ERA-CLIM2
Final Publishable Report

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Project title: European Reanalysis of the Global Climate System

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[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

[2] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

The ERA-CLIM2 Consortium	
ECMWF	European Centre for Medium-Range Weather Forecasts
METO	UK Met Office
EUMST	The European Organisation for the Exploitation of Meteorological Satellites
UBERN	Universität Bern
UNIVIE	Universität Wien
FCiências.ID **(former FFCUL)**	Associação para a Investigação e Desenvolvimento de Ciências (FCiências.ID; http://www.fciencias-id.pt/); please note that till end of April 2017 was called FFCUL: Fundação da Faculdade de Ciências da Universidade de Lisboa (Portugal)
RIHMI	All-Russian Research Institute of Hydrometeorological Information-World Data Centre
MERCO	Mercator Océan Société Civile
METFR	Météo-France
DWD	Deutscher Wetterdienst
CERFACS	Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique
CMCC	Centro Euro-Mediterraneo Sui Cambiamenti Climatici
FMI	Ilmatieteen Laitos
UREAD	The University of Reading
INRIA	Institut National de Recherche en Informatique et en Automatique
UVSQ	Université de Versailles Saint-Quentin-en-Yvelines

Table 1. List of the ERA-CLIM2 Consortium.

1 Executive Summary

ERA-CLIM2 was a European Union Seventh Framework project that started in January 2014 and finished in December 2017. It aimed to produce coupled reanalyses, i.e. physically consistent data sets describing the evolution of the global atmosphere, ocean, land-surface, cryosphere and the carbon cycle.

The main contributions of the ERA-CLIM2 project to climate science have been to rescue and re-process past conventional and satellite data, improve the capacity for producing state-of-the-art climate reanalyses that extend back to the early 20th century, along with uncertainties, and generate unique and extremely valuable data sets covering the whole 20th century.

Thanks to ERA-CLIM2, many older data have been rescued and digitized, and have been delivered to relevant database providers so that they can be used in future reanalysis. Furthermore, new assimilation methods [e.g. use of a stronger coupling method between the ocean and the atmosphere and the direct assimilation of sea-surface temperature (SST) data] have been developed and tested within the project, and are planned to be used in future reanalyses production.

Understanding climate change is highly dependent on the availability of global satellite and conventional observational data in the atmosphere, the land and the ocean and sea-ice, and the development of coupled ocean-land-atmospheric models and assimilation systems that can ingest these data. A continuous cycle of research and development activities in data-assimilation, of data rescue and observation re-processing, production and diagnosis and evaluation is required to improve future reanalyses, so that they can provide a continuously improving depiction of the time evolution of the Earth system.

Considering the European activities in reanalysis and climate monitoring, a sensible way to be able to continue to generate increasingly accurate reanalyses would be to fund follow-on activities either through a new stream of European projects, or directly as part of the European Union Copernicus Climate Change Service (C3S) activities. In this way, Europe would continue to maintain a leading position in this field, building on the investments already made and the successes of projects such as ERA-CLIM and ERA-CLIM2.

2. Summary description of project context and objectives

ERA-CLIM2 aimed to produce reanalyses, physically consistent data sets that describe the evolution of the global atmosphere, ocean, land-surface, cryosphere and the carbon cycle. Reanalyses are generated by combining first guess estimates, usually defined by model forecasts, with data from a range of observing platforms (surface, upper-air, satellites) using objective methods (named data assimilation systems). Reanalyses covering long period (say few decades), named climate reanalyses, can be used to monitor the evolution of the Earth-system climate, and they provide long (multi-decadal) time series of gridded estimates for many different climate variables.

Reanalyses are one of the main contributions of the ERA-CLIM2 project to climate science. The other two key contributions are to rescue and prepare observations, and to advance the data assimilation systems required to generate operational reanalysis, such as the ones planned by C3S. Without the observation and the research and development activities performed also by this project, and the former ERA-CLIM project (Grant Agreement No. 265229 ending 31 December 2013), C3S on-going and future reanalyses would be of inferior quality.

ERA-CLIM2 has been 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. More specifically, ERA-CLIM2 was one of the designated precursor projects of C3S supposed to help to build the C3S infrastructure and production capabilities. Indeed, ERA-CLIM2 made a substantial contribution to data rescue activities and post-processing of past observations, and to the development of coupled assimilation methods. Furthermore, ERA-CLIM2 generated the first European coupled (atmosphere, ocean, land-surface, cryosphere and the carbon cycle) reanalyses spanning the 20th century and 9 years of the satellite era at higher resolution. The rescued and re-processed observations, and the coupled reanalyses have helped the development and implementation of the C3S services.

The ERA-CLIM2 contribution to the European effort to support climate monitoring can be grouped into four main areas:

- *Observation data rescue and post-processing* – Activities under this theme included a large effort on data rescue for historic in-situ weather observations around the world, and substantial work on the reprocessing of satellite climate data records;
- *Research and development of data assimilation systems* – Activities under this theme aimed to advance the development and testing of 'coupled assimilation methods', capable to include observations from different Earth-system components (land surface, ocean, sea-ice, atmosphere, …) to produce a more correct and better status of the Earth-system evolution;
- *Reanalyses' production* – Activities under this theme aimed to generate the innovative reanalysis data-sets, such as the first coupled ocean-land-atmosphere reanalysis of the 20th century, and to provide access to the reanalysis data;

- *Evaluation and uncertainty estimation* – Activities under this theme aimed to develop visualization and evaluation methods capable also to give indications of the uncertainty in the reanalysis, and to apply them to assess their quality.

ERA-CLIM2 in numbers	
4	The number of the project years (Jan 2014 to Dec 2017).
9	The number of years covered by CERA-SAT, the first European ensemble of coupled reanalyses covering some satellite years.
10	The number of ensemble members in the CERA-20C and CERA-SAT reanalyses, generated to provide uncertainty estimations.
16	The number of organizations in the ERA-CLIM2 Consortium.
50	The approximate number of people were funded (either full- or part-time) by ERA-CLIM2.
110	The number of years covered by CERA-20C (from 1901 to 2010), the first European coupled reanalysis of the 20th century.
1,100	The approximate number of person-months funded by European Union contribution to the ERA-CLIM2 project.
500,000	The approximate number of coupled assimilation cycles needed to generate the 110-years CERA-20C.
700,000	The approximate number of station-days of upper-air data that have been rescued and digitized by the ERA-CLIM2 people.
1,300,000	The approximate number of snow-course observations that have been rescued and digitized by the ERA-CLIM2 people.
2,200,000	The approximate number of station-days of surface data that have been rescued and digitized by the ERA-CLIM2 people.
7,000,000	The approximate amount (in Euro) of the European Union contribution to the ERA-CLIM2 project.
16,000,000	The approximate total budget (in Euro) of ERA-CLIM2, which includes also monetarized contributions 'in kind'.
1,600,000,000,000,000	1,600 Terabytes is the amount of CERA-20C data.

Table 2. ERA-CLIM2 in numbers: few, key numbers to summarize the ERA-CLIM2 results.

3. Main science and technology results/foregrounds

The core objective of the EU-FP7 ERA-CLIM2 project was to apply and extend current global reanalysis capability in Europe (Fig. 1), to meet the challenging requirements for climate monitoring, climate research, and the development of climate services. This objective has been achieved, and ERA-CLIM2 has contributed to advancing reanalysis science, technology and capacity in all its four main areas of work (see Table 2 for few, key 'ERA-CLIM2' numbers).

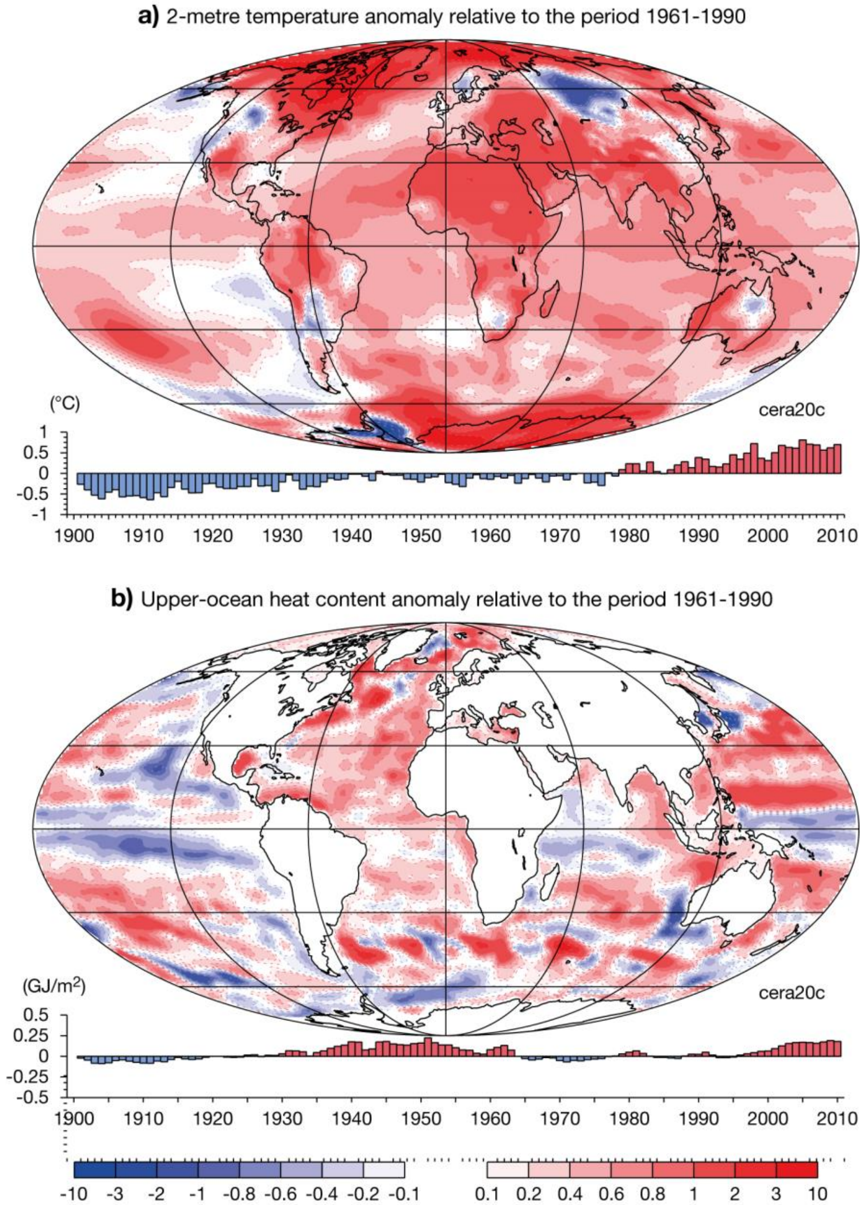

Figure 1. Maps of the yearly-average global-mean anomalies in 2010 relative to the period 1961–1990 for the two-meter temperature (top) and the upper-ocean heat content (bottom) in CERA-20C. The two time series show the evolution of the yearly-average global-mean.

3.1 ERA-CLIM2 key results in observation data rescue and post-processing

Observations are assimilated into a numerical weather prediction model in order to produce the reanalysis, but observations are also used in several other steps. They are 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 digitized 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.

Within ERA-CLIM2, millions of radiosonde profiles were digitized, making it possible to use observations of the third dimension of the atmosphere back to the 1930s. A map showing the stations digitized within ERA-CLIM and ERA-CLIM2 is shown in Fig. 2. 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 validation of reanalysis products. A test reanalysis was performed for a 30-year period including the historical upper-air data and demonstrated the potential benefits. Future reanalysis efforts will incorporate this vast amount of upper-air data and will thus build on the ERA-CLIM2 efforts.

After the termination of ERA-CLIM2, data rescue will be continued by some of the partners within their operational activities. Furthermore, the partners make their expertise and tools available to the community via the Data Rescue Services of Copernicus Climate Change Services. For instance, this concerns the metadata registry used in ERA-CLIM and ERA-CLIM2, which comprises very valuable information on the stations and records digitized.

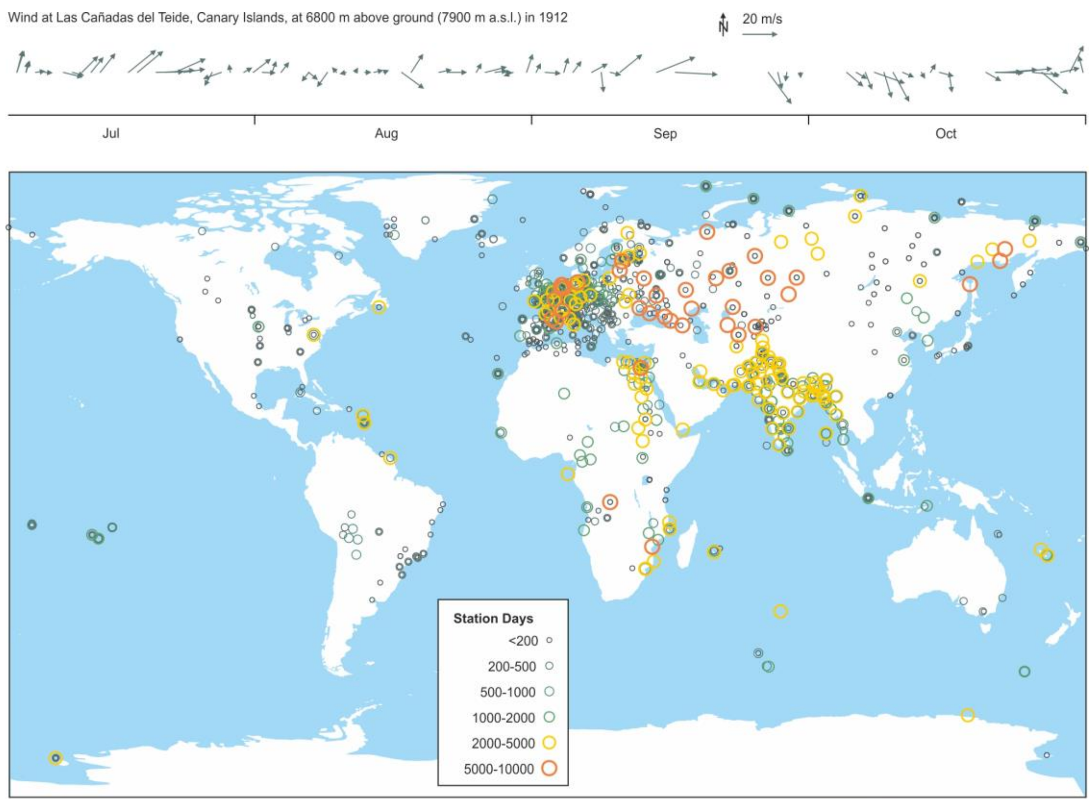

Figure 2. Top: wind at 7900 m (above sea level) obtained with pilot balloons on the station Las Cañadas del Teide on Tenerife, Canary Islands, in 1912. Bottom: map of digitized upper-air data from ERA-CLIM and ERA-CLIM2. The circle size indicates the amount of station days per station. In total, 1400 stations are shown.

Snow is an important component of the climate system, at the interface of the land surface, vegetation and the atmosphere. It is highly relevant for various fields such as ecology, water resources, transport, and tourism. By digitizing large amounts of historical snow data and combining this with satellite products, ERA-CLIM2 generated snow products for various uses, including (but not limited to) reanalyses. Snow course (specified paths of a few kilometers in length around a location, along which, different snow properties are measured regularly) data that cover the Northern Hemisphere extra-tropics have been compiled and made available within ERA-CLIM2. Furthermore, a data set of snow water equivalent was generated from merging different satellite products (microwave and optical) with station data, building on the highly successful GlobSnow product.

Satellite data are the backbone of today's reanalysis data sets, 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 (Fig. 3). In ERA-CLIM2, efforts were put into re-processing satellite data, including some early satellite records, to make them useful for future reanalysis efforts. Specifically, AVHRR GAC (Advanced Very High Resolution Radiometer Global Area Coverage) polar winds (from AVHRR GAC data, 1982-2014), were reprocessed, infra-red (IR) and water vapor (WV) radiances from Meteosat First Generation and Meteosat

Second Generation were recalibrated and atmospheric motion vectors were derived from these products. Radio Occultation data from GRAS/CHAMP/COSMIC were processed using wave optics.

Reprocessing satellite data poses a new challenge to an operational service in terms of processing chains and data throughput, which requires different hardware, archiving facilities, but also expertise than operational processing. At EUMETSAT, these new procedures are now established which will enable future satellite reprocessing work.

Figure 3. First image of METEOSAT-1, taken in 9 Dec. 1977 (Image: ESA).

3.2 ERA-CLIM2 key results in research and development of data assimilation systems

ERA-CLIM2 partners have carried out research and development in ocean and coupled ocean-atmosphere data assimilation (DA) for climate reanalysis, and developed the ocean and land components of the carbon cycle reanalysis. These developments have been done in the context of the coupled data assimilation system (CERA) used at ECMWF (see section 3.3) to produce coupled reanalysis, and are aimed at improving future versions of those reanalyses.

Surface ocean and sea-ice variables are important in the context of coupled reanalyses as they influence the ocean, sea-ice and atmosphere analyses. The existing CERA system uses externally produced analyses of SST, and assimilating the SST data directly would allow the system to make better use of that important data source. Improved methods for assimilating SST and sea-ice concentration data have therefore been developed. The quality of reanalyses which assimilate satellite SST data is dependent on the inter-calibration between different satellite sensors to ensure that there are no artificial trends in time-series of SST. A new methodology was therefore developed in ERA-CLIM2 and Fig. 4 demonstrates the ability of the new method (the red line) to reduce the impact of changes in the observing system on the global mean SST time-series. In the pre-satellite era, the in situ SST observing network is sparse, so a technique has been developed to allow the ocean data assimilation scheme to spread the information from these data more widely, making much better use of these data. Methods to improve the assimilation of sea-ice concentration have also been developed, dealing better with the complicated statistical nature of the errors in sea-ice models and observations. These methods have been shown to improve the representation of sea-ice thickness as well as concentration.

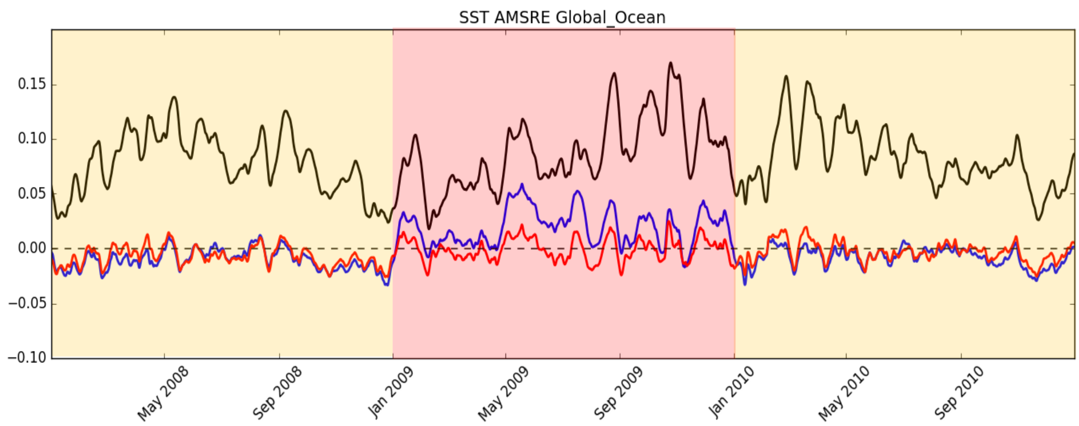

Figure 4. Global mean SST observation-minus-background (K) for the AMSRE microwave SST satellite from Jan 2008 to Dec 2010. Black line – no bias correction; blue line – bias correction using old scheme; red line – new bias scheme. In the middle year (2009), the reference satellite data from AATSR were withheld from all experiments.

In the systems used to produce coupled reanalyses in ERA-CLIM2 the ocean data assimilation system was less sophisticated than the atmospheric one. Developments were therefore carried out to improve the ocean DA system (NEMOVAR) which now has various options for making use of ensemble information in a hybrid ensemble-variational DA scheme. This allows the system to better represent the varying errors in the system due to changes over time in both the observing system and in the atmospheric and ocean state, for example to represent the changing errors in the model forecast in regions such as the Gulf Stream (see Fig 5). The ocean DA system also now has the capability of using 4D-Var methodology, which has been shown in ERA-CLIM2 to provide improved analyses compared with 3DVar in higher resolution ocean models, and work was carried out to allow this to be done with a reasonable increase in computational cost.

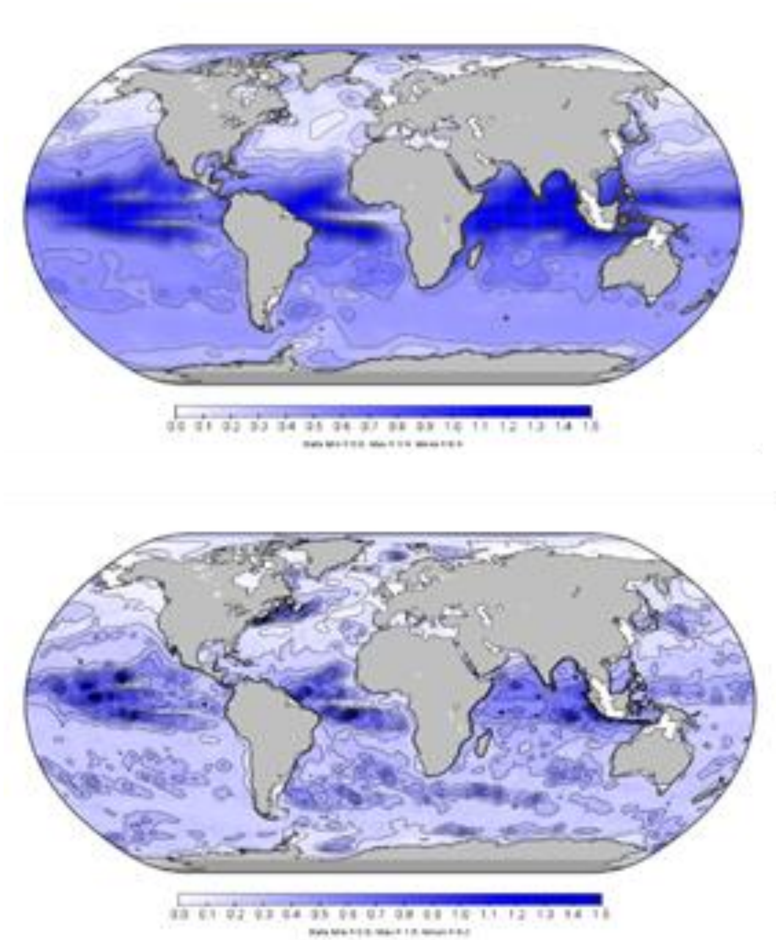

Figure 5. Example of parameterized and hybrid temperature error standard deviations at 100m depth, estimated from the ECMWF 11-member ensemble of ocean reanalyses.

The coupled data assimilation method used in CERA has been implemented such that the DA systems in the ocean and atmosphere are not completely integrated. The strengths and weaknesses of this method were assessed, demonstrating, for example, improvements in the SST-precipitation relationships compared to previous uncoupled reanalyses. Methods for reducing the impact of ocean model biases on coupled reanalyses were also assessed in order to reduce the impact these can have on the quality of both the ocean and atmosphere analyses.

Research was carried out to investigate options for increasing the amount of coupling within the DA, which should allow better use to be made of the observations. First, methods to estimate coupled error covariances statistically from existing data have been developed and assessments made of the covariances between the ocean and atmosphere forecast errors. A novel method for allowing more comprehensive ocean/atmosphere interactions in the DA through simplified physically-based relationships has also been proposed and its impact investigated. Ideas for moving to strongly coupled DA have been proposed and assessed in an idealized framework showing that ocean-atmosphere consistency could be improved compared to weakly coupled DA, moderately at a small additional cost or significantly at a huge additional computational cost.

Improvements to the land carbon component of coupled reanalyses have been made by improving the land model parameters. Various data streams from satellites and in situ sources have been used in a variational data assimilation method to improve the model parameter estimates. Different methods for optimizing the model parameters were assessed, and an approach was selected whereby particular observation types are used to optimize appropriate parts of the model in a stepwise manner. This optimization involved the use of new observation types including vegetation fluorescence. Different strategies for producing ocean carbon reanalyses were also investigated. Ocean biogeochemical models are sensitive to changes in the physics caused by physical ocean data assimilation and the use of various streams of production for the main physical reanalysis in CERA-20C also causes discontinuities when running the biogeochemical model. An approach was therefore defined whereby the bio-geochemical ocean model is coupled to a physical ocean model without DA, and is forced by the outputs of an existing coupled ocean/atmosphere reanalysis. The initial conditions of the biogeochemistry and the ocean model parameters were set-up to produce a simulation which gave good estimates of the main biogeochemical variables and the carbon flux.

3.3 ERA-CLIM2 key results in reanalyses production

The reanalysis capabilities developed in the ERA-CLIM project have been extended to the ocean and sea-ice components in the ERA-CLIM2 project. A new assimilation system (CERA) 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.

CERA-20C is 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. The air–sea interface is relaxed towards the sea-surface temperature from the HadISST2 monthly product to avoid model drift while enabling the simulation of coupled processes. No data assimilation is performed in the land, wave and sea-ice components, but the use of the coupled model ensures a dynamically consistent Earth system estimate at any time.

One of the benefits expected from a coupled assimilation system is a more consistent treatment of the air–sea interface. When decoupled, the ocean and atmospheric systems use boundary conditions that do not take into account ocean–atmosphere feedbacks. In the atmospheric-only ERA-20C reanalysis produced by the ERA-CLIM project, the atmospheric lower boundary conditions come from the HadISST2 sea-surface temperature and sea-ice product, which does not contain any information about the ocean dynamics. In the ocean-only ORA-20C reanalysis, the ocean is forced by the ERA-20C fields, which are fixed and cannot adjust to the ocean model behaviour. The long-term heat fluxes received by the ocean therefore suffer from inconsistencies at the air–sea interface. The resulting net heat fluxes over the ocean in ORA-20C show a negative trend from the 1940s onwards that tends to cool the ocean. To keep the ocean model close to the observed state, the ocean data assimilation has to compensate with a growing positive temperature increment (Fig. 6).

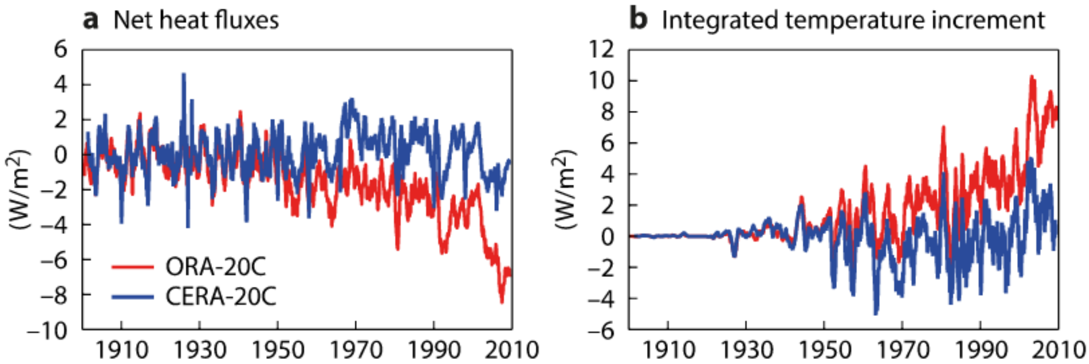

Figure 6. Time series of CERA-20C and ORA-20C control member values of (a) the global average of net air–sea heat fluxes and (b) the integrated temperature increment over the ocean.

In CERA-20C, the ocean and the atmosphere communicate every hour through the air–sea coupling at the outer-loop level of the variational method. Changes in the state of the atmosphere directly impact the ocean properties and vice versa. The combination of the coupled data assimilation and improvements in the atmospheric data assimilation corrects for the spurious trend in the net heat fluxes received by the ocean seen in ORA-20C. On average, heat flux and ocean temperature increments in CERA-20C oscillate around 0 W/m, suggesting a more balanced system.

CERA-SAT has been produced part of ERA-CLIM2 and spans 8 years between 2008 and 2016. It is a proof-of-concept for a coupled reanalysis at higher resolution with the full observing system available in the modern satellite age. The impact of the ocean coupling implemented in CERA-SAT has been assessed for a possible use for future C3S reanalyses and operational weather forecasting. The initial observation misfits with respect to different satellites (so-called background departures) are illustrated in Fig. 7. They show that CERA-SAT is consistently closer to observations in the tropical regions, indicating a clear benefit of ocean-atmosphere coupling in that region. The degradation in the extra tropics is a known issue of the coupled model underlying the CERA assimilation system and presents a clear need for further research and effort.

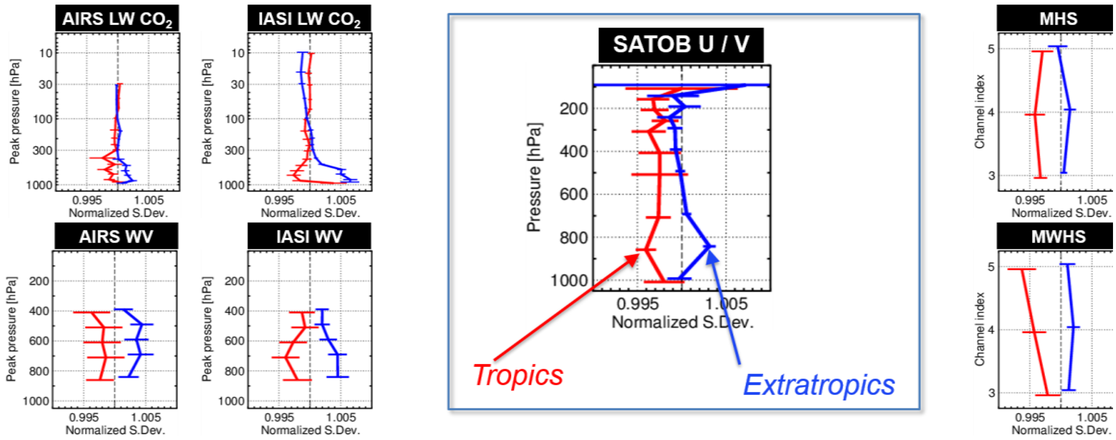

Figure 7. Differences in background standard deviation (CERA - CNTR) for selected satellites over the Tropics (red) and the extra-tropics (blue). Values below 1 (left of the vertical dashed line) indicate that the ocean coupling in the CERA system allows fitting better the observations. The comparison has been performed over September 2015-August 2016 and bars indicate the 95% confidence level.

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. 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 and CERA-SAT reanalyses.

3.4 ERA-CLIM2 key results in evaluation and uncertainty estimation

CERA-20C and CERA-SAT are ensembles of coupled reanalyses, the first of their kind, a fact that opens new opportunities but also poses new challenges for evaluation. The sample distributions of the reanalysis products should be a realistic representation of the true uncertainty. To check this, one can compare against other reanalysis products or against independent observations. The Oceanic Heat Content (OHC) of the upper 300m from the CERA20C ensemble has been compared in Fig. 8 with pure ocean reanalyses and overall good agreement has been found. The large uncertainty before 1950 is consistent with the sparse observation coverage during this time. Short term variations are caused by internal variability; volcanic eruptions in the 1950s, of e.g. Agung 1963, El Chichon 1982, Pinatubo 1991 lead to temporary cooling. The increase since 1970 is well represented by observations and is the manifestation of global warming in the ocean state.

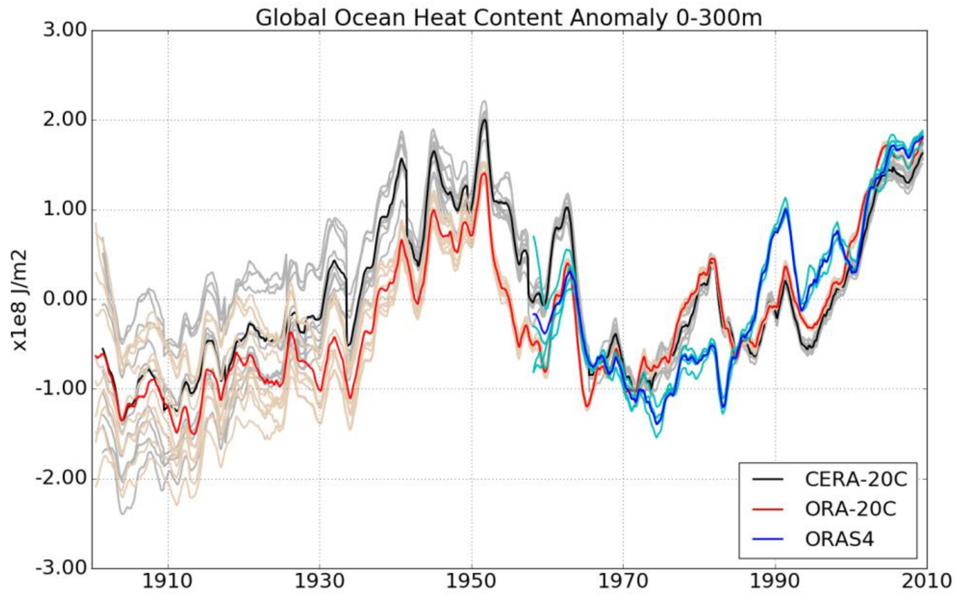

Figure 8. Global 0-300m OHC anomalies with respect to 1958-2010. ORA-20C ensemble (10 members) are in light red, with the ensemble mean in red. CERA-20C ensemble (10 members) in grey, with the mean in black, ORAS4 ensemble (5 members) in light blue with the ensemble mean in blue. An OHC increase of $1x10^8$ J/m^2 corresponds to a temperature increase of 0.08K averaged over the top 300m.

Comparisons of ensembles against independent observations are even more revealing. A detailed evaluation of precipitation in CERA-20C and ERA-20C (produced in ERA-CLIM) with rain gauge-based precipitation estimates from GPCC (Global Precipitation Climatological Center) indicates overall better quality for CERA20C, particularly in Africa and the Indian Monsoon region, although the observations still lie outside uncertainty bounds for low precipitation over Africa, for example. The apparent overestimation of precipitation over Northern Asia is not necessarily an error in the reanalyses but could also be caused by systematic underestimation of frozen precipitation in the GPCC data set. One may argue here that the uncertainties in preparing the GPCC data sets, should also be represented as ensemble, which is subject to future work.

Besides these showcase comparisons several additional advanced diagnostics on the energy, water and carbon cycles have been developed and performed to meet the needs of evaluating a coupled reanalysis system. Special emphasis has been put into quantifying the redistribution of heat between tropical ocean basins during El Nino events and difficulties of contemporary climate models to reproducing this redistribution could be clearly demonstrated. Indirect estimation of the net surface energy flux at the surface could be made significantly more accurate due to an improved formulation of the atmospheric budget equation. Changes in the coupled Arctic energy budgets of three subsystems (Atmosphere, Ocean and Cryosphere) have been assessed as well. Details may be found in the publications listed in the appendix.

As outlined in section 3.1, input data rescue and consolidation is essential for successful reanalyses. As such also the uncertainties and biases of certain input data sets, particularly of the upper air observing system, have been assessed and, where possible, reduced.

Another important aim in ERA-CLIM2 was to estimate not only classical budget quantities but to have also a realistic depiction of the global carbon cycle. Representing the carbon sink due to land vegetation growth is particularly challenging. Two approaches have been implemented. One has employed the land biosphere model ORCHIDEE, which simulates interacting carbon stocks and has been driven by meteorological input from CERA-20C and CERA-SAT. The second approach has been to evaluate output from the ECMWF operational land surface scheme that has been extended to include carbon fluxes. It is much more tightly integrated into the forecast model used for producing the reanalyses than ORCHIDEE but on the other hand lacks long-lived dynamic carbon stocks which are components of ORCHIDEE. Such comparisons of very different representations of the carbon cycle, particularly of the terrestrial land sink, will help improving both approaches in the future and our knowledge of climate change.

4. The potential impact and exploitation of results, and main dissemination activities

4.1 ERA-CLIM2 potential impact and exploitation of results

The Copernicus Climate Change Service (C3S) has provided the natural vehicle to transfer the ERA-CLIM2-funded research and development into operational systems and services. Indeed, the interaction between ERA-CLIM2 and C3S has been a very effective mechanism for integrating outcomes of ERA-CLIM2 and the other four pre-cursor projects: CLIPC (Climate information portal), EUCLEIA (European climate and weather events: interpretation and attribution), QA4ECV (Quality assurance for essential climate variables) and UERRA (Uncertainties in ensembles of regional reanalyses) into user-oriented applications.

C3S has provided a natural way to continue some of the activities started within the ERA-CLIM2 project, transforming them into lasting operational services. Examples of ERA-CLIM2 activities with high potential for contribution to C3S are:

- Development of a coupled (3-dimensional ocean, sea-ice, land and atmosphere) assimilation system that can be used to generate climate reanalyses for the 20th century and consistently derived reanalyses of the global carbon cycle; the version of the CERA (Coupled ECMWF REanalysis system) system used to generate CERA-SAT has been handed-over to C3S, so that it can be used as a prototype coupled assimilation system to generate the next C3S reanalysis, ERA6.

- Development of a global data rescue registry for keeping track of in-situ climate data rescue efforts world-wide; based on activities started in ERA-CLIM, and pursued in collaboration with the ACRE initiative and many other existing data rescue efforts and projects;
- Development of a global in-situ snow data collection based on work started in the CORE-CLIMAX (COordinating Earth observation data validation for RE-analysis for CLIMAte ServiceS) coordination activity;
- Further development of the ERA-CLIM Observation Feedback Archive and associated tools.

Numerous quality-controlled historic weather measurements with potential high impact for climate reanalysis have already been added to international public data collections such as ICOADS (International Comprehensive Ocean-Atmosphere Data Set) and ISPD (International Surface Pressure Databank), for use in reanalysis and other climate applications.

4.2 ERA-CLIM2 dissemination activities

ERA-CLIM2 dissemination and outreach activities can be classified in four areas:

i. ERA-CLIM2 project General Assemblies and Review Meetings;
ii. Conferences co-organized by ERA-CLIM2;
iii. ERA-CLIM2 presentations to conferences;
iv. Further outreach and communication activities.

4.2.i ERA-CLIM2 project General Assemblies and Review Meetings

The four ERA-CLIM2 General Assemblies (GAs) were organized on purpose in four different locations, to facilitate the exchange of information with people working at the hosting institutes:

- The First General Assembly was held at ECMWF (19-21 Nov 2014);
- The Second General Assembly was held at EUMETSAT (9-11 Dec 2015);
- The Third General Assembly was held at the Univ. of Vienna (16-18 Jan 2017);
- The Fourth General Assembly was held at the Univ. of Bern (12-13 Dec 2017).

The ERA-CLIM2 Review Meetings were held in similar locations:

- The Month-27 Review/Progress Meeting at ECMWF (25-26 April 2016);
- The Month-36 Review Meeting at the Univ. of Vienna (19 January 2017);
- The Month-48 Review Meeting at the Univ. of Bern (15 Dec 2017).

All presentations given at these events can be accessed from the ERA-CLIM2 web site, following the appropriate links at: http://www.era-clim2.eu/meetings.

4.2.ii Conferences co-organized by ERA-CLIM2

ERA-CLIM2 people plaid a key role in organizing and/or co-organizing the following conferences:

- *ERA-CLIM2 User workshop on observations for reanalyses* – Organized as one of the sessions of the 9th ACRE (Atmospheric Circulation Reconstructions over the Earth) Workshop and Historical Weather and Climate Data Forum (University of Maynooth, Ireland, 20-24 June 2016; http://www.met-acre.net/meetings.htm)
- *International Workshop on Coupled Data Assimilation* - Co-organized with Météo-France and the World Meteorological Organization (WMO) (Mete-France, Toulouse, 18-21 October 2016 (presentations can be accessed by following the link: http://www.meteo.fr/cic/meetings/2016/CDAW2016/)
- *ERA-CLIM2 Symposium on 'Climate Reanalyses and Services for Society'* – This was an open meeting organized to inform the public on the value of reanalyses as monitoring tools, and their potential use to provide climate services (University of Bern, Switzerland, 14 December 2017; presentations can be accessed by following the appropriate link from the ERA-CLIM2 web page http://www.era-clim2.eu/meetings)
- *5th International Conference on reanalysis (ICR5)* - Organized in Rome (the ERA-CLIM2 project coordinator, Roberto Buizza, was co-chair of the ICR5 Scientific Organizing Committee), it gave the opportunity to the ERA-CLIM2 people to present their work to the international community working on reanalysis (presentations can be accessed and talks can be viewed by following the appropriate links from the ICR5 web page https://climate.copernicus.eu/events/5th-international-conference-reanalysis).

4.2.iii ERA-CLIM2 presentations at conferences

ERA-CLIM2 work and results were presented at conferences, workshops and seminars, including the following 29 events:

1. World Weather Open Science Conference, (Montreal, Canada, 16-21 August 2014);
2. European Geophysical Union (EGU) General Assembly 2015 (Vienna; 12-17 Apr 2015);
3. Arctic Science Summit Week (ASSW) 2015 (Toyama, Japan, 23-30 April 2015);
4. GODAE (the Global Ocean Data Assimilation Experiment) OceanView Data Assimilation Task Team workshop (Exeter, UK; 20-22 May 2015);
5. Copernicus Workshop on Climate Observation Requirements (ECMWF, Reading, UK; 29 Jun - 2 Jul 2015);
6. The Year of Polar Prediction (YOPP) Summit (Geneva, Switzerland; 13-15 Jul 2015);
7. National Oceanic and Atmospheric Administration (NOAA) Climate Data Record Program conference (Asheville, USA; 4-6 Aug 2015);
8. Workshop on 'Trait-based approaches to ocean life', Woods Hole Oceanographic Institution (Woods Hole, New Hampshire, US; 5-8 Oct 2015);
9. GODAE OceanView Science Team meeting (Sydney, Australia; 2-6 Nov 2015);

10. 96th American Meteorological Society (AMS) Annual Meeting (New Orleans, US; Jan 2016);
11. International Society for Optics and Photonics (SPIE) Asia Pacific Remote Sensing conference (New Dehli, India; 4-7 Apr 2016);
12. European Geophysical Union (EGU) General Assembly 2016 (Vienna; 17-22 Apr 2016);
13. SPECS (Seasonal-to-decadal climate Predictions for the improvement of European Climate Services)/PREFACE (Enhancing Prediction of Tropical Atlantic Climate and its Impacts)/WCRP (WMO World Climate Research Program) Workshop on Initial Shock, Drift, and Bias Adjustment in Climate Prediction (10-11 May 2016);
14. GODAE (the Global Ocean Data Assimilation Experiment) OceanView Data Assimilation Task Team meeting (Santa Cruz, USA; Jul 2016);
15. VICS (Volcanic Impacts on Climate and Society) conference (Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, 6-8 June 2016)
16. Coordination Group for Meteorological Satellites (CGMS) International Winds Working Group (Monterey, USA; 27 June - 1 July 2016);
17. European Space Agency (ESA) Living Planet Symposium (Prague, Czech Republic; 9-13 Sep 2016);
18. 16th European Meteorological Society (EMS) Annual Meeting & 11th European Conference on Applied Climatology (ECAC) (Trieste, Italy; 12–16 Sep 2016);
19. EUMETSAT conference (Darmstadt, Germany; 26-30 Sep 2016);
20. Workshop on 'EU research projects and communication of uncertainties relevant for the C3S' (Brussels, Belgium; 28-29 Sep 2016);
21. 97th AMS Annual Meeting (Seattle, US; 22-26 Jan 2017);
22. Arctic Science Summit Week (ASSW) 2017 (Prague, Czech Republic; 31 March -7 April 2017);
23. European Geophysical Union (EGU) General Assembly 2017 (Vienna; 23-28 Apr 2017);
24. COST (European Cooperation in Science and Technology)/CLIVAR (Climate and Ocean: Variability, Predictability and Change) workshop on ocean reanalyses and inter-comparison (Toulouse, France; 29-30 Jun 2017);
25. 7th WMO International Symposium on Data Assimilation (Florianopolis, Brazil; 11-15 Sep 2017);
26. ECMWF Annual Seminar on 'Ensemble prediction: past, present and future' (Reading, UK; 11-15 Sep 2017) - Roberto Buizza, coordinator of the ERA-CLIM2 project, acted as chair of the Scientific Organizing Committee of this Seminar;
27. GODAE OceanView Data Assimilation Task Team and Observing System Evaluation Task Team meeting (La Spezia, Italy; 11-13 Oct 2017);
28. 5th International reanalysis conference on reanalysis (Rome, Italy; 13-17 Nov 2017)
29. ECMWF workshop on 'Observations and analysis of sea-surface temperature and sea ice for NWP and Climate Applications' (Reading, UK; 22-25 Jan 2018);

4.2.iv Further outreach and communication activities

A project brochure has been produced (deliverable 6.4) in May 2017: printed copies were sent to all the Institutes of the ERA-CLIM2 Consortium and to the European Union Project Manager. Copies were also were distributed at the 4th GA and at the 'ERA-CLIM2 Symposium' organized at the Univ. of Bern. The brochure can be downloaded from the project's web-site, by following the link at the home page (http://www.era-clim2.eu/home). A paper that describes the project has been accepted for publication in the Bulletin of the American Meteorological Society (*Buizza et al*, 2018).

Several other communication/outreach/coordination activities with other projects were performed, including the following 8 reports:

1. *WMO SCOPE-CM* (Sustained, Coordinated Processing of Environmental Satellite Data for Climate Monitoring) - Within this coordinated activity space agencies collaborate on generating an inter-calibrated fundamental climate data record of the infrared, water vapour, and visible channels on board of the heritage of all geostationary satellites. The ERA-CLIM2 work greatly contributes to this international activity (relates to deliverable 3.12).
2. *WMO GSICS* (Global Space-based Inter-Calibration System) - Within this coordinated activity, space agencies collaborate on establishing common procedures to re-calibrate past/present/future satellite instruments, with the focus on passive images and microwave sounders. The ERA-CLIM2 activities are reported in this framework by which visibility of European activities is strongly enhanced (relates to deliverable 3.12).
3. *EU H2020 FIDUCEO* - This project is addressing the recalibration of the reference HIRS (High-Resolution Infrared Radiation Sounder) data used in ERA-CLIM2 at fundamental level. This leads to further improvements of reference data used for the calibration of Meteosat data at a later stage. The experiences gained in ERA-CLIM2 helped to identify relevant issues in the HIRS data and to inform FIDUCEO. It also further completes the Meteosat re-calibration by addressing the visible channel of Meteosat First Generation (relates to deliverable 3.12).
4. *EUMETSAT CM SAF* (Climate Monitoring Satellite Application Facility) - The CM SAF is a primary user of the recalibrated Meteosat radiances outside the ERA-CLIM2 project and enhances the use of the project results. Their work was fundamental to establish confidence into the Meteosat First Generation re-calibration coefficients. In addition, a work relation with the CM SAF exists on the re-calibration of satellite radiances that are being used within ERA-CLIM2 (relates to deliverable 3.11).
5. *EU-FP7 Space Call 'sister' projects (UERRA, ERA-CLIM2, QA4ECV, EUCLEIA and CLIPC)* – The ERA-CLIM2 coordinator participated to several tele-conferences with the coordinators of the other EU sister projects that were precursors to C3S. As part of this coordination work, the coordinators of the five sister projects co-authored a report on 'Common Lessons Learned', where 'common' means relevant to all projects and to the operational production of reanalysis within Copernicus activities (deliverable 9.3).
6. *Workshop on 'EU research projects and communication of uncertainties relevant for the C3S'* (Brussels, 28-29 September 2016) – This WS gave the opportunity to the coordinators of the 5 EU-FP7 sister project (UERRA, ERA-CLIM2, QA4ECV, EUCLEIA

and CLIPC) not only to discuss issues linked to uncertainty (the topic of the project), but also to update each other on the status and progress of the 5 projects;

7. *Production of a video* that explains the generation of a historical reanalysis in a simple way using the analogy of a football kick (https://www.youtube.com/watch?v=Ux46HVU7H_g) and an interactive visualization of the CERA-20C reanalysis (http://earth.fdn-dev.iwi.unibe.ch/). Both were presented at several opportunities (Swiss Climate Summer School, Monte Verita, 5 September 2017, Researcher's Night, University of Bern, 16 September 2017, public presentation at University of Bern, 29 September 2017, Symposium on 'Climate Reanalyses and Services for Society', Bern 14 December 2017)
8. Uses cases on the value of historical reanalyses were published in book form (http://www.geography.unibe.ch/dienstleistungen/geographica_bernensia/online/gb2017g92/index_ger.html).

5. Address of the action's public website and related information

The ERA-CLIM2 project web-site is: http://www.era-clim2.eu/.

The web site includes information about the project, the list of partners, the list of publications, all the reports associated to the project's deliverables, links to data portals and links to relevant reanalysis' web sites. It also includes links to the four project General Assemblies, where all the presentations can be accessed and downloaded.

6. In conclusion

ERA-CLIM2 has contributed to advancing reanalysis science and development in four main areas:

- ***Observation data rescue and post-processing***: ERA-CLIM2 funded a large effort on data rescue for historic in-situ weather observations around the world, and substantial work on the reprocessing of satellite climate data records and enabling the use of historical satellite data for reanalysis;
- ***Data assimilation methods***: ERA-CLIM2 led to the development and testing 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 estimate of the Earth-system evolution, especially at the surface;
- ***Reanalysis production***: ERA-CLIM2 generated innovative reanalysis data-sets, such as the first European coupled ocean-land-atmosphere reanalysis of the 20th century that includes also the carbon component;

- ***Evaluation and uncertainty estimation***: ERA-CLIM2 advanced our understanding of the quality of uncoupled and coupled reanalyses, and led to the development of methods for estimating uncertainty in reanalyses.

7. Acknowledgements

As project coordinator, let me conclude by thanking the commitment and the work of all the ERA-CLIM2 people, especially of the work-package leaders (Stefan Brönnimann, Manuel Fuentes, Leopold Haimberger, Patrick Laloyaux and Matt Martin); the support and work of the European union Project Manager (Dr Monika Kacik) and of the external examiners; the support of the European Union Framework-7 (Grant Agreement number 607029); and the support and contributions 'in kind' of the ERA-CLIM2 Consortium. Thank you very much: without these contributions we would not have been here!

8. Appendix A - List of ERA-CLIM2 publications

All the work performed within the project has been reported and discussed extensively in the projects deliverables, and the most interesting results achieved within ERA-CLIM2 have been written in peer-reviewed publications. To date (9 February 2018), 68 ERA-CLIM2 publications that either use ERA-CLIM2 data, or were written as part of ERA-CLIM2 work, have been published or are under revision/preparation. Here is their list:

1. Ballesteros Cánovas, J. A., M. Stoffel, M. Rohrer, G. Benito, M. Beniston, S. Brönnimann, 2018: Ocean-to-stratosphere linkages caused extreme winter floods in 1936 over the North Atlantic Basin. Scientific Reports. *Submitted.*
2. Brönnimann, S., 2015: Verschiebung der Tropen führte bereits früher zu Dürren. Hydrologie und Wasserbewirtschaftung, **59**, 427-428.
3. Brönnimann, S. (Ed.) (2017) *Historical Weather Extremes in Reanalyses.* Geographica Bernensia, **G92**, 132 pp.
4. Brönnimann, S., A. M. Fischer, E. Rozanov, P. Poli, G. P. Compo, P. D. Sardeshmukh, 2015: Southward shift of the Northern tropical belt from 1945 to 1980. *Nature Geoscience*, **8**, 969-974 (doi:10.1038/NGEO2568).
5. Brönnimann, S., A. Malik, A. Stickler, M. Wegmann, C. C. Raible, S. Muthers, J. Anet, E. Rozanov and W. Schmutz, 2016: Multidecadal Variations of the Effects of the Quasi-Biennial Oscillation on the Climate System. *Atmospheric Chemistry and Physics*, **16**, 15529-15543.
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7. Brönnimann, S., M. Jacques-Coper, E. Rozanov, A. M. Fischer, O. Morgenstern, G. Zeng, H. Akiyoshi, and Y. Yamashita, 2017: Tropical circulation and precipitation response

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10. Brugnara, Y., Brönnimann S., Zamuriano, M., Schild, J., Rohr, C., Segesser, D., 2016: December 1916: Deadly Wartime Weather. *Geographica Bernensia*, **G91**, pp. 8. ISBN 978-3-905835-47-2 (doi:10.4480/GB2016.G91.01).
11. Brugnara, Y., S. Brönnimann, M. Zamuriano, J. Schild, C. Rohr and D. Segesser, 2017: Los reanálisis arrojan luz sobre el desastre de los aludes de 1916. *Tiempo y Clima*, **58**, 16-20.
12. Brugnara, Y., S. Brönnimann, M. Zamuriano, J. Schild, C. Rohr and D. Segesser, 2017: Reanalysis sheds light on 1916 avalanche disaster. *ECMWF Newsletter*, **151**, 28-34 (available from ECMWF, Shinfield Park, Reading, RG2 9AX, UK).
13. Buizza, R., Brönnimann, S., Fuentes, M., Haimberger, L., Laloyaux, P., Martin, M., 2017: The ERA-CLIM2 EU- FP7 project. *Project brochure,* pp 8. (available from the ERA-CLIM2 web site http://www.era-clim2.eu/home).
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9. Appendix B - List of acronyms

- AATSR: Advanced Along-Track Scanning Radiometer (one of the Announcement of Opportunity instruments on board the European Space Agency satellite ENVISAT);
- ACRE: the 'Atmospheric Circulation Reconstructions over the Earth' project;
- AMSRE: Advanced Microwave Scanning Radiometer - Earth Observing System (sensor on NASA's Aqua satellite);
- AVHRR: Advanced Very High Resolution Radiometer;

- CERA: Coupled data assimilation system developed at ECMWF, and used in ERA-CLIM2 to generate the coupled reanalyses;
- CERA-20C: the first European coupled reanalysis completed by ERA-CLIM2, that covered 110 years (1901-2010) and included 10 members, to be able to estimate reanalysis' uncertainty;
- CERA-SAT: coupled reanalysis of the satellite era covering the period 2008-2016, produced by ERA-CLIM2;
- CERFACS: Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique;
- CHAMP: CHAllenging Mini-satellite Payload) (ow earth orbit) satellite;
- CLIPC: the EU-FP7 'Climate information portal' project;
- CMCC: Centro Euro-Mediterraneo Sui Cambiamenti Climatici;
- CORE-CLIMAX: COordinating Earth observation data validation for RE-analysis for CLIMAte ServiceS;
- COSMIC: Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) satellite program;
- C3S: Copernicus Climate Change Service;
- DA: data assimilation;
- DWD: Deutscher Wetterdienst;
- ECMWF: European Centre for Medium-Range Weather Forecasts;
- EUCLEIA: the EU-FP7 'European climate and weather events: interpretation and attribution' project;
- ERA-CLIM: European Reanalysis of the Global Climate System (the project that preceded ERA-CLIM2; Grant Agreement No. 265229 ending 31 December 2013);
- ERA-CLIM2: European Reanalysis of the Global Climate System 2nd project (Jan 2014 to December 2017);
- ERA-Interim: the ECMWF reanalysis, Interim version;
- ERA-5: the ECMWF reanalysis version-5, produced by C3S, under production, which will replace ERA-Interim in 2019;
- ERA-6: the ECMWF reanalysis version 6 that will replace ERA-5 in 2022-2005;
- EU-FP7: European Union Framework-7;
- FCiências.ID: Associação para a Investigação e Desenvolvimento de Ciências;
- FFCUL: Fundação da Faculdade de Ciências da Universidade de Lisboa;
- FMI: Ilmatieteen Laitos;
- GA: General Assembly;
- GPCC: Global Precipitation Climatological Center;
- GRAS: GNSS (Global Navigation Satellite System) Receiver for Atmospheric Sounding;
- HadISST: Hadley Centre Sea Ice and Sea Surface Temperature data set;
- HadISST2: 2nd version of the HadISST data set;
- ICR5: the 5th International Conference on Reanalysis, held in Rome in November 2017;
- INRIA: Institut National de Recherche en Informatique et en Automatique;
- IR: infra-red (IR);
- MERCO: Mercator Océan Société Civile;

- METFR: Météo-France;
- METO: UK Met Office;
- NEMO: the Nucleus for European Modelling of the Ocean;
- NEMOVAR: the NEMO variational data assimilation system;
- ODB: the ECMWF Observation Data Base;
- OHT: Oceanic Heat Content;
- ORA-20C: ocean reanalysis of the 20^{th} century produced at ECMWF;
- ORAS4: the ECMWF ocean reanalysis version 4;
- ORCHIDEE: global process-oriented Terrestrial Biosphere Model;
- QA4ECV: the EU-FP7 'Quality assurance for essential climate variables' project;
- RIHMI: All-Russian Research Institute of Hydrometeorological Information-World Data Centre;
- SST: sea-surface temperature;
- UBERN: Universität Bern;
- UERRA: the EU-FP7 'Uncertainties in ensembles of regional reanalyses' project;
- EUMST and EUMETSAT: The European Organisation for the Exploitation of Meteorological Satellites;
- UNIVIE: the Universität Wien;
- UREAD: the University of Reading;
- UVSQ: Université de Versailles Saint-Quentin-en-Yvelines;
- WV: water vapor;
- WMO: the World Meteorological Organization;
- 4d-Var: 4-dimensional (3 in space plus time) variational assimilation system;