimilation framework [13,14]. Unlike operational forecasting systems, which undergo frequent upgrades in

model physics and assimilation techniques, reanalysis employs an unchanged modeling configuration throughout the assimilation period, thereby ensuring temporal homogeneity and long-term consistency in the generated datasets [15].

A wide range of observational inputs—including satellite radiances, radiosonde measurements, surface meteorological observations, marine data from ships and buoys, and aircraft-based observations—are integrated within the reanalysis framework to produce spatially continuous and physically coherent representations of key climate variables [16]. This comprehensive assimilation approach enables the reconstruction of past weather and climate conditions even in data-sparse regions, making reanalysis products indispensable for climate diagnostics and historical analysis [17].

Due to their global coverage, multi-variable availability, and extended temporal span, reanalysis datasets are extensively used in climate variability studies, extreme weather assessment, hydrological modeling, and climate change impact analysis [18]. However, reanalysis products are not free from uncertainties. Errors may arise from observational gaps, inhomogeneities in historical data records, model parameterization biases, and assumptions inherent in the data assimilation process [19]. These limitations necessitate careful evaluation and validation, particularly when reanalysis datasets are applied to regional-scale studies or used to assess long-term climate trends, especially over complex climatic regions such as the Indian monsoon domain [20].

3. Global Reanalysis Products

Global reanalysis products developed by leading meteorological agencies form the backbone of contemporary climate and weather research. These datasets integrate multi-source observations using advanced numerical weather prediction (NWP) models and data assimilation schemes, offering spatially and temporally consistent representations of the Earth system. Among the most widely used international

reanalysis products are ERA5, MERRA-2, JRA-55, and NCEP/NCAR, each designed with specific strengths, applications, and limitations.

3.1. ERA5 (ECMWF)

ERA5, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), represents the fifth-generation global atmospheric reanalysis and the successor to ERA-Interim. It provides hourly estimates of atmospheric, land, and ocean variables at a horizontal resolution of approximately 31 km, with 137 vertical levels extending from the surface to the stratosphere [21]. The use of advanced four-dimensional variational (4D-Var) data assimilation and improved model physics enables ERA5 to capture fine-scale atmospheric processes more accurately than previous reanalyses [22].

ERA5 has demonstrated superior performance in representing temperature extremes, heatwaves, surface fluxes, and large-scale circulation patterns, making it particularly valuable for climate trend analysis, urban heat stress assessment, and hydrological modeling [23]. However, studies have reported that ERA5 may underestimate localized and convective precipitation, especially over monsoon-dominated regions such as the Indian subcontinent, where complex land–atmosphere interactions and orographic effects play a significant role [24]. Additionally, the high spatial and temporal resolution increases computational demands for large-domain or long-term analyses.

Strengths:

- High spatial (~31 km) and hourly temporal resolution
- Advanced 4D-Var data assimilation system
- Improved representation of temperature extremes and surface processes

Limitations:

- Underestimation of localized and convective rainfall in monsoon regions
- High computational and storage requirements

3.2. MERRA-2 (NASA)

The Modern-Era Retrospective Analysis for Research and Applications Version 2 (MERRA-2), developed by NASA's Global Modeling and Assimilation Office (GMAO), is specifically designed to improve the representation of atmospheric composition, aerosols, and radiation processes [16]. MERRA-2 assimilates satellite-based aerosol optical depth (AOD) observations, enabling explicit treatment of aerosol–radiation and aerosol–cloud interactions.

This reanalysis product is extensively used in air quality assessment, climate forcing analysis, and energy budget studies, particularly for understanding the role of aerosols in regional and global climate variability [25]. While MERRA-2 performs well in representing radiative fluxes and atmospheric composition, its relatively coarser spatial resolution (~50 km) limits its ability to capture fine-scale meteorological features and localized precipitation extremes, especially over heterogeneous terrains [26].

Strengths:

- Explicit aerosol and atmospheric composition assimilation
- Strong performance in radiation and energy balance studies

Limitations:

- Coarser spatial resolution than ERA5
- Reduced accuracy in regional precipitation patterns

3.3. JRA-55 (JMA)

JRA-55, produced by the Japan Meteorological Agency (JMA), is a long-term global reanalysis spanning from 1958 to the present, making it particularly suitable for multi-decadal climate variability and circulation studies [27]. It employs a consistent data assimilation framework and incorporates modern satellite observations across the entire period through reprocessing techniques.

JRA-55 is widely used for analyzing large-scale atmospheric circulation, teleconnection patterns, and long-term climate trends. However,

its relatively lower spatial resolution and simplified land-surface representation can result in reduced accuracy of surface variables over complex terrains, including mountainous and coastal regions [28].

Strengths:

- Long and temporally consistent climate record
- Reliable representation of large-scale circulation patterns

Limitations:

- Lower spatial resolution
- Limited accuracy of surface parameters over complex topography

3.4. NCEP/NCAR Reanalysis

The NCEP/NCAR Reanalysis, developed jointly by the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR), was one of the earliest global reanalysis products and remains widely used due to its extensive temporal coverage beginning in 1948 [13]. Despite advances in newer reanalyses, NCEP/NCAR continues to support long-term climate diagnostics and historical trend analysis.

However, its coarse spatial resolution and outdated model physics introduce well-documented biases in temperature, precipitation, and surface energy fluxes, limiting its suitability for high-resolution or regional-scale studies [29].

Strengths:

- Very long historical data record
- Low computational cost and ease of access

Limitations:

- Coarse spatial resolution
- Known biases in temperature and precipitation estimates

4. Indian Reanalysis and Gridded Climate Datasets

Recognizing the limitations of global reanalysis products in representing regional climatic features, especially over the Indian monsoon domain, national agencies such as the India Meteorological Department (IMD), Indian Institute of Tropical Meteorology (IITM), and the

Ministry of Earth Sciences (MoES) have developed high-resolution gridded observational datasets and initiated regional reanalysis efforts. These datasets are specifically designed to capture India's complex climatic characteristics, including monsoon variability, extreme rainfall events, heatwaves, and cyclones.

4.1. IMD Gridded Observational Datasets

IMD has developed several high-resolution gridded datasets for key meteorological variables, including rainfall, temperature, and humidity, based on dense networks of surface observations across India. The most widely used datasets include daily rainfall at 0.25° and 0.5° resolution and daily maximum and minimum temperature at 1° resolution [30].

IMD gridded rainfall datasets have become the national benchmark for monsoon studies, hydrological modeling, drought assessment, and extreme rainfall analysis due to their superior representation of spatial rainfall variability over the Indian subcontinent [31]. These datasets are particularly effective in capturing localized heavy rainfall events associated with the southwest monsoon, which are often underestimated in global reanalysis products.

However, IMD datasets are purely observation-based and lack dynamical consistency across atmospheric variables. As a result, they are less suitable for studies requiring vertically resolved atmospheric fields or energy budget analysis [32].

Strengths:

- High relevance for Indian monsoon and extreme rainfall studies
- Dense observational input and national-scale consistency
- Widely accepted for operational and research applications in India

Limitations:

- Limited number of variables compared to reanalysis products
- Absence of full atmospheric state representation

4.2. IITM–MoES Regional Reanalysis Initiatives

To bridge the gap between global reanalysis and local observations, IITM under MoES has initiated regional reanalysis and high-resolution modeling efforts using advanced mesoscale models such as WRF. These initiatives aim to dynamically downscale global reanalysis products while assimilating Indian observations to improve representation of regional processes [33].

Regional reanalysis products developed under MoES programs have demonstrated improved skill in simulating monsoon circulation, low-level jets, land–atmosphere interactions, and extreme precipitation events over India [34]. By operating at higher spatial resolutions (typically 9– 25 km), these datasets better capture orographic rainfall along the Western Ghats, heat stress over urban regions, and coastal weather systems.

Despite their advantages, regional reanalysis datasets are computationally expensive and often limited in temporal coverage compared to global reanalysis products. Long-term consistency and public accessibility also remain ongoing challenges [35].

Strengths:

- Enhanced representation of monsoon dynamics and regional extremes
- High spatial resolution suitable for impact and urban studies
- Improved land–atmosphere coupling

Limitations:

- Shorter temporal records
- High computational and storage requirements

4.3. ISRO Satellite-Derived Climate Products

ISRO contributes significantly to India's climate data ecosystem through satellite-derived datasets such as land surface temperature (LST), soil moisture, vegetation indices, and radiation products from missions like INSAT, Megha-Tropiques, and Resourcesat [36]. These datasets complement IMD observations and reanalysis products by providing high-resolution spatial information, particularly over data-sparse regions.

Satellite products are extensively used in urban heat island studies, drought monitoring, and land–climate interaction analysis. However, uncertainties related to cloud contamination, retrieval algorithms, and temporal discontinuities limit their standalone use for long-term climate diagnostics [37].

5. Comparative Evaluation of Global and Indian Reanalysis Datasets

A systematic comparison of international reanalysis products and Indian-standard datasets is essential to understand their suitability for climate and weather research over the Indian subcontinent. While global reanalysis products provide dynamically consistent, multi-variable datasets, Indian datasets emphasize regional realism and observational density, particularly for monsoon-driven processes.

5.1. Spatial and Temporal Resolution

Global reanalysis products such as ERA5 and MERRA-2 offer continuous global coverage with relatively high temporal resolution (hourly to sub-daily), making them suitable for synoptic-scale and long-term climate studies [21,22]. However, their spatial resolution, though improved in recent versions, often remains insufficient to capture localized extremes and complex topographic influences over India.

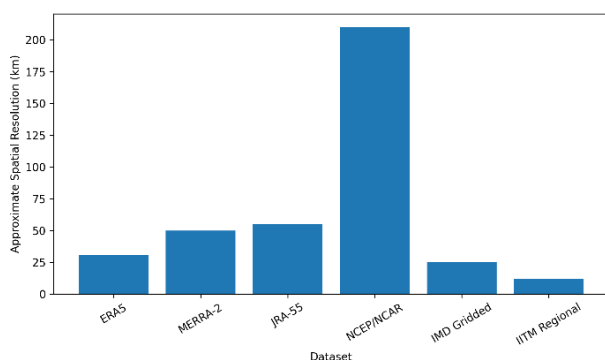


Figure 1. Spatial Resolution of Climate Reanalysis Products.

In contrast, IMD gridded datasets provide finer spatial resolution for surface variables, especially rainfall, enabling better representation of mesoscale variability and extreme precipitation

events [30,31]. Regional reanalysis initiatives by IITM–MoES further enhance spatial detail by dynamically downscaling global datasets, improving simulation of monsoon circulation and land–atmosphere feedbacks [33]. The differences in spatial resolution among global reanalysis products and Indian climate datasets are illustrated in **Figure 1**, highlighting the finer spatial detail offered by IMD gridded observations and IITM–MoES regional reanalysis compared to global products.

5.2. Representation of Monsoon and Extreme Events

The Indian summer monsoon is a highly nonlinear system influenced by orography, land–sea contrast, and intraseasonal oscillations. Studies have shown that global reanalysis products tend to underestimate monsoon rainfall intensity and spatial heterogeneity, particularly along the Western Ghats and northeastern India [38].

IMD observational datasets and IITM regional reanalysis products demonstrate superior skill in capturing monsoon onset, active–break cycles, and extreme rainfall events [39]. This makes Indian datasets more suitable for impact-based studies such as flood modeling, drought assessment, and agricultural applications.

5.3. Variable Availability and Physical Consistency

Global reanalysis products provide a comprehensive suite of atmospheric, land surface, and radiation variables with vertical profiles, enabling studies on energy balance, circulation dynamics, and climate feedbacks [17]. Indian gridded datasets, while highly accurate for surface variables, are limited in scope and lack full atmospheric state representation. Regional reanalysis products partially address this limitation by offering dynamically consistent atmospheric fields at higher resolution, though their temporal extent is often shorter than global reanalysis datasets [35]. A summary of the differences in variable availability, physical consistency, spatial resolution, and applicability across global and

Indian datasets is presented in Table. 1, which highlights the complementary strengths of each dataset category and reinforces the need for integrated global-regional analysis frameworks for climate and weather research over India.

5.4. Dataset Selection Considerations

The comparative evaluation highlights that no single dataset is universally optimal. Global reanalysis products are well suited for large-scale circulation studies, climate trend analysis, and energy balance research, whereas Indian datasets are more reliable for regional impact studies and operational applications. An integrated global–regional framework, combining the strengths of both datasets, is therefore recommended for climate resilience planning and weather risk assessment in India [40].

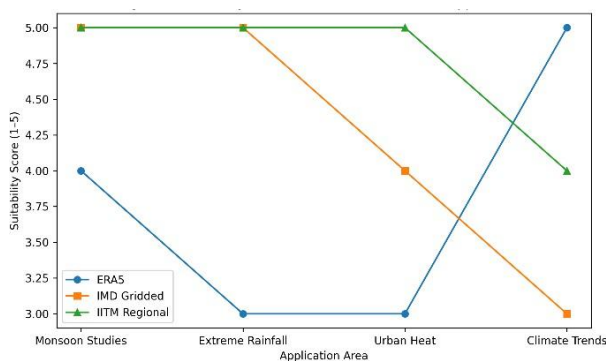


Figure 2. Suitability of Climate datasets for Indian applications.

The suitability scores shown in Figure 2 were derived from a qualitative expert assessment based on spatial resolution, representation of extremes, regional validation, and documented application in peer-reviewed studies. The scores are intended as comparative indicators rather than absolute performance metrics.

5.5. Integrated use of Global and Indian Reanalysis Datasets

An integrated approach combining global reanalysis products with Indian-standard datasets offers a robust framework for climate and weather studies over the Indian subcontinent. While global reanalysis products such as ERA5 and MERRA-2

provide dynamically consistent, multi-variable fields with long temporal coverage, Indian datasets deliver higher spatial fidelity and improved representation of regional climatic features, particularly the Indian Summer Monsoon and extreme precipitation events. The complementary strengths of these datasets enable more accurate assessments of climate variability, extremes, and impact-based applications. Strategic dataset selection or hybrid usage—depending on spatial scale, temporal resolution, and research objectives—can substantially enhance the reliability of climate diagnostics and model validation exercises over India.

6. Conclusions and Future Research Directions

This study presents a systematic comparative assessment of major international reanalysis products and Indian-standard climate datasets, highlighting their respective strengths, limitations, and applicability for climate and weather research. International reanalysis products demonstrate superior temporal consistency, global coverage, and multi-variable integration, making them well suited for large-scale climate trend analysis and atmospheric circulation studies. However, their limitations in resolving regional-scale processes—particularly over monsoon-dominated and topographically complex regions—remain evident.

Indian datasets, developed using dense observational networks and region-specific methodologies, show enhanced performance in capturing localized rainfall patterns, temperature extremes, and land–atmosphere interactions. The analysis underscores that no single dataset is universally optimal; rather, the effectiveness of a dataset depends strongly on the research objective, spatial scale, and climatic variable of interest. The integrated use of global reanalysis and Indian datasets emerges as the most scientifically robust approach for advancing climate diagnostics, impact studies, and policy-relevant assessments over India.

Future research directions are summarized as follows.

- Development of hybrid global–regional reanalysis frameworks that assimilate high-density Indian observational networks into global modeling systems to enhance regional climate representation.
- Implementation of advanced bias-correction and downscaling techniques, including machine learning and artificial intelligence approaches, to improve the reliability of reanalysis products for local-scale applications.
- Comprehensive uncertainty quantification across multiple reanalysis datasets, with particular emphasis on extreme precipitation, heatwaves, droughts, and compound climate events.
- Expansion of reanalysis evaluation to urban and coastal climate processes, including urban heat island effects, coastal heat stress, and land–sea interaction dynamics.
- Integration of reanalysis data with hydrological, agricultural, and disaster impact models to support sector-specific climate risk assessments and decision-making.
- Long-term assessment of climate change signals and trend consistency across global and Indian datasets to improve confidence in detection and attribution studies.
- Enhancement of land–atmosphere–hydrology coupling in regional reanalysis systems to better capture feedback mechanisms influencing monsoon variability.
- Strengthening open-access data infrastructure, interoperability, and standardization between international and Indian climate data repositories to promote reproducibility and collaborative research.

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Table 1. Comparative Characteristics of Reanalysis and Indian Climate Datasets

Dataset	Spatial Resolution	Temporal Coverage	Key Strengths	Major Limitations
ERA5 (ECMWF)	~31 km	1940–present	High resolution, extreme event analysis	Underestimates local monsoon rainfall
MERRA-2 (NASA)	~50 km	1980–present	Aerosol & radiation processes	Coarser precipitation representation
JRA-55 (JMA)	~55 km	1958–present	Long-term climate consistency	Lower surface accuracy
NCEP/NCAR	~210 km	1948–present	Long historical record	Strong biases, coarse resolution
IMD Gridded Rainfall	0.25°	1901–present	Best monsoon rainfall realism	Limited variables
IITM–MoES Regional Reanalysis	9–25 km	Limited periods	High regional accuracy	Short temporal coverage

Table 2. Comparative Evaluation

Parameter	Global Reanalysis (ERA5, MERRA-2)	Indian Datasets (IMD, IITM)
Spatial Resolution	Moderate to High	High (India-focused)
Temporal Coverage	Long-term (1950s–present)	Moderate
Monsoon Representation	Moderate	Excellent
Variable Diversity	Very High	Limited
Suitability for Local Studies	Moderate	High