

EARTH SYSTEM SCIENCE

Looking back on 10 years of climate monitoring by the Copernicus Climate Change Service

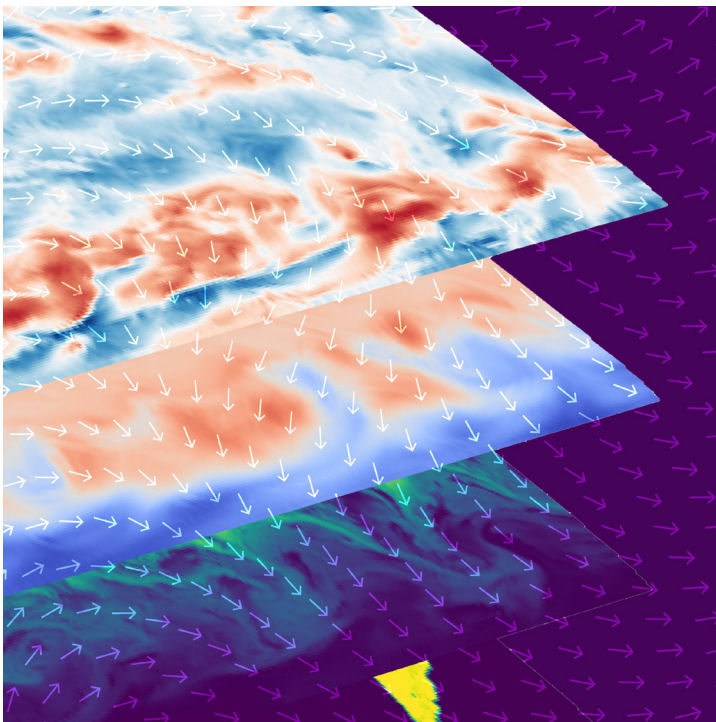


Illustration of the Anemoi ERA5 dataset

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Looking back on 10 years of climate monitoring by the Copernicus Climate Change Service

10 years that are the ten warmest calendar years on record for the globe

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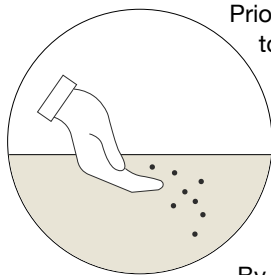
In September 2015 the Copernicus Climate Change Service (C3S) published its first temperature summary (<https://climate.copernicus.eu/average-surface-air-temperatures-august-2015>), covering global and European statistics for the previous month and year. Stemming from a discussion between reanalysis scientists and those with communications roles at ECMWF, it was the first public climate monitoring communication from C3S. It built on the vision that climate monitoring in near-real time with a global and pan-European perspective would be one of the key pillars of C3S, complementing activities at the national level and to be implemented by ECMWF in cooperation with contracted partners across Europe.

While workflows and communication products have evolved, many of the underpinning thoughts and approaches remain the same. The changes have been driven by an increased cross-community awareness of climate monitoring possibilities and data availability, but also by user and stakeholder demand.

The scientific and technical team behind the monitoring has also evolved over time, from a few individuals across several parts of C3S, growing into a dedicated 'Climate Intelligence' team within ECMWF and leveraging expertise across the Copernicus community. In this article, this team reflects on ten aspects that have shaped C3S monitoring activities and provides a glimpse into how we are imagining the future.

Preparing the ground

"By 2015 we were sure our data were suitable for monitoring key aspects of Earth's changing climate and had been charged with implementing C3S' mission to provide consistent and authoritative information on climate change. C3S colleagues have done an outstanding job of evolving our initial monthly temperature updates into a comprehensive and accessible set of monthly, seasonal and annual reports." Adrian Simmons, writer of the first bulletin.



Prior to 2015 and the launch of C3S-led activities, ECMWF was already contributing to various international monitoring efforts, such as the Bulletin of the American Meteorological Society State of the Climate and World Meteorological Organization (WMO)-led reports. Working with others in the climate community, ECMWF had invested heavily in producing reanalyses that had been proven, as documented in the scientific literature and in the 4th assessment cycle of the Intergovernmental Panel on Climate Change (IPCC AR4), to be fit for monitoring some of the key atmospheric variables.

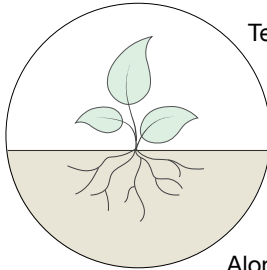
By 2015, the then state-of-the-art reanalysis ERA-Interim was thus deemed to be reliable for monitoring several variables, including global surface air temperature. Major efforts had also been invested by the in situ and space-based observational communities to produce quality-assured products, paving the way for multiple lines of evidence to be used in climate monitoring. These developments laid the foundations for climate monitoring to become a key pillar of C3S.

The temperature summary, published monthly from September 2015 onward, has grown over time to include more details on Europe and the polar regions. Separate summaries for hydrological variables and sea ice were introduced in 2017, and the name Climate Bulletin (<https://climate.copernicus.eu/climate-bulletins>) was adopted soon after. Timely delivery has been a driving factor, and this product continues to mostly rely on reanalysis, which remains one of the first climate-quality datasets to be updated each month for the relevant variables. The most recent additions to the Climate Bulletins include the monitoring of sea-surface temperature, daily variations in some variables, and occasional inclusions of additional topics of interest. Other more technical but time-consuming developments include the transition from ERA-Interim to ERA5 in 2019 and to the 1991–2020 reference period in January 2021.

From pilot to flagship product

“Having grown over time from a collection of analyses and articles to a dedicated report, the Global Climate Highlights, published each January, provide timely and concise information on the climate of the previous year. The relevance of providing fit-for-purpose global climate monitoring products is internationally acknowledged as an essential instrument to inform policy making strategies.” Francesca Guglielmo, Global Climate Highlights lead editor.

The final Climate Bulletin of each year, published in early January, became a key opportunity to look back on global temperatures of the previous calendar year and how they compare to the recent past and to the pre-industrial period (Figure 1). The near-real-time nature of ECMWF’s reanalyses, supported by other global temperature datasets, allows C3S to be the first to be able to report on the previous year’s global temperature.



Temperature monitoring remains crucial, especially in the context of the Paris Agreement. Even before its adoption at the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP) in 2015, global temperature was already considered a key indicator for human-induced climate change. The Paris Agreement reinforced this by setting specific thresholds: preferably below 1.5°C and well below 2°C above pre-industrial levels.

Alongside annual temperature averages, our approach has also been to provide five-year averages in line with the regular UNFCCC Global Stocktakes. Our team continues to refine the way ERA temperatures relate to the pre-industrial period, aligning as closely as possible with the latest IPCC reports, WMO and climate community activities.

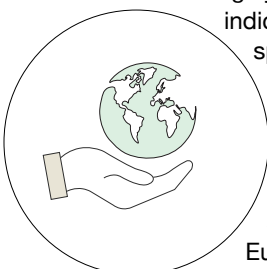
This end-of-year release has gradually grown in scope, starting with the inclusion of trends in greenhouse gas concentrations for the 2018 edition, in collaboration with the Copernicus Atmosphere Monitoring Service. Since the 2023 edition, it completed its transformation to what is now called the ‘Global Climate Highlights’ (<https://climate.copernicus.eu/global-climate-highlights>) (GCH). This report includes analysis of global surface air and sea-surface temperature, greenhouse gas concentration trends and other variables relevant to significant events or topics of the previous year.

The GCH 2024 marked an exception in that Berkeley Earth, ECMWF, NASA, NOAA, the UK Met Office and the WMO made a concerted effort to coordinate the release of their data, highlighting the exceptional conditions experienced during 2024.

Expanding to an Earth system perspective

“Drawing on the expertise of around 100 scientists across Europe and the rest of the world, the annual European State of the Climate report combines key insights from around 40 different datasets covering a huge range of topics and variables. The ESOTC presents complex climate data in an accessible and engaging way for a broad audience.” Rebecca Emerton, European State of the Climate lead editor.

While global temperature has become the flagship indicator of the Paris Agreement, the Earth system is complex. This is reflected in the Global Climate Observing System (GCOS) concept of Essential Climate Variables (ECVs). ECVs have underpinned the C3S provision of data from reanalysis, in situ and especially the satellite observing system since the start. In 2017, GCOS also defined a set of seven key climate



indicators, based on a subset of ECVs, with the necessary quality and sufficient spatiotemporal coverage to describe the imprint of climate change globally and holistically.

After consultation with stakeholders, such as the European Environment Agency, these GCOS indicators, as well as the Climate Bulletins of 2017, were taken as a starting point for our team, other colleagues at ECMWF and C3S’ in situ and satellite ECV data providers to design and produce what became the first European State of the Climate (ESOTC) report (<https://climate.copernicus.eu/ESOTC>).

This first edition, published in 2018, established the format of a web-based report complemented by a PDF summary, and provided a blueprint for the production workflow, including internal and external scientific review. It covered five global and four European indicators, and included five sections describing the European climate of 2017 in a historical context, mostly focusing on the variables already covered in the Climate Bulletins. The ESOTC is published a few months after the end of the reporting year, in April, and this means more datasets, including not only reanalyses, but also in situ and satellite data and model reconstructions covering most or all of the previous calendar year,

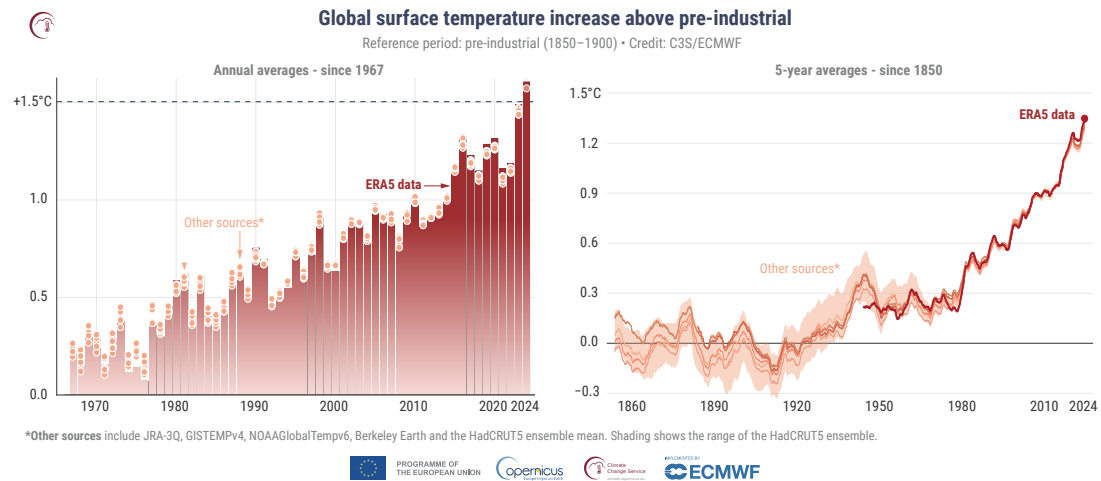


FIGURE 1 Global surface air temperature increases relative to the average for the 1850–1900 pre-industrial reference period, based on several global temperature datasets shown as annual averages since 1967 (left) and as 5-year averages since 1850 (right). Credit: C3S/ECMWF. First published in the C3S Global Climate Highlights 2024.



FIGURE 2 Illustration of how the representation of some of the key messages of Spotlight sections has evolved over time in the ESOTC. Examples from the 2018, 2021 and 2024 reports.

are available. This allows information on a much wider range of variables from across the Earth system compared to the monthly Climate Bulletins and annual GCH, which are published in near real-time. Since the second edition, known as ESOTC 2018 (describing the 2018 calendar year), the ESOTC now contains around 12 monitoring sections for Europe, ranging from more typical meteorological variables, such as temperature and precipitation, to variables that more closely represent impacts on human and

natural systems, such as measures of wildfire danger and emissions, river flow, heat stress and even wind and solar power potential. The ESOTC also includes two or three ‘Spotlight’ sections, which focus on topics unique to the year, such as extreme events, significant regional contrasts or other notable topics. Examples include ‘dry and warm spring and summer’ (<https://climate.copernicus.eu/dry-and-warm-spring-and-summer>) in the ESOTC 2018, ‘the warm winter of northeastern Europe’ (<https://climate.copernicus.eu/esotc/2020/warm-winter>) in the ESOTC 2020 and ‘flooding’ (<https://climate.copernicus.eu/esotc/2024/flooding>) in the ESOTC 2024, particularly associated with storm Boris in central and eastern Europe and flooding in Valencia.

Over the eight editions of the ESOTC, major changes in terms of content have been introduced. For instance:

- The ESOTC 2020 saw the inclusion of a global section, dedicated sections focusing on the Arctic and the separation of the C3S Climate Indicators into their own product.
- The Climate Indicators have increased in number, in most cases covering the globe, Europe and the Arctic, and are described in more detail. The current Indicators are: surface air and sea-surface temperatures, glaciers, ice sheets, ocean heat content, sea ice, sea level, and greenhouse gas concentrations and fluxes.
- Since the ESOTC 2023, which was the first jointly produced with the WMO (described in the collaboration section), the report has included a ‘Climate policy and action’ subsection, covering new topics each year, such as extreme weather and human health, or climate adaptation and resilience to weather and climate extremes.
- The ESOTC 2024 saw one of the biggest overhauls yet, significantly reducing the volume of content and introducing a more streamlined and concise main report. This included removing the global section, as much of this content is now covered by the GCH and in the Climate Indicators. For the first time, the full report was published not only as a microsite, but also as a unified PDF, with a much shorter summary, and the introduction of new resources, such as a graphics gallery.

Providing accessible and attractive reports and products

A key consideration across all products, but especially with the ESOTC as a testing ground, is the wish to provide information, text and visuals that are understandable by a variety of non-specialist users and readers. For example, the full ESOTC report goes through several iterations of editorial review by our copy editor to ensure the language is accessible and to remove or explain jargon. To provide a

succinct overview of the key messages, a report summary is also created (Figure 2).

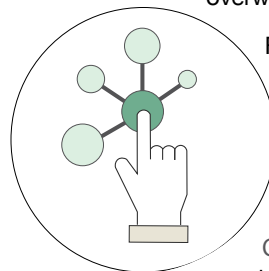


To highlight key findings, several products have been developed in collaboration with the ECMWF communication team and external collaborators, such as infographics, animations, videos, social media materials, press briefings and much more.

Beyond reporting – interactive exploration of data and insights

“Climate Pulse has led to a new cohort of C3S users having access to climate monitoring data on demand via a simple visual interface and application accessible through different platforms.” Julien Nicolas, scientific lead for Climate Pulse.

An overarching objective of our Climate Intelligence team has been to increase the accessibility of C3S climate data by developing products which offer a tailored user journey across our various climate datasets to a broad audience. The aim is to enable users to explore the data behind our products at their own pace and according to their personal interests, with no need to download and analyse the files. Interactivity is one way of doing this, allowing us to display multiple layers of information at once while ensuring users are not overwhelmed by content.



For example, 2024 saw the introduction of interactive and responsive charts within the ESOTC. Enabling users to explore data directly within the charts and to add extra layers of information, these features have since also become an integral part of the Climate Bulletins and the GCH.

Another interactive development introduced in 2024 was the web application Climate Pulse (<https://pulse.climate.copernicus.eu/>) (Figure 3). This application extends beyond the monthly means and anomalies typically considered in the Climate

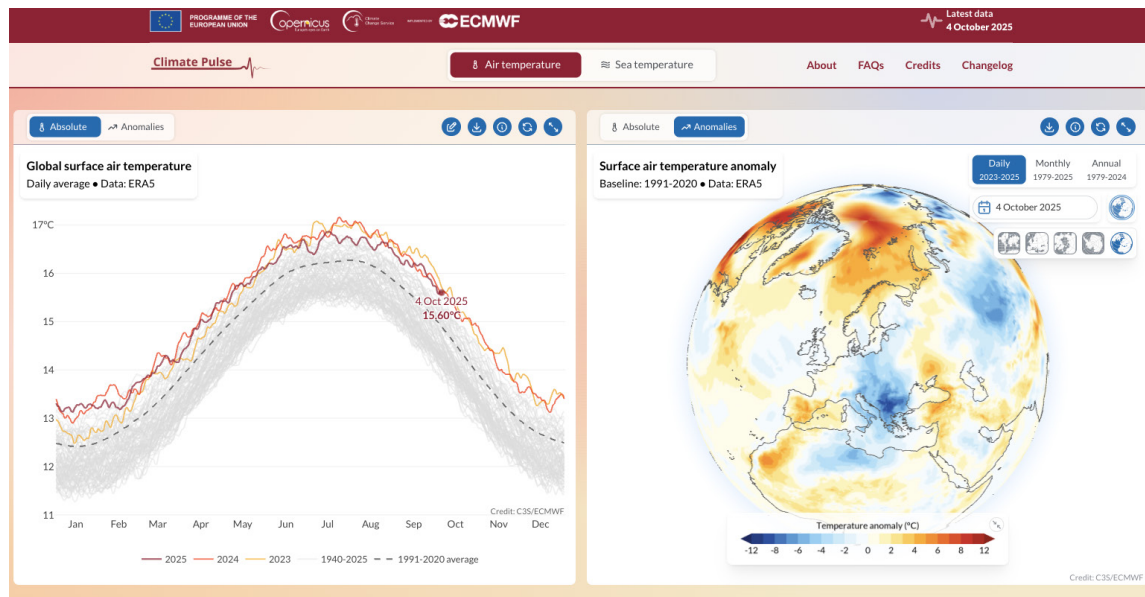


FIGURE 3 Preview of an upgraded version of Climate Pulse, with easier navigation between daily, monthly and annual values, and the possibility to choose alternative map views.

Bulletins, providing daily time series and maps of surface air and sea surface temperature actual values and anomalies. It was our response to the surge in demand – both internally and from the public – to track developing global air and sea-surface temperatures, especially as daily records were being broken by a large margin in 2023 (<https://climate.copernicus.eu/copernicus-and-wmo-july-2023-track-be-hottest-month-record>). The app is based on ERA5 data, available just two days behind real time, and allows users not only to monitor current conditions without waiting for our monthly reports, but also to place them in the context of previous months and years. An updated version of Climate Pulse that will improve exploration at a regional level was released in October 2025.

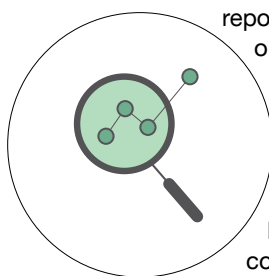
Only 18 months after launch, the take-up of this application is already impressive, with 600 to 1,000 unique users per day, and it is used internally to stay abreast of the most recent fluctuations in global temperatures.

Interactive monitoring applications are now becoming an important cornerstone of our products. The latest is Thermal Trace, published in August 2025, which allows users to explore heat and cold stress across the globe and their changes over time (see separate article in this Newsletter).

Traceable access to underlying data and information

Climate monitoring relies on high-quality data and can only be described as fully transparent once the data and the processing methods it builds on are made freely available. The provision of accessible data and associated documentation is also the primary mission of the Copernicus programme.

A key step towards free and open data was the publication of the gridded ERA5 dataset, along with post-processed data, including monthly and 12-monthly climatologies and anomalies, in the Climate Data Store, just a few months after the service's beta-launch in 2018. For a long time, the data underlying the graphics in the Climate Bulletins were only made available for timeseries and only for key charts in other

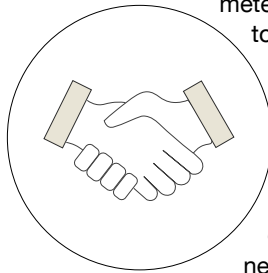


reports. A step-change came with the ESOTC 2023, which allowed users to not only download the high-resolution charts, but also to access the post-processed data behind them. In the following year, the GCH and ESOTC 2024 were accompanied by bespoke graphics galleries collecting all charts discussed in the reports together with supplementary figures. This allows users to quickly retrieve all graphics from a report from a single location. The team is currently developing a similar gallery for the Climate Bulletins. But while much progress has been made, there is work to do, such as providing access to the code that converts raw data to post-processed output, and providing traceable information even further up the data processing chain, such as that ingested into ERA5.

Collaboration as a key to success

While high-quality data, well-designed software and scientific workflows now underpin C3S' climate monitoring, none of what has been achieved so far could have been done without collaboration.

The monitoring activities started within the ECMWF reanalysis team, but it was an interaction between scientists and communication experts that led to the first public product. Collaborations have since grown. Within ECMWF, colleagues provide invaluable input to the Climate Bulletins and represent the editorial backbone of the ESOTC and GCH. However, the conception and implementation of both the Climate Indicators and the ESOTC have relied on collaboration across the Copernicus community and beyond. This has involved data providers, subject experts, and monitoring teams at national meteorological and hydrological services, who have contributed in different ways to the various phases of production – from conception, analysis and writing to content review, media liaison, and post-publication activities such as online discussion panels.



Collaboration with the WMO has been part of ECMWF activities since the start, for instance through our provision of data and editorial input into the WMO Global State of the Climate. In recent years, the WMO started to endorse State of the Climate reports (Figure 4) for its individual Regional Climate Centre (RCC) network regions.

When the WMO European report was first introduced in 2021, ECMWF was coordinating it together with RCC Region VI (Europe), while working in parallel on the ESOTC. Since 2023, the ESOTC has been produced jointly with the WMO, with the aim of providing a single authoritative report for Europe. This collaboration has provided ECMWF with a larger global platform and a new forum in which we can engage with our Member and Co-operating States.

“ The alarming findings of the European State of the Climate Report show us how important it is to have an independent, world-class Earth observation system. As such, Copernicus makes a crucial contribution to resilience and preparedness in the EU. This is both in support of Europe's efforts to mitigate the effects of climate change and to lead the new economy that will emerge.”	“ At ECMWF, we are grateful for the European Commission's continued support towards the Copernicus programmes for Climate Change and Atmosphere Monitoring Services, as well as their support of our contribution to the Copernicus Emergency Management Service. The 2024 ESOTC report is a testament to the dedication of our staff and collaborators, whose excellent work makes it possible to produce such a high-quality and well-regarded publication.”	“ WMO collaborates with the Copernicus Climate Change Service and other partners to strengthen the provision of climate information and services. These are essential to increase resilience to extreme weather and climate impacts. WMO is committed to expanding early warning systems. We are making progress but need to go further and faster.”
ANDRIUS KUBILIUS EU Commissioner for Defence and Space	FLORENCE RABIER Director-General, ECMWF	CELESTE SAULO Secretary-General, WMO

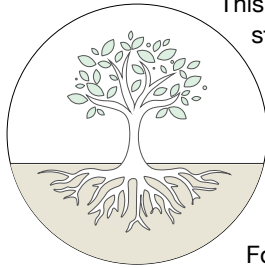
FIGURE 4 The 2024 edition of the European State of the Climate report was endorsed by Andrius Kubilius, EU Commissioner for Defence and Space, and Celeste Saulo, Secretary-General, WMO.

Building a recognisable voice

“The most recent decade of C3S climate monitoring has seen an increase in the exposure of ECMWF in the global media, with climate monitoring data regularly quoted by UN agencies. This recognition results from a strategic vision to ensure that C3S is seen as a trusted voice and a service that can provide data quickly and accurately to enable others to tell the critical stories about the implications of our warming world.” Samantha Burgess, Strategic Lead for Climate.

To build a recognisable voice in climate monitoring takes time, a focus on scientific rigour and continuous reassessment. Here we provide some examples of how we have achieved this and how we quantify the results.

Visual identity is crucial to establishing brand recognition, and to building trust and credibility. We have worked to achieve a consistent look across our climate monitoring communication materials and reports.



This includes, for example, the development and implementation of a clear visual style guide to steer the look and feel of the ESOTC. The same approach is being adopted across all our graphical products.

Another way to ensure broad reach is through effective communication and outreach activities, including engagement with the press and through social media. This has been achieved through collaboration between the Climate Intelligence team, the communication team and external partners.

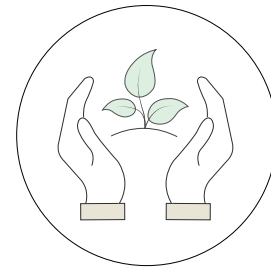
For example, while the temperature summaries from the Climate Bulletins were originally shared with our press agency and through social media as a few bullet points, every product is now associated with a press release. Since 2021, for the broader products such as the GCH and the ESOTC, the report release has also been accompanied by a press briefing. These changes were made to create further engagement, and to respond and adapt to increased demand.

Success can be measured in several ways, such as the number of mentions of C3S and our products in news media around the world. This has grown from close to 160 for the ESOTC in 2019 to around 15,650 for the latest GCH. The number of different countries covering C3S monitoring has also grown over time. The number of media mentions for the latest GCH release was over three times more than the year before and is a testament to the strength of collaboration with the release of data and of the publication being coordinated across all international groups who operationally monitor global temperatures. Figure 4 illustrates the European and global support for the ESOTC 2024.

Lessons learnt

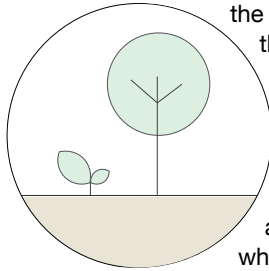
Over its 10 years of activity, our team has learnt many valuable lessons about the challenges and intricacies of operational climate monitoring and climate communications. Sticking to our theme of ten, here are ten of the lessons we have learnt along the way:

1. Reference periods are unavoidable and will lead to lengthy discussions.
2. Long-term observations are essential for climate monitoring, but their continued availability cannot be taken for granted.
3. Thorough review and scientific detail versus accessible, swift and creative reports is a balancing act.
4. Carefully crafted visuals and text are more effective for communication but require more time and effort to create.
5. Repetition is both your friend and your enemy; reporting on the same quantities and statistics is essential for tracking change but limits the space for exploring new topics.
6. The messages the data reveal are rarely uplifting.
7. Use terms like ‘warmest’, ‘coolest’, ‘wettest’, or ‘driest on record’ with caution, given the varying lengths of data records.
8. ‘Word clouds’ are useful to highlight which words are used most in a report, informing that for us typically these are ‘average’, followed by ‘Europe’ and ‘anomalies’.
9. Climate events follow their own schedule, not ours.
10. Collaboration brings fresh perspectives and expertise in new areas, but requires commitment, flexibility and firm deadlines.



Looking ahead

We have looked back ten years, but what is planned for the next ten? In the immediate future, we are working to make the workflow more efficient through increased automation and by exploring how AI could support our work, further improving transparency and accessibility across the production chain and



expanding our visual identity across all products. By early 2027, it is expected that ERA6, the next-generation reanalysis, with higher resolution and advances in terms of the underlying model and ingested data, will start to become available. We are confident that this will lead to an updated portfolio of monitoring products for our team to rely on. In addition, while the monitoring of extreme events has always been part of our work, there has been no regular workflow in place that allows close-to-real-time analysis. This will change with the implementation of the new C3S operational attribution office, which will provide tools and workflows to analyse extreme events – starting with temperature extremes – as they happen, while putting them in the context of climate change.

Examining how some end-of-the-year press release titles have evolved in the last decade highlights significant changes in our climate that have already taken place and offers some insight into what the next ten years might bring.

In 2017, the title was ‘Earth on the edge: Record breaking 2016 was close to 1.5°C warming’ (<https://climate.copernicus.eu/earth-edge-record-breaking-2016-was-close-15degc-warming>) and in 2025 ‘Copernicus: 2024 is the first year to exceed 1.5°C above pre-industrial level’ (<https://climate.copernicus.eu/copernicus-2024-first-year-exceed-15degc-above-pre-industrial-level>). In the first case, it referred to the month of February 2016 nearing the 1.5°C threshold and in the second case the whole calendar year had passed the threshold. While the underlying increase is largely related to the human-induced greenhouse gas concentration increases in the atmosphere, both 2016 and 2024 temperatures saw a temporary boost due to the influence of El Niño. It is not hard to imagine that we will soon have such cases without that boosting influence. Based on the estimates provided by the ‘C3S Global Temperature Monitor’ (<https://apps.climate.copernicus.eu/global-temperature-trend-monitor/?tab=source-code>) over the last five years or so, the long-term 1.5°C threshold will be breached sometime between 2028 and 2032.

It is not just the Paris Agreement temperature thresholds that matter, but all the associated changes across the Earth system, which become increasingly apparent with every additional fraction of a degree. So, C3S monitoring will continue, with the hope of being the bearer of more positive news at some point.

Over the past decade, the monthly climate bulletin has grown into one of the cornerstones of the Copernicus Climate Change Service. What began as a way to share regular updates on climate trends has become a trusted reference for policymakers, scientists media, and citizens worldwide. Its consistent and transparent monitoring of our changing climate is now central to our mission. - Carlo Buontempo, C3S Director

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