The ERA-CLIM2 EU-FP7 project

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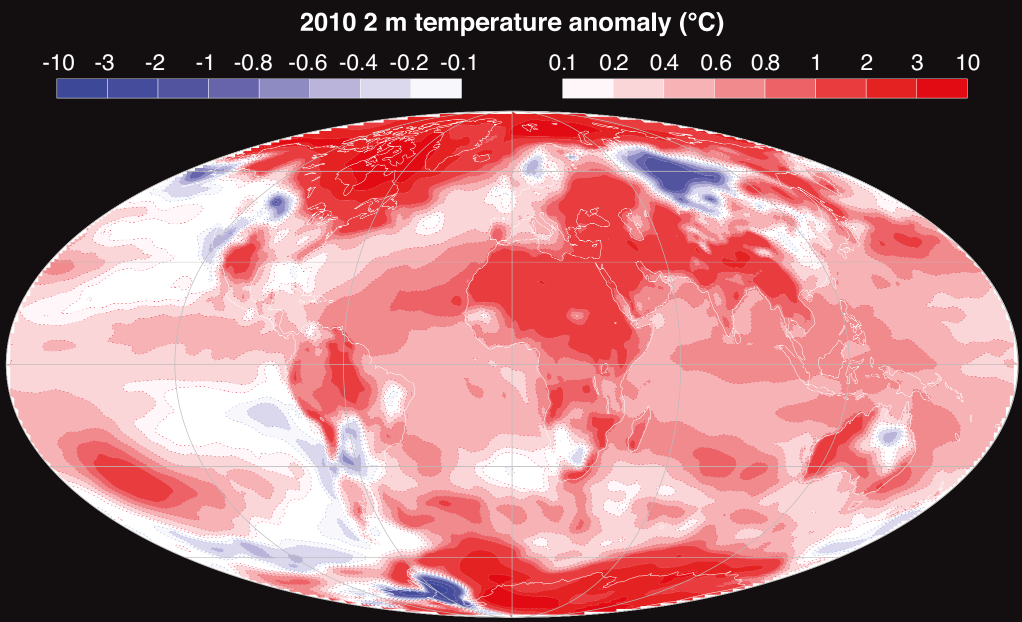
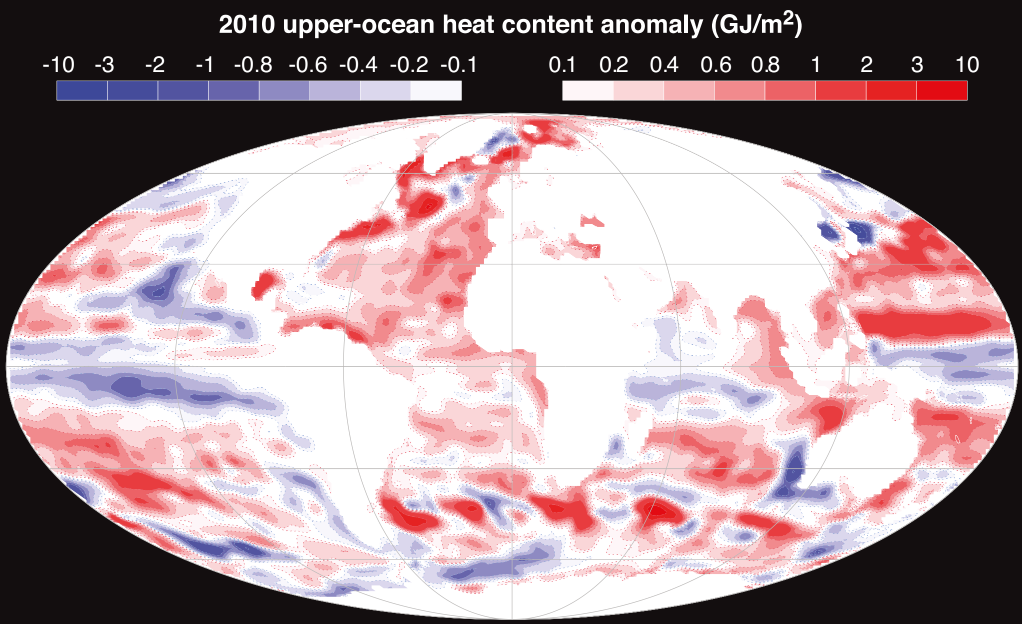




ERA-CLIM2 funded the production of the first European coupled reanalysis of the 20th century, CERA-20C. The two figures show the 2-metre temperature anomaly in the atmosphere (*top*) and the upper-ocean heat content anomaly (*bottom*) for 2010, the last year of CERA-20C, with respect to the 1961–1990 average.

The ERA-CLIM2 project

ERA-CLIM2 is a four-year research project funded by the European Union's Seventh Framework Programme (FP7; Grant Agreement No. 607029). It started on 1 January 2014 and it aims to produce coupled reanalyses. A reanalysis is a physically consistent dataset describing the evolution of the global atmosphere, ocean, land surface, cryosphere and carbon cycle (Figure 1).

The main contributions of the ERA-CLIM2 project to climate science are to improve the capacity for producing state-of-the-art climate reanalyses (see box) that extend back to the early 20th century, and to generate unique datasets of great value to scientists and other users. This includes work to rescue and prepare observations, and to advance the data-assimilation systems required to generate operational reanalyses, such as the ones planned by the EU-funded Copernicus Climate Change Service (C3S).

ERA-CLIM2 is at the heart of a concerted effort in Europe to build the information infrastructure needed to support climate monitoring, climate research and climate services, based on the best available science and observations. ERA-CLIM2 is one of the designated precursor projects of C3S. It has rescued and post-processed a large volume of observations, and assimilation methods and reanalyses produced thanks to ERA-CLIM2 have started to support the development and implementation of the C3S services.

ERA-CLIM2's main activities

1. Observation data rescue, post-processing and re-processing, for historical in-situ weather observations around the world and satellite climate data records;
2. Research and development of coupled assimilation methods, capable of including observations from different Earth system components (land surface, ocean, sea ice, atmosphere, chemical components, …) to produce a more consistent and better representation of the Earth system's evolution;
3. Reanalysis production, aiming to generate innovative reanalysis datasets;
4. Evaluation and uncertainty estimation, including visualisation and evaluation methods capable of indicating uncertainty in the reanalysis.

Reanalysis as a tool to monitor climate change

Since its creation in 1975, the European Centre for Medium-Range Weather Forecasts (ECMWF) has been a key player in the production of reanalyses. The initial focus was on producing atmospheric reanalyses covering the modern observing period, from 1979. The first of these reanalyses, FGGE (First GARP Global Experiment, where GARP stands for Global Atmospheric Research Program), was produced in the 1980s, followed by ERA-15 (European Reanalysis, 15-year version), ERA-40 and ERA-Interim. The next reanalysis in this series, ERA5, went into production in 2016 after many years of research and development.

Generating reanalyses for longer-term climate monitoring is very challenging because they need to be extended further back in time, when the observing system was very sparse. Observations were much more limited before the availability of satellite data from the 1970s onwards, and even more so before the arrival of radiosonde measurements in the 1930s. To tackle the unavoidable issue of the ever-changing observational network, the European Union Framework Programme 7 (FP7) started the ERA-CLIM (European Reanalysis of Global Climate Observations) project, which adopted a whitelisting approach to data selection for reanalyses covering the whole 20th century. As part of this project, ECMWF produced the uncoupled atmospheric reanalysis ERA-20C, which covers the period January 1900 to December 2010. The ERA-20C reanalysis assimilated only conventional observations of surface pressure and marine wind, obtained from well-established climate data collections. ERA-20C delivered three-hourly products

What is a **reanalysis?**

A reanalysis provides a data-rich description of the recent climate by combining models with observations. To produce a reanalysis, weather observations collected in past decades are fed into a modern numerical weather prediction system, which provides a physically consistent description of the Earth system. Using a model simulation of the Earth system ensures that the reanalysis is physically consistent and spatially and temporally complete, and that it encompasses many variables for which observations are not always available. Constantly correcting the simulation towards past observations ensures that the reanalysis is consistent with those observations.

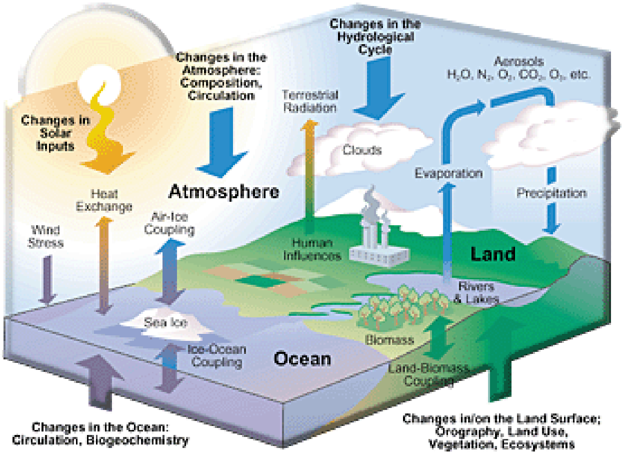


Figure 1. Major components of the global climate system and their main interactions.

describing the spatial and temporal evolution of the atmosphere, land surface and waves.

As part of the FP7 ERA-CLIM2 project, the reanalysis capabilities developed in the ERA-CLIM project have been extended to the ocean and sea-ice components. A new assimilation system (CERA, the Coupled European Reanalysis system) has been developed to simultaneously ingest atmospheric and ocean observations in the coupled Earth system model used for ECMWF's ensemble forecasts. This approach accounts for interactions between the atmosphere and the ocean during the assimilation process and has the potential to generate a more balanced and consistent Earth system climate reconstruction (Figure 2).

One of the key deliverables of the ERA-CLIM2 project is CERA-20C, the first ten-member ensemble of coupled climate reanalyses of the 20th century. It is based on the CERA system, which assimilates only surface pressure and marine wind observations as well as ocean temperature and salinity profiles. CERA-20C data allows users to investigate how the ocean, land, atmosphere and sea ice evolved throughout the 20th century using a unique and consistent dataset (Figure 3). Since this dataset includes ten realisations, generated taking into account observation and model uncertainties, it also provides a confidence measure.

There is now a strong demand for detailed information of CO2 fluxes and carbon pools from the climate modelling community, who want to understand and quantify the carbon cycle at global and regional scales, and from policy-makers and citizens, who want to take well-informed decisions on CO2 emissions at regional and local scales (Figure 4). For this reason, ERA-CLIM2 is also producing associated global reanalyses of carbon fluxes and stocks using terrestrial biosphere and ocean biochemistry models, which are forced by the CERA-20C reanalysis.

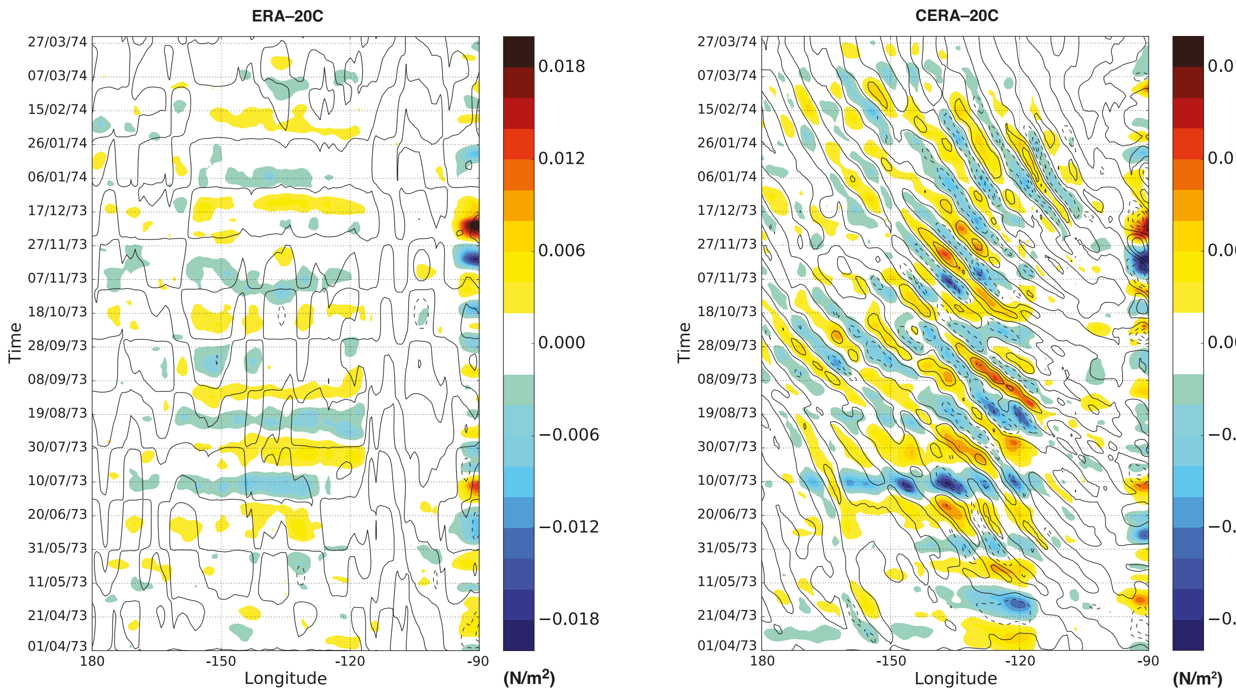


Figure 2. Spatially high-pass filtered wind stress (shading) and sea-surface temperature (contours, ranging from -1 to 1°C in 0.25°C increments) for ERA-20C (left) and CERA-20C (right) over the period 01/04/73 to 27/03/74. CERA-20C is able to represent Tropical Instability Waves (TIWs) thanks to the ocean dynamics, and the atmosphere is responding accordingly with the surface wind stress sensitive to the ocean TIWs. In ERA-20C, there are no TIWs or wind stress signals.

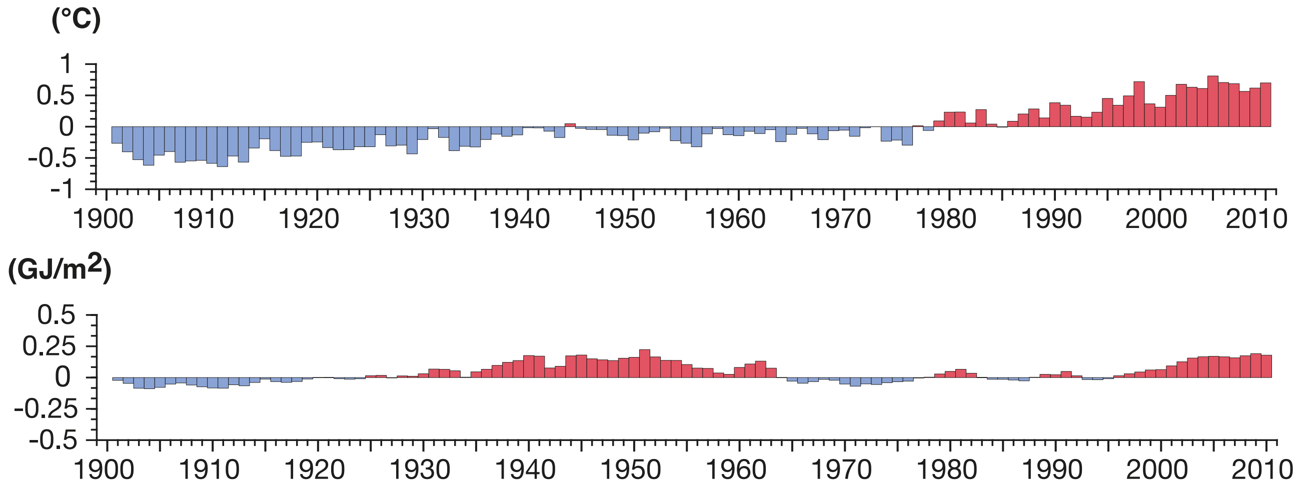


Figure 3. The two time series show the evolution of yearly global-mean anomalies relative to the period 1961–1990 for two-metre temperature (*top*) and upper-ocean heat content in the CERA-20C reanalysis (*bottom*).

Observation data rescue

Observations are not just assimilated to produce a reanalysis but are also used to constrain the boundary conditions, to calibrate certain relations and to validate the final product. Particularly when going back in time, not all observations are available for immediate use in a reanalysis. For example, a large proportion of historical meteorological observations has not yet been digitised because the data have thus far not been considered valuable. Even in the rather recent past, the availability of satellite products (and the computer code to read and process the data) is an issue that needs to be addressed.

Major efforts were therefore undertaken in ERA-CLIM2 to collect observations and to make them available for reanalyses. Such an undertaking requires a much broader vision than the production of any particular reanalysis. Historical observations are also a legacy, and producing reanalyses or other data products must be seen as a continuous effort. In this spirit, ERA-CLIM2 contributed to the sustained production of reanalyses by collecting observations.

One of the pieces of this giant jigsaw puzzle is shown in Figure 5. This is the transcript of a radiosonde ascent performed in Trappes (France) on 21 December 1945. Within ERA-CLIM2, millions of radiosonde profiles were digitised, making it possible to use observations of the third dimension of the atmosphere back to the 1930s. Although the radiosonde data were not incorporated into the CERA-20C reanalysis produced in ERA-CLIM2, they were used in various ways in the project, such as for the

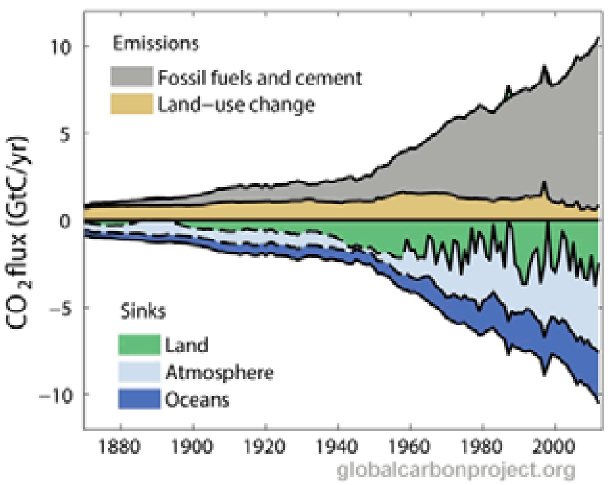
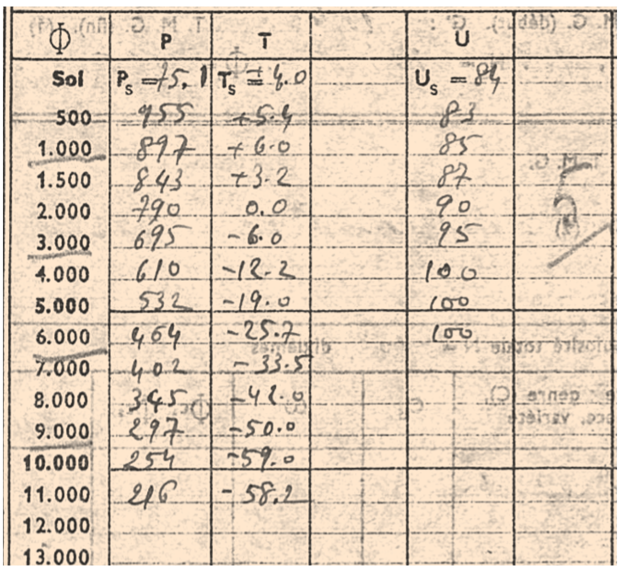


Figure 4. Evolution of the global carbon budget from 1870 to 2012 for emissions and sinks. On average, only half of the CO2 from anthropogenic emissions has remained in the atmosphere until now. The other half has been captured by the land and oceans, in approximately equal proportions.



Φ	P	T	U
Sol	P_s = 15,1	T_s = 4.0	U_s = 84
500	955	+5.4	83
1.000	897	+6.0	85
1.500	843	+3.2	87
2.000	790	0.0	90
3.000	695	-6.0	95
4.000	610	-12.2	100
5.000	532	-19.0	100
6.000	464	-25.7	100
7.000	402	-33.5	
8.000	345	-41.0	
9.000	297	-50.0	
10.000	254	-57.0	
11.000	216	-58.2	
12.000			
13.000			

Figure 5. Data sheet of radiosonde ascent from Trappes, France, on 21 December 1945.

Figure 6. First image of METEOSAT-1, taken on 9 December 1977. (Image © ESA)

validation of reanalysis products. Future reanalysis efforts will incorporate this vast amount of upper-air data and will thus build on the ERA-CLIM2 efforts.

Satellite data are the backbone of today's reanalysis datasets, but due to the short length of individual records they require careful calibration and reprocessing. Moreover, much better use could be made of early satellite data from the 1980s and even the 1970s (Figure 6). In ERA-CLIM2, efforts were put into re-processing satellite data, including some early satellite records, to make them useful for future reanalysis efforts.

Data assimilation methods for reanalysis

The ERA-CLIM2 reanalyses have been produced using a modern, state-of-the-art data assimilation system, capable of combining observations in the atmosphere and ocean with a coupled ocean–land–atmosphere model. Part of the work within ERA-CLIM2 was devoted to improving such a data assimilation system.

A crucial part of the coupled climate system is the interface between the ocean, including sea ice, and the atmosphere. In the existing CERA system, sea-surface temperature (SST) is constrained to follow a global analysis, which is calculated externally. Enabling the next CERA system to directly assimilate SST observations will allow the system to combine them with temperature profile data and model data in a more consistent manner, thereby improving the accuracy of the reanalysis. Care has to be taken to deal properly with biases in satellite data, which could otherwise introduce spurious trends.

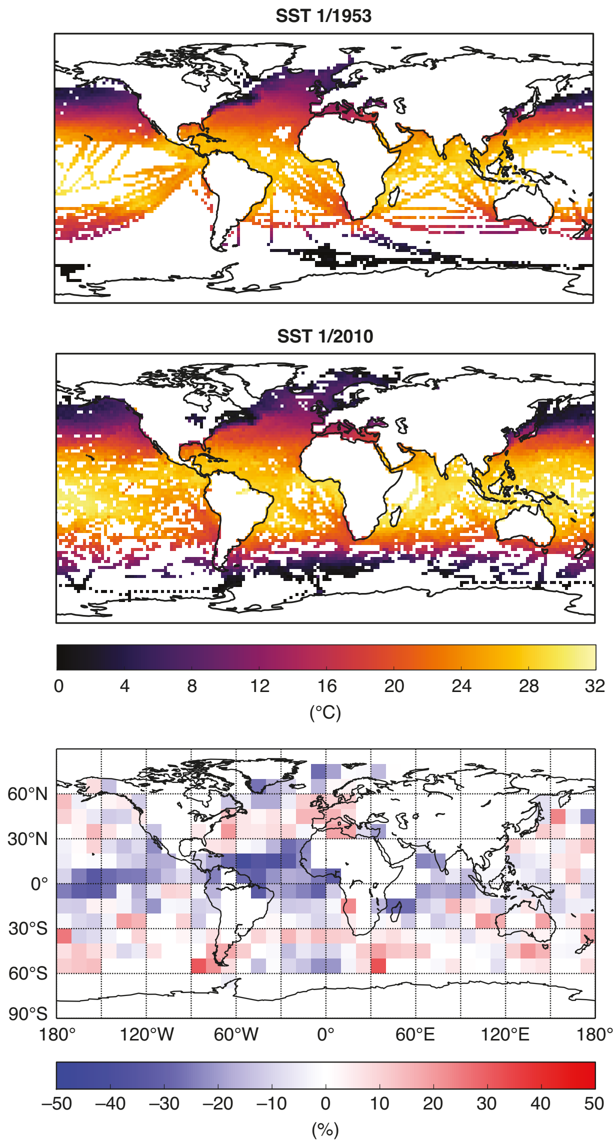


Figure 7. Examples of sea-surface temperature (SST) observations in °C from January 1953 (*top panel*) and January 2010 (*middle panel*), and percentage reduction in error in SST from assimilating the January 1953 data using the new version of NEMOVAR (*bottom panel*).

Figure 7 illustrates how a new method for using sparse observational information in the data assimilation has led to improved results. The assimilation of sea-ice concentration during the satellite era has also been improved. Sea-ice concentration estimates have error characteristics which make it difficult to assimilate them in most data assimilation algorithms. Techniques have been tested which transform the sea-ice concentration into a form that avoids this problem.

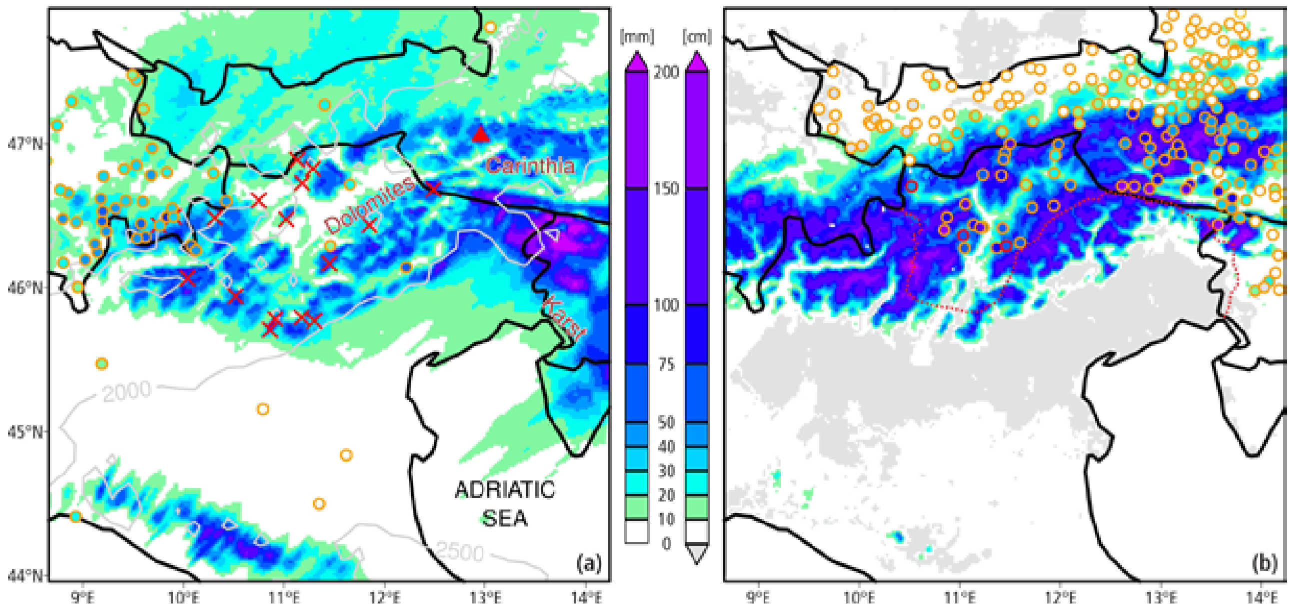


Figure 8. Results from the dynamical downscaling of ERA-20C: (a) total precipitation (shading) on 13 December 1916 and mean freezing level (grey contours; in m) and (b) change in snow depth between 5 and 13 December 1916. Circles represent observations, red crosses show the locations of documented major avalanches on this day. The military front line in 1916 is shown as a red dotted line.

The ocean data assimilation system used in CERA is a state-of-the-art variational system called NEMOVAR (Nucleus for European Modelling of the Ocean Variational assimilation system). This is a very flexible framework for assimilating data into the NEMO ocean model. In NEMOVAR, ocean data can now be assimilated using similar techniques to those already used in the atmosphere including the use of ensemble information.

Reanalysis and society

Reanalyses provide information on past weather events that can be very valuable to present-day society, as was demonstrated by an ERA-CLIM2 study. In December 1916, in the middle of the First World War, a massive snowfall event in the Southern Alps triggered countless avalanches, which killed thousands of soldiers and civilians.

This event was studied using dynamical downscaling of the ERA-20C reanalysis (the uncoupled reanalysis produced by the FP7 project ERA-CLIM, the precursor of ERA-CLIM2) in combination with historical observations. By looking at reanalysis data (Figure 8), the atmospheric conditions that led to such a disastrous event could be understood: a blocking flow situation, moisture transport from the warm

ERA-CLIM2's key deliverables

1. Observation data: ERA-CLIM2 contributed to the rescue, digitization and re-processing of millions of observations; these data are now ready to be used in the next reanalyses, e.g. the ones that will be produced by the European Union Copernicus services.
2. Data assimilation methods: ERA-CLIM2 helped to advance coupled assimilation methods capable of including observations from different Earth system components to produce a more consistent and better representation of the Earth system's evolution.
3. Reanalysis production: ERA-CLIM2 produced the first ensemble-based, coupled ocean (including sea ice), land and atmosphere reanalysis of the 20th century using surface observations, and eight years of ensemble-based, coupled reanalysis of the satellite era.
4. Evaluation and quality control: ERA-CLIM2 promoted the development of new, ensemble-based evaluation and uncertainty estimation methods.
5. Support of European efforts in climate monitoring: ERA-CLIM2 contributed to capacity building both in data processing and in the science required to generate high-quality reanalyses that can be used to monitor the climate, thus helping Europe to provide leadership in this area.

ERA-CLIM2 in numbers

The production of climate reanalyses requires a huge effort and resources. Here are few numbers from the ERA-CLIM2 project:

- 4: the number of years spanned by the project (January 2014 to December 2017);
- 10: the number of members in the CERA-20C and CERA-SAT reanalyses;
- 16: ERA-CLIM2 involved 16 organizations (*see below*);
- 110: the number of years spanned by CERA-20C (from 1900 to 2010);
- 1,100: about 1,100 person-months were funded by European Union contribution to the ERA-CLIM2 project;
- 500,000: the number of coupled assimilation cycles needed to generate CERA-20C;
- 700,000: about 700k station days of upper-air data have been digitized;
- 1,300,000: about 1.3M snow course observations data have been digitized;
- 2,200,000: about 2.2M station days of surface data have been digitized;
- 7,000,000: about 7M euros was the European Union contribution to the ERA-CLIM2 project funding;
- 16,000,000: about 16M euros was the total ERA-CLIM2 budget;
- 1,600,000,000,000,000: 1,600 terabytes is the amount of CERA-20C data.

Mediterranean Sea towards the Alps, and a rapidly rising snow line, leading to a dangerous rain-on-snow situation.

Estimating uncertainty

As more reanalysis products are developed, it is necessary to quantify their accuracy to assess the progress made as well as to enable their appropriate use by the research community. Traditionally, accuracy has been specified using confidence intervals calculated by the data producers, taking into account errors of the input observations as well as of the assimilating models. For many use cases, however, it is preferable to have an ensemble of several realizations of a quantity. This enables better uncertainty estimates in downstream applications that use reanalysis data as input, such as crop harvest estimates, trace gas flux estimates for natural ecosystems, or even for designing development plans.

CERA-20C and the upcoming CERA-SAT (the Coupled European Reanalysis of the Satellite era, in production) include ten reanalyses, run in parallel. These ten-member ensembles can be used to estimate the range of possible states for all the output variables, thus allowing users to estimate the range of uncertainty around past Earth system states.

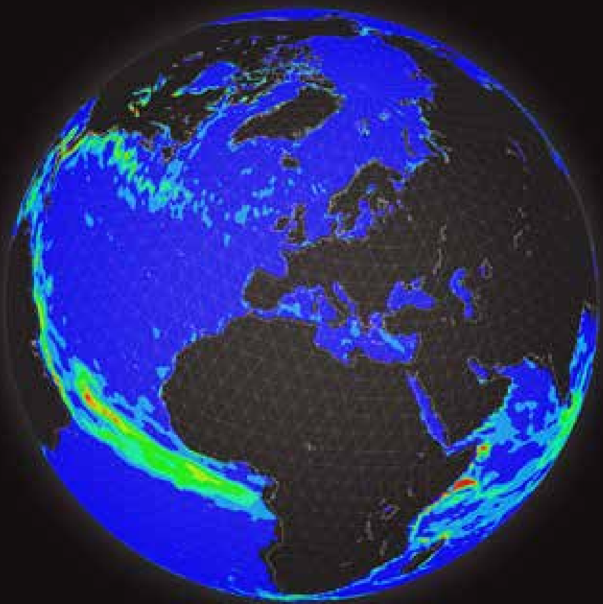
The members have been generated by perturbing the input observations and the SST, which is relatively uncertain particularly in the first half of the 20th century. The SST perturbations lead to variations in important output parameters, such as surface precipitation.

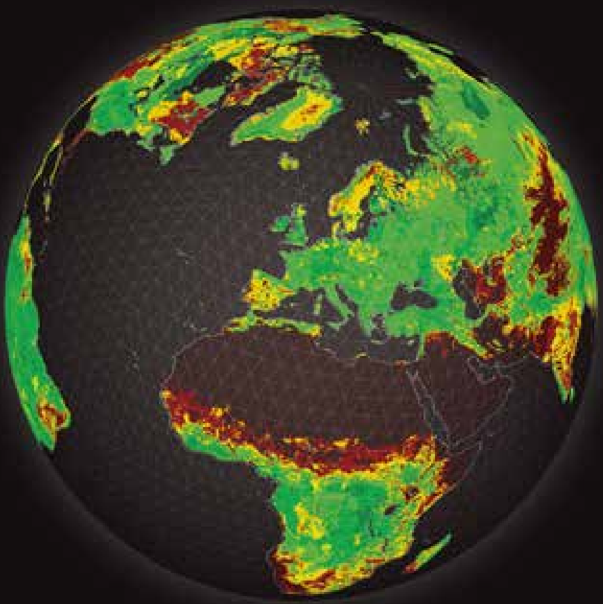
The ERA-CLIM2 Consortium included 16 organisations

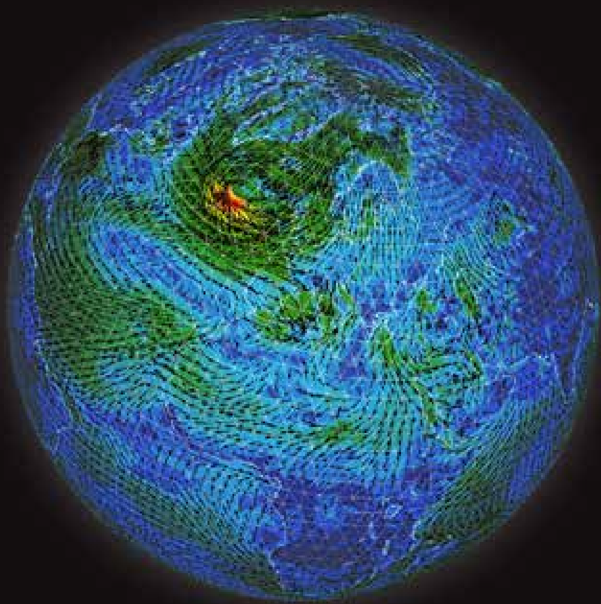
(in alphabetical order)

1. Associação para a Investigação e Desenvolvimento de Ciências (FCiências. ID); until the end of April 2017 it was called Fundação da Faculdade de Ciências da Universidade de Lisboa (Portugal);
2. Centre Européeen de Recherche et de Formation Avancée en Calcul Scientifique (CERFACS; France);
3. Centro Euro-Mediterraneo Sui Cambiamenti Climatici (CMCC; Italy);
4. Deutscher Wetterdienst (DWD; Germany);
5. European Centre for Medium-Range Weather Forecasts (ECMWF; Europe);
6. European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT; Europe);
7. Ilmatieteen Laitos (FMI; Finland);
8. Institut National de Recherche en Informatique et en Automatique (INRIA; France);
9. Mercator Océan Société Civile (MERCATOR; France);
10. Météo-France (MF; France);
11. Russian Research Institute of Hydro-meteorological Information (RIHMI; Russia);
12. UK Met Office (UKMO; UK);
13. Universität Bern (Switzerland);
14. Universität Wien (Austria);
15. Université de Versailles Saint-Quentin-en-Yvelines (France);
16. University of Reading (UK).

2 May 2017







ERA CLIM2

SEVENTH FRAMEWORK PROGRAMME

ECMWF