The Copernicus Climate Change Service: Climate Science in Action

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ABSTRACT

The Copernicus Climate Change Service (C3S) provides open and free access to state-of-the-art climate data and tools for use by governments, public authorities, and private entities around the world. It is fully funded by the European Union and implemented by the European Centre for Medium-Range Weather Forecasts ECMWF together with public and private entities in Europe and elsewhere. With over 120,000 registered users worldwide, C3S has rapidly become an authoritative climate service in Europe and beyond, delivering quality-assured climate data and information based on the latest science.

Established in 2014, C3S became fully operational in 2018 with the launch of its Climate Data Store, a powerful cloud-based infrastructure providing access to a vast range of global and regional information, including climate data records derived from observations, the latest ECMWF reanalyses, seasonal forecast data from multiple providers and a large collection of climate projections. The system has been designed to be accessible to non-specialists, offering a uniform interface to all data and documentation as well as a Python-based toolbox that can be used to process and use the data online.

C3S publishes European State of the Climate reports annually for policymakers, as well as monthly and annual summaries which are widely disseminated in the international press. Together with users, C3S develops customized indicators of climate impacts in economic sectors such as energy, water management, agriculture, insurance, health and urban planning. C3S works closely with national climate service providers, satellite agencies and other stakeholders on the improvement of its data and services.

CAPSULE

The Copernicus Climate Change Service provides authoritative information about the past, present and future climate, in addition to tools to enable mitigation and adaptation strategies by policymakers and businesses.

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1. Introduction

The impact of climate change on society and the environment is pervasive and profound. In the context of the UNFCCC Paris Agreement and the Global Stocktake, the need to monitor the effectiveness of mitigation and adaptation efforts has become even more acute. Advances in climate science, supported by a vast amount of observational data, have made it possible to understand, analyse and model the changing climate and its impacts with a steadily increasing degree of confidence (IPCC, 2021). In this regard, climate science has undergone a 'quiet revolution' similar to numerical weather prediction (Bauer et al, 2015), which happened gradually as opposed to any single scientific breakthrough. Progress in weather analysis and forecasting has gone hand in hand with hugely improved operational services, guaranteeing ubiquitous access to weather data and value-added information products in support of governments, businesses, and the public, most of whom have the data literally at their fingertips.

In terms of quality and access to information, the situation with climate services is very different (e.g. Nightingale et al., 2018). Models and data abound, but are mainly used by scientists, whose work relies on research infrastructures and community initiatives. The outcomes of climate research are widely disseminated in comprehensive assessment reports prepared by the Intergovernmental Panel on Climate Change (IPCC). There remains, however, a large gap between scientific products and the type of condensed information needed by authorities and organisations involved with mitigation and adaptation efforts (e.g. Findlater, 2021).

The Copernicus Climate Change Service (C3S, see https://climate.copernicus.eu/) was established by the European Commission (EC) in 2014 (European Union, 2014) to offer for climate what has already been achieved for weather, and more (Thépaut et al., 2018, Buontempo et al., 2020). C3S is implemented by ECMWF together with over 300 public and private entities from more than 40 countries in Europe and elsewhere. Today, C3S provides reliable, open, and free access to the best data available on the past, present and potential future climate, together with many of the tools needed to combine and transform those data into useful information products. End-users of products and services include European Union Directorate-Generals, national and regional governments, local authorities, public and

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commercial entities, the media and the public. Although the main target of C3S is the European domain, many data and products have global coverage and reach out to worldwide users.

C3S is one of six thematic information services within Copernicus, which also operates the Sentinel missions. In addition to C3S, Copernicus includes the Copernicus Atmosphere Monitoring Service (CAMS, described elsewhere in this issue), the Copernicus Marine Environment Monitoring Service (CMEMS) and the Copernicus Land Monitoring Service (CLMS). Two Copernicus information services have been established to address emergency management and security.

C3S does not have any equivalent in the world and is unique in several ways. It is a long-term effort, fully funded by the EU as an operational climate service embedded in the Copernicus Earth observation programme (www.copernicus.eu). It provides reliable access to quality-assured data, tools and applications via the Climate Data Store (CDS, see https://cds.climate.copernicus.eu/), under a free and open use license designed to stimulate development of downstream climate services. The CDS data catalogue covers a wide range of climate datasets, including satellite and in-situ observations and derived climate data records, global and regional reanalyses and projections, and seasonal climate forecasts. Many of the datasets are brokered from climate data providers around the world; others are produced by C3S using European and wider international capabilities. The Service relies on and actively supports development of standards and conventions that enable consistency and interoperability of data and tools. Substantial resources are devoted to user support and training, management of user requirements, quality assessment of data and quality assurance of products and services.

This paper describes the C3S implementation (section 2) and achievements: the Climate Data Store (section 3), applications and use cases (section 4), quality assurance (section 5) communication and user engagement (section 6) before concluding with some lessons learnt and outlook for the second phase (2021-2028) that has just started.

2. C3S Implementation

C3S was established in 2014 by the EU as a major contribution to the global climate agenda and in particular the Global Framework for Climate Services (GFCS: Hewitt, 2012). High-level requirements are to provide access to authoritative data and information on

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climate change to support EU adaptation and mitigation policies, to enable and facilitate a healthy market for climate services, and to leverage existing capabilities in Europe and globally where possible. The Service comprises four main components: a Climate Data Store (CDS) for access to data and tools; a series of applications and use cases for specific policy, economic and societal sectors; an evaluation and quality control function to manage user requirements and quality assurance; and user engagement and outreach activities concerned with promoting the Service and stimulating user uptake. The EC, who manages Copernicus, prescribes certain fundamental operating principles such as a free and open use license for all products and services, and maximum use of competitive procurement for implementation of the Service. ECMWF was selected by the EC to manage and operate C3S based on its outstanding track record as a 24/7 provider of medium-range weather products and services to its Member States, for its extensive High Performance Computing (HPC) infrastructure, and for its ability to produce high-quality climate reanalyses and seasonal forecasts, which play a key role in the Service. In addition, ECMWF has long-standing collaborations with ESA and EUMETSAT, who manage the Copernicus space component. The scientific background of C3S is rooted in key international initiatives such as the Global Climate Observing System (GCOS) and the World Climate Research Programme (WCRP), and builds on the outcomes of several EU collaborative research projects including ERA-CLIM2 (Buizza et al., 2018), QA4ECV (Boersma et al., 2018), UERRA (Unden et al., 2016), CLIP-C (Juckes et al., 2016), and EUCLEIA (Klehmet and Burkhardt, 2016).

In the absence of an existing model for a multinational climate service organisation with comparable scope, the implementation of C3S followed a graduated approach, starting with capacity building and proof-of-concept developments for some of the main service elements. To help understand user requirements and possible solutions for implementation, ECMWF conducted a series of workshops and meetings with stakeholders, including a wide range of potential users and data providers, national meteorological services in Europe, and climate service providers in the US such as the NOAA National Centers for Environmental Information (NCEI) and the International Research Institute for Climate and Society (IRI).

C3S launched its first regularly scheduled service in September 2015 in the form of a monthly climate bulletin. The bulletins describe the observed global and regional changes of key climate variables such as near-surface air temperature, precipitation, soil moisture and sea-ice (https://climate.copernicus.eu/climate-bulletins). They rely on C3S data and products

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and are published as soon as possible after the end of each month, typically within a week. The monthly bulletins, as well as annual summaries attract very high uptake by policymakers and the international media due to their early availability.

Development of the backbone of the Service, the CDS, took several years to complete. Its public launch in 2018 marked the moment that C3S could be considered fully operational. This means, for example, that data used in the monthly climate bulletins and other climate change assessments are transparently available to users. Since then, a large variety of climate datasets have been added to the CDS catalogue; numerous applications and use cases have been published; a comprehensive quality assurance framework has been implemented for many of the products and services; and a wide range of user support, training and outreach activities have been undertaken to ensure high awareness and successful user uptake of the Service. As of March 2022, the CDS had more than 120,000 registered users from over 170 different countries. In an average quarter, more than 25,000 active users process data on-line and/or download them at an average rate of 70 terabytes per day. These numbers represent only the direct users and do not reflect the multiplier effect of secondary downstream users, applications and cloud platforms.

3. The Climate Data Store

The aim of the Climate Data Store (https://cds.climate.copernicus.eu/, Fig. 1) is to vastly improve access to high-quality climate data for a wide range of users with different backgrounds, and to make it much easier to discover, process and combine those data into useful information products (Raoult et al., 2017). The CDS is a cloud-based service that provides users with a single-entry point and a uniform interface to a wide range of climate datasets hosted by multiple providers, including observations, climate data records, reanalyses, seasonal forecasts, climate model output, and various other data products. All data in the CDS are described with names and units using a common data model, regardless of original data type and provider. Datasets can be selected from a searchable catalogue, leading to web pages containing detailed overviews, with forms for sub-setting and downloading data, links to documentation, and quality assurance information, complemented in several cases with quick data viewers.

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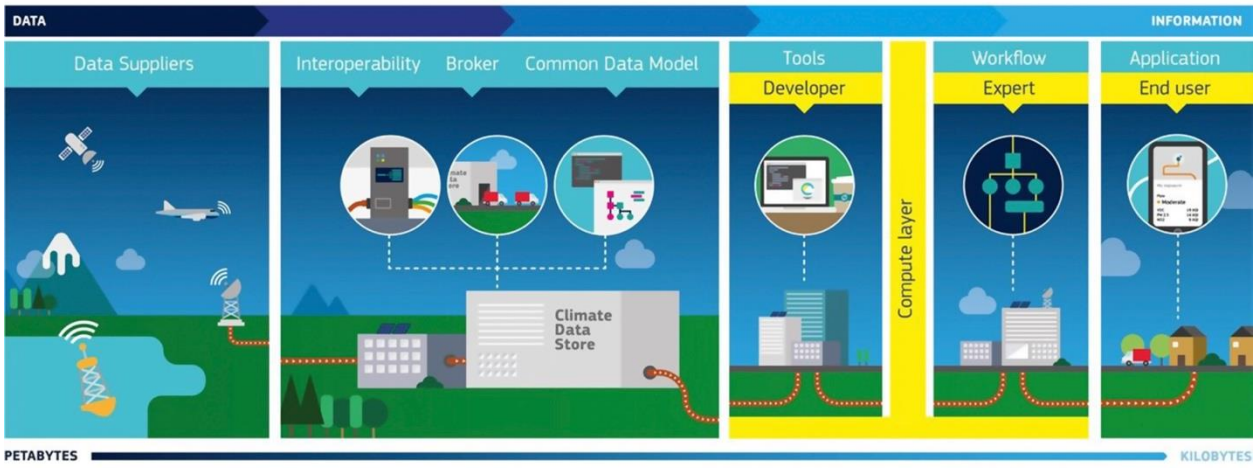

Fig. 1: C3S overall value chain and structure, from data suppliers to applications via the Climate Data Store.

The CDS cloud infrastructure includes a versatile Python-based toolbox that allows developers and expert users to work with and next to datasets online, by selecting variables and spatial domains, performing simple calculations, combining, visualizing, downloading results, etc. The goal is to avoid downloading large amounts of data. The toolbox enables the combination of different datasets, e.g., for plotting observations and model projections in a single time series. A Toolbox Editor is available for code development, which can be used to experiment with online use of data and to create, copy, modify and save applications. The toolbox is open source and fully documented, and a complete API (Application Programming Interface) is available for offline use. Applications created with the CDS toolbox are intended for end-users who want to explore and interpret data, generate new knowledge, or require highly processed information for assessment, decision-making and planning in specific locations and socio-economic sectors. A large variety of applications have been published in the CDS and can be found in the catalogue. Under the hood, the CDS secures access to data in the form required, using adaptors designed to deal with the myriad of technical steps that so often frustrate users.

The CDS has been designed as a distributed and extendable service infrastructure for multiple data providers, reusing existing capabilities where possible. The core interface, with a web portal, catalogue broker and user management function, has been implemented at ECMWF on a private cloud with several petabytes of disk storage to enable fast access to reanalyses and other data that are in high demand. The CDS is interoperable with ECMWF's MARS (Meteorological Archive and Retrieval System), the ESGF (Earth System Grid

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Federation), and a variety of other systems such as OpenDAP, WPS and ftp/web servers, hence allowing access to those via the CDS catalogue without distinction. New protocols can easily be added thanks to a plugin architecture. The CDS is also compliant with the WMO Information System (WIS).

As a Community Activity of the Group on Earth Observations (GEO) and contribution to its System of Systems (GEOSS), C3S also engages actively on broader interoperability questions, through collaborations with entities such as the Open Geospatial Consortium (OGC) on their Climate Change Service Pilot initiative (https://www.ogc.org/projects/initiatives/ccspilot).

The CDS catalogue contains well over 100 climate datasets, mostly in four groups: (1) observations and basic data products, (2) global and regional reanalyses (3) seasonal forecast data from multiple providers, and (4) global and regional climate projections. The catalogue also includes various datasets prepared for specific applications. Together, these data describe the past, present and possible future evolution of the climate based on the best available science.

a. Observations

Observations are the primary source of information about how climate change is impacting the Earth system. Yet, it is notoriously difficult to correctly use and process observations, for scientists and non-specialists alike. C3S has made great strides by providing a single point of access to a large variety of observational data, using consistent data descriptions and access methods, all subject to strict quality control and a high degree of documentation and quality assurance.

The overarching principle for integrating an observational dataset in the CDS is that it should be usable as a Climate Data Record (CDR), i.e., covering several decades with sufficient quality and consistency to enable detection of long-term changes embedded in diurnal, seasonal and multi-annual variations. C3S uses GCOS requirements (GCOS, 2016) as a guidance for the selection and production of all CDRs integrated in the CDS. The catalogue includes more than 20 observations-based Essential Climate Variables (ECV: Bojinski et al., 2014) pertaining to atmospheric physics, atmospheric composition, the ocean, land hydrology and cryosphere, and the land biosphere, mainly derived from satellite observations (Fig. 2). The majority of ECV datasets contain CDRs for several related

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parameters (for example, sea-ice concentration, sea-ice edge, sea-ice type, sea-ice thickness) on a regular grid. Many of the CDRs are extended forward in time on a regular schedule as new observations become available, to support close monitoring and assessment of climate change.

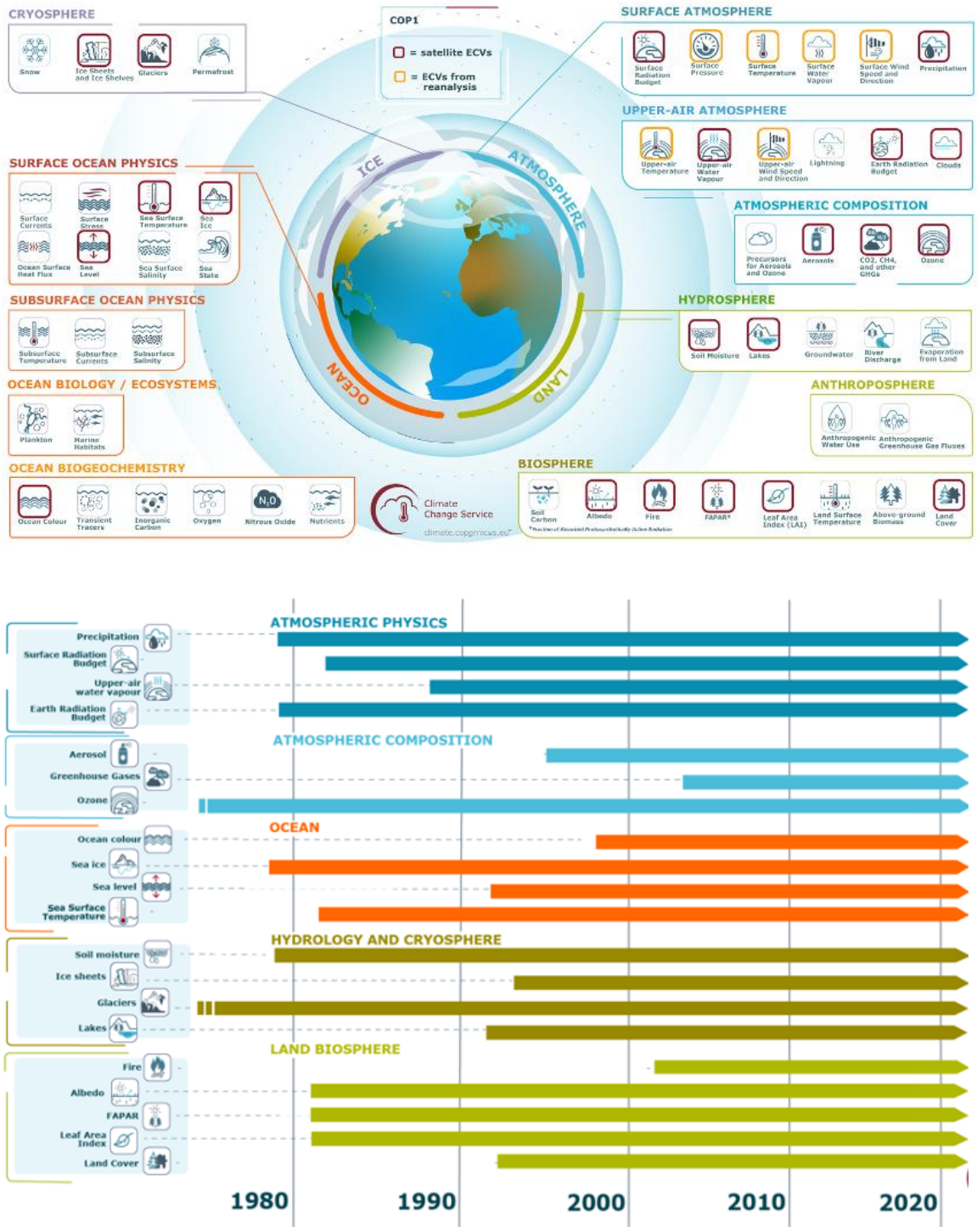

Fig. 2: GCOS ECVs for the atmosphere, land, ocean and cryosphere and C3S contribution. Top: the 27 ECVs currently available in the Climate Data Store (March 2022)

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are highlighted in red (for those based on satellite observation) and orange (derived from reanalysis data). Bottom: respective time span of the corresponding climate data records.

Most ECV datasets in the CDS catalogue are produced by C3S and its partners, or brokered from agencies such as EUMETSAT, ESA, NASA and NOAA. The satellite-based CDRs products, most of which provide global coverage, are supplemented by several high-resolution CDRs products for the European domain, generated in the E-OBS project based on *in-situ* station observations (Cornes et al., 2018).

For climate data prior to the satellite era, CDS users have access to merged collections of quality-controlled near-surface meteorological observations made over land back to 1755, and over ocean back to 1851 (Thorne et al., 2017). These historical collections are produced and maintained by C3S and incorporate data from numerous sources around the world, including national meteorological services and major international data centres. NOAA has provided substantial in-kind resources by contributing the vast amount of climate observations contained in the archives of the National Centers for Environmental Information (NCEI). C3S and its partners apply numerous quality control checks and homogeneity tests to observations and metadata to ensure optimal spatial and temporal consistency of station data. The work is carried out following WMO standards, e.g., related to station identification and other metadata (WMO, 2017; WMO, 2018a).

In addition to surface-based data, the CDS catalogue includes several collections of atmospheric observations from GCOS networks, including data from the Global Reference Upper Air Network (Seidel et al., 2009) used to determine atmospheric trends and to calibrate other observing systems; meteorological observations reaching back to 1978 building on the Integrated Global Radiosonde Archive (Durre et al., 2006) with uncertainty estimates; in-situ total column ozone and ozone soundings from 1924 to present from the World Ozone and Ultraviolet Radiation Data Centre (woudc.org) supporting the quadrennial Scientific Assessments of Ozone Depletion as part of the Vienna convention for the protection of the ozone layer (WMO, 2018b).

The ability to provide accurate information on the past climate is severely limited by the scarcity of observations in many regions of the world, especially prior to the 1970s when global observations from meteorological satellites started to be used substantially for numerical weather prediction. To further expand historical climate data collections, C3S has created a Data Rescue Service (https://datarescue.climate.copernicus.eu/) for historical

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weather observations that builds upon the WMO International Data Rescue (I-DARE) Portal (Brönnimann et al., 2018). It offers various tools for digitization of original records and quality control of data. An automated facility for submitting newly rescued data records to major international archives is in place (https://datadeposit.climate.copernicus.eu/home/). C3S also conducts a range of data rescue activities for early satellite data records, many of which are in danger of disappearing (Poli et al., 2017), and can improve the accuracy of climate reanalyses in the 1960s and 1970s.

b. Climate reanalyses

The majority of C3S users requiring information about past weather and climate use reanalysis data, which integrates observations from numerous observing systems together with information from a skilful forecast model. Reanalyses provide multi-decadal time series of spatially complete and physically consistent climate variables and are amongst the most-used datasets in geophysical sciences.

The global and regional reanalysis datasets in the CDS are increasingly important for monitoring climate change and supporting downstream climate services. Global reanalysis data are used by C3S to construct climate data records for some ECVs, such as air temperature, humidity, precipitation, soil moisture and wind, to complement the satellite-based ECV products available in the CDS.

C3S enabled development of ECMWF's latest ERA5 reanalysis (Hersbach et al., 2020) using a recent version of the ECMWF Integrated Forecasting System (IFS). ERA5 provides hourly, daily and monthly data from 1950 to the present (Bell et al., 2021), for hundreds of variables at a global resolution of approximately 30km on 137 levels from the surface to about 80km altitude (see example result in Fig. 3). ERA5 was produced using a 10-member ensemble of 4D-variational data assimilation method, which also enables uncertainty estimation for all variables. The entire ERA5 dataset assimilates more than 100 billion observations and takes up more than 9 petabytes of storage, with roughly 25% of the most requested data stored on disk for rapid access.

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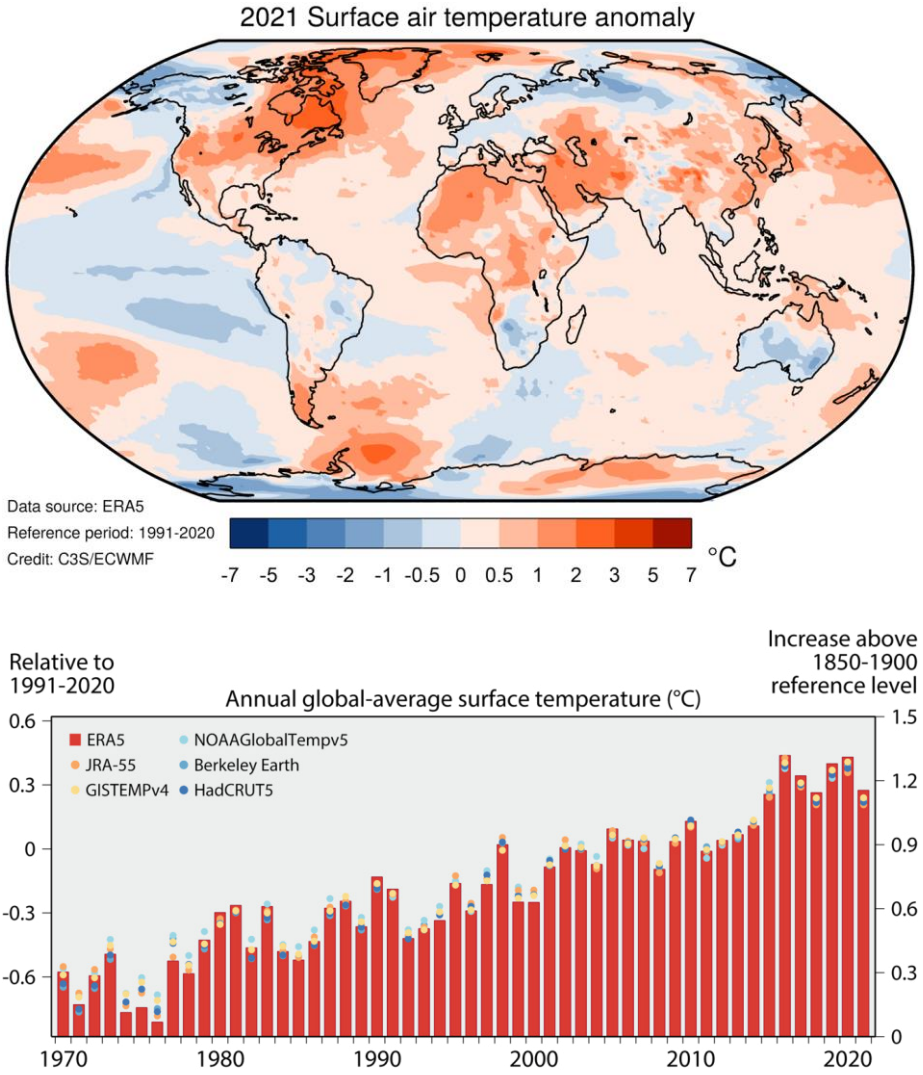

Fig. 3: ERA5 surface air temperature (°C) anomalies: global map for 2021 shown relative to the 1991–2020 average (top) and time series of annual global-average compared to other estimates (bottom).

Along with ERA5, a global dynamical downscaled version of the land-surface component, ERA5-Land (Muñoz-Sabater et al., 2021), has been produced at 9km resolution, providing additional information related to variables describing the water and energy cycles. Both the ERA5 and ERA5-Land datasets continue to be extended forward in time as new observations are assimilated. Updates for ERA5 (and soon for ERA5-Land as well) are published daily in the CDS, within 5 days of real-time.

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User uptake of ERA5 and ERA5-Land has been very high, representing 94% of the total 72 Pb downloaded and 79% of all users in the CDS., and with 240+ citations in the IPCC WGI 6th Assessment Report (IPCC, 2021).

C3S coordinates development of two regional reanalysis systems for the European and Arctic domains, both using ERA5 boundary conditions. The CDS catalogue includes atmospheric data from the UERRA reanalysis for Europe, at a horizontal resolution of 11km for the period from 1961 to 2019 (Unden et al., 2016). Production of an improved reanalysis for Europe (CERRA) at 5.5km resolution covering the period 1980 to 2021 with uncertainty estimates is being completed and will be available in the CDS later in 2022. The C3S Arctic Regional Reanalysis (CARRA), based on the HARMONIE-AROME system (Bengtsson et al., 2017), covers two subdomains of interest for Arctic change processes and economic activities, at 2.5km resolution for the period from 1991 to present. Both CERRA and CARRA datasets will be updated regularly with 2-3 months delay behind real time.

c. Seasonal forecasts

Climate predictions are designed to describe future variations of the climate system over long-time horizons (months, seasons, years, decades). Predictability on such time scales comes from the slow-varying components (ocean, land, sea-ice) of the climate system if properly initialized with satellite and in-situ observations.

Climate models used for prediction are however subject to errors and drifts, partly due to inherent limits of predictability of the climate system, or the accrual of various numerical approximations. Appropriate use of seasonal forecasts requires reliable information about skill which can be estimated from hindcasts (i.e., historical/retrospective forecasts) covering a substantial period (i.e., several decades). C3S has implemented a multi-system seasonal forecasting service (Palmer et al., 2005) that combines products from multiple WMO Global Producing Centres in Europe (currently ECMWF, Météo-France, DWD in Germany, Met Office in the UK and CMCC in Italy) and elsewhere (USA, Japan, Canada) following common requirements, in terms of variables, forecast length, ensemble size and various technical aspects (timeliness, data formats, etc). Data and graphical products based both on individual contributions and the combined C3S multi-system forecast (see skill example on Fig. 4), are published monthly in the CDS and are available on regular 1ºx1º latitude-longitude grids at 6, 12, or 24-hourly intervals depending on the variable. C3S also plans to

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provide access and use of multi-year (decadal) climate predictions for decision-making in the context of four economic sectors (insurance, agriculture, infrastructure and energy).

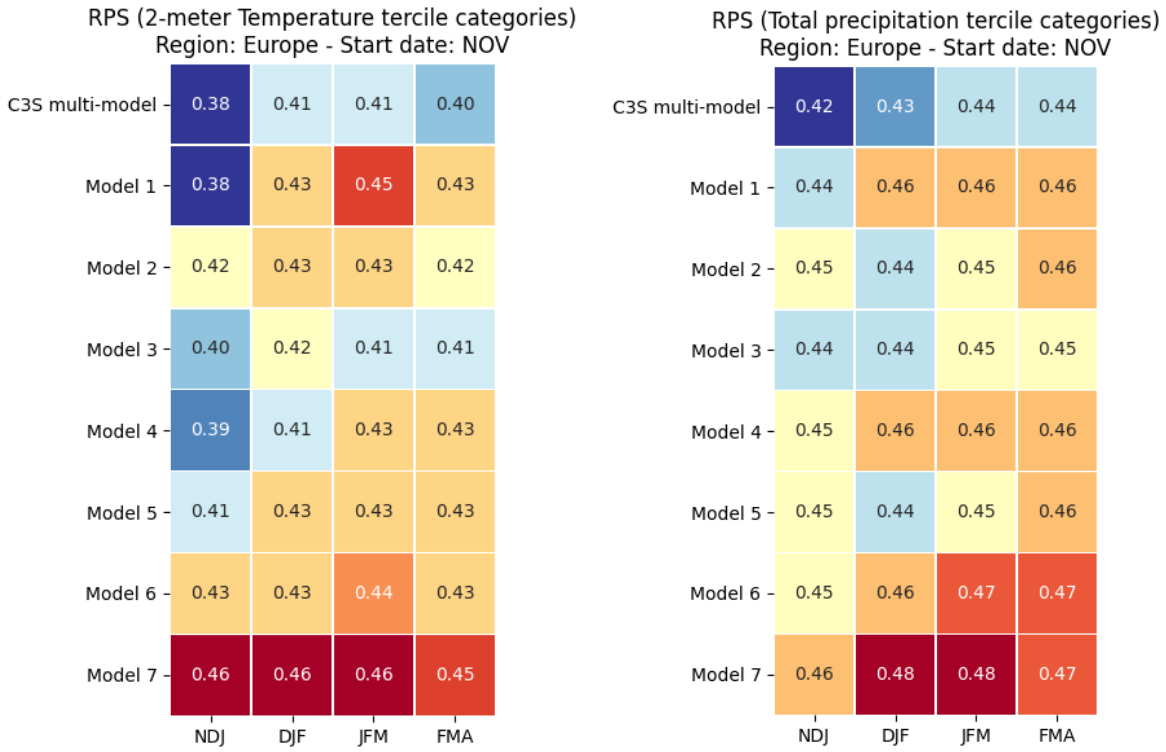

Fig. 4: Comparison of multi-model and individual seasonal prediction skill over Europe (Ranked Probability Score, the smaller/bluer, the better) for 2-meter temperature (left) and total precipitation (right) tercile categories averaged over the 1993-2016 hindcast period for 3-month windows (NDJ=November/December/January, etc) for a November start date.

d. Climate projections

Climate projections are numerical simulations constrained by plausible future climate scenarios based on hypothetical specifications of greenhouse gas emissions, concentrations, and other factors affecting the planet's radiative balance using climate and Earth-system models. They support the preparation of the Assessment Reports produced by the Intergovernmental Panel on Climate Change (IPCC). Simulations by over 50 climate and Earth-system modelling centres are coordinated within the WCRP Coupled Model Intercomparison Project (CMIP: Eyring et al, 2016) for global projections and within its regional equivalent at higher resolution over 14 domains, the Coordinated Regional Downscaling Experiment (CORDEX: Gutowski, 2016) in support of impact and adaptation

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studies. The main data repository for CMIP and CORDEX is the Earth System Grid Federation (ESGF), which is a distributed data infrastructure. C3S provides operational support to several ESGF European nodes to ensure efficient access to projections in the CDS.

Global climate projections in the CDS constitute a quality-controlled subset of scenario simulations for the 21st century and beyond, based on predefined Representative Concentration Pathways (RCP) for CMIP5 models and Shared Socioeconomic Pathways (SSP) for CMIP6 models (see example of result on Fig. 5). Historical simulations from 1850 to the early 2000s are also included.

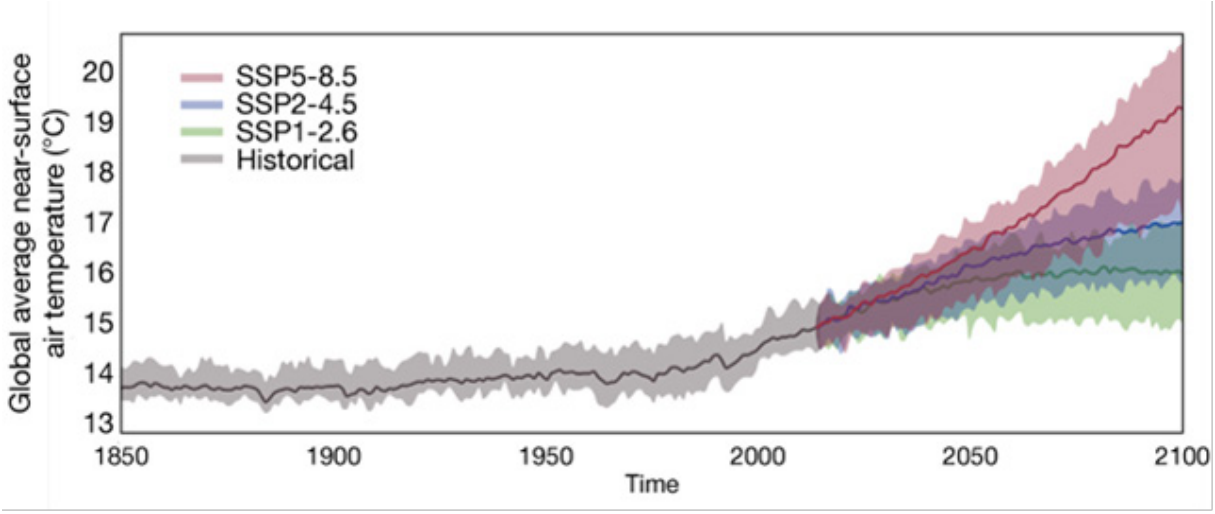

Fig. 5: Visualization of CMIP6 data generated in the CDS Toolbox, showing annual global mean and spread of 2m temperature changes between 1850 and 2100: model simulations for the historical period (grey) and future projections under three different emission scenarios (colored) (see Eyring et al., 2016 for details).

The regional climate projections in the CDS are a quality-controlled subset of the wider CORDEX dataset available on ESGF from 5 CORDEX experiment types (evaluation, historical and 3 RCP scenarios) that have been downscaled from CMIP5 outputs. Additionally, C3S supported production of several high resolution (~12km) simulations for Europe, resulting in an ensemble of 130 simulations. Additional world-wide regional climate projection datasets were curated, uploaded to the ESGF and published on the CDS. This enhanced CORDEX dataset underpins the new IPCC Interactive Atlas (see https://interactive-atlas.ipcc.ch/).

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4. Applications and use cases

Access to high quality data is only the first step for users who need to solve concrete problems related to climate change. Users also need the means to select, combine and transform data into useful information products according to their needs. The CDS infrastructure offers users the possibility to build applications combining simple tools into workflows to be executed online. These CDS applications often take the form of an interactive web page that can activate a workflow that generates on demand graphics, text or other outputs based on the selected input data. Such a dynamic generation ensures that CDS outputs are based on the most up-to-date data available. All applications are public and can be found in the CDS catalogue, together with documentation and source code, which can be copied and modified at will. The diversity and number of applications fully leverage the strength of the catalogue and flexibility of the toolbox.

For example, the *ERA5 Explorer application* (Fig. 6) provides a clickable map for generating local statistics for several climate variables based on ERA5 reanalysis data (see https://cds.climate.copernicus.eu/cdsapp#!/software/app-era5-explorer?tab=app).

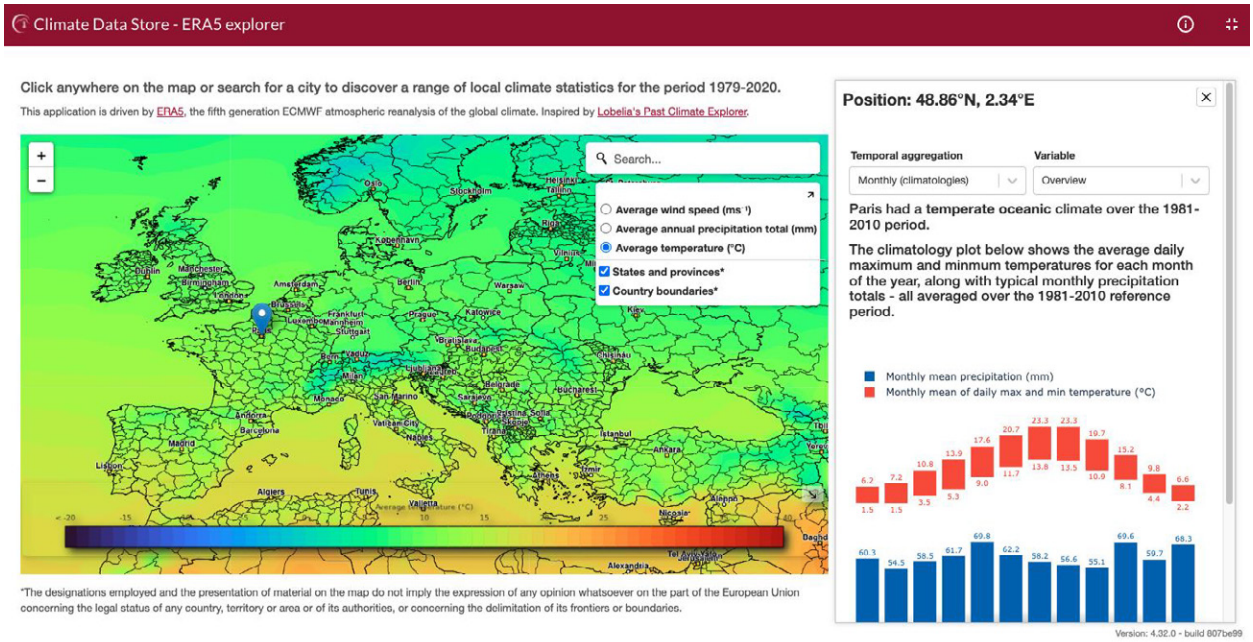

Fig. 6: Screenshot of the ERA5 Explorer application.

Similarly, *the Global temperature trend monitor application* (Fig. 7) can be used to monitor recent surface air temperature trends and estimate when global warming will reach

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the 1.5°C limit proposed in the Paris agreement. The application uses ERA5 data for the linear trend estimation and CMIP5 projections to put those estimates in context (see https://cds.climate.copernicus.eu/cdsapp#!/software/app-c3s-global-temperature-trend-monitor?tab=app).

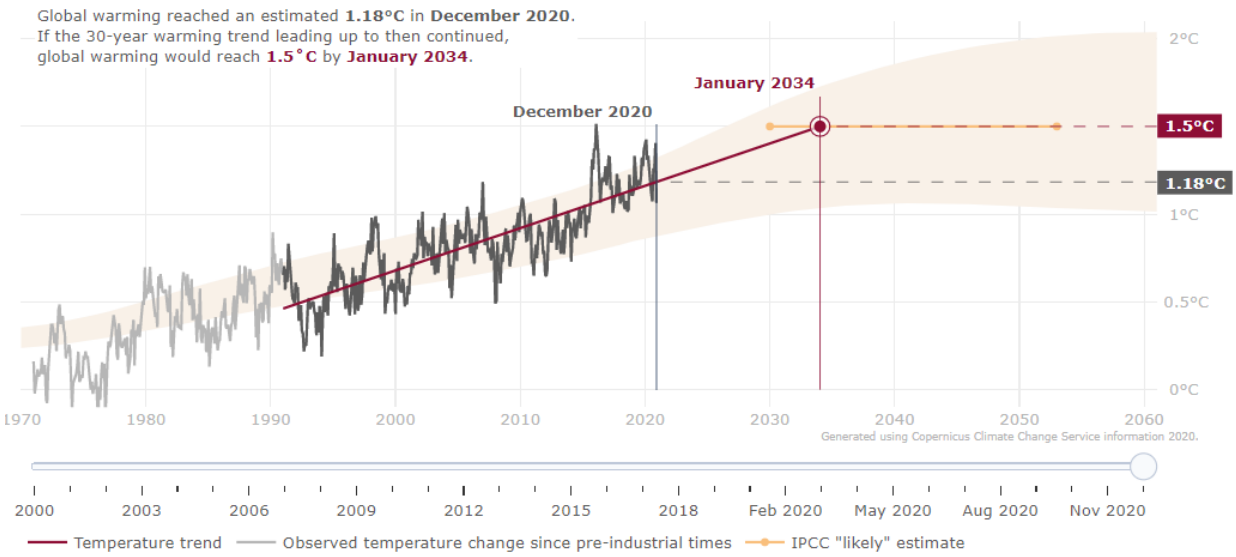

Fig. 7: Screenshot of the Global temperature trend monitor application.

C3S invests a large effort working with users in various societal sectors to develop CDS applications that effectively link climate information with planning and decision making. This has resulted in demonstrator projects and use cases in several socio-economic sectors such as agriculture, transportation, water management, energy generation, etc. supporting downstream applications for national public authorities and private companies.

For example, *The European energy and climate data explorer* (Fig. 8) is a CDS application that provides insights into the effect of climate change and variability on energy supply and demand, based on ERA5 reanalyses and regional climate projection data over Europe (see https://cds.climate.copernicus.eu/cdsapp#!/software/app-energy-explorer-europe?tab=app).

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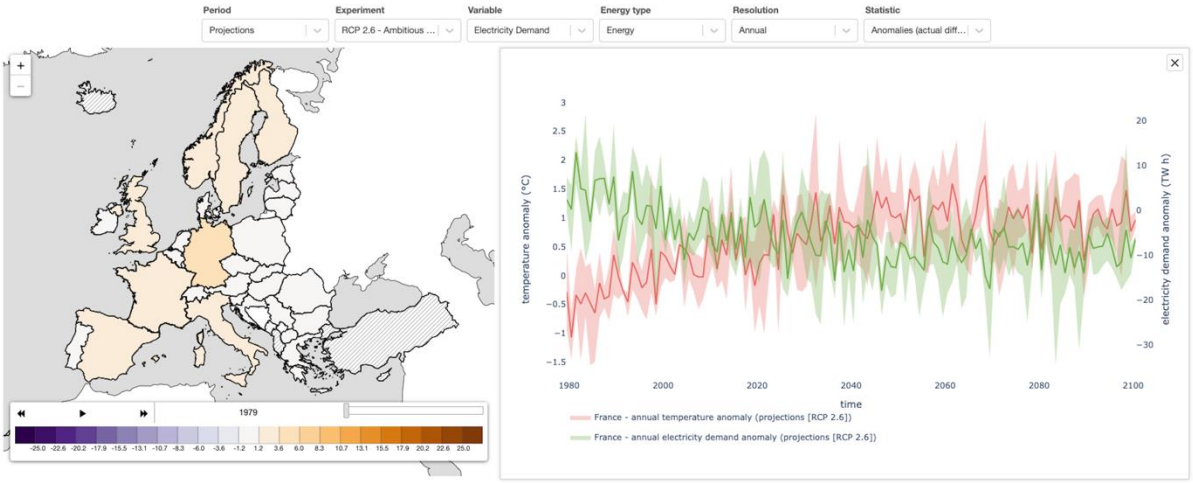

Fig. 8: Screenshot of The European energy and climate data explorer application.

Addressing the health sector, the *Monthly climate explorer for COVID-19* (Fig. 9) application provides ways to explore possible linkages between weather (ERA5 reanalysis) and air pollution (CAMS global atmospheric composition reanalysis) variables alongside mortality data from Johns Hopkins University (see https://cds.climate.copernicus.eu/cdsapp#!/software/app-c3s-monthly-climate-covid-19-explorer?tab=app).

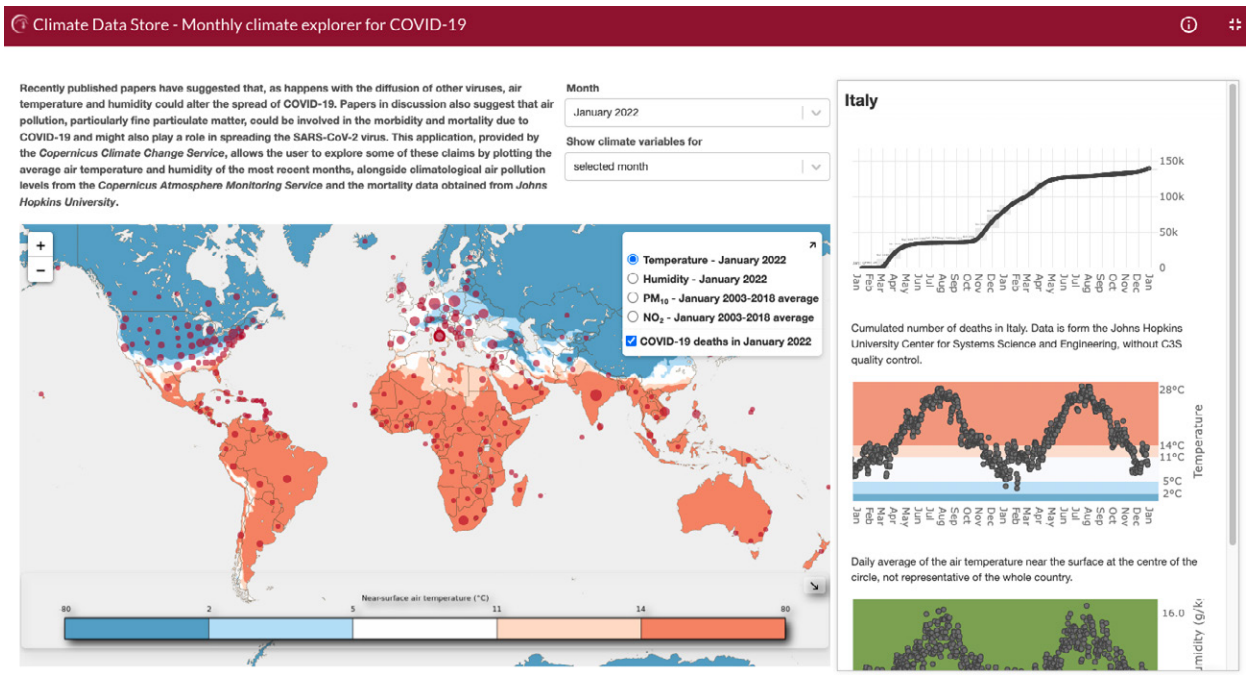

Fig. 9: Screenshot of the Monthly climate explorer for COVID-19 application.

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Many of the sectoral use cases serve as demonstrators to show how climate data can be used in practice. They exemplify how a range of businesses use C3S data to make informed decisions to operate in a more sustainable way.

C3S also offers access to the CDS via an API, which makes it possible to access data and derived climate impact indicators on platforms other than the CDS. A set of 20 applications of CDS data has been published on the European Climate Data Explorer (ECDE). Hosted on the Climate-ADAPT platform and managed by the European Environment Agency (EEA), the ECDE portal provides interactive access to many climate indices from the Copernicus Climate Change Service in support of national and local adaptation strategies in Europe. The platform illustrates the multiplier effect of the CDS, enabling access to additional many thousands of users.

5. Quality assurance

Appropriate use of climate information for planning and decision making requires high-quality data and tools with strong user support. Effective evaluation and control of data quality, aimed at providing useful guidance to users, is critical for C3S to be a trusted and authoritative voice on climate. Accordingly, C3S is implementing a comprehensive quality assurance framework for CDS data, tools and applications (e.g. Lacagnina et al., 2022; Yang et al., 2022) which includes end-to-end management of user requirements (Fig. 10).

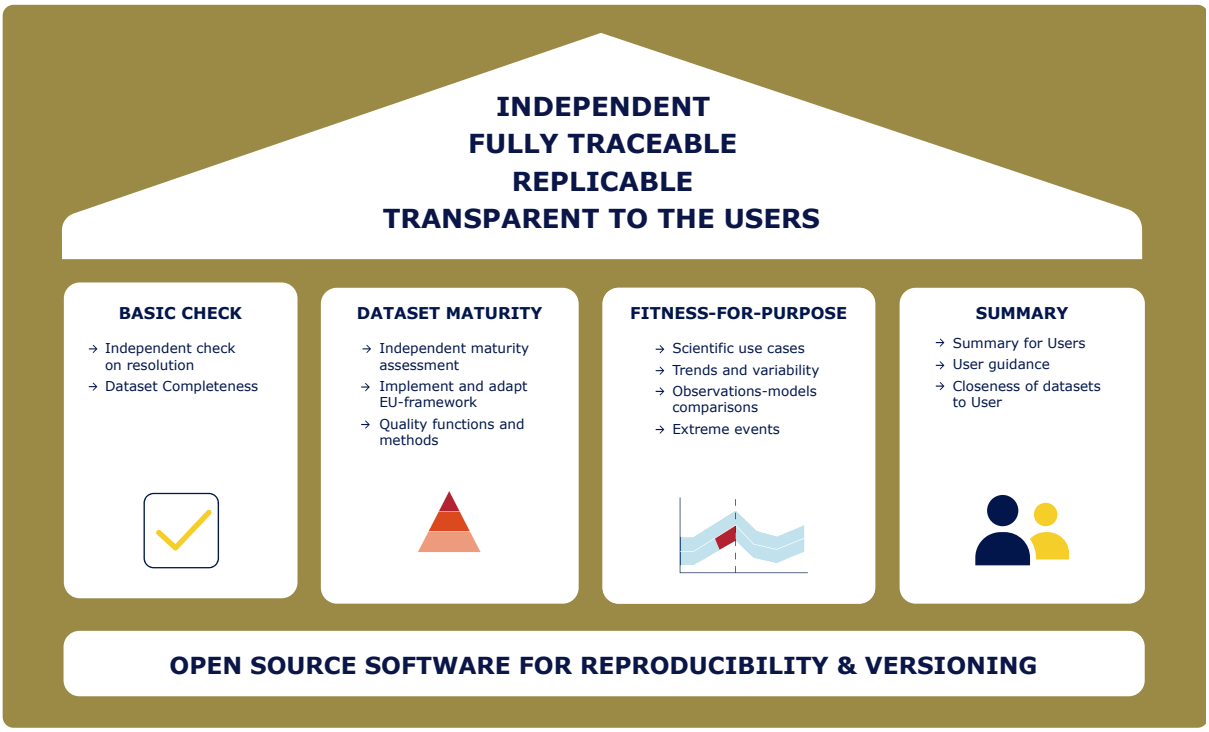

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Fig. 10: the fundamental elements of the C3S Evaluation and Quality Control.

A range of quality assurance information has been published in the CDS for many of the datasets. Assessments of CDS tools and applications are also being prepared for eventual publication in the CDS. Quality of Service (QoS) of the CDS infrastructure is continually monitored and assessed in real-time (https://eqc.climate.copernicus.eu/monitoring). A live dashboard providing CDS usage information is available at https://cds.climate.copernicus.eu/live/.

Quality assurance information for CDS content is collected in Quality Assurance Reports (QAR), designed to provide detailed information about relevant aspects of quality, uncertainty and usability. Development of such information for any particular dataset, tool or application is a laborious process, involving C3S dedicated staff, data providers and/or software developers, as well as independent reviewers. QARs are developed using automated workflows and dedicated collaborative content management tools.

The QARs for datasets follow standard templates for each type of data (e.g., observation, prediction, projection). The QAR typically contains results of routine checks on data integrity and completeness, information on metadata quality and documentation, descriptions of relevant use cases, and a grading of data maturity. QARs are living documents following the life cycle of a dataset, starting with its initial publication in the CDS and continually updated with information on new assessments, use cases, dataset extensions, etc.

Quality assurance of CDS applications addresses five main criteria: relevance, accessibility, clarity, completeness and reliability, with due consideration of purpose and providers of the application; source data used; quality of documentation and how well it describes applicability and limitations; dissemination policy, data access and visualization methods; compliance with relevant standards; user involvement in designing the application.

C3S maintains a database containing thousands of user requirements that are continually gathered by various means, including user support interactions. The user requirements are periodically clustered, analysed and synthesized in terms of actionable recommendations to guide the evolution of the Service.

C3S User Support is managed jointly with CAMS by a dedicated team, which maintains self-help facilities such as Frequently Asked Questions (FAQs), a Knowledge Base,

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documentation and tutorials, and a User Forum (Fig. 11). The Knowledge Base contains a wealth of information from data providers and technical experts and is accessed more than 100,000 times per quarter. A Help Desk, staffed during European business hours, uses a ticketing system to register and respond to all user requests. Those that require specific technical expertise are forwarded to specialists within C3S. A virtual assistant provides help through an interactive chat box in the CDS.

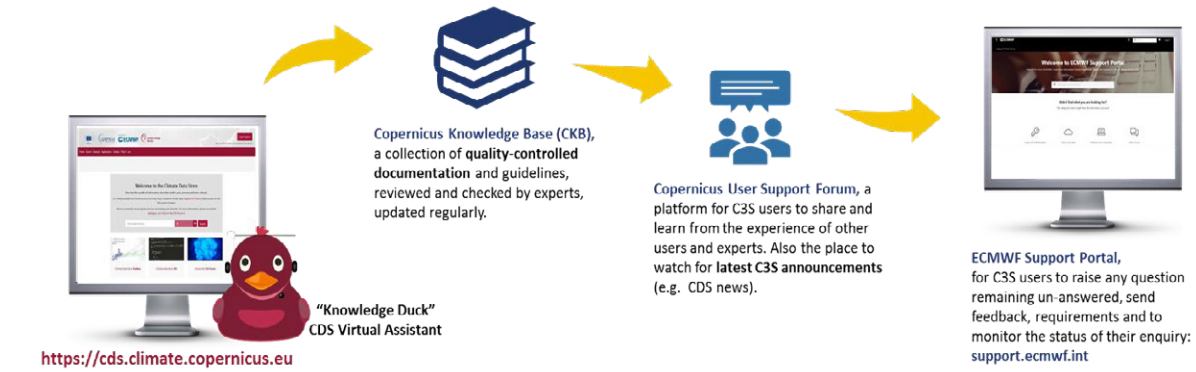

Fig. 11: illustration of the User support journey along the various resources available to users, from self-help to expert advice.

6. Communication and user engagement

A variety of user engagement and communication activities ensure high visibility of the C3S brand and maximum uptake of its products and services. C3S has a regular presence at major international scientific conferences, the UNFCCC Conference of the Parties (COP), and various meetings dedicated to the management of the Copernicus programme. C3S also organises training events for users including the media and many other meetings and workshops dedicated to user engagement and the evolution of the Service. Communicating and working with the media is a key component of outreach activity. The Service issues press releases to accompany its analyses, receives enquiries and conducts interviews in multiple languages each month, resulting in international uptake across all tiers and formats.

The C3S website has received over 4 million unique page views since its launch in August 2015. The content evolves continually as new products and services become available, with the gradual integration of the CDS, applications, use cases and demonstrators,

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user support services, reports and bulletins, news articles etc. It provides access to a User Learning Services platform with high-quality training resources for online self-paced learning.

Prominent on the website are the various climate monitoring products derived from C3S data, including the monthly Climate Bulletins (https://climate.copernicus.eu/monthly-maps-and-charts) and associated annual summaries, the latter receiving over 3500 media mentions across 105 countries for its release in January 2022. C3S climate monitoring products are routinely used in WMO State of the Global Climate reports. The C3S annual European State of the Climate (https://climate.copernicus.eu/ESOTC, Fig. 12), which provides a more detailed monitoring of climate change for Europe, received media -pickup over 900 times across 51 countries following its April 2021 release on TV, radio, print and online. Social media channels on Twitter (with 45,000 followers), Facebook, Instagram and LinkedIn are shared with CAMS.

Fig. 12: Some front pages of the interactive editions of the European State of the Climate (ESoTC).

C3S, along with CAMS, sponsors monthly Euronews and CNN environmental programming, providing data and visualisations, and contributing to storylines for broadcast and online content (Fig. 13). Over 11 million people are reached via the Euronews Climate

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Now programme, and over 200 million people via the CNN Climate Update, broadcast across all regions of the globe, with over 23 million in Europe.

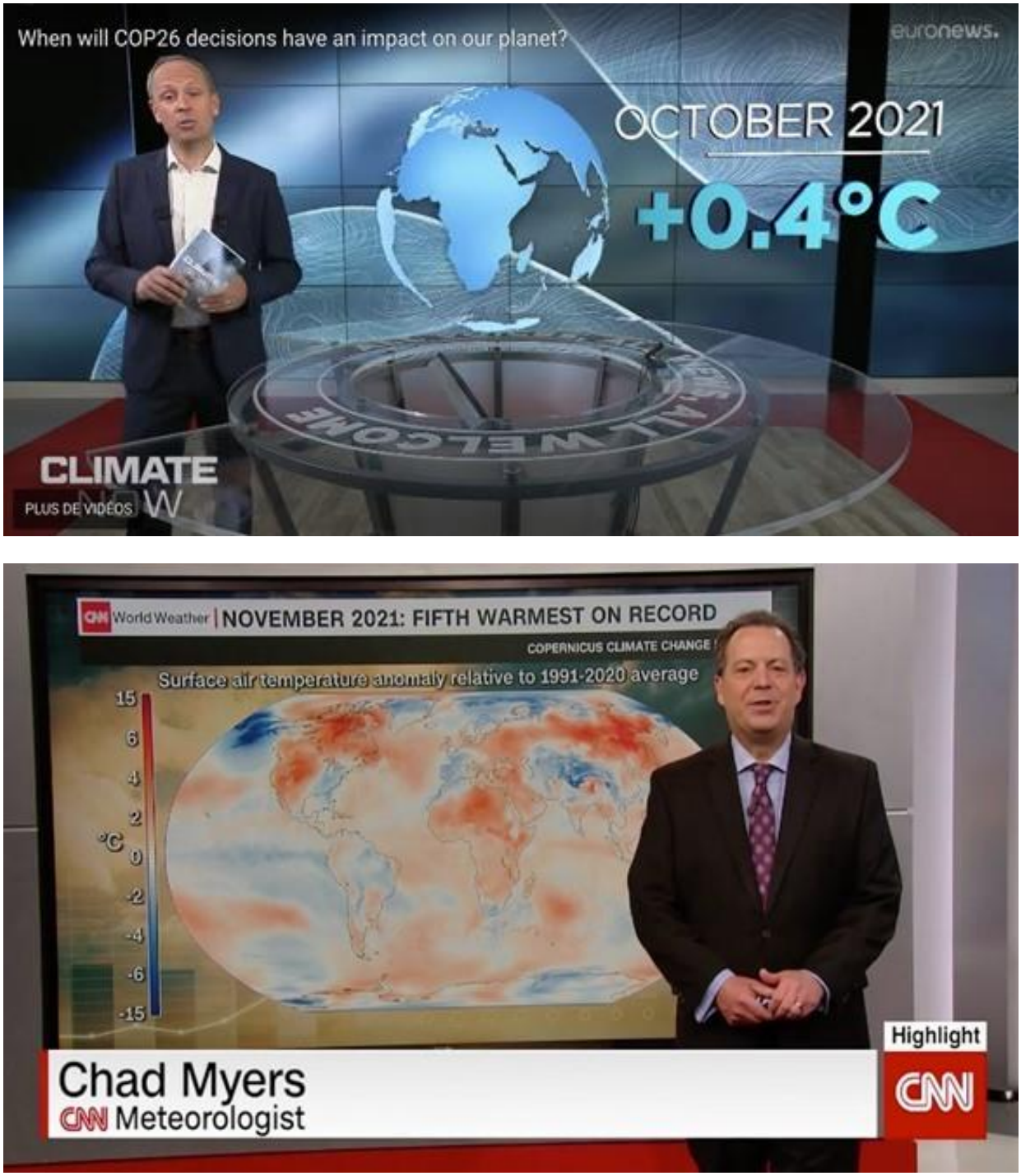

Fig. 13: Euronews ClimateNow (top) and CNN ClimateUpdate (bottom) broadcast snapshots.

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7. Conclusions and outlook

C3S became fully operational after a few years of intense preparatory work and is now a mature service with over 120,000 registered users. Reaching an operational status so quickly has been possible by taking full advantage of the operational infrastructure of ECMWF and the expertise of the meteorological and climate community in Europe. Users increasingly rely in the CDS for climate-related products and information. These include climate change indicators in support of the Paris Agreement and several Sustainable Development Goals (SDGs). C3S has become a trusted resource for the international press and media (e.g., CNN, Euronews, New York Times, Le Monde...).

Many technical challenges had to be overcome to reach this point, and several still exist. More work is required to improve the performance of the CDS and to ease the work with data on-line. Systematic application of a comprehensive quality assurance framework began only recently and will need to be extended to all products and services in coming years. Nevertheless, the original vision of C3S as an authoritative climate service in Europe is well on its way.

C3S has been beneficial for ECMWF and its Member States by expanding its scope and footprint, by elevating climate reanalysis from a research activity to an operational service, and by strengthening development of Earth system modelling and data assimilation. Copernicus activities are now fully integrated in the Centre's long-term strategy.

C3S is entering a new phase, with secure funding from the EU for the period 2022-2028 (European Union, 2021). Further evolution of services is vital to ensure that C3S products continue to address emerging policy needs, meet the highest possible quality standards, and keep pace with new science and technologies. The Service will continue to exploit Earth observations from the Sentinels and contributing missions. Users remain central to the Service, and several new efforts on capacity building and engagement at national level are planned.

The CDS infrastructure will be enhanced to offer users new options for interacting with data, such as Jupyter notebooks. New ECV products will be added to the catalogue, prioritized on terrestrial ECVs. The ERA5 reanalysis will be extended as far back as 1925 to enable the production of a century-long high-resolution reanalysis for the European domain. Production of ERA6, a new coupled Earth-system reanalysis covering a minimum of 75

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years, will start in 2024. A regional reanalysis for the entire Arctic region will also be produced. Meanwhile, reliable access to state-of-the-art multi-system seasonal climate forecast data and a large collection of model data from CMIP6 and CORDEX will continue to be supported.

As a result of increased user needs and public interest, a pilot extreme events and attribution service to quantify the effects of climate change was developed and tested on four different temperature and precipitation events. C3S will establish rapid prototyping of applications and products in response to climate-related questions from businesses, EU policymakers and the public. An attribution component may form part of the operational offer pending resources to be identified.

New EC Research and Innovation projects will start later this year to underpin these evolutions and keep C3S systems fully up-to-date.

The success of C3S is built on effective collaboration. In coming years, C3S will seek to strengthen existing synergies and find opportunities for new ones. Several new ECV products will be developed together with other Copernicus entities such as Mercator Océan International, EEA, ESA, and EUMETSAT. C3S will work closely with CAMS on implementation of the new anthropogenic CO2 Monitoring and Verification Support capacity (CO2 MVS; Janssens-Maenhout et al., 2020). The recent launch by the EC of Destination Earth (DestinE; Bauer et al., 2021) offers opportunities for fruitful collaboration on HPC, Earth system modelling, climate reanalysis and deep learning.

Copernicus, in particular its Climate Change Service with its climate policy supporting mandate, is a much-needed resource for the implementation of the European Green Deal and the 2020 EU Climate Law, with the ambition for Europe to become the first climate-neutral continent by 2050.

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Data Availability Statement.

C3S follows the Copernicus Programme Data Policy. The Regulation requires Copernicus data and information to be made available on a full, open and free of charge basis, subject to limitations concerning registration, dissemination formats, and access restrictions. Data can be accessed via the Climate Data Store at https://cds.climate.copernicus.eu/.

REFERENCES

Bauer, P., Stevens, B. and Hazeleger, W., 2021: A digital twin of Earth for the green transition. *Nat. Clim. Change*. 11, 80–83. https://doi.org/10.1038/s41558-021-00986-y

Bauer, P., Thorpe, A. and Brunet, G. 2015: The quiet revolution of numerical weather prediction. *Nature* 525, 47–55. https://doi.org/10.1038/nature14956.

Bell, B., and Coauthors, 2021: The ERA5 global reanalysis: Preliminary extension to 1950. *Quart. J. of the Royal Meteor. Soc*. 147.741: 4186-4227. https://doi.org/10.1002/qj.4174

Bengtsson, L., and Coauthors, 2017. The HARMONIE–AROME model configuration in the ALADIN–HIRLAM NWP system. *Mon. Wea. Rev*., 145(5), pp.1919-1935. https://doi.org/10.1175/MWR-D-16-0417.1

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-21-0315.1.

Boersma, K. F., and Coauthors, 2018: Improving algorithms and uncertainty estimates for satellite NO2 retrievals: results from the quality assurance for the essential climate variables (QA4ECV) project. *Atmos. Meas. Tech*., 11(12):6651–6678, December. https://doi.org/10.5194/amt-11-6651-2018

Bojinski S, Verstraete M, Peterson T, Richter C, Simmons A, Zemp M., 2014: The Concept of Essential Climate Variables in Support of Climate Research, Applications, and Policy. *Bull. Amer. Meteor. Soc*. 95 (9); p. 1431-1443. JRC87032, https://doi.org/10.1175/BAMS-D-13-00047.1

Brönnimann, S., and Coauthors 2018: A roadmap to climate data rescue services. *Geoscience Data Journal*, 5(1), pp.28-39. https://doi.org/10.1002/gdj3.56

Buizza, R., Brönnimann, S., Haimberger, L., Laloyaux, P., Martin, M.J., Fuentes, M., Alonso-Balmaseda, M., Becker, A., Blaschek, M., Dahlgren, P. and De Boisseson, E., 2018. The EU-FP7 ERA-CLIM2 project contribution to advancing science and production of earth system climate reanalyses. *Bull. Amer. Meteor. Soc*., 99(5), pp.1003-1014. https://doi.org/10.1175/BAMS-D-17-0199.1

Buontempo, C. and Coauthors, 2020: Fostering the development of climate services through Copernicus Climate Change Service (C3S) for agriculture applications. *Weather and Climate Extremes*, 27. https://doi.org/10.1016/j.wace.2019.100226

Cornes, R.C., van der Schrier, G., van den Besselaar, E.J. and Jones, P.D., 2018: An ensemble version of the E- OBS temperature and precipitation data sets. *J. of Geophys. Res. Atmos*, 123(17), pp.9391-9409.

Durre, I., Vose, R.S. and Wuertz, D.B., 2006: Overview of the integrated global radiosonde archive. *J. of Climate*, 19(1), pp.53-68. https://doi.org/10.1175/JCLI3594.1

European Union, Regulation (EU) 2021/696 of the European Parliament and of the Council of 28 April 2021 establishing the Union Space Programme and the European Union Agency for the Space Programme, *Official Journal of the European Union*, L 170/69, 12.05.2021. Available on-line at https://eur-lex.europa.eu/eli/reg/2021/696/oj

European Union, Regulation (EU) No 377/2014 of the European Parliament and of the Council of 3 April 2014 establishing the Copernicus Programme. *Official Journal of the European Union* L 122/44, 24.4.2014. Available on-line at https://eur-lex.europa.eu/eli/reg/2014/377/oj

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-21-0315.1.

Eyring, V., Bony, S., Meehl, G., Senior, C., Stevens, B., Stouffer, R., and Taylor, K.. 2016: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, *Geosci. Model. Dev*., 9(5), pp. 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016.

Findlater, K., Webber, S., Kandlikar, M. and Donner, S (2021): Climate services promise better decisions but mainly focus on better data. *Nat. Clim. Change*. 11, 731–737. https://doi.org/10.1038/s41558-021-01125-3

GCOS, 2016: *The Global Observing System For Climate: Implementation Needs*. GCOS Rep 200, 341 pp. Available online at https://library.wmo.int/doc_num.php?explnum_id=3417

Gutowski Jr., W. J., and Coauthors, 2016: WCRP COordinated Regional Downscaling EXperiment (CORDEX): a diagnostic MIP for CMIP6, *Geosci. Model Dev*., 9, 4087–4095, https://doi.org/10.5194/gmd-9-4087-2016, 2016.

Hersbach, H., and Coauthors, 2020: The ERA5 global reanalysis. *Quart. J. Roy. Meteor. Soc*., 146, 1999– 2049. https://doi.org/10.1002/qj.3803.

Hewitt, C., Mason, S. and Walland, D., 2012: The Global Framework for Climate Services. *Nature Clim. Change* 2, https://doi.org/10.1038/nclimate1745

IPCC, 2021: Climate Change 2021: *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

Lacagnina, C., and Coauthors, 2022. Quality Management Framework for Climate Datasets. *Data Science Journal*, 21(1), p.10. DOI: http://doi.org/10.5334/dsj-2022-010

Muñoz-Sabater, J., and Coauthors, 2021: ERA5-Land: a state-of-the-art global reanalysis dataset for land applications, *Earth Syst. Sci. Data*, 13, 4349–4383, https://doi.org/10.5194/essd-13-4349-2021.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-21-0315.1.

Janssens-Maenhout, G. and Coauthors, 2020: Toward an Operational Anthropogenic CO2 Emissions Monitoring and Verification Support Capacity, *Bull. Amer. Meteor. Soc*., Volume 101: Issue 8 https://doi.org/10.1175/BAMS-D-19-0017.1

Juckes, M., and Coauthors, 2016: *A Climate Information Platform for Copernicus (CLIPC): managing the data flood*. In EGU General Assembly Conference Abstracts (pp. EPSC2016-15396).

Klehmet, K. and Burkhardt, R., 2016: *Attribution of storm surge events in the Baltic Sea*. In EGU General Assembly Conference Abstracts (pp. EPSC2016-6794).

Nightingale, J., and Coauthors, 2019: Ten Priority Science Gaps in Assessing Climate Data Record Quality. *Remote Sensing*. 2019; 11(8):986. https://doi.org/10.3390/rs11080986

Palmer, T.N., Doblas-Reyes, F.J., Hagedorn, R. and Weisheimer, A., 2005: Probabilistic prediction of climate using multi-model ensembles: from basics to applications. *Philos. Trans. of the Roy Soc. B: Biological Sciences*, 360(1463), pp.1991-1998. https://doi.org/10.1098/rstb.2005.1750

Poli, P., and Coauthors, 2017: Recent advances in satellite data rescue. *Bull. Amer. Meteor. Soc.*, 98(7), pp.1471-1484. https://doi.org/10.1175/BAMS-D-15-00194.1

Raoult, B. and Coauthors 2017: Climate service develops user-friendly data store. *ECMWF Newsletter*, 151, https://www.ecmwf.int/en/newsletter/151/meteorology/climate-service-develops-user-friendly-data-store (2017)

Seidel, D. J. and Coauthors 2009: Reference Upper-Air Observations for Climate: Rationale, Progress, and Plans. *Bull. Amer. Meteor. Soc*., 2009, 90, 361–369, doi:10.1175/2008BAMS2540.1

Thépaut, J.-N., Dee, D., Engelen, R., Pinty, B. 2018: *The Copernicus programme and its climate change service*. IGARSS IEEE International Geoscience and Remote Sensing Symposium (2018) https://ieeexplore.ieee.org/document/8518067

Thorne, P.W., and Coauthors, 2017: Toward an Integrated Set of Surface Meteorological Observations for Climate Science and Applications. *Bull. Amer. Meteor. Soc*., 98, 2689-2702. doi:10.1175/BAMS-D-16-0165.1

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-21-0315.1.

Unden, P., Renshaw, R., Bazile, E., Brunet, M., Kaiser-weiss, A. and Klein Tank, A., 2016: *UERRA-Uncertainties in Ensembles of Regional Reanalyses*. In EGU General Assembly Conference Abstracts (pp. EPSC2016-15450).

WMO (2017): *WIGOS Metadata Standard*, WMO no. 1192, World Meteorological Organization, Geneva, 51pp.

WMO (2018a): *Guide to Instruments and Methods of Observation. Part I. Measurement of meteorological variables*, WMO no. 8, World Meteorological Organization, Geneva, 573 pp.

WMO (2018b): *Scientific Assessment of Ozone Depletion, Global Ozone Research and Monitoring Project*, WMO no. 58, Geneva, 588 pp.

Yang, C., and Coauthors, 2022, Independent Assessment of Essential Climate Variables: Lessons learnt from Copernicus Climate Change Service, *Bull. Amer. Meteor. Soc.*, Accepted for publication. https://doi.org/10.1175/BAMS-D-21-0109.1

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-21-0315.1.