ERA-CLIM2

4th General Assembly

12-13 December 2017 (Univ. of Bern)

Report

At the ERA-CLIM2 4th General Assembly (GA4), held at the University of Bern on 12-13 December 2017, about 30 people from the ERA-CLIM2 partners assessed the project's progress just two weeks before its conclusion (31 December 2017). GA4 follows GA1 held in November 2014, GA2 held in December 2015 and GA3 held in January 2017. During the meeting, open and outstanding scientific and technical issues were discussed, and the work-packages' plans to advance work were presented.

This GA4's report was prepared by the ERA-CLIM2 Coordinator (Roberto Buizza) and the Leaders of work-packages 1-4 (Patrick Laloyaux, Matthew Martin, Stefan Brönnimann and Leopold Haimberger), with input from all the GA4's participants. The report is organized as follows:

- Section 1 briefly summarizes the main goal and objectives of ERA-CLIM2;
- Section 2 reports the work progress of the past 12 months of the main work-packages (WP1, WP2, WP3 and WP4);
- Appendix A lists the GA4 program;
- Appendix B lists ERA-CLIM2 publications.

1 ERA-CLIM2 main goal and objectives

The main goal of ERA-CLIM2 is to apply and extend the current global reanalysis capability in Europe, in order to meet the challenging requirements for climate monitoring, climate research, and the development of climate services.

The five main objectives for the ERA-CLIM2 project (see Section B1.1 of Annex I of the Grant Agreement) are:

i. Production of an ensemble of 20th-century reanalyses at moderate spatial resolution, using a coupled atmosphere-ocean model, which will provide a consistent data set for atmosphere, land, ocean, cryosphere, including, for the first time, the carbon cycle across these domains;

ii. Production of a new state-of-the-art global reanalysis of the satellite era at improved spatial resolution, which will provide a climate monitoring capability with near-real time data updates;

iii. Further improvement of earth-system reanalysis capability by implementing a coherent research and development program in coupled data assimilation targeted for climate reanalysis;

iv. Continued improvement of observational data sets needed for reanalysis, in-situ as well as satellite-based, with a focus on temporal consistency and reduction of uncertainties in estimates of essential climate variables;

v. Development of tools and resources for users to help assess uncertainties in reanalysis products.

More information about the ERA-CLIM2 project and a copy of the GA4 talks (see Appendix A for the Agenda and Appendix B for the list of participants) can be accessed from the ECMWF web site, following the links below:

– Project: http://www.ecmwf.int/en/research/projects/era-clim2

– GA4 presentations: https://www.ecmwf.int/en/4th-general-assembly-university-bern-12-13-december-2017

2 Progress report and plan for 2017

The past 12 months have seen the completion of 9 years of the higher-resolution, coupled CERA-SAT reanalysis: this is the first coupled reanalysis of part of the satellite-era, generated using a coupled 3-dimensional ocean, sea-ice, land and atmosphere model, and all available observations. CERA-20C has been used to generate the land and ocean carbon reanalyses of the 20th century. More data have been rescued and post-processed, and have been delivered to relevant data bases so that they can be used in future reanalysis (e.g. in the ECMWF/Copernicus ERA5 reanalysis under production, and in the future ERA6 reanalysis). New assimilation methods have been developed, tested and integrated in the software repositories.

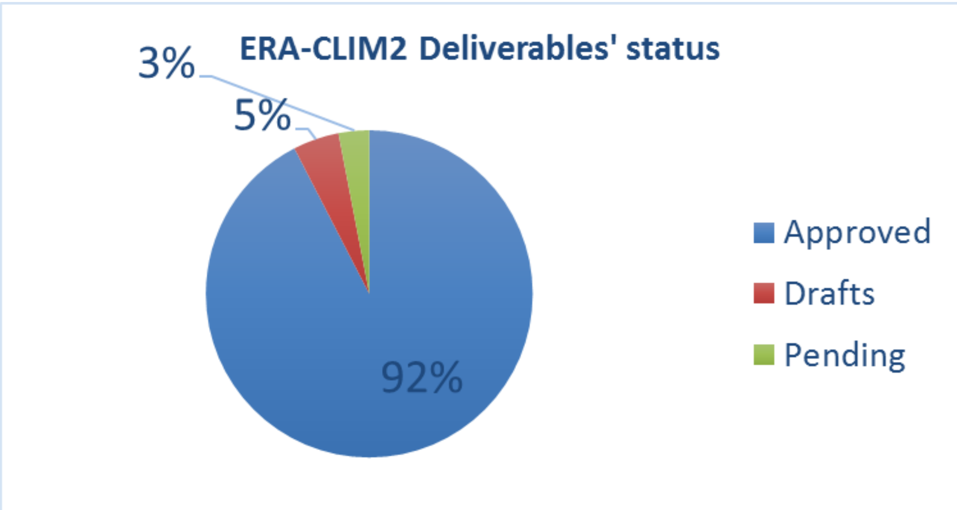

Figure 2.0.1. ERA-CLIM2's deliverables' status on 22 December 2017.

In terms of deliverables (Fig. 2.0.1), 61 of the 66 deliverables have been completed: the remaining 5 are expected to be completed before the project's closure. 66 publications either written by authors funded by ERA-CLIM2, or that used ERA-CLIM2 data have been published and/or submitted (see Appendix B).

The progress and plan for 2017 of the ERA-CLIM2 four main work packages, prepared by the ERA-CLIM2 Work-package leaders with input from all participants, are presented below.

2.1 Work-package 1 – Global 20th century reanalysis

Three new reanalysis datasets have been produced this year: CERA-20C/Carbon (D1.2), CERA-SAT (D1.3) and CERA-SAT/Carbon (D1.4).

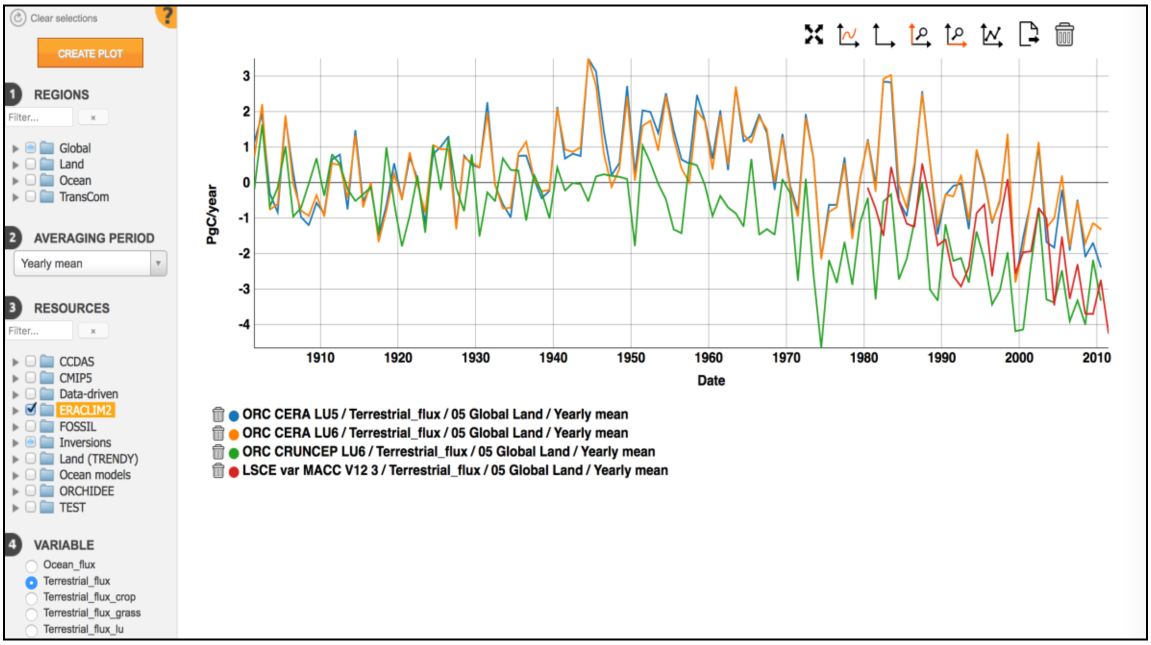

Figure 2.1.1 Illustration of the website facility that displays the temporal evolution of the CERA-20C/Land Carbon product, with the different menus on the left and the interactive graphic on the right.

CERA-20C/Carbon is the land and ocean carbon cycle reanalysis of the 20th century forced by the atmospheric fluxes of the coupled reanalysis CERA-20C. The ocean component has been produced at Mercator-Ocean with the PISCES biogeochemical model to reconstruct the evolution of the main nutrients controlling phytoplankton growth and the biogeochemical cycles of oxygen and carbon. CERA-20C/Carbon Ocean is available at 2 temporal resolutions. Monthly mean PISCES outputs are available for alkalinity, air-to-sea CO2 flux, surface pCO2, chlorophyll, Dissolved Inorganic Carbon (DIC), Iron, nitrate, net primary production, dissolved oxygen, Photosynthetically Available Radiation (PAR), phosphate and silicate variables. Annual means are available for all variables of the PISCES model. CERA-20C/Land Carbon is based on the ORCHIDEE biogeochemical model used in the IPSL Earth System Model (IPSL-ESM). It provides an historical reconstruction of the land carbon fluxes and stocks for different Plant Functional Types (PFTs). The main carbon fluxes and stocks are provided, separately for different groups of plant functional types (Gross Primary Production, Growth Respiration, Maintenance Respiration, Heterotrophic Respiration, Emission from vegetation conversion, Total biomass). The land carbon fluxes and stocks can be visualized through a web-portal that provides a user-friendly interface to analyse the main features of the CERA-20C/Land carbon reanalysis: http://eraclim.globalcarbonatlas.org/ (User/Passwd: eraclim / eraclim2017). The password protection will be dropped at the end of the project (end of December 2017) and the site will include also the ocean carbon reanalysis. The web site provides two different visualizations facilities:

- A mapping facility to view the spatial distribution for a specific year or month of the different carbon fluxes and stocks.
- A « time series » facility to view the temporal evolution of the land carbon fluxes and stocks aggregated over an ensemble of pre-defined regions (continental to regional scales) over the last century.

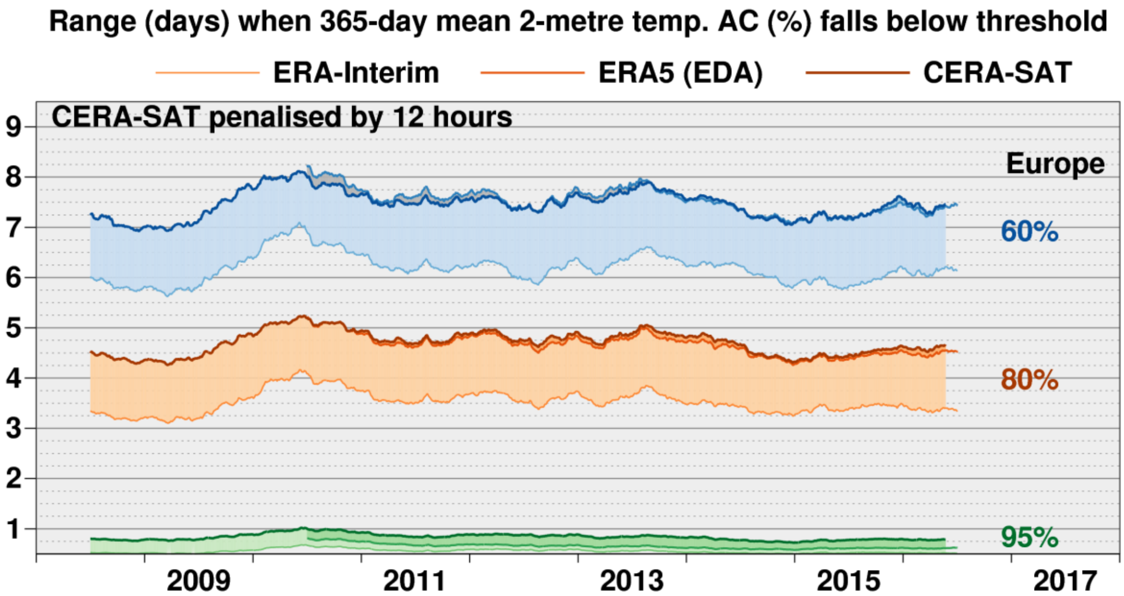

Figure 2.1.2 Number of days when the 2-metre temperature anomaly correlation falls below a given thresholds for the forecasts initialised by ERA-Interim, ERA5 and CERA-SAT.

CERA-SAT is a reanalysis dataset spanning 8 years between 2008 and 2016. It is a proof-of-concept for a coupled reanalysis with the full observing system available in the modern satellite age. CERA-SAT has been created using the ECMWF's coupled assimilation system (CERA) and comprises an ensemble of 10 individual members. The ensemble accounts for model and observational errors and can be used to infer information on the uncertainty of the analysed fields. The CERA-SAT product describes the spatio-temporal evolution of the atmosphere with a native resolution of approximately 65km in the horizontal on 137 vertical model levels between the surface and 0.01 hPa. The ocean component is based on the tripolar ORCA025 grid, with a ¼ degree horizontal resolution at the equator (27km) and 12 km in the Arctic Ocean. The 75 vertical model levels sample the ocean from surface to bottom, with a first layer of 1-meter width. To produce the CERA-SAT dataset in a reasonable period of time, the period 2008-2016 was divided into 4 different streams of 2-3 years. Each production stream was initialised from the uncoupled reanalyses ERA-Interim (atmosphere) and ORAS5 (ocean). The first 6 months of each production stream were used for spin-up to produce the final climate dataset for the period 2008-2016. The CERA-SAT reanalysis is made publically available through the Meteorological Archiving and Retrieval System (MARS). The MARS can be accesses and the data selected and retrieved through the MARS Catalogue available at http://apps.ecmwf.int/mars-cataloque.

CERA-SAT/Carbon provides two associated land reanalyses based on the CHTESSEL and the ORCHIDEE land surface models. Using two different models for this reanalysis will provide a first hint on the uncertainties associated to land carbon, water and energy fluxes over the CERA-SAT period. CERA-SAT/CHTESSEL is a 10-member ensemble of land-surface reanalyses spanning 8 years between 2008 and 2016. The CHTESSEL model is forced by the atmospheric fields from the CERA-SAT reanalysis. Additionally, in-situ and satellite observations of selected geophysical variables are assimilated through a dedicated land data assimilation system. CERA-SAT/ORCHIDEE reconstructs land fluxes and carbon stocks for the period 2008-2014 using the control member of the CERA-SAT reanalysis. An additional simulations forced by the climate CRU-NCEP atmospheric fluxes has been produced to provide a hint on the impact of climate uncertainties on the land fluxes/stocks.

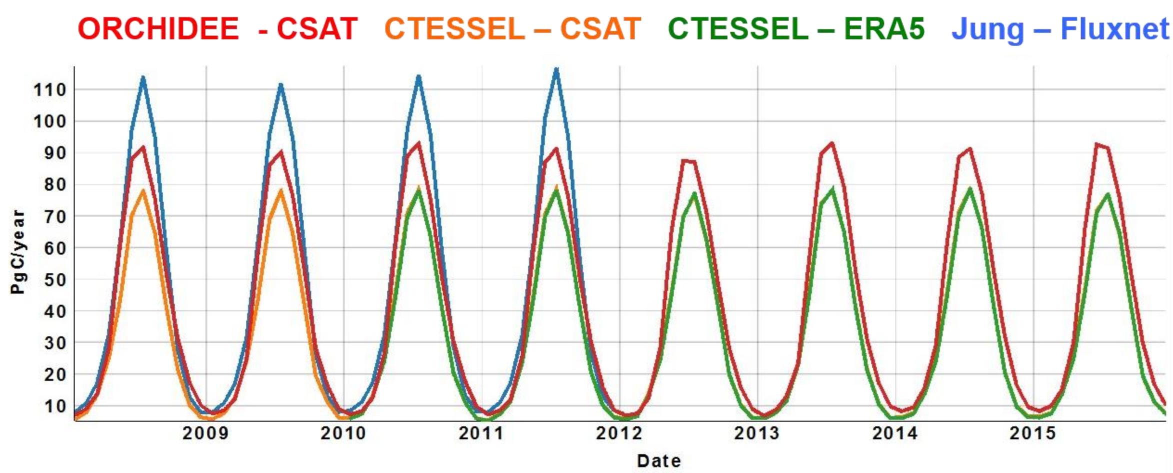

Figure 2.1.3 Time series of the Gross Primary Production (uptake of carbon by the vegetation) in the Northern Hemisphere from CERA-SAT Carbon produced by the ORCHIDEE model (red) and by the CTESSSEL model (orange).

Besides the production of CERA-20C/Carbon, CERA-SAT and CERA-SAT/Carbon, a first assessment of CERA-20C (D1.1) has been completed focusing on the performance of the CERA assimilation system and on the climate trends. This assessment includes a study on ocean and sea-ice trends. Further developments have been also made to improve the assimilation of Tropical cyclone best track observations (IBTrACS) for a possible future reanalysis of the 20th century. Finally, the assimilation of radiosondes observations has been investigated to extend further back in time reanalyses of the satellite era such as ERA5.

2.2 Work-package 2 – Future coupling methods

The partners of WP2 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. Relevant developments have been made available for implementation in the CERA (Coupled ECMWF Reanalysis) framework developed at ECMWF. The work package addressed the special requirements for the pre-satellite data-sparse era and the requirement to maintain a consistent climate signal throughout the entire reanalysis period.

The work package consists of four main work areas:

1. To include SST and sea-ice assimilation in the ocean data assimilation system NEMOVAR
2. To improve the ocean analysis component in NEMOVAR, including use of ensembles and 4D-VAR
3. Development of the carbon component of coupled earth system reanalysis
4. Developments towards fully coupled data assimilation.

As of the 4th General Assembly, all WP2 deliverables have been completed, reviewed and submitted. All relevant code developments have been made available in the NEMOVAR code repository hosted at ECMWF and a new version of the NEMOVAR code (v5), containing all the ocean DA developments made in ERA-CLIM2 is about to be released. In terms of research publications, 13 papers related to WP2 have been published, submitted or are in preparation.

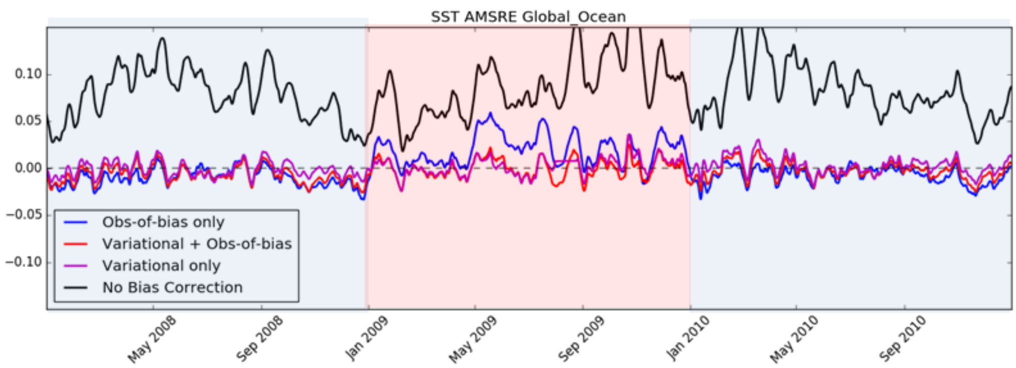

Fig. 2.2.1. Global mean observation-minus-background time-series for the AMSRE microwave SST satellite from Jan 2008 to Dec 2010. Black line – no bias correction; blue line – bias correction using only observations-of-bias; purple line – variational bias correction; red line – combined scheme. During the middle year (2009), the reference satellite data from AATSR were withheld from all experiments.

2.2.1 SST and sea-ice assimilation development

The SST data assimilation developments made by the Met Office in ERA-CLIM2 were in two main parts. The first developed improved schemes for satellite SST bias correction. Theoretical and idealized studies were carried out to determine the most appropriate scheme for producing consistent estimates of the biases when few reference observations are available. Reanalysis experiments were then carried out with the NEMO/NEMOVAR system at ¼ degree resolution, assimilating in situ and satellite SST, satellite sea surface height (SSH) data, in situ temperature and salinity profiles and satellite sea-ice concentration data. Various bias correction schemes were tested, and comparisons to AMSRE data are shown in Fig. 2.2.1. These results demonstrate that the proposed bias correction scheme (the red line) produces a stable time-series during the three year experiment, even when the main reference satellite data from AATSR were withheld during the middle year. The technical developments required for this have been included in the ECMWF NEMOVAR repository.

The second development for improved assimilation of SST data is a scheme for improving the assimilation of sparse historical data through the use of Empirical Orthogonal Functions (EOFs). The scheme was integrated within the NEMOVAR framework and was coded in such a way that it could be combined with the existing background error covariance model in NEMOVAR. Experiments were carried out to assess the impact of using EOFs compared to the existing error covariances by sub-sampling modern day data to resemble the past observing system. Monthly objective analyses of the data using a hybrid scheme (EOF combined with Gaussian functions) produced improved fit to withheld data. Tests in a cycling reanalysis framework using EOFs generated from a 100-year coupled climate simulation showed small improvements in some regions, but further work is needed to deal with the effect of model bias on the spreading of information using large-scale EOFs, particularly in the sub-surface ocean.

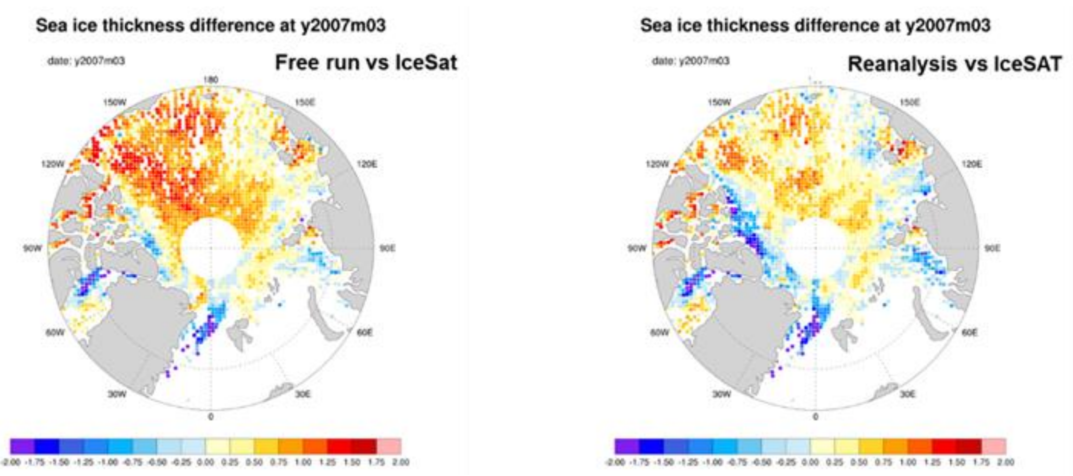

Fig. 2.2.2. Comparison of the model sea-ice thickness with IceSAT data for March 2007 from a free model run (left) and a run assimilating sea-ice concentration data (right).

Sea-ice assimilation developments were made by Mercator-Ocean. They investigated multi-variate assimilation to adjust sea-ice thickness when assimilating only concentration data, and tested the use of anamorphosis transformations to deal better with the non-Gaussianity of sea-ice variables. Assimilation of sea-ice concentration was shown to improve the fit to data, not only of sea-ice concentration, but also of sea-ice thickness (see Fig. 2.2.2). Tests of the anamorphosis transformations were carried out in idealised frameworks and showed that an Ensemble Kalman Filter (EnKF) using the transformation produced posterior distributions which agreed better with those of a Particle Filter, compared with a standard EnKF.

2.2.2 Development of the ocean analysis component in NEMOVAR and assessment of methods for simplified air-sea balance in data assimilation

Two methods have been developed by CERFACS to use ensemble perturbations to define the background error covariance matrix:

1. Estimate parameters (variances and correlation length scales) of the covariance model.
2. Define a localized, low-rank sample estimate of the covariance matrix.

Hybrid formulations of both 1 and 2 have also been developed in which the ensemble component is linearly combined with a parameterized component. Both methods 1 and 2 include optimally-based algorithms for filtering parameters and for estimating hybridization weights and localization scales. Fig 2.2.3 shows an example of the standard parametrized error standard deviations at 100m depth as well as a hybrid ensemble-parameterized estimate of the standard deviations. The latter provides improved structures of the standard deviations in western boundary currents where the errors are expected to be larger than in the parameterized estimates.

The correlation operator, localization operator and parameter filter are based on an algorithm that involves solving an implicitly formulated diffusion equation. The diffusion model has been completely revised to make it more general, to eliminate numerical artefacts near complex boundaries, and to improve computational efficiency and scalability on high-performance computers. Details have been documented in a peer-reviewed article (Weaver *et al.,* 2016) and in an ECMWF technical memorandum (Weaver *et al.,* 2017). All methods have been integrated into a new version of NEMOVAR (v5) that is available in the central code repository at ECMWF. The operational scripts at ECMWF have been adapted to run NEMOVAR v5 in an Ensemble of Data Assimilations (EDA) framework. Preliminary experiments testing ensemble and hybrid (parameterized + ensemble) variances show positive results compared to parameterized-alone variances.

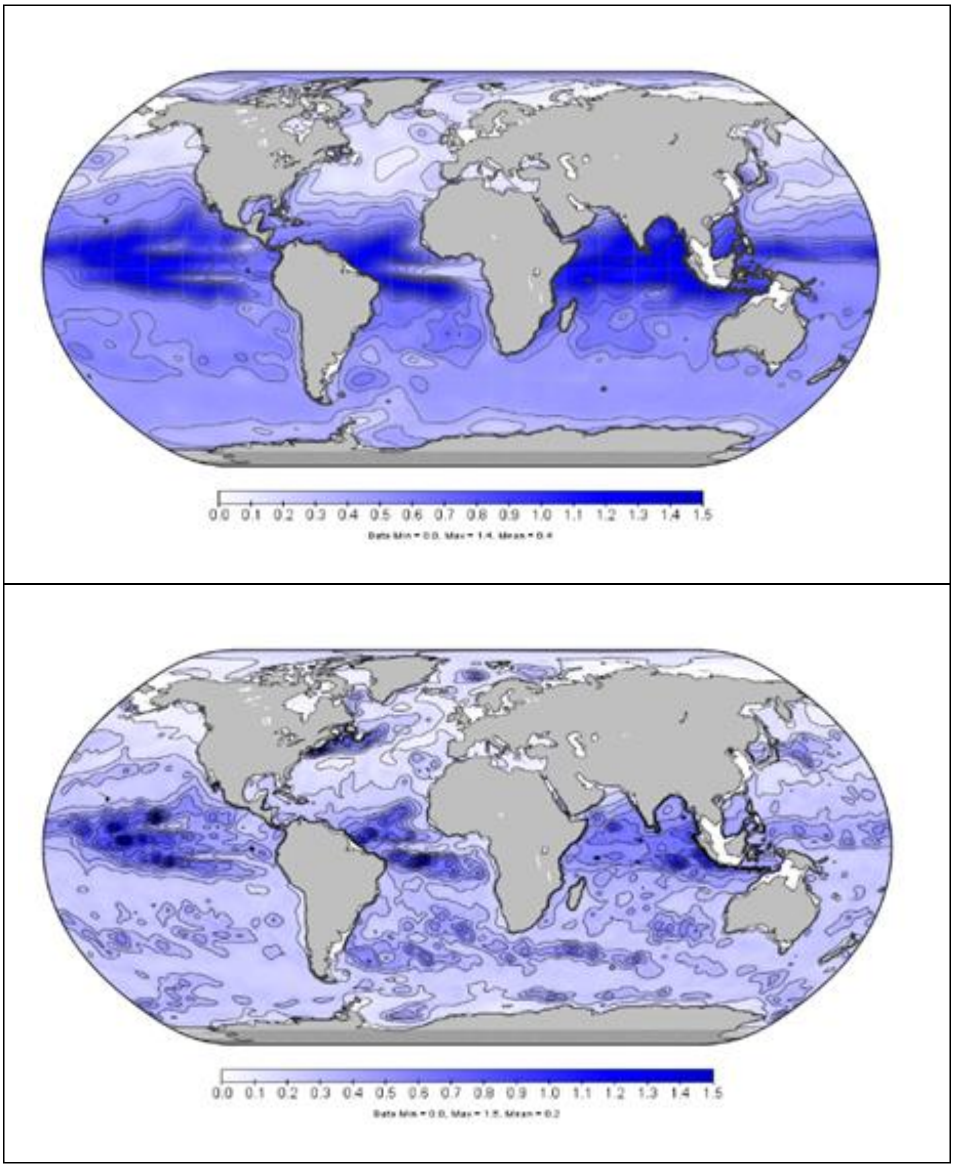

Fig. 2.2.3. Example of parameterized and hybrid temperature error standard deviations at 100m depth, estimated from the ECMWF 11-member ensemble of ocean reanalyses.

A new way of specifying air-sea error covariances in data assimilation was proposed and tested by CMCC. To couple the sea-surface variables with 2m atmospheric variables, balances might be thought of as purely statistical, purely analytical, or mixed (balanced + unbalanced components). A balance operator was introduced that maps the increments of SST onto those of surface air temperature and humidity using a tangent-linear version of the CORE bulk formulae. This scheme was tested in a simplified coupled model in which the ocean model was NEMO and an atmospheric boundary layer model was used. Results were compared to ensemble estimates of the air-sea relationships. Negligible impact was found in the Extra-Tropics (probably due to the coupling being dominated by dynamical rather than thermo-dynamical processes in those regions). In the tropics, persistent impact was found throughout the forecast length in the Atlantic. In other basins the impact emerges later in the forecast and was positive everywhere, although significant improvements were found only in the Atlantic Ocean as shown in Fig 2.2.4.

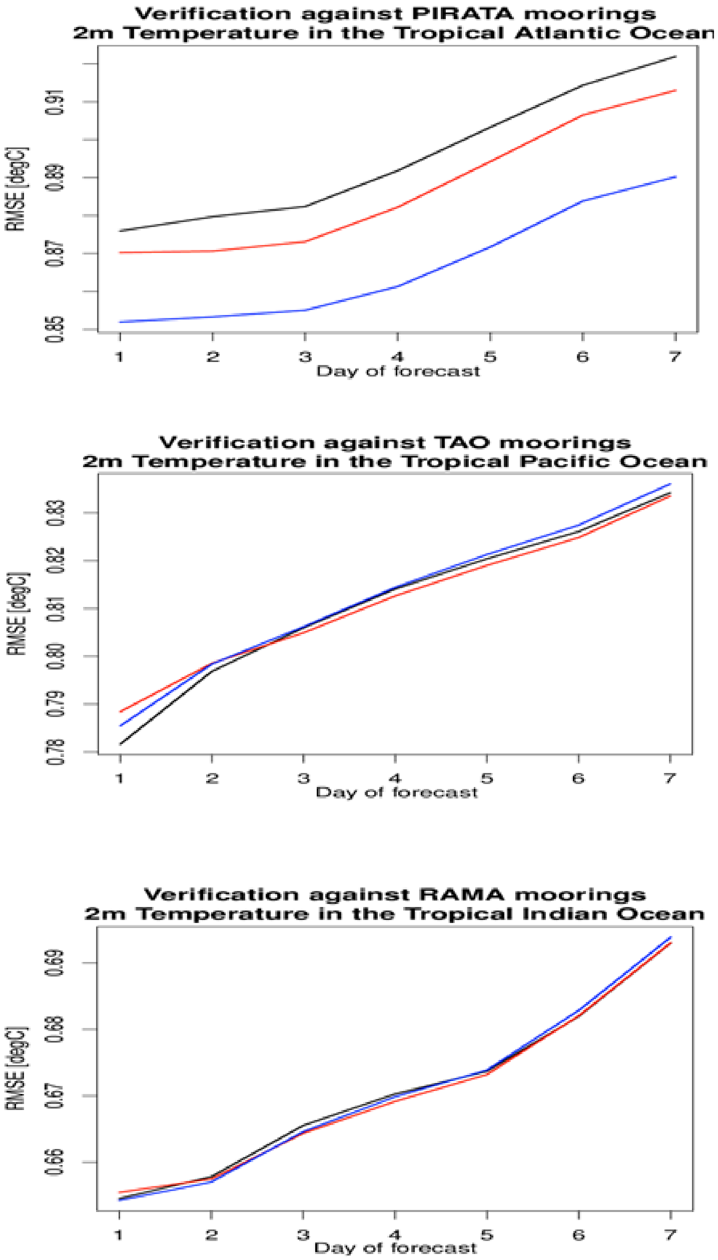

Fig. 2.2.4. Root-mean-square-error in 2m air temperature compared with PIRATA mooring data in the tropical Atlantic Ocean (top left), TAO mooring data in the tropical Pacific (top right), and RAMA mooring data in the tropical Indian Ocean (bottom), as a function of forecast lead time. The black line is weakly coupled assimilation, the red line is strongly coupled assimilation using linearized air-sea balance relationships, and the blue line is strongly coupled assimilation using statistical relationships.

Assessment of the potential impact of 4DVar compared with the 3DVar-FGAT scheme already used in the ocean component of CERA was carried out by INRIA. For the one degree version of NEMO used in CERA-20C, assimilating only T and S profile data, there was very little impact of 4DVar. However, tests in the ¼ degree version of NEMO which is used in CERA-SAT in which SSH data were also assimilated, showed there to be a noticeable impact of using 4DVar, particularly for improving the SSH and velocity fields. However, at high resolution the cost of the ocean analysis becomes dominant and increasing its cost further would limit the achievable length of CERA-SAT. Two options were tested in order to reduce the cost of 4DVar, and both have been made available in the NEMOVAR repository. The first uses a lower resolution grid in the inner loop while the second introduces drastic simplification of the equations used for the tangent-linear and adjoint models. With both of these developments in the ¼ degree model, multi-incremental 4DVar can be made as quick as 3DVar.

2.2.3 Development of the land and ocean carbon components of coupled earth system reanalysis

For the land carbon component, LSCE produced an updated variational data assimilation system to optimize the ORCHIDEE model parameters. An updated version of the model was used in order to be consistent with the one used for CMIP6. The tangent-linear version of the model was then generated using automatic software. An assessment was then carried out of the benefit of different optimisation strategies (e.g. genetic algorithms compared with gradient methods). An evaluation of the benefits of simultaneous vs stepwise optimisation was then carried out, with the stepwise optimisation strategy being adopted to produce optimised model parameters. The assimilation of new data streams in these optimizations was also carried out, including observations of vegetation fluorescence.

The ocean carbon component was developed by Mercator-Ocean. They developed a configuration of CERA-20C/ocean carbon by running many sensitivity tests to single out the best initial conditions, NEMO version and parameter settings. The choice of coupling strategy with the coupled ocean–atmosphere reanalysis CERA-20C was then investigated. It was decided that the best strategy was to run the coupled physical-biogeochemical ocean model forced by atmosphere fluxes coming from CERA-20C to avoid issues associated with the physical ocean data assimilation and the use of various streams of production for the main physical reanalysis, both of which introduced discontinuities when running the biogeochemical model online with the main reanalysis. A first 20th century experiment ERA-20C/ocean carbon forced by the output of the previous ERA-CLIM project (ERA-20C) was carried out and an assessment made of this long experiment, including the main biogeochemical variables and the carbon flux.

2.2.4 Developments towards fully coupled data assimilation

Continued work to assess the strengths and weaknesses of the weakly coupled assimilation method used in CERA-20C was carried out by the University of Reading. In particular, they investigated SST-total precipitation (TP) intra-seasonal relationships. These are shown to be better represented in CERA-20C than in ERA-20C, mainly due to coupled model. Lead-lag plots in Fig. 2.2.5 demonstrate both the importance of the coupled model when there are few observations (green dashed line vs purple dashed line) and the assimilation of ocean/atmosphere observations (green solid line vs green dashed line).

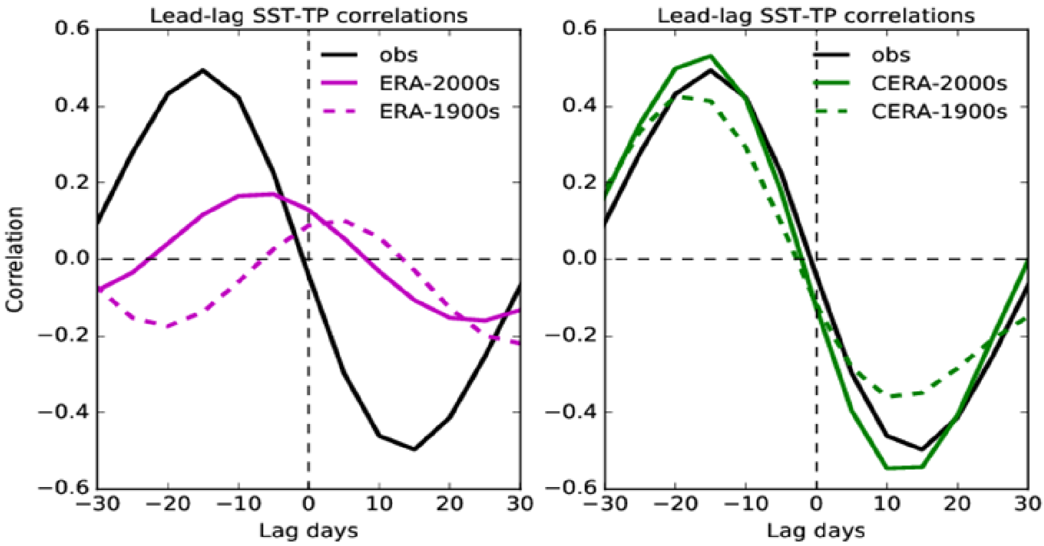

Fig. 2.2.5. Lead-lag correlations between SST and total precipitation in a region in the western Tropical Pacific. The left plot shows results from ERA-20C uncoupled reanalysis while the right plot shows results from the CERA-20C coupled reanalysis. In both plots, the dashed line is the results from the 1900s while the solid colored lines are from the 2000s, and the black solid lines are observational estimates.

The drifts and biases in the CERA-20C coupled reanalysis have also been investigated by University of Reading. CERA-20C was run without any ocean bias correction, and average temperature increments show there to be significant model biases, particularly in the tropical Pacific, associated with biases in the slope of the thermocline. Tests in the year 2009 of the online and offline bias correction schemes, which are used in the ocean-only ORAS5 reanalysis, showed that the bias correction significantly reduces these average temperature increments (see Fig. 2.2.6), with the online scheme having the most impact. The ocean bias correction also produced improvements in the horizontal and vertical ocean velocities, and had impacts on the atmospheric reanalysis with reduced 10m wind increments in the tropics.

Investigations into the use of strongly coupled data assimilation have been carried out by INRIA. Common tractable coupling algorithms lead to flux inconsistency (asynchronicity), and can be damaging to the system behaviour. The question is whether we can improve the ocean-atmosphere flux consistency through data assimilation. In order to answer this question, a stand-alone single column ocean-atmosphere model was developed and interfaced with the ECMWF OOPS framework for developing data assimilation algorithms. A collection of 4DVar cost functions were proposed, penalising the flux consistency and/or controlling the ocean-atmosphere interface conditions. Convergence of the minimisation of the various algorithms (including CERA) was studied. The main outcomes of the work are that ocean-atmosphere flux consistency can indeed be improved, moderately at a small additional cost or significantly at a huge additional cost. Global (outer) convergence can also be improved compared to CERA, so more benefit can be expected from the first outer iterations.

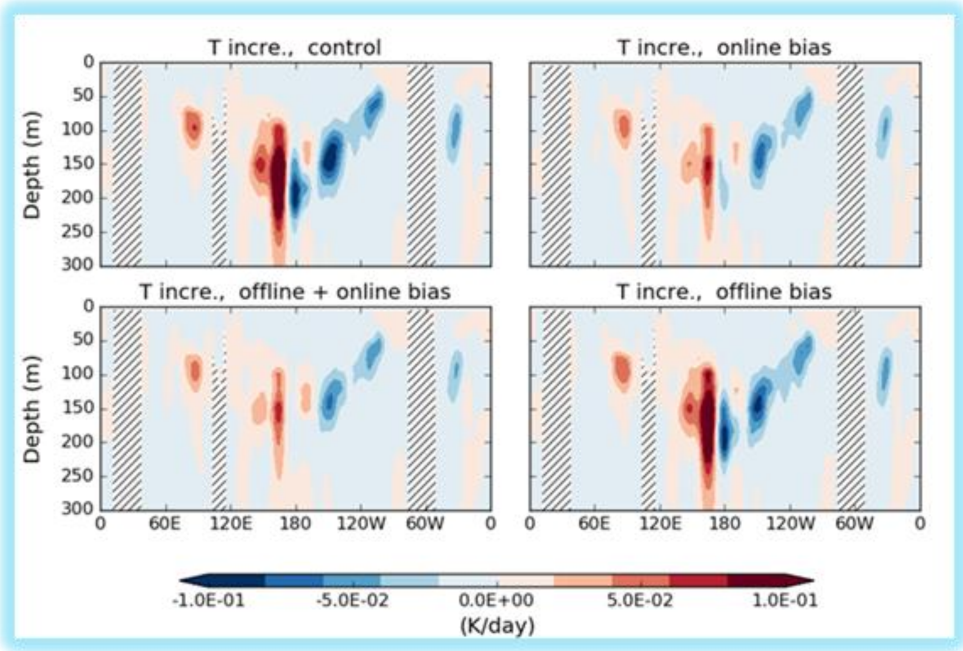

Fig. 2.2.6. Average temperature increments as a function of depth along the equator for the year 2009 from: CERA-20C (top-left); a run with online bias correction (top-right); a run with both online and offline bias correction (bottom-left); and a run with offline bias correction (bottom-right).

2.2.5 Summary of WP2

Many developments have been delivered by WP2 partners in ERA-CLIM2 which could be included in future coupled climate reanalyses. Ocean data assimilation developments have been incorporated into a new version of the NEMOVAR code (hosted at ECMWF) including: SST bias correction; EOF error covariances; hybrid ensemble-variational DA; 4DVar. The ocean data assimilation is now much closer in terms of complexity to the atmospheric assimilation scheme used in CERA. Coupled data assimilation research has led to some useful ideas for improving future versions of CERA including: improved understanding of methods to increase the coupling in the DA either through linearized air-sea balance or methods used to improve coupling in models; improved understanding of the ocean bias correction in the coupled system. Improvements have also been made to the ocean and land carbon components of the reanalysis.

2.3 Work-package 3 – Earth-system observation

Earth-system observations are crucial to reanalyses. First and foremost, observations provide information on the state of the atmosphere and ocean that can be assimilated into a numerical weather prediction model in order to produce the reanalysis. However, observations are also used in several other steps along the processing chain. They are used to constrain the boundary conditions of the numerical weather prediction model, to calibrate statistical relations used in the processing (e.g., for geophysical parameter estimation from satellite data), to determine and correct the error of other observations, and to evaluate the final reanalysis product.

Work package 3 encompasses all activities in ERA-CLIM2 that relate to observations, spanning from archive research on sea-ice sightings by whaling ships to satellite data reprocessing. This work can be structured into data rescue and quality control of surface and upper-air data, snow data products, marine data products, and satellite data reprocessing.

In order to better organise the data rescue work, ERA-CLIM2 has further developed the metadata base that was inherited from ERA-CLIM, now termed "registry". This registry has been updated and made cross-searchable. Furthermore, maps can be plotted. As an example, Fig. 2.3.1 shows the upper-air data rescued within ERA-CLIM and ERA-CLIM2. In the future, this registry should become a tool for the climate observations community. Within Copernicus C3S, the registry will be further developed and will incorporate metadata from all other existing holdings.

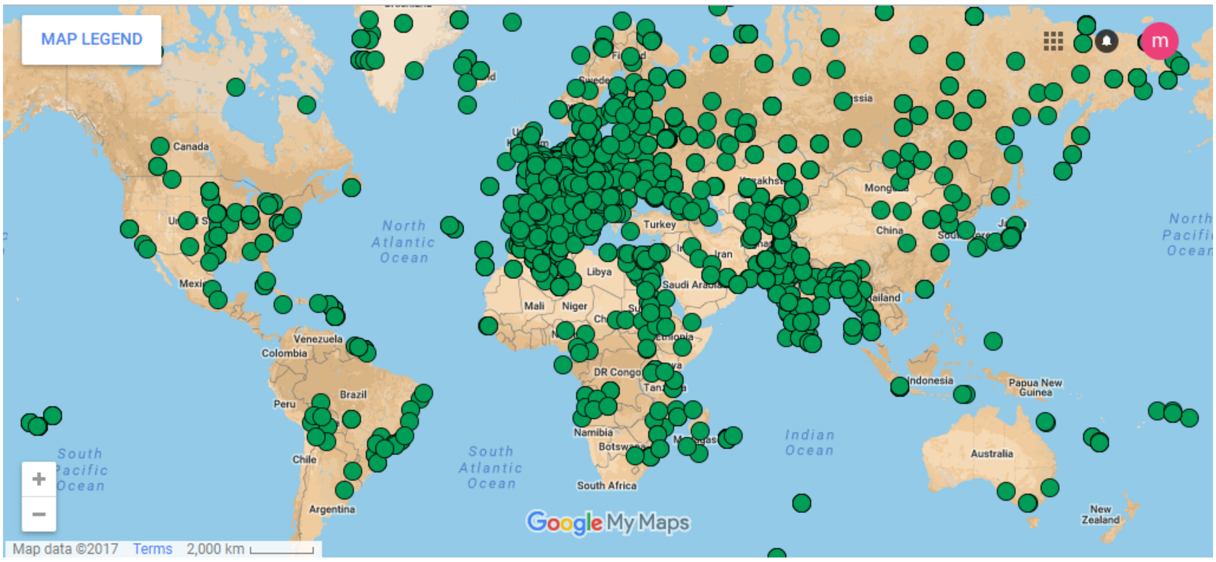

Fig. 2.3.1. Map of the locations of fixed upper-air stations rescued in ERA-CLIM and ERA-CLIM2 as plotted through the registry.

The data rescue work has been carried out throughout the project and will continue. Tables 2.3.1 and 2.3.2 summarize the amount of data imaged, rescued, and quality controlled within ERA-CLIM and ERA-CLIM2. The same holds true for the quality control (QC). All surface data were QC'ed at FCiências.ID. The upper-air data digitised by FCiências.ID and MétéoFrance were sent to RIHMI for QC, from where they were distributed to Univ. Vienna, Univ. Bern and ECMWF. These activities have continued and a version 2.1 of the Comprehensive Historical Upper-Air Network (CHUAN) was released in July 2017.

The data rescue work will continue. At MétéoFrance, this work was transformed into an operational activity. Data rescue will also be continued at FCiências.ID. A new version of CHUAN (v2.2) might be released in spring 2018.

Source	Cataloged	Digitized	QC'ed
Backward extension (<1965) of meteorological data from 246 Russian stations	2738595	2738595	2738595
41 Chilean stations 1950-1999	383151	357456	36682
76 Portuguese stations in Portugal and ex-colonies in Africa and Asia	1020727	1009131	605478
South China Sea logbooks for 100 stations	830286	830286	830286
Snow data for 20 stations in Russia	622325	622325	622325

Table 2.3.1: Surface observations (in station days) digitized within ERA-CLIM and ERA-CLIM2.

Source	Imaged	Digitized	QC'ed
Russian radiosonde data, for 41 stations, 1938-1964	167401	167401	167401
Daily Weather Report, Germany, 1903-1934	118020	117837	114187
India Meteorol. Dept., 1928-1936	113779	113779	113779
Indian Daily Weather Report, 1938-1942	106379	106379	106379
Pakistan daily Weather report, 1949-1956	101714	101714	101714
Daily Weather Report, Cairo, 1920-1953	68184	68184	68184
Aerological Observations, Netherlands, 1909-1940	59054	59054	59054
International Days, 1923-1928	53883	53883	53725
Monthly Bulletin, Portugal (Mozambique), 1938-1956	27402	23292	23292
Annual Bulletin, Finland, 1919-1934	19583	19583	19583
Moving upper-air data, 1888-1947	9000	9000	9000
MétéoFrance Data Base, 1948-1958	0	33818	33818
Comptes Rendus, 1923-1957	216608	86476	67201
Other French sources, 1900-1957	98894	35375	25210
Spanish data, 1912-1961	14519	14519	14519
Portuguese Annals, 1939-1972	27093	27093	27093
Other sources, upper-air	77632	75746	75762

Table 2.3.2: Upper-air observations (in station days) digitized and processed within ERA-CLIM/ERA-CLIM2 (CHUANv2.1).

The FMI prepared two snow data sets. One data set comprises ca. 30 000 snow courses since 1935. Figure 2.3.2 shows an example of a snow course. The snow course should represent the typical landscapes of a site and be representative for a region. Along the course, snow is measured ca. every 100 m and the snow depth is then averaged. This data set of snow depth, snow water equivalent and snow density is made available via http://litdb.fmi.fi/eraclim2.php.

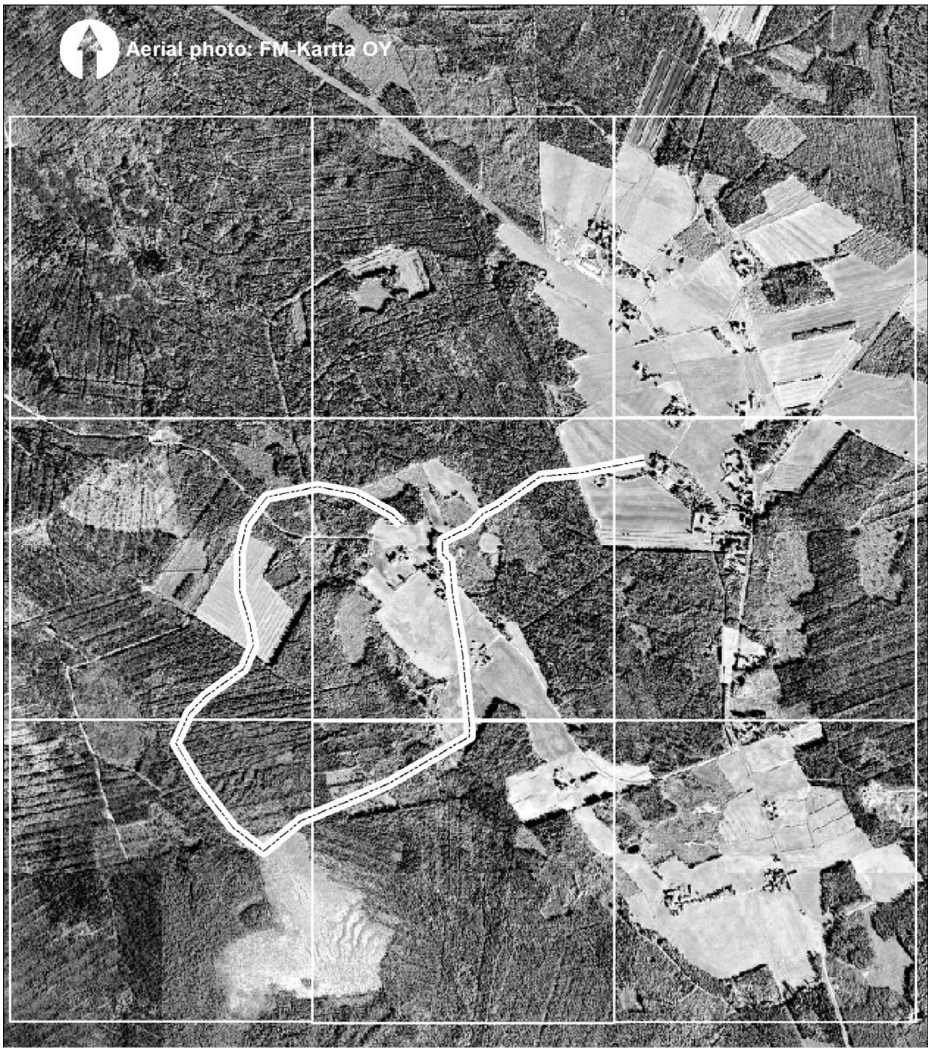

Fig. 2.3.2. Example of a snow course from Finland.

In addition to snow courses, FMI also prepared a satellite derived snow water equivalent product, which constitutes a further development of the successful GlobSnow data set. Daily maps of snow cover for the 1979-2016 period (based on combination of space-borne microwave radiometer data, optical satellite data and in situ observed synoptic snow depth observations) are available at: http://www.globsnow.info/swe/archive_v2.1_Eraclim

EUMETSAT reprocessed satellite data from various platforms and sensors. They processed AVHRR polar winds (from AVHRR GAC data, 1982-2014), recalibrated infra-red (IR) and water vapour (WV) radiances from Meteosat First Generation and Meteosat Second Generation and derived atmospheric motion vectors from these products. Finally, they processed Radio Occultation data from GRAS/CHAMP/COSMIC/GRACE using wave optics. While the processing was delayed due to IT system issues, all of the products except the Atmospheric Motion Vectors are produced. The Atmospheric Motion Vectors will be delivered in January 2018.

Reprocessing satellite data posed a new challenge to an operational service such as EUMETSAT. Reprocessing requires completely different processes, including hardware and archiving facilities, than operational processing. Prior to ERA-CLIM2, EUMETSAT had never embarked on a large data processing project. These new procedures were now established within ERA-CLIM2, and the work at EUMETSAT will be continued.

The vision of work package 3 was summarised in a common publication that was submitted to the Bulletin of the American Meteorological Society.

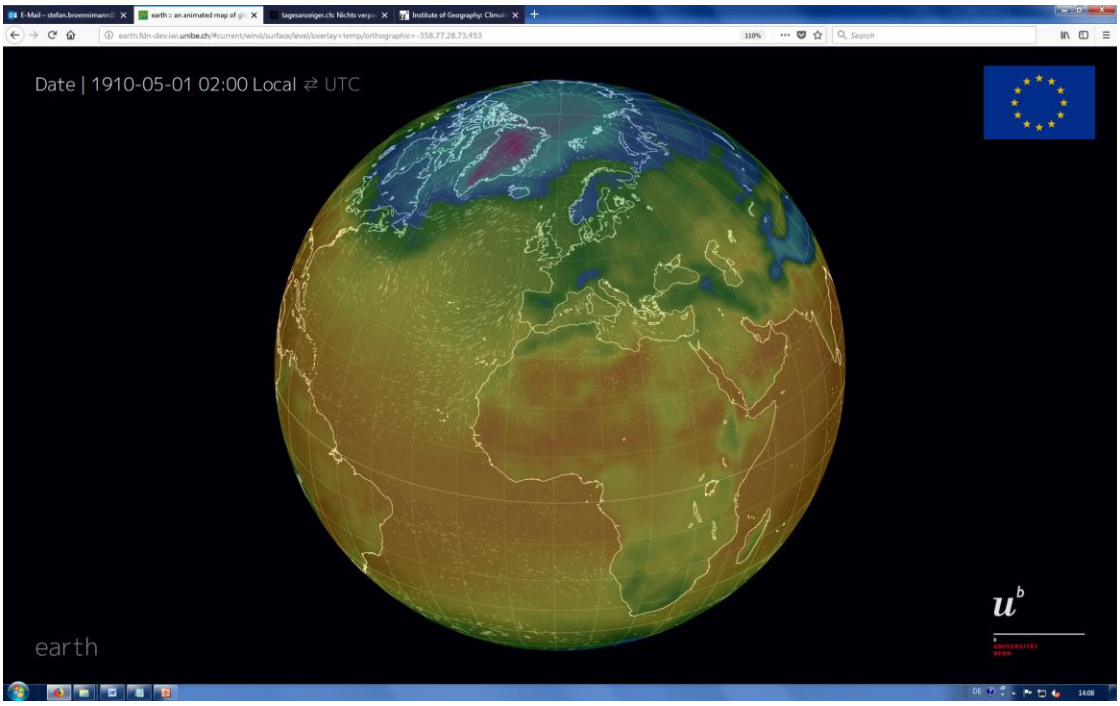

Fig. 2.3.3. Interactive visualization of CERA-20C on the Univ. Bern website.

In addition to the work on observations, UBERN also engaged in several outreach activities. A video was produced which explains data assimilation and the generation of a historical reanalysis in a simple way using the analogy of a football kick (http://www.geography.unibe.ch/ueber_uns/aktuell/index_ger.html#e634655). Further, an interactive visualization of the CERA-20C reanalysis was developed (http://earth.fdn-dev.iwi.unibe.ch/, Fig. 2.3.3). Finally, a book was published with ten case studies of historical extreme weather events that were studied in different reanalysis data sets http://www.geography.unibe.ch/dienstleistungen/geographica_bernensia/online/gb2017g92/index_ger.html).

2.4 Work-package 4 – Quantifying and reducing uncertainties

For both observations and reanalyses, the errors need to be quantified and reduced. For observations, particularly in the pre-satellite era, that means first of all to digitize and check as many as possible, as has been described in Work-package 4. The second step is then to reduce biases in the observations and in the assimilation process, since they are the main source for uncertainties in low frequency variability and trends.

After assimilation the state and flux quantities calculated in the reanalyses need to be compared with the state of the art (other reanalyses and independent observation data) to assess the quality of the products. Intercomparison of reanalyses, which are petabyte-sized data sets, has many aspects, and priorities had to be set. We concentrated on CERA20C, since CERA-SAT has been finished relatively late in the project, and we concentrated on upper air temperature, energy budget components and precipitation, since those are most essential for intercomparison with climate model and for driving regional climate models, hydrological and biogeochemical models.

2.2.3 Upper air bias adjustment

The bias adjustments for radiosonde data as documented in Haimberger et al. (2012) and as used in ERA-Interim had to be updated to cover the pre-IGY period and to 2017 in order to be suitable for the Copernicus reanalysis ERA5, which is planned to reach back to 1950. For this task the upper air data collected in the CHUAN 2.1 archive, which contains all upper air data digitized within ERA-CLIM and ERA-CLIM2 up to July 2017 have been converted into the so-called ODB2 format. Together with the data holdings at NCAR, in the ERA40 BUFR archive and in the MARS, which are also available in ODB2 format, the raw upper air data set is ready for assimilation back to at least 1950.

Based on this data set bias adjustments have been calculated using an updated version (v1.6) of the RAOBCORE/RICH homogenization software as described in Haimberger et al. (2012). As reference series either a concatenation of ERA-preSAT (1939-1966, Hersbach et al. 2017), JRA55 (1967-1978) and ERA-Interim (1979-2016) (“eijra”) or a concatenation of CERA20C (1939-1957) and JRA55 (1958-2016) (“jrace20c”) have been used for break detection. The same reference, or a reference composed of neighbouring radiosonde records have been used for break adjustments. Trying different reference data allowed for estimating the uncertainty in the adjustment process.

In the new RAOBCORE version, a substantial and pervasive temperature bias over Former Soviet Union (FSU) radiosondes in the upper troposphere could be much better adjusted. The impact of the adjustments on temperature trends at 300 hPa in the pre-satellite era is evident in Fig. 2.4.1. At later periods the agreement of adjusted radiosonde temperatures with MSU satellite brightness temperatures and GPS-RO measurements has improved as well. Furthermore, monthly mean solar elevation dependent bias adjustments, which have been calculated from departure statistics from ERA-Interim or JRA55 and are zero in the annual mean, have been added in RAOBCORE v1.6 in the satellite era (1979-) to account for seasonal variations of the radiosonde temperature bias. In addition to this, QC on FSU upper air data and surface data from Portugal and former dependencies have been performed.

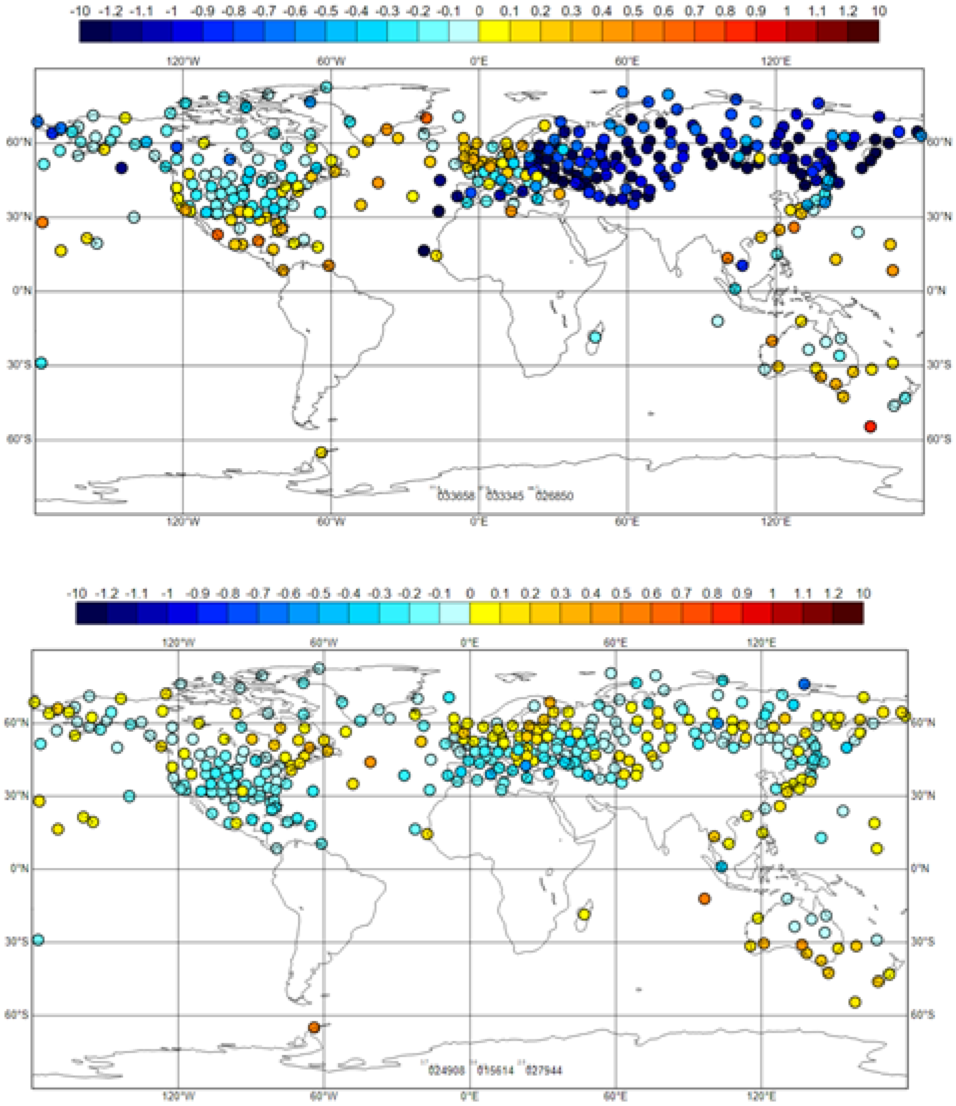

Figure 2.4.1: Linear temperature trends in K/decade (indicated by colour of bullets) from unadjusted radiosonde time series (top) and adjusted radiosonde time series using CERA20C as reference for the period 1954-1974 at 300 hPa. At least 19 years of data out of 21 years had to be available for a bullet to be plotted.

Diagnostic evaluations of coupled budgets of energy, water and carbon can help to detect biases in climate models as well as in reanalyses. Not surprisingly they are required in CMIP6 model intercomparisons and they are highly recommended by GCOS. A comprehensive evaluation of precipitation from 1900 onward, using GPCC gauge-based precipitation as reference, revealed that CERA20C precipitation is more realistic than ERA20C. Systematic errors have been detected also in CERA20C, particularly in the Tropics, where CERA20C develops a strong dry bias over Amazonia and Indonesia under El Nino conditions. This has a strong effect on the results of ecosystem models such as ORCHIDEE, where precipitation is one of the most important driver. From 1988-2010 also daily precipitation could be compared with GPCC. Fig. 2.4.2 compares the maximum number of consecutive dry days in ERA-20C, CERA20C and the GPCC Full Data Daily product.

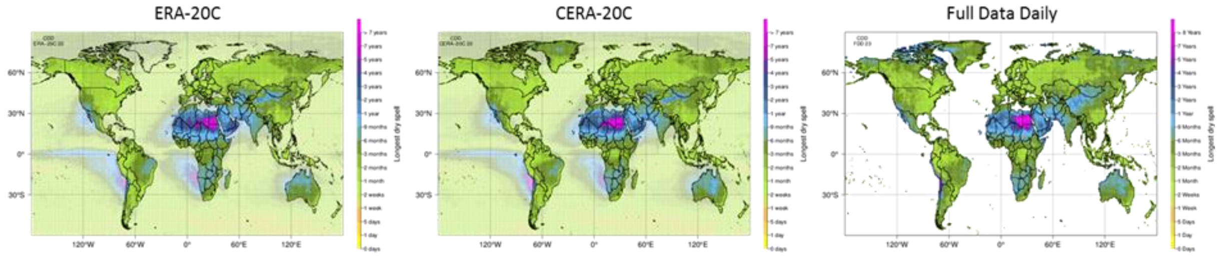

Figure 2.4.2: Longest period of consecutive dry days in the 23-years overlap period 1988-2010; left: ERA-20C, centre: CERA-20C ensemble mean, right: GPCC Full Data Daily data set.

Budget evaluations have become a valuable means of assessing the performance of climate model as well as of climate change itself. Within ERA-CLIM2 a well-established method for inferring the net surface energy balance could be substantially improved. Taking into account the vertical enthalpy flux related to evaporation and precipitation (which have been mostly ignored so far), reduces the discrepancy between indirectly inferred and directly evaluated surface flux estimates by 30-40% (Fig. 2.4.3). Since the ocean loses enthalpy through evaporation at higher temperatures than it receives enthalpy through rain, snow and runoff, this also means that the ocean needs about an extra W/m^2 more energy input from the classical surface energy fluxes in order to be in balance with the observed oceanic heat content change (Mayer et al. 2017).

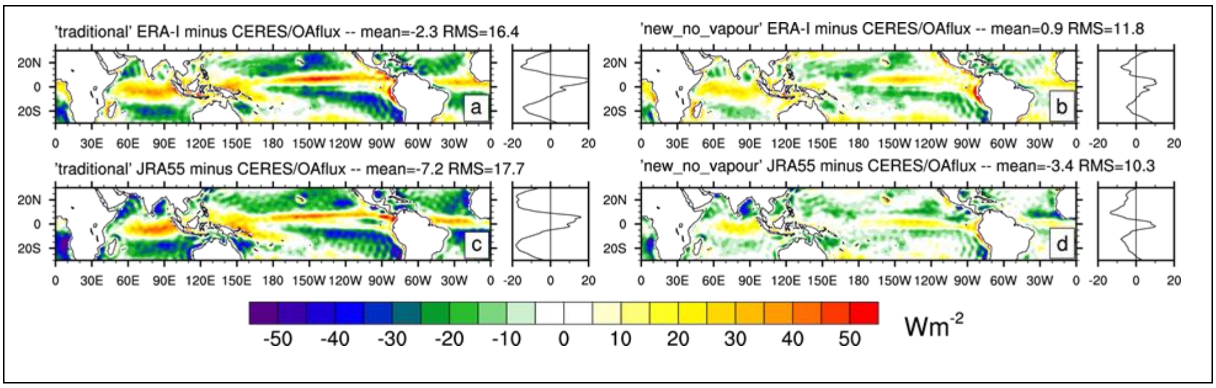

Figure 2.4.3: Difference of inferred net surface energy flux based on Rad_{TOA} from CERES and a) ERA-Interim based "traditionally" computed energy divergence, b) improved ERA-Interim based energy divergence, c) JRA55-based "traditionally" computed energy divergence, d) improved JRA55-based energy divergence, and net surface energy based on net surface radiation from CERES (Wielicky et al. 1996) and OAflux (Yu and Weller, 2007) turbulent fluxes. See Mayer et al. (2017) for details.

The depiction of low frequency variability and trends of essential climate variables is an important quality benchmark for any reanalysis. A high degree of temporal homogeneity of the analysed state quantities is needed but hard to achieve because the global observing system has changed dramatically during the past 10 decades. There is also considerable uncertainty in the boundary conditions, such as sunspot activity, volcanic activity and aerosol concentrations. These have profound impacts on the variability of both atmosphere and oceans. The temporal behaviour of reanalysis fields can give valuable hints to errors in the forcing conditions but also to errors in the assimilating model or the background error formulation. Figure 2.4.4 indicates that the volcanic forcing in CERA20C, taken from CMIP5 input, has been too weak, at least at the 50 hPa level. Radiosonde temperatures show much more pronounced temperature maxima at the time of major volcanic eruptions (Bezymianny 1955-57, Agung 1963, El Chichon 1982, Pinatubo 1991). The same figure shows that CERA20C is capable of reproducing the general stratospheric cooling trend, in contrast to 20CRv2c, which shows no cooling.

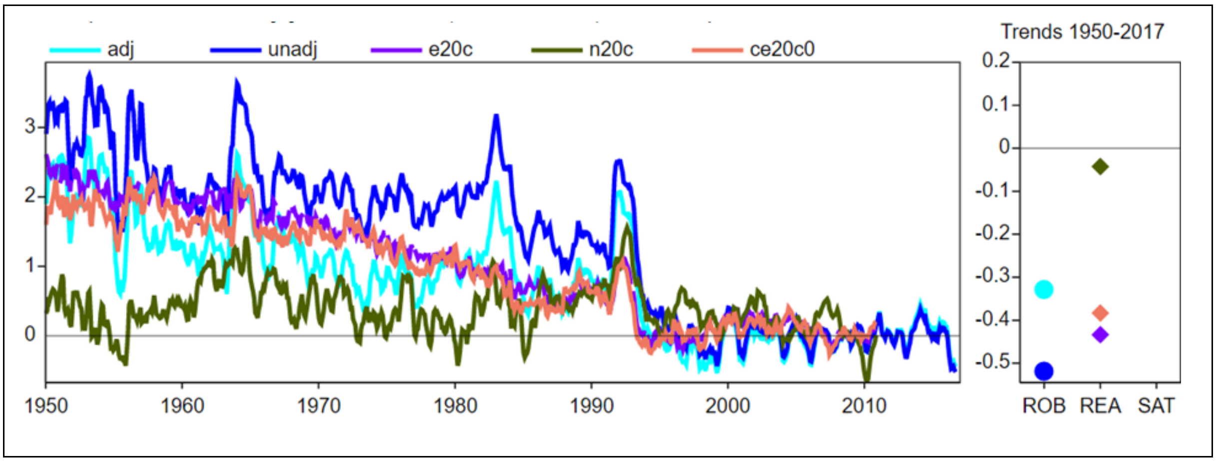

Figure 2.4.4: Global mean (all 10ºx10º grid boxes with at least one radiosonde station) temperature anomalies with respect to 2007-2011 in units K at 50 hPa. Dark blue=unadjusted radiosondes, light blue=RAOBCORE adjusted radiosondes, peach=CERA20C, violet=ERA20C, olive=20CR. Right panel: Linear trends in units K/10a. Eruptions with Volcanic Explosivity index >=5 in 1955/57, 1963, 1982, 1991.

The NOAA 20th century reanalysis has been able to capture major hurricanes such as the Galveston hurricane 1900 by assimilating best track data from hurricane centres. These have been rejected in ERA20C and CERA20C. Experiments by Y. Kosaka have demonstrated that less restrictive quality control for best track data permit the analysis of strong hurricanes in CERA20C, although there is a tendency to exaggerate the size of the storms.

ERA-CLIM2 has significantly contributed towards reducing uncertainties through improved methods for bias correction and budget estimation. Several still existing sources of uncertainty that need to be addressed in the future have also been revealed. As for modelling and data assimilation, evaluation of budgets should be done in coupled mode, yielding less uncertain estimates of fluxes at the interfaces of the climate subsystems.

3 Conclusions

As the project is finishing, GA4 has given us the opportunity to appreciate the scale and quality of the project's achievements. Thanks to the very effective and efficient collaboration between Institutes with different areas of expertise, we have managed to prepare unique datasets that will be helping us to understand the Earth-system evolution since 1900. For the first time, thanks of this project, we have advanced coupled data assimilation methods, we have more observations available to reconstruct the past climate, and we have generated a unique set of consistent Earth-system data. These datasets describes not only the time evolution of the physical variables of the coupled Earth-system (3-dimentional Ocean, sea-ice, land and atmosphere) but include also the carbon component.

4 Appendix A – Agenda of the ERA-CLIM2 4th General Assembly

Tuesday 12 December (0900-1800), Kuppelsaal, Main Building, University of Bern		
0900-	Registration	
1030-1045	Welcome and Introduction	Roberto Buizza
1045-1455 ***WP1*** *(Global 20th century reanalysis) and* ***WP5*** *(Service developments)*		
1045-1105	Overview WP1 / WP5	P. Laloyaux
1105–1130	Biogeochemical reanalysis	C. Perruche
1130-1155	CERA-SAT	D. Schepers
1155–1220	Land Carbon reanalysis	P. Peylin / N. Vuichard
1220-1330 Lunch		
1330-1355	CERA-SAT ocean component and further developments	E. de Boisseson
1355-1420	Tropical cyclone representation	Y. Kosaka
1420-1445	Improving the use of historical surface and upper-air observations	P. Dahlgren
1445-1745 ***WP2*** *(Future coupling methods)*		
1445-1455	Overview of WP2	M. Martin
1455-1515	SST assimilation developments	D. Lea and J. While
1515-1535	Sea-ice assimilation developments	C.-E. Testut
1535-1555	Ensemble B in NEMOVAR	A. Weaver
1555-1625	Coffee break	
1625-1645	Ensemble covariances in coupled DA	A. Storto
1645-1705	Impact of 4DVar and research into fully coupled DA	A. Vidard
1705-1725	Land carbon optimisations	P. Peylin
1725-1745	Strengths/weaknesses in existing coupled DA, coupled error covariances and model drift/bias correction	K. Haines/X. Feng
1745-1820 **Discussion** *(WPs 1, 2 and 5)*		
1820-2000	Reception	
2000	End of first day	

Wednesday 13 December (0900-1800) Kuppelsaal, Main Building, University of Bern		
0845-1225 **WP3** *(Earth System Observations)*		
0845-0910	WP3 Overview and accomplishments	S. Brönnimann
0910-0935	RIHMI Input for WP3 within ERA CLIM2 Project	A. Sterin
0935-1000	Data Rescue, QC and a metadatabase: FCiências.ID's contribution to WP3	M. A. Valente
1000-1025	Upper air data rescue Météo-France's contribution to WP3	S. Jourdain
1025-1050	Snow in situ and satellite data	J. Pulliainen
1050-1110 Coffee break		
1110-1135	Satellite data records for reanalysis	J. Schulz
1135-1200	Met Office contribution to WP3 in 2017	N. Rayner
1200-1710 **WP4** *(Quantifying and reducing uncertainties)*		
1200-1205	Overview of WP4	Leo Haimberger
1205-1225	Uncertainties and bias corrections for radiosonde temperatures	Leo. Haimberger
1225-1350 Lunch break		
1350-1410	Bias corrections for radiosonde humidity	Michael Blaschek
1410-1430	Quality control for observations	M. Antonia Valente
1430-1450	ERA20C and Cera-20C precipitation in comparison to GPCC daily and monthly analyses	Markus. Ziese
1450-1510	Uncertainties associated to the land carbon balance; comparison between ORCHIDEE and CTESSEL	Philippe Peylin
1510-1530	Comparison with other reanalyses, Trends and low frequency variability	Leo Haimberger
1530-1610 Coffee break		
1610-1630	Comparisons of ERA reanalyses with the station Upper Air data	Alexander Sterin
1630-1650	Uncertainties in energy budgets	Leo Haimberger, Michael Mayer,
1650-1800 **Discussion** The ERA-CLIM2 project: lessons learned and open questions for the future		

5 Appendix B – List of ERA-CLIM2 publications (updated on 10/12/17)

1 Ballesteros Cánovas, J. A., M. Stoffel, M. Rohrer, G. Benito, M. Beniston, S. Brönnimann, 2017: 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., 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

4 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.

5 Brönnimann, S., M. Jacques Coper, A. Fischer, 2017: Regnerischere Südseeinseln wegen Ozonloch. Physik in unserer Zeit 48, 215-216.

6 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 to Ozone Depletion and Recovery. Environ. Res. Lett. 12, 064011, doi:10.1088/1748-9326/aa7416.

7 Brönnimann, S., R. Allan, C. Atkinson, R. Buizza, O. Bulygina, P. Dahlgren, D. Dee, R. Dunn, P. Gomes, V. John, S. Jourdain, L. Haimberger, H. Hersbach, J. Kennedy, P. Poli, J. Pulliainen, N. Rayner, R. Saunders, J. Schulz, A. Sterin, A. Stickler, H. Titchner, M. A. Valente, C. Ventura, C. Wilkinson, 2018: Observations for Reanalyses. Bull. Amer. Meteorol. Soc. (submitted).

8 Brönnimann, Stefan; Rob Allan, Roberto Buizza, Olga Bulygina, Per Dahlgren, Dick Dee, Pedro Gomes , Sylvie Jourdain, Leopold Haimberger, Hans Hersbach, Paul Poli, Jouni Pulliainen, Nick Rayner, Jörg Schulze, Alexander Sterin, Alexander Stickler, Maria Antonia Valente, Maria Clara Ventura, Clive Wilkinson, 2017: Preparing Observation Data for European Reanalyses in ERA CLIM and ERA CLIM2 Projects, CODATA 2017. St. Petersburg. Book of Abstracts.

9 Brugnara, Y., Brönnimann S., Zamuriano, M., Schild, J., Rohr, C., Segesser, D., 2016: December 1916: Deadly Wartime Weather. Geographica Bernensia G91. 8 pp. ISBN 978-3-905835-47-2, doi:10.4480/GB2016.G91.01

10 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.

11 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.

12 Buizza, R., Brönnimann, S., Fuentes, M., Haimberger, L., Laloyaux, P., Martin, M., Alonso-Balmaseda, M., Becker, A., Blaschek, M., Dahlgren, P., de Boisseson, E., Dee, D., Xiangbo, F., Haines, K., Jourdain, S., Kosaka, Y., Lea, D., Mayer, M., Messina, P., Perruche, C., Peylin, P., Pullainen, J., Rayner, N., Rustemeier, E., Schepers, D., Schulz, J., Sterin, A., Stichelberger, S., Storto, A., Testut, C.-E., Valente, M.-A., Vidard, A., Vuichard, N., Weaver, A., While, J., and Ziese, M., 2017: The ERA-CLIM2 project. Bull. Amer. Met. Soc., *in press*.

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14 de Boisséson, E., Balmaseda, M.A. & Mayer, M. Clim Dyn (2017). Ocean heat content variability in an ensemble of twentieth century ocean reanalyses. https://doi.org/10.1007/s00382-017-3845-0

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17 Feng, X., and K. Haines, 2017: Atmospheric response and feedback to sea surface temperatures in coupled and uncoupled ECMWF reanalyses, In preparation.

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26 Lavrov A.S., Sterin A.M., 2017: COMPARISON OF FREE ATMOSPHERE TEMPERATURE SERIES FROM RADIOSONDE AND SATELLITE DATA, Russian Meteorology and Hydrology. 2017. T. 42. № 2. C. 95-104.

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