BAMS Essay

The State of Earth Observing System Today: Updates Compiled from Recent EUMETSAT Meteorological Satellite Conferences

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ABSTRACT: This work presents highlights from the 2021 and 2022 EUMETSAT conferences, drawn from their presentations, posters, and panel discussions and placed into the wider context of the global Earth Observing (EO) system. These highlights collectively reveal much about the current state of knowledge about the EO system, its potential future evolutions, and how that system can be used to produce useful products and services. European, American, and Asian space agencies presented their visions for the next generation of operational satellite programs and demonstrated how these will continue to improve environmental forecasting and monitoring products. User communities presented updates on the use of satellite data, including climate records, novel precipitation retrievals, drought monitoring, weather forecasting, and retrievals of a broadening range of trace gases. On the technology side, discussion on the impact of artificial intelligence (AI) on Earth observation was a major theme, particularly for weather forecasting, data assimilation, or other environmental predictions. Cloud computing was another topic due to its potential to streamline the workflow of EO scientists, enhancing collaborations and unlocking access to previously unavailable data or computing resources. Finally, discussion on the miniaturization of observational instruments was another major theme of both conferences, highlighting both the possibility of novel or enhanced observations and the emerging economic case for commercial entities to operate fleets of meteorological satellites.

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1. Introduction

Since the middle of the last century, a multitude of satellites have been launched for the purpose of collecting observations of Earth. Today, the ability to predict high-impact weather events; observe the land, atmosphere, and oceans; or reconstruct the past weather and climate of Earth depends critically on satellite-based observations. Satellites have already revolutionized how human beings view, understand, and predict planet Earth (WMO 2015).

In the last decades, international coordination across operational meteorological agencies has facilitated the exchange and exploitation of large amounts of satellite data. The Coordination Group for Meteorological Satellites (CGMS, short description in Brown and Wooldridge 2015) facilitates the flow of operational weather and climate data from geostationary (GEO) and low-Earth-orbit (LEO) meteorological satellite systems. The changing technological landscape, with the miniaturization of sensors together with advances in small satellites (Millan et al. 2019; Stephens et al. 2020), makes the space observational capacity much more flexible and open to market solutions and offers new dimensions to global observing needs.

The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) organizes an annual conference to discuss the status of meteorological satellite systems and future evolutions. This is a forum for the discussion of the impact of satellite data in environmental forecasting and applications of satellite data to key sectors. The EUMETSAT conference gathers an international community at the interface between remote sensing science and operations.

In 2021 and 2022, the conferences revealed a fast-changing landscape at the crossroads between users' needs and technological/scientific advancements. Key challenges, such as future constellation concepts and achieving maximum exploitation of the upcoming programs, are under discussion within operational satellite agencies, i.e., EUMETSAT, the U.S. National Oceanic and Atmospheric Administration (NOAA), or Asian agencies such as the Chinese Meteorological Agency (CMA) or Japan Meteorological Agency (JMA).

While the specific session topics of the 2021 and 2022 EUMETSAT conferences are listed in the appendix (Table A2), there were a number of common themes addressed in both:

- New missions and satellite architecture
- Marine applications
- Atmospheric composition and air quality
- Greenhouse gas emissions and climate
- Numerical weather prediction (NWP) and nowcasting
- Observations of the land and cryosphere
- Future information technology and "big data"

In this paper, we draw upon these themes from the conferences to present the current status of the global, operational Earth Observing (EO) system, as well as a view on how this system will evolve in the near-term future.

2. Part 1: Where we are now

The number of entities with the ability to put satellite hardware into space has grown substantially since the 1950s. Multiple innovations across the space, materials, and computing sectors reduced costs to the point where launch services are now both offered and used by private firms as well as by governments. The result has been more satellites in space, with reportedly ~8000 registrations of objects being put into orbit (Geospatial World 2022). With more satellites has come more data, especially EO data, with predictions that this volume of data are expected to rise exponentially over the next few decades (Guo 2017).

Figure 1 presents the expected cumulative growth in the total data volume from EUMETSAT's geostationary Meteosat programs. The size of the bars represents a budget for data storage services across all data products from the Meteosat programs though actual data acquisition (i.e., filling of the budget) is continuous with operations over time. This explains the large growth in Meteosat Second Generation (MSG) between 2023 and 2024, followed by a leveling off from 2025 to 2027. A similar pattern would be expected for Meteosat Third Generation (MTG) in the future.

Over the period 2023–27, the volume anticipated by EUMETSAT operations that will be retrieved by MSG and MTG is expected to grow by an order of magnitude. MTG in particular highlights this growth. It is expected to retrieve a cumulative ~1000 TB in its first year of operation and up to ~20000 TB by the end of 2027, 4 years into the program's 20-yr operational lifespan. The Meteosat trend matches the broader trend in the explosive growth of data volume across all sectors (Yao et al. 2020). Such growth has also been seen in other EO programs, such as Copernicus, which publish annual reports detailing the growth of data of the Sentinel missions.

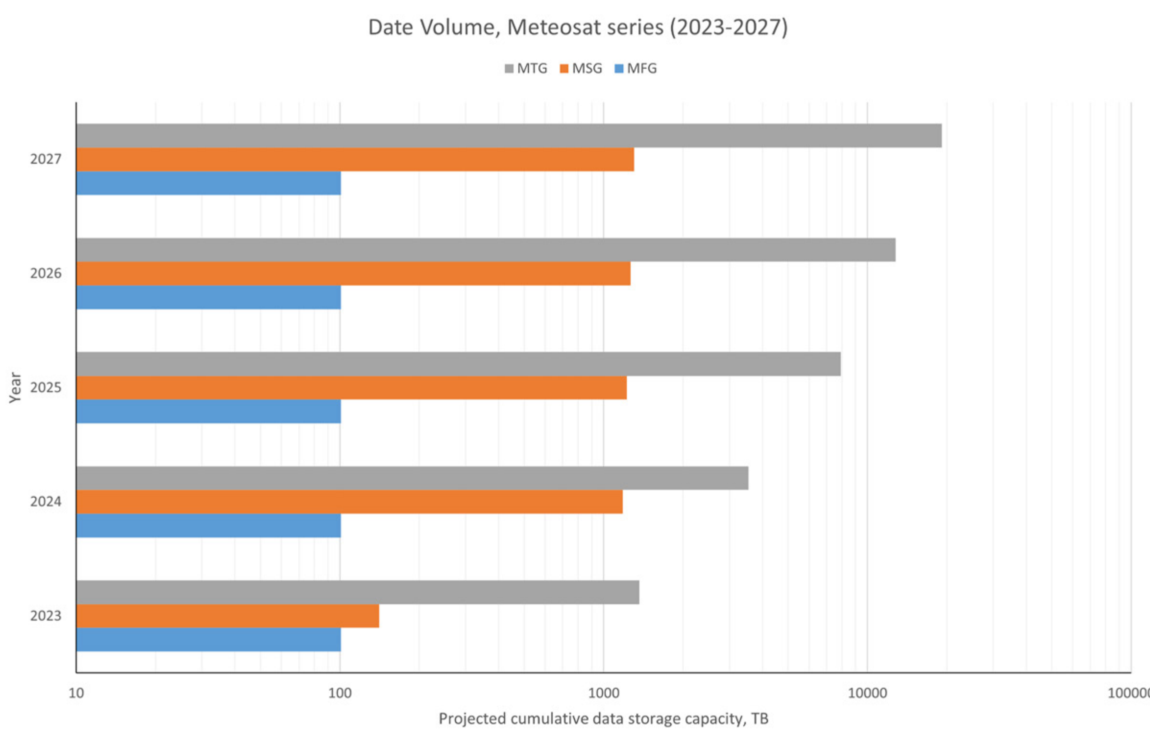

Fig. 1. Cumulative data storage (TB) volume, budgeted for each of the EUMETSAT geostationary programs (Meteosat) over the period 2023–27. MFG: Meteosat First Generation. Note: The scale is exponential.

In 2021, the report showed exponential growth in user download volumes from under 10 PiB (~11 300 TB) in 2015 to over 320 PiB (~360 300 TB) in 2021 (Copernicus 2021), implying a doubling in the volume just under once every year.

Despite the constant growth of the EO sector, the challenge remains to decide where to invest resources to best suit users' needs. The term "Users" refers to all users of satellite data, up and down the EO value chain: from government services to companies to individuals. Operational agencies like EUMETSAT engage in a rigorous process of user consultation, with a strong focus on the services provided by the national meteorological agencies of its member states. This involves engaging with the users to estimate the future evolution of products and services which, in turn, are translated into technical requirements in terms of spatial, spectral, and temporal resolution before implementing their satellite programs.

Specialized users contribute to the gathering of requirements, logging them into publicly accessible repositories. The World Meteorological Organization's (WMO) Observing Systems Capability Analysis and Review (OSCAR) tool (WMO-OSCAR 2023) logs current satellite observational capabilities and keeps a constantly updated record of user requirements as they arise. The process categorizes observational requirements into one of three categories according to WMO's rolling review of requirements (WMO 2022): threshold, goal, and breakthrough. Threshold is the minimum requirement that should be met so as for the data to be useful. Goal is achieving an ideal requirement, beyond which further improvements are not necessary. Breakthrough is a level between threshold and goal, where meeting the breakthrough requirements represents a major improvement to the current state of the observing system within a particular application area.

While investments in EO are growing, there remain a number of specific areas where the users have particularly requested improvements. In the next sections, inspired by the themes of the 2021 and 2022 EUMETSAT conferences, we discuss several examples of recent missions and other advancements in the use of satellite data, which highlight both how the users' needs are being addressed and areas where improvements are still required.

a. Marine applications: Ocean observations and coupling to the atmosphere. If we consider the interface between the ocean and the atmosphere, a critical parameter requested by the marine community remains surface winds. Sea surface winds are observed by satellites through different types of instruments, either "classical"—e.g., scatterometers, synthetic aperture radars (SARs), and altimeters—or more innovative, like Global Navigation Satellite System (GNSS) reflectometry (Park et al. 2011; Dong and Jin 2019), such as the proposed European Space Agency (ESA) mission HydroGNSS (Unwin et al. 2021). Regardless of the type of sensor, conference goers agreed on the need to improve the spatial resolution and our knowledge of small-scale variability in wind speeds, especially in coastal areas and during extreme events like tropical cyclones as a prerequisite for better forecasts.

Most operational scatterometers have a horizontal resolution of ~25 km (Lin et al. 2008). WMO-OSCAR lists the goal resolution requirement for sea surface winds as 15 km. Some instruments, such as the Indian Space Research Organisation's (ISRO) OSCAT (Mohapatra and Mitra 2021) (12.5 km) or CMA's WindRAD (Liu et al. 2023) (10 km), are already meeting this requirement when operating in their high-resolution modes. This will also be the case with the new scatterometer instrument (SCA) (Rostan et al. 2016) on board the EUMETSAT Earth Polar Satellite, Second Generation (EPS-SG). SCA will make measurements of cross-polarized signals for the first time, allowing retrieval of strong winds, down to 15–20 km (EUMETSAT 2019). This is twice the resolution of its EPS predecessor, ASCAT, and with better accuracy characteristics (Fois et al. 2020).

In addition to improving resolution, there is also a need to improve sampling. The current configuration of the scatterometer constellation is satisfactory in terms of the number of

Table 1. Operational scatterometer instruments in LEO as of January 2024. Adapted from information available from WMO-OSCAR (2023). NSOAS – National Satellite Ocean Application Service, CNSA/CNES – Chinese/French space agencies, CSCAT – (Hauser et al. 2019), and HSCAT – (Jiang et al. 2012).

Instrument	Satellite	Operating agency	Orbit
OSCAT	Oceansat-2	ISRO	1153 ECT
HSCAT	*HY-2B*	NSOAS	0600 ECT
CSCAT	*CFOSAT*	CNSA/CNES	0700 ECT
ASCAT	*MetOp-B*, *MetOp-C*	EUMETSAT	0931 ECT, 0931 ECT
OSCAT-3	Oceansat-3	ISRO	1200 ECT
WindRad	*FY-3E*	CMA	0540 ECT

scatterometers in flight, but the phasing of the constellation is not optimal. As summarized in Table 1, all of the instruments are clustered within morning orbits between 0540 and 1200 equatorial crossing time (ECT). Currently planned scatterometer missions: *Oceansat-3A* (launch: ~2025), *MetOp-SG-B* (2025), and *FY-3J* (2027), would enter the 1200, 0930, and 0500 ECT orbits, respectively.

Another requested improvement by those in the marine community, particularly those involved with ship route planning or sea-and-rescue missions, is improved precision and resolution for ocean topography variables, such as significant wave height. Doppler altimetry, which is operational with the Sentinel-3 and the Sentinel-6 missions—a session theme of the 2021 conference—has allowed for global ocean topography maps with a resolution of 100 km every 10 days and those with a resolution of 25 km every 7 days (Copernicus 2024). Both the Sentinel-3 and Sentinel-6 altimeters possess a high-resolution SAR mode, up to 300 m, allowing them to observe the topography of inland waters and coastal features (Le Roy et al. 2007; Donlon et al. 2011, 2021).

The Surface Water and Ocean Topography (SWOT) (Morrow et al. 2019) mission, launched in December 2022, provides similar observations with an even better 2D sampling resolution, down to WMO-OSCAR goal levels of 15 km. As with Sentinel-3/Sentinel-6, SWOT will be equipped with high-resolution SAR capability (100 m). SWOT covers approximately 86% of Earth's surface (78°S–78°N). While observations are not quite global, Sentinel-3/Sentinel-6 is complementary to SWOT, as they provide observations over the poles.

Moving to ocean color, observations have unlocked a new understanding of marine biogeochemistry, driven by bacteria and phytoplankton, in a diverse range of areas. These observations serve as validation for ocean models within the Earth system (Groom et al. 2019). In a practical sense, they have become critical in monitoring coastal and marine regions for harmful algal blooms, sediment plumes, or other hazards, with direct and indirect implications for human and ecosystem health.

There are several operational instruments for ocean color currently in orbit. In LEO, there are currently the Sentinel-3 (Donlon et al. 2011), Hai-Yan (Chen et al. 2020), and the Oceansat series (Chauhan and Navalgund 2009). In GEO, there is the recently launched (2020) *GEO-KOMPSAT-2B* (Ahn et al. 2010), which was presented by the Korea Meteorological Administration (KMA) at the 2022 conference. *GEO-KOMPSAT-2B* is currently the only ocean color instrument in geostationary, observing wide areas of the Pacific Ocean.

In terms of user requirements, the Global Ocean Observing System (GOOS) reports that users have specified a target uncertainty of 25% for water-leaving radiances and 30% for chlorophyll-a for climate applications (GOOS 2018), where uncertainty is defined as mean relative error, relative to the signal. More recently, scientists and modelers in marine communities have expressed higher accuracy requirements for water-leaving radiances and chlorophyll-a: 10%–25% and 25%, respectively (Groom et al. 2019).

In 2022, the National Aeronautics and Space Administration (NASA) presented the Plankton, Aerosol, Cloud, Ocean Ecosystem (PACE) mission (Gorman et al. 2019), which was launched at the beginning of 2024. PACE features one of the most advanced ocean color instruments (OCIs) ever put into orbit, meeting many of the GOOS requirements for ocean color. OCI observes broad spectral ranges from UV to near-IR (350–885 nm) and, in a first for ocean color instruments, is hyperspectral with a resolution of ~5 nm. There are also seven discrete shortwave IR bands at 940, 1038, 1250, 1378, 1615, 2130, and 2260 nm (Gorman et al. 2019). PACE's payload also includes two polarimeter instruments—SPEXone and HARP2—for measuring aerosols. These are used to both correct the ocean color observations as well as generate a suite of new aerosol products (NASA 2022a,b). Simulations have suggested that SPEXone observations in particular will improve forecast skill when assimilated into global NWP models (Hasekamp et al. 2019).

Sea surface temperature (SST) is a fundamental variable which is critical when describing the global circulation of energy. Participants of both conferences spoke of the need for both the improvement and continuity of measurements though analyses have shown there is little danger of a gap in SST observations (CGMS 2022). SST today is observed by many instruments both in GEO, e.g., the Advanced Baseline Imager (ABI) instrument (Schmit et al. 2005) on the recently launched *GOES-18* (2022) or *GOES-U* (2024), and in LEO, e.g., Cross-track Infrared Sounder (CrIS) (Bloom 2001) on the *NOAA-20*/*NOAA-21* missions. Improved observations are planned, including from the EPS-SG and MTG programs, as well as from Copernicus with the Sentinel-3 follow-on (Coppo et al. 2010).

On the LEO side, the MetOp-SG-A missions will carry the newly developed Infrared Atmospheric Sounding Interferometer—New Generation (IASI-NG) instrument which will have two spectral bands for observing SST: IAS-3 (770–1000 cm^{-1}) and IAS-11 (2420, 2450, 2600, and 2700 cm^{-1}) (Jurado et al. 2022). IASI-NG will double the spectral resolution and number of channels, as well as half the noise levels of its predecessor, IASI (Jurado et al. 2022).

On the GEO side, the MTG program features instruments capable of measuring SST on both the imager (MTG-I) and sounder (MTG-S) missions. The flexible combined imager (FCI), on board the imager mission, has 16 spectral channels and delivers cloud-sensitive observations in the 3.7 and 11 μm midwave IR and thermal IR channels, at a spatial resolution of 1–2 km, every 10 min (ESA 2024). When operating in high-resolution mode, FCI delivers images of selected regions every 2.5 min, with up to 0.5-km spatial resolution. This will improve upon the current *Meteosat-11*-/SEVIRI-derived near-real-time SST product, with higher temporal and spatial resolution.

From Copernicus 2.0, in addition to the Sentinel-3 follow-on mission, the Copernicus Imaging Microwave Radiometer (CIMR) (Donlon et al. 2023) is planned for 2028. CIMR is a two-satellite constellation equipped with a microwave radiometer. Its principal mission is to support European arctic policy by meeting a number of high-priority user requirements—quantifying SST, sea surface salinity, and sea ice concentration—in the polar regions.

b. Atmospheric composition: Air quality, chemistry, and greenhouse gases. The capabilities of satellite observations to monitor atmospheric composition and to evaluate tropospheric content variations at the regional scale are growing rapidly. The observational requirements and uses of existing data have been responding synergistically to the needs of diverse user communities. International climate agreements have been an important driver, as have national priorities such as the healthcare sector, air quality, and monitoring of wildfires.

For example, a recent novel algorithm development, presented at the 2021 conference, has allowed for the retrieval of vertical profiles of aerosol extinction from cloud-free measurements from the Tropospheric Monitoring Instrument (TROPOMI), on board the Sentinel-5P mission (Lemmouchi et al. 2022). This has allowed for the three-dimensional modeling of wildfire plumes, where derived aerosol optical depths are shown to correlate with reference missions MODIS and VIIRS, as well as the ground network AERONET.

The number of chemical species which can be retrieved is also fast-growing. High-resolution (3.5 km × 7 km) column retrievals of bromine monoxide (BrO) from TROPOMI have been demonstrated (Seo et al. 2019). The high resolution has allowed for the characterization of small-scale variability, such as in salt marshes, and has been proposed as a parameter for volcanic eruption forecasting (Warnach et al. 2022). Meanwhile, novel satellite retrievals for trace gases in the troposphere, such as glyoxal (OCHCHO), have been demonstrated and validated by Differential Optical Absorption Spectroscopy (DOAS) (Lerot et al. 2021).

The first of NASA's "Earth Venture" (NASA 2022b) initiatives, the Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission (Zoogman et al. 2017), was successfully launched in April 2023. The primary mission of TEMPO is to provide high-resolution atmospheric composition/air quality observations, provide information for use in chemical and pollution models, monitor exposure of the population to selected pollutants, and evaluate the effect of emission control strategies. TEMPO measures UV-Vis and near-IR spectra at an hourly rate, with a spatial resolution of ≤2.0 km in the north–south direction and ≤4.75 km in the east–west direction (NASA 2020), although ozone (O_3) products have a coarser resolution (8.0 km × 4.75 km). It retrieves concentrations of selected pollutants over North and Central America: total column ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), formaldehyde (HCHO), OCHCHO, H_2O, halogen oxides, and some aerosol, cloud, and foliage properties (Zoogman et al. 2017). Since February 2024, only unvalidated O_3, NO_2, and HCHO products have been made available to users via NASA's data store. There are secondary scientific objectives which TEMPO addresses, such as improving the state of understanding of NO_x emissions from difficult-to-estimate sources (e.g., soil emissions, lightning strikes).

Continued air quality coverage in North America is planned through NOAA's Geostationary Extended Observations (GeoXO) program, beginning at the end of the 2030s. The program was recently approved by the U.S. Department of Commerce in December 2022. It will be a three-member constellation: GeoXO-East, GeoXO-West, and GeoXO-Central. The central mission features the geostationary Atmospheric Composition instrument (ACX), which will provide hourly observations of pollutants over North and Central America. Currently, ACX's highest priority measurements are: O_3, NO_2, HCHO, OCHCHO, SO_2, and particulate matter from smoke, ash, and dust (Adkins 2022).

TEMPO is part of a three-mission constellation together with European and Korean contemporaries. The European contributions are the Sentinel-4, and Sentinel-5 series, with Sentinel-4 being the direct counterpart TEMPO. Sentinel-4 (Gulde et al. 2017), a mission under the Copernicus Programme, will be hosted on MTG-S with launch planned for 2025. The payload contains passive imaging spectrometers with two channels (UV-Vis and near-IR), covering three spectrometric bands: ultraviolet (305–400 nm), visible light (400–500 nm), and near-infrared (750–775 nm); it will make hourly observations with a spatial resolution of ~8 km^2 [ESA's European Space Research and Technology Centre (ESA-ESTEC) 2017]. This will cover most of Europe and large parts of North Africa (30°–45°E and 30°–65°N) (ESA-ESTEC 2017). Sentinel-4 will measure total column and tropospheric O_3 and NO_2, total column SO_2, HCHO, OCHCHO and aerosol, cloud and surface parameters (ESA-ESTEC 2017). Both Sentinel-4 and Sentinel-5 draw heritage from ESA's SCIAMACHY and Global Ozone Monitoring Experiment (GOME) instruments from the *Envisat* (Burrows et al. 2007) and

ERS-2 missions (ESA 2011), EUMETSAT's GOME-2 from the MetOp missions (ESA 2006), and TROPOMI from Copernicus Sentinel-5P (Fehr 2016).

The polar-orbiting Sentinel-5 mission (Bézy et al. 2014) is hosted on the MetOp-SG-A satellites, with launch planned for 2025. It will feature seven different spectral bands in five, passive-grating imaging spectrometer channels: two UV (270–300 nm and 300–370 nm), UV-Vis (3700–500 nm), near-IR (745–773 nm), and two shortwave IR (1590–1675 nm and 2305–2385 nm). It will observe O_3, NO_2, SO_2, HCHO, OCHCHO, methane (CH_4), and carbon monoxide (CO) with a spatial resolution ~7.5 × 7.5 km^2 and 50 × 50 km^2 for the UV channels.

Both TEMPO and Sentinel-4 will join the third member of the GEO UV-Vis constellation: the current Geostationary Environment Monitoring System (GEMS) instrument (Kim et al. 2020), onboard *GEO-KOMPSAT-2B*, in operation since 2020 [Korea Aerospace Research Institute (KARI) 2022]. GEMS is a UV-Vis grating imaging spectrometer, with a spectral range of 300–500 nm and a spectral resolution of 0.6 nm. It observes total column and ozone profiles, BrO, NO_2, SO_2, chlorine dioxide (OClO), and aerosols. It covers 5°–45°N, 75°–145°E.

While Sentinel-4 and Sentinel-5's roles in monitoring atmospheric composition from an air quality point of view are important, at the 2022 conference, the WMO also highlighted the need for accurate and better-resolved observations of greenhouse gases (GHGs), in particular, N_2O, CO_2, and CH_4. Characterizations of CH_4 emissions and sinks remain uncertain, as shown by the considerable disagreement between GHG inventory estimates made using "top down" and "bottom up" methods of emissions inventories (Deng et al. 2022).

Satellite observations can support these efforts, increasing confidence in "top down" estimates. While Sentinel-5 and its predecessor Sentinel-5P are able to retrieve CH_4, the Copernicus carbon dioxide monitoring mission (CO_2M) (Sierk et al. 2021) will be able to retrieve CO_2 and CH_4 concentrations with a resolution of 4 km, far better than existing missions. CO2M also offers good synergy with other major GHG-observing missions, such as the Japanese-led Greenhouse Gases Observing Satellite (Hamazaki et al. 2005) and GOSAT-2 missions (Imasu et al. 2023), which also measure CO_2 and CH_4 and have been operational since 2009 and 2018, respectively.

Beyond the gas phase, difficulties persist in generating an accurate estimate of the global aerosol budget. Sources of particulates can either be primary (directly emitted) or secondary (formed through chemical reaction pathway). Chemical composition influences the physical properties of aerosols, thereby influencing their fate in, and effects on, the atmosphere. The observation and modeling of such processes are relevant for improving weather prediction (Coopmann et al. 2018; Ménard et al. 2019) and understanding climate (Agusti-Panareda et al. 2014). An example would be whether a given aerosol ultimately forms clouds (Boucher et al. 2013) or the impact of its optical properties on the radiative forcing budget during its lifetime. Size and deposition rates also affect health and air quality via inhalation (Lelieveld et al. 2015).

Earth Cloud, Aerosol, and Radiation Explorer (EarthCARE) (Illingworth et al. 2015) is an aerosols-focused mission, presented during the 2022 conference. Developed through a collaboration between ESA and the Japanese space agency, EarthCARE (launch: 2024) is a sun-synchronous satellite with four instruments in its payload: a backscatter lidar, a cloud profiling radar, a multispectral imager, and a broadband radiometer. Its mission is to retrieve top-of-atmosphere radiances and build up three-dimensional profiles of clouds and aerosols, to study the relationships between aerosols, clouds, and Earth's radiation balance, providing new physical information for improving NWP and climate models (Wehr et al. 2023). EarthCARE's lidar will deliver information on aerosol optical depth and extinction which, when combined with backscatter and polarization information, should lead to the unprecedented ability to identify aerosol type (Illingworth et al. 2015).

c. Weather prediction: NWP, nowcasting, and extreme weather events. Although nowcasting systems have traditionally been distinguished as mainly observation- or NWP-based, they are increasingly combining both sources of information. In both 2021 and 2022, conference participants noted the integration of observation-based nowcasting and NWP to provide smooth, consistent forecasts—aimed to present outputs with consistency in quality, skill, and content, regardless of the underlying method, with lead times from minutes up to few hours ahead (Schmid et al. 2019).

Fast-developing atmospheric instabilities (i.e., mesoscale convective systems, squall lines, thunderstorms) remain the prediction target of nowcasting systems (Di et al. 2021). Specialized users in the hydrology community request reliable predictions up to 6 h ahead, increasing the need for combined radar- and satellite-based information. Data timeliness is critical, especially in rapidly developing situations such as continental summer storms. Such instabilities are often associated with high temporal and spatial variations in atmospheric temperature and moisture profiles. Future infrared sounders, such as the MTG-S infraRed sounder (IRS) (Tjemkes et al. 2015), will have 1960 channels within two major spectral bands and a high temporal (30 min over Europe, 6-h full disc), spectral (0.625 cm^{-1}), and spatial (4 km) resolution. The main mission of IRS is to provide users with high-resolution, three-dimensional information about the atmosphere, especially during preconvective situations, for operational meteorology.

A key question for conference participants was whether satellite infrared sounders remain competitive compared to other sources of information for nowcasting applications. Recent research projects, presented during the NWP sessions of the 2021 conference, near-Realtime Precipitation Estimation and Prediction (RealPEP) (Trömel et al. 2021) and Seamless Integrated Forecasting System (SINFONY) (DWD 2020), are exploring the value of a range of observational sources for seamless nowcasting prediction.

In 2022, preparation for new information coming from the next generation of EUMETSAT was the major theme of the conference. It is anticipated that new sensors will produce an enormous increase in data volume compared to what centers are used to dealing with today. In response, MétéoFrance presented simulations demonstrating how IRS data could be best utilized for NWP (Coopmann et al. 2022). They used several techniques: spatial sampling, principal component analysis, and channel selection as methods of thinning test data. Channel selection is a method that has been employed before for extracting useful information from previous generations of infrared instruments, including IASI (Collard 2007), from which IRS draws heritage. Their sensitivity analysis of each channel led to a proposed selection of 300 channels to be provided to centers though recent experiments utilizing information theory techniques have shown that channel selection in IR sounders leads to a significant loss of information. For example, a selection of 100 channels on CrIS contained 1.5–2 times less information than the full-spectral channel dataset (Smith et al. 2021), implying that there remains work for centers to do in order to maximize data utilization.

A key user requirement for NWP remains the ability to make observations of winds, particularly in remote areas or on a global scale. WMO-OSCAR has listed breakthrough requirements for lower troposphere winds at 100-km horizontal resolution, 1-km vertical resolution, and a measurement uncertainty of 3 m s^{-1} (WMO-OSCAR 2023). ESA's Aeolus Doppler wind lidar (DWL) mission (ESA 2018) has been able to meet or exceed each of these requirements. The DWL possessed two detection channels, Rayleigh and Mie, with a vertical resolution of 1 km for the Rayleigh channel and between 0.5 and 1 km for the Mie channel, validated by the German Deutsches Zentrum fuer Luft- und Raumfahrt (DLR) (Witschas et al. 2020). The horizontal resolution for each channel has been determined as 90 km (Rayleigh) and down to 10 km (Mie) and a variable uncertainty of ~2 m s^{-1} (Straume-Lindner et al. 2021). The ECMWF operationally assimilated several months of Aeolus observations to study the impact on global NWP. The results showed Aeolus observations were responsible for ~3% (Rennie et al. 2021) of the statistical impact in the short-range forecast (24 h) over a 6-month period in 2019, according to the forecast sensitivity to observation impact (FSOI) metric (Cardinali 2009). Statistically significant impact in the medium-range forecast (2–5 days) was also seen using the observing system experiment (OSE) methodology, which runs a forecast with and without a given set of observations. The impact on the 2–3-day forecast was on the order of +1%–2% but more neutral by day 5. Improvements were particularly pronounced in the polar regions and in the tropics, where observations are sparse. These impact figures were used in an EUMETSAT analysis (EUMETSAT 2023) to estimate the socioeconomic benefit of the operational follow-on, EPS-Aeolus, and its sister mission, EPS-Sterna. EPS-Aeolus was found to generate an economic benefit-to-cost ratio of 20:1, generating €13.6 billion of benefits for EUMETSAT member states. The mission is currently in development, with a launch planned for 2028.

d. Earth surface: Land observations and the cryosphere. The impact of Earth observations is most often felt over the land, with high relevance to the daily lives and livelihoods of many. The National Meteorological Administration of Romania, host of the 2021 conference, held a special session to promote a suite of recently released, operational agro-meteorology products. One product gives users weekly and up-to-seasonal predictions of drought conditions, such as atmospheric indicators of water stress (e.g., low rainfall) or indicators of thermal vulnerability (e.g., land/air temperature or scorching heat intensity). The system combines meteorological data with in situ data for physical (temperature, moisture) and ecological (phenological observations) monitoring (Irimescu and Alexandru 2020).

At the other end of the spectrum, the 2022 conference focused on flooding. Responding to requests from users in hydrology communities for satellite-derived estimates of precipitation, the Italian Dipartimento della Protezione Civile presented a multisensor approach to investigate severe precipitation, combining satellite (SEVIRI, ASCAT) and ground-based (radar, lightning) data products in Italy (Ciabatta et al. 2024). These multisensor precipitation estimates are then fed into hydrological modeling which is used to estimate river discharge over a 6-yr period. This research extends the functionality of an existing operational product, developed by the European hydrology community, which offers daily precipitation estimates from the integration of satellite-derived soil moisture products and state-of-the-art microwave products, known as SM2RAIN (Brocca et al. 2013).

Observations of Earth's sparsely observed polar regions are another frequently requested requirement. Variables such as sea ice thickness, snow depth, and ice-type classification are needed by several communities to improve NWP, marine, and other products. The mission that will address these requirements most directly is the Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) (Kern et al. 2020) mission, an operational follow-on to ESA's *CyroSat-2* mission (Wingham et al. 2006). CRISTAL (launch: 2028) will carry a dual-frequency SAR altimeter and will make observations of snow and ice in the polar regions.

Another program aimed at providing more observations over the poles is the ESA pathfinder mission, *Arctic Weather Satellite* (*AWS*; launch: 2024), and its planned EUMETSAT follow-on, EPS-Sterna (launch: 2029). Their primary missions are to support global NWP and nowcasting. EPS-Sterna is a constellation of three small platforms in scattered orbits (0330, 0730, 1130 ECT), selected to be complementary to the MetOp-SG (0930 ECT) and *NOAA-21* (1330 ECT) orbits. This configuration will achieve ~90% global coverage in ~3 h, with particularly high revisit times over the polar regions, averaging 20 min between observations at high latitudes. The Sterna missions, equipped with a 19-channel, hyperspectral microwave sounder instrument, will provide temperature and humidity profiles and cloud characteristics with high spatial resolution (10–40 km). Sterna will generate €32.7 billion (EUMETSAT 2023) of economic benefits to EUMETSAT member states, through providing valuable observations for use in global NWP, regional (Nordic) nowcasting, and climate models.

e. Monitoring the climate. For the last few decades, monitoring climate change has been a key goal of EO systems. Accurate predictions of the future state of the climate and what these predictions mean for human activities rely on accurate observations of the land, oceans, and atmosphere, at a global scale, over long periods of time (IPCC 2022).

In both 2021 and 2022, the focus of participants from the climate community was on creating long-term data records of satellite observations or geophysical variables, particularly those described by the essential climate variables (ECVs) (WMO 2014; Bojinski et al. 2014). Such data records are used in climate modeling and more innovative systems, such as digital twins (Hoffmann et al. 2023), to understand the impacts of climate change at the global and down to the regional scale.

Figure 2 summarizes the progress toward climate data records that were presented during the conferences, divided into the same themes that were derived from the conference sessions. From the marine community, records of ocean heat content in the North Atlantic—and the significance for climate dynamics—were presented. For atmospheric composition, there were new records for ozone columns, derived from GOME/GOME-2, Ozone Monitoring Instrument (OMI), Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY), and TROPOMI, as well as IASI-derived records of ammonia over northern Europe (Luo et al. 2022). Swedish Meteorological and Hydrological Institute (SMHI) presented an extension to the existing CLARA-A3 (Karlsson et al. 2023) cloud data record. CLARA-A3 contains satellite-derived (MetOp, NOAA) cloud parameters such as cloud mask and cloud-top temperature/pressure/height and radiation parameters, such as surface net radiation, top-of-atmosphere upwelling, or short/longwave radiation.

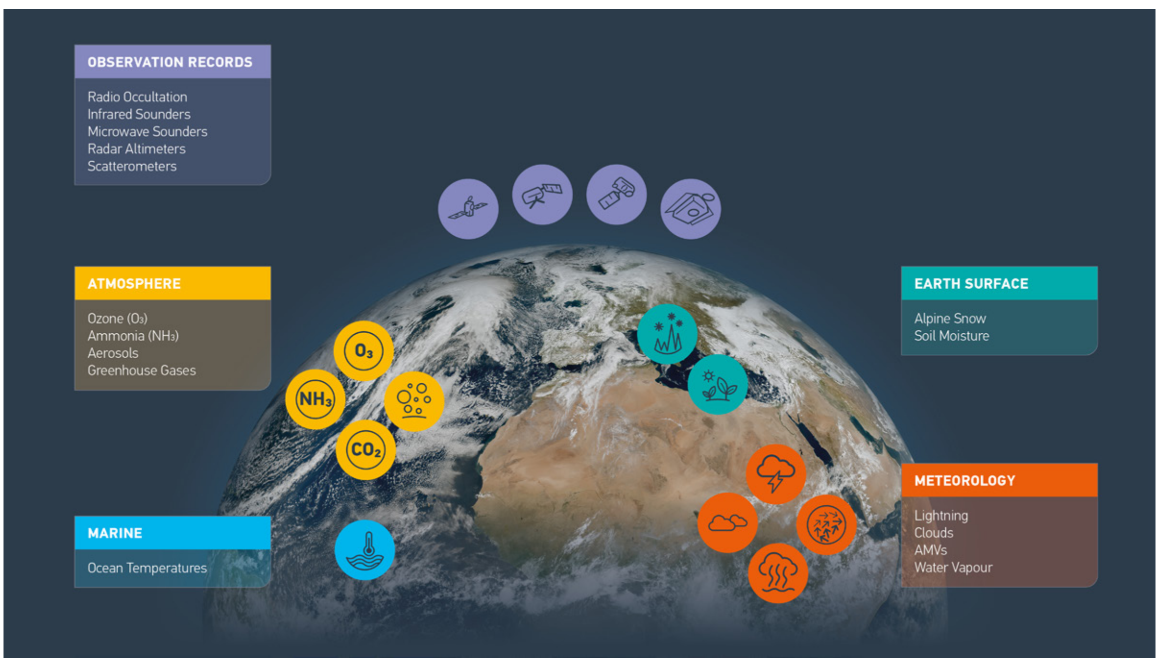

Fig. 2. Summary of new updates to climate records presented during the 2021 and 2022 conferences. This includes records that are new or either enlarged (e.g., cover more time) or enhanced (e.g., in terms of accuracy or resolution) in some way. Records cover both geophysical variables (i.e., L2 data or above) and instrument radiances (L1 data). AMV = atmospheric motion vectors.

SMHI extended the record from 34 to 42 years. For land, totally new records were presented, such as the 40-yr Alpine snow record from the University of Bern (Weber and Wunderle 2022), which was generated from Advanced Very High Resolution Radiometer (AVHRR) records from the polar-orbiting NOAA and MetOp satellites. New or extended records derived from instruments such as GNSS-Radio Occultation (GNSS-RO) [Radio Occultation Meteorology Satellite Application Facility (ROM-SAF) 2021] were also presented, giving users access to ~20 years of bending angles and related geophysical parameters (e.g., temperature, humidity).

3. Part 2: Forecasting the future

a. Artificial intelligence/machine learning. Progress in artificial intelligence/machine learning (AI/ML) systems is beginning to be felt across many of the traditional providers and users of satellite data. This is increasingly the case in operations and data services but has been ongoing in user communities for years.

While attempts to make an entire weather forecast using only AI/ML techniques are not new, they have hit important milestones recently. Good examples include FourCastNet (Pathak et al. 2022), GraphCast (Lam et al. 2022), and PanguWeather (Bi et al. 2023). These models create computationally inexpensive forecasts with similar accuracy to the ECMWF's Integrated Forecasting System (IFS), widely considered the best traditional global NWP model. Much like IFS, however, these ML forecast models still rely on receiving a steady stream of observations put into a specific, regularly spaced representation of geophysical variables, known as an analysis, to operate correctly. The mathematical framework used to combine observations (satellite, conventional, etc.) with forecast data (i.e., into an analysis) is known as data assimilation. Data assimilation can also feasibly be automated with AI, with such AI assimilation schemes currently being explored by NOAA (Boukabara and Maddy 2022). At the 2022 conference, Boukabara presented excellent efficiency, in terms of both the time and computing resources required to assimilate and fuse observations to be used in NOAA's Global Forecasting System (GFS) model. It should be noted that all of the major AI forecast models, thus far, require large quantities of high-quality data to train the models. The dataset used, ERA5 (Hersbach et al. 2020), is a 40-yr collection of gridded geophysical variables produced by the ECMWF assimilation system, referred to as a reanalysis.

Data fusion, i.e., combining data from disparate observations in a model to produce some new output, describing a complex, often nonlinear relationship, represents a promising use case for ML. Several novel approaches were presented at the 2021 and 2022 conferences. For example, Rashkovetsky et al. (2021) presented a model which used a combination of MODIS and Sentinel-1, Sentinel-2, and Sentinel-3 data to quickly identify fire-affected areas in California from space. The model was trained by associating different wavelengths, as observed by the different satellite instruments, with data from a California wildfire database with ~1000 parameters. When the different instrument inputs are put into the model, it can quickly identify fire-affected areas, with an accuracy of up to 96% in cloud-free scenes. The system also functioned well in a variety of weather conditions (i.e., cloudy scenes) with the correct combination of instruments. Such a system, though not yet operational, would greatly assist authorities with monitoring for wildfires over large, sparsely populated areas, providing crucial time for planning and executing a response.

Other novel data fusion techniques presented at the conferences included innovative precipitation systems leveraging commercial cellular network towers (Lian et al. 2022), combined with satellite and conventional data.

b. Cloud computing. Cloud computing is the on-demand availability of computing resources by networked machines often in physically different locations, up to the global scale.

Cloud systems are useful as they can be applied to a number of EO-relevant tasks: data storage, processing, and—when coordinated well between interested parties—accessibility and findability. Communities have noted that the ability to access computing processing resources on demand opens up possibilities for new research or operations, previously limited due to local computing resources.

A major advantage of this delocalized model is that large capital costs associated with securing necessary computing resources for institutions can be significantly reduced. Users are also increasingly able to access sophisticated digital services, such as AI/ML or digital twins, giving new options for data use and analysis. Data management and storage services within the cloud encourage the rapid dissemination of data and increase the chance of collaborations, even across different communities (Yang et al. 2016). Cloud service providers may also offer "data as a service," which allows users to quickly find relevant, well-structured datasets to facilitate their work.

There are also disadvantages to the cloud model. Clouds, as networked computer servers, are subject to downtimes for reboots, maintenance, etc. In a future where work is done principally within clouds, these downtimes could cause serious disruptions to research and operations. Furthermore, this only considers accidental or intentionally planned losses of service; cloud-based systems are also subject to service outages due to cyberattacks. Downtimes can be mitigated, however, through deliberate design choices, a good example being Azure's "availability zones" (Microsoft Azure 2024). These are groups of data centers which are close enough to each other to be connected in a low-latency, high-performance network but far enough away that they are unlikely to be affected by local issues, such as severe weather or power outages. The data centers which make up clouds also come with significant environmental concerns. The international energy agency (IEA) estimated that data centers' energy demand was already responsible for ~1% of all GHG emissions globally (IEA 2024). Additionally, increased usage of AI/ML has driven an upward demand for electricity, potentially doubling data center electricity demands by 2026 (IEA 2024). This demand could be mitigated, however, by taking advantage of renewable energy sources and efficient data center design. Legal barriers to data mobility are also starting to emerge, restricting opportunities for collaborations. Countries are increasingly setting rules on how data can and cannot transferred within and outside their borders in an attempt to gain a form of "digital sovereignty" (The New York Times 2022), citing concerns of privacy, security, and competitiveness.

Nonetheless, the adoption of cloud technologies will likely improve access to computing power and vast quantities of data, in turn necessitating a restructuring of the workflow currently employed by EO communities. During the 2022 conference's session on cloud computing, a problem noted by many was that relevant data are often hard to find, showing accessibility and findability are still relevant, unsolved problems. Cloud computing helps improve this suboptimal data ecosystem in several ways:

1) Projects which centralize and standardize similar datasets into a single virtual repository are currently being explored, such as the European Weather Cloud initiative (ECMWF 2024) or Destination Earth (https://destination-earth.eu/), which will deliver data access and cloud processing to the ECMWF, EUMETSAT, and national meteorological services.
2) Efforts taken at the (inter)national level have pushed data publishing toward standardized formats. In June 2019, the European Union adopted the open data directive to guarantee the accessibility of data generated by publicly funded projects (European Commission 2024). These data must be accessible by application programmable interfaces (APIs), hastening their integration into cloud services. Similarly in the United States,

the 2019 OPEN Government Data Act introduced a number of similar measures, requiring U.S. government agencies to publish data and literature on open licenses and in machine-readable formats.

3) The rise of so-called data-as-a-service companies. These companies have a business model to tie together datasets from different repositories into a single stream, which is tailored to a specific user.

c. SmallSats and commercial data providers. Miniaturization of instrument components has led to a dramatic decrease in the size and weight of satellites, while the cost of mass-producing them has gone down. By convention, satellites are commonly classified by mass, whereas satellites of less than 500 kg are considered small satellites, or “SmallSats” (Kopacz et al. 2020).

When compared to the larger platforms that have been typical for major operational programs, there are a number of advantages to using SmallSats. In addition to the relatively low cost per unit, launch costs are substantially lower (specifically for LEO). With many launches and carefully coordinated orbits, SmallSats can provide both broad (up to global) coverage and high revisit times (Kramer and Cracknell 2008). A multiagency review (Boukabara et al. 2021) of the future of the EO system offers an excellent overview of the arguments for, and the challenges of, a series of disaggregated, operational SmallSats. Since this model relies on launching more satellites, more frequently, as opposed to the usual operational time frame of ~7 years per satellite over a 15–20-yr period, it is possible to allow for the gradual evolution of sensors between launches. This allows agencies to respond to technological or user requirement changes in the EO landscape with more flexibility.

SmallSats have, however, created new challenges in the space industry. Lower cost of launch and operation has resulted in congestion in low-Earth orbit. With more than 8000 objects in space, concern about collisions and debris has been growing among satellite operators. In response, ESA has begun producing annual reports on the state of the space environment [ESA’s European Space Operations Centre (ESA-ESOC) 2023]. Sharp increases in debris, in terms of both the number of objects and their total mass, have been cataloged in LEOs since 2020, with simulations suggesting many more. Damage caused by satellite–satellite collisions or debris can lead to an exponential growth in debris, endangering functioning hardware and limiting the usage of large sections of low-Earth orbits (Bastida Virgili et al. 2016). The crowdedness of space has also caused issues with communications systems, with telemetry operating on the same radio frequencies interfering with one another and disrupting the operations of satellite missions (Oliva et al. 2016; Draper 2018).

The favorable economics for building, launching, and operating SmallSats is leading to a proliferation in companies offering commercial EO data, the so-called new space revolution. Since 2020, both NOAA and EUMETSAT have been purchasing GNSS-RO data from private firms Spire Global (EUMETSAT and NOAA) and GeoOptics (NOAA only). GNSS-RO observations—referred to as profiles—coming from private firms have been operationally assimilated into NWP models (Lonitz et al. 2021) for several years, alongside GNSS-RO data from government-run programs. The Spire Global and GeoOptics profiles are seen as supplementary by space agencies, a partnership which allows them to reach the desired 16 000–20 000 profiles/day requirement (Harnisch et al. 2013), defined in theoretical studies and needed to maximize impact in NWP. GNSS-RO can also be applied to climate analyses (Gleisner et al. 2022) and to space weather models (Angling et al. 2021).

The number of firms and types of observations are expanding. For example, Spire Global aims to add hyperspectral microwave sounders (Spire Global 2020) to its operations in the near future. In response to increased capabilities, NOAA's commercial data program has also expanded its scope. NOAA now hosts annual industry days and offers points of entry for companies that offer novel solutions to acquiring EO data which are able to probe other parts of the Earth system.

Investments into new space are robust and continuously expanding. However, there are several critical areas where users have requested guarantees to ensure the continuity of the services, including the following:

- Quality/accuracy: The accuracy and significance of downstream applications in weather prediction systems heavily depend on the availability of high-quality data with minimal errors.
- Continuity: Observations enhance prediction systems by utilizing data assimilation. In operational weather prediction centers, data assimilation schemes are customized to accommodate the type and number of observations from specific instruments and combine them optimally with forecast data. Therefore, maintaining consistency in the characteristics of observations, including their errors, improves the system's effectiveness and reduces maintenance expenses.
- Quantity/coverage: The expansion of services offered by meteorological agencies necessitates a greater volume of more diverse data across various spatial and temporal scales.

These needs can be efficiently met by using a blend of reference payloads and constellations of SmallSats. Nevertheless, it is essential to thoroughly examine the ideal alignment between these high-level requirements and the market's development.

4. Part 3: Summary and conclusions

In 2021 and 2022, EUMETSAT brought together scientists and other experts from the global Earth-observing community to participate in their annual meteorological satellite conferences. Participants used the forum to present and discuss the findings of new scientific studies, the performance and capabilities of new missions, the promise of emerging technologies, and the changing nature of users' requirements to meet the demands of today's society. New missions are addressing each of the major application areas that have been identified from the themes of the conferences: marine, atmospheric composition, weather prediction, land, and climate. These missions answer the requirements of the user communities, logged into databases such as WMO-OSCAR, and are being coordinated between the various global space agencies to ensure a reliable and continuous delivery of data.

Figures 3–5 summarize through Sankey-style diagrams the launched or firmly planned operational EO missions over the period 2020–50, including all missions discussed. The list of missions presented was adapted from the WMO's Integrated Global Observing System (WIGOS) Vision 2040 (WMO 2020), an initiative which outlines the evolution of the global EO system. The list was filtered according to the start date of 2020, the year leading up to the first conference, and for operational missions that are made by members of the CGMS, reducing the number of small demonstrator/research missions. Figure 3 includes all operational, geostationary missions; Fig. 4 contains all large, operational low-Earth orbit missions; and Fig. 5 contains all the smaller, topical missions, such as PACE or the Copernicus missions. In each case, the left column shows the name of the mission (or satellite series); the middle column shows the instrument types in each mission payload; and the right column shows how those instruments can be applied to each part of the Earth system. The thickness of each line from the second to the third column is determined by

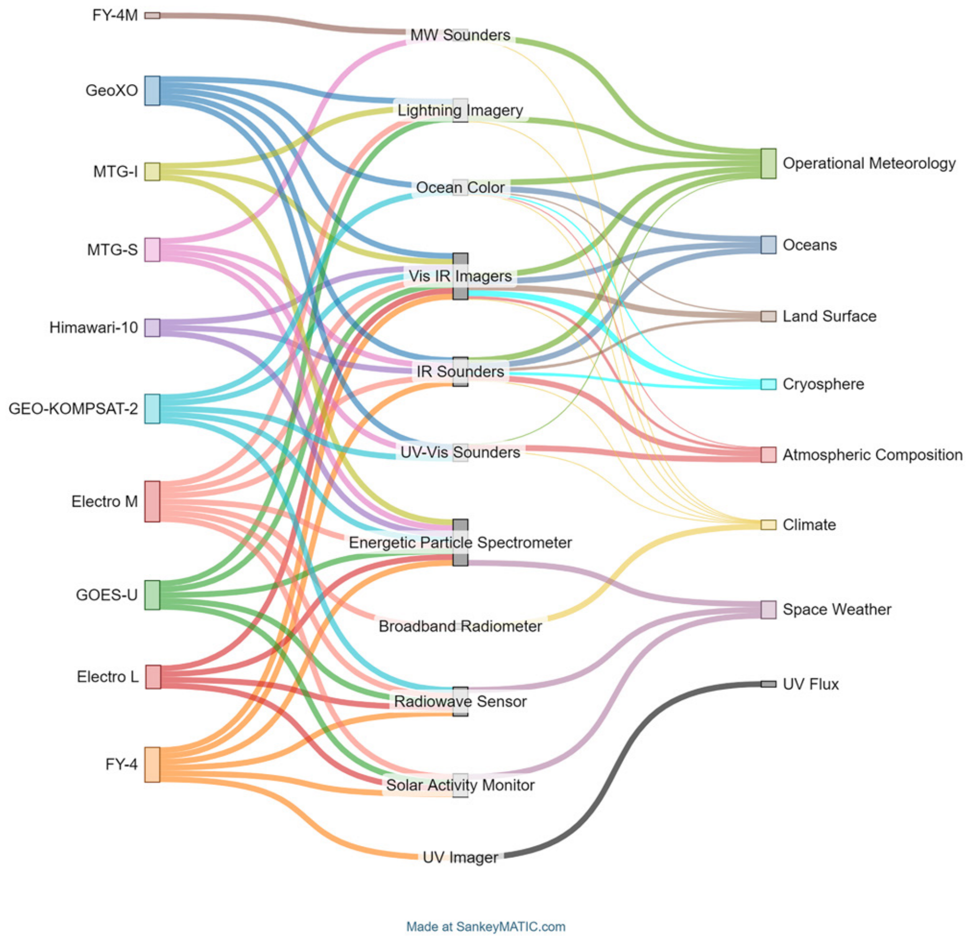

Fig. 3. Planned and new operational geostationary (GEO) missions covering the period 2020–50. Missions selected according to contributions to the WIGOS initiative from operational space agencies, determined by membership in the CGMS, as of 2020. (left) Names of missions. (center) A list of instrument classifications, taken from the WMO-OSCAR space-based capabilities. (right) Broad categories of applications across the different Earth systems. Connections between the right and center columns are determined by the payloads of the missions though they may represent more than one instrument. The connections between the center and left columns are determined by the authors' understanding of how important each instrument type's contribution is to the communities surrounding each application area. Each mission is connected by a unique colored line to each instrument it possesses and then to each application area by another unique colored line. Connections to climate are based on observational value to the creation of long-term climate records. Planned instrument information is collected from WMO-OSCAR and is correct up to March 2024. Note: Feng-Yun-4 (FY-4) includes *FY-4B–E*. GeoXO includes the East/West and Central missions. GEO-KOMPSAT-2 includes both the *GEO-KOMPSAT-2A* and *GEO-KOMPSAT-2B* missions.

how important data from that source is to a given community (e.g., ocean color is highly relevant to marine communities).

Novel uses of satellite data, presented at every EUMETSAT conference, continue to highlight the added value of satellite programs in diverse areas of the economy. This includes everything from weather prediction to monitoring for wildfires or from assessing water quality in the ocean to predicting where flooding or droughts might occur. Additionally, progress on ensuring high-quality, long-term records for climate models continues to be made, with more accurate, novel, and extended records from many different parts of the Earth system presented by conference participants.

Emerging technologies are opening up new opportunities for data usage, management, and acquisition. New AI/ML models have allowed more diverse sets of data to work together

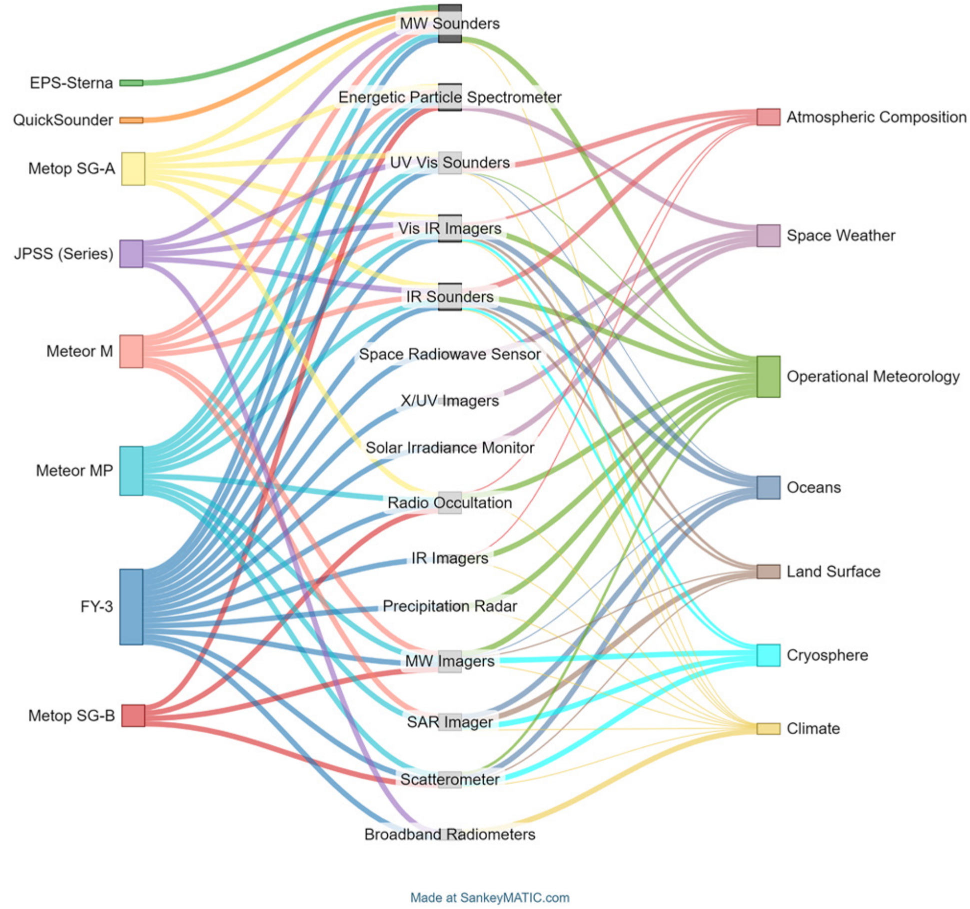

Fig. 4. Planned and new operational LEO missions covering the period 2020–50. Missions selected according to contributions to the WIGOS initiative from operational space agencies, determined by membership in the CGMS, as of 2020. (left) Names of missions. (center) A list of instrument classifications, taken from the WMO-OSCAR space-based capabilities. (right) Broad categories of applications across the different Earth systems. Connections between the right and center columns are determined by the payloads of the missions though they may represent more than one instrument. The connections between the center and left columns are determined by the authors' understanding of how important each instrument type's contribution is to the communities surrounding each application area. Each mission is connected by a unique colored line to each instrument it possesses and then to each application area by another unique colored line. Connections to climate are based on observational value to the creation of long-term climate records. Planned instrument information is collected from WMO-OSCAR and is correct up to March 2024. Note: Feng-Yun-3 (FY-3) includes *FY-3E–I*. JPSS includes *NOAA-21* but no additional planned follow-up(s) from the NEON program.

harmoniously to produce impressive results, such as the progress seen in fully data-driven weather forecasting models. Cloud computing, by allowing easy access to datasets and services such as computing power, facilitates a more cooperative model of both research and operations and may come to redefine the existing EO workflow. SmallSats, with low costs of production and operation, have enabled a boom in commercial data providers and allow space agencies to take a more agile approach to future missions.

The future of operational Earth observation is fast-changing and challenging. EUMETSAT conferences have become a major annual event for many researchers, user communities, businesses, and other space agencies. The 2021 and 2022 conferences were particularly interesting, coming during a period of change for the EO community, as users began preparation for the new generation of advanced satellites and as the capabilities of new technologies began to come into focus.

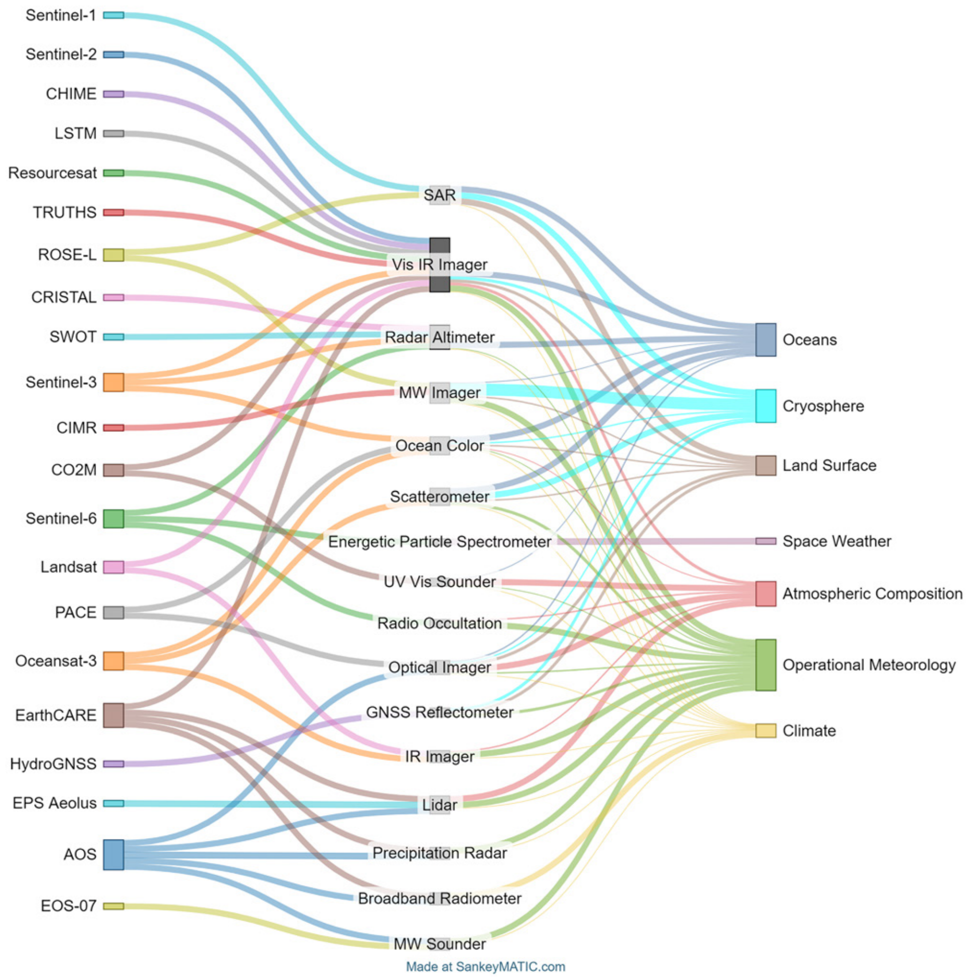

Fig. 5. Planned and new topical missions covering the period 2020–50. Missions selected according to contributions to the WIGOS initiative from operational space agencies, determined by membership in the CGMS, as of 2020. (left) Names of missions. (center) A list of instrument classifications, taken from the WMO-OSCAR space-based capabilities. (right) Broad categories of applications across the different Earth systems. Connections between the right and center columns are determined by the payloads of the missions though they may represent more than one instrument. The connections between the center and left columns are determined by the authors' understanding of how important each instrument type's contribution is to the communities surrounding each application area. Each mission is connected by a unique colored line to each instrument it possesses and then to each application area by another unique colored line. Connections to climate are based on observational value to the creation of long-term climate records. Planned instrument information is collected from WMO-OSCAR and is correct up to March 2024.

Acknowledgments. The authors thank the EUMETSAT Strategy, Communications and International Relations division for help with creating figures and both the National Meteorological Administration of Romania and the Royal Meteorological Institute of Belgium for their work in arranging the conferences. The authors would also like to thank the EUMETSAT data services for providing data to be used in the presented figures. Finally, the authors thank all conference presenters and participants whose work formed the foundations of this paper.

Data availability statement. Video recordings of conference talks, as well as accompanying slides and posters from both conferences, can be found and accessed online on the EUMETSAT website. The EUMETSAT Meteorological Satellite Conference 2021 is accessible at https://eumetsat.kuoni-congress.info/2021/programme/. The EUMETSAT Meteorological Satellite Conference 2022 is accessible at https://www.eumetsat.int/eumetsat-meteorological-satellite-conference-2022.

APPENDIX
Additional Information

a. Note on the figures. The Sankey diagrams (Figs. 3–5 were generated using the online tool SankeyMatic (https://sankeymatic.com/), produced by Steve Bogart. The .txt files used to generate the figures in the tool are available on request (Bogart 2014, 2024).

b. List of acronyms. Table A1 shows the main acronyms used in this publication.

TABLE A1. List of acronyms.

Acronym	Meaning
ABI	Advanced Baseline Imager
ACX	Atmospheric Composition Instrument
AERONET	Aerosol Robotic Network
AI	Artificial intelligence
AI/ML	Artificial intelligence/machine learning
API	Application programmable interface
AVHRR	Advanced Very High Resolution Radiometer
AWS	*Arctic Weather Satellite*
CGMS	Coordination Group for Meteorological Satellites
CIMR	Copernicus Imaging Microwave Radiometer
CLARA-A3	Cloud Albedo and Radiation climate data record
CNES	Centre National D'Etudes Spatiales
CNSA	Chinese National Space Administration
CrIS	Cross-track Infrared Sounder
CRISTAL	Copernicus Polar Ice and Snow Topography Altimeter
DLR	Deutsches Zentrum fuer Luft- und Raumfahrt
DWL	Doppler wind lidar
EarthCARE	Earth Cloud, Aerosol, and Radiation Explorer
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV(s)	Essential climate variable(s)
EO	Earth Observation
EPS	Earth Polar System
EPS-SG	EUMETSAT Polar System, Second Generation
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FSOI	Forecast sensitivity to observation impact
GEMS	Geostationary Environment Monitoring System
GEO	Geostationary (orbit)
GeoXO	Geostationary Expanded Observations
GFS	Global Forecasting System
GHG(s)	Greenhouse gas(es)
GNSS-RO	Global Navigation Satellite System-Radio Occultation
GOOS	Global Ocean Observing System
IASI-NG	Infrared Atmospheric Sounding Interferometer—New Generation)
IEA	International energy agency
IFS	Integrated Forecast System
(N/SW/M)IR	Near-/Shortwave/Mid-Infrared
IRS	Infrared sounder

(*Continued*)

Table A1. (*Continued*).

Acronym	Meaning
ISRO	Indian Space Research Organisation
JMA	Japan Meteorological Agency
KMA	Korean Meteorological Administration
LEO	Low-Earth orbit
MFG/MSG/MTG	Meteosat First/Second/Third Generation
MTG-I/MTG-S	MTG-imager/MTG-sounder
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical weather prediction
OSCAR	Observing Systems Capability Analysis and Review
OS(S)E	Observing System (Simulation) Experiment
PACE	Plankton, Aerosol, Cloud, Ocean Ecosystem
SAR	Synthetic aperture radar
SMHI	Swedish Meteorological and Hydrological Institute
SST	Sea surface temperature
SWOT	Surface Water and Ocean Topography
TEMPO	Tropospheric Emissions: Monitoring of Pollution
TROPOMI	Tropospheric Monitoring Instrument
UV-Vis	Ultraviolet(/visible) light
WIGOS	WMO Integrated Global Observing System
WMO	World Meteorological Organization

c. EUMETSAT Conference 2021: Session topics. Table A2 shows the session titles for EUMETSAT conference in 2021.

Table A2. List of the session titles from the 2021 EUMETSAT conference.

Session	Title
1	Status of meteorological satellite systems and future evolutions
2	First results from Sentinel-6 Michael Freilich
3	How the new generations of satellites revolutionise weather forecasting: MTG and EPS-SG user preparation
4	Impact of satellite data in global NWP (joint with ECMWF)
5	From agriculture to hydrology: the future of land applications
6	Marine meteorology from the tropics and to the polar regions
7	Climate and greenhouse gases monitoring from space
8	Air quality from space: the contribution of satellite data
9	Evolving data services: are we ready for artificial intelligence and machine learning applications?

d. EUMETSAT Conference 2022: Session topics. Table A3 shows the session titles for EUMETSAT conference in 2022.

Table A3. List of the session titles from the 2022 EUMETSAT conference.

Session	Title
1	Present and future horizons for satellite programs
2	EUMETSAT's next generation satellites: a foundation from seamless prediction systems (from minutes to days)
3	Exploring the applications and impacts of new satellite data
4	Advancing the digital transformation of our community, from the European Weather Cloud to AI/ML and big data
5	New horizons for user requirements
6	Assessing climate variability and change using satellite observations
7	From rainfall to hydrology, when operational products make a difference
8	New methods to exploit and visualize EO data

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