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CERA-SAT: A coupled satellite-era reanalysis

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CERA-SAT: A coupled satellite-era reanalysis

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ECMWF has completed the production of a new research reanalysis, CERA-SAT, which reconstructs the state of the atmosphere, the ocean, sea ice, ocean waves and the land surface between 2008 and 2016. Reanalyses are produced by combining models with observations in a process called data assimilation. The same technique is also used in numerical weather prediction (NWP) to establish the initial conditions on which forecasts are based.

CERA-SAT demonstrates the application of coupled data assimilation in the satellite era. In this context, coupling means that atmospheric, ocean, sea-ice, ocean-wave and land-surface observations are assimilated in a consistent manner. First assessments show that coupling as implemented in CERA-SAT improves the quality of the reanalysis in the tropics but degrades it in the extratropics. The deterioration in the extratropics is believed to be caused by shortcomings in the representation of boundary currents in the coupled model. Insights gained from assessing the performance of CERA-SAT will be used to develop coupled data assimilation in operational weather forecasting and the next generations of ECMWF's reanalyses.

Accounting for coupled processes between Earth system components is beneficial for weather forecasting, a clear example of which is tropical cyclogenesis. For climate assessment purposes, introducing coupling makes it possible to diagnose the key role that the oceans play in storing and transporting heat energy. Heat that is absorbed by the upper ocean eventually affects other components of the Earth system by melting ice shelves, increasing evaporation at the ocean surface, or directly reheating the atmosphere.

Drive towards coupling

The Centre's ten-year Strategy to 2025 places great emphasis on the need to account for all relevant interactions between different components of the Earth system in ECMWF's Integrated Forecasting System (IFS). One aspect of this is the development of a coupled forecasting model accounting for interactions between the atmosphere, the ocean, waves, sea ice and the land surface. Another is the growing research effort being devoted to coupled data assimilation.

A strong push towards increased coupling between Earth system components has been realised in the context of reanalysis production at the Centre. The ECMWF atmosphere-only climate reanalysis capabilities have been extended to include coupling with ocean, sea-ice and land-surface components in the ERA-CLIM2 project.

An important result has been the development of the CERA assimilation system, which enables the simultaneous and coupled assimilation of observations of the atmosphere, ocean, sea-ice and land components of the Earth system (*Laloyaux & Dee*, 2015; *Laloyaux et al.*, 2016). Built around the coupled Earth system model used for ECMWF ensemble (ENS) and seasonal forecasts (SEAS5), the CERA assimilation system makes it possible for ocean observations to have a direct impact on the atmospheric analysis and for atmospheric observations to have an immediate impact on the analysed state of the ocean. The aim is to achieve a consistent analysis of the Earth system. The CERA assimilation system was successfully used to produce CERA-20C (*Laloyaux et al.*, 2017), a 10-member ensemble of coupled climate reanalyses spanning the 20th century while assimilating only a limited range of observation types (surface pressure, marine wind observations and ocean temperature and salinity profiles).

Coupling in CERA-SAT

The CERA-SAT reanalysis applies the CERA data assimilation method to the modern-day observing system, providing a proof of concept for coupled data assimilation with higher model resolutions and the full range of observations used in NWP today.

CERA-SAT combines an eddy-permitting quarter-degree ocean model with an atmosphere modelled at approximately 65 km horizontal resolution (by comparison, CERA-20C has a horizontal resolution of 125 km). The ocean model is constrained by in-situ observations of temperature and salinity profiles and satellite observations of sea-surface height anomalies. For atmospheric assimilation, the full observing system is available, including surface weather stations and satellite observations of temperature,

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humidity, wind and composition (ozone). At the boundary between the ocean and the atmosphere, ocean waves and sea ice are analysed, the latter using gridded and interpolated sea-ice maps as observations.

Sea-surface temperature is a key driver of the coupling processes between the ocean component and the atmospheric component. In CERA it is relaxed towards an external analysis (OSTIA) during each integration of the coupled model.

The CERA-SAT land data assimilation system is weakly coupled in the sense that it initialises the main land surface prognostic variables of the coupled model: snow water equivalent, snow density, snow temperature, soil temperature and soil moisture, as described by de Rosnay et al. (2014). The system uses a combination of conventional observations from the SYNOP network for snow depth, screen level temperature and relative humidity; satellite-based observations of soil moisture from ASCAT on the MetOp series of satellites; and snow cover observations provided by NOAA (US National Oceanic and Atmospheric Administration) from NESDIS (National Environmental Satellite, Data, and Information Service) IMS (Interactive Multisensor Snow and Ice Mapping System).

The coupling introduced by CERA allows ocean observations to impact the analysed atmospheric state and vice versa through, for instance, heat exchange across the surface of ocean water and sea ice; the interaction of near-surface winds with ocean currents and surface roughness; and the exchange of heat and moisture over land during the 24-hour coupled forecast which provides the background for the analysis.

For more details on the coupling of different Earth system components in CERA-SAT, see Box A and Figure 1.

Coupled data assimilation in CERA-SAT

A

The CERA-SAT reanalysis has been produced using the CERA coupled assimilation system (Laloyaux et al., 2016). This system was set up to use a 24-hour assimilation window shared between the atmospheric, ocean, wave and land components. At the outer-loop level, the atmosphere, land and wave models used in the IFS are coupled in a single executable to the community ocean model NEMO and the LIM2 sea-ice model developed at the Belgian Université catholique de Louvain.

The resulting coupled model is used to produce 24-hour forecasts (the background). The background is combined with observations to produce separate analyses for the atmosphere, ocean, wave, sea-ice and land components. The resulting increments (corrections to the background based on the observations) are then applied in another integration of the coupled model. In effect, this design ensures that interactions between Earth system components are taken into account when observation misfits are calculated as well as when the increments are applied. For CERA-SAT, the CERA system was configured with two such outer-loop iterations.

The CERA-SAT reanalysis additionally includes a separate land surface data assimilation (LDAS) that is weakly coupled by means of a shared coupled model integration using the land surface model H-TESSEL of the IFS (see also Figure 1).

Within the land surface data assimilation, snow cover as well as 2-metre temperature and relative humidity are analysed using a 2-dimensional Optimal Interpolation (OI) scheme. Analysed screen level variables are subsequently used as input for a soil and snow temperature analysis through a 1-dimensional OI scheme, as well as for the soil moisture analysis based on a simplified Extended Kalman Filter (EKF).

Once the second outer loop and the LDAS have been completed, the physically consistent analyses are stored and used to initialise the next analysis cycle.

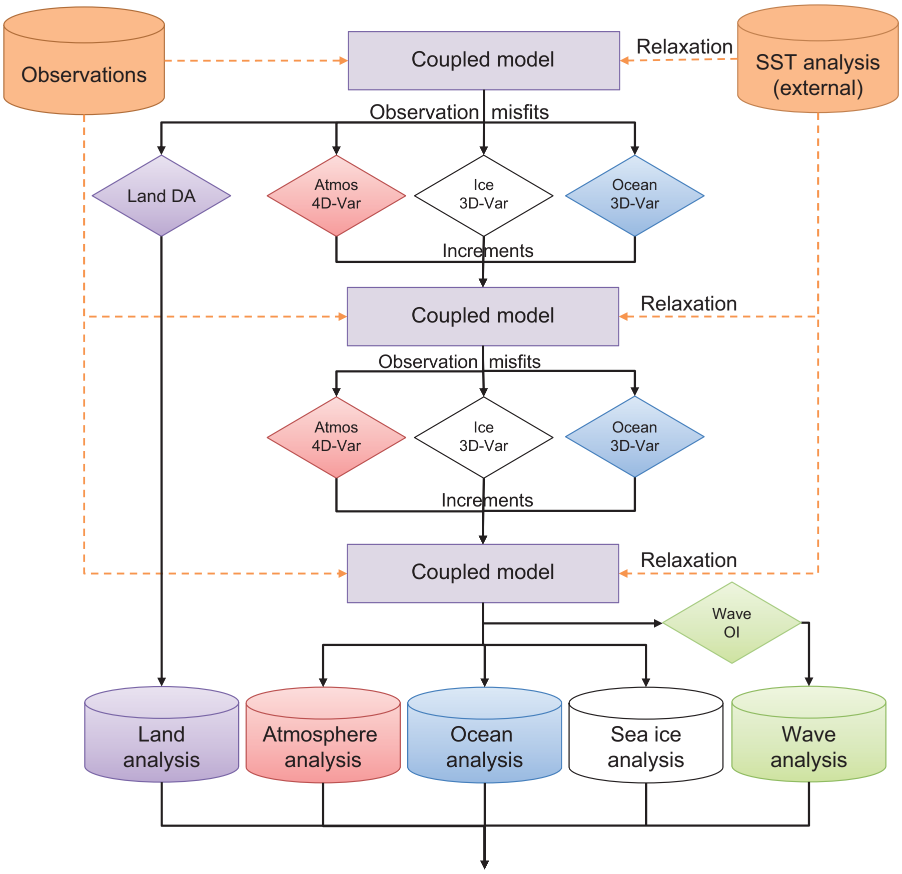

Figure 1 The coupled CERA assimilation system as configured for CERA-SAT production. Observation misfits are derived from the coupled model integration, after which parallel assimilation systems produce analysis increments. These increments are then applied within the coupled model. Repeating this procedure twice in two outer loops makes it possible for the atmosphere, ocean and sea-ice models to reach a balanced state. The land surface analysis (Land DA) is weakly coupled through the first coupled model integration.

The CERA-SAT product

The CERA-SAT reanalysis uses IFS Cycle 42r1 with a horizontal resolution in the atmospheric model of TL319, corresponding to about 65 km, and 137 levels in the vertical reaching up to 0.01 hPa. The ocean component, NEMO v3.4, is specified on the tripolar ORCA025 grid corresponding to an approximate horizontal resolution of 0.25 degrees with a meridional refinement towards the equator. In the vertical, there are 75 levels, with the top level spanning the first metre. The land surface model H-TESSEL comprises four soil layers, including three in the top metre of soil.

In order to produce a reanalysis covering a reasonable number of years within the constraints of available resources, the nine-year CERA-SAT dataset was produced in four separate parts, or production streams. Each stream was initialised with the atmospheric state from the ERA-Interim reanalysis and the ocean state taken from the ORAS5 ocean-only reanalysis. Six months were allowed for spin-up at the start of each stream.

The CERA-SAT reanalysis product is provided as a 10-member ensemble of data assimilations (EDA), each providing analyses of the atmosphere, the ocean, waves, the land surface and sea ice at 3-hourly intervals. In addition to the 137 model levels, the atmospheric product is also made available on 37 pressure levels, 16 potential temperature levels, and the 2 PVU potential vorticity level. The CERA-SAT reanalysis is being made publicly available through ECMWF's Meteorological Archival and Retrieval System (MARS). The atmospheric, land, sea-ice and wave reanalysis can be accessed at *http://apps.ecmwf.int/datasets/*. The data can be selected and retrieved through the MARS Catalogue under the name 'ERA-CLIM2 coupled reanalysis of the satellite era (CERA-SAT)'.

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First results

To facilitate impact studies comparing the coupled reanalysis approach used in CERA-SAT with conventional uncoupled reanalysis, a CERA-SAT-like uncoupled control reanalysis (CTRL) was produced in parallel. The control experiment uses the same assimilation setup (window, observing system, etc.) but lacks the interactive ocean and sea-ice components, using a prescribed sea-surface temperature and sea-ice concentration instead and running the uncoupled atmospheric model for both the background and longer-range forecasts.

Improved fit to satellite observations

One way to quantify the impact of the CERA assimilation approach compared to the conventional uncoupled approach is to compare background departures (the difference between observations and a 24-hour forecast, called the background). Generally, smaller background departures signal a (re)analysis that is in better agreement with observations and can thus be said to be of better quality.

The impact of coupled assimilation on background departures is illustrated in Figure 2. It shows the difference in background departures (expressed as normalised standard deviations) between CERA-SAT and CTRL for selected satellite observations averaged over a complete year and stratified for the tropics and the extratropics. From the plots, it is clear that CERA-SAT is consistently closer to observations than CTRL in the tropics, indicating a clear benefit of ocean–atmosphere coupling in that region. The opposite, however, is true in the extratropics, where the coupled reanalysis generally shows a degradation in the background fit to observations.

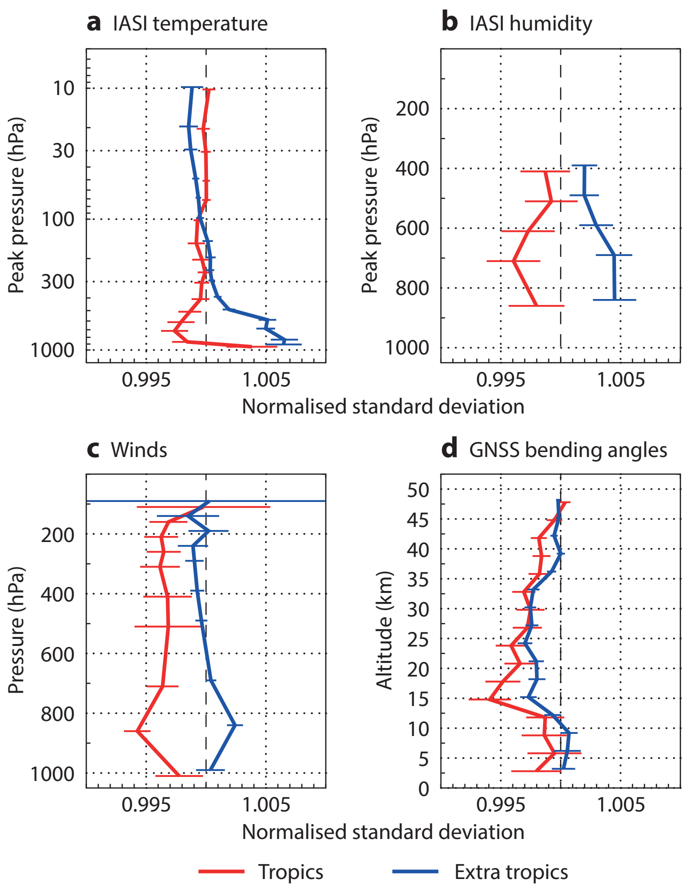

Figure 2 Difference in background departures (CERA-SAT minus CTRL), expressed as the normalised standard deviation, for selected satellite instruments and variables. Values smaller than one indicate a better fit of the background to selected satellite observations in CERA-SAT. The observations are of (a) temperature from the IASI instrument, (b) humidity from the IASI instrument, (c) winds from a suite of instruments and (d) GNSS (Global Navigation Satellite System) bending angles. The comparison spans the full year from September 2015 up to and including August 2016. Bars indicate 95% confidence intervals.

The degradation in the extratropics is likely a symptom of known shortcomings in the coupled model related to the representation of boundary currents (currents with dynamics that are determined by the presence of a coastline). Through the coupling introduced by CERA, errors in the representation of these currents propagate into the atmospheric analysis, predominantly through an erroneous sea-surface temperature.

These shortcomings are a known feature of the coupled forecast model and are currently accounted for in the operational ECMWF coupled forecasts by explicitly correcting for them. Work is ongoing to identify the precise cause of these shortcomings and to improve the performance of the coupled model accordingly.

Forecast scores

As an integral part of the CERA-SAT reanalysis production, daily 10-day coupled forecasts were produced, initialised from the 00 UTC coupled analyses. Similarly, uncoupled forecasts (prescribing daily sea-surface temperature and sea-ice concentration valid on the forecast day) were initialised from the uncoupled control reanalysis.

In order to assess the impact of coupling in both the forecast and the data assimilation on forecast performance, forecast error with and without coupling can be compared. Figure 3 shows the difference in the standard deviation of forecast error for 5-day mean sea level pressure and 500 hPa geopotential, verified against own analysis and assessed over a full year, from September 2015 to August 2016. With coupling, reductions in forecast error of up to about 10% are evident in tropical areas, while in the extratropics standard deviations are increased, signalling degraded forecast skill in the CERA-SAT reanalysis with respect to the uncoupled control experiment.

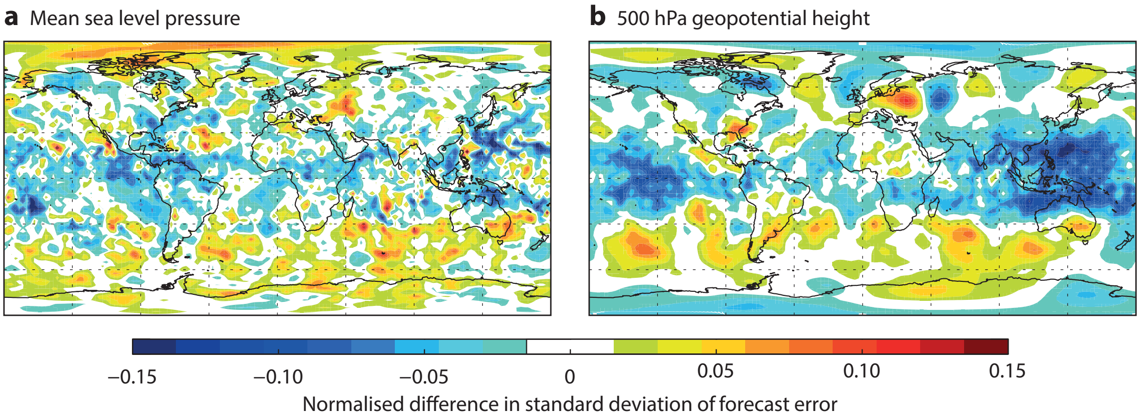

Figure 3 Normalised difference in standard deviation of forecast error for (a) mean sea level pressure and (b) 500 hPa geopotential height, for 5-day forecasts verified against own analysis, between CERA-SAT and CTRL. Blue colours indicate a reduction in standard deviation for CERA-SAT compared to CTRL.

Ocean heat budget

The world's oceans have a tremendous capacity to store heat energy. This stored energy can warm the planet for decades after it is absorbed, hence knowing how much heat energy the ocean absorbs and releases is essential to understand the global climate. The changes in ocean heat content in CERA-SAT have been investigated through an ocean heat budget analysis (Figure 4a). The heat content variation of the total column ocean is equal to the sum of the atmospheric surface heat fluxes, the temperature assimilation increments, the weak relaxation to the 3-dimensional climatology of temperature and salinity profiles from the World Ocean Atlas 2013 (WOA13), and the relaxation to the OSTIA SST analysis. The 3D relaxation is negligible in well-observed periods. Over the CERA-SAT period, the heat content variations are overall positive indicating a heat gain in the ocean. Both heat fluxes and assimilation increments provide heat to the ocean. The contribution of the SST relaxation to the budget is substantially negative, counteracting the impact of both surface fluxes and increments. The SST relaxation constrains the ocean surface towards the OSTIA SST analysis.

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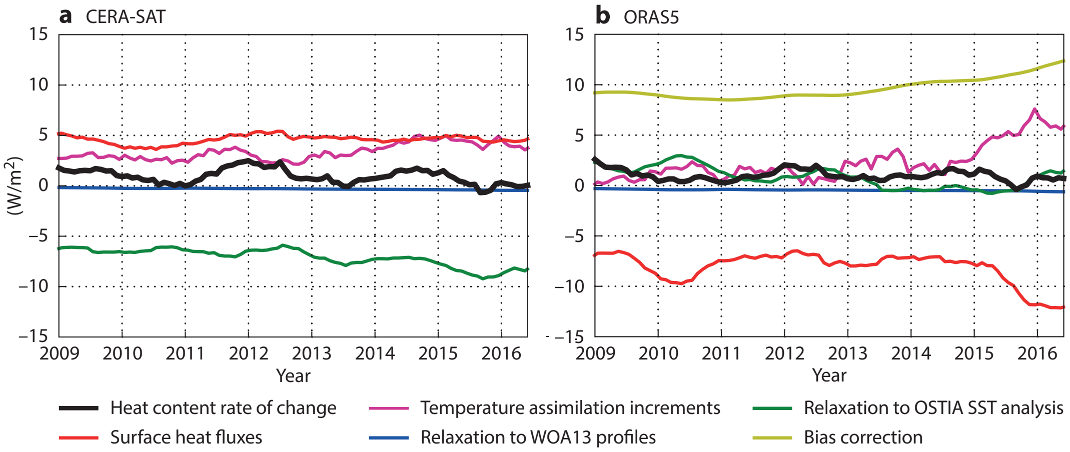

Figure 4 Global ocean heat budget in (a) CERA-SAT and (b) ORAS5. The rate of change in heat content of the total column ocean is the sum of the surface heat fluxes, the temperature assimilation increments, the weak relaxation to the 3-dimensional climatology of temperature/salinity profiles from WOA13 and the relaxation to the OSTIA SST analysis.

The same kind of ocean heat content analysis has been conducted for the ocean-only reanalysis ORAS5 (Figure 4b). As in CERA-SAT, the ocean gains heat over the whole period, and assimilation increments make a positive contribution to the budget, albeit a relatively small one up to 2014. On the other hand, atmospheric heat fluxes are substantially negative and the SST relaxation is relatively small. The impact of the heat fluxes on the budget is counterbalanced by a bias correction term that was not used in CERA-SAT. This suggests that the bias correction in ORAS5 works to correct the bias resulting from the response to the heat fluxes, similarly to what the SST relaxation does in CERA-SAT. The difference is that the bias correction impacts the whole ocean column while the SST relaxation influences only the top ocean layers. While the total heat content variation is similar in CERA-SAT and ORAS5, the vertical distribution of heat can thus be expected to be different.

This analysis shows that the ocean heat budget is far from resembling a realistic situation, such that variations in ocean heat content result from atmospheric heat fluxes only, and significant research is needed to identify and correct the causes of that. The next CERA system is expected to use a similar ocean bias correction scheme to the one used in ORAS5. Such a scheme has been shown to have a positive impact in the ocean-only analysis system (*Balmaseda et al.*, 2007) and similar behaviour is expected in CERA (*Feng et al.*, 2017).

CERA-SAT in the reanalysis portfolio

The performance of CERA-SAT lies between that of two existing ECMWF reanalyses of the satellite era. Figure 5 shows time series of 500 hPa geopotential height and 2-metre temperature forecast scores over Europe. Here, forecast performance is expressed as the lead time at which the anomaly correlation (against own analysis) drops below a certain threshold: 95, 80 or 60 per cent in this case. In this metric, longer lead times indicate a better reanalysis.

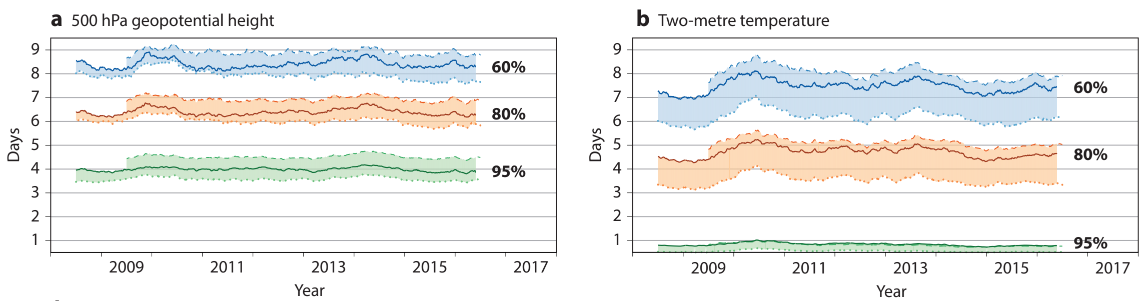

Figure 5 Time evolution of forecast skill in Europe for (a) 500 hPa geopotential height and (b) 2-metre temperature forecasts produced using ERA-Interim, ERA5 and CERA-SAT, expressed in terms of the number of days after which the anomaly correlation coefficient (12-month running mean) falls below a certain threshold (60, 80 and 95%).

CERA-SAT is compared to two other reanalyses: ERA-Interim and ERA5 (*Hersbach & Dee*, 2016). ERA-Interim is the current operational reanalysis produced at ECMWF, based on a 12-year-old IFS release. It provides an atmospheric reanalysis with approximately 80-kilometre spatial resolution on 60 vertical levels. ERA-Interim is scheduled to be phased out and replaced by ERA5, which is currently being produced at ECMWF for the EU-funded Copernicus Climate Change Service (C3S) operated by the Centre. ERA5 benefits from a recent IFS cycle (41r2) and provides atmospheric fields at about 30 km resolution on 137 levels. ERA5 is currently publicly available from 2010 onward.

Clearly, CERA-SAT is not able to match the overall quality of ERA5, while comfortably beating the ageing ERA-Interim reanalysis. The deficit with respect to ERA5 is likely related to the higher model resolution of ERA5 as well as the aforementioned shortcomings in boundary current representation in the coupled model propagating into the atmospheric reanalysis in the CERA system.

The CERA-SAT reanalysis has been produced first and foremost as an experimental dataset to aid research and development work undertaken at ECMWF towards coupled data assimilation and climate reanalysis. As such, it cannot be expected to perform as well as the current generation of ECMWF reanalysis products in terms of quality, temporal coverage and user support.

Outlook

CERA-SAT can serve as a proof of concept for using the CERA system in the context of the modern-day NWP observing system. As a result, efforts are now under way at ECMWF to implement and evaluate a version of CERA in the operational codebase and to correct the problems with boundary current representation in the coupled model. CERA-SAT will thus facilitate the future implementation of coupled data assimilation in operational weather forecasting and in the next generation of ECMWF reanalyses. The former holds the promise of more consistent Earth system analyses and, as a result, better forecasts. The latter will help us to better understand the changing climate and to assess and predict its impact.

Further reading

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