BAMS Article

The Copernicus Atmosphere Monitoring Service

From Research to Operations

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ABSTRACT: The Copernicus Atmosphere Monitoring Service (CAMS), part of the European Union's Earth observation program Copernicus, entered operations in July 2015. Implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) as a truly European effort with over 23,500 direct data users and well over 200 million end users worldwide as of March 2022, CAMS delivers numerous global and regional information products about air quality, inventory-based emissions and observation-based surface fluxes of greenhouse gases and from biomass burning, solar energy, ozone and UV radiation, and climate forcings. Access to CAMS products is open and free of charge via the Atmosphere Data Store. The CAMS global atmospheric composition analyses, forecasts, and reanalyses build on ECMWF's Integrated Forecasting System (IFS) and exploit over 90 different satellite data streams. The global products are complemented by coherent higher-resolution regional air quality products over Europe derived from multisystem analyses and forecasts. CAMS information products also include policy support such as quantitative impact assessment of short- and long-term pollutant-emission mitigation scenarios, source apportionment information, and annual European air quality assessment reports. Relevant CAMS products are cited and used for instance in IPCC Assessment Reports. Providing dedicated support for users operating smartphone applications, websites, or TV bulletins in Europe and worldwide is also integral to the service. This paper presents key achievements of the CAMS initial phase (2014–21) and outlines some of its new components for the second phase (2021–28), e.g., the new Copernicus anthropogenic CO_2 emissions Monitoring and Verification Support capacity that will monitor global anthropogenic emissions of key greenhouse gases.

KEYWORDS: Atmosphere; Numerical weather prediction/forecasting; Reanalysis data; Air quality; Societal impacts; Atmospheric composition

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Every human on Earth inhales approximately 14 kg of air per day, which is an order of magnitude higher than the intake of food and water. Our health is thus greatly influenced by ambient air quality, which has a similar impact on life expectancy as smoking (Lelieveld et al. 2020; Fuller et al. 2022). Air pollutants have also many other impacts including on crop yields (e.g., Burney and Ramanathan 2014), as well as acidification and eutrophication of ecosystems. Atmospheric reactive gases and aerosols, from both human and natural sources such as from anthropogenic combustion processes (energy production, transport, …), agriculture, uplift of sand and dust, wildfires and biomass burning, and volcanic eruptions can affect health, the safe operation of transport systems, the availability of solar power, formation of clouds and rainfall, and can interfere with remote sensing by satellite of land, ocean, and other atmospheric properties. Human activities also result in emissions of greenhouse gases (GHG), including almost 40 billion tons of fossil fuel CO_2 annually (Friedlingstein et al. 2022), which together with other GHG drive global warming and its many manifestations such as global average temperature and sea level rise.

The Copernicus Atmosphere Monitoring Service (CAMS; see https://atmosphere.copernicus.eu/), was established in 2014 by the European Commission (European Union 2014) to provide society with comprehensive, quality-assured, and documented global- and European-scale data and information related to air pollution and health, solar energy, GHG, and the impacts of changing atmospheric composition on climate. It builds on a successful uninterrupted series of collaborative research and innovation projects, which started in 2005 with GEMS (Hollingsworth et al. 2008) and followed with MACC, MACC-II, and MACC-III (Peuch et al. 2016b, 2014, 2016a), as well as extensive user and stakeholder engagement for defining the scope and initial portfolio of the service.

CAMS is implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) in collaboration with many contractors in Europe. CAMS makes use of ECMWF's operational infrastructure and modeling tools to generate near-real-time global analyses and forecasts of atmospheric composition, as well as consistent long-term reanalyses. CAMS also provides higher-spatial-resolution products over Europe generated with an ensemble of regional models, as well as several supplementary products aimed at meeting user needs in the policy domain, industry, and the science community.

CAMS is one of six thematic information services of the European Union (EU)'s Copernicus Earth observation program (Fig. 1). In addition to CAMS, ECMWF also manages the Copernicus Climate Change Service (C3S). Copernicus was established by the European Commission in 2014 as a long-term effort aimed at monitoring our planet and its environment to serve public

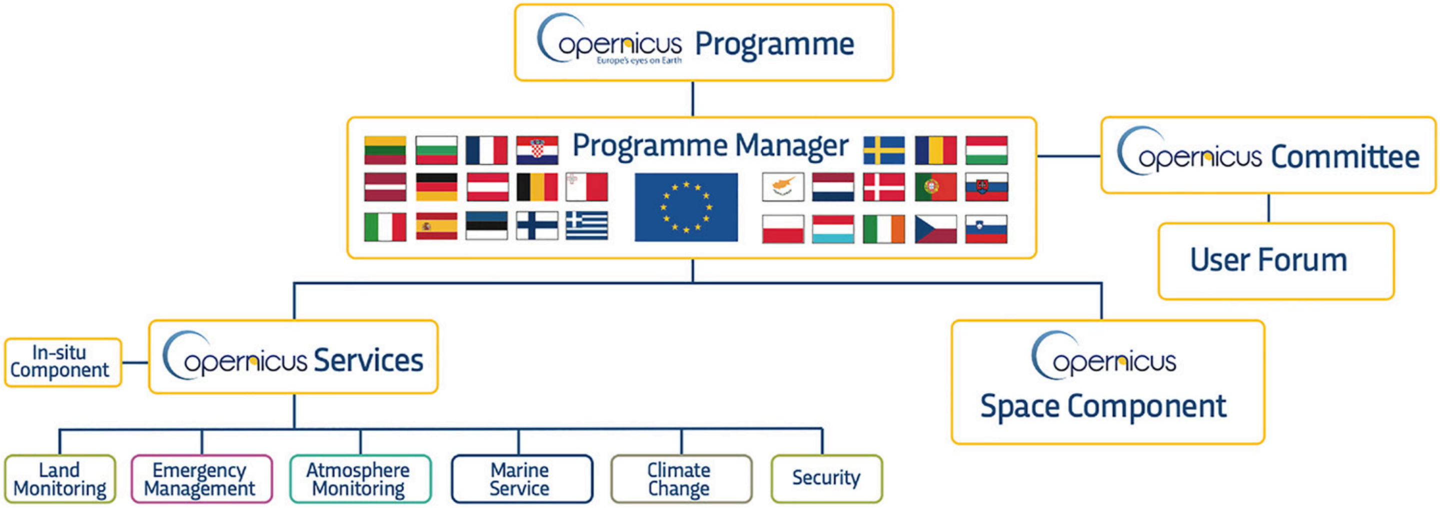

Fig. 1. High-level structure of the Copernicus Programme.

authorities, businesses, and citizens. The program supports the development and operations of the Sentinel satellites, as well as the activities needed to process, analyze, and transform observational data into timely and actionable information provided on a free and open basis to anyone.

This paper summarizes the implementation of CAMS and its main achievements during the first funding phase (2014–21) of the Copernicus Programme (European Union 2014). The second section explains the CAMS mission and briefly describes how the service, led by ECMWF, is implemented as a collaborative effort together with 200 entities distributed in over 30 countries in Europe and elsewhere. The third through sixth sections describe CAMS products, how they are generated, and the underpinning science. The seventh section summarizes CAMS user support, training, and communication activities. A few conclusions and lessons learned are presented in the eighth section, which also describes key elements of the planned evolution of CAMS for its second phase 2021–28. We invite the reader to also consult the companion paper on the Copernicus Climate Change Service (C3S) in this *BAMS* issue (Buontempo et al. 2022), as the two services share some commonalities.

CAMS implementation

The mission of the Copernicus Atmosphere Monitoring Service is to monitor Earth's atmosphere and its composition at global and regional scales, and to provide users with continuous access to up-to-date and high-quality data and information products related to atmospheric composition. CAMS production systems continually generate descriptions of the current situation (analyses), predictions for a few days ahead (forecasts), and retrospective data records for recent years (reanalyses). The main focus areas are air quality and atmospheric composition, ozone and ultraviolet radiation, emissions and surface fluxes, solar radiation, and climate forcing. All data and products are available under an open and free data policy, and easy to access via application programming interfaces (APIs) and a dedicated portal.

Target users for CAMS are the European Commission and its agencies; public institutions in EU member states; businesses and other commercial entities; the scientific research community; media and the public, either directly or indirectly through other public or commercial users. The EU and its member states rely on CAMS in policy areas addressing the environment, climate, energy, transport, research, and international cooperation. CAMS contributes to many international activities including the World Meteorological Organization's (WMO) Global Atmosphere Watch program (GAW), the Group on Earth Observations (GEO), the World Health Organization (WHO), the United Nations Environment Programme (UNEP), and the United Nations Framework Convention on Climate Change (UNFCCC). Selected CAMS outputs can for instance be found on WMO's public website (https://public.wmo.int/en/our-mandate/focus-areas/environment/atmospheric-composition-forecast-and-assessments).

CAMS is implemented by ECMWF on behalf of the European Commission and involves numerous European public and commercial entities. ECMWF manages the service as a whole and is responsible for generating global atmospheric composition products using its existing numerical weather prediction (NWP) infrastructure, as well as for the CAMS user support, and for coordinating training and communication activities. Most other elements of the service are implemented by competitive procurement, including the generation of multisystem regional air quality products, independent assessments of product quality and suitability, and critical support activities to ensure reliable access to data from in situ observational networks.

Figure 2 outlines the implementation of CAMS production systems and data flows. It involves four main elements: acquisition and preprocessing of input observations from satellite and in situ instruments, as well as ancillary data needed to estimate emissions of pollutants and greenhouse gases; modeling and data assimilation for global products; ensemble modeling and data assimilation for regional European products; and generation of various supplementary products and services. Each of these elements are described in detail in subsequent sections of this article.

ECMWF has implemented strict quality control in all CAMS production systems, and routinely provides quality assurance information for products based on independent assessments by external scientific and technical experts. As part of the CAMS evaluation and quality assurance (EQA), automated monitoring and verification systems have been implemented to monitor skill scores and other statistical measures of product quality, as well as a variety of service performance indicators such as user uptake and satisfaction, service specifications, and policy uptake. These automated indicators and performance metrics are complemented for the main products lines by detailed evaluation and quality control reports, which are edited on a quarterly basis and include expert assessments also based on independent observations that are not available in near–real time.

Users who want to explore datasets or lack the adequate technical environment prefer simple tools to visualize and extract pieces of data. Most products are disseminated to users via the dedicated Atmosphere Data Store (ADS; https://ads.atmosphere.copernicus.eu), which

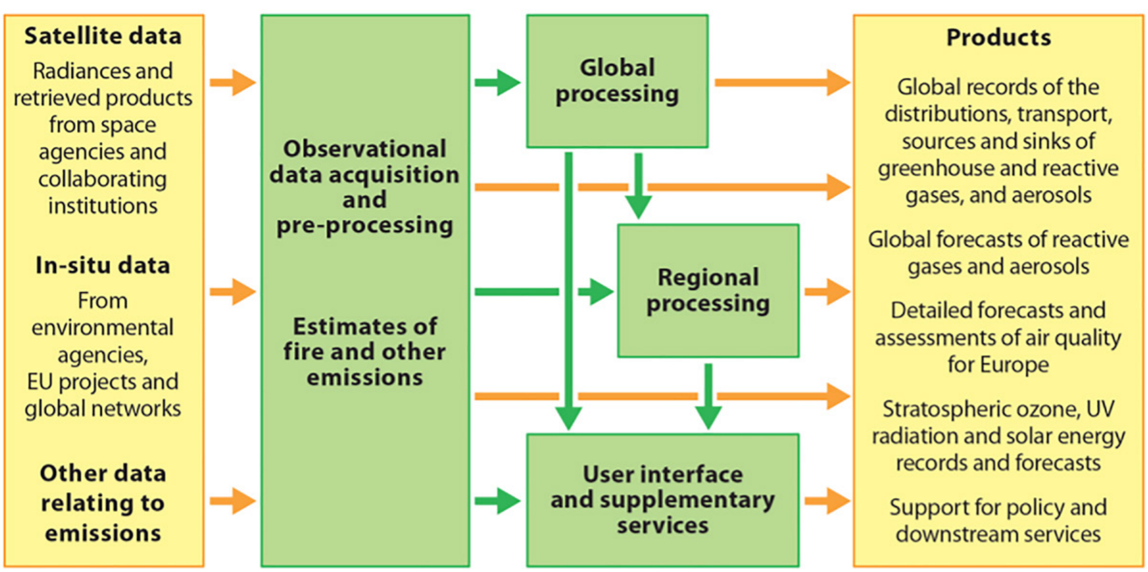

Fig. 2. Illustration of the main CAMS internal data and information flows (green), while the orange arrows indicate the flow of data into the service and the flow of products out to downstream-service providers and end users.

offers a searchable catalogue, standardized machine-to-machine interfaces to data, access to metadata, data subsetting, downloading, and many other features. The ADS is a twin of the Climate Data Store developed within the C3S. Details of its design and features can be found in the companion paper for C3S also in this issue. The CAMS global forecasts and fire emissions are also made available through the operational ECMWF Production Data Store for time-critical users such as regional modeling centers. A large range of visualizations are generated daily for display on the CAMS website for monitoring daily analyses and forecasts. CAMS provides technical user support during European working hours via a dedicated help desk. In addition, users have 24/7 access to a knowledge base and online user forum. All user queries are logged into an online tracking system. New user requirements are registered in a database, which is periodically analyzed in terms of feasibility and potential impact to help plan service upgrades and new developments. Full documentation is provided on data products and underlying production/processing systems. CAMS uses electronic mailing lists to inform users about changes to its forecast services, such as system upgrades and potential changes to the timing of the product availability. This follows very much the standard practices of ECMWF for weather forecasts.

CAMS production methods and systems are regularly upgraded and improved to meet user requirements, based on new model releases, introduction of new observing systems, advances in data assimilation, increases in available computing capability, etc. Typically, most of the systems are updated once or twice per year, except the one used for the CAMS global reanalysis that needs to remain "frozen" to ensure consistency of the time series.

Observations

Observations are key to all CAMS products. CAMS uses data assimilation to combine observations from multiple sources with its numerical models to generate analyses, i.e., spatially complete estimates of all atmospheric variables to initialize the forecasts. Different sets of observations are also used to assess the quality of the products.

Satellite data. The global production currently assimilates over 90 different satellite meteorological and atmospheric composition related data streams, with close to 800 million observations per day being processed continually. Some satellite datasets for GHG are acquired with a delay of a few days ("research" products, with less stringent timeliness requirements) and these are used for assimilation into the CAMS delayed-mode forecasting suites and reanalyses. A list of the satellite atmospheric composition observations used is kept up-to-date on the CAMS website (https://atmosphere.copernicus.eu/satellite-observations) and reproduced here (Table 1). At present CAMS only assimilates retrievals regarding atmospheric composition variables.

In situ data. CAMS requires access to timely and quality-controlled data streams from a large variety of in situ observing networks, as listed in Table 2, for the global and regional production systems, either for assimilation or verification. CAMS has established agreements with respective providers to ensure data provision meets operational requirements for the service.

Global products

The global production system represents the backbone of the CAMS global portfolio. It is based upon ECMWF's Integrated Forecasting System (IFS) using in-line representation of atmospheric composition covering GHG, reactive gases, and aerosols for the specific CAMS configurations (Flemming et al. 2015; Rémy et al. 2019). CAMS is operated alongside the ECMWF operational NWP activities, benefiting from its highly available and reliable computer infrastructure.

Table 1. **Satellite observations of atmospheric composition variables that are used in the various CAMS systems: Global real-time forecast (GRTF), global delayed mode (GDM), global reanalysis (REA), Global Fire Assimilation System (GFAS), global surface net flux inversions of GHG (GHGI). "A" (assimilation) means that the dataset is used to produce analyses and they affect the forecasts. "M" (monitoring) means that the data are going through the system for diagnostic purpose only: they do not affect analyses or forecasts. "P" (planned) means that the dataset is used in research mode before it can be M and A. Symbol "—/" stands for "same as previous entry". AOD means aerosol optical depth. FRP means fire radiative power.**

Instrument	Satellite	Space agency	Provider	Variables	Status
AATSR	*Envisat*	ESA	ESA	AOD	REA(A)
AHI	*Himawari-8*	JMA	IPMA	FRP	GFAS(P)
GOME-2	*MetOp-B*, *MetOp-C*/*MetOp-B*, *MetOp-C*/*MetOp-A*/*MetOp-A*, *MetOp-B*	EUMETSAT–ESA	AC SAF	O_3, NO_2, SO_2/HCHO/O_3, NO_2, SO_2,HCHO/O_3, NO_2	GRTF(A)/GRTF(M)/GRTF(M)/REA(A)
IASI	*MetOp-B*, *MetOp-C*/*MetOp-A*/*MetOp-A*, *MetOp-B*, *MetOp-C*/*MetOp-A*, *MetOp-B*/*MetOp-A*, *MetOp-B*/*MetOp-A*, *MetOp-B*	EUMETSAT–CNES/—/—/—/—/EUMETSAT	AC SAF/AC SAF/ULB–LATMOS/LMD/LMD/EUMETSAT	CO/CO/O_3, SO_2/CH_4/CO_2/CH_4, CO_2	GRTF(A)/GRTF(M)/GRTF(P)/GDM(A)/GDM(P)/REA(A)
Imager	GOES-E, GOES-W	NOAA	IPMA	FRP	GFAS(P)
MIPAS	*Envisat*	ESA	ESA	O_3 profile	REA(A)
MLS	EOS *Aura*	NASA	NASA	O_3 profile	GRTF(A)/REA(A)
MODIS	EOS *Aqua*, *Terra*	NASA	NASA	AOD/AOD/FRP	GRTF(A)/REA(A)/GFAS(A)
MOPITT	EOS *Terra*	NASA	NCAR	CO	GRTF(A)/REA(A)
OCO-2	*OCO-2*	NASA	NASA	CO_2	GDM(P)/GHGI(A)
OMI	EOS *Aura*	NASA	KNMI	O_3, NO_2, SO_2/O_3, NO_2	GRTF(A)/REA(A)
OMPS	*SNPP*, *NOAA-20*	NOAA	EUMETSAT	O_3	GRTF(A)
PMAp	*MetOp-A*, *MetOp-B*/*MetOp-C*	EUMETSAT	EUMETSAT	AOD	GRTF(A)/GRTF(M)
SBUV-2	*NOAA-19*/*NOAA-14*, *NOAA-16*, *NOAA-17*, *NOAA-18*, and *NOAA-19*	NOAA	NOAA	O_3 profile	GRTF(M)/REA(A)
SCIAMACHY	*Envisat*	ESA	KNMI	O_3, NO_2, CH_4, CO_2	REA(A)
SEVIRI	MSG	EUMETSAT	ICARE/LSA SAF	AOD/FRP	GRTF(P)/GFAS(P)
SLSTR	Sentinel-3	ESA–EUMETSAT	EUMETSAT	AOD/FRP	GRTF(P)/GFAS(P)
TANSO	*GOSAT*	JAXA	SRON/Uni. Bremen/SRON–Uni. Bremen/SRON	CH_4/CO_2/CH_4, CO_2/CH_4	GDM(A)/GDM(A)/REA(A) GHGI(A)
TROPOMI	*Sentinel-5P*	ESA–NSO	ESA–KNMI–DLR/—/ESA–KNMI–SRON–DLR	O_3, SO_2/NO_2, CO, HCHO/CH_4	GRTF(A)/GRTF(M)/GDM(P)
VIIRS	*SNPP*, *NOAA-20*	NASA–NOAA	EUMETSAT	AOD	GRTF(P)

The global products are delivered to the users, but also provide boundary conditions for the CAMS regional models. To operate the global services continuously, input data acquisition and output data dissemination is provided using ECMWF's existing operational systems and proven procedures.

The system produces twice-daily global analyses and forecasts up to 5 days ahead of atmospheric composition at resolution T511L137 (roughly 40 km and 137 vertical levels) including 56 reactive trace gases in the troposphere, stratospheric ozone, and seven different types of aerosols (Rémy et al. 2022). The global production includes the daily fire emission estimates based on satellite active fire observations from the Global Fire Assimilation System (GFAS; Kaiser et al. 2012). The CAMS global system relies upon a comprehensive set of emissions and surface fluxes for trace gases and aerosols including inventory-based anthropogenic emissions, biomass burning (from GFAS), online modeled wind-blown desert dust, and sea salt emissions, as well as natural and biogenic fluxes

Table 2. In situ observing networks used in CAMS. "S," "TC," and "P" refer to "surface," "total column," and "profile," respectively.

Variables	Use in CAMS	Data providers (networks)
CO, NO_2, O_3, SO_2, $PM_{2.5}$, PM_{10}, pollen (S)	Assimilation and EQA of regional services	EEA/EIONET, EAN, EMEP
CO_2 (TC)	Assimilation for CO_2 flux inversions	NOAA CCGG, WDCGG, RAMCES
CH_4 (TC)	Assimilation for CH_4 flux inversions	NOAA CCGG
N_2O (TC)	Assimilation for N_2O flux inversions	NOAA CCGG, AGAGE, CSIRO, NIES, ECN, EMPA, U. of Edinburgh, FMI, HMS, MPI-Jena, Tohoku Uni., CONTRAIL
Aerosol, CH_4, CO, CO_2, NO_2, O_3 (S)		ACTRIS, GAW, EMEP, EEA, U.S. EPA, ICOS
CO, O_3 (P)	EQA of global services	GAW, IAGOS, SHADOZ
Aerosol, CH_4, CO, CO_2, NO_2, O_3 (TC)		GAW, ICOS, TCCON, NDACC, AERONET
Global, direct at normal incidence and diffuse solar radiation	EQA of solar services	BSRN, EnerMENA, SHMI, LEGMC, LHMS, KNMI, Academy of Sciences Moldova
UV radiation	EQA of UV forecasts	COST-713 UV Index Database, ARPANSA, IMS

calculated offline using C3S ERA5 (Hersbach et al. 2020). The initial conditions of the forecast are based on the analysis combining a previous forecast with satellite observations through a 4D-Var data assimilation process. GHG forecasts are computed separately with a few days' delay and much higher resolution (TCo1279/L137, about 9-km horizontal resolution and 137 vertical levels).

CAMS delivered two global reanalyses over the period 2003 to the present, one for aerosols and chemical species (EAC4; Inness et al. 2019) and one for GHG (EGG4; Agustí-Panareda et al. 2022), respectively. They are produced using 4D-Var data assimilation with a 12-h assimilation window with a horizontal resolution of about 80 km and 60 vertical levels reaching 0.1 hPa. The historical record of the ozone layer from 2003 to the present is based on the CAMS global reanalysis of the atmosphere. The ozone layer is being monitored on a regular basis showing, for instance, the extent and magnitude of the ozone hole each year as it develops and recovers. CAMS and associated C3S outputs, supporting information and explainers are often highlighted in press and media.

Upgrades of the global production system used for forecasts (real time and delayed mode), once or twice a year (see https://confluence.ecmwf.int/display/COPSRV/CAMS+Global), are managed by running development and operational systems in parallel for a period of a few months, with in-depth analysis of differences. Following again in the steps of NWP, results are synthesized in the form of "scorecards" (Fig. 3) covering the main aspects of interest and supporting decision to go ahead or not with the candidate version.

CAMS provides extensive quality and performance information. This comes both in the form of routinely updated quality monitoring graphics (https://atmosphere.copernicus.eu/global-services) and of quarterly EQA reports.

Continuous development of the CAMS global system. Similarly to NWP, CAMS relies on fast and effective research-to-operations procedures, which allow the system to remain cutting edge, while delivering at the same time operational services. We describe here briefly some of the targeted developments that have been brought to the system in recent years. These developments had a typical horizon of 2–3 years and allowed making substantial step changes on top of the more incremental influx of developments coming with every development cycle of the global system.

Regarding GHG aspects, the two main achievements were a new CH_4 wetland model based on Bloom et al. (2017) optimized considering temperature and latitudinal dependency, and a new Farquhar photosynthesis model (Agf) based on Yin and Struik (2009) optimized through a Bayesian assimilation. Both developments were successfully implemented into

Property	*Rel. score*	*Property*	*Rel. score*
Global AOD	-	CO surface	n
Ångstrøm exponent	- -	CO profiles (aircraft)	n
Dust AOD	++	CO columns (satellite, FTIR)	n
Dust PM10 Mediterranean	++	Tropospheric NO_2 column	+
Surface PM10, Europe and US	++	Fire-produced NO2 and HCHO	+
Surface PM2.5, Europe and US	+	HCHO column	n
Ozone, free troposphere (ozone sonde)	n	Ozone stratospheric profile	++
Ozone tropospheric profile (aircraft)	n	UV radiation (UV-index)	-
Surface ozone, Arctic	n	Surface methane	-
Surface ozone, Midlatitude	+	Methane column	-
Surface ozone, Antarctic	-	Surface CO_2	n
Surface ozone, Europe	+	CO_2 column	n
Ozone column	n		

Fig. 3. Example of IFS scorecard (System 47r1) relative to previous version illustrating the improvements (denoted by ++ and + signs) or deterioration (denoted by −− and − signs) on atmospheric composition model performance (from https://atmosphere.copernicus.eu/cycle-47r1).

the land surface component of the CAMS global system and are undergoing final testing and adjustment.

Three independent modules based on the CB05/BASCOE, MOCAGE, and MOZART models have been included in the IFS and are used to investigate the sensitivity of forecasts to the representation of reactive chemistry processes (Huijnen et al. 2019). Other key developments included the coupling to the aerosol scheme for the simulation of secondary inorganic and organic aerosols, the revision of photolysis rate calculations, and upgrades to the reaction rate constants, as well as the online integration of dry deposition velocities replacing the use of precalculated monthly mean values.

Regarding representation of aerosol processes, the main achievements were (i) substantial updates of dust and sea salt emission modeling, (ii) the introduction of inorganic aerosol (nitrates, ammonia), (iii) linking the aerosol scheme to the chemistry scheme for secondary aerosols, and (iv) a new dry and wet deposition scheme. The latest aerosol representation schemes are described in Rémy et al. (2019, 2022).

Other important efforts include the benchmarking of different radiative transfer models in preparation of aerosol radiance assimilation. Finally, some efforts are devoted to the improvement of numerical aspects of the IFS, including mass conservation/fixing aspects (Agustí-Panareda et al. 2017). A key recent outcome was a computing cost saving of 15%, which was achieved by reordering the solver code and moving to single precision instead of double precision as previously used.

Concerning GFAS, the most substantial evolution was to move from daily to hourly outputs, and the upcoming replacement of the earlier land-cover map by fire-specific biome-like maps for improved geospatial emission factor allocation, primarily based upon the ESA CCI land-cover products. Another key development going into operations is a much improved near-real-time (NRT) algorithm for pollutant plume injection height (Rémy et al. 2017).

It is a priority for CAMS to ensure uptake of new data streams, such as those from the Copernicus Sentinels, for ingestion into the global production for users to benefit from improved products and added-value services as soon as the retrievals meet quality requirements for operational use. This is also a major stream of development activities for the CAMS global system.

Regional products

Regional processing (Marécal et al. 2015), including associated developments and products, focuses on a dedicated domain over Europe. It is implemented downstream from the global processing via boundary conditions using a multisystem ensemble approach of currently 9 models (and evolving toward 11 models in the coming year). Each of the models is operated by the main institution that developed it rather than run centrally; this allows the teams to continually upgrade the system following CAMS requirements, which would not be possible with open-source or commercial modeling tools. The ensemble approach not only outperforms individual models, but also provides detailed uncertainty estimates, which were an essential user requirement to support decision making (Fig. 4). Such an approach also stimulates emulation and leverages expertise from the leading regional modeling groups in Europe, and links naturally to the national air quality forecasting activities.

The regional products provide users with accurate information concerning air quality all over Europe. The regional production consists of daily updated hourly analyses and forecasts up to 96 h ahead, annual interim reanalyses made available a few weeks after the end of each year and computed using surface observations that are in an interim stage of validation, and annual reanalyses, which are computed using fully validated observations made

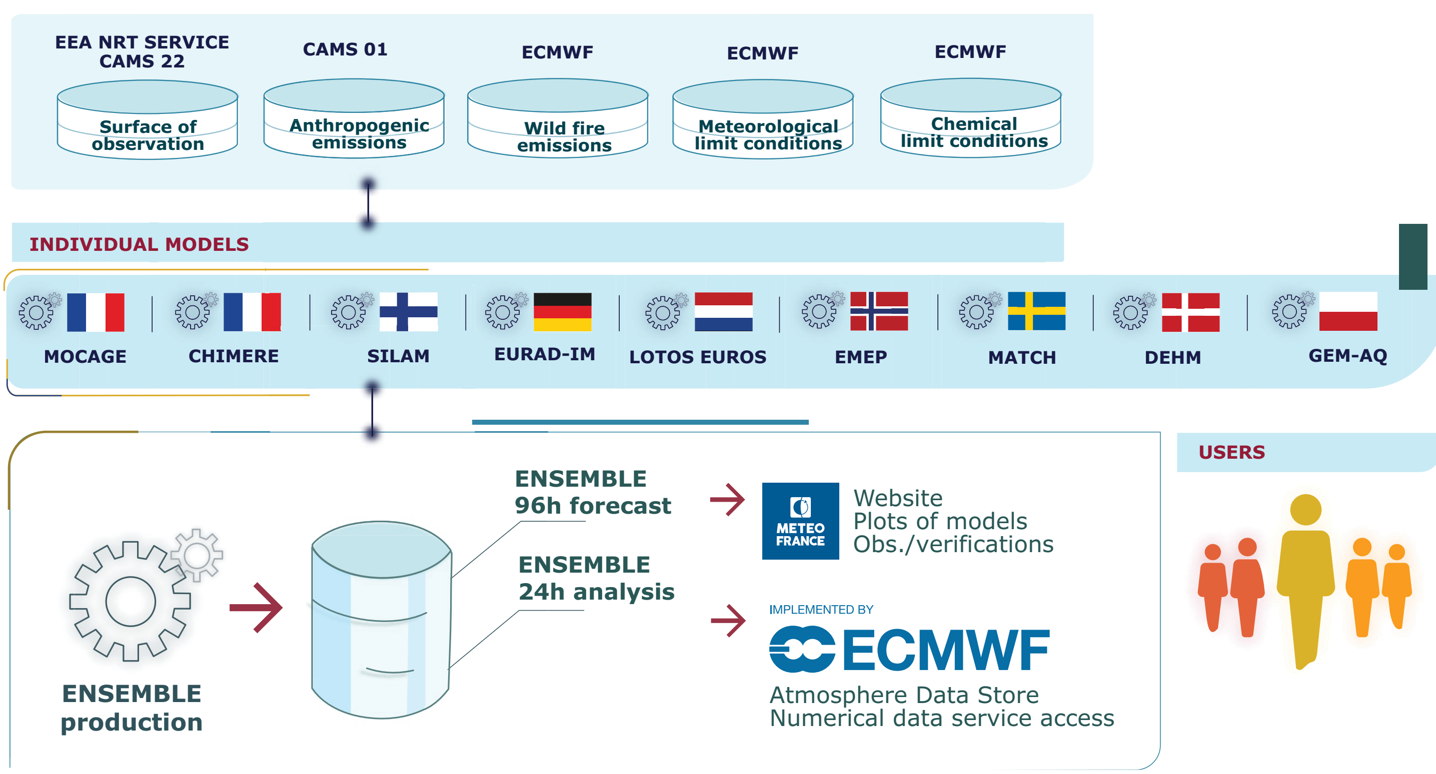

Fig. 4. Schematic of the regional multisystem ensemble production. See Marécal et al. (2015) for more information.

by the European Environment Agency (EEA) member states and available typically around two years after the year concerned. All these products have a horizontal resolution of 0.1° (approximately 10 km), use the same ECMWF operational meteorological forcing, the same chemical boundary conditions for gases and aerosols from the CAMS global production and CAMS GFAS fire emissions, the same CAMS inventory-based European emissions and assimilate the same set of surface air quality observations. The systems in the ensemble differ regarding the characteristics of the modeling (transport, chemistry, and aerosol schemes, ...) and data assimilation approaches, which are sufficient to generate spread between their outputs. Up-to-date information about the CAMS regional analysis and forecast products available is provided at https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-europe-air-quality-forecasts?tab=overview.

Near-real-time data acquisition and preprocessing include data from ECMWF (weather forecasts and chemical boundary conditions from the CAMS global system) and in situ air quality observations collected by the EEA from most countries in and around Europe. An automatic classification methodology filtering observations addresses the heterogeneity and representativeness to improve the compatibility with the horizontal resolution of CAMS regional products (Joly and Peuch 2012). A fraction of the data are deliberately not assimilated and set aside for independent verification of the analyses and reanalyses.

Individual regional model products are centrally collected and combined to deliver ensemble products and corresponding uncertainty information under strict operational conditions to guarantee a high-level front-end service delivery and timeliness. The most used regional products of CAMS are the real-time analyses and forecasts, which feed directly or indirectly (through postprocessing) a wide variety of routine time-critical applications for public entities running, for instance, official air quality information systems in EU member state countries, for academia. and for commercial companies. CAMS analyses and reanalyses are also widely used to initialize and provide chemical boundary conditions for high-resolution modeling investigating anomalous events or field campaigns. A major application area of CAMS regional output relies on downscaling, especially when looking at impacts of air quality on human health and ecosystems. Some examples in the health sector include de Hoogh et al. (2016) and Schneider et al. (2020). Regional reanalyses are also pivotal for the production of the European air quality assessment reports under the CAMS policy services (see next section).

The regional systems have been upgraded regularly all at the same time, notably with the inclusion of hourly GFAS inputs, new versions of anthropogenic surface emissions (including a revision of how condensables from wood burning are handled), addition of pollen species, and the addition of tracers to isolate the fraction of aerosol coming from natural sources.

As with global products, EQA is provided both online with automated diagnostics (Fig. 5) and by means of quarterly reports (https://atmosphere.copernicus.eu/regional-services) for each regional modeling system as well as for the ensemble median, focusing on surface concentrations of the main regulatory pollutants. In addition, a separate quarterly report evaluates the interface with the global system and addresses above-surface concentrations.

Continuous development of the regional systems. R&D activities focus on improving the individual modeling and assimilation systems as well as the ensemble processing across regional providers making findings and results available for subsequent integration in the systems.

Dedicated regional reruns with extended output data (e.g., speciated PM, deposition parameters, precipitation, meteorology, emissions) were compared. It was found that the large differences between the models' outputs for the natural components dust and sea salt can be attributed to how they implement the contribution coming from the boundaries and the inner domain production.

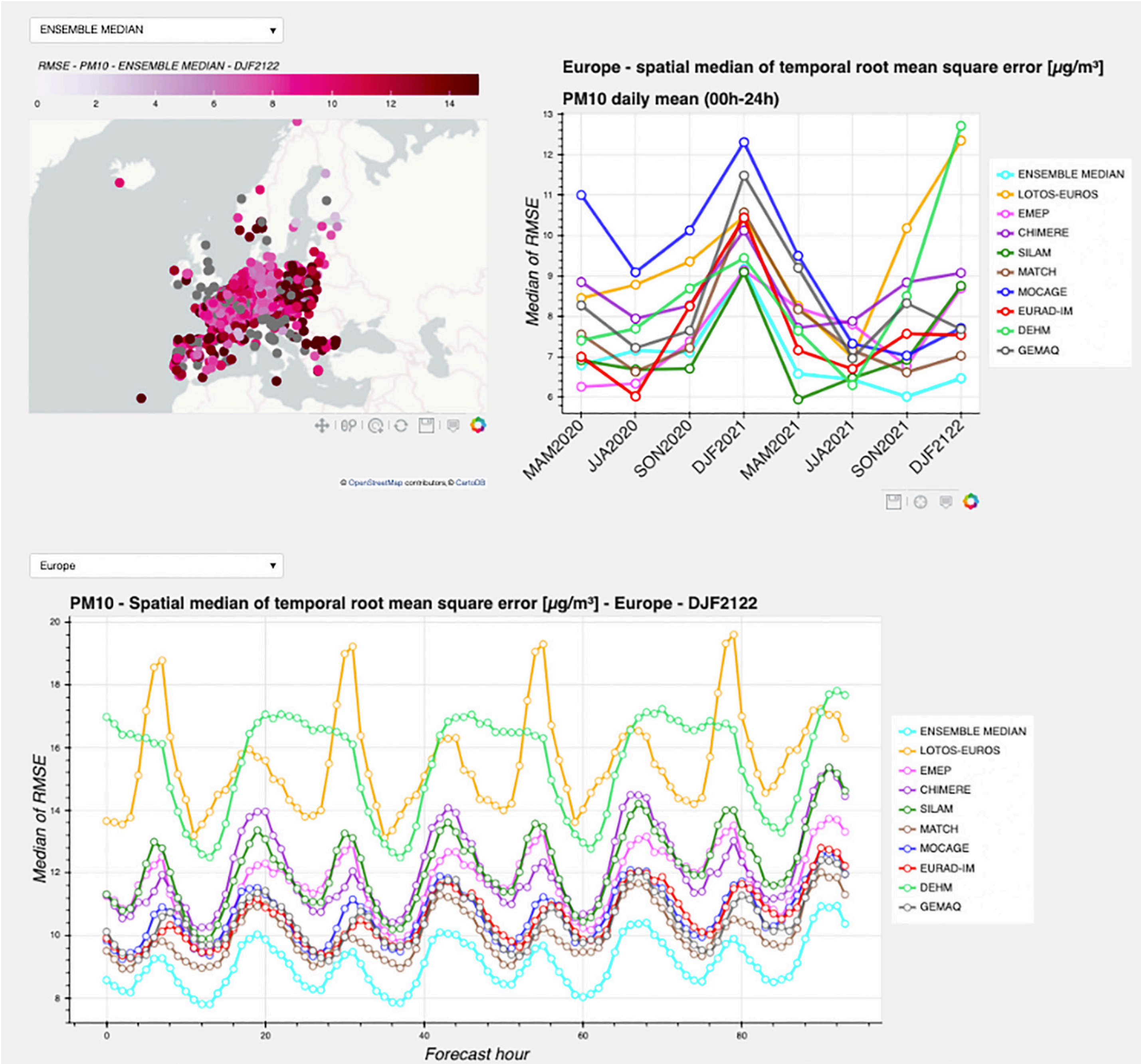

Fig. 5. Example of verification of PM_{10} forecast against available observations. See https://regional.atmosphere.copernicus.eu.

Some of the research also focused on investigating how to extend the impact of assimilation over a longer period in the forecast. Observation operators for the assimilation of Sentinel data into the regional model systems have also been released with promising benefits for species such as NO_2.

Advanced artificial intelligence/machine learning (AI/ML) postprocessing methods alternative to the one operationally used in CAMS (the median value from the different models for each variable and at each grid point and time step) have been investigated to combine individual model outputs in the ensemble, with sometimes impressive skill improvements at marginal cost. The main optimization methods tested for producing ensemble outputs were from the least squares family including standard least squares (MLS) and with nonnegative coefficients (MLSnn), least absolute shrinkage and selection operator (LASSO) and Tikhonov-type regularized least squares (RIDGE). Also, efforts to develop postprocessing of raw model forecasts [also called "model output statistics" (MOS)] have been devoted to providing adjusted point forecasts considering all the European sites providing observations routinely (Bertrand et al. 2022); such techniques can overcome limitations of the 10-km resolution of the regional systems and provide very accurate and almost unbiased forecasts. Some dedicated efforts also focused on presenting uncertainty in the air quality forecasts. All the above efforts have paved the way for new upgrades during 2022 and 2023, including operational MOS-adjusted forecasts for over a thousand observational sites in Europe.

Supplementary products

The supplementary services, which extend beyond the core global and regional monitoring and forecasting services, cover policy support through dedicated tools and assessment reports; solar and UV radiation products; atmospheric inversions for CO_2, methane (CH_4), and (N_2O) surface fluxes; and climate forcings (separately for carbon dioxide, methane, tropospheric ozone, stratospheric ozone, interactions between anthropogenic aerosols and radiation, and interactions between anthropogenic aerosols and clouds) that in particular support the academic sector and the Intergovernmental Panel on Climate Change.

Policy products are designed to support communication actions of policy-makers toward the general public, and for regulatory reporting according to the European Air Quality Directives. The online CAMS Air Control Toolbox (ACT) (Fig. 6) offers a flexible framework to explore the benefit of emission reduction strategies (Colette et al. 2022). The ACT has been designed through regular exchanges with users in the air quality policy domain, who were requiring a tool to assess the effectiveness of short-term measures on emissions to mitigate upcoming air pollution events. On a daily basis, users can simulate reductions of the emissions from four activity sectors (traffic, industry, residential heating, agriculture) and see what quantitative impact these would have on the forecast for the next few days. The methodology is based on a series of daily precomputed forecasts, which allow results to be displayed immediately. Initially, this tool offered only a selection of sectoral emissions reductions over the whole of Europe, but it was refined to assess the impact of reductions in individual countries. The CAMS Policy Scenario products are intended to illustrate the benefit expected from long-term mitigation scenarios following the Gothenburg protocol and National Emission Ceilings (NEC) targets for the atmospheric dispersion conditions of seven pollutants, by providing daily alternative forecasts based on the emissions corresponding to these mitigation targets and comparing with those based on current emissions.

The online CAMS source/receptor (S/R) capacity is provided for a range of EU cities. On a daily basis, it is possible to assess the local and imported (from outside the city area) contributions to forecasted particulate matter (PM_{10}, $PM_{2.5}$) and ozone (O_3), as well as the country of origin and in the case of aerosol, the chemical composition (Pommier et al. 2020; Pommier 2021). This tool is particularly useful in the case of major pollution episodes, for which specific reports are made available (https://policy.atmosphere.copernicus.eu/EpisodesAnalysis.php) and illustrated using the S/R tool. Aggregated S/R statistics are produced on an annual basis and synthesized in reports, which provide an overview of the origin and source apportionment of air pollution in the selected European cities (https://policy.atmosphere.copernicus.eu/YearlyStatistics.php?).

CAMS publishes annual air quality reports based on the regional reanalyses (both the ones using surface observations in an interim stage of validation and the ones using fully validated observations) describing the status of air pollution in Europe. They provide a description of the evolution of regulatory air pollutant concentrations (nitrogen dioxide, ozone, particulate matter) and the notable anomalies in a multiyear context, with a detailed analysis of the most severe large-scale episodes. Dedicated workshops for users in the policy sector are organized every year to facilitate interaction and keep CAMS dedicated line of "policy-support" products in line with users' current and emerging needs.

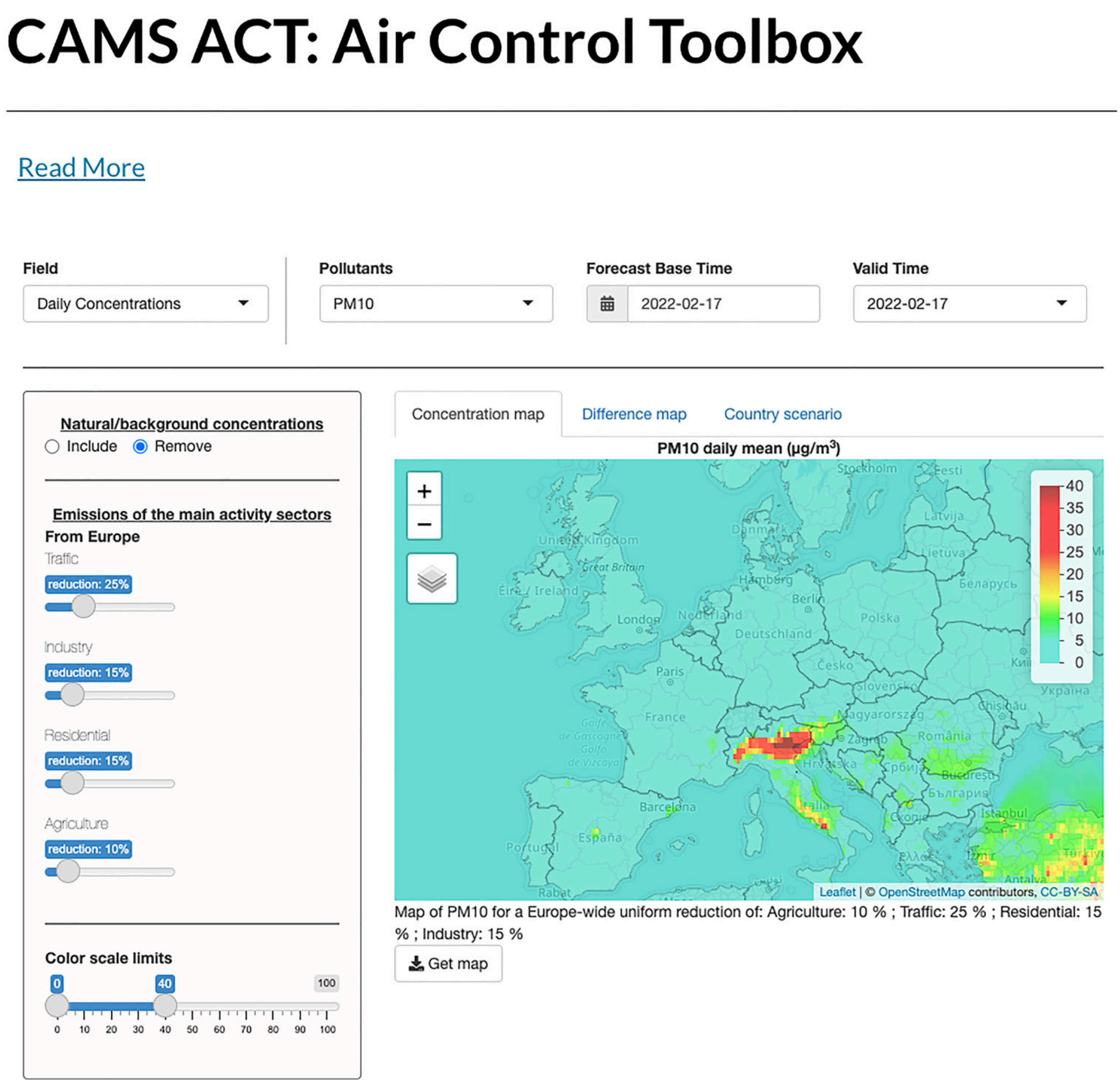

Fig. 6. Screenshot of the CAMS Air Control Toolbox illustrating the impact of short-term pan-European emissions reduction measures from various sectors on air quality over the next days. See https://policy.atmosphere.copernicus.eu/CAMS_ACT.php.

The CAMS solar radiation services provide historical values (2004 to the present) of global, direct, and diffuse solar irradiance, as well as of direct normal irradiance, which depend on various atmospheric quantities, such as clouds, aerosol optical properties, water vapor, ozone concentrations, ground albedo, and elevation. These information products fulfil the needs of European and national policy developments and commercial downstream services, e.g., for the integration of solar energy systems into energy supply grids. CAMS also delivers global UV irradiance analyses and forecasts, enabling health impact studies and downstream services such as smartphone applications and wearable technologies.

Natural and anthropogenic surface fluxes of GHG are key drivers of Earth's climate evolution and their monitoring is therefore essential. Atmospheric inversions of CO_2, CH_4, and N_2O

over the last decades are extended each year by CAMS to provide gridded estimates of global net fluxes at monthly resolution at least (Chevallier et al. 2019; Chevallier 2021).

CAMS produces climate radiative forcing relative to atmospheric composition, which quantify the effect of anthropogenic activities on Earth's energy budget. This is done by comparing today's atmospheric composition, using the CAMS reanalysis from 2003 to the present to numerical simulations of the preindustrial atmosphere, which are computed using the global system but using anthropogenic emissions estimated for the preindustrial era. Climate forcing is broken down into several components using radiative transfer modeling (Bellouin et al. 2020): aerosol direct and interaction with clouds, CO2, CH4, and stratospheric and tropospheric ozone. These are being used e.g., in IPCC Assessment Reports.

A near-real-time aerosol alert system (available at https://aerocom-alerts.met.no) provides an indication of significant anomalies of speciated aerosol optical depth (AOD) as well as particulate matter $PM_{2.5}$ and PM_{10} for the next few days.

A so-called CAMS weather room led by ECMWF and building on global and regional products is used to monitor and document noteworthy or anomalous events such as volcanic eruptions, large wildfires, ozone holes, sand and dust plumes, or pollution episodes in near–real time. This both serves for communications purposes and interaction with users but also feeds the process of identifying cases where forecasts have been particularly good or bad, which can guide future development objectives. The room, currently restricted to ECMWF staff and contractors, is planned to be part of an open resource to the community.

Communication and user engagement

As a user-driven service, CAMS requirements are recorded continually in the User Requirements Database (URDB) and prioritized and consolidated to support the short-, medium-, and longer-term evolution of the products and services. A wealth of user uptake and engagement activities are coordinated jointly between CAMS and C3S, including high-level interactions with international organizations (WMO, ESA, EUMETSAT, UNFCCC, IPCC, …), EU DGs (DEFIS, RTD, ENER, ENV, CLIMA, INTPA, …), national authorities and public administrations, industry, cities, and the general public.

To stimulate downstream application development and increase the geographical coverage of its uptake in all European countries, CAMS has supported the development of 17 use cases through competitive calls and covering a variety of sectors: downscaling air quality, support for tourism, aircraft maintenance, pollen, and allergic symptoms forecasts (Fig. 7). Many more have been developed since then within the community.

Windy, which provides leading weather forecast visualization services on smartphones and the web (see windy.com), now also features seven CAMS parameters for its global audience (Fig. 8). Well over a million individual users worldwide have used CAMS layers on Windy, accounting for 3%–5% of their traffic.

CAMS global and European forecasts are broadcast on leading media (Fig. 9). The CAMS branded Euronews Air Quality updates based on the ensemble forecasts reaches more than 10 million people annually in nine languages. The CNN Air Quality Update is broadcast across all regions of the globe and reaches approximately 225 million people annually.

The communication and outreach activities target a wide audience including policy-makers and governments, industry, academia, media, and the public with the overall aim to raise awareness about products and services and expand the user base. This has been achieved in various ways: proactive and reactive press activity via news releases, interviews and events, content creation and cross-channel campaigns (e.g., 10 million page views annually, 45,000 Twitter followers), active participation at European Commission level and international bodies [e.g., United Nations Framework Convention on Climate Change (UNFCCC)], bespoke press tours as media-focused education and engagement opportunities, targeted advertorial placements, etc.

User support aims at facilitating the user experience and is managed by ECMWF in coordination with C3S and involves also some of the CAMS providers for handling more specific queries. It offers a help desk, an online knowledge base with frequently asked questions, as well as a user support forum implemented under Confluence, extensive documentation on production systems and data, and regular user satisfaction surveys.

Training activities include three streams: online material, summer schools, and targeted events like hackathons. Various massive open online courses (MOOCs), attended on occasions by more than 5,000 people, were organized on topics such as the monitoring of atmospheric composition, use of Jupyter Notebooks to exploit CAMS datasets, renewable energy, AI, and machine learning. Those events were regularly organized jointly with partners such as EUMETSAT, ESA, Mercator Ocean International, or EEA. Some material is permanently accessible online (e.g., open GitHub repository for notebooks, full courses such as www.atmospheremooc.org).

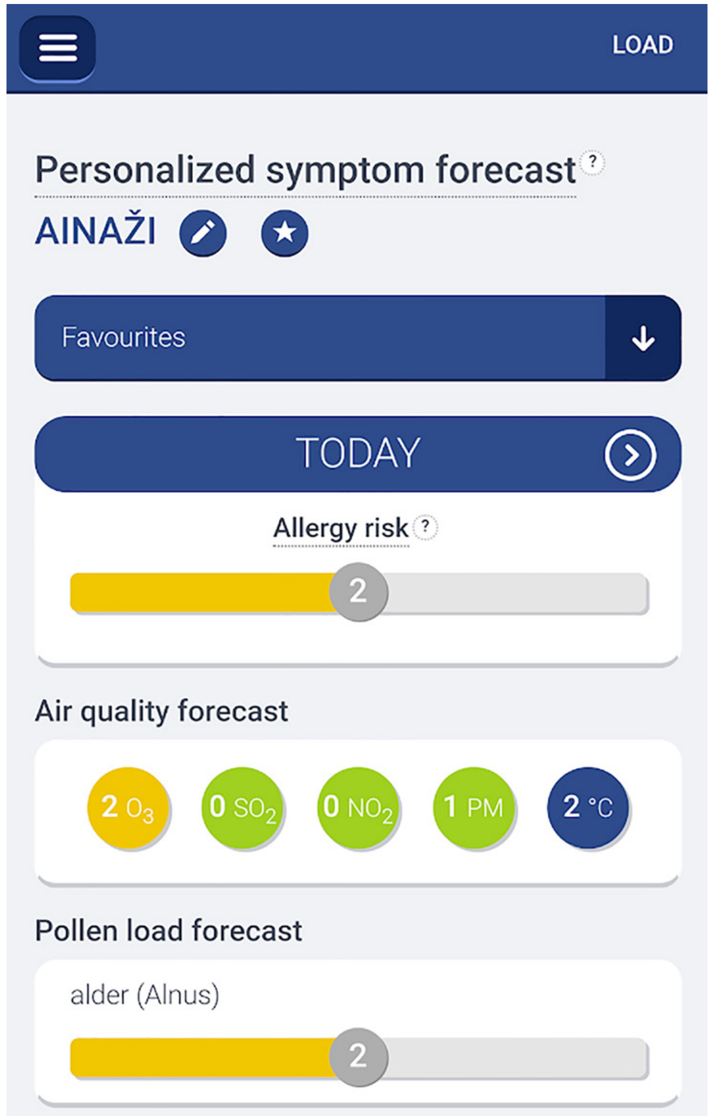

Fig. 7. Screenshot of the Personal Allergy Symptom Forecasting System (PASYFO) application developed by the University of Šiauliai, one of the CAMS use cases. It provides personalized allergy symptoms forecasts in Lithuania and Latvia. See https://atmosphere.copernicus.eu/pasyfo-forecasts-personal-allergy-symptoms.

Conclusions and outlook

CAMS has been operational since July 2015, building on scientific excellence and continual innovation and science knowledge transfer, as well as experience gathered during precursor EU research projects and regular feedback from users.

At the end of 2021, CAMS counted already over 23,500 registered users, including approximately 3,000 that critically depend upon CAMS outputs on a routine basis for forecasts and daily updated monitoring products. This number represents only the direct users and does not reflect the multiplier effect downstream applications and top-tier broadcast media. Raw or processed outputs are effectively reaching an audience of hundreds of millions. CAMS is routinely used as an authoritative resource by international press and media on the topics that it covers: air quality episodes, pollens, ozone holes, wildfires and smoke transport, volcanic eruptions, or GHG.

Despite major challenges such as the global COVID-19 pandemic, the service has proven to be extremely resilient with close to perfect time-critical data provision. Data flows, processing,

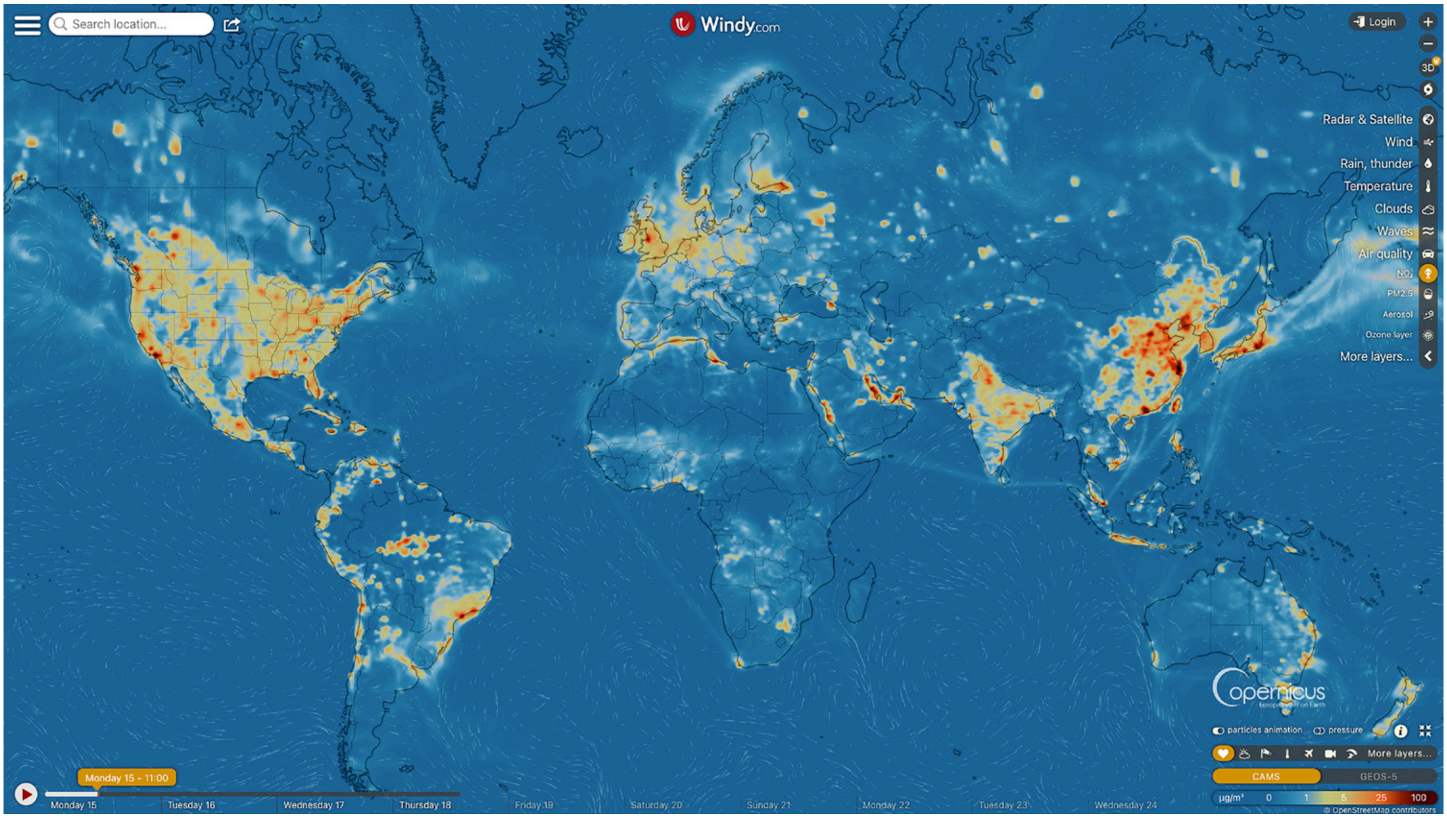

Fig. 8. Example of a CAMS data layer on Windy showing a global NO_2 forecast.

production, and dissemination have proceeded seamlessly, and the number of users is growing continuously.

For the next phase of the program 2021–28 (European Union 2021), the continuous evolution of service and infrastructure is vital to exploit new technologies, maintain the highest quality of products and meet the evolving user requirements (emerging policy needs, new markets, etc.).

The main foreseen addition to the CAMS portfolio of products will be on observations-based emissions of pollutants and GHG, which will be obtained by inverse modeling techniques and will rely on new satellite observing capacity and enhanced efforts on in situ measurements and data assimilation techniques. CAMS will provide the European Union and users worldwide with a comprehensive and consistent picture on the actual level of emissions by all countries and is hence expected to become a real game changer for policy monitoring. In particular, CAMS will implement and operate the anthropogenic CO_2 Monitoring and Verification Support (MVS) capacity, which will enable the monitoring of GHG emissions at global and local scales (e.g., detection of emitting hot spots such as megacities or power plants) as described in Janssens-Maenhout et al. (2020). CAMS will also deliver new air quality observations-based emission products relying on inverse modeling techniques by exploiting upcoming Sentinel-4 and Sentinel-5 data. Being in a geostationary orbit, Sentinel-4 will bring unprecedented capacity to assess emissions over Europe by offering an hourly revisit together with a spatial resolution of about 5 km × 5 km. CAMS will also utilize similar data over North America (TEMPO) and Asia (GEMS). Those missions will also be beneficial for improving estimations of CO_2 emissions from information on co-emitted species such as NO_2 or CO.

Global and regional atmosphere products will continue to be improved by ensuring the timely uptake of new Earth observation streams. A special emphasis will be put toward operationalization of deposition products (e.g., of nitrogen, sulfur, dust), detailed

Fig. 9. (top) The Euronews Air Quality update offers every day to its European viewers air quality forecasts of major European cities. Each city is featured with an air quality index, from 1 (very good) to 5 (very poor). (bottom) The CNN Air Quality Update is a daily broadcast that shows the air quality levels and forecasts around the globe. These tailored forecast reports are featured on the regional CNN feeds: EMEA, North America, Latin America, Asia, and South Asia regions. Euronews and CNN have chosen to communicate using an air quality index based on the definition of the European Environment Agency.

representation of stratospheric chemistry and addition of uncertainty information for all the CAMS products.

A new global reanalysis will be produced with the aim to include full stratospheric chemistry and, most likely, increased horizontal resolution. The regional reanalyses will be extended back from 2010 maybe as far as 2000 to support chronic impact studies on health, ecosystems, and agriculture.

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

A dedicated National Collaboration Programme will be created to enable each country to benefit from CAMS support (data and expertise) to fulfil their monitoring and reporting obligations, in particular the Air Quality Directive and reporting on GHG to UNFCCC.

Besides continuing to provide over the next seven years consistent and quality-controlled information related to air pollution and health, solar energy, GHG and climate forcing, everywhere in the world, CAMS will be a resource for the implementation of the European Green Deal, which commits the continent to cut down pollution and become carbon-neutral by 2050, and of the United Nations' Agenda 2030.

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Data availability statement. CAMS 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 Atmosphere Data Store at https://ads.atmosphere.copernicus.eu/.

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