BAMS Meeting Summary

Toward Future Reanalyses That Meet Evolving Needs in Science, Public Services, Policymaking, and Socioeconomic Activity

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The Sixth WCRP International Conference on Reanalysis (ICR6)

***What*:** Reanalysis producers, observation data providers, numerical modelers, and members of the user community came together to discuss progress, challenges, and future priorities with the aim of guiding the development and use of reanalysis data in science, public services, policymaking, and social/economic activity.

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***Where*:** Tokyo, Japan

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1. Background

Reanalysis goes back to the dawn of modern operational numerical weather prediction (NWP). Relying on using a consistent data assimilation system for an extended period back in time at reduced resolution to manage cost, reanalysis integrates historical observations into physically consistent gapless fields and, in the case of an atmospheric reanalysis, provides a comprehensive picture of the historical global atmospheric circulation. There have been continued efforts to improve data quality and to include not only the atmosphere but also other Earth system components (e.g., land, ocean, and cryosphere). Demands for higher resolution and quality have become a driving force of regional reanalysis. The increasing usage across successive Intergovernmental Panel on Climate Change (IPCC) assessment cycles attests to the improvement in the quality and comprehensiveness of reanalysis. Reanalysis data have enabled significant contributions not only to research on the climate system concerning its variability and predictability but also to operational services such as the Copernicus Climate Change Service (C3S) and the Copernicus Marine Service (CMEMS), offering great potential for applications in socioeconomic activity. Reanalyses' recent usage as training datasets for machine learning (ML) activities may revolutionize the provision of weather forecasts and how weather/ocean forecasts benefit from reanalysis.

The Sixth World Climate Research Program (WCRP) International Conference on Reanalysis (ICR6) took place in Tokyo from 28 October to 1 November 2024 and brought together reanalysis producers, observation data providers, numerical modelers, and members of the user community to discuss progress, applications, challenges, and future priorities in the field. The ultimate aim was to guide the development and use of reanalysis data in science, public services, policymaking, and socioeconomic activity.

2. ICR6 structure

ICR6 attracted 194 participants from 27 countries and regions. The first 4 days of the conference program included 62 oral presentations and six poster sessions, where a total of 83 posters were presented. Oral and poster presentations were organized around the following seven topics:

- global reanalysis production status/plans
- regional reanalysis production status/plans
- observations for reanalyses
- methods for reanalyses
- evaluations of reanalyses
- applications of reanalyses in science and society
- exploration of ML approaches in the context of reanalysis

The recordings of presentations from speakers who have agreed to share them publicly are available online (https://www.youtube.com/@ICR6-WCRP).

Rapporteurs of the seven topics collaborated with session chairs in summarizing the findings and recommendations to report back to the wrap-up session on the final day. It was followed by a panel discussion, which focused on the theme of "toward future reanalyses that meet evolving needs in science, public services, policy making and social/economic activity." The purpose of the panel discussion was to review the successes and limitations of current reanalyses and discuss priorities for future reanalyses, considering prospective changing user needs and technological advances.

The following sections summarize the findings and recommendations presented in the wrap-up session and the panel discussion.

3. ICR6 findings

a. Global reanalysis production status/plans. There have been continued efforts to produce new generations of global reanalyses at various institutes worldwide for atmosphere, ocean, ocean biology, land, atmospheric composition, ocean waves, and ice and progressively integrate into coupled Earth system reanalyses.

Enormous progress has been made. As an example, the Fourth Assessment Report (AR4) of the IPCC Working Group I advised caution with the use of reanalysis for understanding climatic trends and low-frequency variations (Trenberth et al. 2007), while the latest AR6 states much increased confidence, increasingly using reanalyses as the sole or one of the primary lines of evidence in its assessments (e.g., precipitation minus evaporation, zonal-mean circulation, and upper-air temperatures) (Chen et al. 2021; Gulev et al. 2021). The representation of tropical cyclones has been significantly improved, e.g., improved detection rates and long-term consistency of maximum 10-m wind speed around detected tropical cyclone centers in the Japanese Reanalysis for Three Quarters of a Century (JRA-3Q; Kosaka et al. 2024). For the ocean, the representation of circulation and sea ice has improved, while increased resolution has allowed for permitting and even resolving mesoscale eddies. In addition to improvements in NWP and ocean prediction systems, such achievements were also made possible by accessing more and better processed historical observations and better handling of biases in observations and in the NWP and ocean models. The increasing availability of uncertainty estimates allows users to identify where reanalyses are dominated by observations or by the model. The increasing need for climate services and ML developments has made state-of-the-art reanalysis more relevant than ever.

Nevertheless, many challenges remain. The conservation of mass and energy budgets and the handling of fluxes between Earth system components are long-standing issues (e.g., Mayer et al. 2024; Wild and Bosilovich 2024). Further improvements to the quality of the mean state remain on the agenda.

b. Regional reanalysis production status/plans. ICR6 was the first in this conference series to hold a dedicated session for regional reanalyses, which have been conducted over domains such as North America, Europe, the poles, Australasia, India, and East Asia. Although convection-permitting global reanalyses are still some years away, current high-resolution regional reanalyses assimilate dense observations and capture mesoscale phenomena and localized terrain and land/sea contrast effects. One such example is the assimilation of radar precipitation, although their operational data records may suffer from artificial trends caused by equipment/algorithm upgrades. To address this issue, reprocessing of radar/rain gauge analyzed precipitation in Japan is underway and resultant data will be assimilated in a regional reanalysis for Japan [Regional Atmospheric Reanalysis for Japan–Climate Change Actions with Co-Creation Powered by Regional Weather Information and E-technology (RRJ-ClimCORE); Nakamura et al. 2022]. Regional reanalyses are expected to serve a wide range of applications, including agriculture, energy, insurance, and transport, from which the need for user-friendly online platforms arises. Plans for next-generation regional reanalyses include improved data quality, introduction of a convective-scale data assimilation and an ensemble approach, and extension of the reanalysis period further back in time.

c. Observations for reanalyses. Reanalyses are ultimately dependent upon the quantity and quality of the observational constraints that can be applied. Attendees highlighted innovations in both data quantity and quality which will inform the improvements in the next generation of reanalysis products. Despite the substantial recent advances, they also highlighted how far we remain from the ideal case where all known sources of data have been rescued, quality assured, and made available for ingestion into reanalyses.

Several presentations highlighted the advancements made in the rescue, collation, and reformatting of both in situ and satellite records internationally via programs such as C3S. These efforts have greatly increased the volume of data and its usability. The efforts have benefited from developments at the World Meteorological Organization (WMO) around data policies and policy directions of numerous governments and institutions toward open data sharing. The Global Climate Observing System (GCOS) noted that reanalysis centers can play an important role in advocating for data sharing given their increased relevance in the context of applications in service to society including training artificial intelligence (AI)/ML forecast products.

It was noted with concern that the preservation and collation of the fundamental data records rest on very few institutions and experts for both in situ and satellite records. Broadening institutional and expert support would be highly beneficial. While reanalyses and other value-added products will, inevitably, eventually be superseded by newer versions, these original data constitute the fundamental data record and must therefore be actively curated and preserved for the benefit of generations to come.

Looking forward, the efforts of the WMO to both create a more spatially complete set of measurements via the Global Basic Observing Network (GBON; WMO 2021) and ensure their long-term support via the Systematic Observations Financing Facility (SOFF; WMO 2021) were welcomed. If fully implemented, this would provide a much more comprehensive set of data constraints over global land regions moving forward, enabling high-quality near-real-time data provision.

Further progress on ensuring the quality of anchor observations such as radiosondes is key. The newest version of the radiosonde dataset created by the University of Vienna for reanalyses shows improved performance in pilot ERA6 runs and has been expanded to include additional variables. In addition, assimilating the actual location of the sonde rather than assuming a direct vertical ascent improves performance.

d. Methods for reanalyses. There are a variety of approaches for producing reanalyses, which are usually based on the state-of-the-art operational system of the producing center. Over time, as well as improved observations (section 3c), the models also improve, for example, increasing resolution and advancing the data assimilation system.

Some novel approaches to better synthesize model and observational information were presented. A four-dimensional variational scheme with a model error term (weak constraint 4D-Var; Laloyaux et al. 2020) has been developed, which can be used to estimate model biases in the current well-observed period and then apply the estimate to correct model biases during earlier periods. Ensemble-based data assimilation methods have been developed that can deal with non-Gaussian and nonlinear observations [e.g., a quantile-conserving ensemble filtering framework (Anderson 2022, 2023; Anderson et al. 2024), Gaussian transformation]. Development of coupled data assimilation approaches is ongoing to expand the scope of consistency across the entire Earth system. Novel diagnostic methods of monitoring observation impacts [e.g., ensemble forecast sensitivity to observations (Yamazaki et al. 2021, 2023), adjoint sensitivity analysis] were presented, which can be useful to improve future reanalyses. Developing cost-effective data assimilation methods, including ultralow-cost postprocessing techniques, is crucial for reanalyses improvement, as limited computing resources and expanding system complexity challenge computational capacity.

e. Evaluations of reanalyses. Evaluating reanalyses is essential to understanding their limitations and benefits, both within the scientific community and for downstream users. ICR6 focused on four key areas: ocean reanalysis, atmospheric reanalysis, regional extreme events and flood forecasting, and the integration of ML with reanalysis.

The ocean reanalysis community has been putting effort into the evaluation of ocean reanalyses for decades, and the first coordinated effort was established in 2014 [Ocean Reanalyses Intercomparison Project (ORA-IP)] as a CLIVAR–GSOP/GODAE joint initiative (Balmaseda et al. 2015). The ocean reanalysis workshop of the European Copernicus Marine Service, held in Toulouse in 2023, emphasized the need for long-term, high-resolution, and high-quality (uncertainty quantification and better representation of oceanic variables) ocean reanalyses (Yang et al. 2025). To address these needs, collaborative initiatives and new global and regional ocean reanalysis evaluation exercises are planned for 2025. Tools like StraitFlux have proven effective for accurately computing water strait fluxes and validating oceanic transport across various reanalysis and climate model grids, though challenges persist in narrow straits and complex bathymetry regions (Winkelbauer et al. 2024). Additionally, long-term ocean reference observations remain vital for validating and calibrating reanalysis fields, ensuring their accuracy and reliability.

For atmospheric reanalysis, intercomparisons and diagnostics have provided valuable insights into climate variables such as stratospheric temperature, Brewer–Dobson circulation, and tropical precipitation (e.g., SPARC 2022). New-generation products like JRA-3Q have shown significant improvements, although there are still challenges with variability in stratospheric temperature representations and accurate depictions of tropical upwelling and intraseasonal oscillation amplitudes.

In the area of regional extreme events and flood forecasting, products like the BoM Atmospheric Regional Reanalysis for Australia, version 2 (BARRA2; Su et al. 2022, 2024), and ERA5 (Hersbach et al. 2020) have been effective in calibrating flood forecasting models in Australia, while RRJ-ClimCORE has successfully reproduced some extreme rainfall events in Japan. However, high-intensity events are often underestimated, even with high-resolution models.

The integration of ML with reanalysis data has shown promise, particularly in analyzing ozone variability and identifying contributing factors in data-sparse regions like the Himalayas. Nevertheless, data availability and quality in these regions remain a significant challenge.

f. Applications of reanalyses in science and society. The range of applications of climate reanalysis is diverse and rapidly expanding. The renewable energy sector is one example where reanalysis data are used to make informed decisions on infrastructure and technology. They require high-quality data of a variety of variables and often postprocess the data to suit their specific needs. An example of the use of reanalysis data in the renewable energy sector is to evaluate the energy potential of sites, where making the right choice on developing infrastructure can significantly affect the success and economic gains from an expensive investment.

The provision of reanalysis data allows for a vast range of scientific studies, including examining specific events, as well as analyzing long-term trends (Storto and Yang 2024). Such research can be translated into informing climate risks of future extreme events occurring in a warming world (Hawkins et al. 2023a,b).

There are many downstream uses of reanalysis data, using traditional atmospheric reanalysis as well as datasets covering other aspects of Earth system, such as the ocean, which can be used to force bespoke models developed by users.

Clearly, there is a large socioeconomic benefit associated with applications of reanalysis data outside of the pure scientific research community. Efficient data access, clear documentation, and reducing the gap between users and producers have been keys to success. It is important to quantify the benefits of such datasets to support stable funding of reanalysis efforts and user support.

Global climate reanalysis is now formally an operational activity of the WMO Integrated Processing and Prediction System (WIPPS) (WMO 2024). Several global reanalysis producing centers will continue to produce mandatory products, and these will be served to users through one data portal that will facilitate easy comparison and visualization.

g. Exploration of ML approaches in the context of reanalysis. Accurate reanalyses represent a critical need in the training pipeline for ML models. In some cases, ML models do not exhibit biases that have been long-standing in traditional models because they were trained on reanalyses that do not exhibit the same biases (Wang et al. 2024). Examples of ML techniques included developments of both ML parameterizations (in particular, for cloud condensation nuclei and cloud droplet number concentration) and ML forecast models (specifically, for forecasting regional subseasonal precipitation, local monthly forecasts of temperature, and downscaling climate simulations.) Performance of these models varied: They do not consistently provide the best forecasts, and they can struggle to capture extremes.

Importantly, the ML models presented were trained on several different reanalyses, including (but not limited to) ERA5. In fact, training an ML model on multiple reanalyses can improve performance (Bodnar et al. 2024). In addition, training these models on recent observation-rich periods can lead to more accurate model predictions. While most examples utilized ML techniques trained on reanalysis data, some work aiming at developing ML techniques to aid in the production of future reanalyses, specifically to improve quality control of observations prior to assimilation, was also presented.

4. Recommendations

ICR6 reaffirmed that reanalysis provides essential scientific information for society in the era of increased awareness of climate change worldwide. To make reanalysis data more compelling and usable, ICR6 came up with recommendations in five broad thematic areas.

a. Development and production.

- Ensure continuous investment in the development of traditional reanalyses: Improved observational datasets, model complexity and resolution, and data assimilation methods remain essential for making reanalyses more accurate and less biased.
- Further develop coupled data assimilation approaches: to expand the scope of consistency across the entire Earth system and to improve the capability of monitoring energy and water fluxes between Earth system components.
- Better reproduce extreme events: High-intensity events, which are often underestimated even in regional reanalyses, still need to be better reproduced by increasing resolution. To train ML models that can accurately capture extremes, reanalysis datasets also need to cover a long period.
- Maintain and enhance the diversity of reanalyses: The diversity of reanalyses helps to meet diverse user needs (e.g., high-resolution, long-term, various Earth system components) as well as to identify uncertainties through intercomparison. Diverse reanalysis can also provide a variety of training datasets, which improves ML models.

b. Observations.

- Create sustained collaborations between reanalysis and observational data communities: Long-term collaborations need to be sustained between the reanalysis community and the communities working on data rescue, curation, harmonization, reprocessing, quality control, bias correction, and improving observation operators (e.g., radiative transfer models). The Copernicus program in Europe has highlighted how sustained funding can help build long-term relationships.
- Better quantify presatellite sea ice extent: The lack of realistic estimates of sea ice extents prior to the satellite era is a major impediment to many reanalysis products, at least regionally. Efforts to better quantify sea ice extent may include a virtuous feedback loop: Atmospheric and ocean dynamics from existing reanalyses may provide a useful constraint in such efforts.

c. Evaluations and applications.

- Better quantify and communicate uncertainties: It is important to distinguish between different sources of uncertainty, i.e., parametric uncertainty vs structural uncertainty (Thorne et al. 2005) when analyzing further back in time. For the former, an ensemble approach should be adopted as the resolution increases toward a convective scale. For the latter, the uncertainty in the mean state in reanalysis can be inferred by evaluating several reanalyses that use different data assimilation systems and cover the same historical periods as far back as possible.
- Strive for better communication with users: Collaboration with users is essential to continue producing data that are relevant and sufficient for the users. It is vital to document best

practices for applying reanalysis data, to ensure that it is being used appropriately, and to develop robust validation guidelines for sector-specific reanalysis applications. In order to sustain the current applications of reanalysis data and to continue expanding the user base, the data need to be reliable, have open access and a sustainable supply, and also be provided with clear and comprehensive documentation and user-friendly tools.

- Combine reanalyses with future climate projection: This enables the construction of storylines of plausible "worst case" extreme events to inform about current and future climate risks.

d. Embracing ML methods.

- Clearly distinguish between requirements for ML training datasets and those for traditional uses of reanalyses as climate datasets: While future reanalyses can be developed with ML training in mind, the non-ML needs of reanalyses, e.g., process understanding, should not be compromised.
- Consider ML applications when processing/storing reanalysis data (e.g., use of analysis-ready cloud-optimized formats like Zarr).
- Explore opportunities for using AI/ML to improve and/or simplify reanalysis methods, evaluation, and interpretation.

e. Sustained collaboration.

In order to address these recommendations, it is expected that the restructured WCRP Earth System Modelling and Observations (ESMO) and its Working Group on Observations for Researching Climate (WGORC) will consider how to encourage global cooperation among reanalysis producers, observation data providers, numerical modelers, and members of the user community on a long-term basis.

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