ECMWF Newsletter

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European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen terme

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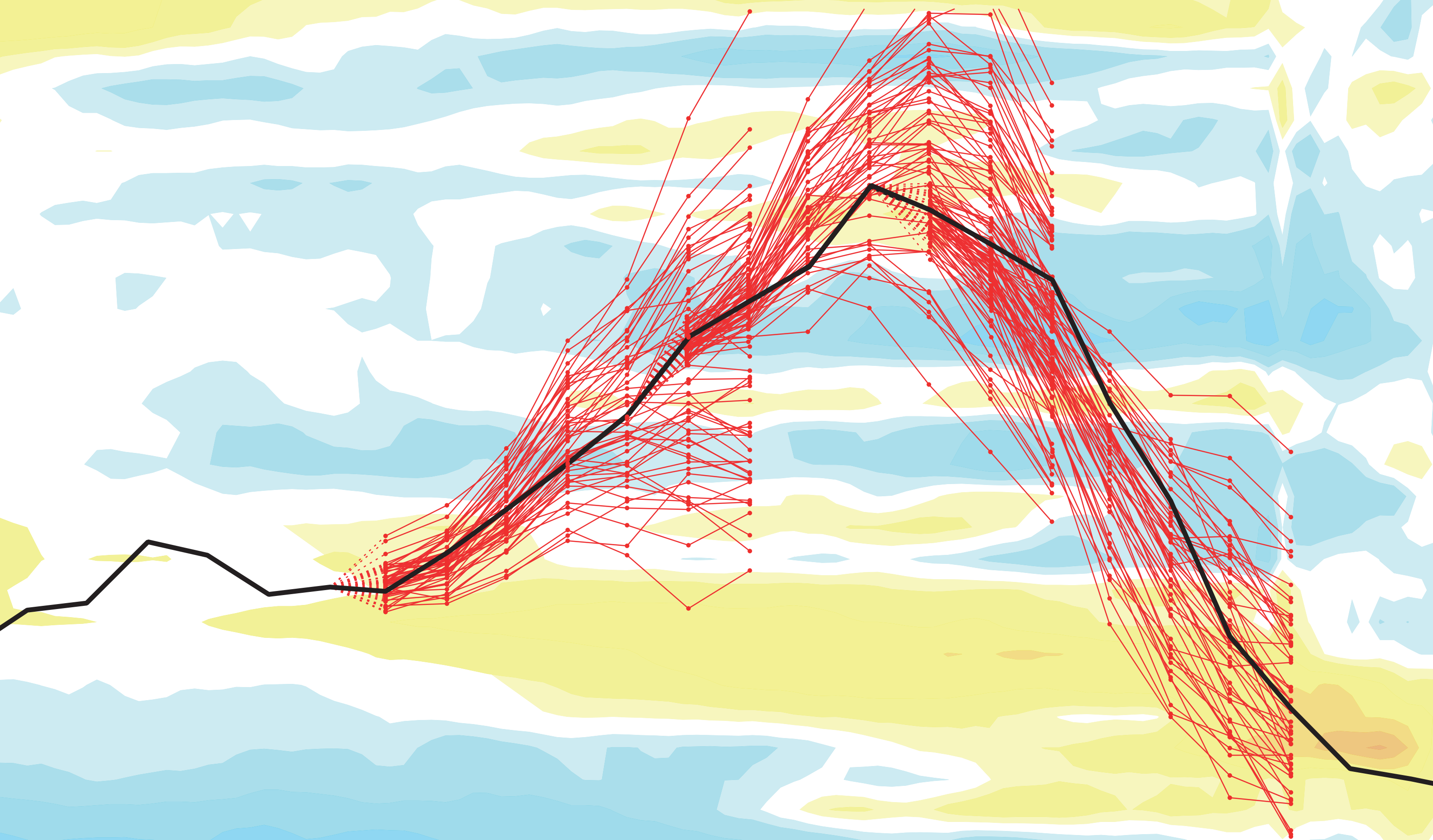
The 2015/16 El Niño and beyond

A user-friendly Climate Data Store

Reanalysis sheds light on avalanche disaster



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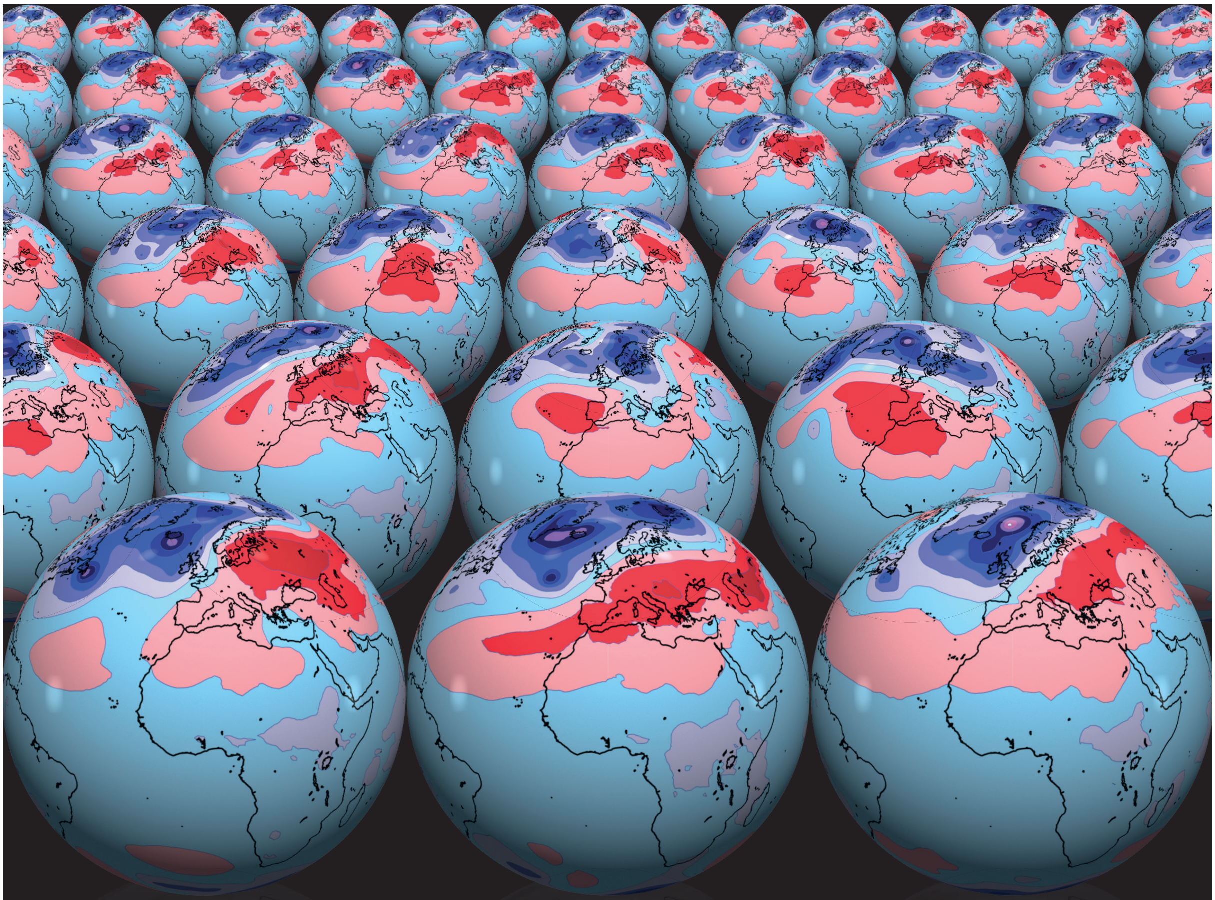

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The *ECMWF Newsletter* is published quarterly. Its purpose is to make users of ECMWF products, collaborators with ECMWF and the wider meteorological community aware of new developments at ECMWF and the use that can be made of ECMWF products. Most articles are prepared by staff at ECMWF, but articles are also welcome from people working elsewhere, especially those from Member States and Co-operating States. The *ECMWF Newsletter* is not peer-reviewed.

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Seamless transitions

The 2015/16 El Niño turned out to be in the same class as the exceptional events in 1982/83 and 1997/98. How well was it predicted? ECMWF's forecasts of the event as well as the EUROSIP multi-model forecasts produced at ECMWF provide an impressive demonstration of the power of seasonal forecasting. Months in advance they successfully predicted the onset, peak and decline of the 2015/16 El Niño. These forecasts, described in detail in this Newsletter, illustrate the world-class capabilities of ECMWF's seasonal forecasting system.

But of course there is always room for further improvements. SEAS5, ECMWF's new seasonal forecasting system, will become operational later this year. It promises to bring even higher-quality seasonal forecasts in the tropics. It will also provide seasonal predictions of sea ice. Another major advance is that it is well aligned with ECMWF's extended-range system. This marks a significant step on the road towards seamless forecasting across a wide range of timescales, from the medium range out to seasonal forecasts.

A second transition that is under way is the move of multi-model seasonal forecasting at ECMWF from a research environment into operations. The EUROSIP multi-model forecasts combine output from five major forecasting centres: ECMWF, the UK Met Office, Météo-France, the US National Centers for Environmental Prediction (NCEP) and, since March this year, the Japan Meteorological Agency (JMA). Plans are now in place for all these forecasts to be included in the new seasonal forecasting service that is being trialled by the EU-funded Copernicus Climate Change Service (C3S) operated by ECMWF.

The C3S prototype service already brings together ECMWF, the UK Met Office and Météo-France as core providers and will soon include Italy's Euro-Mediterranean Center on Climate Change (CMCC) and Germany's national meteorological service, DWD, as additional providers. These are now set to be joined by NCEP and JMA: a shining example of international cooperation for the benefit of users in Europe and beyond. C3S will have dedicated resources to enable the successful operation of this new seasonal service. Continuous product development will happen at a faster pace than was possible in the EUROSIP framework. At the same time, all providers including ECMWF will keep full control of their own seasonal forecasting systems.

Continuously driving improvements in seamless forecasting from the medium range all the way to seasonal forecasts requires constant improvements in ECMWF's computing resources. As described in this Newsletter, 2016 saw a significant upgrade of ECMWF's high-performance computing facility. This upgrade will take ECMWF to 2020, at which point a further significant expansion of computational capabilities will be needed, together with a new data centre. We have every confidence that 2017 will be the year in which we lay the foundations for a seamless transition to a new data centre and more powerful computing resources that will take us into the next decade.

Florence Rabier
Director-General

The cold spell in eastern Europe in January 2017

LINUS MAGNUSSON

A significant part of the winter 2016/2017 was dominated by blocking conditions over Europe bringing warm air towards north-western Europe and cold air into southern Europe. For large parts of eastern Europe the second week in January was the most extreme of the winter. Russia experienced the coldest Orthodox Christmas in 120 years, and temperatures dropped to almost -30°C in Romania and the former Yugoslav Republic of Macedonia. In Sofia, Bulgaria, ECMWF's Extreme Forecast Index (EFI) for short-range (1-day) forecasts reached -1 for three consecutive days (8–10 January). The 3-day average temperature in the city over that period was -12°C, which is 10 degrees below normal. At the same time a lot of snow fell in various parts of southern Europe, including southern Italy and Greece.

Synoptically, the wintry weather was caused by the advection of a pool of cold air from northern Russia to the southwest. This development was linked to the amplification of a ridge over the north-eastern Atlantic and of a trough downstream. Later the trough formed a cut-off low over south-eastern Europe.

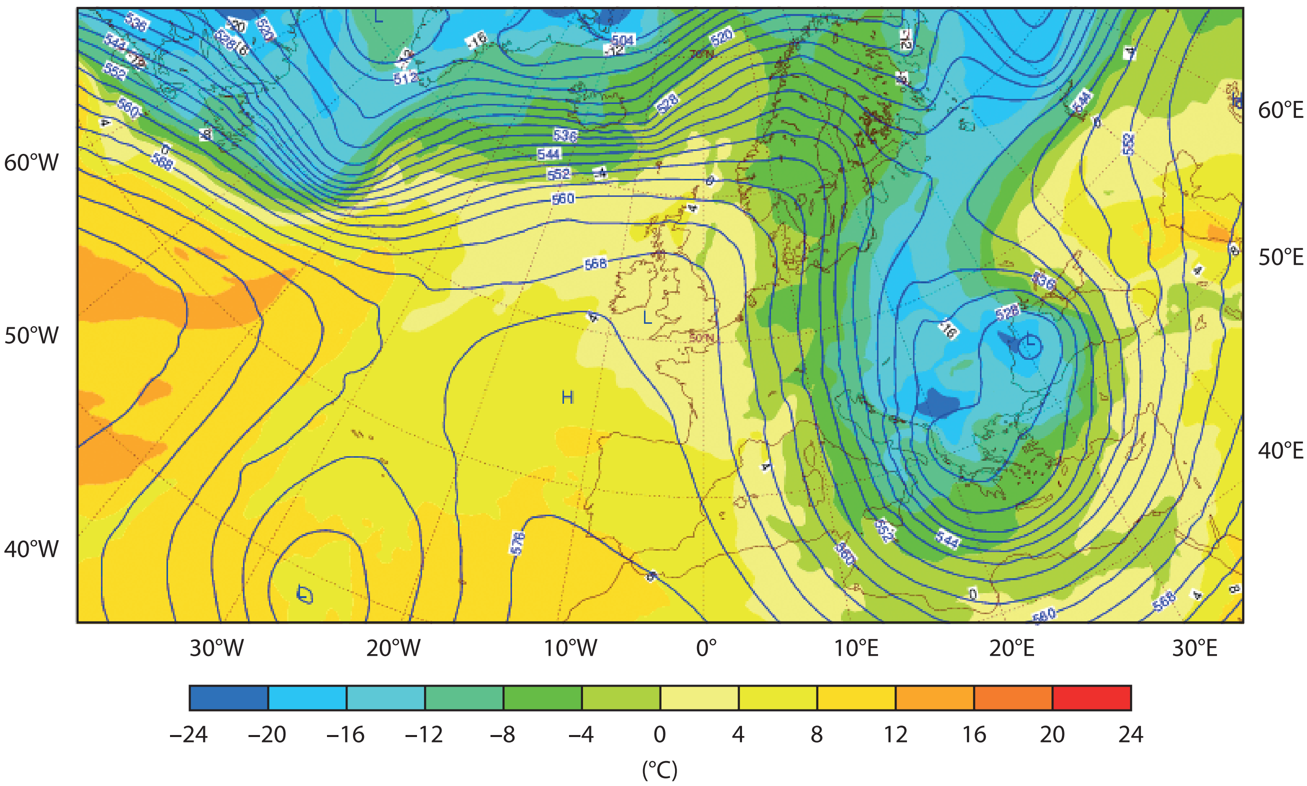
Forecast quality

How well was the cold spell predicted? Focusing on the average temperature in Sofia between 8 and 10 January, no signal was present in forecasts issued before the last day of December (including monthly forecasts). During that time, the ensemble forecast distribution was close to the climate distribution. However, from 1 January (8 to 10 days before the event) all members predicted colder than normal temperatures, and from 4 January (4 to 6 days before the event) all ensemble members predicted temperatures below the 10th percentile of the model climate. The broad geographic area where cold temperatures were predicted is evident in the EFI and SOT (Shift of Tails) plots from the same date.

The short-range forecasts (1 to 3 days before the event) were clearly outside the 1st percentile of the model climate for 3-day average temperature. However, the predicted 3-day averages (around -17°C) are much lower than the observed average of -12°C. A plausible reason is that the local conditions around the observation station were influenced by the heat created in the city. A possible solution to this issue is to include an urban tile in the model, which is part of ECMWF's long-term plans. More rural observation stations showed considerably lower temperatures at the same time (not shown).

Model climate

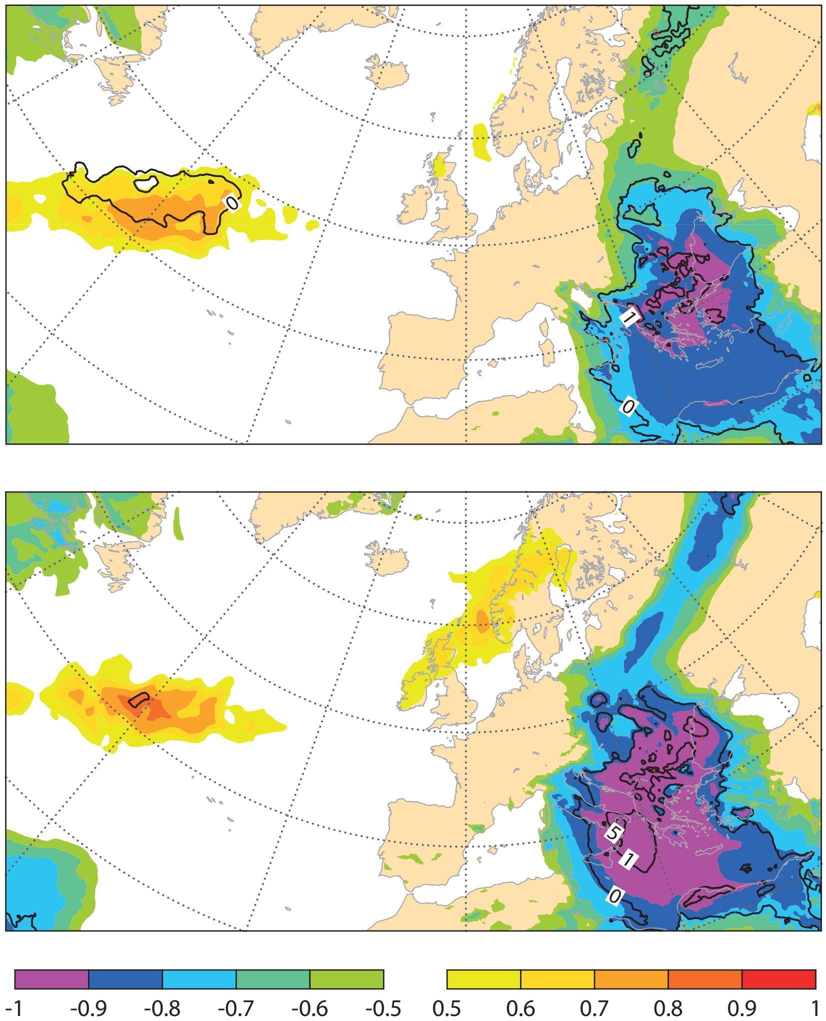
The cumulative distribution functions of the observed climate and the model climate (derived from re-forecasts) for midday (12 UTC) temperatures in January for Sofia are very similar in normal and warm conditions. In cold conditions, on the other hand, the model climate is colder than the observed one. The difference might be related to the urban setting of the station (as mentioned above) and/or systematic model errors. The discrepancy shows the benefit



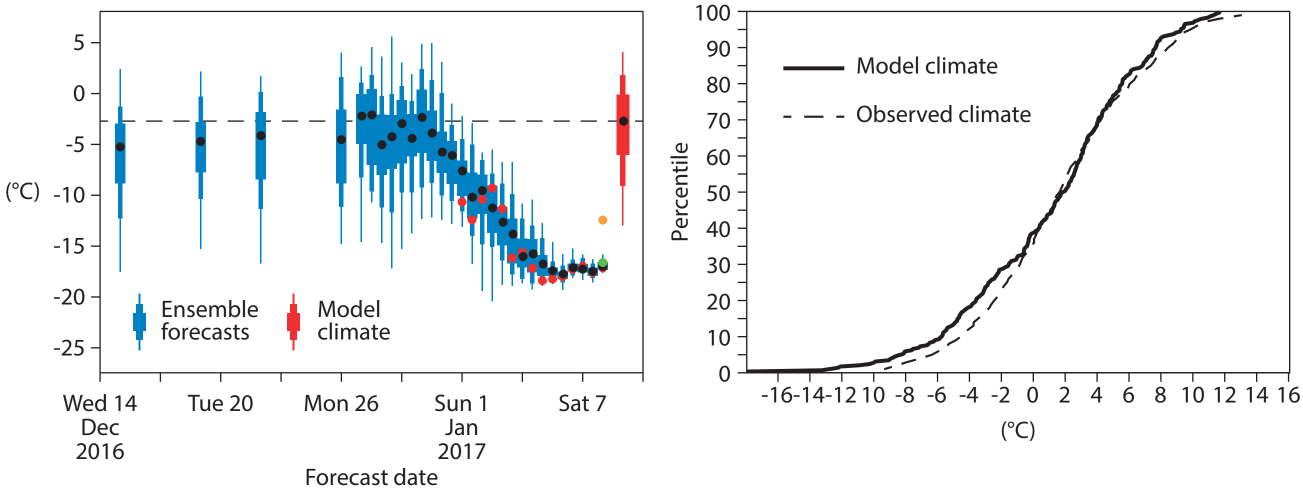
Synoptic situation. Analysis of 500 hPa geopotential height (contours, in decametres) and 850 hPa temperature (shading) on 8 January 00 UTC.

of using the model climate instead of the observed climate when calculating anomalies and points to the need for calibration under certain circumstances. It is worth noting that in other locations the opposite difference can be seen: the model is too warm in cold conditions during winter, especially in rural regions in northern Europe.

To summarise, the extended-range forecasts failed to predict the cold period in the second week of January in eastern Europe, while it was well captured in medium-range forecasts. In short-range forecasts the predicted temperatures were too low, probably because they failed to take into account local conditions, pointing to the need for post-processing.



Extreme Forecast Index and Shift of Tails. EFI (shading) and SOT (contours) forecasts for average 2-metre temperature from 8 to 10 January starting from 00 UTC on 4 January (top) and 00 UTC on 8 January (bottom).



Forecasts and climatologies for Sofia. The box-and-whisker plot (left) shows ensemble forecasts of the average 2-metre temperature from 8 to 10 January in Sofia at successively shorter forecast ranges. The model climate is shown in red. High-resolution (HRES) forecasts are shown as red dots, the analysis is indicated by a green dot and the observed value by an orange dot. The box-and-whisker symbols mark the 1st, 10th, 25th, 75th, 90th and 99th percentile and the median is marked with a black dot. The dotted line represents the median of the model climate. The cumulative distribution functions (right) show the model climate (solid line) and the observed climate (dashed line) for 2-metre temperature at 12 UTC in January in Sofia.

ECMWF launches eLearning

ANNA GHELLI, SARAH KEELEY

To meet the training needs of our Member and Co-operating States, ECMWF has started a project which aims to produce a set of publicly available eLearning modules, initially on foundational material for our numerical weather prediction, software and product courses. eLearning has a number of potential benefits: it can expand the reach of training, and it can give learners flexibility in terms of when, where and how they want to learn. The first two ECMWF eLearning modules, on Convection and Metview, will be available from May 2017 and others will follow later this year.

eLearning modules

The following eLearning modules are expected to be available by August 2017:

- ecCodes for GRIB decoding
- ecFlow
- Convection – part 1 - Overview
- Convection – part 2 – Mass flux approach and the IFS scheme
- Introduction to ensemble forecasting
- Introduction to MARS
- Introduction to Metview
- Introduction to parametrization
- Learning how to cope with forecast jumpiness
- Monthly forecasts
- Single Column Model

What is eLearning?

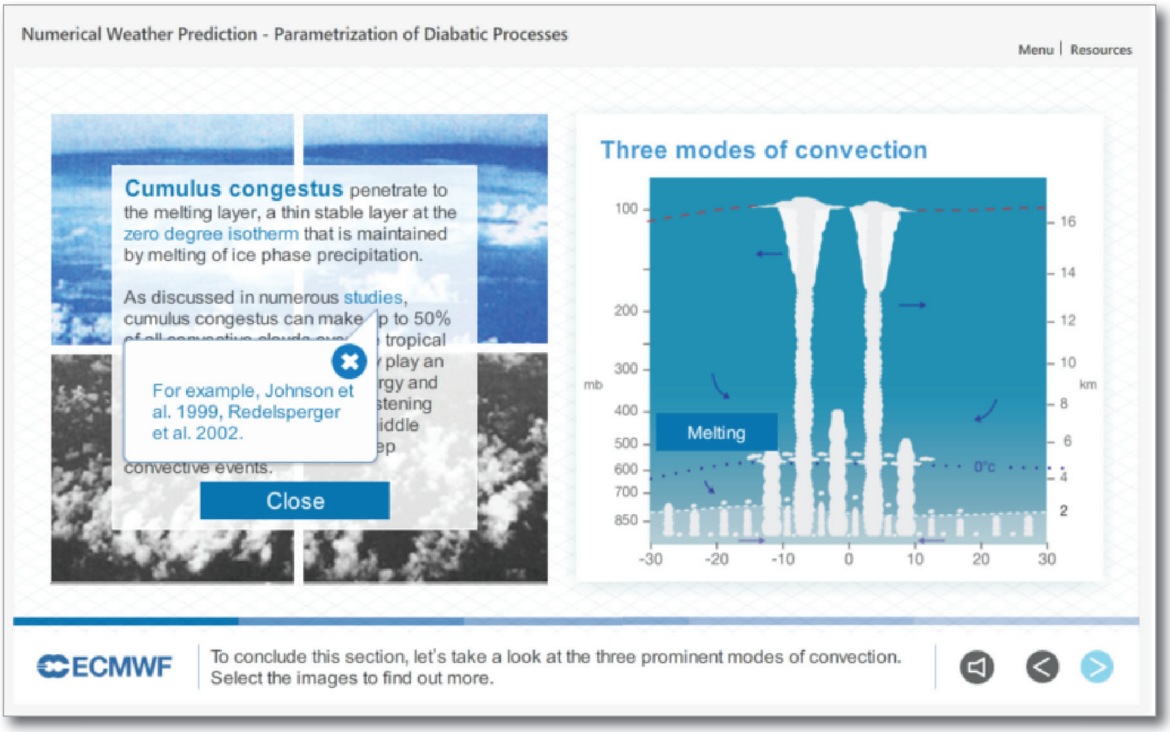
How do we gain knowledge that will shape our lives? Traditional teaching approaches rely on the formal interactions between student and teacher in specially adapted environments such as classrooms or lecture theatres. Centuries ago only relatively small numbers of students could gain advanced knowledge through oral presentations from scholars. The invention of the printing press in Europe in the 15th century meant that written texts could be made available more widely, influencing the way education and training worked. In recent decades, technology has further expanded the potential reach of education and training. At the same time, teaching methods have evolved towards a more active role for students, who help to shape the way learning happens. Such an approach allows for learning to take place not only in formal settings, such as in a classroom, but in a flexible manner taking advantage of new technology: 'self-paced learning', 'mobile learning' and 'learning anytime and anywhere' are just some examples of the buzzwords that reflect this trend.

eLearning is a flexible and student-driven kind of learning that relies on effective multimedia resources. It supports diverse learning styles and can complement traditional classroom teaching. eLearning leverages technology to create and design engaging and effective multimedia resources.

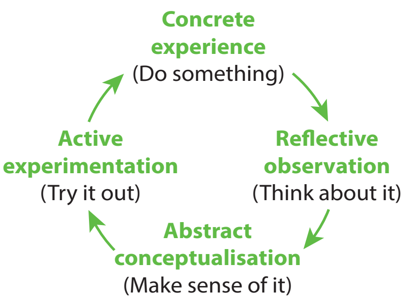
How do we learn?

eLearning is not just about converting lecture notes into multimedia resources but also about creating an environment where tailored learning is facilitated. As with any other successful teaching methodology, understanding how people learn is an essential ingredient in creating eLearning modules.

Pedagogy has developed models that describe the way we learn. These models can help us to frame the way we build eLearning resources. The work of T. Mayes and S. de Freitas ('Review of e-learning theories, frameworks and models', Joint



Multimedia resources. The eLearning modules combine text with audiovisual material in an interactive manner.



Information Systems Committee, London, 2004) highlights three perspectives that relate to the processes used in learning: associative learning (learning as an activity); cognitive learning (learning through understanding); and situative learning (learning as a social practice). Within each of these perspectives there are numerous approaches to learning, for example building on prior knowledge, internalising and reflecting on concepts, or problem-based learning. These perspectives and approaches can be used as the basis to construct the learning models that underpin eLearning.

The associative perspective assumes that our brains are not designed to recall information in isolation but as part of an information group; it focuses on learning through association and reinforcement. For example you may find it difficult to remember a date, but if that date is associated with an event or a series of events of which you have good memories, then it will stick in your mind. Models and frameworks associated with this perspective encourage problem-based learning.

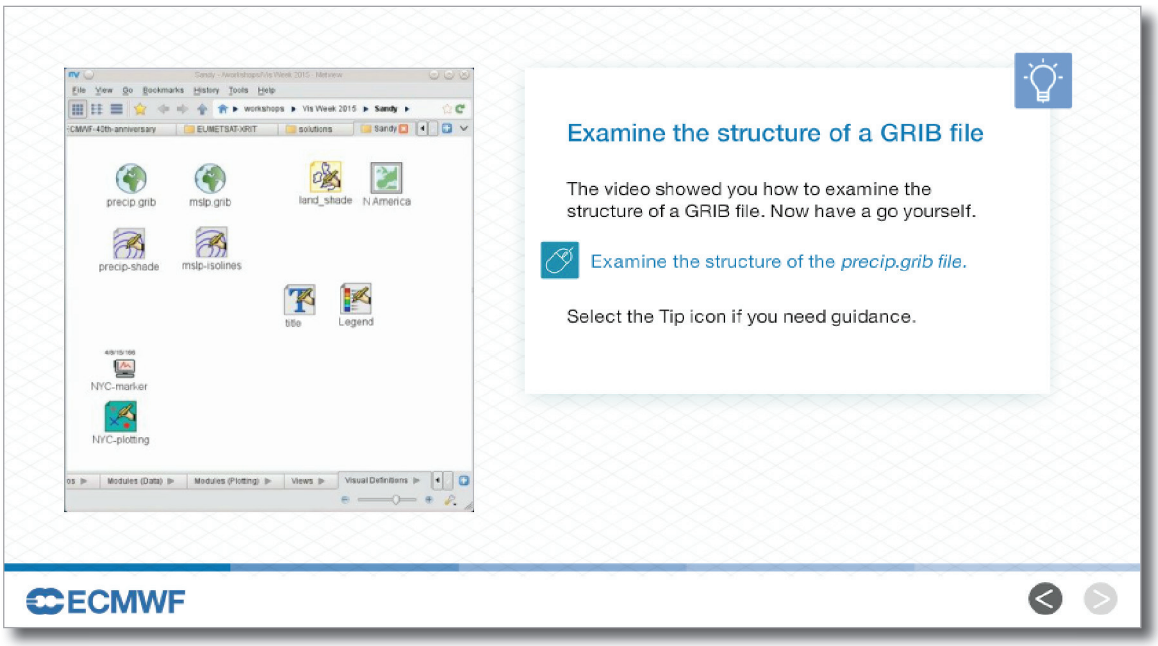
Learning through understanding is the key mechanism in the cognitive perspective: knowledge is imparted through explanation, inference and problem solving. Kolb's learning cycle is the best-known pedagogical model supporting this perspective. It is a continuous cycle that goes from concrete experience by doing, to reflective observation, to abstract conceptualisation and active experimentation, for example planning or trying out what we have learnt. This perspective can be translated into eLearning by using simulations of real-world situations with a support system that guides the learner through a learning path.

In the situative perspective, learning happens by making topics meaningful through social practice. In the context of eLearning, this perspective depends on social platforms such as online communities and wikis. These can be used as shared knowledge (a knowledge base) where information and feedback is collected and learning can happen by developing communities.

ECMWF's approach

eLearning opens up great opportunities for ECMWF to support the training requirements of its Member and Co-operating States. The new eLearning modules will provide the background knowledge on which face-to-face courses at ECMWF can build. This will enable us to spend the course time on more complex material or to shorten training events to reduce costs for Member States. Other initiatives such as WMO Global Campus and future EUMETNET training programmes may also find the new ECMWF eLearning modules useful as resources to make available to their member states.

The ECMWF initial phase of development focuses on topics that are often requested by users and used in multiple training settings, such as the OpenIFS workshops and face-to-face training. The self-contained modules, which can be used stand-alone or as part of blended courses (eLearning combined with face to face), will follow a learner-centred approach to allow for different knowledge levels and learning styles. They will mainly focus on the associative and cognitive perspectives. The modules are being created in collaboration with instructional designers who are working with ECMWF experts. These modules are being created using an instructional design methodology as set out by Mayes & de Freitas (2004), which assumes that information is processed through two channels (auditory and visual) of limited capacity. In order to minimise overload, the learner filters, selects, organises and integrates the information presented in the resources. These assumptions and learning principles are guiding the creation of our eLearning modules.



Exercises. Practical exercises are an integral part of the eLearning modules.

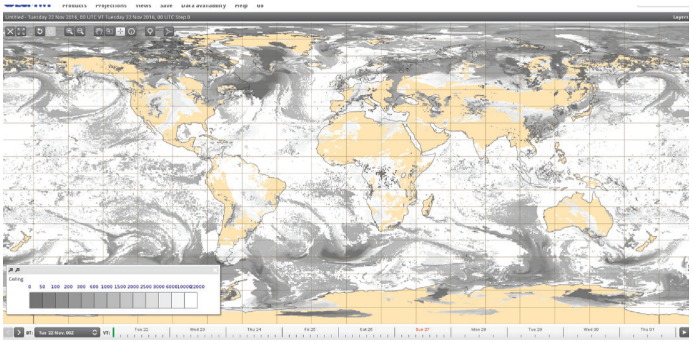
New layers in updated ecCharts service

CIHAN SAHIN,
SYLVIE LAMY-THÉPAUT

New diagnostic parameters and wave output fields have been made available in ecCharts, a web-based application providing easy access to ECMWF's medium-range forecasts in a graphical format and in their native resolution. The rich web user interface of ecCharts offers an interactive set of tools to display and explore the meteorological situation in far greater detail than is possible using standard web charts provided on ECMWF's website. It provides an extensive range of parameters and products (currently around 230 layers) from ECMWF's high-resolution and ensemble forecasts (HRES and ENS), which users can combine to create their own products.

ecCharts is updated twice a year, in June and November. These updates introduce new layers and features compiled by ECMWF based on internal developments and user feedback collected from various channels, including ecCharts help pages, workshops, meetings and Member State visits.

The latest update of ecCharts was implemented at the end of November 2016 and coincided with the operational testing period of a new version of ECMWF's Integrated Forecasting System (IFS Cycle 43r1). Between early October and the implementation of the IFS upgrade on 22 November, all ecCharts layers were duplicated to present graphical products from the new IFS cycle together with operational data. This facility provided a convenient way of monitoring the new IFS version's performance compared to the operational version in real time.



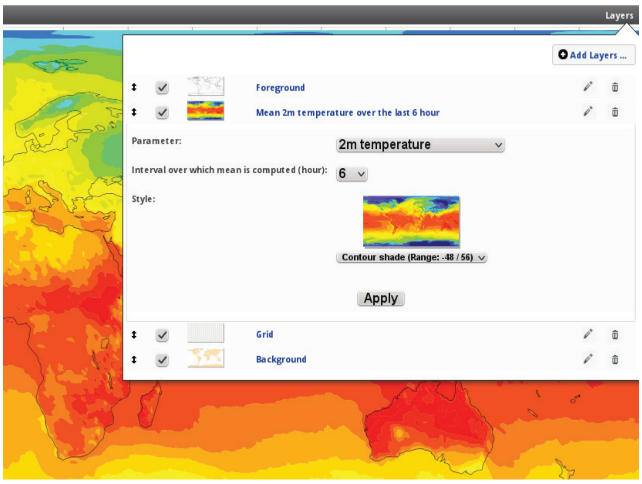
New parameters. An example of a new parameter introduced in IFS Cycle 43r1 and now available in ecCharts is 'ceiling': the height of the level where cloud fraction becomes >50% and condensate content more than 10^{-6}.

In addition to providing existing ecCharts layers for the new IFS version, users are now also able to visualise some of the new parameters introduced by IFS Cycle 43r1. Those parameters include cloud and freezing level layers and eight new wave model layers, including the magnitude and direction of the wave energy flux that is responsible for the impact of waves on coastlines and offshore structures.

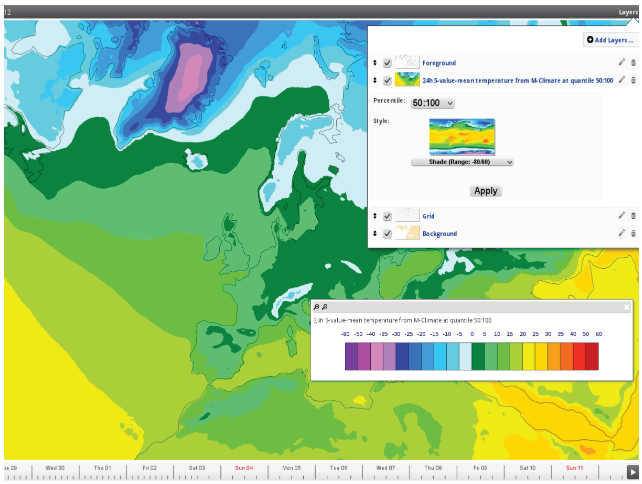
Other HRES parameters made available in the ecCharts update include cloud base height, total column water and water vapour and potential vorticity at various pressure levels.

One of the new layers enables users to compute and plot 2 m mean temperature over a user-controlled interval up to a selected forecast valid time. The interface enables users to choose one of the 2 m temperature parameters (instantaneous, minimum and maximum 2 m temperature) and the interval over which the mean is computed.

Another major addition is the introduction of model climate (M-Climate) parameters. The model climate is the reference climate that is used to compute severe weather parameters, such as the Extreme Forecast Index (EFI). The model climate is based on five weeks of re-forecasts using an 11-member ensemble over the last 20 years (in total 1980 realisations). It is produced twice a week. The model climate always uses the same IFS version



New mean temperature layers. Two-metre mean temperature over an interval can now be visualised in ecCharts.



M-Climate editing layer. A new editing layer makes it possible to control the M-Climate percentile and offers several different styles.

as ENS. There are several M-Climate layers in ecCharts (the same parameter set as in the EFI) offered at pre-defined percentiles. Users can customise the chart by editing and selecting a percentile (available percentiles are 0, 1, 10, 25, 50, 75, 90, 99 and 100%) as well as applying different contouring options.

M-Climate parameters are produced as 'daily' values twice a week (on Mondays and Thursdays). In ecCharts, they are provided for all forecast runs and all time steps of a standard ENS field (3-hourly up to day 6 and 6-hourly up to day 15) to make it possible to overlay M-Climate fields with daily forecast fields.

The update also contains two additional parameters (2 m minimum and maximum temperature) available as Cumulative Distribution Function (CDF) plots for a selected position, complementing 2 m mean temperature CDF plots. They are available through Meteogram view in the ecCharts interface.

Most ecCharts layers are also available through Web Map Service (WMS). WMS is a standard protocol for serving georeferenced map images. The ecCharts WMS service enables user applications to request georeferenced maps from ecCharts layers. Since March 2017, it has been possible to make requests in Web Mercator projection (in addition to standard projection), which is commonly used by applications such as Google Maps.

All ENS layers in ecCharts are available 40 minutes earlier since 8 March thanks to the change in ECMWF's dissemination schedule implemented that day.

More detailed explanations of the latest ecCharts update (including previous updates) can be found at https://software.ecmwf.int/wiki/display/ECCHARTS/Updates.

To find out more about ecCharts or make a request, please visit https://software.ecmwf.int/wiki/display/ECCHARTS.

ECMWF–CMEMS agreement on sea-level anomaly data

PATRICIA DE ROSNAY, FLORIAN PAPPENBERGER, HAO ZUO, IOANNIS MALLAS

In February 2017, ECMWF concluded an agreement with the Copernicus Marine Environment Monitoring Service (CMEMS) which formalises the terms under which CMEMS provides the Centre with sea-level anomaly products for ocean data assimilation. The ocean data assimilation system is a crucial component of ECMWF's Earth system approach. It produces both real-time and reanalysed ocean states and it relies on the assimilation of conventional and satellite observations. In particular, radar altimeter sea-level anomaly (SLA) data assimilation improves the representation of the seasonal and inter-annual variability of sea level changes, which is important for extended-range and seasonal-range weather forecasts.

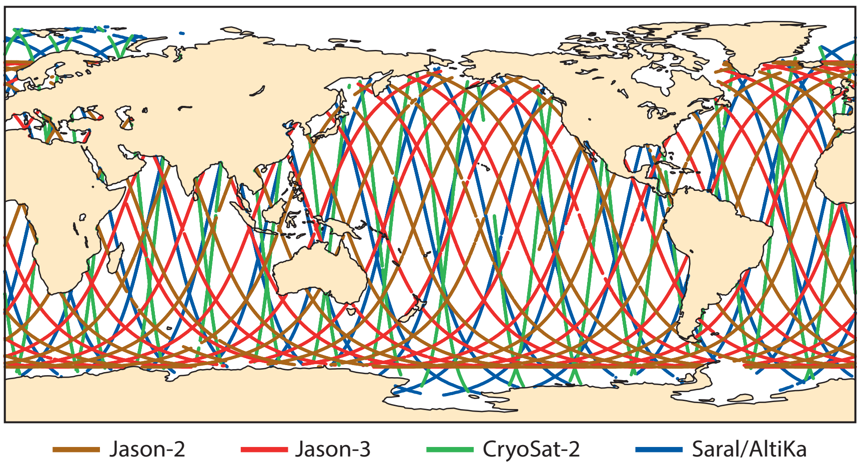
The dedicated major-account ECMWF–CMEMS agreement concluded in February 2017 defines the list of CMEMS SLA products used by ECMWF for ocean data assimilation. It specifies a number of conventions used for the data transfer protocol, such as file name conventions, technical specifications for file transfer and minimum notification periods required by ECMWF for testing purposes before CMEMS implements product changes. CMEMS also provides ECMWF with information about upgraded or new Level 3 and Level 4 global SLA products, as such changes may have an impact on operational numerical weather prediction at ECMWF.

The CMEMS SLA data currently used include observations from several sensors as illustrated in the coverage map, with observations from Jason-2, Jason-3, CryoSat-2 and SARAL/AltiKa operationally assimilated at ECMWF. Future developments in ocean data assimilation and coupled ocean–atmosphere data assimilation will open up possibilities to use a wider range of ocean-related observations.

What is CMEMS?

The Copernicus Marine Environment Monitoring Service (CMEMS) is part of the EU's Copernicus Earth observation programme. It is operated by the French centre of global ocean analysis and forecasting, Mercator Océan.

CMEMS has been designed to respond to issues emerging in the environmental, business and scientific sectors. Using information from both satellite and in situ observations, it provides daily state-of-the-art analyses and forecasts, which offer an unprecedented capability to observe, understand and anticipate marine environment events. For more details, visit the CMEMS website: http://marine.copernicus.eu.



Sea-level anomaly observation coverage. The map shows the coverage of sea-level anomaly observations in a daily near-real-time along-track multi-mission radar altimeter SLA product from CMEMS as used in the ECMWF ocean analysis system on 14 February 2017.

Forecast performance 2016

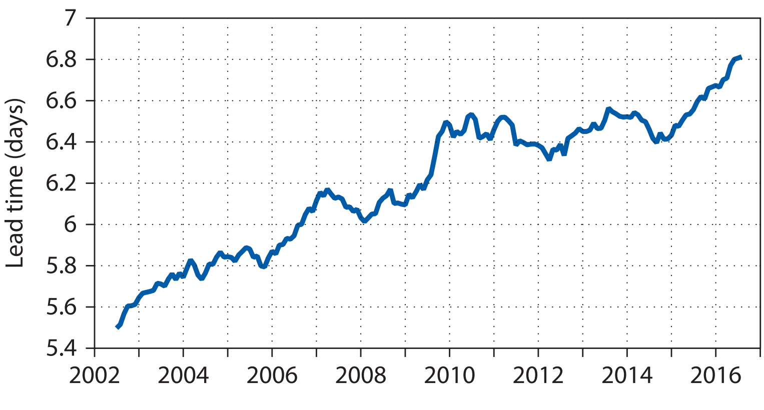
THOMAS HAIDEN, TIM HEWSON, MARTIN JANOUSEK, DAVID RICHARDSON

ECMWF maintains a comprehensive range of verification statistics to evaluate the accuracy of its forecasts. Each year, a summary of verification results is presented to ECMWF's Technical Advisory Committee (TAC). Their views about last year's performance of the operational forecasting system are given in the box.

The overall performance of the operational forecasts is summarised using a set of headline scores endorsed by the TAC, which highlight different aspects of forecast skill. Upper-air performance of the high-resolution forecast (HRES) in the northern hemisphere extratropics is monitored through the anomaly correlation of 500 hPa geopotential height. Upgrades to the Integrated Forecasting System (IFS) in May 2015 (Cycle 41r1) and in March 2016 (Cycle 41r2) have led to a substantial increase in medium-range forecast skill. The forecast range at which the anomaly correlation drops below 80% now exceeds the highest levels reached previously by 0.2 days. Note that part of the increase seen during 2015–2016 is due to a concurrent increase in atmospheric predictability in this period. However, comparison with forecasts from other global centres shows that ECMWF has consolidated its lead both for the HRES and for ensemble forecasts (ENS). Similar improvements are found for the southern hemisphere and for other upper-air skill metrics. The 500 hPa height root-mean-square error in both hemispheres has reached its lowest level so far. As shown in the second figure, ENS upper-air skill, as measured by the continuous ranked probability skill score of 850 hPa temperature, has now increased beyond the levels seen during the anomalously predictable period in 2010. Upper-air skill in the tropics has slightly improved when verified against observations but not against analyses due to increased analysis activity.

Surface skill has increased for 2 m temperature and humidity, 10 m wind speed, precipitation, and total cloud cover, with reductions in errors on the order of 1–2% in the early medium range. However, there are still issues with seasonally and diurnally varying regional biases in 2 m temperature which need to be resolved. Improvements in the forecast of total cloud cover are seen both in the direct verification against SYNOP and in the verification of solar radiation fluxes against satellite observations.

Forecasts of tropical cyclones have been comparable in skill to the previous year in terms of position errors both for the HRES and ENS, while speed errors have been further reduced. Tropical cyclone intensity has improved in terms of bias, but mean absolute errors have been larger than in the previous year.



Skill of the HRES as measured by ECMWF's primary deterministic headline score. Results for geopotential at 500 hPa in the northern hemisphere extra-tropics show that the medium-range forecast skill continues to increase due to recent model upgrades. The chart shows 12-month running average values of the forecast range at which the anomaly correlation drops below 80%.

Wave forecast skill has further increased with respect to both wave height and peak period, allowing ECMWF to maintain its lead compared to other global wave forecasting systems.

The presence of a strong El Niño enhanced predictability on the seasonal timescale. Positive anomalies of 2 m temperatures over North America and northern Eurasia during the northern-hemisphere winter 2015–16 were captured well by the seasonal forecast. The westernmost parts of Europe were influenced by a persistent cold anomaly over the North Atlantic, which was also predicted by the model. During the northern-hemisphere summer of 2016, sea-surface temperatures in the eastern tropical Pacific had reverted back from the previous El Niño to slightly negative anomalies. In terms of large-scale anomaly patterns, the seasonal 2 m temperature forecast captured the major features. However compared to the period December 2015 to February 2016, there was less skill on smaller, sub-continental scales.

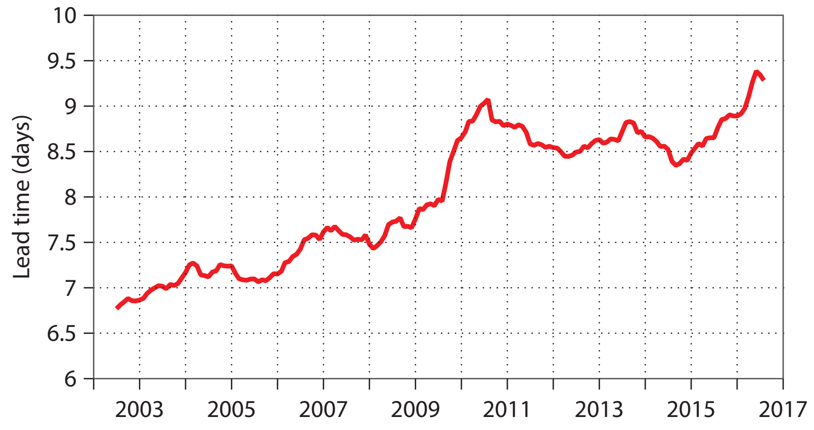
Verification results provided by Member and Co-operating States focused on surface parameters in the shorter ranges, where they compared IFS forecasts with limited-area model (LAM) output. This feedback is greatly appreciated as it helps to improve future model versions. Among the issues reported were large 2 m temperature errors in stable situations, and a tendency to underestimate high wind speeds over mountainous areas. It was also noted by some states that over Europe there was generally too much convective activity over mountainous areas, but too little over some lowland areas. Meanwhile we also received reports of sporadic problems with sea-surface temperature and sea-ice cover within the IFS.

The complete set of annual results is available in ECMWF Tech. Memos No. 792 on the 'Evaluation of

ECMWF forecasts, including the 2016 resolution upgrade' and No. 797 on the 'Use and Verification of ECMWF products in Member and Co-operating States (2016)'. Both are downloadable from http://www.ecmwf.int/en/research/publications. These documents present recent verification statistics and evaluations of ECMWF forecasts (including weather, waves and severe weather events), whilst No. 792 also includes information about changes to the data assimilation/forecasting and post-processing systems. The performance of the monthly and seasonal forecasting systems is also assessed.

The following are other sources of information about verification and forecasting system changes:

- Verification pages on the ECMWF web server are regularly updated. They are accessible at http://www.ecmwf.int/en/forecasts/charts.
- Interactive plots showing inter-comparisons of global model forecast skill can be found on the WMO Lead Centre for Deterministic Forecast Verification (WMO-LCDNV) web page at http://apps.ecmwf.int/wmolcdnv/.
- All IFS forecasting system cycle changes since 1985 are described at http://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model.



Skill of the ENS as measured by ECMWF's primary probabilistic headline score. Results for temperature at 850 hPa in the northern hemisphere extratropics show that in the year 2016 the medium-range probabilistic forecast skill reached its highest level so far. The chart shows 12-month running average values of the forecast range at which the continuous ranked probability skill score (CRPSS) drops below 25%.

Assessment of ECMWF's Technical Advisory Committee, 13–14 October 2016

With regard to its overall view of the ECMWF operational forecasting system, the Committee:

a. in view of the overall performance level of its weather forecast system, congratulated ECMWF on the improved forecast skill as revealed by the headline scores;

b. noted that this improvement was very clear relative to ERA-Interim benchmarking, but that some of the other centres have also made marked improvements over this period. However ECMWF still maintains its lead in the medium range;

c. welcomed ECMWF's continued focus on weather parameters that have an impact on users, such as 2 m temperature, rainfall, and wind; was pleased to note in particular the improvement in forecasting cloud cover, although several member states still noted occasional problems with low-level clouds;

d. congratulated ECMWF on the clear impact of model changes on forecast performance, most notably 41r2 and associated gains in predictability (3 to 6 h gain according to the first two headline scores); noted that other parameters were also positively affected by this model and resolution change; suggested that e-suite headline score time series be plotted alongside o-suite scores to help document these gains;

e. noted that improvements in the ENS resolution in the 10–15 day period have significantly improved the forecasting capability at that time range;

f. congratulated ECMWF on the good communication with Member States (MSs) prior to the 41r2 implementation, and especially the provision of e-suite products on EC Charts in real time;

g. noted that MSs renewed their appreciation for the provision of new parameters targeting high-impact weather such as precipitation type, visibility, and the EFI for CAPE shear; encouraged ECMWF to develop further these diagnostics such as lightning density in consultation with MSs and provide verification results accordingly;

h. welcomed the continued development of EC Charts facilities, and encouraged ECMWF working with MSs in its efforts to improve the performance of the service;

i. welcomed the ongoing development of facilities offered to MSs for reporting model forecast problems or document severe weather case studies; encouraged ECMWF to include in its report to TAC a summary of the actions that have been taken;

j. noted that forecasters in MSs occasionally report negatively on ENS unphysical behaviour of some members, welcomed first results from research being done on new stochastic physics (SPP) that should improve on that issue.

Complex supercomputer upgrade completed

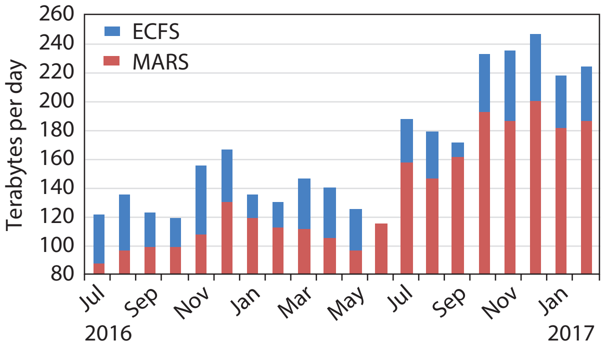
MIKE HAWKINS

You may not be able tell from looking at the outside or from the size of the electricity bill, but the ECMWF High Performance Computing Facility (HPCF) is now much bigger than it was at the beginning of 2016. After an upgrade that involved replacing almost 1,800 processor blades, the system now has 260,000 processor cores to run work on, equivalent to more than 200 desktop computers for everyone at ECMWF. It also has more than 900 terabytes of memory, enough to store almost 750 years of MP3 music.

Cray provide ECMWF with an HPCF under a multi-year, multi-phase service contract. In December 2015, we agreed to extend this contract for two years, until the end of September 2020. This gave ECMWF a better alignment with the timescales of the data centre relocation programme. It has also provided the Centre with a much more powerful phase two system from 2016 and a new 'Novel Architecture Platform' to support the work of the Scalability Programme.

The new contract enabled a full upgrade of both existing Cray clusters, replacing all of the existing compute nodes that used Intel 'Ivy Bridge' processors with the latest Intel 'Broadwell' processors along with extra storage and two new cabinets of nodes. Two generations of progress in processor technology have allowed Intel to pack more than seven billion transistors on one chip. This has resulted in an increase in the core count from 12 to 18, but with a reduction in the power consumption from 130 W to 120 W per chip. The new processors have a new microarchitecture and new instructions, including Advanced Vector Extension (AVX2) instructions to improve performance on some codes. Since the upgrade was a full swap, we avoided the problem of running a heterogeneous system. Different instruction sets would have caused some programs to fail to execute on the older processors or to give different results. Different processor speeds and memory sizes would have made scheduling workload difficult and inefficient. With a homogeneous system, we can fully optimize the workload to take advantage of the new architecture.

Blade swap. Cray engineers moving a trolley load of compute blades. The trolley holds half the number of blades that are in a compute rack.



Primary data growth. The evolution of the average daily increase in primary data stored in the Data Handling System clearly shows the impact of the upgraded HPCF.

Minimal disruption

The team planning and executing the upgrade faced a key challenge: unlike in previous upgrades, the installation did not take place while the existing service continued to run as usual. Instead, the team had to take apart the system providing the service and replace it with a new one. Minimising the impact and especially the time the system was out of service was vital. This was especially important as an upgrade to the Integrated Forecasting System to implement a horizontal resolution increase had to take place over the same period. A three-step approach was decided on:

- Step 1: upgrade part of one cluster to allow large-scale user code testing and to practise the upgrade procedure
- Step 2: upgrade the remaining part of the cluster
- Step 3: upgrade all of the second cluster.

This staged approach allowed ECMWF to get access to the new technology for large-scale code testing while retaining operational resilience. It also allowed Cray to practise their install procedure to meet the logistical challenge.

The first step was reported on in the spring 2016 Newsletter. It made available 700 nodes for large-scale testing from the beginning of April until mid-May. The bigger challenge was to swap out the remaining blades. A Cray system is made up of compute nodes. Nodes live on blades and blades live in cabinets. There were 19 cabinets in ECMWF's original configuration, each with 48 processor blades, giving 912 blades per cluster. Some of these nodes have special functions, such as connecting to the storage or networks, so their blades did not need to be replaced. But this still left 904 blades on each machine to be swapped. Since Cray had already replaced 144 blades, only 760 blades remained for the first cluster. In May, Cray unpacked the blades, replaced them in the machine, and packed up the old ones for shipment, in under two days. They then repeated this process a month later, but this time with all 904 blades of the second cluster. That was an impressive feat, especially considering that at more than 30,000 kilogrammes the weight of the blades to be moved for one system is roughly the equivalent of five African elephants. After each upgrade, Cray ran an extensive suite of tests to 'burn in' the new hardware before handing it back. The downtime for each system was kept to just a week.

Scalability

Exploiting the potential of new HPC architectures is one of the challenges for the Scalability Programme. ECMWF already has a GPGPU cluster with 68 NVIDIA Tesla K80 GPUs. To complement this resource, on 14 September Cray delivered a standalone machine with 32 nodes of Intel Xeon Phi 'Knights Landing' processors. Each node has one processor with 64 cores, 16 gibibytes of high-bandwidth memory and 96 gibibytes of DDR4 memory, which is enough to run the forecast model at its operational configuration.

Extra computational power enables more work to be done, which in turn creates more data to be managed, as can be seen in the data storage chart. Because of the upgrade, the Data Handling System was enhanced with extra servers and disk cache to support the growing volume of data, which passed 200 petabytes at the end of 2016.

The configuration of the Cray systems will remain stable, except for software upgrades, until they are replaced by new systems in 2020. The process to find those successor systems has already started with a project to bring together science requirements from the new Strategy, assessments of future technology and a study of the socio-economic benefits of improved forecasts and services to present a business case for the next procurement to Council.

Open data in the spotlight during week of events

JULIA WAGEMANN, STEPHAN SIEMEN, FABIO VENUTI, ERIK ANDERSSON

Between 28 February and 5 March, ECMWF held a week of events focusing on freely available data from ECMWF activities, including the EU-funded Copernicus Climate Change and Atmosphere Monitoring Services operated by the Centre. The week was scheduled to coincide with International Open Data Day on 4 March 2017, which aims to raise awareness of the importance and benefits of open data.

A series of three events considered open data from different perspectives. A one-day workshop on improving the socio-economic impact of numerical weather prediction (NWP) data was aimed at policy-makers and professionals. It provided a forum to discuss the opportunities and consequences of introducing an open data policy for weather forecast data. The two-day Workshop on Meteorological Operational Systems (MOS) is biennially organised by ECMWF and this year focused on how to serve large volumes of (open) data and how to give users easy access to data. The week finished with a two-day open data hackathon aimed at developers, scientists and data enthusiasts to explore creative uses of data freely available from ECMWF.

Teamwork. Twenty teams worked day and night at the #OpenDataHack event. (*Photo: Maurizio Latini*)

Socio-economic impact

The workshop on improving the socio-economic impact of NWP data provided a forum to discuss future challenges in the dissemination of meteorological data. It also explored how ECMWF and national meteorological services can ensure that the private sector can continue to exploit the economic value of weather information. One of the main outcomes was the recognition that the implementation of open data by just publishing vast amounts of data will not automatically bring great benefits. Alongside an open data policy, new solutions have to be implemented to provide innovative data discovery, selection and access systems.

ECMWF is currently working towards a strategy for Data Services and this workshop was part of the exploratory phase, in order to better understand the challenges and costs of providing ECMWF forecast data in the future.

Meteorological Operational Systems (MOS)

The Workshop on Meteorological Operational Systems this year focused on how (open) data can best be brought to users. Increasingly large and complex data sets challenge data centres to look at new technologies and work practices to ensure continuous data uptake and exploitation. This goes beyond the mere provision of data. New strategies for efficient processing and fast visualisation are required. Possible solutions are cloud-based approaches and moving processing/visualisation to where data is stored. Presentations from services around the world showed that the current trend is to bring the processing to where the data is. The volume of data stored in various data centres is simply too large to be moved to users. ECMWF's MARS archive, for example, is the world's largest archive of meteorological data and holds around 180 petabytes of data. The traditional exhibition of operational meteorological visualisation systems was also part of the workshop.

#OpenDataHack @ECMWF

Over 70 developers, data wranglers, scientists and data enthusiasts came to #OpenDataHack @ECMWF on 4 and 5 March to explore creative uses of open weather and climate data from ECMWF and the three Copernicus services for Climate Change (C3S), Atmosphere Monitoring (CAMS) and Emergency Management (EMS). Reading Buses and Snowflake Software were two additional open data providers for the #OpenDataHack.

The aim was to raise awareness of freely available data from ECMWF and to have direct contact with users who are interested in working with ECMWF open data. The hackathon was divided into three challenge categories: Get Out, Get Geeky and Get Creative. A panel of six judges, including ECMWF's Director-General Florence Rabier and Director of Copernicus Services Juan Garces de Marcilla, nominated a winner for each category.

The winner of the Get Out challenge was the HydroNEXT team, who developed a web application that uses river discharge forecast data from the GloFAS project and river flow data from the Copernicus SWICCA project to calculate the projected energy generation of a specific hydro-electrical plant.

The winner of the Get Geeky challenge was the team 'Reading Buses accident and breakdown prediction', who developed a machine-learning model that predicts the probability of accidents for buses depending on weather conditions. Besides bus data, the model uses climate reanalysis data, such as total precipitation, snowfall, evaporation and total column ozone.

The Get Creative category had two winners: Team Diversity investigated the impact of weather and climate on animal migration in Kenya, based on a geospatial analysis. The second first place was awarded to team CWS+, which developed a water disease prevention system for Kenya. Based on rainfall predictions, the system predicts the likelihood of diseases, droughts, water shortage problems and floods.

The hackathon had two main outcomes. First, the realisation that meteorological data is challenging to access and to work with, especially for users outside the MetOcean community. Second, the recognition that open weather and climate data is particularly beneficial when combined with other open data sources.

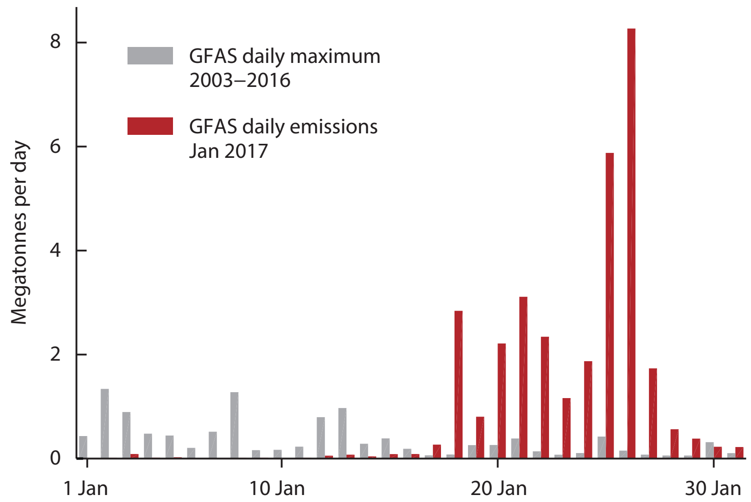
More details on all three events can be found on the ECMWF website: www.ecmwf.int/en/learning/workshops/open-data-week-at-ecmwf.

Devastating wildfires in Chile in January 2017

MARK PARRINGTON, FRANCESCA DI GIUSEPPE, CLAUDIA VITOLO, FREDRIK WETTERHALL

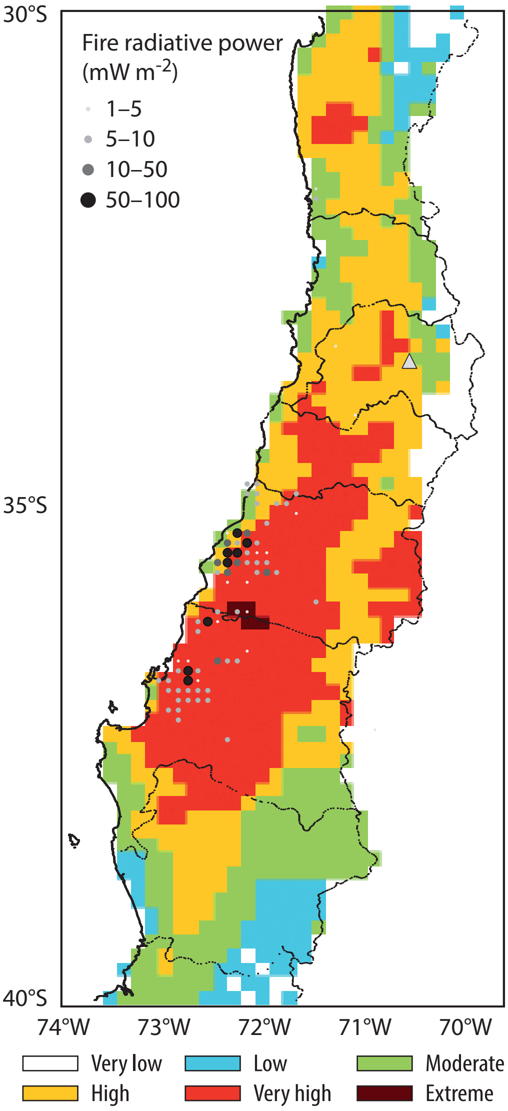
Strong winds, high temperatures and long-term drought conditions led to some of the worst wildfires in Chile's history during the last two weeks of January 2017. Fires in the central regions of O'Higgins, Maule and Bío Bío south of Santiago were widely reported by the global media. The Emergency Response Coordination Centre of the European Commission (ERCC) reported that between 1 July 2016 and 2 February 2017 approximately 3,000 fires had affected more than 575,000 hectares and 6,000 people.

ECMWF monitors global wildfire emissions and smoke transport and produces forecasts of fire danger under activities for the Copernicus Atmosphere Monitoring Service (CAMS) and the Copernicus Emergency Management Service (Copernicus EMS).



Fire emissions of CO_2. Time series of daily emissions of CO_2 from fires in Chile in January 2017.

Data from the CAMS Global Fire Assimilation System (GFAS) provides information on the distribution of observed fire activity and indicates the relative intensity of each observed fire. The time series of daily CO_2 fire emissions for Chile shown in the chart is used here to indicate the relative fire intensity. It highlights the unusual nature of the January activity. There were 13 consecutive days between



Fire danger classes. GEFF 5-day forecast of fire danger classes (shading) for Chile initialised on 26 January 2017 for the period 26–30 January, with GFAS fire locations and intensities (fire radiative power) for the same period.

Useful web links:

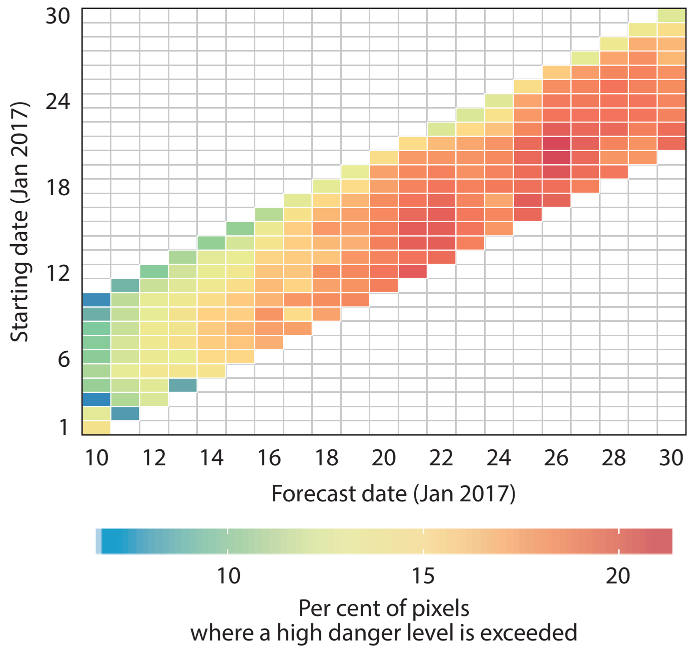
CAMS website: http://atmosphere.copernicus.eu/

Copernicus EMS website: http://emergency.copernicus.eu/

GFAS data: http://apps.ecmwf.int/datasets/data/cams-gfas/

GEFF-reanalysis data: http://apps.ecmwf.int/datasets/data/geff-reanalysis/

GEFF-realtime data (expected release time May 2017): http://apps.ecmwf.int/datasets/data/geff-realtime/



Fire danger forecasts. Time series of 10-day GEFF fire danger forecasts during January 2017 for the area shown in the fire danger class map (left), showing the proportion of that area in which a high danger level was predicted to be exceeded.

17 and 29 January in which the daily total emission far exceeded the climatological maximum over the years 2003–2016. The total emission of CO_2 for the whole of January was estimated to be more than 30 megatonnes, which is six times greater than typical January totals for Chile and accounted for approximately 8% of the January 2017 total global fire emissions. The smoke plumes from these fires extended for several hundred kilometres over the Pacific Ocean in global forecasts of atmospheric composition produced by CAMS.

Fire danger forecasts

The Global ECMWF Fire Forecast (GEFF) system provides daily forecasts of fire danger using the high-resolution and ensemble prediction system up to 10 days ahead. GEFF forecasts of fire danger represented by the Fire Weather Index (FWI) indicate the predicted fire intensity at the flame front if there were to be a fire. They correspond well to the observed fire activity in central Chile: the peak emissions between 17 and 29 January are reflected in forecasts initiated up to seven days earlier. Both the geographical distribution and the timing of the peak danger were well predicted in the FWI forecasts. The most intense observed fire emissions in January occurred in regions where the predicted fire danger was high (i.e. fire danger classes 'high' and above). This gives us some confidence in the performance of the GEFF system in representing fire danger in a non-European region.

CAMS is operated by ECMWF under a delegation agreement with the European Commission and provides near-real-time forecasts and analyses of atmospheric composition globally and for Europe. The GEFF system was developed under Copernicus EMS activities and is the global fire modelling component of the European Forest Fire Information System (EFFIS). Fire danger classes and indices have been calculated for Chile using 40 years of ERA-Interim data in the GEFF reanalysis.

Copernicus fire danger forecast goes online

FRANCESCA DI GIUSEPPE, MATTHEW MANOUSSAKIS, BLAZEJ KRZEMINSKI, CLAUDIA VITOLO, FREDRIK WETTERHALL, FLORIAN PAPPENBERGER

Copernicus fire danger forecast products from the Global ECMWF Fire Forecast (GEFF) system are now available for download through the ECMWF public dataset web interface. The products have been developed at ECMWF over the last three years as part of the EU-funded Copernicus Emergency Management Service. They complement other Copernicus products related to fire, such as the biomass-burning emissions made available by the Copernicus Atmosphere Monitoring Service (CAMS) operated by ECMWF. The latter product is calculated daily by the CAMS-Global Fire Assimilation System (GFAS) based on active fires detected by the MODIS satellite instrument.

Two fire danger datasets are available for download: GEFF-reanalysis and GEFF-realtime. GEFF-reanalysis provides historical records of global fire danger conditions from 1980 to today. It is updated as new ERA-Interim data become available. GEFF-realtime provides real-time high-resolution deterministic and lower-resolution probabilistic fire danger forecasts up to 15 days ahead using weather forcings from the latest model cycle of ECMWF's Integrated Forecasting System (IFS). The real-time dataset is updated every day with a new set of forecasts. Forecasts for the past year are available for immediate retrieval using the web interface, while older forecasts are archived on ECMWF servers and can be accessed upon request. This allows users to assess the system's performance for recent events.

The development of GEFF was funded through a third-party agreement with the European Commission's Joint Research Centre (JRC). A subset of GEFF data is also feeding the European Forest Fire Information System (EFFIS) web portal, an operational platform which gives access to timely fire danger information at a pan-European scale. Thirty-eight local and national authorities across Europe are part of the EFFIS network and have been relying on GEFF output for the early identification of regions prone to fire events as a result of persistent drought conditions.

With the new data download service, users will be able to access the complete GEFF database, which comprises the Canadian Fire Weather index and the US and Australian fire danger models. The web interface enables users to navigate through the GEFF datasets in a dynamic and user-friendly way. Whenever a selection is made (e.g. of a particular model or parameter), the user interface is updated automatically in order to reflect data availability. In this way the system prevents users from submitting requests for data that do not exist and visualises the dataset layering. Once users have made their selections, they can submit the request to download the requested data. Alternatively they can view the corresponding Python script request and use the ECMWF Web-API service to download the data in a programmatic way.

The release of the GEFF dataset is in line with the data and information policy of the Copernicus programme, which provides users with free, full and open access to environmental data. No registration is required for discovery and exploratory services, but it is a prerequisite if users wish to download GEFF data. Registration is free of charge.

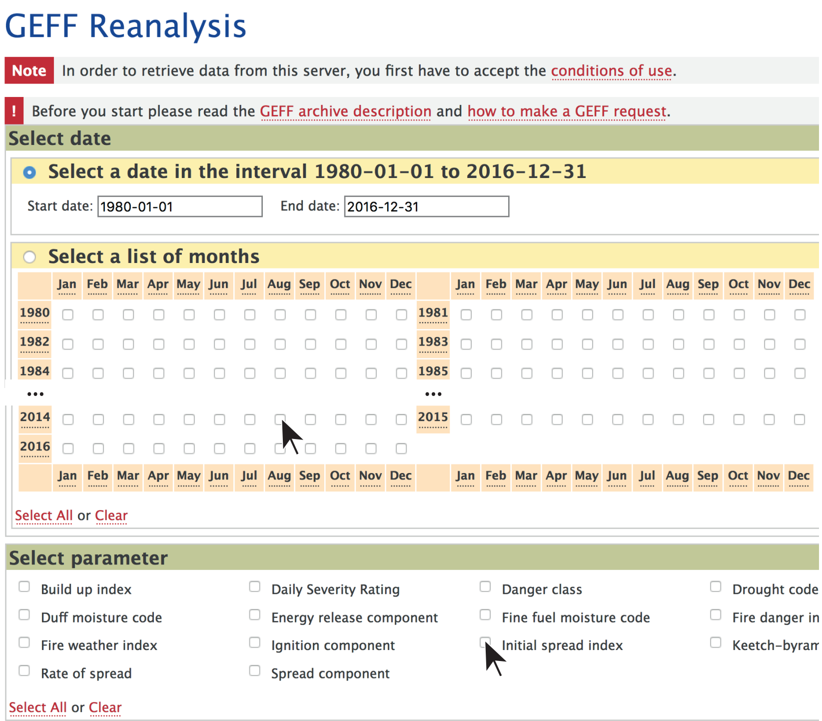
To access GEFF data, please follow the links below.

GEFF-reanalysis:
http://apps.ecmwf.int/datasets/data/geff-reanalysis/

GEFF-realtime (expected release time May 2017):
http://apps.ecmwf.int/datasets/data/geff-realtime/

ECMWF public dataset documentation:
https://software.ecmwf.int/wiki/display/WEBAPI/Access+ECMWF+Public+Datasets

ECMWF Web-API FAQ:
https://software.ecmwf.int/wiki/display/WEBAPI/WebAPI+FAQ



GEFF datasets on the web. Users can specify a timeframe and select a number of parameters when accessing the GEFF-reanalysis and GEFF-realtime datasets.

Talks with Italy on new data centre under way

Negotiations with Italy on ECMWF's new data centre started in March, when a delegation led by Director-General Florence Rabier visited Bologna and Rome. The talks come after ECMWF's Council mandated Dr Rabier to prepare a high-level agreement with the Italian government on Bologna as the new location of the data centre, for approval by Council at its next session.

Proposed new data centre. Italy is proposing to host the data centre in Bologna. (*Image: gmp von Gerkan, Marg & Partner*)

ECMWF's current data centre, which accommodates the high-performance computing facility, is located on the Centre's premises in Reading, UK. The need to significantly expand it led to a process to identify a new site. A panel of international experts and representatives of ECMWF Member States considered a range of proposals and found that Bologna was the best from the point of view of the requirements and overall interests of ECMWF.

ECMWF joins OpenWIS Association

BAUDOUIN RAOULT

ECMWF is in the process of joining the OpenWIS Association as an associate member. OpenWIS is an international non-profit organisation which aims to facilitate collaboration on the development, promotion and sharing of open source software for the exchange of global meteorological information.

The founding members of the OpenWIS Association are Météo-France, the UK Met Office, the Korean Meteorological Administration, the Australian Bureau of Meteorology and Météo-France International. The US National Weather Service and the Finnish Meteorological Institute have since joined the association.

The main software package in the OpenWIS Association's portfolio is also called OpenWIS. It is designed to implement the technical requirements of the WMO Information System (WIS). ECMWF has played an active role in the creation of the WIS. In 2011, it was endorsed by the WMO's Executive Council as a Data Collection and Production Centre (DCPC). The Centre relies on the OpenWIS software to fulfil that role.

Being an associate member will allow the Centre to attend the OpenWIS Technical Committee. This will give us an opportunity to provide input into future developments of the OpenWIS software. ECMWF will also be able attend the OpenWIS Association Steering Committee meetings as an observer.

ECMWF installs electric vehicle charging points

SARAH BAKER

ECMWF has installed two electric vehicle charging points which staff and visitors can currently use free of charge at the Centre's premises in Shinfield Park, Reading, UK. The move is intended to support the use of hybrid and fully electric cars, which bring a range of environmental benefits compared to internal combustion engine vehicles.

Fully electric vehicles produce zero emissions at the point of use, thus reducing road pollution. They are also quieter than other cars. As an incentive to change to electric, in the UK such vehicles are exempt from road tax and congestion charges in London and elsewhere. The cost of running electric vehicles is also relatively low, with a full charge giving a typical range of 100 miles costing around £2 to £3. Driving 100 miles in a petrol or diesel car will cost around £9 to £13 in fuel.

Charging points. ECMWF has installed two 16 A (3.6 kW) charging points free to use by staff and visitors at Shinfield Park.

doi:10.21957/m3c157

The 2015/2016 El Niño and beyond

TIM STOCKDALE, MAGDALENA BALMASEDA, LAURA FERRANTI

Two years ago, forecasting systems were predicting the development of a potentially major El Niño – a warming of the equatorial Pacific Ocean which has impacts on weather patterns around the world. The 2015/16 El Niño turned out to be in the same class as the biggest such events recorded in the 20th century. Its evolution was well predicted by ECMWF forecasts as well as by EUROSIP multi-model forecasts. The latest forecasts for 2017 at the time of going to press are indicating the possibility of another El Niño developing later this year. El Niño is the warm phase of the El Niño Southern Oscillation (ENSO). The cool phase is known as La Niña.

To illustrate our El Niño forecasting capabilities, we review the major event that occurred in 2015/16: what happened in the tropical Pacific and how well was it predicted? We show that the event contributed to successful seasonal forecasts of European winter temperatures, and we discuss the latest El Niño forecasts (March 2017), both from ECMWF and from the multi-model EUROSIP system.

The evolution of the 2015/16 El Niño

The two strongest El Niños of the 20th century were those of 1982/83 and 1997/98, each of which was considered at the time a 'once-in-a-century' event. The El Niño of 2015/16 is in the same class as those of 1982/83 and 1997/98, and it set new records in the NINO4 and NINO3.4 regions in the western and central Pacific.

Figure 1 shows the spatial structure of the El Niño at its peak in November 2015. The vast extent of the event – more than 10,000 km in zonal (east–west) extent – and its ability to influence the deep tropical convection that drives the general circulation of the atmosphere is what gives El Niño its global impact. El Niño variability is generally monitored by the use of indices, calculated from average sea-surface temperatures (SST) over the regions marked on the map. NINO3.4, covering the central region of the equatorial Pacific, is most commonly used as a measure of the overall strength of an ENSO event.

The 2015/16 El Niño can best be understood by looking at the evolution of NINO3.4 SST (Figure 2). In a normal year, there is a pronounced seasonal cycle in SST, as indicated by the red line. El Niño conditions are normally monitored as anomalies with respect to this mean seasonal cycle. At the beginning of 2015, the equatorial Pacific was already warm, as a leftover from borderline El Niño conditions which developed during 2014. The SST warmed at the usual rate during March, but continued warming through April and into May, with temperatures approaching 29°C. Normally, the ocean surface cools from June to September, as zonal winds strengthen and upwell cooler water at the equator, but in 2015/16 equatorial waters stayed warm for a whole year, with peak temperatures reached in November. Thus the usual seasonal cycle was completely upended. Due to the nature of the coupling between ocean and atmosphere in the equatorial Pacific, this dramatic change in SST was both a symptom and a cause of corresponding major changes in atmospheric winds and precipitation patterns.

The 2015/16 El Niño broke warming records in the central

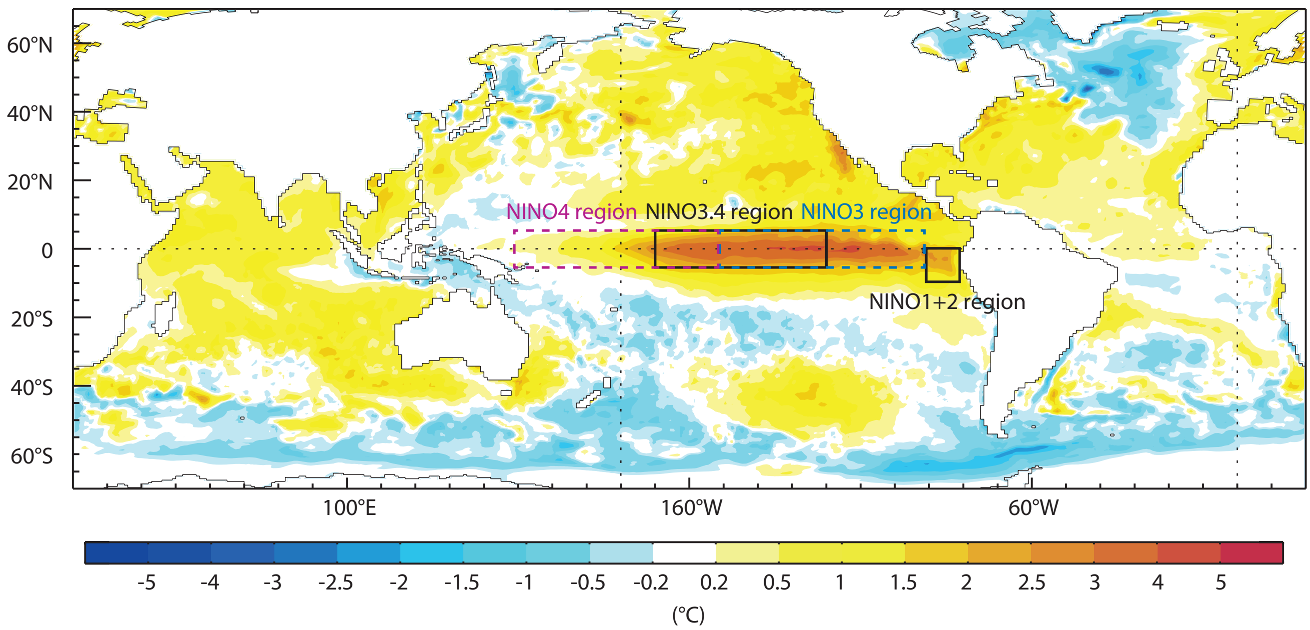


Figure 1 Average sea-surface temperature anomalies in November 2015, when the El Niño event peaked in the NINO3.4 region. The chart shows SST anomalies compared to the 1981–2009 average.

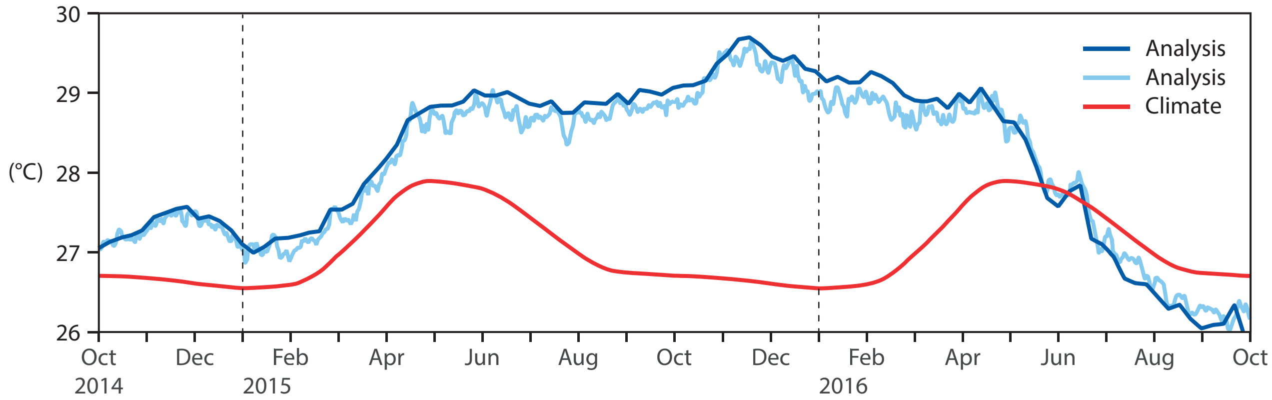


Figure 2 Time evolution of observed sea-surface temperatures in the NINO3.4 region from October 2014 to October 2016 according to two different analyses, OIv2 (dark blue line) and OSTIA (light blue line). The SST NINO3.4 mean seasonal cycle, defined as the climatological SST variations during the year, is represented by the red line. The difference between the red and blue lines is the SST anomaly.

Pacific, represented by the NINO3.4 and NINO4 indices. At its peak in November 2015, the NINO3.4 SST anomaly reached 3.0°C, breaking the previous record of 2.8°C set in January 1983. In the NINO4 region, large positive anomalies are hard to achieve because average conditions are already warm. In 2015, the anomaly reached 1.7°C, a substantial increase of 0.4°C on the previous record, set in 2009. SST analyses become less precise going back in time, but the size of the anomalies in NINO4 and NINO3.4 means we are fairly confident that these are record values for the whole of the observational period back to 1860. By contrast, in the eastern Pacific (monitored by indices for the NINO3 and NINO1+2 regions) the El Niño remained below the level of the 1982/83 and 1997/98 events. It must be borne in mind that the anomaly records depend on the reference climate, which in this case is a 30-year climate (1981–2010).

Figure 3 puts the current event in the context of the last 20 years. It shows the evolution of SST anomalies at the equator from January 1997 (bottom) to December 2016 (top), with conspicuous spikes in 1997/98 and at the end of 2015. It shows that at the equator the 2015/16 event was exceptionally strong, but not quite as strong as 1997/98. The peak warm anomalies were not so long-lived either, decaying quickly after November 2015. The aftermaths of the events are also remarkably different: 1997/98 was followed by an intense and long-lived cold La Niña episode, while the 2016 La Niña has been weak and short-lived. In between, the chart shows fluctuations between warm El Niño conditions and colder La Niña episodes in the central and eastern Pacific.

How well was the 2015/16 El Niño predicted?

Forecasts in March 2015 suggested the possibility of a substantial El Niño event developing later that year (*Stockdale*, 2015). Figure 4 shows a series of ECMWF ensemble forecasts from 1 March, 1 August and 1 November 2015 for SST anomalies with respect to the 1981 to 2010 climate in the NINO3.4 region. They demonstrate a close match between the predicted and observed SST tendencies. The forecast from 1 March correctly predicted the observed warming between March and September, although there was a large spread of possible outcomes, indicating great uncertainty, at longer lead times. It is well known that between March and May the predictability of El Niño is low. The forecast from 1 August captured the timing of the peak of the warming that occurred at the end of the year, and its incipient decline. However, most ensemble members overestimated the peak magnitude. Finally, the 1 December forecast correctly and confidently predicted a rapid fall in SST anomalies during the next six months, although the predicted decline between December 2015 and February 2016 is too steep. The ensemble prediction suggested that uncertainty was relatively low as the spread is relatively small even at longer lead times.

Experience has shown that, at seasonal timescales, the most reliable forecasts are obtained by combining and calibrating the output from a number of independent forecasting systems. At ECMWF, output from four major forecasting centres (ECMWF, the UK Met Office, Météo-France and NCEP, the US National Centers for Environmental Prediction) is combined to make the EUROSIP multi-model products. EUROSIP calibrated NINO plumes show a probability distribution computed from the ensemble with a weighting that takes into account the reliability of each model. The distribution is plotted showing the 2nd, 10th, 25th, 50th, 75th and 98th percentiles of the distribution.

Figure 5 shows the EUROSIP probability spread of SST anomalies in NINO3.4 forecasts from 1 March 2015,

Useful web links

A

ECMWF and EUROSIP ENSO forecasts are available on ECMWF's website: *http://www.ecmwf.int/en/forecasts/charts*

Information on the EUROSIP multi-model forecasting system can be found here: *http://www.ecmwf.int/en/forecasts/documentation-and-support/long-range/seasonal-forecast-documentation/eurosip-user-guide/multi-model*

For more information on the Copernicus Climate Change Service's prototype seasonal forecast products, visit: *http://climate.copernicus.eu/seasonal-forecasts*

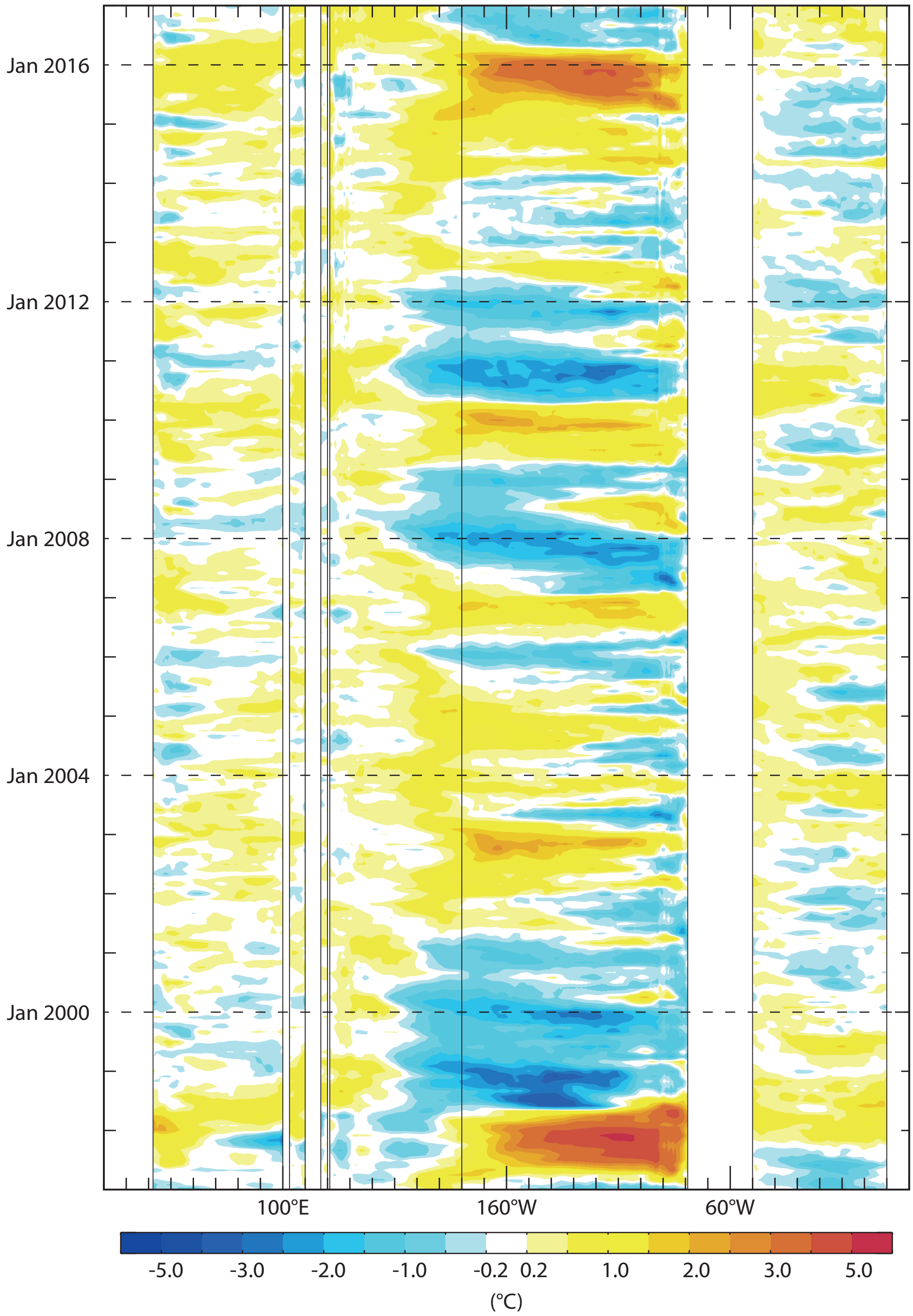


Figure 3 Observed sea-surface temperature anomalies at the equator from January 1997 up to December 2016, compared to the 1981–2009 average.

1 August 2015 and 1 December 2015. It shows that, here too, the broad evolution of the anomalies was well predicted, especially in the 1 August forecast. For much of the forecast period in the 1 March forecast, the observed SST anomaly lies beyond the 75th percentile. In the EUROSIP forecast from 1 December, the predicted decline in anomalies was again too steep in the first two months, and the observed anomalies were beyond the 98th percentile in February and March.

Overall, both the ECMWF and EUROSIP forecasts successfully predicted the timing of the onset, peak and decline of the 2015/16 El Niño event. The intensity was also captured fairly well albeit with a large uncertainty at longer lead times, especially in the 1 March and 1 August forecasts.

El Niño and European seasonal forecasts

Seasonal forecasts provide global information about atmospheric and oceanic conditions averaged over the next few months. Despite the chaotic nature of the atmosphere, such long-term predictions are possible because some climate phenomena show variations on timescales of seasons or years and are, to a certain extent, predictable. The most important of these phenomena is the ENSO cycle.

Although ENSO is a coupled ocean–atmosphere phenomenon centred over the tropical Pacific, its fluctuations affect the climate in other parts of the globe. During an ENSO event, the enhanced convection over the warm waters in the central and eastern tropical Pacific triggers changes in the

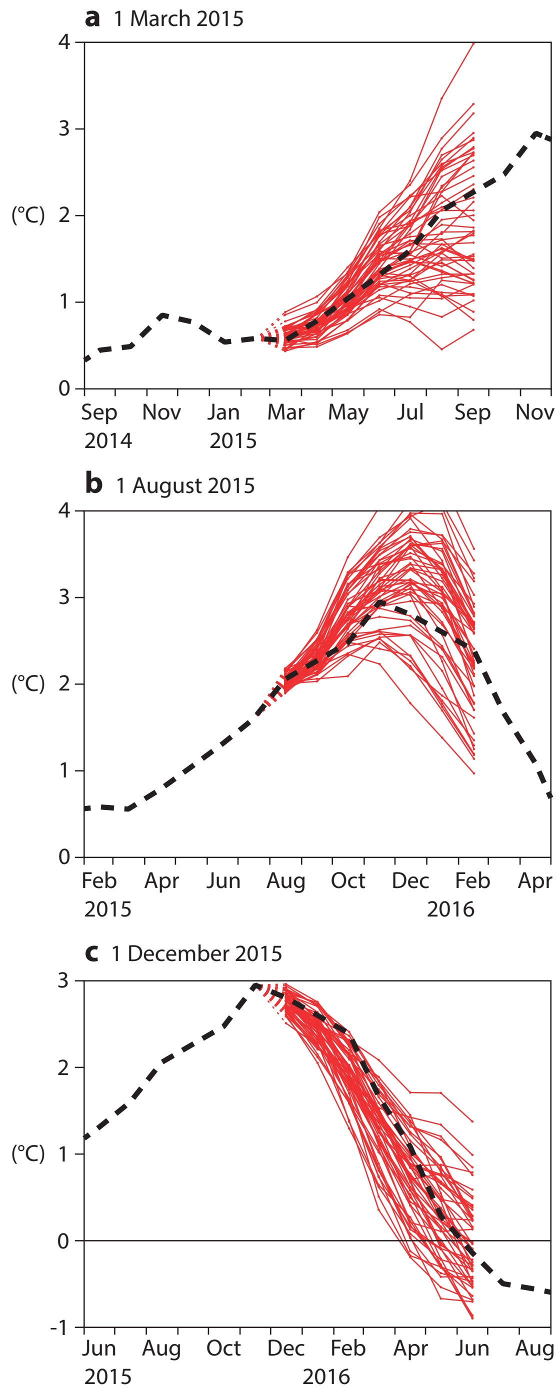


Figure 4 ECMWF ensemble forecasts of monthly mean NINO3.4 SST anomalies with respect to the 1981 to 2010 climate issued on (a) 1 March 2015, (b) 1 August 2015 and (c) 1 December 2015. The dotted line shows the observed evolution of SST anomalies.

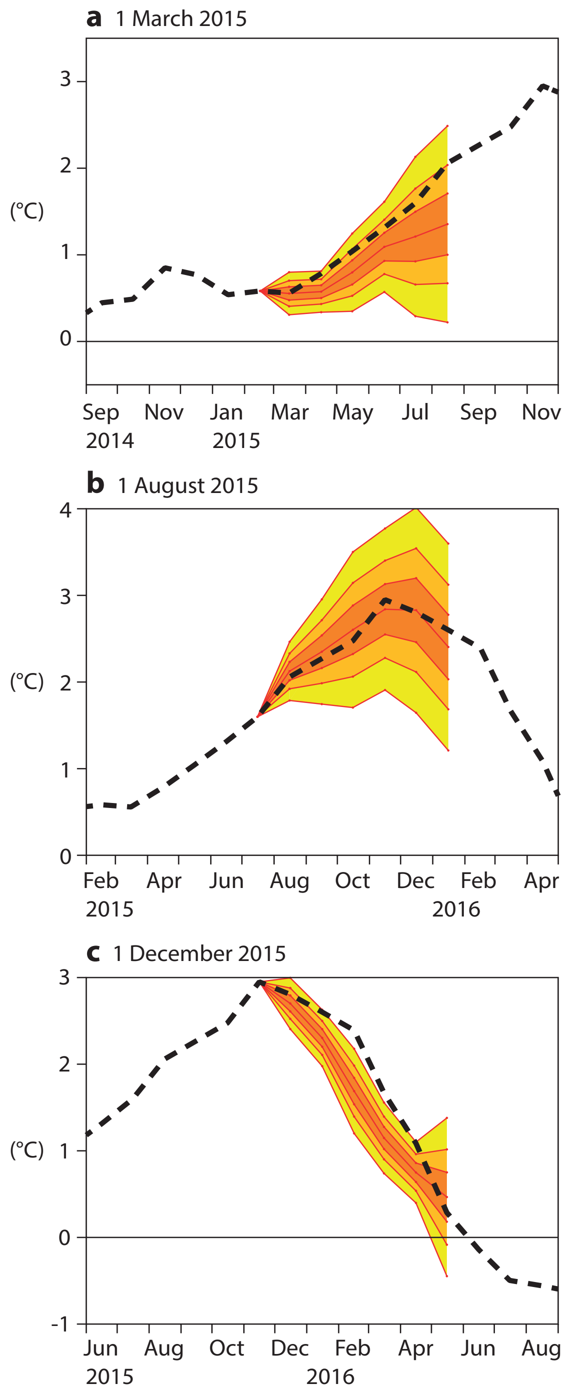


Figure 5 EUROSIP calibrated forecasts of monthly mean NINO3.4 SST anomalies with respect to the 1981 to 2010 climate issued on (a) 1 March 2015, (b) 1 August 2015 and (c) 1 December 2015. The dotted line shows the observed evolution of SST anomalies.

strength of the Hadley circulation, leading to modifications in circulation patterns worldwide including, for example, the position of the jet stream that flows from west to east over the North Pacific in winter months. By strengthening the Hadley circulation, ENSO can trigger a cascade of deviations from normal rainfall and temperature patterns around the globe. These remote impacts are called ENSO teleconnections. ENSO teleconnection patterns are reflected in historical observations and are the basis of any empirical model.

The predictive skill of any dynamical model is strongly associated with the ability to accurately reproduce ENSO teleconnections. It follows that in years when ENSO is active, seasonal predictions are expected to be more accurate than in years when ENSO is in neutral conditions.

The year 2015 was hotter than any previous year in global datasets going back more than 130 years. Global near-surface temperature was well over 0.4°C warmer than the

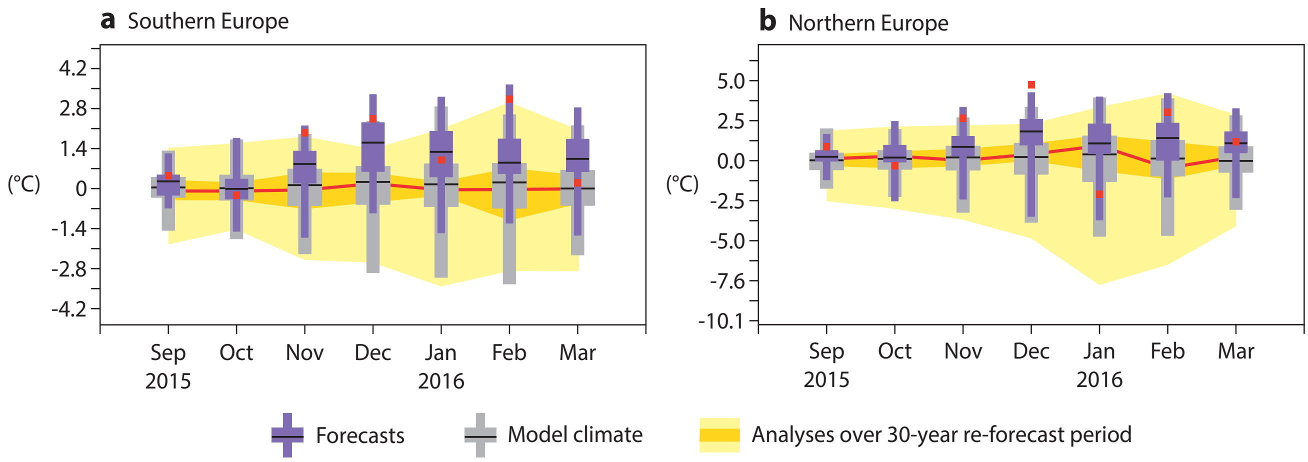


Figure 6 Forecasts from 1 September 2015, model climate and analyses of 2 m temperature anomalies over (a) southern Europe, defined as 10°W to 30°E and 35°N to 50°N and (b) northern Europe, defined as 10°W to 30°E and 50°N to 65°N. The outer limits of the whiskers in the box-and-whisker plots and of the yellow band correspond to the 5th and 95th percentiles, the boxes and the orange band correspond to the lower and upper tercile, while the median is represented by the line in the boxes and the orange band. The verification from the operational analysis is indicated by a red square.

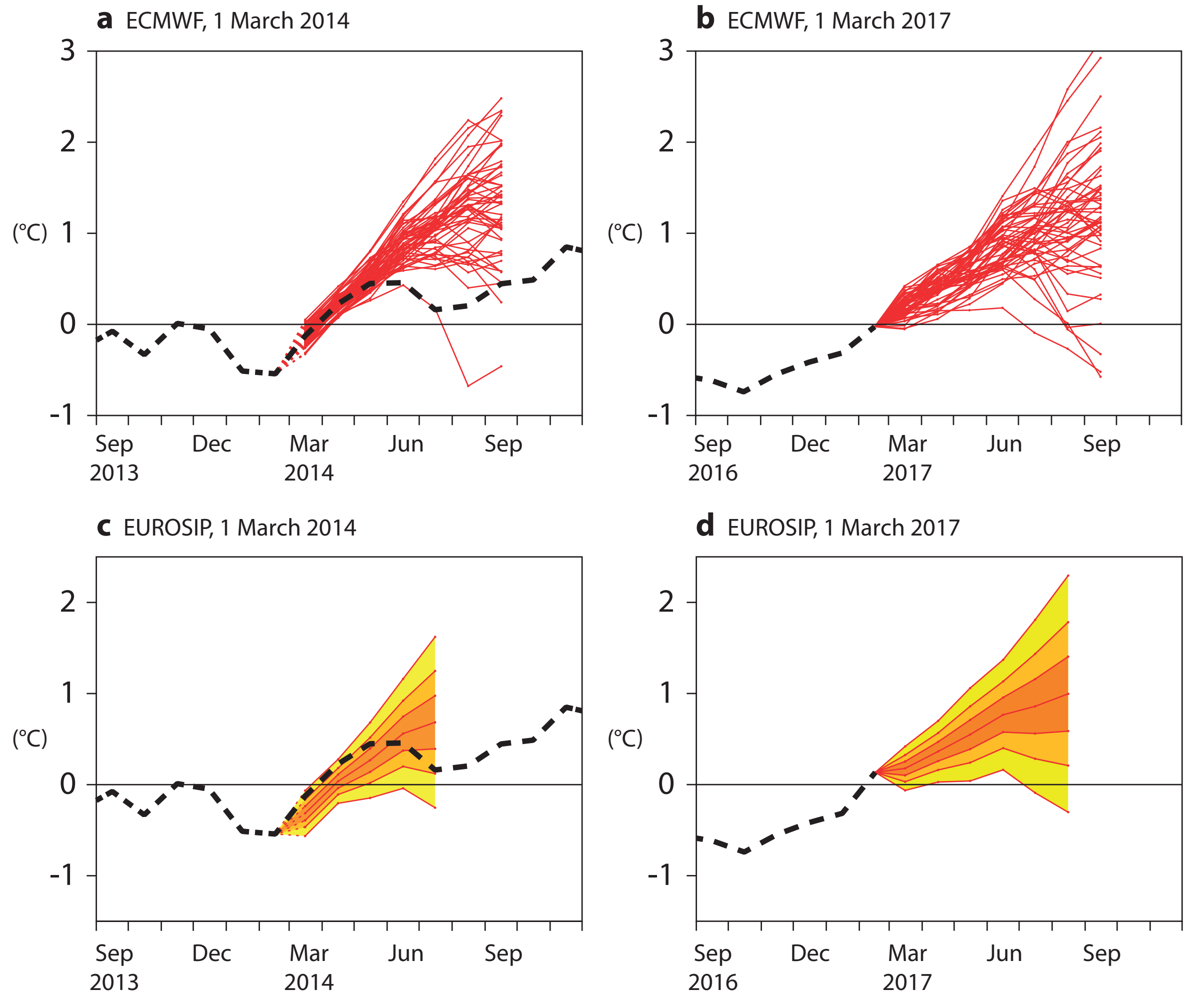


Figure 7 Forecasts of monthly mean NINO3.4 SST anomalies with respect to the 1981 to 2010 climate, showing (a) ECMWF's forecast from 1 March 2014, (b) ECMWF's forecast from 1 March 2017, (c) the EUROSIP calibrated forecast from 1 March 2014, and (d) the EUROSIP calibrated forecast from 1 March 2017.

1981–2010 average and almost 0.1°C warmer than the previous warmest year. The year 2016 was in turn nearly 0.2°C warmer than 2015 and about 1.3°C warmer than pre-industrial levels, according to data released by the EU-funded Copernicus Climate Change Service run by ECMWF. El Niño 2015/16 undoubtedly contributed to the record-breaking global temperatures. The size of that contribution will not be addressed here. It is, however, important to note that because of the warmer climate some of the ENSO impacts detected in historical data might not necessarily materialise. Indeed, the challenge of seasonal prediction is to forecast ENSO impacts in a changing mean climate. Dynamical models such as the one used by ECMWF have the potential to simulate the effects of ENSO in a warming climate.

Seasonal predictions over Europe are particularly challenging. During large El Niño events, impacts on atmospheric circulation over the Euro-Atlantic sector can be seen. However, there are many other factors affecting the climate in Europe (such as sea ice, ocean conditions in the Atlantic basin itself, snow…). Besides, the influence of the equatorial Pacific on Europe depends on a series of stepping stones, some not totally understood and difficult to model. This is why seasonal predictions for Europe are particularly challenging, even in years of high potential predictability, such as El Niño years. It is thus not surprising that the skill of seasonal forecasts is lower over Europe than over North America and the tropics.

On average northern Europe tends to be colder (warmer) during El Niño (La Niña) winters (*Fraedrich & Müller*, 1992). This effect is evident in late winter (January to February). However, in early winter the ENSO effect on European temperatures can be reversed (e.g. *Moron & Gouirand*, 2003; *Fereday et al.*, 2008). The ENSO effect over Europe, when averaged over the full winter season (December to February), can cancel out because of this intra-seasonal variation.

Figure 6 shows the seasonal forecasts of 2 m temperature anomalies for southern and northern Europe from 1 September 2015. The figure shows the extent of the warm anomalies in the analysis, indicating that both November and December were much warmer than the 30-year climate based on 1981–2010. The forecasts gave an accurate indication of the amplitude of such warm conditions with the median of the forecast distribution exceeding the upper third of the model climate. Predicted temperatures over northern Europe provided some indication of a relative cooling in January consistent with the trend that might be expected from an El Niño influence.

Another El Niño?

Forecasts from 1 March 2017 suggest that another El Niño may develop later this year. It is instructive to compare the current situation with that of 2014, when models also predicted the possibility of an El Niño event. Figure 7 shows the ECMWF forecasts and EUROSIP calibrated forecasts of SST anomalies in the NINO3.4 region starting from 1 March 2017 and 1 March 2014 for comparison. It should be noted that the 1 March 2017 EUROSIP forecast includes forecasts from ECMWF, the UK Met Office, Météo-France, NCEP and the Japan Meteorological Agency (JMA), which recently joined EUROSIP.

The March 2014 forecasts showed a wide range of outcomes, including the possibility that a strong event might develop, but in the end El Niño conditions remained weak that year. The 1 March 2017 ECMWF forecast looks broadly similar to the corresponding 2014 one but has a slightly bigger spread of predicted temperatures, indicating slightly greater uncertainty. Meanwhile, the spread of the 1 March 2017 EUROSIP calibrated forecast by July is slightly shifted towards higher temperatures compared to the corresponding spread in the 1 March 2014 forecast. There is another notable difference between March 2014 and March 2017: in 2014, the science community were eagerly expecting a big El Niño to occur, after more than 15 years of at most moderate events. In 2017, by contrast, there was little expectation of another warm event so soon after the big 2015/16 El Niño. Overall, the 1 March 2017 forecasts suggest that a moderate El Niño event is on the cards, but there is still great uncertainty in the longer term and the way forecasts evolve will have to be monitored as the year progresses.

What's next in seasonal forecasting?

The ECMWF seasonal forecast system has been operational for more than five years and will soon be replaced by an upgraded system, SEAS5. SEAS5 will benefit from the latest IFS cycle upgrades, bringing increased resolution in the ocean and atmospheric components. In a development of special interest for Europe, it will for the first time include a dynamic sea-ice model.

In a separate development, the Copernicus Climate Change Service (C3S) is trialling a prototype seasonal forecast service which offers multi-model El Niño forecasts and is expected to replace the EUROSIP multi-model system in due course. The core providers for this service are ECMWF, the UK Met Office and Météo-France. In addition, Italy's Euro-Mediterranean Center on Climate Change (CMCC) and Germany's National Meteorological Service (DWD) will start submitting data for inclusion in the service's product suite in the course of 2017. They are now set to be joined by NCEP and JMA. Further details can be found in (*Brookshaw*, 2017).

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Climate service develops user-friendly data store

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The European Commission has entrusted ECMWF with the implementation of the Copernicus Climate Change Service (C3S). The mission of C3S is to provide authoritative, quality-assured information to support adaptation and mitigation policies in a changing climate. At the heart of the C3S infrastructure is the Climate Data Store (CDS), which provides information about the past, present and future climate in terms of Essential Climate Variables (ECVs) and derived climate indicators.

The CDS is a distributed system. It provides improved access to existing but dispersed datasets through a unified web interface. Among other things, the CDS contains observations, historical climate data records, Earth-observation-based ECV datasets, global and regional climate reanalyses, global and regional climate projections and seasonal forecasts.

The CDS also provides a comprehensive set of software (the CDS toolbox) which enables users to develop custom-made applications. The applications will make use of the content of the CDS to analyse, monitor and predict the evolution of both climate drivers and impacts. To this end, the CDS includes a set of climate indicators tailored to sectoral applications, such as energy, water management, tourism, etc. – the so-called Sectoral Information System (SIS) component of C3S. The aim of the service is to accommodate the needs of a highly diverse set of users, including policy-makers, businesses and scientists.

The CDS is expected to be progressively extended to also serve the users of the Copernicus Atmosphere Monitoring Service (CAMS), which is also operated by ECMWF on behalf of the European Commission.

Requirements

The purpose of the C3S Climate Data Store is to:

- provide a central and holistic view of all information available to C3S
- provide consistent and seamless access to existing data repositories that are distributed over multiple data suppliers
- provide a catalogue of all available data and products
- provide quality information on all data and products
- provide access to a software toolbox, allowing users to perform computations on the data and products
- provide an operational system that is continuously monitored in terms of usage, system availability and response time.

A Copernicus Climate Data Store Workshop was held at ECMWF from 3 to 6 March 2015 to discuss more specific user requirements. The main messages from workshop participants were that:

- User engagement in the creation of the CDS is paramount.
- The CDS must provide different views to different users, based on their level of expertise.
- Login should only be required when downloading data or accessing the toolbox.
- There should be a user support desk, a user forum and training material.
- A 'find an expert' facility should be provided, so that users can get help from a knowledgeable source.
- All products and graphs in the CDS should share a common look and feel, with a special focus on representing uncertainty information.
- Data and product suppliers will have to follow agreed data management principles, in particular the use of digital object identifiers (DOIs).
- All content must be freely available.
- Although data will primarily be in binary form, the ability to display them in graphical form is required.
- It should be possible to sub-set, re-grid or re-project any product, as well as performing format conversions.
- The toolbox should provide advanced data analysis functions that operate on the content of the CDS and that can be combined into workflows, which can be shared between users.
- Workflows are invoked using the CDS web portal and can be parameterised by the end user.
- Tools should be based on existing software, such as Climate Data Operators or Metview.
- Results of workflows should be visualised on the portal.
- Workflows should record which data and tools have been used in order to provide traceability and preserve quality information (provenance).
- The CDS should not stop working under heavy usage; a quality of service module should be implemented.
- All functionalities of the CDS must be available via an application programming interface (API).
- The CDS must be continually monitored and assessed; key performance indicators (KPIs) must be defined and measured.
- The CDS must be based on standards and must be interoperable with other information systems (WIS, INSPIRE, GEOSS, GFCS, WCRP, etc.).

To this list should be added the requirement from the European Commission that the CDS must rely on existing infrastructure and that the data and products must remain with their producers. The CDS therefore had to be developed as a distributed system.

The CDS has been designed to meet these requirements and it will continue to evolve in line with user needs. In particular, the CDS is able to support users with very different needs, from researchers interested in very large volumes of raw data, such as outputs of climate projections, to decision-makers looking for a simple graph showing the result of a statistical analysis based on several sources of heterogeneous data. Users with different levels of expertise can interact with the CDS in different ways to transform data into information, as indicated schematically in Figure 1.

The CDS also supports a variety of data types (observations, fields…) as well as several data formats (NetCDF-CF, WMO-GRIB…). These data are stored using various technologies, such as relational databases, file systems or tape archives, at different sites, and they are accessible via different protocols, such as web services or APIs. The CDS aims to provide all available distributed data using a seamless and consistent user interface.

Although all data and products available through the CDS are to be freely available, they are subject to various licences.

CDS infrastructure

The CDS infrastructure (Figure 2) aims to provide a 'one stop shop' for users to discover and process the data and products that are provided through the distributed data repositories. It also provides the environment to manage users, product catalogues and the toolbox.

Web portal

The web portal is the single point of entry for the discovery and manipulation of data and products available in the CDS. It allows users to browse and search for data and products in the CDS, perform data retrievals, invoke tools from the toolbox and visualise or download results. The web portal also displays the latest information on events and other news regarding the CDS as well as providing a help desk facility, FAQs, and a user forum.

A strong focus on the usability and user experience of the web portal and seamless integration between the different components is paramount. For example, the portal's search facility can be used to search across news articles, the product catalogue and the toolbox catalogue in a single, unified fashion.

Broker

This component schedules and forwards data and compute requests to the appropriate data repository (or the compute layer) via a set of adaptors. It also implements a quality of service module that queues requests and schedules their execution according to a series of rules, taking into account various parameters such as the user profile, the type of request, and the expected request cost (volume of data, CPU usage, etc.). The quality of service module is necessary to protect the CDS from denial-of-service attacks (DoS). Very large requests are given very low priority, and the number of simultaneous requests from a single user is limited. This guarantees that the system always remains responsive.

Adaptors

The role of these components is to translate data and computation requests issued by the broker on behalf of the user into requests that are understood by the infrastructure of each of the data providers. Each supplier is, as far as possible, expected to provide access to its data, products and computation facilities according to some agreed standards, such as OpenDAP, ESGF, OGC Web Coverage Service or a web-based REST API. Adaptors for each of the relevant standards are being developed.

Backend

The backend contains various databases, in particular a web content management system for news articles; a centralised catalogue that describes the data and products in the CDS;

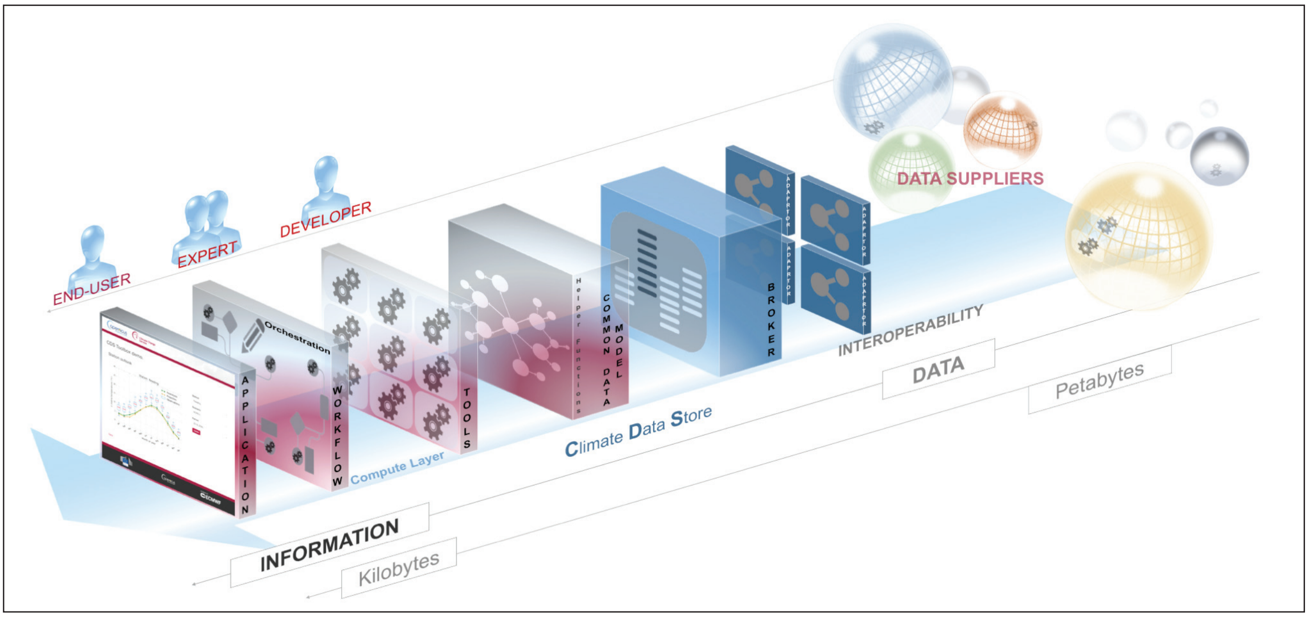


Figure 1 The CDS is designed to meet the needs of different users, including developers, expert users and a wide range of other users, who can interact with the CDS at different levels.

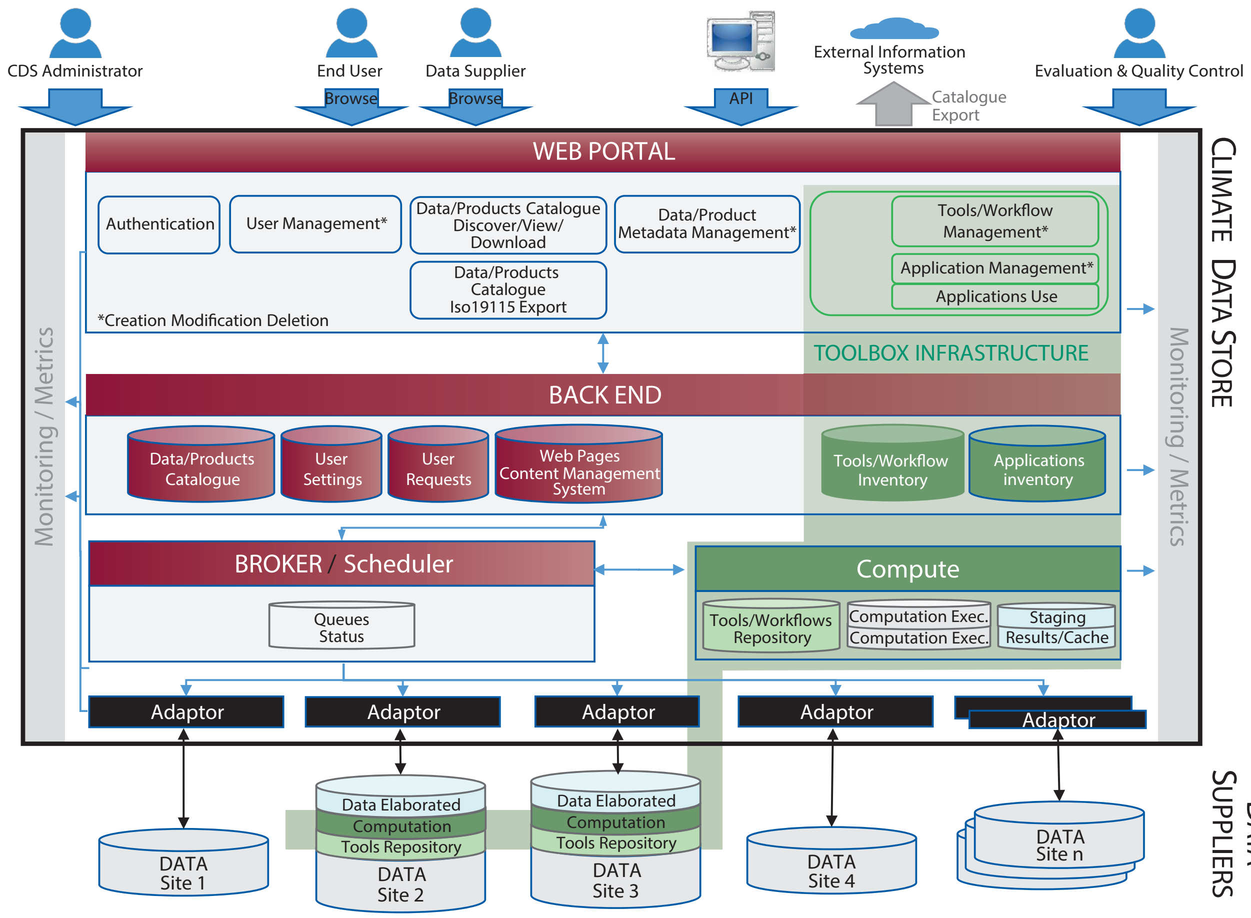


Figure 2 Overview of the CDS infrastructure. The role of each component is described in the text. ECMWF is one of many data sites supplying data to the CDS.

a toolbox catalogue; quality control information; and user-related information, such as the list of data licences users have agreed to and the status of their requests. The content of all databases is browsable and searchable in a seamless fashion since it is indexed in a single search engine. The databases also contain information that is useful for the operation of the CDS:

- information on how to sub-set large datasets
- terms and conditions and licences attached to datasets
- the location, within the CDS, of data and products, access methods and protocols
- information about what tools are applicable to given datasets.

All products and data will be assigned a digital object identifier (DOI). The data and products are described using the ISO19115 metadata record standard and are made available through the OAI-PMH and OGC-CSW protocols for interoperability with the World Meteorological Organization Information System (WIS) and the EU's INSPIRE initiative, respectively.

Compute

This component hosts computations that need to be performed on a combination of data retrieved from possibly several remote data repositories. Computations are limited to those provided by the tools from the toolbox. They can be performed at the data repositories where possible or in the cloud environment hosting the CDS.

Toolbox

The toolbox is a catalogue of software tools that can be classified as:

- *tools* that perform basic operations on data, such as computation of statistics, sub-setting, averaging, value at points, etc.
- *workflows* that combine the output of tools and feed this as input into other tools to produce derived results
- *applications*, which are interactive web pages that allow users to interrogate the CDS through parameterisation; applications make use of workflows and selected data and products in the CDS.

Applications are made available to users of the CDS via the web portal, allowing them to perform computations on the data and products in the CDS and to visualise and/or download their results. The toolbox is described in more detail below.

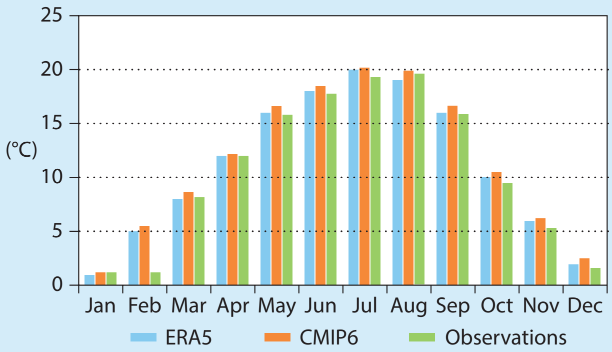
Application programming interface

A web-based, programming-language-agnostic API allows

Toolbox use case

A

This toolbox use case describes a hypothetical application (i.e. an interactive web page on the data portal) in which users can select a city from a drop-down menu and are then presented with the following chart:



Example output of a Toolbox application that combines data obtained from three different data suppliers. The vertical axis is the average monthly temperature in °C.

Each of the bars represents a monthly average of the surface temperature at the selected location, where:

- *ERA5* is a global reanalysis located at ECMWF, covering 1979 to today. The dataset is composed of global fields encoded in WMO-GRIB and the temperature is expressed in Kelvin.
- *CMIP6* is a 200-year climate projection scenario located in an ESGF (Earth System Grid Federation) node accessible via the CDS. The dataset is composed of global fields encoded in NetCDF-CF and the temperature is expressed in Kelvin.
- *Observations* is a time series of observed temperatures located in an SQL database at a hypothetical CDS data supplier called ClimDBase. The temperature is expressed in Celsius.

For the purposes of the example, we assume that there is a service that can map a city name (e.g. Reading, UK) to a latitude/longitude (e.g. 51°N, 1°W).

The following additional assumptions are made:

- The ECMWF data repository holds an extract-point tool that can be run directly on the data to interpolate the value of the data at the requested location from neighbouring points.
- The ESGF data repository holds a subset tool than can be run directly on the data to return data over a small area (four points) around a requested point.
- The ClimDBase data repository holds long time series of observations at various measuring stations and can be queried by station name.
- The compute layer of the CDS is equipped with many more tools including extract-point to interpolate values from neighbouring points at a given location; monthly-average to compute the monthly average from a time-series; and bar-chart to plot a bar chart from several time series.

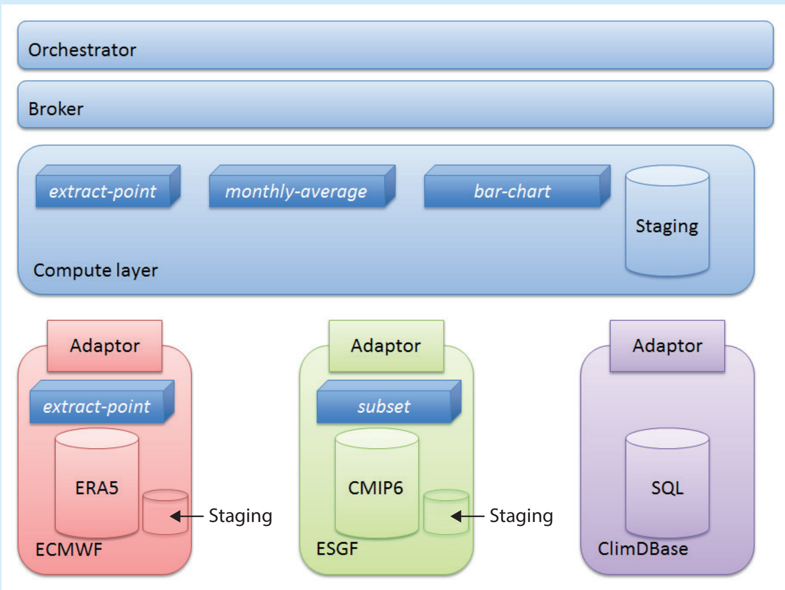
The diagram below illustrates this setup.

Assuming the end user selects 'Reading' in the application, the workflow associated with the application is passed to the orchestrator with city=Reading as a parameterisation. The workflow is then executed.

Each tool is invoked in the right order via the broker, which schedules the execution of the tool at the given location, either at a data supplier's location or in the compute layer. Each tool writes its output to a file in a staging area and returns a URL.

This use case illustrates the following points:

- Data and products in the CDS are available in different formats, with different units etc. For data and products to be processed and/or combined seamlessly by the tools, a common data model must be designed and implemented.
- Tools produce intermediate results: there is a need for staging areas to temporarily hold these results, and for housekeeping jobs to clean up the staging areas regularly.
- The orchestration of workflows relies on knowing what is where, i.e. where are the datasets located in the CDS (which data suppliers), where are the tools located (i.e. at the data supplier or in the compute layer), where are intermediate results located (i.e. in which staging area). The workflows must then make use of this knowledge to call the most appropriate service when invoking a tool. If a tool is available at several locations, the workflow selects the one that will make the best use of available resources (e.g. minimising data transfers).
- Calls to services, as well as their results, only consist of references to the actual data and rely on URLs to point to them.
- Intermediate results are cached to improve the performance of the system.



The toolbox makes it possible to combine tools in the CDS with tools available at the data suppliers to generate the desired output.

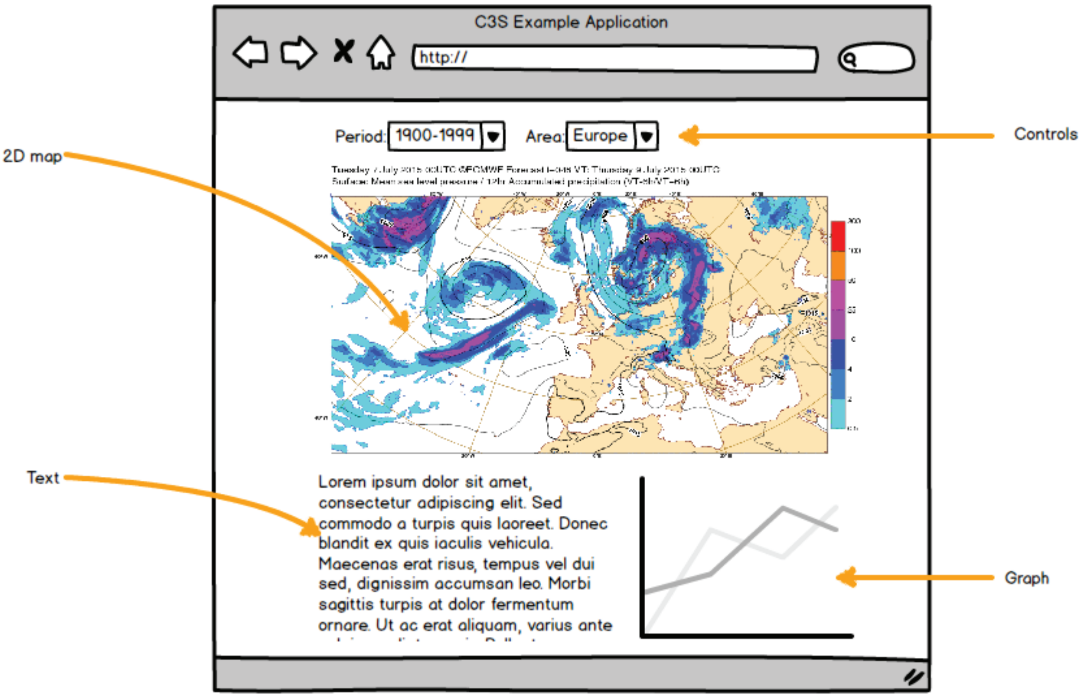


Figure 3 Mock-up of what an application might look like.

users to automate their interactions with the CDS. It provides batch access to all CDS functions, such as data and product retrievals and invocations of the toolbox.

Monitoring and metrics

All aspects of CDS operations will be measured and monitored. Any issues will be notified to 24/7 operators, who can refer them to on-call analysts. The information collected will be used to establish KPIs. Such indicators will measure the system in terms of responsiveness, speed, capacity, search effectiveness, ease of use, etc. These KPIs will be used when reporting to the European Commission and to enable continuous improvements in the service (capacity planning).

Toolbox

The toolbox is used by developers to create web-based applications that draw on the datasets available in the CDS. These applications can then be made available to users. Users are given some control over the applications by interacting with web form elements. This could involve the selection of a range of dates or a geographical area of interest, which is then used to parameterise the application.

All computations are executed within the CDS infrastructure, in a distributed, service-oriented architecture. The data used by the applications do not leave the CDS, and only the results are made available to the users. These results typically take the form of tables, maps and graphs on the CDS data portal. Users may be offered the ability to download these results.

The variety of data types, formats and structures makes their combined use highly challenging. The aim of the toolbox is to provide a set of high-level utilities that allow developers to implement applications without the need to know about these differences.

The toolbox hides the physical location of the datasets, access methods, formats, units, etc. from those who are developing the applications. Developers are presented with an abstract view of all the data available in the CDS. It is anticipated that all the datasets share some common attributes. Most of them represent variables which are either measured or forecast (e.g. temperature, amount of precipitation, etc.), and which are located in time and space. A common data model that is able to represent all datasets in the CDS has been adopted.

The toolbox also provides a series of tools that perform some basic operations on the datasets, such as averaging, calculating differences, sub-setting, etc.

All tools are registered in the toolbox database and documented within the CDS. Application developers implement workflows that invoke the various tools available to them on the datasets in the CDS. These workflows will also present the output from some of the tools as the input into other tools, in order to implement more complex algorithms. As is the case for tools, workflows are also registered and documented so that they can be reused.

Finally, application developers create web pages that present users with a series of widgets (check boxes, drop down menus, etc.) as well as various tables, maps or graphs, and associate the page with a selected workflow. The tables, maps and graphs represent different views on the result of executing the workflow parameterised with the values selected in the widgets. These views are dynamically updated as end users interact with the widgets.

After a validation process, applications may be published on the CDS web portal and made available to all users.

Common data model

The purpose of the common data model (CDM) is to provide a uniform description (conventions, structures, formats etc.) of all data and products in the CDS, so that they can be combined and processed by the toolbox in a consistent fashion. This entails the choice of a common naming convention, the use of agreed units, and a common representation of spatiotemporal dimensions.

The common data model is based on the CF (Climate and Forecast) convention, which is the convention used by the climate research community, in particular for the storage and exchange of climate projections.

Tools

The tools are simple Linux programs that transform some input data into some output data and can be parameterised. Good examples of such tools are the Climate Data Operators from the Max Planck Institute for Meteorology, which are widely used in the climate community to perform basic operations on NetCDF files. Such tools are invoked remotely through the broker as remote procedure calls when located in the compute layer, or via the adaptors when located at the data suppliers' location.

The tools have the ability to perform a wide range of operations over gridded data (point-wise operations) and/or time series data, such as basic mathematical operations (+, - , / , * , cos, sin, sqrt, …), statistical operations (minimum, maximum, average, standard deviation, …), field manipulations (sub-setting, re-gridding in time and space, interpolation, format conversion) and plotting (maps and graphs).

All tools are described in the toolbox catalogue, which will be available on the CDS website. The description provides information about input and output data types and formats, possible parameterisation and what algorithms are being used.

Workflows

A workflow can be defined as an orchestrated and repeatable pattern of processing steps that produce an outcome. In the context of the CDS, workflows can be viewed as Python scripts that invoke the tools remotely, through remote procedure calls, dispatched by the broker to either the compute layer or the data suppliers. The orchestrator is the process that executes the workflows. Workflow processing is carried out in isolation (sandboxing) with the use of containerisation software such as Docker. Like tools, workflows can be parameterised, can make use of input data, and produce output data. They are also described in the toolbox catalogue.

Applications

In the context of the CDS, applications can be seen as web pages that are associated with a workflow, some data sources, and some parameterisations. Each time the user interacts with the widgets on the web page, the workflow is executed, parameterised with the values of the widgets, and any resulting plots or graphs are updated. Figure 3 is a mock-up of what an application might look like. When a user selects a new period or a new area using the drop-down menus, the map and graph are automatically updated accordingly. There are several actions associated with applications:

- *Authoring*: a user can create/update an application by selecting a workflow, providing some fixed parameterisation, laying out some text, maps and graphs and adding some widgets.
- *Publishing*: once authored, an application can be published and catalogued so that other users can use it. Users can clone published applications and modify them for their own use or publish a modified version.
- *Using*: users are limited to the interaction provided by the widgets.

A hypothetical toolbox use case is presented in Box A. It demonstrates how tools, workflows and applications fit together and interact with the orchestrator and the broker.

Status and plans

In order to develop the CDS, ECMWF issued two tenders: one for the infrastructure and one for the toolbox. The tenders were awarded to different consortia made up of organisations ranging from software development and web design to meteorology and climate, bringing a wide spectrum of expertise to the project. One of the main messages voiced by the 2015 workshop participants was that user engagement is the key to building a successful CDS. As a result, the principles of 'Agile' software development were adopted. With Agile, software is delivered in small increments, every few weeks. This makes it possible to provide continuous feedback to developers and to cater for additional user requirements as the project progresses. Outsourcing software development is a new activity for ECMWF. The use of Agile principles has enabled us to work very closely with the selected consortia. At the time of writing, most of the building blocks forming the infrastructure and the toolbox have been developed. There is nevertheless still a lot of work to do before a beta version of the CDS can be offered to selected users, which is expected to happen by July 2017.

It was decided at the outset that the CDS will be deployed into a Cloud infrastructure. A commercial Cloud was selected for the duration of the development phase. This has enabled ECMWF to get acquainted with such technologies. A tender will be issued to select a Cloud solution that will host the operational CDS.

It was also decided that the CDS should be based on open source software where possible, so that other instances could be deployed if necessary. This is particularly important for the development of the toolbox: there is a vibrant community developing scientific libraries in Python, such as Numpy, Scipy, Pandas, xarray, dask, matplotlib etc. These libraries provide many of the algorithms required, and users from the weather and climate communities are already familiar with them. Making use of those libraries will therefore make it easier for users to contribute new additions to the toolbox.

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Reanalysis sheds light on 1916 avalanche disaster

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One of the worst meteorological disasters in history took place in the southeastern Alps during the infamous winter of 1916/17. Avalanches following a massive snowfall event killed thousands of soldiers as well as civilians. Today's numerical techniques open up new possibilities to study this historical event. Combining historical measurements with reanalyses and dynamical downscaling makes it possible to reconstruct weather even down to local scales and thus to the scale captured by historical documents on weather impacts.

Studying past severe weather events and their impacts can help us to better assess present and future weather hazards. With reference to the heavy snowfall event in December 1916, we demonstrate the potential of combining numerical techniques with historical documents – and of combining the expertise of meteorologists and historians – to achieve a better understanding of severe weather events and their societal impacts (*Brugnara et al.*, 2016). In particular, we show that it is possible to downscale ECMWF's ERA-20C climate reanalysis of the 20th century by means of a high-resolution model to gain insights into the meteorological conditions that led to the disaster.

Sequence of events

A century ago, Europe was in the midst of World War I. On the Italian front, the Austro-Hungarian and Italian armies faced each other on some of the harshest battlefields in history – on the summits of the southeastern Alps (Box A). Here, during a large part of the year, the fighting would cease almost completely as a different war took place: a war against cold, ice, and snow. With average precipitation exceeding 2 m per year in some locations, this part of the Alps is one of the wettest places on the continent. Soldiers were literally buried in snow and their bodies, exposed by shrinking glaciers, still provide a painful reminder of that absurd carnage.

Historical background

A

The Kingdom of Italy declared war on the Austro–Hungarian Empire on 23 May 1915, almost one year into World War I. The border between the two countries was mostly on mountainous terrain, where the Austro-Hungarian army withdrew to solidly organised defensive positions. In fact, there were only minor changes to the front line until October 1917, when German troops joined the Austro-Hungarians to breach the Italian lines (famously known as the Battle of Caporetto). This forced the Italians to retreat more than 100 km into the plain of Veneto to the Piave River. However, the front line did not move between Stelvio and Monte Grappa until the end of the war. Eventually, in 1918, the Austro-Hungarian Empire collapsed and Italy ended up on the victorious side.

The cost in terms of human casualties was enormous. In three and a half years, about 650,000 Italians and 400,000 Austro-Hungarian soldiers were killed. In the high-altitude areas of the front line (in some places exceeding 3000 m), the losses caused by avalanches and exposure were of similar magnitude as those caused by enemy fire. Further casualties were caused by supply channels being blocked by the avalanches.

Field mass on the glacier of Marmolada (25 Nov 1916) in honour of the new Emperor of Austria, Charles I. Many of these men perished 18 days later under the avalanche of Gran Poz. (Photo: Austrian National Library)

Avalanche in Vermiglio, Trentino (1916). (Photo: Austrian National Library)

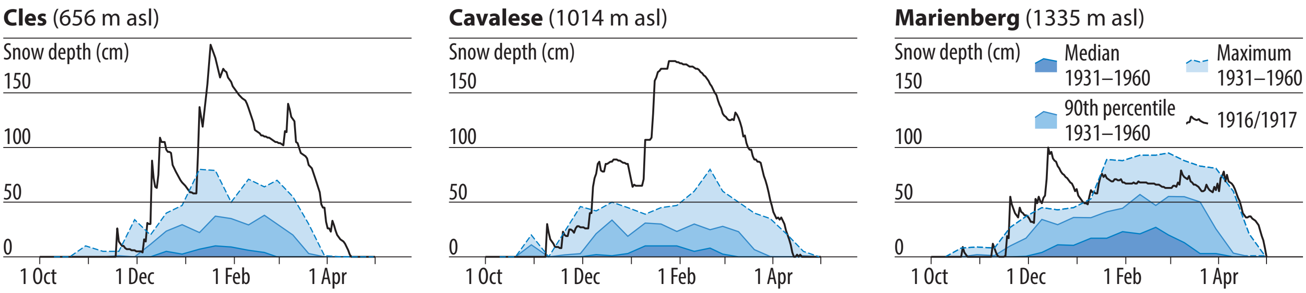

Figure 1 Daily snow depth evolution during the winter of 1916/17 observed at three stations in South Tyrol (see Figure 5 for their locations), compared with the respective statistics for the period 1931–60.

Fate was not on the side of those men as the winter of 1916/17 turned out to be one of the snowiest of the century. Between November 1916 and January 1917, a rain gauge located on today's Italy–Slovenia border measured 1432 mm of precipitation, about 80% of the local mean annual total. After a dry February, an additional 560 mm fell between March and April 1917. Figure 1 shows the snow depth evolution during that winter at three sites. At two of them maximum snow depth reached more than twice the maximum value found at any time during the 1931–1960 period.

Reports by contemporaries suggest that, for most of the mountainous front line between Stelvio and Mount Krn, the shovel was the most important tool for soldiers and civilians alike. Avalanches came down almost daily, causing new casualties again and again. On the front line, tunnels were dug in the snow to reach the foremost positions.

However, there was one particular day that tragically entered the history books: 13 December 1916. On this day, following a week of abundant snowfall, advection of a warm and humid air mass from the Mediterranean brought intense precipitation and a rise of snow level, causing countless avalanches across the region. The number of human casualties was unprecedented for this kind of natural event. An accurate overall death toll is impossible to provide, but estimates of 10,000 by some sources are certainly too high. Official Austrian sources speak of 1,300 deaths and 650 wounded for the period 5–14 December, while later estimates give 2,000 casualties for the avalanches on 12 and 13 December. No Italian estimates seem to exist, but individual accounts suggest that the numbers were similar to those on the Austro-Hungarian side. Dozens of civilians were also killed by the avalanches, which in several cases reached low-altitude settlements that were considered safe.

In view of the unlikelihood of attacks by the opposing side, officers often demanded the withdrawal of soldiers from positions endangered by avalanches. Most of the time, however, the higher echelons, based in warm offices in the valleys, demanded that the troops hold their positions. In the early hours on 13 December 1916 and later in the day, large avalanches plunged down onto Austro-Hungarian and Italian positions. The largest single incident took place on the highest mountain of the Dolomites (Mount Marmolada, 3343 m) at Gran Poz (2242 m), where between 270 and 332 men died.

Having occurred in the midst of a greater tragedy – the Great War – this event passed almost unnoticed at the time, all the more as news from the front underwent censorship. Nevertheless, it represents one of the worst weather-related disasters in European history in terms of loss of human life. It is the kind of event from which we can learn about worst-case present and future extremes. With its well-documented impact, what is required is a detailed, quantitative understanding of the responsible atmospheric processes. Such an understanding may enable us to learn lessons from this tragic event.

Reconstructing past weather

Climate reconstructions have become an important tool in climate science. However, impacts on society often arise from distinct weather events whose relation to climate is not always straightforward. In these instances, weather reconstructions are required. For decades, past weather has been reconstructed by historians, often very precisely, but on a local scale and in a descriptive way. These weather reconstructions cannot be used for applications such as risk modelling. The currently available information on the weather in the Alps in December 1916 is primarily based on qualitative descriptions from diaries, memoirs, and anecdotes passed down through generations. Some quantitative information can be recovered from weather stations of national weather services and used to reconstruct such extreme events. However, these observations are usually limited to the bottom of valleys, where most of the population lives, and give little information on the peaks and slopes, where the event took place. In addition, the war disrupted many weather stations, particularly near the front line, and caused the loss of weather registers.

In recent years, numerical techniques have been developed that enable not only climate reconstructions, but also weather reconstructions. It has been demonstrated that useful global reanalyses can be obtained from assimilating only surface data. Knowledge of air pressure at just a few dozen locations suffices to construct a complete three-dimensional picture of the atmosphere every six hours. This enables an extension of global data sets back to the early days of national meteorological networks in the

a Swiss meteorological yearbook **b** ERA-20C

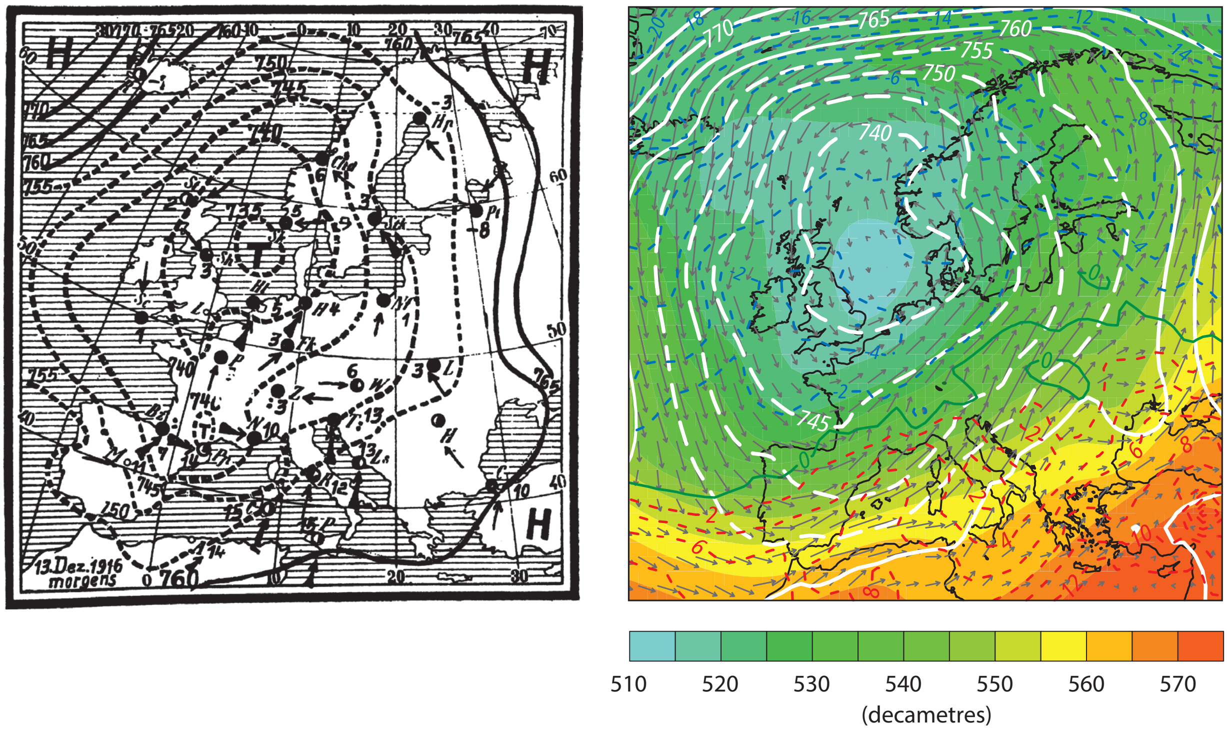

Figure 2 Panel (a) shows a hand-drawn synoptic map of Europe for the morning of 13 December 1916, with contours indicating sea level pressure (mmHg), published in the Swiss meteorological yearbook of 1916. Note that the map is based on asynchronous observations spread over a few hours. Panel (b) shows a synoptic map for 0600 UTC 13 December 1916 from the ECMWF 20th century reanalysis ERA-20C. White contours indicate sea level pressure (mmHg for comparison); coloured contours indicate temperature (°C; green for zero, red for positive values, and blue for negative values); and vectors indicate wind at the isobaric level of 850 hPa (vector length is proportional to wind speed). The shading indicates geopotential height at 500 hPa.

19th century. Two ECMWF reanalyses now cover the entire 20th century, namely ERA-20C (*Poli et al.*, 2016; *Poli et al.*, 2014) and the recently finished CERA-20C, the first coupled reanalysis of the full 20th century (*Laloyaux et al.*, 2016; *Laloyaux et al.*, 2017). They were generated as part of the European Union-funded projects ERA-CLIM and ERA-CLIM2 (European Reanalysis of Global Climate Observations). In addition to surface pressure, ERA-20C and CERA-20C also use marine winds.

All available reanalyses reproduce the meteorological situation in December 1916 well. As an example, Figure 2 shows the fields from the ERA-20C reanalysis together with a synoptic map produced at the time. However, the global reanalyses have a coarse spatial resolution that is insufficient for analysing a regional event in a complex topography such as that of the Alps. Their spatial resolution is usually as low as 100–200 km, which means that the Alps are represented as a plateau about 1 km high. Particularly for variables such as precipitation or snow accumulation, which are strongly related to topography, reanalyses have limited use over the Alps. A further step is dynamical downscaling of the reanalysis, which is similar to operations by meteorologists to provide weather forecasts on a regional scale.

In dynamical downscaling, the reanalysis fields are ingested into a high-resolution weather forecast model that covers a small region. This process can be repeated several times with progressively higher resolutions for smaller areas. To reconstruct the weather in December 1916, we started form ERA-20C and then used four nested simulations with the Advanced Research dynamical solver (ARW) of the Weather Research and Forecasting (WRF) Model, version 3.7.1. Figure 3 shows the four domains used, with resolutions of 54, 18, 6, and 2 km, respectively. The result is an hourly reconstruction of local weather, including snow accumulation. This means that the reconstruction is now at the same scale as the historical descriptions.

These numerical techniques do not replace but complement the work of historians. Whereas reanalyses provide a dynamical interpretation for documented weather phenomena, historical documents provide impacts of the reanalysed weather systems. This encourages interdisciplinary collaboration, as demonstrated by the December 1916 case.

December 1916 reloaded

Contemporary meteorologists analysed the synoptic configuration on 13 December 1916 and their hand-drawn maps can be found in meteorological bulletins and yearbooks (Figure 2a). These show a cyclone centred

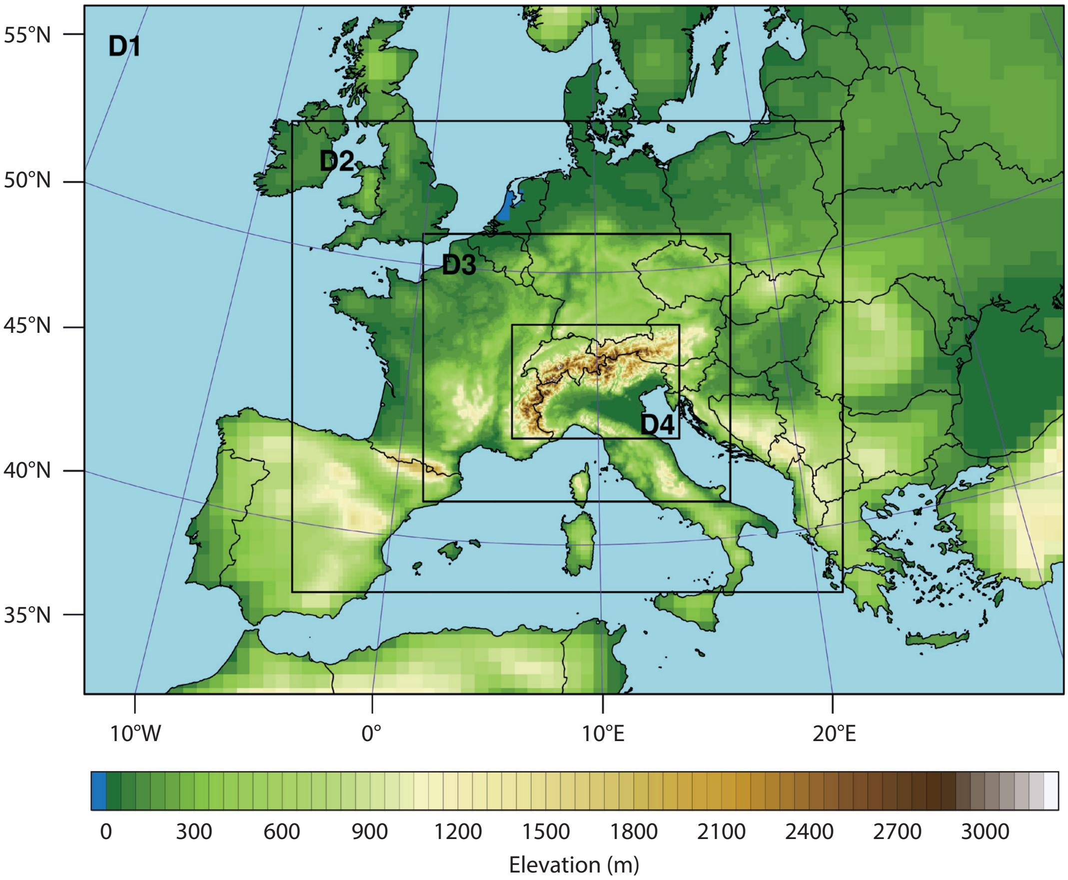

Figure 3 Nested domains at different resolutions (horizontal grid spacing of 54, 18, 6, and 2 km) used for the dynamical downscaling of ERA-20C with the WRF model.

between Scotland and Denmark and a secondary low pressure system over southern France. Figure 2b shows the situation as depicted by ERA-20C. The reanalysis reproduces the hand-drawn map well but provides much additional information. For instance, ERA-20C exhibits higher than normal temperatures over most of the Mediterranean Sea (dashed coloured lines, see also Figure 4).

In order to better understand the event, we must start one or two weeks earlier. Although most of the large avalanches occurred on 13 December, this was a consequence of nine days of relentless precipitation. Reanalyses can help us understand the natural factors that caused this extreme, high-impact event. Atmospheric circulation (Figure 4) was held in the shape of a blocking configuration resembling the negative mode of the so-called East Atlantic–West Russia pattern, one of the leading modes of variability in the Eurasian sector and a mode that is relevant for extremes (*Casanueva et al.*, 2014). It is characterised by a vast high-pressure ridge over western Russia, next to a low pressure area over western Europe. This means that warm and humid air over the western Mediterranean is pushed toward the Alps, where it is lifted and cooled, causing intense precipitation in a small area between the Alpine foothills and the watershed. This configuration therefore usually brings wet spells to the southern Alps and higher-than-normal temperatures in the eastern Mediterranean. In fact, instrumental air temperature records from Greece indicate that December 1916 was the warmest December in the last 120 years. The consequences include positive water temperature anomalies in the Mediterranean, which are a main source of water vapour for the southern Alps.

By downscaling ERA-20C to a grid spacing of 2 km, we find precipitation amounts on 13 December that locally exceed 200 mm in the Julian Alps, in agreement with the local maximum daily amounts observed in December 1916, although the exact date of these maxima is unavailable. The downscaling also produces large spatial variations typical of a complex topography (Figure 5a). An animation of wind and precipitation in the innermost domain as well as an animation of snow accumulation from 6 to 16 December can be found here: *www.geography.unibe.ch/december1916*. The precipitation on 13 December added critical weight to a snow pack that had already increased by up to 2.5 m over the previous days (Figure 5b). On Bernina Pass (2323 m) in Switzerland, snow height was 3.70 m on 12 December and then increased to 5 m.

In addition to the precipitation amount, temperature was a critical factor. The rise in temperature brought rain up to 2000 m, making the snowpack heavier. Below 2000 m, particularly in the southern and eastern part of the affected region, this was a 'rain-on-snow' event, a type of event that is known to trigger avalanches. The combination of intense precipitation and melting snow raised Wörthersee, Carinthia's largest lake, to its maximum observed water level. On the front line, a major Italian offensive had to be delayed, because the troops deployed on the low-lying karst plateau were "drowning in mud", as General Luigi Cadorna reported. The postponement lasted five months and enabled the struggling Austro-Hungarians to transfer critical reinforcements from the eastern front.

Contemporary meteorological observations that were not used in the reanalysis, in particular temperature, precipitation (mostly in Switzerland), and snow depth (in Austria-Hungary), digitised within the ERA-CLIM2 project, are in good agreement with the simulated values although there can be large deviations locally, especially for single days (see Figure 5a). However, taken alone they would draw a rather incomplete picture of the event, because very few daily observations are available for the most affected areas. Taken together, the downscaled reanalysis and the observations provide a detailed, comprehensive view and allow a physically meaningful interpretation. Now that the main

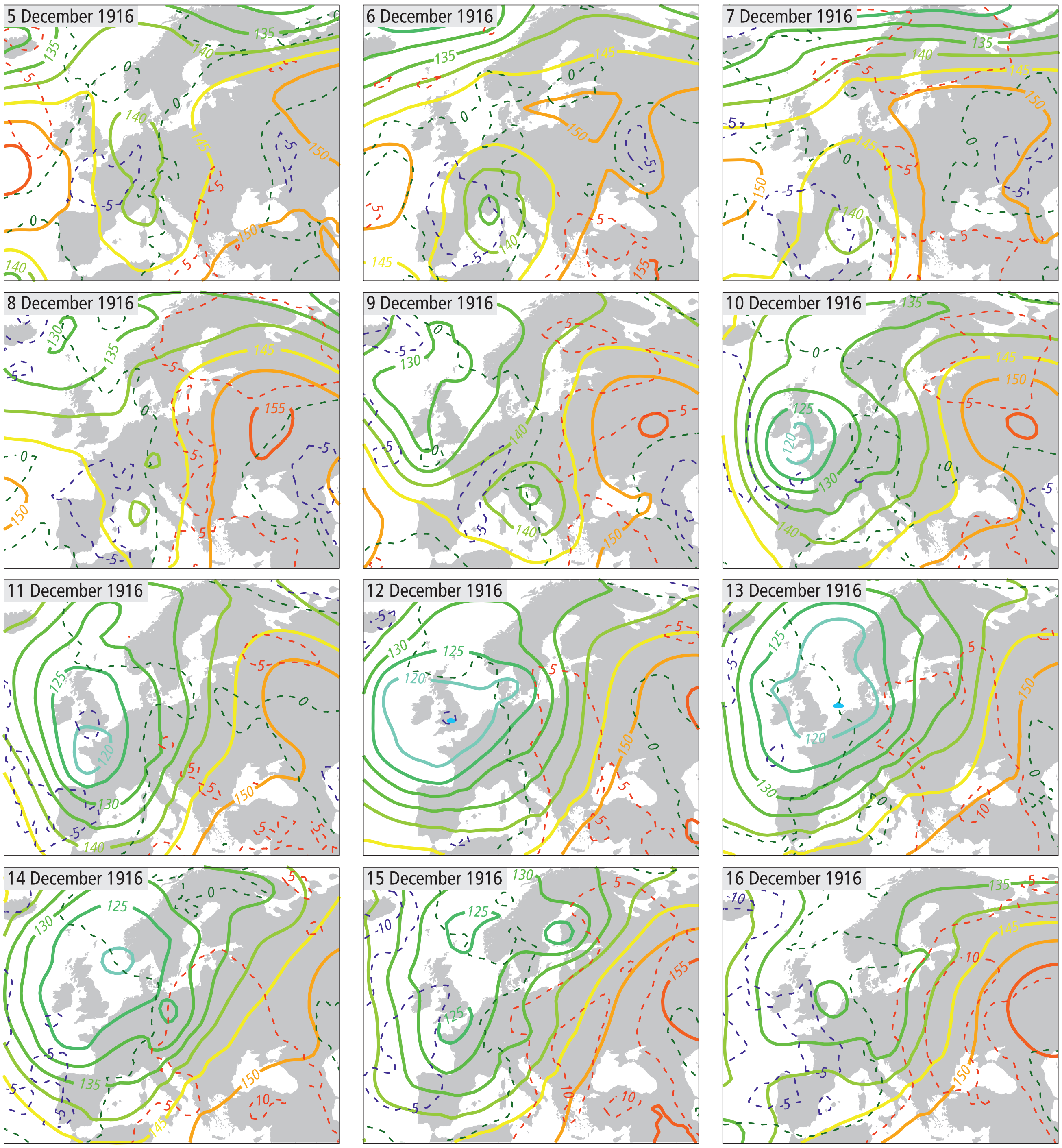

Figure 4 850 hPa geopotential height (solid contours; in decametres) and 850 hPa temperature anomaly with respect to the reference period 1961–90 (dashed contours; in °C) at 0000 UTC for each day from 5 to 16 December 1916 (ERA-20C).

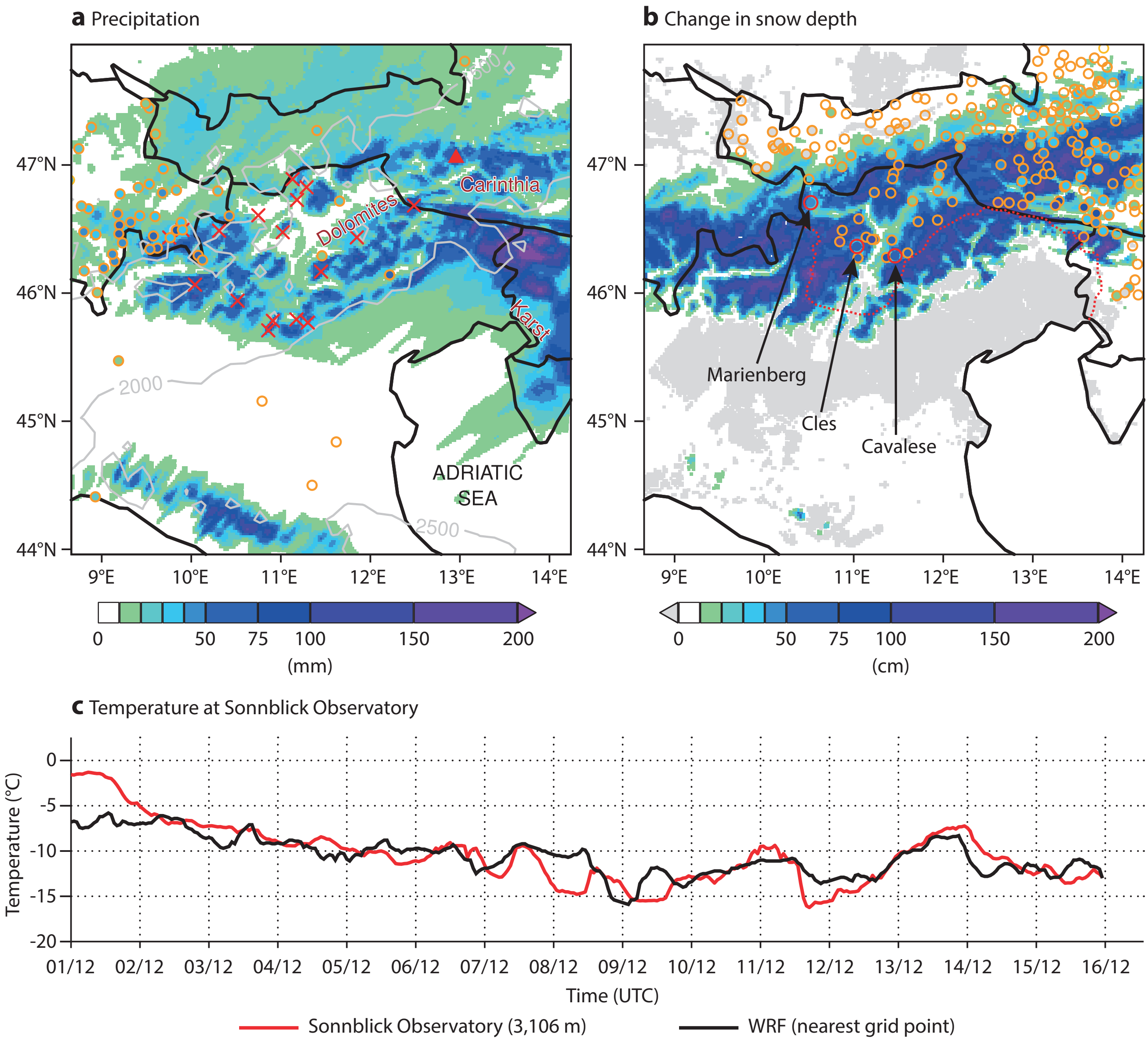

Figure 5 Results from the dynamical downscaling of ERA-20C. Panel (a) shows total precipitation (shading) on 13 December 1916 (defined as the 24 hours until 0700 UTC on 14 December 1916) and mean freezing level (grey contours; in m). Circles represent the location of observations obtained from public datasets and digitised by the authors and red crosses show the locations of documented major avalanches on 13 December 1916. Panel (b) shows the change in snow depth between 5 and 13 December 1916 (at 0700 UTC) with circles representing observations from the network of the Austro-Hungarian hydrographic office (red circles show the locations of the stations referred to in Figure 1). The military front line in 1916 is also shown (red dotted line). Panel (c) shows hourly air temperature between 1 and 15 December 1916 observed at Sonnblick Observatory (the highest staffed weather station in the world at that time) compared with the simulation (temperature at station altitude was extrapolated from the two closest model levels). The position of Sonnblick Observatory is marked in (a) by the red triangle.

ingredients of the weather situation (persistent blocking, possible influence of warm eastern Mediterranean Sea, moisture transport, and temperature increase) and of the societal vulnerability are identified, the behaviour of these factors in a future climate or a future society can be studied.

An instrument with great potential

Several long, historical reanalyses have been produced that provide global, three-dimensional, 6-hourly atmospheric data sets. ERA-20C and CERA-20C cover the 20th century. The Twentieth Century Reanalysis (20CR, *Compo et al.*, 2011) Versions 2 and 2c go even further back, to 1871 and 1851, respectively. Tests have been conducted for the years 1815–17 (encompassing the 'year without a summer' that followed the Tambora eruption) and there is even the potential to employ them for the 18th century in central Europe, where the station network was already relatively dense. Ensemble-based reanalyses, such as CERA-20C, provide additional information in the form of ensemble spread.

However, the reanalyses rely on pressure observations, which have traditionally been undervalued and hence have not yet been digitised in many cases. In fact, reanalyses demonstrate how almost forgotten historical observations can once again become valuable, requiring scientists to go back to the archives – work that is best performed jointly by climatologists and historians. Consequently, large efforts were devoted within the ERA-CLIM and ERA-CLIM2 projects to rescue historical observations, which will be assimilated in future reanalyses. Reanalysis efforts are therefore not just large undertakings that exploit the available data and models to produce a huge data set. They must also prepare the ground for future reanalysis efforts by means of data rescue and further development of coupling methods, bias correction methods, and the like.

It is important also to note that reanalyses are not always able to correctly reproduce real atmospheric circulation, particularly on a local scale. Therefore, they cannot be regarded as the truth. Rather, they represent a physically consistent, possible truth, which becomes meaningful when analysed together with documentary information on the real-world weather.

The results for December 1916 suggest that reliable high-resolution reconstructions can be achieved with only sparse surface data. Combined with detailed historical analyses, they allow insight into an event that is not only historically relevant but still very much present today. Such analyses result in precious information for numerous applications including the attribution of weather events to climate change or other causes, impact analysis, risk assessment, and societal resilience, responses and perception.

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May 17–19	Computing Representatives' Meeting
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Jun 8	Symposium on dynamic meteorology
Jun 12–16	Using ECMWF's Forecasts (UEF)
Jun 21–22	Council
Sep 11–14	Annual Seminar – Ensemble prediction: past, present and future

Oct 2–5	Training Course: Use and Interpretation of ECMWF Products
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Oct 12–13	Technical Advisory Committee
Oct 16	Policy Advisory Committee
Oct 17–18	Finance Committee
Oct 25	Advisory Committee of Co-operating States
Nov 13–16	Workshop on shedding light on the greyzone
Nov 13–17	5th International Conference on Reanalysis (ICR5) (Rome)
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Dec 7–8	Council
Jan 22–25	Workshop on SST and sea-ice analysis

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