doi.org/10.22498/pages.32.1.42

A palaeo-reanalysis of global monthly 3D climate since 1421 CE

PALAEO-RA Team*

A new reconstruction combines an unprecedented amount of climate observations with 12,000 years of climate model simulations in a data assimilation approach.

Reconstructions using data assimilation

Understanding interannual-to-decadal climate variability and extremes requires long datasets. Climate reconstructions have provided this information for decades. However, to understand the underlying mechanisms and relate climatic changes to atmospheric circulation variability, more comprehensive datasets than hitherto available are essential. One way of achieving this is to assimilate as much high-resolution climate information as possible into climate model simulations that provide physically consistent climate states.

Data assimilation (DA) approaches combining real-world atmospheric information with the physics of a climate model have been extremely successful in atmospheric sciences. In paleoclimatology, they are increasingly used to reconstruct the climate of the last millennium (Franke et al. 2017; Goosse and Paul 2013; Tardif et al. 2019). In DA, a first guess (mostly a modeled climate state) is updated by observations to provide the best estimate of climate consistent with both the model and the observations, as well as consistent with the errors in both. In paleoclimatology, offline DA is often used. In contrast to the online version, in which the updated model state at every assimilation time step is used to initialize a new forecast, offline DA only performs the update. This is possible because for atmospheric models, and over the typically seasonal-to-annual timescale of the assimilation, atmospheric initial conditions hardly matter. Offline DA is simple and versatile and can be used with pre-existing model runs. The latest offline DA product is the Modern Era Reanalysis (ModE-RA) suite of products (Valler et al. 2024). ModE-RA provides monthly output using a seasonal assimilation window, such that monthly mean instrumental or documentary data can be assimilated simultaneously with seasonal proxies (e.g. tree rings, plant or ice phenology).

Comprehensive compilation of observations

Crucially, any climate reconstruction relies on sufficient input data. This is the key strength of ModE-RA, which makes use of many times more observations than previous reconstructions. In addition to a large set of tree ring and other natural proxy records that include, among others, the PAGES 2k Network database (PAGES2k Consortium 2017), ModE-RA uses an extended set of documentary proxies (Burgdorf et al. 2023) and a new set of early instrumental measurements (Lundstad et al. 2023). The latter is a systematic compilation of most of the available station data (air pressure, surface-air temperature, and precipitation), supplemented by ca. 1500 newly rescued series. Furthermore, air pressure measurements from ships were assimilated (Freeman et al. 2017). An overview of the data sources is given in figure 1. In total, ModE-RA assimilates hundreds (17th century), thousands (18th century) or tens of thousands (19th century) of values per year. Already in the mid-18th century, the number of values from instrumental and documentary data exceeds that of natural proxies. Only series starting before 1890 CE are included. Therefore, the number of series drops off steeply towards the 21st century as series that end are not replaced. This was done to keep the network stable and comparable over a long time period, and to limit the computation time.

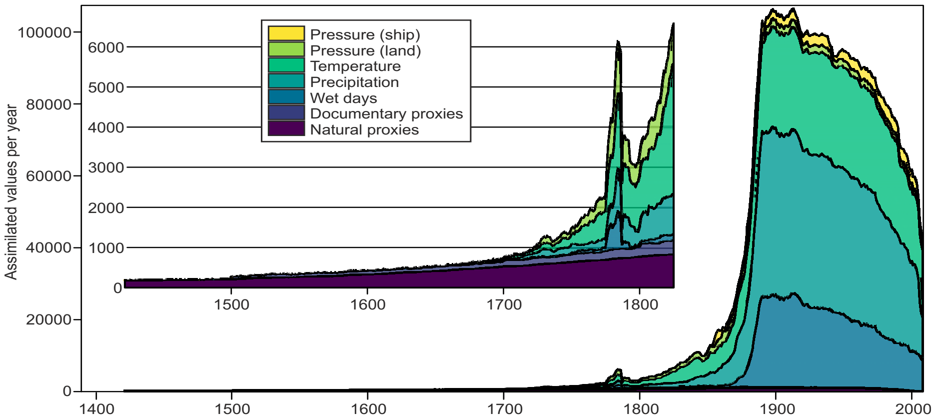

Figure 1: Number of values assimilated per year into ModE-RA, separated into data types.

The observations are assimilated into an ensemble of 20 atmospheric model simulations (Hand et al. 2023) performed with ECHAM6 and providing data at ca. 2°x2° resolution. These simulations, termed ModE-Sim, were externally forced by greenhouse gas concentrations, solar irradiance and volcanic aerosols, according to the PMIP4 protocol (Jungclaus et al. 2017). Sea-surface temperature (SST) boundary conditions are based on the annual PAGES 2k Network SST reconstructions (Neukom et al. 2019) and augmented by adding intra-annual variability based on ocean-variability modes. After 1780 CE we also assimilated SST and marine-air temperature observations into the ensemble of SST reconstructions using offline DA (Samakinwa et al. 2021).

The offline DA technique is similar to the precursor product EKF400v2, with some improvements (Valler et al. 2024). We use an Ensemble Kalman Filter approach, with a hybrid background error covariance matrix that blends the ensemble covariance matrix with a climatological covariance matrix. Each of the 20 members of ModE-Sim is updated, hence ModE-RA is an ensemble of 20 members. DA is performed on anomalies from a 71-year moving average, which is added back at the end. This means that on multidecadal to centennial timescales the assimilation does not add much information, and ModE-RA becomes similar to ModE-Sim.

Instrumental data are not homogenized before assimilation, rather, a breakpoint detection is used to segment the data. The assimilation is then performed in three cycles, progressing from long (>50 year) to short (<5 year) series. Intermediate analyses are stored, and the next shorter series are then debiased, relative to this product. This allows for the use of even shorter series, of which there are many.

Example analyses

In addition to the product ModE-RA in which the model simulations for a given year are updated using observations from that year, we also provide ModE-RAclim. In this version, the first guess consists of a random sample of n = 100 from all years and members. The covariance matrix is constructed from the same sample. This means that ModE-RAclim is an ensemble of 100 members and does not see the time-varying boundary conditions of the model. Analyzing all three products together (ModE-RA, ModE-RAclim and ModE-Sim; see Table 1) allows for disentangling where the information in ModE-RA comes from. This is shown in figure 2a–c, which plots ensemble mean temperature anomalies over Europe in December 1783. The model simulations (Fig. 2c) indicate a 2°C north-south gradient. ModE-RAclim and ModE-RA both show a cooling over Eastern Europe, whereas the Iberian Peninsula is warmer than normal. In this case, most of the information comes from the large number of observations. However, over North Africa, ModE-RA, which sees the boundary conditions, is cooler and more similar to ModE-Sim than ModE-RAclim.

Only the ensemble means are shown in the top row of figure 2, but the 20 (ModE-RA, ModE-Sim) or 100 (ModE-RAclim) members can also be analyzed individually. This is highlighted for 500 hPa geopotential height for the same month in figure 2d. Individual ensemble members provide a more realistic variability over time, whereas the variability of the ensemble mean decreases backward in time, when fewer observations constrain the reanalysis.

Precipitation anomalies in Africa in 1809 CE, after the "unknown" volcanic eruption (Timmreck et al. 2021), indicate a decrease in precipitation due to a decrease of the African monsoon, which can be diagnosed in the 850 hPa wind anomaly field (Fig. 2e). Finally, a 3-year drought period in the 15th century in the USA is studied (Fig. 2f). The 500 hPa geopotential height anomalies indicate a strengthened Great Plains Ridge.

Product	*n*	prior	obs.
ModE-RA	20	time-varying	Yes
ModE-RAclim	100	invariant	Yes
ModE-Sim	20*	time-varying	No

Table 1: ModE-RA products (n = number of members, obs. = assimilation of observations, *ModE-Sim has additional members not used for ModE-RA).

An important feature of the ModE-RA products is the Observation Feedback Archive, which provides detailed information about each observation that has been considered for assimilation. For instance, it includes station coordinates, 71-year climatology and anomaly, background and analysis departures for all members, forward models, and any relevant quality information.

The new dataset provides the best estimate of monthly climate of the past 600 years, given everything we know; the forcings, the laws of physics and arguably the most comprehensive set of climate information ever used in a reconstruction approach. It builds on efforts from several PAGES groups such as PAGES 2k Network, CRIAS and VICS and will benefit many future analyses. However, it should be noted that on multidecadal-to-centennial scales, the reconstruction mostly follows the model simulations.

ACKNOWLEDGEMENTS
Funded by the European Union H2020/ERC grant 787574, MSCA grant 894064 and Swiss National Science Foundation grant 188701. The simulations were performed at the Swiss Supercomputer Centre (CSCS).

AFFILIATIONS
*Stefan Brönnimann, Yuri Brugnara, Angela-Maria Burgdorf, Jörg Franke, Ralf Hand, Laura Lipfert, Elin Lundstad, Eric Samakinwa, Veronika Valler
Institute of Geography and Oeschger Centre for Climate Change Research, University of Bern, Switzerland

CONTACT
Stefan Brönnimann: stefan.broennimann@unibe.ch

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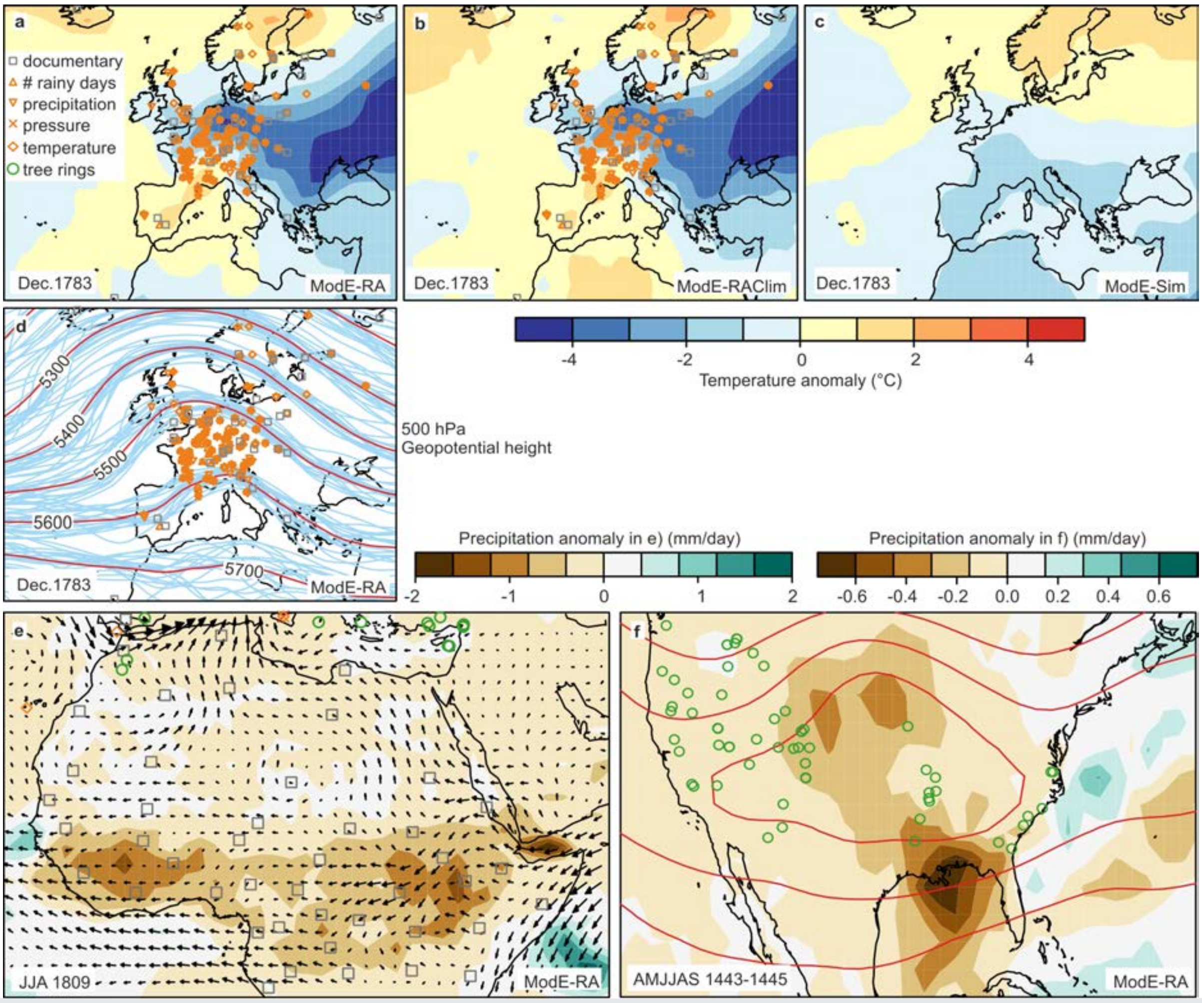

Figure 2: Temperature anomalies (from 1781–1810 CE) in December 1783 CE in **(A)** ModE-RA; **(B)** ModE-RAclim; and **(C)** ModE-Sim. **(D)** 500 hPa geopotential height in December 1783 CE in ModE-RA. **(E)** Anomalies of precipitation and 850 hPa wind in June-August 1809 CE (relative to 1781–1810 CE) in Central and Northern Africa and **(F)** 500 hPa geopotential height over the USA in April–September 1443–1445 CE (relative to 1421–1450 CE). Symbols indicate the assimilated observations. Only the ensemble means are displayed (except in the middle row, where light blue lines show members).