ARTICLE IN PRESS

Weather and Climate Extremes xxx (xxxx) xxx

Contents lists available at ScienceDirect

Weather and Climate Extremes

journal homepage: http://www.elsevier.com/locate/wace

Fostering the development of climate services through Copernicus Climate Change Service (C3S) for agriculture applications

Carlo Buontempo[a,*], Ronald Hutjes[b], Philip Beavis[c], Julie Berckmans[d], Chiara Cagnazzo[e], Freja Vamborg[a], Jean-Noël Thépaut[a], Cedric Bergeron[a], Almond Samuel[a], Alessandro Amici[f], Selvaraju Ramasamy[g], Dick Dee[a]

[a] European Centre for Medium-Range Weather Forecasts, Shinfield Park, RG2 9AX, Reading, UK
[b] Wageningen University and Research, the Netherlands
[c] Telespazio VEGA UK, UK
[d] VITO – Flemish Institute for Technological Research, Mol, Belgium
[e] Institute of Marine Science, National Research Council (CNR-ISMAR), Rome, Italy
[f] B-Open Solutions, Rome, Italy
[g] Food and Agriculture Organization of the United Nations (FAO), Rome, Italy

ARTICLE INFO

Keywords:
Copernicus Climate Change Services (C3S)
Climate Data Store (CDS)
User-driven applications
Agriculture sector

ABSTRACT

To better understand and manage climate risks in climate-sensitive sectors such as agriculture, it is essential to have access to consistent and reliable data and information products. Tailoring these products to the needs of the users they want to serve facilitate informed decision-making and downstream applications. This requires an in-depth understanding of users' needs and the context in which these users operate. Considering the diversity of the economic sectors and their actors it is extremely challenging if not outright impossible to promote the emergence of climate services without empowering a plethora of intermediate users who can act as one of the steps in a potential long knowledge brokers chain that connect the climate data providers and the end-users. In this context, Copernicus Climate Change Service (C3S) has been designed around the Climate Data Store (CDS), a unique entry point to a huge variety of quality-controlled climate data and high-level utilities to process that data to develop user-driven applications. Through the Sectoral Information System, C3S has then developed a series of sector specific applications, which show how the infrastructure can be used to address specific users' needs. This paper presents the key elements of the CDS and selected cases of sectoral application of C3S in agriculture.

1. Introduction

Copernicus is the European Union's Earth Observation Programme, looking at our planet and its environment for the ultimate benefit of all citizens of Europe and beyond. Its main objective is to provide fully open-access data, information and services based on satellite Earth observations, in situ observations and modelling data. The programme is coordinated and managed by the European Commission (EC) but it is implemented through a series of agreements with international organisations. The European Centre for Medium Range Weather Forecasts (ECMWF) has been entrusted by the European Union to implement the Copernicus Climate Change Service, also known as C3S, as well as the Copernicus Atmospheric Monitoring Service (CAMS).

In C3S, the wealth of climate observations, measurements, analysis tools, methods and production of data and information for specific applications by users at different levels and for purposes are considered. These components form the basis for generating a wide variety of climate indicators aimed at supporting adaptation and mitigation in several sectors; for example, agriculture, water management, tourism, energy, and health (Fig. 1).

Climate is a critical factor in the lives and livelihoods of all people and in development as a whole (WMO, 2011). Decision makers are increasingly concerned by the adverse impacts of climate variability and change, and there is a growing demand for better climate services. Whilst our society desperately needs reliable climate information to inform policy decisions and define adaptation plans and strategies, most of the data available still come from activities that were born for research purposes and have only recently (if at all) left the academic

* Corresponding author.
E-mail address: carlo.buontempo@ecmwf.int (C. Buontempo).

https://doi.org/10.1016/j.wace.2019.100226
Received 7 June 2019; Received in revised form 9 September 2019; Accepted 17 September 2019
Available online 17 September 2019

Please cite this article as: Carlo Buontempo, *Weather and Climate Extremes*, https://doi.org/10.1016/j.wace.2019.100226

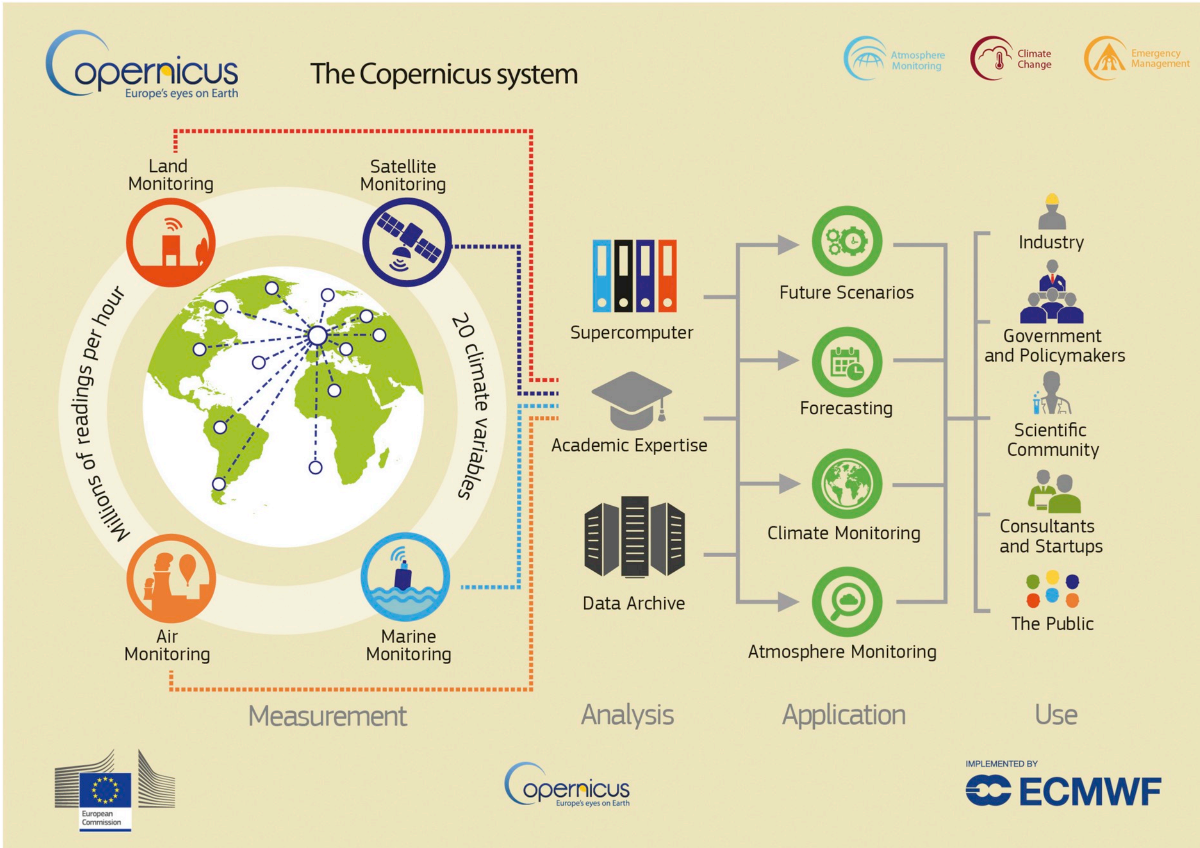

Fig. 1. Components of Copernicus service implementation – from measurement, analysis, application to use.

environment. C3S is stating to demonstrate the importance of having strong links between climate monitoring, analysis, application and use in various climate sensitive sectors.

The C3S is the first integrated network of its kind, built on cooperation between agencies across the globe and bring tangible evidence of using a data-driven approach to reduce uncertainty and risk. More than an additional satellite data service, C3S represents one of first coordinated attempts to operationalise the generation of climate data using the experience of satellite remote sensing and the routine production of numerical weather predictions as guiding principles.

There are three fundamental pillars behind the C3S vision:

1) a climate-resilient society can only be built if a sufficient number of professionals get involved in the development, distribution and use of climate-informed services;
2) in order for this to happen, it is necessary to eliminate the barriers which prevent the access and the easy manipulation of high-quality climate data;
3) in order for the quality of the service to be sufficiently high it is necessary to have an operational set-up which could curate the data and provide the necessary user support, example of good practice, and training.

The launch of the Global Framework on Climate Services (Hewitt et al., 2012) represented the global recognition of the fact that generating climate information is per-se not sufficient to drive a change in society. It is now widely recognised that more effort should be put both toward the definition of the information requirements and its interface with the users. The attempt to rapidly mainstreaming climate services and include it in all sectors of society will only succeed if a sufficient number of people become part of the generation, tailoring and distribution of climate services at all levels.

Whilst there are already a number of organisations which are providing climate services of some shape or form, their number is not sufficient to meet the growing demand for services which comes with the unprecedented climate in which we need to operate. Furthermore, it is not always clear whether such organisations are building on good quality data and procedure as independent references and quality attributes are typically not available.

The simple fact that the past is no longer a good proxy for what we can expect in the future has a number of significant implications for the development of climate services. This often materialise in the need of combining past climate observations with future predictions something which is difficult to do, if not outright impossible without a structured and timely production of the required datasets.

2. Climate Data Store (CDS)

2.1. Computational layers and workflows

The core of the C3S proposition is the Climate Data Store, the CDS (Thépaut et al., 2018). The CDS makes information about the past, present and future climate freely available, and functions as a one-stop shop for users to explore climate data. The CDS combines the functions of a distributed data centre with a set of services and facilities for users and content developers. This is a unified entry point to a wealth of quality-controlled climate data which can be delivered to the users in a reliable and standardised way irrespectively of where on the planet the data is actually stored (Raoult et al., 2018). Each entry into the CDS catalogue comes with quality control information designed to allow users to assess the suitability of a dataset for a specific application. The CDS is designed to allow experts to develop their own data post-processing close to the data store, the result of which is a much reduced need for downscaling huge data sets. The CDS contains a wealth

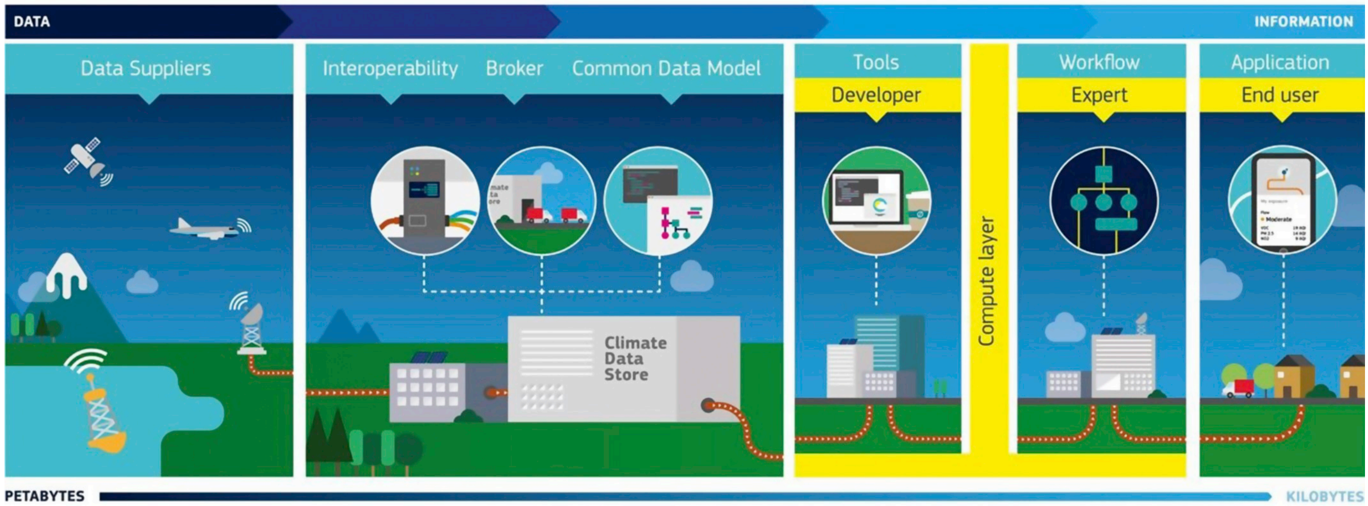

Fig. 2. Climate data store – data and information flow from observations, archiving, analysis and applications.

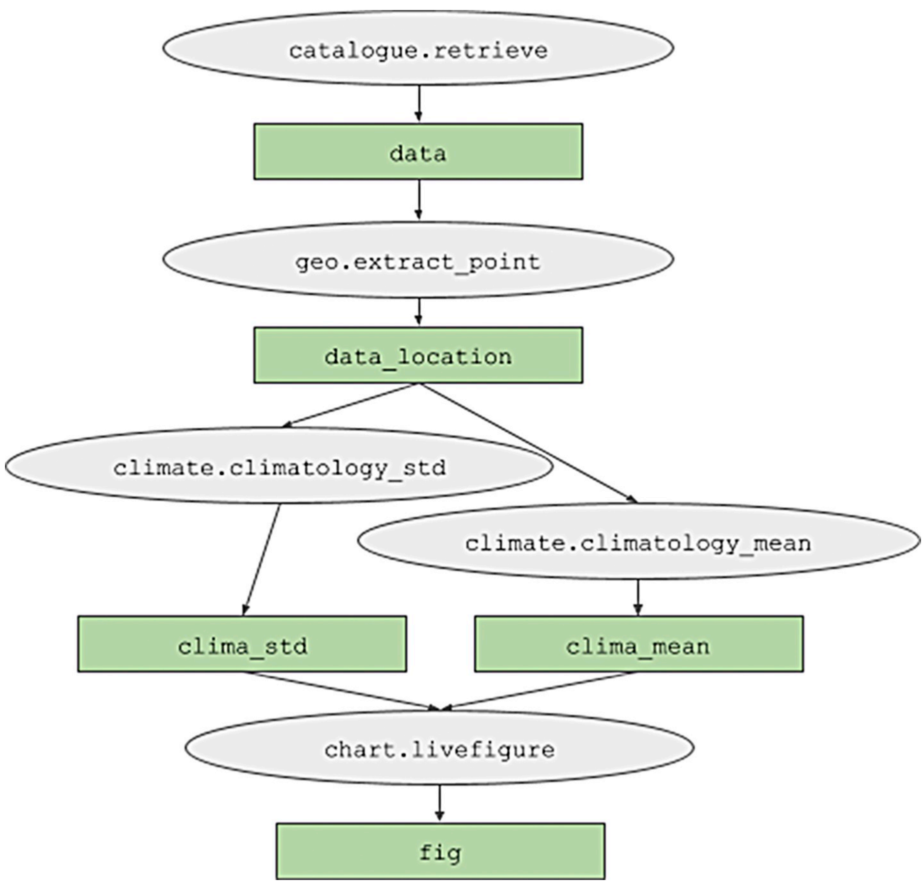

Fig. 3. A top level flow diagram of a workflow developed on the Climate Data Store.

of observations, reanalyses, climate projections and seasonal forecasts. Time series of in-situ observations, reprocessed climate data records from satellites, and output from climate models, including projections and searchable metadata are included in the CDS and users have access to all the necessary climate data and information (Fig. 2).

One of the most informative features of the C3S approach is the inclusion of a computational layer in the setup of the CDS. Given that the size of the majority of the datasets available on the CDS catalogue is typically measured in PBytes, a computational layer becomes a necessary tool for allowing the users to interact with the data efficiently. The CDS computation layer, the CDS Toolbox, provides a series of tools that perform basic operations on the datasets, such as differences or re-gridding, as well as statistical computations such as means or standard deviations.

Such atomic tools can then be combined into more elaborated workflows and present the results graphically on the CDS web site (see Fig. 3). The possibility to develop web-based applications implicitly hides many technical complexities that can significant hinder the development of users facing services. Thanks to the CDS application, developers do not need to worry about the physical location of the datasets, their access methods, formats, units, etc. and focus instead on algorithms.

This entails a significant paradigm shift from ‘downloading the data to your application’ to ‘building your application on top of the data’.

In the CDS, a workflow is a piece of software that acts on the climate data available to generate data or visual designed to meet the requirements of specific users. Anyone who has an account on the system (freely available) can write a workflow. Those workflows which are considered to be of general use can be made public for other to run, re-use or modify. In the CDS parlance these public workflows are called applications.

2.2. CDS toolbox and user-driven applications

The CDS became publicly available at the end of June 2018 and is continuously being extended in terms of datasets and improved in terms of functionalities to subset, process, interrogate and visualise climate data. Once fully established it is expected that developing workflows will become a common way for a vast community of users to deal with their climate data requirements. To facilitate the development of user-driven workflows, C3S promoted the development of exemplary applications to show how the whole infrastructure could be used to address specific sectoral needs.

The delegation agreement between the European Commission and ECMWF explicitly states that applications would need to be developed for ten general sectors including water, agriculture and energy. In response to this requirement ECMWF signed a series of contracts with several organisations with specific expertise in these areas of interest, to develop a set of applications which meet sectoral users’ requirements.

A key requirement in these contracts was the need to use only the datasets available on the CDS catalogue and develop processing tools exclusively based on tools available on the CDS Toolbox. Whilst such an objective was practically impossible to meet during the proof of concept stage (2016–2018) because no CDS was yet available at that point, the transition to operations that took place in October 2018 translated into the development of fully working applications based on the CDS technology.

One of the key advantages of the approach is given by the inherent transparency of the products developed by C3S. Given the growing importance climate change has on our everyday activities, it is essential to ensure that any statement, product or outputs could be traced back to reliable sources, tools and applications. Having a product based on a public workflow simply allows this kind of public scrutiny.

3. Sectoral Information System (SIS)

Climate variability and change place significant stress on the agriculture sector. Highly variable seasonal rainfall, increasing trends of temperature and extreme climate events together with growing demand for food places additional pressure on the food systems and the natural resources. Innovative climate services, adaptation strategies, and sustained policy support are necessary to address the challenges of attaining sustainable agriculture and food security (FAO, 2019).

The C3S Sectoral Information Systems aims to provide data, tools and information to support public and private sectors in their climate sensitive decisions and to encourage businesses to develop downstream applications to address specific needs. Climate sensitive sectors such as agriculture are affected by climate variability and change. C3S readily applicable data and tools help experts and policy makers deal with climate-related challenges. Creating tailored data products are the priority, but custom-made tools are needed to help the decision-makers chose the right decisions for their sectors (ECMWF, 2019).

Climate impacts are location specific and thus, there is a broader recognition of the importance of localized climate services at decentralized levels with an objective to bridge the gap between the climate information providers and the information users (FAO, 2019). Within this context, SIS supports development of downstream applications by promoting development of tools for real-world problems, demonstrating data in action. Through the CDS, anyone can build maps and charts, and those with more experience in software development can apply their own post-processing to create unique products.

The C3S has demonstrated the benefits through climate data tools for each of the climate-sensitive sectors and supported case studies to show how the data can be applied to sector specific problems related to climate change. The case studies demonstrate how climate data can be used to address challenges in many different sectors, including tourism, energy, water management, coastal areas, health, insurance, transport and agriculture. Whilst it is clearly out of the scope of this paper to present all the applications that have been developed at present, it may be worth focusing on a couple of examples to show how the infrastructure works in practice. Given the focus of this special issue, a few agriculture relevant examples have been selected and presented in section 4 of this paper.

4. Application of C3S: selected case studies in agriculture

4.1. Characterizing grape vine growing regions and suitable varieties

Wine production has a predominant economic, social and environmental relevance in Europe, which account for 62% of the global production and about 46% of area under vines in 2018 (OIV, 2019). Climate is one of the main factors controlling winegrape production (Malheiro et al., 2010). Studies addressing the influence of climate variability and change in viticulture are particularly pertinent, as climate is the leading factor for grapevine yield and quality (Santos et al., 2010). Bioclimatic indices describing the suitability of a particular region for wine production are a widely used zoning tool (Malheiro et al., 2010). In this case study, Winkler Index (Amerine and Winkler, 1944) and Huglin Index (Huglin, 1978) were used to characterize grape vine growing regions.

The C3S application case comes from a proof of concept study led by Telespazio. The focus of this case study was the winemaking industry and in particular the challenge the industry faces in maintaining a standard quality of wine in a changing climate. A major factor in the annual growth of grapes is the accumulated temperature over the growing season above a threshold of 10 °C (Growing Degree Days). In general, higher temperatures tend to advance growth, which can have an adverse impact on the quality and typicality of the wine, threatening traditional methods. On the other hand, different varieties of vine are adapted to different climates, so growers must consider carefully their future planting. These were some of the issues facing our case study partner at Buzet Appellation d’Origine Contrôlée (AOC), S.W. France. Like other AOCs, it has a strict geographical boundary as well as compulsory technical specifications (allowed grape varieties, maximum yield, regulation of irrigation, control of alcohol content, etc.). Fortunately, experts at the Cave des Vignerons de Buzet are taking a scientific and pragmatic approach to these challenges.

Specialised indicators have been developed for viticulture, including the Winkler Index (Amerine and Winkler, 1944) and Huglin Index (Huglin, 1978), which have been used to classify wine growing regions and suitable varieties of grape vine. The CDS contains a wealth of data on surface air temperature (past, present and its possible future evolution), and the algorithms of Winkler and Huglin indices quite easy to implement in the CDS toolbox environment in order to produce a useful interface by adopting steps presented in Fig. 3.

For each day over the grapevines growing season, the Growing Degree Day (GDD) was estimated, according to the amount the average temperature exceeds the threshold of 10 °C. The threshold is derived from empirical observations that grapevines cannot grow below it. Variety of grapevines are associated to suitable ranges of the summed GDD that represent the Winkler Index. For example, Champagne grape

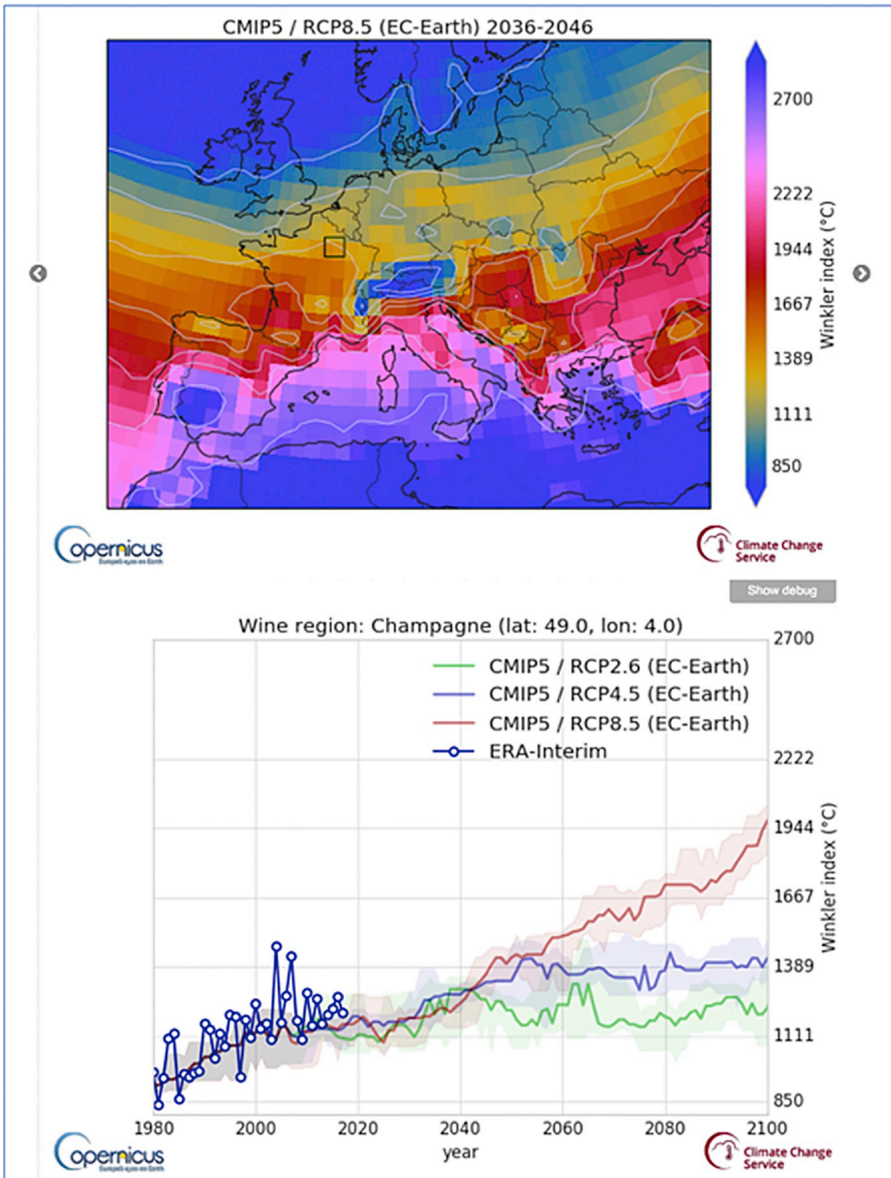

Fig. 4. The interactive display developed for the wine industry. The top plot shows the expected Growing Degree Days maps for Europe for the period 2036–2046. The plot below shows the evolution of the Winkler index over time for one of the key wine-producing regions (in this case the Champagne region) for three different RCPs.

varieties require a WI between 850 °C and 1111 °C. The map in Fig. 4 represents the Winkler index in °C for each grid box as an estimate in a climate change scenario after 2050 from one specific Climate Model (EC-Earth).

The timeseries in Fig. 4 represents the evolution of the Winkler index in the Champagne production region, with climate projections showing that in a "business as usual" scenario (red line), that region will not be favourable anymore to produce Champagne after 2060. On average, climate projections indicate a general northward shift of the wine production region in Europe. In order to estimate the Winkler Index, temperature projections at surface have been bias-adjusted by using ERA-Interim reanalyses (blue line in the time series figure).[1]

Overall, winegrapes are a climatically sensitive crop whereby quality production is achieved across a fairly narrow geographic range (Jones and Alves, 2011). The indices show considerable changes in Europe by middle of this century under climate change. Detrimental impacts on grapevine growth and development and on resulting wine yield and quality parameters are projected for southern Europe due to the

[1] The application first retrieves surface temperature data from both the reanalysis, and the climate projections from CMIP5 ensemble. Both datasets are then cropped to take only the data for Europe. A delta change factor approach is then applied to the data to generate a time-series of temperature values for future periods. The Growing Degree Day index is then calculated, averaged over 10 years interval and finally displayed on a map alongside a smoothed time-series for specific product regions.

Table 1
List of climate indicators (partial) produced by Global Agriculture Service of C3S.

Climate Indicators
• Biologically Effective Degree Days
• Growing Season Length
• Maximum number of consecutive dry days
• Maximum number of consecutive frost days
• Cold Spell Duration Index
• Maximum number of consecutive summer days
• Maximum number of consecutive wet days (Wet spell)
• Mean of diurnal temperature range
• Frost Days & Ice Days
• Heavy precipitation days
• Very heavy precipitation days
• Precipitation sum
• Wet Days
• Simple Daily Intensity Index
• Mean of daily mean temperature
• Mean of daily minimum temperature
• Minimum value of the daily minimum temperature
• Maximum value of the daily minimum temperature
• Tropical nights
• Mean of daily maximum temperature
• Minimum value of daily maximum temperature
• Maximum value of daily maximum temperature
• Warm Spell Duration Index
• Warm and wet days

increased cumulative thermal and dryness effects during the growing season. Conversely, western and central European regions might benefit from future climate conditions through higher wine quality and new potential areas for viticulture. This general assessment is also supported by previous findings (Stock et al., 2005; Malheiro et al., 2010).

4.2. Characterization of the future distribution of vector species

Climate change directly impacts human health through long-term changes in rainfall and temperature, climatic extremes (heatwaves, hurricanes, and flash floods), air quality, sea-level rise in lowland coastal regions, and multifaceted influences on food production systems and water resources (IPCC, 2014). Climate has a direct impact on the dynamics of a subset of infectious diseases, including vector-borne diseases (VBDs), some water-borne diseases such as cholera, and other soil-borne and food-borne pathogens (McIntyre et al., 2017).

A recent review on impact of recent and future climate change on vector-borne diseases by Caminade et al. (2019) concluded that there is a wealth of evidence that climate change has already affected pathogen–vector–host systems, and there are many examples of the early impacts of climate change on animal VBD burden, while the most severe VBD outbreaks affecting humans tend to be affected by a myriad of complex socioeconomic factors and climate. The review further demonstrated that the spread of vectors and the pathogens they transmit worldwide has been anticipated and similar trends are likely in the future if humans fail to mitigate and adapt to climate change and if drug and insecticide resistance continue to rise.

As part of Copernicus Climate Change Service, VITO, analysed the heat exposure and heat-waves for characterisation of the future distribution of specific vectors of diseases. The focus was on the Aedes Albopictus, also known as tiger mosquito, which has become a common occurrence in most part of Southern Europe (European Centre for

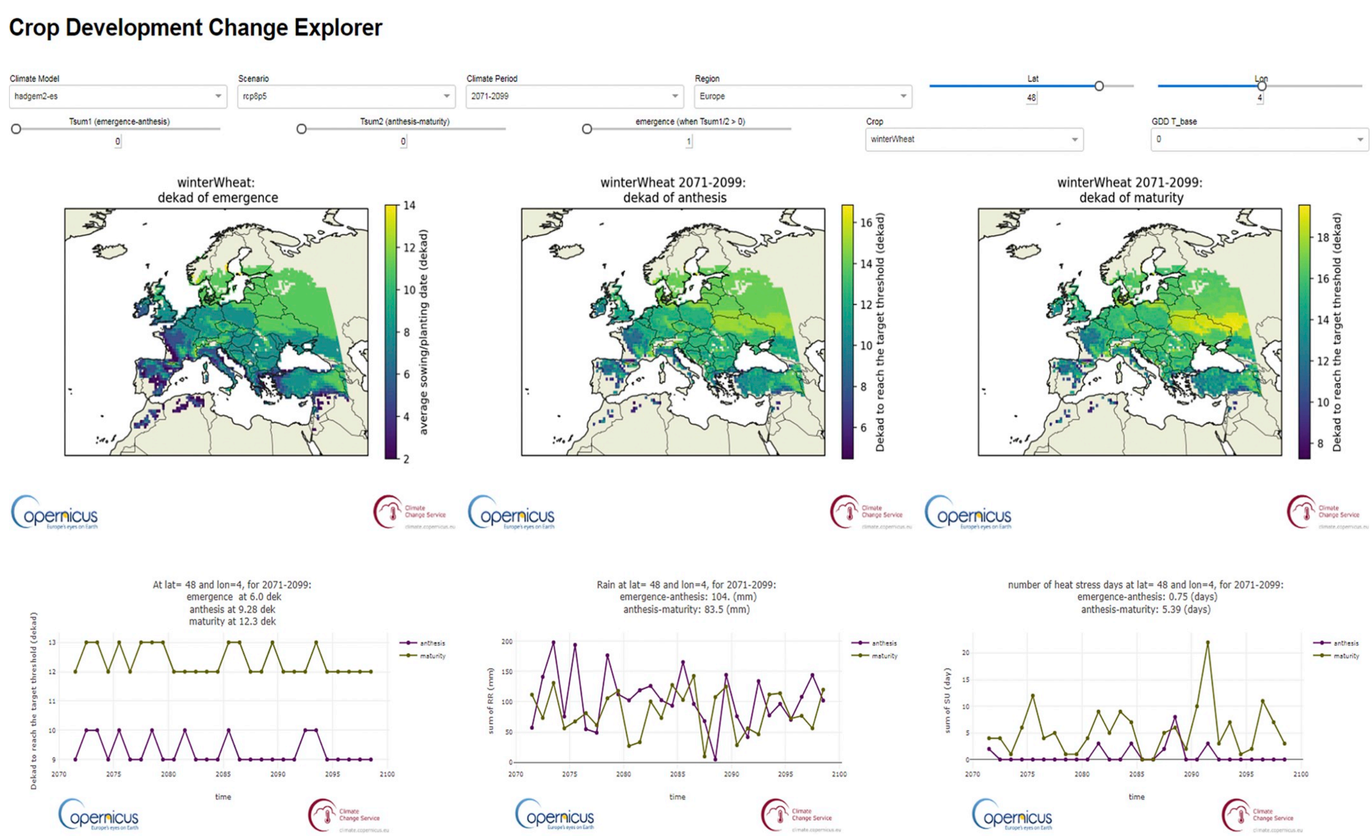

Fig. 5. The interactive display for the cultivar developers. Crops cultivars are defined in terms of thermal requirements and cropping calendar, parameters for which are either defined by the crop selected or set manually by the user. The top rows show maps for the selected region, time horizon and climate scenario of respectively (left to right): dekad of emergence, dekad of anthesis (flowering) and of maturity (ready to harvest). The bottom left figure shows the dekad that crops reach anthesis and maturity for the selected location; the middle figure the amount of rain in the vegetative and reproductive stage and the right figure the number of heat stress days for the same development stages.

Disease Prevention and Control and European Food Safety Authority, 2018). Indeed, such a mosquito is the vector for a number of important human pathologies such as the dengue fever and the Chikungunya in Europe.

The algorithm, which was implemented on the CDS by the contractors, was built around a suitability function based on annual precipitation and the average temperature in January and during the summer period JJA (ECDC, 2009). A suitability distribution for Europe is demonstrated for a 40-yr past period from 1979 to 2018 and for the future climate until 2 100.

Although the application does not have an immediate relevance to agriculture, the approach that was followed in the algorithm is sufficiently generic to potentially cover, without significant modifications, several other vectors, including those pests and diseases affecting agricultural productivity, In this respect, it would be enough to identify the relevant parameters, their thresholds and the function type to define a vector suitability index which the user could then easily visualise.

4.3. Evidence-based policies and planning in agriculture sector

The third example is represented by the Global Agriculture service element developed for C3S by Wageningen Environmental Research. In this case a much more targeted approach to the policy, research and business communities in the agricultural sector has been followed, potentially addressing the respective needs for developing food sector adaptation policies, breeding of more climate resilient crop cultivars, or informing agricultural commodity traders. The main outputs of the case study on agriculture can be clustered in four main categories. The first one is composed of climate indicators for agriculture (Table 1). These are the typical parameters that a standard crop model requires as climate inputs for the calculations. Growing degree days, frost days, potential evapotranspiration are some of the clearest examples of this category of outputs.

The second cluster is composed of the bias-adjusted reanalysis data, a high-resolution (9 km global) version of the ERA5 (Hersbach and Dee, 2016) reanalysis covering most of the near surface parameters and reducing some of the most significant systematic biases. It is C3S intention to make ERA5 stream available with minimal delay (less than 5 days). This dataset will allow crop simulations to be run with a physically consistent dataset representing the present conditions in near real time. The third stream combines satellite observations of crop productivity and crop evaporation proxies with concurrent climate data, to provide historic near real time assessments of crop yield and water use. The fourth stream uses climate data representing all time horizons present in C3S (historical, seasonal forecasts and climate change projections) to drive a hydrological model providing agriculture relevant indicators of available water resources.

A second level of outputs demonstrates the added value of the C3S approach, as it is constituted by the crop specific interpretations of the variables generated by all four data streams, using global crop distribution maps, crop calendars and first order crop development parametrizations. Outputs such as development stage and total above-ground production will be provided routinely for soybean, wheat, rice and maize. An example of the output of this data stream is presented in Fig. 5. Both the data for all streams, and the applications for calculating the specific indicators in stream 1 are expected to become publicly available on the CDS during summer 2019.

5. Conclusions

The C3S represents more than just one of the six services of the Copernicus programme. Making a large quantity of high-quality data freely available for all sort of applications has the potential to disrupt the current way of developing climate services and put new solid bases on how to build a climate resilient society.

Given the size of the datasets it would impractical if not impossible for users to handle those without a suitable interface able to effectively transform petabytes of raw data into a few kilobytes of relevant information. This is what the CDS and its Toolbox are designed to do. Because the uptake of such a novel approach to climate services by the targeted communities of practice (e.g. agriculture) will take some time, a series of sectoral demonstrators have meantime been developed and implemented by ECMWF through target contracts. For similar reasons, a User Learning Service is also in development. This will include knowledge resources that address both ends of the chain, i.e. the various data sets provided, as well as potential applications in each of the sectors, among which global agriculture.

The examples presented in this paper show how raw climate variables can be transformed into agricultural specific indicators through a traceable, reproducible and transparent methodology that other people can readily use or follow as examples when developing their own analysis. One of the inherent advantages of this approach is that once a user relevant algorithm has been developed for a specific data stream, the same piece of code can easily be copied and redeploy for a different data stream or a different geographical area, to generate new indicators and user relevant information.

In order to support climate risk management in agriculture and to ensure sustainable agricultural development, it is necessary for a network of professionals capable of developing applications able to incorporate climate observations and trends into the tactical and strategical decisions. The Copernicus Climate Change Service in general and the climate data store in particular have been designed with this aim in mind but in order for this vision to be fulfilled it is necessary for the agricultural experts to start developing their data-based solutions. What we have shown here for grape vine in Europe can be replicated for other cultivars and to other regions. The newly available data and infrastructure can support better management of climate risks in agriculture.

Disclaimer

The designations employed, the presentation of material, boundaries of the maps, mention of specific companies or products of manufacturers and the entire content and the views expressed in this paper are those of the author(s) and do not necessarily reflect the views or policies of the organisations to which they are affiliated.

Acknowledgments

The activities described in this paper have been funded by the Copernicus Climate Change Service. ECMWF implements the Copernicus Climate Change Service and the Copernicus Atmosphere Monitoring Service on behalf of the European Commission. The authors would like to thank VITO's subcontractors: AVIA-GIS from Belgium, the Centre for Health Education and Diseases Prevention from Lithuania, the National Public Health Institute from Hungary and the Department of Epidemiology Lazio Regional Health Service from Italy for the successful collaboration. We would also like to thank Dr. Jérôme Helbert from Telespazio France, for leading the case study on viticulture, and Sébastien Labails, Viticulture Innovation at the Cave des Vignerons de Buzet.

References

Amerine, M.A., Winkler, A.J., 1944. Composition and quality of musts and wines of California Grapes. Hilgardia 15 (6), 493–675. http://hilgardia.ucanr.edu/fileaccess.cfm?article=152225&p=PXFBTI.

Caminade, C., McIntyre, K.M., Jones, A.E., 2019. Impact of recent and future climate change on vector-borne diseases. Ann. N. Y. Acad. Sci. 1436 (1), 157–173.

European Centre for Disease Prevention and Control (ECDC), 2009. In: Development of Aedes albopictus Risk Maps. Technical Report 0905. See. http://ecdc.europa.eu/en/publications/Publications/0905_TER_Development_of_Aedes_Albopictus_Risk_Maps.pdf.

European Centre for Medium-Range Weather Forecasts (ECMWF), 2019. Sectoral information system (SIS) – tools for climate-sensitive industry sectors. In: Copernicus

Climate Change Services (C3S). European Centre for Medium Range Weather Forecasts (ECMWF), UK (Reading).

European Centre for Disease Prevention and Control and European Food Safety Authority Mosquito maps [internet] Stockholm (ECDC), 2018. Available from: https://ecdc.europa.eu/en/disease-vectors/surveillance-and-disease-data/mosquito-maps.

Food and Agriculture Organization of the United Nations (FAO), 2019. C. In: limate Services for Food and Agriculture – Enabling Use of Climate Ifnromation for Adaptation to Climate Variability and Change in Agriculture and Food Security. Food and Agriculture Organization of the United Nations (FAO), Rome. http://www.fao.org/3/a-az620e.pdf. (Accessed 12 May 2019).

Hersbach, Dee, 2016. https://www.ecmwf.int/en/newsletter/147/news/era5-reanalysis-production.

Hewitt, C., Mason, S., Walland, D., 2012. The global framework for climate services. Nat. Clim. Chang. 2 (12), 831–832.

Huglin, P., 1978. Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole. C. R. Académie d'Agriculture (Acad. Agric.) 1117–1126, 1978.

Intergovernmental Panel on Climate Change (IPCC), 2014. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability (Field C.B., Barros V.R., Dokken D.J., et al). Part A: Global and Sectoral Aspects Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY.

Jones, G.V., Alves, F., 2011. Impacts of climate change on wine production: a global overview and regional assessment in the Douro Valley of Portugal. Proceedings of the Global Conference on Global Warming 2011, 11–14 July 2011, Lisbon, Portugal.

Malheiro, A., Santos, J.A., Fraga, H., Pinto, J.G., 2010. Climate change scenarios applied to viticultural zoning in Europe. Clim. Res. 43, 163–177.

McIntyre, K.M., Setzkorn, C., Hepworth, P.J., Morand, S., Morse, A.P., Baylis, M., 2017. Systematic assessment of the climate sensitivity of important human and domestic animals pathogens in Europe. Sci. Rep. 7, 7134.

Organisation Internationale de la Vigne et du Vin (OIV), 2019. In: State of the Vitiviniculture World Market. State of the Sector in 2018. April 2019. http://www.oiv.int/js/lib/pdfjs/web/viewer.html?file=/public/medias/6679/en-oiv-state-of-the-vitiviniculture-world-market-2019.pdf.

Raoult, B. Bergeron C., López Alós, A., Thépaut, J.N., Dee, D., 2018. https://www.ecmwf.int/en/newsletter/151/meteorology/climate-service-develops-user-friendly-data-store.

Santos, J.A., Malheiro, A.C., Karremann, M.K., Pinto, J.G., 2010. Statistical modelling of grapevine yield in the Port Wine region under present and future climate conditions. Int. J. Biometeorol. https://doi.org/10.1007/s00484-010-0318-0.

Stock, M., Gerstengarbe, F.W., Kartschall, T., Werner, P.C., 2005. Reliability of climate change impact assessments for viticulture. Proceedings of the VII international symposium on grapevine physiology and biotechnology. Acta Hortic. (Wagening.) 689, 29–39.

Thépaut, J., Dee, D., Pinty, B., 2018. The Copernicus programme and its climate change service. In: IGARSS 2018 - 2018 IEEE International Geoscience and Remote Sensing Symposium(2018), pp. 1591–1593. https://ieeexplore.ieee.org/document/8518067/authors#authors.

World Meteorological Organization (WMO), 2011. Climate Knowledge for Action: A Global Framework for Climate Services – Empowering the Most Vulnerable. World Meteorological Organization (WMO) publication No.1065. WMO, Geneva.