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Towards a Global Ground-Based Earth Observatory (GGBEO): Leveraging existing systems and networks

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REVIEW ARTICLE

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Towards a Global Ground-Based Earth Observatory (GGBEO): Leveraging existing systems and networks

Hanna K. Lappalainen [a], Alexander Baklanov [b], Jaana Bäck [c], Christos Arvanitidis [d,e], Sara Basart [f], Natacha Bernier [g], Dominique Berod [f], Thomas Bornman [h], Pier Luigi Buttigieg [i], Gregory Carmichael [j], Juanjo Dañobeitia [k], Yann-Hervé De Roeck [l], Sagnik Dey [m], Evangelos Gerasopoulos [n], Gregor Feig [o], Shahzad Gani [a,m], Helen Glaves [p], Silja Häme [a,q], Eija Juurola [q], Jörg Klausen [r], Paolo Laj [a,f], Barry Lefer [s], Henry W. Loescher [t,u], Michael Mirtl [v], Beryl Morris [w], Hiroyuki Muraoka [x], Hibiki M. Noda [y], Clare Paton-Walsh [z], Nicolas Pade [aa], Andreas Petzold [bb], Emmanuel Salmon [cc], Dick Schaap [dd], Serge Scory [ee], Krishna Achuta Rao [m], Jaswant Rathore [m], Martin Steinbacher [ff], Georg Teutsch [gg], Alex Vermeulen [hh], Xiubo Yu [ii], Steffen Zacharias [v], Leiming Zhang [jj], Tuukka Petäjä [a], Jürg Luterbacher [kk], James W. Hannigan [ll,mm] and Markku Kulmala [a]

[a]Institute for Atmospheric and Earth System Research / Physics, University of Helsinki, Helsinki, Finland; [b]University of Copenhagen, København, Denmark; [c]Institute for Atmospheric and Earth System Research / Forest Sciences, University of Helsinki, Helsinki, Finland; [d]lifewatch ERIC, Seville, Spain; [e]HCMR, IMBBC, Thalassocosmos, Greece; [f]World Meteorological Organization WMO, Geneva, Switzerland; [g]Meteorological Research Division, Science and Technology Branch, Environment and Climate Change Canada, Quebec, Canada; [h]South African Environmental Observation Network, Gqeberha, South Africa; [i]Joint Research Group for Deep-Sea Ecology and Technology, Alfred Wegener Institute, Bremerhaven, Germany; [j]Department of Chemical and Biochemical Engineering, University of Iowa, Iowa City, Iowa, USA; [k]Spanish National Research Council (CSIC), Barcelona, Spain; [l]EURO-ARGO ERIC, Campus Ifremer, Technopole Brest Iroise, Plouzané, France; [m]Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, New Delhi, India; [n]National Observatory of Athens (NOA), Penteli, Greece; [o]Department of Geography, University of Pretoria, Pretoria, South Africa; [p]British Geological Survey, Keyworth, Nottingham, UK; [q]ACTRIS ERIC Head Office, Helsinki, Finland; [r]Federal Office of Meteorology and Climatology Meteoswiss, Zurich Airport, Switzerland; [s]NASA Headquarters, Washington, DC, USA; [t]National Ecological Observatory Network (NEON), Boulder, Colorado, USA; [u]Institute of Alpine and Arctic Research, University of Colorado, Boulder, Colorado, USA; [v]UFZ Helmholtz Centre for Environmental Research, Leipzig, Germany; [w]TERN Australia, Indooroopilly, Australia; [x]National Institute for Environmental Studies, Gifu University, Gifu, Japan; [y]National Institute for Environmental Studies, Tsukuba, Japan; [z]University of Wollongong, Wollongong, Australia; [aa]EMBRC-ERIC, Paris, France; [bb]Forschungszentrum Jülich GmbH, Jülich, Germany; [cc]ICOS ERIC Head Office, Helsinki, Finland; [dd]MARIS B.V, The Netherlands; [ee]Royal Belgian Institute of Natural Sciences, Brussel, Belgium; [ff]Laboratory for Air Pollution / Environmental Technology, EMPA, Duebendorf, Switzerland; [gg]Helmholtz-Zentrum für Umweltforschung /Environmental Research Center, UFZ, Leipzig, Germany; [hh]ICOS ERIC Carbon Portal, Lund, Sweden; [ii]Chinese Ecosystem Research Network (CERN), Chinese Academy of Sciences, Beijing, China; [jj]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing,

CONTACT Hanna K. Lappalainen hanna.k.lappalainen@Helsinki.fi INAR Physics, University of Helsinki, Gustaf Hällströmin Katu 2, Helsinki, 00560, Finland

Present affiliation of Natacha Bernier is Météo-France, Toulouse, France
Secondary affiliation of Sagnik Dey is Department of Health, Policy and management, Korea University, Seoul, South Korea
Primary affiliation of Gregor Feig is South African Environmental Observation Network, Pretoria, South Africa
Present affiliation of Hiroyuki Muraoka is Graduate School of Agricultural and Life Sciences, The University of Tokyo, Bunkyo-ku, Tokyo, Japan

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China; [kk]Center for International Development and Environmental Research and Department of Geography, Climatology, climate Dynamics and Climate Change, Justus Liebig University of Giessen, Giessen, Germany; [ll]Network for the Detection of Atmospheric Composition Change (NDACC), NASA, USA; [mm]National Center for Atmospheric Research (NCAR), Boulder, Colorado, USA

ABSTRACT

To tackle the planetary environmental and climate crisis and meet the United Nations' Sustainable Development Goals (SDGs), we must fully leverage the potential of Earth observations (EO). This involves integrating globally sourced data on the atmosphere, hydrosphere, cryosphere, lithosphere, along with ecological and socio-economic information. By harmonizing and integrating these diverse data sources, we can more effectively incorporate observational data into multi-scale modeling and artificial intelligence (AI) frameworks. This paper is based on discussions from the "Towards Global Earth Observatory" workshop held from May 8–10, 2023, organized by the World Meteorological Organization (WMO) and the Atmosphere and Climate Competence Center (ACCC), in collaboration with the Institute for Atmospheric and Earth System Research (INAR) at the University of Helsinki. The current state of EO and data repositories is fragmented, highlighting the need for a more integrated approach to establish a new global Ground-Based Earth Observatory (GGBEO). Here, we summarize the current status of selected in-situ and ground-based remote sensing observation systems and outline future actions and recommendations to meet scientific, societal, and economic needs. In addition, we identify key steps to create a coordinated and comprehensive GGBEO system that leverages existing investments, networks, and infrastructures. This system would integrate regional and global ground-based in situ and remote sensing systems, marine, and airborne observational data. An integrated approach should aim for seamless coordination, interoperable and harmonized data repositories, easily searchable and accessible data, and sustainable long-term funding.

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1. Introduction

Our planet is facing an acute and systemic crisis. In 2023 and 2024, we observed alarming increases in ocean temperatures (Cheng et al., 2024), record low Antarctic ice cover (Purich & Doddridge, 2023), more frequent and intense extreme heat events like the Cerberus heat wave in Europe (Tripathy & Mishra, 2023), and record-breaking wildfires in Canada (Barnes et al., 2023; Blunden & Boyer, 2024). These events are no longer anecdotal; they indicate multiple planetary tipping points that are either imminent or have already been surpassed (Richardson et al., 2023). Recent reports on planetary-scale environmental boundaries highlight that out of nine "planetary control variables": (i) climate change, (ii) ocean acidification, (iii) stratospheric ozone depletion, (iv) atmospheric aerosol loading, (v) biogeochemical flows, (vi) freshwater change, (vii) land system change, (viii) biosphere integrity, and (ix) novel entities (e.g., harmful chemicals and materials)-six are at increased risk of breaching a tipping point. Only three variables (stratospheric ozone depletion, atmospheric aerosol loading, and ocean acidification) currently remain within a "safe operating space," but they are still at risk (Richardson et al., 2023; Rockström et al., 2024).

Despite advancements in multi-scale, high-resolution modeling (e.g., Stevens et al. (2024)) and increased availability satellite data, there is an urgent need for more comprehensive and reliable Earth Observation (EO) data. Additionally, the development of next-generation environmental services (Guo, 2018; Kulmala, 2018) must be harmonized, open, and aligned with the FAIR (Findable, Accessible, Interoperable, Reusable) and TRUST (Transparency, Responsibility, User focus, Sustainability, and Technology) principles (Lin et al., 2020; Wilkinson et al., 2016). With unprecedented volumes of open, web-accessible and machine-to-machine readable data and revolutions in Artificial Intelligence (AI)-assisted synthesis and processing, we are now better equipped to investigate and explain the mechanisms involved in ecosystem responses and feedbacks to atmospheric, terrestrial, and aquatic systems. This also enhances our ability to select and test mitigation and adaptation measures (Stevens et al., 2024). Political, thematic, and regional silos in EO activities and data persist, obstructing the development of planetary-scale information systems that are crucial for humanity to effectively manage adaptation to and mitigation of adverse changes in the Earth system.

Only a holistic effort to merge EO systems into a single global Earth Observatory (GEO) and the initiatives such as Global Ground-Based Earth Observatory (GGBEO) can transcend thematic, project-centric, and local/regional data provision. Such a globally harmonized effort is essential to supply the necessary observations at the appropriate spatio-temporal resolution. In our current era, global civilization continues to redefine "big data" and increasingly publishes data openly. Integrating big data enables us to quantify the interconnections and feedbacks within the Earth system, enhancing our understanding of global challenges such as climate change, biodiversity loss, and human-induced pollution (Carmichael et al., 2023; Lenton et al., 2019; Kulmala et al., 2021; Petzold et al., 2024; Zacharias et al., 2024; Kigali Declaration).

A long and rich legacy of EO has developed over the last century, with substantial, if dispirit, elements of a global ground-based in-situ and remote-sensing operational networks delivering key data (see Appendices 1 and 2). However, areas of Africa and southern America and parts of Asia as well as the ocean regions remain under-sampled. The GGBEO can capitalize on the existing observation networks' social structure, research infrastructures, domain knowledge, and data repositories in a unified and coordinated manner. This will allow the community to leverage the existing foundation and determine what additional elements are necessary. A step in this direction has already been taken with the definition of the World Meteorological Organization's (WMO) Global Basic Observing Network (GBON) and the WMO Executive Council's decision to develop an architecture for a global Greenhouse Gas Monitoring Infrastructure (WMO EC-75/Doc. 4(3)). The WMO proposed that the Global Greenhouse Gas Watch (G3W) will build on the existing Global Atmosphere Watch (GAW) network and facilitate the exchange and use of observations under the WMO Unified Data Policy (Resolution 1, Cg-2021). This collaboration will involve the scientific community, other United Nations agencies, the Integrated Global Greenhouse Gas Information System (IG3S), and existing international Greenhouse Gas monitoring entities (GAW and partners, GCOS, CEOS, CGMS, GEO, IOC/GOOS, and ICOS European Research Infrastructure Consortium (ERIC). In addition to observations within the WMO Integrated Global Observing System (WIGOS), that includes GBON, GAW, GCOS, GOOS, WHOS, are partners providing data and analysis of the atmosphere, ocean, lithosphere, ecosystem, biodiversity, and socio-economic state. These provide insight, experience and the basis for the future observation system (Acronyms: see Appendix 1). Furthermore, in Europe, European Environmental Research Infrastructures (ENVRI) activities aim to integrate the data systems of the present environmental European Strategy Forum on for Research Infrastructures (ESFRIs).

The aim of this paper is to discuss the key properties of current ground-based terrestrial, marine, and airborne Earth observations and data repositories, and to outline the next steps towards a more holistic, integrated, accessible approach. This foundation will support the establishment of a future global Earth Observatory. We examine the lessons learned from this journey and explore the forthcoming steps required to establish a new, coordinated, and comprehensive GGBEO as part of the Earth Observation system.

This paper is based on discussions and synthesis from the "Towards Global Earth Observatory" workshop held from May 8–10, 2023, organized by the WMO Atmosphere and Climate Competence Center (ACCC), in collaboration with the Institute for Atmospheric and Earth System Research (INAR) at the University of Helsinki. The workshop gathered approximately 50 participants representing in-situ networks and research infrastructures, remote sensing, and modeling communities from Europe, North America, Australia, and Asia (see Appendix 3).

2. Current ground-based Earth observation system

2.1. Current organization of the ground-based observations

Currently, most observation systems are specialized and focus exclusively on specific domains such as the hydrosphere, atmosphere, biosphere, and lithosphere, with cross-cutting realms like hazards, risks, and socioeconomics (urban). These systems are typically developed from the perspective of a particular scientific discipline, such as atmospheric or marine sciences, or ecology, often concentrating on specific subtopics or variables, such as atmospheric aerosols, ozone, or greenhouse gases in certain geographical areas. These areas are typically organized into national, continental, and global networks. For example, in the terrestrial domain, significant national observation systems include ecosystem networks like South African Environmental Observation Network (SAEON) (van JaarsveldI et al., 2007) and Chinese Ecosystem Research Network—CERN (Fu et al., 2010). These systems also extend to continental coverage, with examples including Australia's TERN (Cleverly et al., 2019), the Integrated European Long-Term Ecosystem Research (eLTER) network, and the National Ecological Observatory Network (NEON) in North America. All of those contribute to the Global Ecosystem Research Infrastructure (GERI) (Loescher et al., 2022). In addition to these thematic systems, integrated interdisciplinary networks, stations, and initiatives/programs have been developed to provide a more comprehensive approach to ecosystem monitoring.

Another example is from the oceanic environment. Marine observations are divided into geographic regions: the Arctic Ocean, North Atlantic, South Atlantic, North Pacific, South Pacific, Indian, and Southern Oceans, as well as comprehensive all-seas systems. These observation systems are often categorized further into oceanographic and biological domains. For example, the "Comprehensive All-Atlantic Ocean Observing System" (ATLAN) focuses on oceanographic observations, while biological monitoring is exemplified by the European Multidisciplinary Seafloor and water column Observatory (EMSO), coordinated by the European EMSO-ERIC (www.emso.eu). Coastal observation systems are considered a separate category, with initiatives like JERICO-RI, described as "an integrated pan-European, multidisciplinary, multi-platform research infrastructure dedicated to a holistic assessment of coastal marine system changes." Historically, marine platforms illustrate how national infrastructures have evolved into global programs. For instance, radiosonde data, which dates back nearly a century, represents one of the earliest networks for global weather forecasting (Durre et al., 2006; Grant et al., 2009; Imfeld et al., 2021; Ramella Pralungo et al., 2014). In the realm of ocean observations, the global Argo program began in 1999. Fifteen years later, in 2014, Euro-Argo ERIC was established to coordinate Europe's contribution, comprising one-quarter of the global fleet. The introduction of the first biogeochemical (BGC) floats followed in 2016 (see Appendix 2 for the history line). The European Marine Observation and Data Network (EMODnet), established in 2009, is a major initiative of the European Commission (EC). EMODnet provides in-situ marine environmental and human activity data and data products for a diverse range of end users from various sectors.

The current eco-system of these observation systems encompasses individual observation stations, networks of observations, systems of systems, infrastructures, data centres, and extensive observation programs. These categories demonstrate the complexity of the systems at a wide range of scales and domains. A comprehensive analysis of the current systems is needed, which has been initiated and in progress by the European Observatory of Earth Observation Networks (ENEON) in collaboration with the ERA-PLANET GEO Essential (Lehmann et al., 2022). Additionally, it is important to understand and take account of how observational networks and systems have developed over time. The histories of ICOS and ACTRIS from a European perspective illustrate that focused ambitions similar to the GGBEO took more than a decade to materialize. Furthermore, we could explore the growing importance of monitoring essential climate variables through integrated atmospheric research infrastructures such as ACTRIS, IAGOS, and the ICOS Atmosphere Thematic Centre, as described by Petzold et al. (2024).

2.2. Data exchange and data systems

EO data exchange has a long history and has developed differently across various disciplines. The new GGBEO should encompass all stages of the process, from observation planning to data collection and harmonization to the dissemination of new knowledge and innovations. Coordination Centres on Observations, such as those established at the European level (e.g., the Europa Biodiversity Observation Network—EUROPABON Project and its Proposal for an EU Biodiversity Observation Coordination Centre—EBOCC), provide valuable insights that could significantly benefit global efforts.

Investment at the European level has led to the development of the European Open Science Cloud (EOSC), a technological "system of systems" for science, which offers both experience and support to enhance EO initiatives. ENVRI-hub is an environmental data portal that provides services from European environmental research infrastructures (Petzold et al., 2024). The hub (https://envri-hub.envri.eu) offers open data access across Earth system disciplines and strives to provide a user-friendly interface for scientists interested in interdisciplinary environmental research, allowing them to conduct analyses with the computing resources offered by the hub. The ENVRI Science Cluster represents a state-of-the-art platform in the research infrastructure (RI) landscape, where numerous data repositories and portals have otherwise developed alongside observation systems. The ENVRI cluster is connected to the EOSC via ENVRI-FAIR (more on this in Section 3).

In Table 1, we list a wide not complete range of different EO systems and related data portals. The table highlights the current lack of a single system where end users can easily access observations from different fields. Instead, data must be retrieved from multiple data portals, each with different data practices. For example, data from observation networks and RIs, such as the WMO GAW sites and European RIs (e.g., ICOS, ACTRIS, IAGOS, Euro-Argo), is collated and made available by centralized data and metadata portals like the "Observation Systems Capability Analysis and Review Tool" (OSCAR), as well as numerous national portals. To ensure that data portals remain relevant over time, the European Commission (EC) has recommended standard design features for inclusion when designing open data portals (Simperl & Walker, 2020). The EC recognizes that portals are central points of access for datasets, enabling data to be found and their development is associated with the emergence of FAIR (Findable, Accessible, Interoperable, Reusable; Wilkinson et al., 2016) and Open Data principles (Simperl & Walker, 2018).

3. Limitations of the current ground-based observation systems and needed future developments

3.1. Drivers towards the new Global Ground-Based Earth Observatory (GGBEO)

In the existing EO systems, data collection is conducted discipline by discipline and processed separately (Figure 1a). Over the years, several groups have proposed establishing a large joint EO system and integrated data infrastructures to combine environmental data and analysis (Huber et al., 2021), strongly supporting the need for GGBEO. Actions towards this goal and a more integrated European data system have been initiated by the ENVRI-FAIR project of the European Union's Horizon 2020 program (EU H2020). This project connects ENVRIs to the European Open Science Cloud (EOSC) and provides a set of interoperable FAIR data services (Petzold et al., 2019). Previous work has addressed questions related to different types of observations, their co-location and coverage, how to process and use that data, and how to create a global system that integrates everything. The previously mentioned GERI serves as an example of how to bring together in-situ observatories from Europe, the USA, China, Australia, and South Africa to collaborate on global environmental and climate challenges.

There is an increasing need to establish common priorities that act as key drivers for coordinating efforts across major policy frameworks, such as the Paris Agreement on Climate Change, the Sendai Framework for Disaster Risk Reduction, the Global Biodiversity Framework, the New Urban Agenda, and, overarching all, the SDG 2030 Agenda (Guo, 2018; Kulmala et al., 2021; Petzold et al., 2024). Policymakers must recognize the value of high-quality observation systems for planetary monitoring and employ this information in support of the SDGs. A successful example of need-based observation is the early detection and monitoring of ozone depletion in the 1980s (Brasseur & Simon,

Table 1. Examples of observation systems (alphabetical order) and related data repositories and portals. The table is incomplete but highlights the plethora of existing elements and the fragmentation of the landscape.

Acronym	Name	Data portal
ACTRIS ERIC(***)	Aerosol, Clouds and Trace gases Research Infrastructure	https://dc.actris.nilu.no/
AERONET	AErosol RObotic NETwork	https://aeronet.gsfc.nasa.gov/new_web/data.html
AIR	Air Pollution data portal	https://www.who.int/data/gho/data/themes/air-pollution
AnaEE	Analysis and experimentation on ecosystems	https://www.anaee.eu/services/data-and-models-portals
Argo	Argo, A Global *in situ* observing system	https://globalocean.noaa.gov/research/argo-program/
Arosa site	Arosa-Davos	https://www.woudc.org
ASCENT	Network Atmospheric Science & Chemistry Measurement Network	ascent.research.gatech.edu, https://ascent.research.gatech.edu/database
ATLAN	A comprehensive All-Atlantic Ocean Observing System	https://atlantos-h2020.eu/project-information/integrated-data-portal/index.html
CERN	Chinese Ecosystem Research Network, China	http://cernbio.ib.cas.cn/about_the_data/data_contents/
CHE	The CO_2 Human Emissions (CHE) Data Portal	https://che-project.eu/data-portal
ClimateAdapt	ClimateAdapt	https://climate-adapt.eea.europa.eu/en/metadata/tools/risk-data-hub
CLOUDNET	A network of stations for the continuous evaluation of cloud and aerosol profiles in operational NWP models	https://cloudnet.fmi.fi/, https://github.com/actris-cloudnet/dataportal
DataTerra	DataTerra	https://www.data-terra.org/en/distributed-data-and-services-platform/
DIAS	Data Integration and System Program	https://diasjp.net/en/data/
EARLINET	A European Aerosol Research Lidar Network to Establish an Aerosol Climatology	https://www.earlinet.org/index.php?id=125
EEA	European Air Quality (AQ) Portal	https://aqportal.discomap.eea.europa.eu/index.php/content-of-the-aq-portal/
EFTEON	Expanded Freshwater and Terrestrial Environmental Observation Network	https://efteon.saeon.ac.za/
EISCAT	European Incoherent Scatter Scientific Association (Incoherent Space Weather Radar)	https://eiscat.se/scientist/data/
eLTER	The European Long-Term Ecosystem, critical zone and socio-ecology Research Infrastructure (soon to be ERIC)	https://elter-ri.eu/ https://elter-ri.eu/elter-pilot-services
EMBRC	European Ocean biological resource center	https://www.embrc.eu/service-catalogue *EMBRC's data is not flowing yet, but will be available through ENA and metadata through EMODnet, OBIS and GBIF.
EMOBON	European Ocean Omics Biodiversity Observation Network	https://www.embrc.eu/services/emobon *EMO BON is operated by EMBRC as its genomic observatory. That is the only observation data coming from EMBRC.
EMODnet	European Marine Observation and Data Network	https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/search?resultType=details&sortBy=sortDate&from=1&to=20
EMSO ERIC	European Multidisciplinary Seafloor Observatory (ERIC)	www.emso-eu
ENA	The European Nucleotide Archive	https://www.ebi.ac.uk/ena/browser/home
ENVRI-FAIR	ENVironmental Research Infrastructures building FAIR services	https://envri.eu/home-envri-fair/
EPOS ERIC	European Plate Observing System (ERIC)	https://www.ics-c.epos-eu.org
EUMETNET	EUMETNET	https://www.eumetnet.eu/emc_training_bulleti/data-download-web-pages/data_download/
EUROArgo	Euro-Argo European Research Infrastructure Consortium (ERIC)	https://www.euro-argo.eu/Argo-Data-access, https://argo.ucsd.edu/data/

(*Continued*)

Table 1. (Continued).

Acronym	Name	Data portal
EuroGOOS	European component of the Global Ocean Observing System of the Intergovernmental Oceanographic Commission of UNESCO (IOC GOOS)	https://eurogoos.eu/products/
EWS	Early Warning Systems: Systems designed to provide advance notice of potential threats or hazards	https://climate-adapt.eea.europa.eu/en/metadata/adaptation-options/establishment-of-early-warning-systems
Fluxnet	Fluxnet	https://fluxnet.org/data/fluxnet2015-dataset/fullset-data-product/
GERI	Global Ecosystem Research Infrastructure	https://global-ecosystem-ri.org/about/
GAW	Global Atmosphere Watch	https://community.wmo.int/en/activity-areas/gaw
G3W	Global Greenhouse Gas Watch—a new operational observation system WMO	https://public.wmo.int/en/our-mandate/focus-areas/environment/greenhouse-gases/global-greenhouse-gas-monitoring-infrastructure
GEOSS	Global Earth Observation System of Systems	https://www.geoportal.org
GOSAT	Greenhouse gases Observing SATellite GOSAT series consists of three satellites: GOSAT, GOSAT-2 and GOSAT-GW. The first URL is the data portal of GOSAT and the second one is that of GOSAT-2.	https://data2.gosat.nies.go.jp/index_en.html https://prdct.gosat-2.nies.go.jp/index.html
GKH	GEO Knowledge Hub	https://gkhub.earthobservations.org/
GOSAT-NIES	GHG and Water cycle	https://gosat-gw.nies.go.jp/en/index.html
IAGOS	In-service Aircraft for a Global Observing System	https://www.iagos.org/
ICOS	Integrated Carbon Observation System (ERIC)	https://www.icos-cp.eu/data-services/about-data-portal
IGAC	International Global Atmospheric Chemistry Project	https://igacproject.org/activities
INVEMAR	INVEMAR	http://www.invemar.org.co/web/guest/acuerdo-de-acceso-uso-a-datos
ISDC	International SKYNET Data Center	https://www.skynet-isdc.org/data.php
IUS	Integrated Urban Weather, Environment and Climate Systems and Service	
JaeTER	Japan Long-Term Ecological Research Network	http://www.jalter.org/en/
JERICO	Joint European Research Infrastructure network for Coastal Observatory	https://www.jerico-ri.eu/data-access/
LifeWatch ERIC	e-Science European infrastructure for biodiversity and ecosystem research (ERIC)	https://www.lifewatch.eu/; https://metadatacatalogue.lifewatch.eu/srv/eng/catalog.search;jsessionid=CA318B762820B34B33A08A44F18356D2#/search?facet.q=type%2Fdataset
LTER	Long Term Ecological Research Network (USA)	https://lternet.edu/
Mauna Loa Observatory	The National Oceanic and Atmospheric Administration (NOAA), Mauna Loa Observatory (USA)	https://gml.noaa.gov/ccgg/trends/data.html
NDACC	Network for the Detection of Atmospheric Composition Change	www.ndacc.org
NEON	National Ecological Observatory Network (USA)	https://www.nsf.gov/news/special_reports/neon/data/
OSCAR/ Surface	WMO metadata portal covering all surface-based observing systems coordinated by or otherwise related to WMO	https://oscar.wmo.int/surface
PANACEA	PANhellenic infrastructure for Atmospheric Composition and climatE change	https://panacea-ri.gr/
PEN	Phenological Eyes Network	http://www.pheno-eye.org/
SAEON	South African Environmental Observation Network (South Africa)	https://catalogue.saeon.ac.za/
SAFAR-India	SAFAR System of Air Quality and Weather Forecasting and Research	http://safar.tropmet.res.in/PRODUCTS-21-6-Details

(*Continued*)

Table 1. (Continued).

Acronym	Name	Data portal
SeaDatNet	SeaDatNet—Pan-European infrastructure for Ocean data measured by the countries bordering the European seas	https://www.seadatanet.org/Data-Access
SIOS	Svalbard Integrated Arctic Earth Observing System	https://sios-svalbard.org/Data
SMCRI	Shallow Marine and Coastal Research Infrastructure	https://smcri.saeon.ac.za/data/
SMEAR	Station for Measuring Ecosystem- Atmosphere Relations	https://smear.avaa.csc.fi/
TCCON	Total Carbon Column Observing Network (USA)	http://www.tccon.caltech.edu/
TERENO	Terrestrial Environmental Observatories (Germany)	https://www.tereno.net/
TERN Australia	Terrestrial Ecosystem Research Network	https://portal.tern.org.au/
WDCGG	The World Data Centre for Greenhouse Gases	https://gaw.kishou.go.jp/search
WMO	WMO world data centres	https://community.wmo.int/en/activity-areas/gaw/research-infrastructure/world-data-centres
World Data Center(s) portal	World Data Center System part of the International Council of Scientific Union (ICSU)	https://community.wmo.int/en/meetings/world-data-centres
WHOS Portals	WHOS-Global Portal on hydrometeorological data	https://community.wmo.int/en/whos-portals

*Data Repositories: A system for storing and managing data.
**Data Portals: An online platform that provides access to datasets and often includes additional tools for exploration and visualization. Data repositories can be part of the infrastructure that supports data portals, as portals may source their data from various repositories to make it accessible through a centralized interface.
***ERIC: European Research Infrastructure Consortium, the European Research Infrastructure Incorporation legal mechanism.

1981). This prompted the international community to respond by establishing the long-standing tradition of global ozone assessment reports, starting in 1985, developed by WMO/UNEP (https://ozone.unep.org).

The ground-based EO component has been highlighted as a crucial asset for modern urban development, enabling cities to become smart, sustainable, and resilient (Gerasopoulos et al., 2022). Concrete examples related to SDG-11 "Sustainable Cities and Communities" include the multi-Agency UN initiative "United for Smart Sustainable Cities" (U4SSC), the "Integrated Urban Hydrometeorological, Climate and Environmental Services" (IUS) by WMO, and the EU Horizon 2020 RI-URBANS project (riurbans.eu) developing Service Tools for facilitating air quality monitoring networks addressing European Air Quality directive requirements. Overall, these projects aim to build urban systems tailored to cities' needs by combining dense observation networks, high-resolution forecasts, multi-hazard early warnings, disaster management, and climate services (WMO, 2021). Greater involvement of the private sector, citizens, and research communities in the future observation system is essential for advancing the SDGs.

In addition to SDG implementation, we also need to look at global megatrends when justifying the need to establish a GGBEO. The World Economic Forum's (WEF) Global Risks Report (2025) highlights the leading global risks for 2027 and 2035, offering a vital perspective for the GGBEO concept. For 2027, the top risks include "misinformation and disinformation," "extreme weather events," "state-based armed conflict," "societal polarization," and "cyber espionage & warfare." By 2035, the list shifts, with "extreme weather events" topping the list, followed by "biodiversity loss

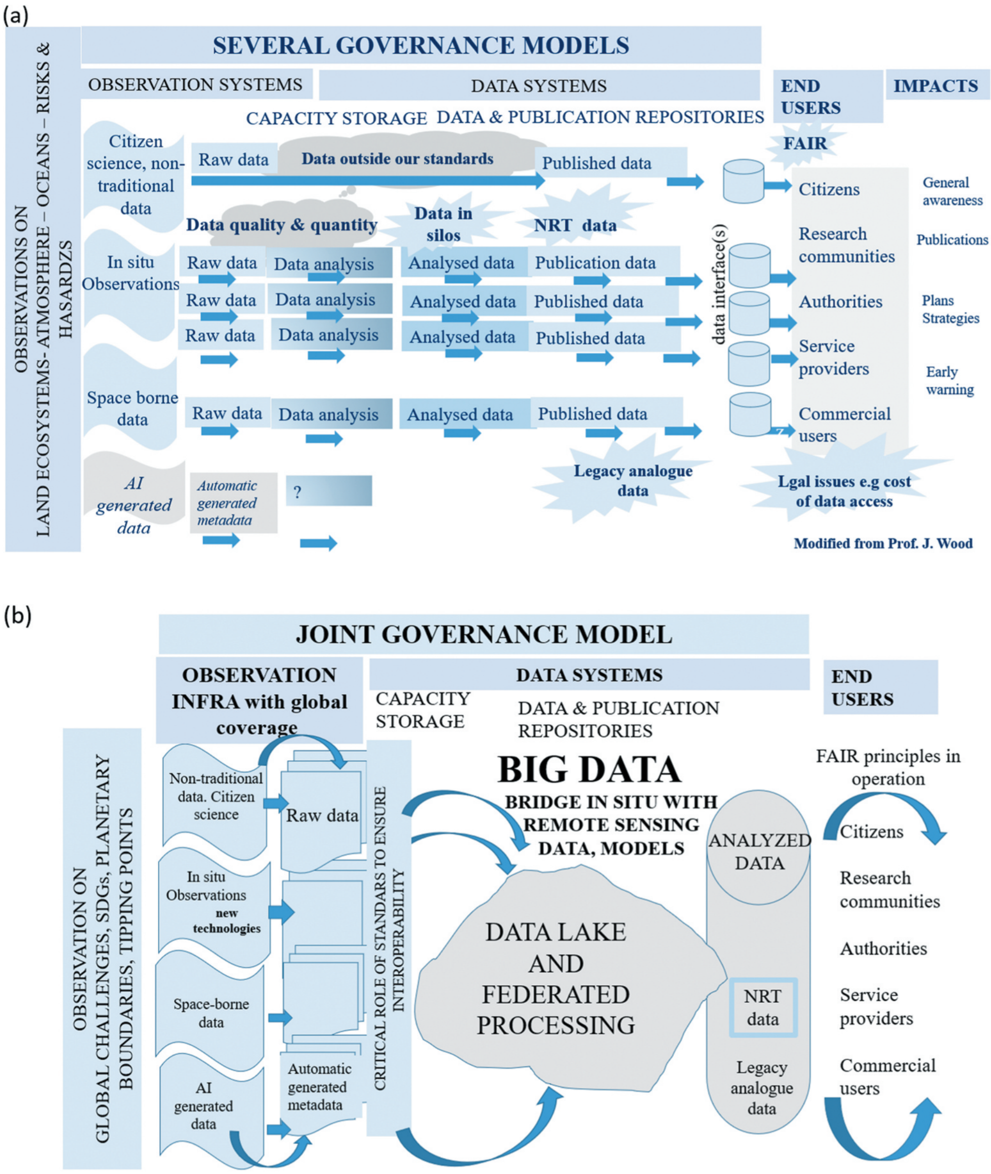

Figure 1. (a) The current state of existing observation systems and data flows is primarily shaped by environmental monitoring and observations of land ecosystems, the atmosphere, oceans, and associated risks. Data collection is conducted by various disciplines and processed separately, although initial steps toward creating integrated data platforms are underway. (b) The future observation system will be driven by local, regional, and global challenges, with data fusion and analysis integrating ground-based measurements, space-borne data, and models, leveraging AI technologies. This underscores the need for a new joint governance model and a unified data portal.

and ecosystem collapse," "critical change to Earth systems," "natural resource shortages," and "misinformation and disinformation." This underscores the urgency for the Global Earth Observatory approach, reinforcing the momentum behind the GGBEO initiative.

Addressing "biodiversity loss and ecosystem collapse," the GGBEO enhances the Global Basic Observation Network by offering comprehensive in-situ data integration, combining weather prediction parameters with ecological metrics crucial for ecosystem services. It supports societal applications such as carbon market quantification, disaster forecasting, and the validation of ecosystem restoration and ocean acidification trends, thus bolstering resilience against climate and biodiversity challenges.

The GGBEO provides essential data for environmental quality improvement, pollution monitoring, and the establishment of a comprehensive greenhouse gas (GHG) budget. It identifies pollutant sources, enhances disaster preparedness, supports carbon footprint verification, and optimizes infrastructure through modern monitoring methodologies.

In response to "critical changes to Earth systems," GGBEO plays a pivotal role in enhancing our understanding of land-atmosphere interactions and their climatic effects, which are crucial for effective climate change mitigation. While European infrastructures like ICOS and ACTRIS comprehensively monitor global atmospheric parameters, there is often a lack of coordinated observations outside Europe, impacting scientific confidence. Better integration of these observations can significantly improve understanding.

Monitoring regional climate variations due to changing environmental conditions is vital. Reliable climatic data is crucial for refining hazard prediction models and evaluating cloud-aerosol interactions. Near-real-time data dissemination supports chemical weather prediction, providing critical information for policymakers.

Flagship GGBEO stations significantly propel adaptation and mitigation efforts. They support policy-relevant science, contribute to IPCC assessments, and reinforce global stocktake for the Paris Agreement. GGBEO also aids the EU's Land Use, Land-Use Change and Forestry (LULUCF) policy development and identifies regulatory responses to pollution, offering innovative insights for mitigating the impacts of transport. In summary, GGBEO enhances the "environmental security" of citizens and societies, especially over the long term.

Overall, our expectations for the future rely on the integration of big data, the use of AI techniques, and the development and adoption of new technologies (Figure 1b). The strategy for future observations and architecture of networks need to be driven by sustainable development goals, environmental challenges, and global tipping points, while incorporating and respecting the ethos of long-term observations. As RIs and observation networks expand geographically, new technologies (such as AI) and instruments (like low- and moderate-cost sensors) will develop rapidly to meet increasing network needs and quality requirements. It is clear that a GGBEO would redefine the observation community's role within modern digital data ecosystems. AI, digital twins, and virtualization engines will become integral to a holistic architecture. This shift will also challenge the FAIR principles, particularly the importance of standards, interoperability, and meeting end-user expectations. Additionally, it will set new standards for governance models and management. Alongside the development of technical infrastructure, establishing a legal and financial framework for managing the systems is crucial. Moreover, multi-level broad coordination is needed to bring all these perspectives together to establish a modern GGBEO. These aspects are discussed in more detail in Sections 3.2–3.6.

3.2. Challenges of the current ground-based observation networks

3.2.1. Geographical coverage and engagement of the Global South

For over 150 years, the World Meteorological Organization (WMO) and its predecessor have led the establishment of a global network for the free international exchange of meteorological data. Since the 1980s, new observation networks and data portals have emerged, driven by organizations like the WMO, the European Commission, and initiatives such as OpenAQ (openaq.org). Early efforts lacked coordination, leading to fragmented systems and inefficient data use. Recent advancements, especially through Europe's ESFRI/ENVRI initiatives, have promoted more integrated systems (Petzold et al., 2019, 2024). In Asia, the ILTER East Asia–Pacific Regional Network highlights effective cross-country collaboration (Kim et al., 2018). In the marine domain, the Maritime Aerosol Network (AERONET-MAN), the In-service Aircraft for a Global Observing System (IAGOS) or the Cooperating Networks within the NDACC serve as notable examples of extended networks operating in international areas.

Kulmala (2018) estimated that at least one thousand well-equipped "flagship" ground-based stations would be needed globally to comprehensively and continuously monitor the Earth system and key ecosystems. These stations would be integrated with satellite remote sensing data, laboratory experiments, and models to provide a complete picture of environmental changes. Examples of existing comprehensive stations include Mace Head, Cabauw, Jungfraujoch, SMEAR-II, and SIOS (Svalbard Integrated Arctic Earth Observing System) in Europe; Mauna Loa in Hawaii, USA; Mount Kenya in East Africa; and advanced stations in China like the Station for Observing Regional Processes of the Earth System (SORPES) in Nanjing (Ding et al., 2016) and the AHL/BUCT station in Beijing (Liu et al., 2020). These well-equipped stations could serve as the basis of a new GGBEO network. However, there are still very few fully integrated stations that measure a wide range of parameters from all environmental domains in a standardized manner.

Furthermore, the Global South remains sorely under-sampled compared to the Global North.

A key question from the Global South is how to build capacity and engage meaningfully with global communities. Current practices often result in tokenism rather than genuine collaboration, highlighting the need for partnerships that ensure the Global South has a seat at the decision-making table. Significant limitations exist, such as the lack of infrastructure, limited funding, and capacity-building challenges, including a shortage of trained personnel. We note political stability is necessary for success in any region of the world. One strategy could be joint planning and implementation in key regions, involving local stakeholders from the outset with a clear value proposition. Unfortunately, we lack sufficient equity mechanisms in most regions that must be reenforced simultaneously. The WMO has a few mechanisms, such as the Global Framework for Climate Services (GFCS), Climate Risk and Early Warning Systems (CREWS), the new Global Basic Observing Network (GBON), and the Systematic Observations Financing Facility (SOFF), but these are underfunded and currently limited to certain countries and variables.

To engage the Global South, funding agencies must prioritize stronger involvement of local researchers and offer clear value to indigenous communities. This goes beyond providing instruments, extending to mentorship for long-term support in maintenance, data curation, and participation in the technical, scientific, and strategic development of EO systems (Gani et al., 2022). Examples include the International Network to Study Deposition and Atmospheric Composition in Africa (INDAAF) supported by France, initiatives in Kenya (supported by Switzerland), Rwanda (supported by the USA), and South Africa's Welgegund station (supported by Finland; Booyens et al., 2015). However, sustainability and long-term commitment remain ongoing challenges.

Engaging under-sampled regions requires a comprehensive strategy for knowledge transfer, training, and capacity development. While numerous training opportunities exist, better coordination among key global actors like the WMO and support through United Nations bodies in sustainable development is needed (e.g., WMO (2024)). Local and regional expertise and commitment need to be included in the discussions, planning and execution of decisions. The World Academy of Science (TWAS) could serve as a channel, and European research infrastructures could play a role in training, given their experience and commitment to standardization of measurements. A clear funding strategy, potentially supported by the EU, is essential. Access to global training opportunities through existing collaborative networks and possibly supported by GGBEO should incentivize participation. Improved coverage in international areas, including oceans, and rapidly urbanizing areas should be prioritized, with effort distribution reflecting countries' GDP. Construction of harmonized observation networks to tackle the global challenges is needed to address the long-term sustainability challenges of the society. There are real opportunities for improving quality of life in the near term, for example through co-designing the observation networks tailored to meet stakeholder needs and requirements at local and regional scales leveraging the experience of mature networks.

3.2.2. Scaling discrepancies between in situ and remote sensing data

The integration of ground-based (in situ) observation networks such as GGBEO with space-based remote sensing is critical for producing accurate, multi-scale environmental data and continues to be an active research focus area. Ground-based measurements offer high-resolution, high precision localized insights into ecological and biophysical processes, while satellite data provide broad spatial coverage and long-term continuity even as they move toward spatially and temporally finer scales in some regions. However, differences in scale, measurement methods, and observation frequency often result in discrepancies that need to be resolved for coherent analysis. To bridge these gaps, coordinated calibration and validation activities are essential which include ground-based remote sensing instrumentation (GBRS). The GGBEO would provide reference measurements that can be used to calibrate satellite sensors and validate satellite remote sensing products. This ensures consistency in observed parameters such as vegetation indices, soil moisture, and atmospheric composition across scales. For atmospheric composition GBRS instrumentation often provide data with vertical sensitivity profiles that can be employed synergistically to translate between in situ and satellite data forms. Especially in the multi-instrumented flagship stations with boundary layer information. Advanced data assimilation techniques and machine learning models can further align these data sources by identifying patterns and relationships that allow for reliable upscaling (from ground to regional/global scales) or downscaling (from satellite to site level). For a detailed GGBEO plan and implementation (see Figure 2) we need deep

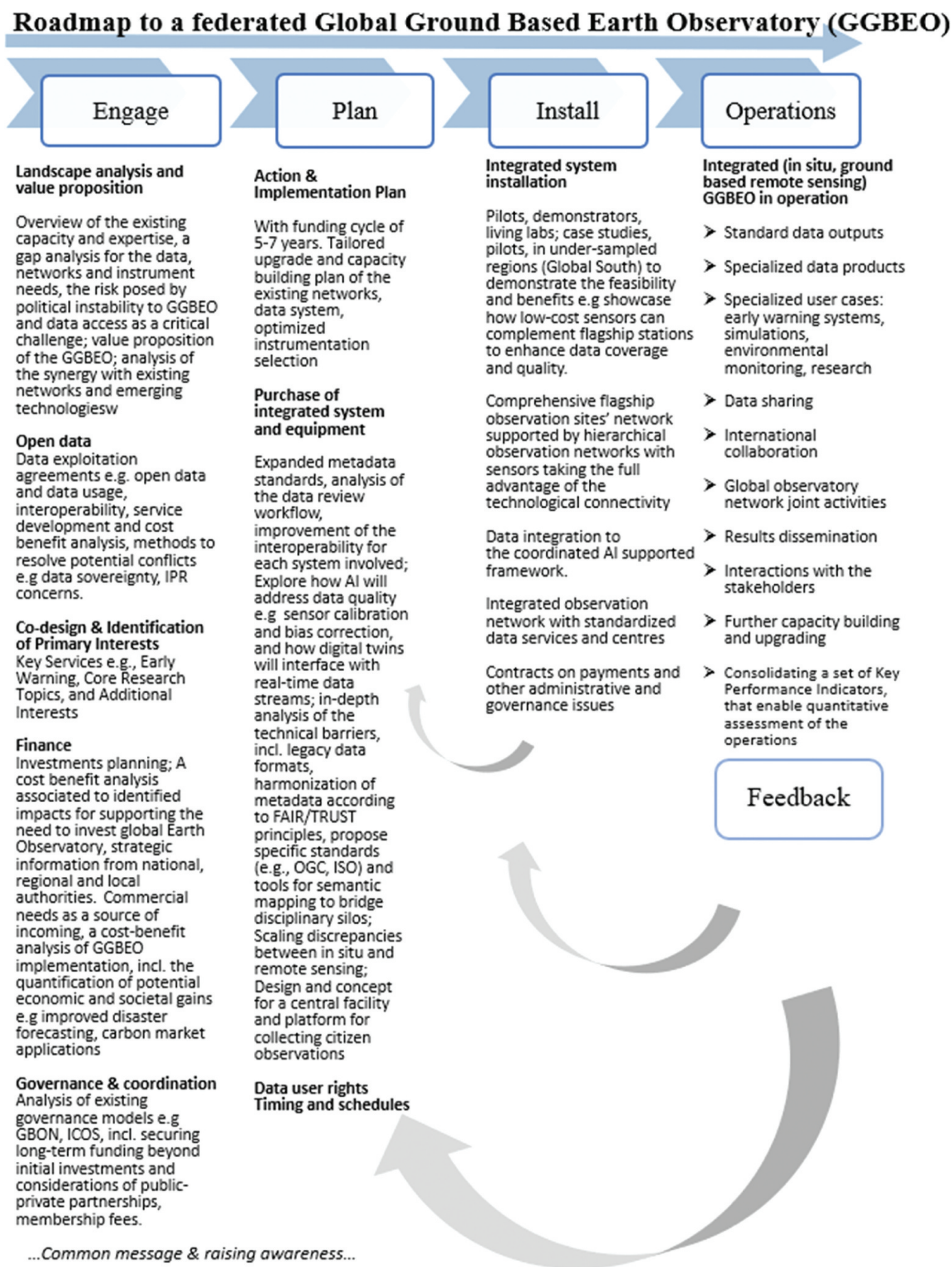

Figure 2. Steps towards building and implementing a GGBEO (engage, plan, install, use, and share). When implemented, the different phases will likely overlap in terms of schedule, and different domains and continents will be in different phases. Early-stage co-design is crucial for successful system development. A common message and increased awareness of GGBEO and the value of its observations for sustainability are essential to foster citizen engagement and meaningful stakeholder dialogue. Following the initial GGBEO implementation, feedback will guide improvements and shape the next-generation system.

analysis of the harmonized data protocols, shared metadata standards, and interoperable data infrastructures, such as those promoted through ENVRI and other European RI frameworks, are equally crucial to enable seamless integration. Ultimately, this synergy enhances the quality and utility of environmental information, supporting both scientific research and evidence-based decision-making on issues like climate change, biodiversity, and land-use dynamics.

3.2.3. Hierarchy of observation networks and new technologies

The GGBEO will not reinvent successful paradigms. Rather build on the attributes of effective existing operational networks. For example, the NDACC's (De Mazière et al., 2018) success is built on the expertise of the Instrument Work Groups that maintain state of the art observational capability even as these techniques evolve. It was initially constituted as a tiered network with primary (fully instrumented) and complementary (partially instrumented) stations, it evolved to fewer fully and many more partially instrumented stations. Still, it could be reorganized into hierarchical system as envisioned by ESFRI (ESFRI Landscape Analysis [ESFRI], 2024). Such a network would range from moderate cost sensors at distributed stations to comprehensive state of the art flagship stations. Indeed, the synergy of flagship stations with in situ and GBRS instrumentation is a key attribute of the GGBEO paradigm.

Hari et al. (2016) proposed a hierarchical network of standard, advanced, and flagship measurement stations, each with specific, well-defined roles. This structure can effectively address spatial scales, heterogeneity, and the complexity of ecosystems. A recent WMO report (Malings et al., 2024) emphasizes the value of incorporating low-cost sensors into this tiered network, alongside flagship, flux, and weather stations. Similarly, Nasta et al. (2024) have outlined a comparable vision for hydrosphere observation. Concrete steps have been taken by the Commission for Observation, Infrastructure, and Information Systems (INFCOM-2), which approved the "Tiered Networks" approach in 2022 (WMO INFCOM-2 Decision 6.1(7)/1). A case study in under-sampled regions such as the Global South could illustrate how low-cost sensors enhance data quality and coverage when paired with flagship stations. The MegaSense program, initiated by the University of Helsinki in 2017, exemplifies a hierarchical network involving flagship, advanced, and low-cost stations integrated with AI. It utilizes high-end instruments, commercial transmitters, dense sensor arrays, and consumer wearables, using 4 G and 5 G technologies. Piloted in Beijing—one of the most polluted cities—MegaSense addressed urban pollution challenges, improving predictions through machine learning. This approach aims to calibrate low-cost sensors with accurate stations and use tested machine learning based calibration models for the low-cost sensor (Motlagh et al., 2020; Tabandeh et al., 2025; Zaidan et al., 2020, 2023). Its credibility could be as a part of the GGBEO, further supported by new international pilots at the Global South.

Currently, the Global Climate Observing System (GCOS, 2021) provides essential climate variables (ECVs) and defines the spatio-temporal requirements for climate observations, including goals, thresholds, and breakthroughs. Thus, an observing network at threshold conditions is effectively covered. Low-cost sensors, which result in low operating network costs, could be a good solution for filling observation gaps in specific areas and applications. It is estimated that new low-cost technology can achieve up to 90% of the accuracy provided by more expensive instruments for some data products. However, the seemingly small investment costs for the sensors are often dwarfed by the much higher cost of operations, processing and calibrations. These sensor networks can be calibrated with AI and flagship stations. Although cost evaluation is relevant for comparing state of the art vs. moderate vs. low-cost instruments, the actual cost of existing and maintenance logistical infrastructure, technology setups, data and communications systems cannot be underestimated. Attention must be given to sensor calibration to ensure the continuing integrity of long-term data streams at all quality levels (e.g., Stavroulas et al. (2020)). The recent WMO report (2020) provides lessons learned from introducing state-of-the-art technology in terms of accuracy, reliability, and reproducibility of different sensors used for measuring reactive and greenhouse gases, and aerosols. The larger amounts of data with inferior quality compared to data recorded by mature instrumentation call for novel data science and data analysis approaches. Bittig et al. (2018) provides a strong example of using an alternative approach: affordable O_2 sensors on Argo floats instead of expensive and highly sensitive nitrate sensors. In this case, AI is employed to interpret the proxy data.

In addition to the emerging need for low-cost technologies to ensure global coverage of observations, it is crucial that well-equipped flagship stations maintain their high standards and readiness to address new scientific and societal questions through infrastructure renewal and upgrading. And as the physical area grows (e.g., Global South) the need for new flagship stations needs to be assessed and will grow. New technological developments, such as novel mass spectrometers, IR and UV-Vis spectrometers, lidars, and radars, will provide new scientific opportunities and breakthroughs. The GGBEO concept could support these technological advancements, while physical and virtual co-location would be a great opportunity to reduce costs.

We also need to be aware of the very limited traceability of products generated by machine learning, AI fusion, or other techniques that are fed into different applications. Uncertainties and representativeness of this sub-generated data needs to be explicitly documented. Approaches for objective and self-descriptive quality assurance must still be developed as part of the GGBEO strategy. Legislation may not yet be ready to welcome potential new technologies. New digitally generated data can be created using specific standards and protocols that ensure interoperability. The WIGOS Metadata Standard may provide partial solutions for documentation.

3.3. Observation community's role in modern digital ecosystems from data silos to robust and sustainable federations

A key feature of observation networks is harmonized measurement protocols, agreements on data formats, data provision and data sharing as well as descriptions of the network and observations themselves (metadata). For example, the WMO's WIGOS Metadata Standard and NDACC data protocols are a model for this.

Currently, many observation systems or countries have the capacity to share data and information effectively on a global scale. However, this is not happening in practice. As a result, we cannot synthesize their valuable digital assets to face Earth's impending and imminent crises. Furthermore, we are unable to collectively assess the state of the planet to formulate new indicators for scientifically and societally important dynamics. For example, in 2017, the Tropospheric Ozone Assessment Report (TOAR) activity consolidated to a comprehensive global database all available ground-based in situ and remote sensing ozone observations. By compiling O_3 data from global repositories, multinational data centers, national networks, and individual researchers, data from almost 10,000 measurements were collected (Schultz et al., 2017; Gaudel et al., 2018). During this process, considerable efforts were required to harmonize and synthesize data formats and metadata information from various networks and individual data submissions. TOAR-II takes this to the next step of improved homogenization, using tools such as satellite data and analysis tailored to specific research questions. However, the resulting data sets are the existing wide range of data generated under very different auspices, a future GGBEO effort would be coordinated at the acquisition step for an ongoing global ozone monitoring effort.

Generally, a lack of coordinated data flows has led to a degree of randomness in the density of observations across time and space. What is required is to effectively plan where to concentrate future efforts and investments—for example, determining where flagship stations are essential, where advanced stations are best suited, and where low cost sensors may suffice. These decisions must be informed by the understandings that requirements will vary depending on the specific data products needed. This has significant implications for improving the models and machine-learning solutions that are increasingly relied upon by diverse and expanding use communities. We urgently need efforts to harmonize ground-, air-, space-, and aquatic-based observations with the assimilation needs and simulation capabilities of models and AI agents. With tight coupling, both the observational and computational domains will inform, augment, cross-validate, and complement one another to furnish humanity with unprecedented insight where it is needed most, filling key gaps (Figure 1b).

3.3.1. Data flow, storage, standards and protocols

Transforming the status quo requires a new, interoperability-first model for processing, storing, exchanging, and delivering digital assets (knowledge, information in optimized formats, digitized data products, as well as software, codes, documentation, etc.). The envisioned system cannot and would not rely on any user or client system to know that a given data portal or web service associated with an observing system exists. Even the largest Earth observation systems are not well-known across scientific communities and even if they were, it is unlikely that their data systems would be readily usable to humans or machine agents due to the plethora of implementations, codes, and standards that are often discipline specific or idiosyncratic. We note that even as we speak, more of these unique data structures and portals, destined for limited use, with good intention, are being built.

This is especially true as AI comes into its own: an AI-ready flavor of the FAIR Principles is emerging, closely associated with re-serving data in analysis-ready, cloud-optimized (ARCO) formats. The transition is inevitable, yet no global leadership is in place to de-silo EO data systems globally, using open frameworks without dependence on (and thus localized, de facto governance by) commercial or national/regional infrastructures. This creates significant challenges to ensuring that relevant data products are available and usable at the all scales including local and by the people and communities (CARE Principles for Indigenous Data Governance; Carroll et al., 2020, 2022; Creutzig et al., 2019).

While a generalized supply chain for EO data evades us, there are promising examples at smaller scales. Rising to the challenges of the UN Decade of Ocean Science for Sustainable Development, the International Oceanographic Data and Information Exchange (IODE) of UNESCO's Intergovernmental Oceanographic Commission (IOC) is coordinating a federation of global data systems to form the Ocean Data and Information System (ODIS; Buttigieg et al., in prep.). Using extant and widely adopted semantic and serialization standards, alongside web architectural patterns, members of the ODIS Federation are sharing detailed catalogs of their digital assets (including metadata about methods used to generate the data) to create a global overview of ocean data and information from multiple domains. Through the Ocean Data 2030 Programme, this distributed and harmonized knowledge base will be deepened and expanded to promote integration-on-demand and data space dynamics.

3.3.2. Meeting the future: digital twins and virtualization engines

While a common basis for EO data supply will revolutionize many endeavors, there are immediate, large-scale beneficiaries and partners worth a special mention. AI-readiness has been noted above, but what application-oriented, transformative digital ecosystems will such capacities be embedded in, and how will they engage with globally coordinated EO data flows? Digital twins will not only allow us to observe and simulate the complex Earth system more comprehensively and accurately, bridging gaps with the physical world and our understanding of it, but such an information system will also enable a much more interactive way for scientists, service providers, and decision-makers to work (Bauer et al., 2021a; Bauer et al., 2021b). Initiatives like Destination Earth (DestinE), an EC flagship for a sustainable future, and the DITTO Digital Twins of the Ocean are prime examples of this implementation (Bahure et al., 2023).

According to the GEO Post-2025 Strategy, there is a clear shift from traditional Earth observation toward "Earth Intelligence"—a more advanced, insight-driven approach that integrates EO data with AI. AI is becoming increasingly integral to GEO initiatives, currently playing a key role in model development and training. One example is the Global Agricultural Monitoring (GEOGLAM) initiative, which already leverages AI to analyze both satellite and in-situ data, resulting in more accurate forecasts of crop conditions and yields. GEO is also leading efforts to demonstrate how AI can be applied beyond image analysis to support a wide range of applications. This transition highlights the urgent need for high-quality in-situ observations and the development of the GGBEO system.

Data quality, quantity, and coverage are fundamental issues that require significant coordination efforts among observation platforms. It is also necessary to solve the technical issues of interoperability of methods and databases, as well as the applicability, availability, and usability of data from and for all areas of research (co-location, co-development of data). In terms of AI, we need to determine the best way to integrate different in situ environmental data and bridge them seamlessly with remote sensing data and models and systems like Earth Virtualization Engines (EVE, Stevens et al., 2024). For example, EVE will be made up of international centers with extensive computational and data handling capabilities. Each EVE center includes climate-related data information. EVE can improve climate projections worldwide with more detail and connect them digitally to data about Earth's physical, biological, chemical, and social aspects. It has modeling abilities that go beyond what many countries or existing centers can do (Stevens et al., 2024).

In the past 10 years, the research community has not considered AI as a serious research tool, this is rapidly changing, yet there is no regulatory framework for the use of AI technology. Of utmost importance to this community is the quality of the data to be ingested into the AI based models. New technology here, should be interpreted as a new research strategy. Data can be cast or re-cast into given formats. Codes (including AI) can be used to ingest data from various formats, so it supports the realities of the environment being observed and goals of the project. Yet preservation of data quality and metadata must be maintained.

3.4. FAIR principles and lessons learned

The FAIR principles summarize the need to harmonize data among observational platforms, but they do not present the means to achieve these goals. Progress in implementing the FAIR principles for Findable and Accessible data is improving, but Interoperable and Reusable data remain a challenge. A FAIR policy that accommodates differences at local, national, regional, and global scales needs to be developed to include the evolving capabilities of the Global South. Here, we summarize the main points and lessons learned from the discussion at the "Hyytiälä Global Earth Observatory workshop" in 2023.

- All existing data must be identified, re-negotiated, and included in long-term financing strategies. Detailed discussions on data access and liability issues are necessary. Data ownership concerns, such as the desire to publish first, can be bottlenecks. Additionally, data storage and access should be available to everyone, not just big data analytics companies.
- Data openness is improving, yet its usability with new AI technologies remains uncertain. We must explore how to effectively utilize this data and develop new methods to integrate it with AI technologies. Access to data is vital for AI, as more data enhances AI system performance. However, not all data is suitable for every application; it must meet specific requirements to be useful. We also need to consider the intended use, especially in business AI contexts, where some institutes are imposing restrictions on the commercial use of AI. In this era of AI progress, it is crucial to address the risks associated with data usage and establish regulations.
- While open data is intrinsic to EO system put forth here with AI, care must be taken. The main difficulty with openness is documenting where the data used by AI comes from. Attribution of the data needs to follow the chain of processing to implementation of AI results. We need regulation of datasets and products for transparency and accessibility.
- Some countries have rules that limit data sharing. Legal issues may also limit data access. For example, in the case of early warning systems, the data restrictions are related to civil protection and access for socio-economic usage. In certain industries like renewable energy, data are seen as an asset one can buy or sell.
- Lowering the cost of data access can create the challenge of cost recovery to ensure the sustainability of any infrastructure. This is relevant for the inclusion of other contributor communities and networks as well.
- In the case of Near Real Time (NRT) data, access has some barriers linked to national authorities and in some cases to the context (global datasets tend to be open, but

some countries have restricted access). Access may be linked to organizational cultures and data sharing traditions. NRT data is sometimes restricted due to an embargo until manuscript publication.

- There is a growing demand from end users for NRT data access. However, legal issues surrounding data access arise, particularly in the context of Early Warning Systems. To highlight these issues and streamline global efforts, the WMO recently launched the Early Warnings for All (EW4All) initiative: a ground breaking effort to ensure everyone on Earth is protected from hazardous weather, water, or climate events through life-saving early warning systems by the end of 2027.
- As we transition from a scientific to a commercial context or research to operational, we continue to encounter barriers to the open sharing and access of NRT data. Real-time data are valuable, and "information is power." It is crucial to involve commercial operators (industry) in data access. Currently, the Earth science community (with typically national (public) support) provides its data for free, while private companies benefit without reinvesting in the infrastructure. This situation highlights the need for a business plan, a cost-benefit analysis and negotiations.

3.4.1. Interoperability: critical role of data standards

There are limits to global harmonization, and free and open access to all observations may not always be possible or desirable. Data quality might not be sufficient for broad sharing. The requirements for the observing system may change over time as new scientific and societal questions arise, necessitating adjustments, such as the measurement of new variables. In any case, the raw data must be reliable and serve as the backbone for quality assurance (QA). An exemplar could be the WMO system, which is considered a system of systems. The entire data processing workflow for the GGBEO should be evaluated in light of the growing opportunities offered by artificial intelligence (AI) and machine learning (ML) techniques. Camarillo-Naranjo et al. (2018) introduced a climate data-flow model aligned with the WMO Guidelines on Climate Data Management (WMO, 2007), demonstrating how standardized frameworks can support global-scale data integration and analysis. Wicquart et al. (2022) have proposed a comprehensive workflow—from data collection to quality control—designed to improve the integration of ecological datasets. Their approach enables the creation of synthetic datasets, allowing for the analysis of larger and more complex monitoring data.

The development of standard approaches is critical to ensure interoperability, and there are already many standards in use (e.g., ICOS, OGC/ISO, WIGOS, ACTRIS, GEOMS) that still need to be harmonized among observational platforms. These existing standards should be used as a basis when building the common global observatory. Digitally born data (e.g., data generated by digital sensors, software applications, or devices) can be created using specific standards and protocols that support interoperability. For analogue legacy data, such as handwritten documents, printed materials, and photographs, the situation is much more difficult. These data are undoubtedly of significant value, but substantial investment in curation and verification is required to make them accessible for digital applications, and they tend not to be underpinned by recognized standard protocols.

Citizen science enables us to proactively promote trust to science and produce valuable supporting data for example on air quality and biodiversity monitoring.

However, very often citizen-based observations and data is scattered and biased based on geographical location. Ground-based Earth observations can be used to assess the quality of the citizen observations. Open central facility and platform for collecting citizen observations is needed. As an example from Finland, Citobs crowdsourcing platform has been developed for defining and gathering on-site observations which will be further developed into a common public network of digital services. Different organizations can co-operate on gathering the citizen observations and other measurements for targeted needs (e.g., measuring perceived air quality or noise). This will allow novel data analysis, participatory outreach activities with the citizens and innovative services in synergy with observations on scientific disciplines.

AI can be used not only with standard scientific data but also with citizen science, non-strategized, and non-conventional data. The Open Geospatial Consortium (OGC) could be a useful collaborator here. OGC develops and publishes standards for geospatial and location-based services and includes various members such as Microsoft, Google, academia, and other organizations involved in the geospatial industry. The standards developed by OGC aim to facilitate the interoperability and exchange of geospatial data and services across different platforms and systems and are sometimes published in conjunction with ISO.

A variety of highly sophisticated services targeted to wider user groups may and will be developed based on observational data. AI technology, AI based models and their applications are developing rapidly and a great opportunity, there is no real horizon in view. Yet there is still no clear definition of what is considered AI-ready data. Issues of data quality and its definitions across the very wide range of data types are not set. Programmatically accessible metadata information needs to be provided with the data to allow users to assess the type and quality based on their own criteria, knowledge and goals. Provenance information supports the quality assessment process. For example, in the ocean observation domain, standards are being set even across Research Infrastructures (RIs) so that metadata fully reflects the quality and source issues.

3.4.2. Reusable: improvement of interoperability

Improving data reusability involves breaking down barriers between different data sources and silos ensuring that various systems can work together smoothly. Some data portals, such as ENVRI-Hub and GEOSS, manage this effectively, while others, like GCOS, face challenges. In the future, systems like EVE will rely on this ability to work with different systems.

We need effective user interfaces and explore how AI integration and other techniques can enhance the development of user-oriented services and applications through machine-readable interfaces. Additionally, incorporating mechanisms for self-descriptive information reading should be a key component of the integrated observation strategy, as seen in ENVRI-FAIR.

Several points should be discussed to improve interoperability, such as automatic (read homogeneous) annotation and generation of metadata, handling data that does not comply with standards, and managing legacy analogue data. Metadata should include provenance information, and the entire data curation process, including methods and descriptions and should be transparent. Legacy analogue data has value but requires unique investments to be reproduced at recognized standards and made usable in digital applications. Data not complying with agreed standards (e.g., Privacy Policy & Data Protection, LCS) should also be included as part of the integrated observation system as it can. The Cloud Optimized GeoTIFF Standard (OGC) already defines standards for exchange. As we make it easier for different data systems to work together, next steps of developing better services for users and improving data reuse follow.

3.5. User expectations and services development

There are several barriers hindering the maximal use of data. Sometimes there is a lack of understanding regarding user groups and their needs. As a result, data may not be easily discoverable, or users may not even be aware that the data they are interested in exists. Furthermore, the user interfaces, documentation, instructions, and terminology may be difficult to understand for users from different backgrounds with varying expertise and skills. Often, there is no training for the end-users of data. Sometimes even basic documentation, such as data descriptions, does not exist. Importantly, there may be licensing barriers that prevent the usage of datasets originating from different sources.

New efficient communication channels among observation networks, data portals, researchers, and decision-makers are needed to develop new services and web-based platforms providing coordinated environmental information to a wide range of users. Ideally, the requirements of any potential services should come from the user communities. The key end-users are often regional and local authorities rather than the government. However, the challenge is that some of these services depend on national governments, each with its own specific agendas. The WMO has established the Service Technical Commission to streamline the development of observation and prediction systems into specialized services, which may be a useful model.

We should also keep in mind the diversity of end users and their different needs for services. The same dataset can be used in different contexts, reflecting the diversity of service requirements. The stakeholder consultation process may become challenging when, for example, end users request indicators that the data providers are not familiar with. Mobilizing resources for customized projects aligned with identified societal needs could prove beneficial in this context. It would be beneficial to establish guidance on data use for various applications. Drawing insights from approaches such as ENVRI-FAIR in a lessons-learned manner should be considered as a foundation for designing future service development strategies.

3.6. Governance, management and financial aspects

The governance of the GGBEO would require a new type of overall coordination to ensure that long-term financing and resources are available across geopolitical boundaries, comprehensively addressing the legal questions to implement FAIR principles (Wilkinson et al., 2016). This would also provide mechanisms to determine how to welcome potential new technologies with new data (Petzold et al., 2024). However, when implementing the GGBEO governance model in line with FAIR/TRUST principles within a shifting geopolitical landscape, several key strategies are vital. First, we need to develop a scalable and adaptable governance framework that prioritizes transparency and inclusivity, ensuring participation despite geopolitical tensions. Promoting continuous international collaboration and dialogue is crucial to maintaining mutual understanding and engagement. Establishing multilateral agreements with international organizations would reinforce commitment to these principles, facilitating data sharing and governance. Implementing decentralized data stewardship will empower regional nodes while maintaining global standards. Assembling cross-disciplinary teams to address interdisciplinary and convergent challenges will enhance resilience against geopolitical pressures. Additionally, introducing clear conflict resolution mechanisms will help swiftly address and resolve disputes, ensuring ongoing cooperation within the governance model (see also Figure 2).

Additionally, it is important to consider other levels of governance and funding related to measurement observation stations, facilities, data integration, interoperability, and interfaces. The development of the governance and financial framework of the global earth observatory can strongly benefit from the GRI (Global Research Infrastructure) framework developed by the Group of Senior Officials (GSO) on research infrastructures. Under this framework, the International Conference on Research Infrastructures (ICRI) is organized every two years. It is also important to define the decision-making mechanism for the GGBEO and the related bodies.

Experienced and top-level management should be established. However, heavy top-down governance and coordination should be avoided. WIGOS, coordinated by WMO, and GEO could serve as guidance for GGBEO overall governance. This would be based on combining the experiences from WMO/WIGOS, such as GAW, and research infrastructures like GBIF (Global Biodiversity Information Facility), OBIS (Ocean Biodiversity Information System), ICOS, ACTRIS, eLTER, and the integrated approach for European environmental research infrastructures by ENVRI (e.g., Santi et al. (2023); Snowden et al. (2019)). The governance related to any newly established entities (e.g., data and other services) must be accounted for.

Under the WMO leadership, we should aim to establish and identify the GGBEO stations for comprehensive, interoperable data on weather, climate, atmosphere, hydrosphere, lithosphere, biosphere, and the socio-economic environment. This would provide a real-world component and comparison for the digital twins (Kumar et al., 2018).

The cornerstone of the financial framework for the global observatory should be directing the main resources to data interoperability and interfaces, flagship, advanced and low-cost sensor stations. Operations of the GGBEO should be funded mainly by its partner organizations or countries, similar to the ERIC model in Europe (e.g., ERIC Forum Policy Brief [ERIC], 2022; European Commission, 2022; European Roadmap for Research Infrastructures, the European Strategic Forum on Research Infrastructures [ESFRI], 2018). Development funding from external sources also plays a crucial role, as does sustainable funding to support long-term observations in countries where current observational data gaps exist. A proper balance between in-kind contributions and cash contributions should be sought. Lean governance for coordinating the financial aspects is needed.

The main cost categories to consider when budgeting for the new integrated observation system include personnel, data storage and services, implementation, maintenance and upgrade of facilities and equipment, calibrations, upgrades and end of life replacement, technical staff training, communication and education-related costs, and supply chain. Establishing funding mechanisms that support long-term observations, particularly in thematic areas and geographical regions where observation gaps exist, is crucial. The financial framework plays a crucial role in enabling improvements in observations and research infrastructure in the Global South. The Systematic Observations Financing Facility (SOFF), a UN Fund, co-created by WMO, UNDP, and UNEP, is a good example of a funding mechanism to support closing the climate and weather observations data gap in countries where these gaps exist. However, upscaling this type of funding is needed to extend support to more countries and larger regions. Data needs, "existing data" versus "data that we use," should be considered rigorously. It may incur high costs due to additional processing and quality assurance (QA) efforts required for outdated formats or systems that are not compatible with current technologies. In addition to data needs, the effects of inflation are often not sufficiently considered in overall financial budgeting. There are already examples of existing funding mechanisms from international organizations like WMO and GBIF.

The added value of planned investments should be analyzed in detail, including the sum of the operational costs of the RI, taking into account periodic replacement and the significance of data interruption and infrastructure damage due to extreme events. This issue is more relevant in some areas than others, but the possibility of extreme events exists everywhere. Estimating the costs for this type of damage might be difficult to approximate. A cost-benefit analysis, associated with identified impacts supporting the need to invest in these initiatives, is strategic information needed by national, regional, and local authorities.

For investment plans into the hierarchy of stations and their geographical coverage, such as the Global South, we need to demonstrate the wide use of data to funding agencies, which can in part be achieved by data portal operators reporting their data usage. The volume of data use is a key point in determining how the system should be optimally implemented, including opportunities and risks from potential commercial uses of the system. Any information on data usage and impact would help the observational community develop common messages to raise awareness among stakeholders about the value of the observations and the importance of sustaining them as a long-term resource. Usage is not the only metric, the cost to the world of not going forward with the GGBEO should be considered.

4. Future vision and steps forward

A decade from now, we likely envision a GGBEO that provides high-quality, standardized observational data across all realms of environmental research. The GGBEO would bring together numerous networks, research infrastructures, and research organizations within the field of Earth System Research. It would base its operations on these existing structures, providing users with easy access to data and ensuring data interoperability. This observatory would serve as a wellspring of big data, including non-traditional data and those produced with AI, essential for various services, predictions, and simulations forecasting the future behavior of the Earth system. Additionally, the data enabling services for stakeholders would also serve the research community in discovering yet unknown processes, feedbacks, and interactions within the Earth-Human system. The GGBEO would align with supporting socio-economic data and provide a user-friendly interface for data mining and comprehensive analysis.

At the global level, the scientific community needs more coordination, funding, and resources to develop a systematic action and implementation plan towards the GGBEO. This plan should be based on existing infrastructures and structures, starting with an analysis of the current observation capacity, data processes, and organizational structures.

In Figure 2, we introduce steps (engage, plan, install and operate) towards building and implementing a GGBEO. When implemented, the different phases will likely overlap in terms of schedule, and different domains and continents will be in different phases. To ensure the GGBEO is truly inclusive and representative of global needs, it must integrate perspectives from the Global South, particularly in regions that are often underrepresented in global initiatives. This inclusivity is essential for addressing diverse regional challenges and achieving a truly global GGBEO.

4.1. The first step: engage

The preparatory phase should last at least three years. This first step involves conducting a landscape analysis of existing global and regional observation networks, learning from integrated efforts such as ENVRI, and gathering information on which various stakeholders have agreed to measure globally. It includes adopting standard protocols for observations that are acceptable across cultural groups and knowledge systems. Documenting the existing assets will articulate "what the current observing system is" and "what is already in place", even if all the pieces are not connected, and what investments have been made. We should leverage experiences from the development of current international and continental research infrastructures. Establishing a rolling review of requirements, comparing our assets with these requirements, performing a gap analysis for data, analytical capabilities, and networks, communicating needs, and evaluating the value of observations are essential steps.

As a part of the engage process and to ensure that the GGBEO enhances indigenous knowledge systems while advancing comprehensive scientific understanding, several strategies would be implemented. First, indigenous communities would be engaged as stakeholders early in the process to effectively integrate their knowledge systems. It is crucial to develop ethical guidelines that prioritize indigenous data sovereignty, recognizing their ownership and control through data sharing agreements. Providing training and resources will empower indigenous communities to manage and utilize the collected data, creating mutual benefits for both the scientific community and indigenous peoples by valuing traditional knowledge insights. Transparent communication must be maintained to allow indigenous communities to express concerns and influence how their knowledge is applied. Gaining informed consent from these communities is essential, ensuring they understand how their contributions will be utilized. Finally, cultural practices should be respected and integrated into scientific contexts without compromising their integrity.

4.2. The second step: plan

The implementation plan needs to take shape over a funding cycle of 5–7 years, with well-defined milestones. Immediate action and an implementation plan are imperative for realizing this vision. While the implementation will occur in stages, we are not starting from scratch. The new WMO-GBON v2 and v3 approaches, which design, define, and monitor the basic surface-based observing network at the global level, along with the G3W, a new global greenhouse gas monitoring initiative to support mitigation actions under the Paris Agreement, are concrete steps towards global coordination. Several programs and activities provide an extensive pool of lessons learned to be used as a reference to establish an implementation plan for GGBEO and set us on the path to actualizing segments of our vision.

4.3. The third step: install

Once the implementation plan has been developed, we can move to installations, such as pilots, demonstrators, and new entities that integrate the current system. Demonstrators include testbeds, living laboratories, and integrated field laboratories that can be further developed by users for their own needs, making our data findable by new tools and accessible to AI. Integrating the more straightforward elements and progressively tackling complexity will ensure that constructing more cohesive systems occurs synergistically in parallel. The GGBEO needs to be connected to a comprehensive network of flagship observation sites and supported by hierarchical observation networks and sensors, taking full advantage of future technological and connectivity developments.

4.4. The fourth step: operations

The final steps involve the operational system, maintenance, and further development phase. The GGBEO will start its operation to provide a user-friendly interface for data mining and comprehensive analysis under common coordination and management. In the last stages, continuous interaction and information sharing with end users and the organizations whose networks form the basis of the global observatory become crucial. To implement the GGBEO effectively, a set of Key Performance Indicators (KPIs) should be established for quantitative assessment. These KPIs should include metrics specifically related to activities in the Global South, such as capacity-building outcomes (e.g., trained staff and upgraded facilities), participation in global networks, frequency of accessible data, collaboration in research activities, financial resource sharing, and support for institutional long-term commitments.

5. Concluding remarks

The scientific community currently lacks coordination, funding, and resources to develop a systematic action and implementation plan, that would start with the analysis of current observation capacity, data processes, and organizational structures. Implementing a new type of global observation system requires resolving a wide range of challenges. Beyond technological, governance, and coordination challenges, a radical change in culture and mindset is needed to fully understand the value of FAIR data and to convince decision-makers and legislators of the importance of a global observing system for impactful regulatory and political action. Additionally, fast-developing AI promises unlimited potential for the development of observation systems and future emerging data services (Stevens et al., 2024). On the other hand, users' new data requirements must be ready to adapt. It is crucial to involve commercial operators (industry) in data access. As we transition from a scientific to a commercial context, we continue to encounter barriers to the open sharing and access of near-real-time (NRT) data. Real-time data are valuable, and "information is power." However, currently, the Earth science community provides data for free, while private companies benefit without reinvesting in the infrastructure. This situation highlights the need for a business plan and a cost-benefit analysis when establishing a GGBEO.

As an observation community, we call for new modes of collaboration to efficiently develop a global observation network plan in a short time frame while continuing to produce comparable data from different regions worldwide. Data from higher resolution systems is essential for data assimilation, reanalysis, verification, and emulation. Additionally, a high-resolution system is necessary to enhance other types of short-duration or lower-quality data. Recently, Kindling and Strecker (2022) conducted an extensive analysis of data quality assurance in research data repositories. Their survey revealed that quality assurance in repositories is multifaceted, highlighting the need for further research to understand individual and institutional approaches to data quality assurance.

Coordination and management of a global observation system is a significant challenge at many levels, including scientific, technical, financial, and administrative. Additionally, developing global systems includes challenges such as agreeing on common user requirements, legal aspects such as data access rights and ownership, introducing changes in business processes, coordinating application development, coordinating software releases, and encouraging local users to support global systems (e.g., Creutzig et al. (2019)). The proposed GGBEO initiative aligns with actions like GEOSS, GCOS, and WIGOS by integrating comprehensive environmental data across meteorology, atmospheric composition, and ecosystems. It shares the goal of establishing a global network to enhance data availability, interoperability, and accessibility, supporting informed decision-making and scientific research. Additionally, GGBEO emphasizes standardizing data formats and methodologies to ensure comparability and usability across platforms. However, GGBEO differs by focusing on enhanced ecosystem and marine parameters, offering a broader scope than primarily land-based systems. It emphasizes NRT data dissemination and interactive feedback mechanisms for greater responsiveness and adaptability. GGBEO also prioritizes localized observations, particularly in underrepresented regions, to fill data gaps and achieve global harmonization. Uniquely, GGBEO leverages cutting-edge technology to innovate data usage across sectors, setting new standards for environmental observation. By fostering cross-disciplinary collaboration, it integrates natural and social sciences, offering unique perspectives on global environmental challenges. Through these alignments and innovations, GGBEO strategically complements existing global initiatives while addressing specific gaps and delivering novel contributions to environmental observation.

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Notes on contributors

Dr. Hanna K. Lappalainen is a docent and the Secretary General of the Pan-Eurasian Experiment (PEEX) Program at the University of Helsinki, Institute for Atmospheric and Earth System Research (INAR), Finland. She also serves as the Director of the of the Atmosphere and Climate Competence Center (ACCC) Impact Program. Dr. Lappalainen is the lead editor of the PEEX Science Plan and has extensive experience in coordinating large- scale research projects. Her contributions have been recognized with several honors, including the NASA Goddard Team Award for the EOS-AURA satellite OMI Team in 2005 and the Silver Medal from the International Eurasian Academy of Sciences (IEAS) in 2015. She co-leads "Arctic-boreal Hub" of the Universities of the Arctic network with Academician Markku Kulmala. She obtained her PhD from the University of Helsinki, Finland and has been engaged in research on atmospheric biogenic volatile organic compounds and plant phenology.

Prof. Alexander Baklanov (PhD in Geophysics, 1983; Dr.Sci. in Meteorology and Climatology, 1998; Professor of Meteorology, 2008), has worked in atmospheric and environmental sciences since 1979, with research focuses on developing next-generation online coupled meteorology-chemistry models, boundary layer dynamics, and urban climate studies. He is a Professor at the Niels Bohr Institute, University of Copenhagen. Over the past 10 years, he served in Research Department of the World Meteorological Organization (WMO), where he was responsible for integrated modelling and cross-cutting urban research activities. He is a member of the Academia Europaea, the International Eurasian Academy of Sciences (IEAS), and Founding Editor of the Urban Climate journal. He led several international research projects on urban environment and climate, including ArcticRISK, NordRisk, FUMAPEX, MEGAPOLI, EnviroRISKS, EuMetChem, EnviroHIRLAM, PEEX MP, IMTECC, and IUS4CRC. He was the WMO focal point for the UN Initiative "United for Smart and Sustainable Cities", the UN Coalition for Combating Sand & Dust Storms. He was one of the developers of the WMO methodology for Integrated Urban Hydrometeorological, Climate and Environmental Systems for sustainable cities. Currently, he is a member of GEO Resilient Cities and Human Settlements WG, and is a lead author for the IPCC Report on Climate Change and Cities. He has published 15 books and more than 300 journal publications.

Prof. Jaana Bäck is an expert in biogeochemical cycles, terrestrial ecology and soil processes in boreal and arctic ecosystems, especially the feedbacks between ecosystems and atmosphere. She is contributing in the development of national, European and global research infrastructures for integrated, long-term Earth system observations. She is the Coordinator of the H2020 Advanced community project "eLTER PLUS", and a Co-coordinator of the ESFRI process of the European Long-Term Ecosystem, Critical Zone and Socio-ecology RI. Prof. Bäck is leading the "Ecosystem processes" Research Group at the University of Helsinki, and is also responsible for the ecosystem research at the SMEAR network (www.atm.helsinki.fi/SMEAR/) also and serves on the SMEAR Board of Directors. In addition, she is a member of the national IPCC working group.

Dr. Silja Häme is an aerosol physicist with over ten years of experience in atmospheric research, complemented by extensive in research coordination and project management, particularly in the development and implementation of national and European research infrastructures. She currently serves as the Coordinator of ACTRIS-Finland national activities and leads European ACTRIS Topical Centre Units hosted by the University of Helsinki, focusing on nanoparticles and condensable trace gases. She also works at the ACTRIS ERIC Head Office (established in 2023) and previously contributed to the interim ACTRIS Head Office beginning in 2017, playing a key role in the establishment and implementation of ACTRIS as a pan-European research infrastructure. Before her involvement with ACTRIS, Dr. Häme worked with the European research infrastructure AnaEE (Analysis and Experimentation on Ecosystems) as a project manager for AnaEE-Finland national activities and supported the establishment of AnaEE. She also contributes to Finnish flagship—the Atmosphere and Climate Competence Center (ACCC). She has made significant contributions to the following European research infrastructure projects, including: EU-FP7-AnaEE Preparatory Phase Project, EU-H2020-ACTRIS Preparatory Phase Project, EU-H2020-ACTRIS Implementation Project and EU-H2020-ATMO-ACCESS. She is a former Fulbright scholar (Columbia University, New York, USA 2012–2014).

Prof. Tuukka Petäjä has over 20 years of research experience in experimental atmospheric sciences. He is the Vice-Director of Institute for Atmospheric and Earth System Research, where he is responsible for research in aerosol domain and the development of research infrastructures. He is also the Scientific Advisor for the ACTRIS research infrastructure, which holds ESFRI Landmark status. His research interests encompass a wide range of topics, including: 1) Aerosol-cloud interactions, 2) Development of mass spectrometric methods for atmospheric aerosols and trace gases; 3) Measurement techniques for aerosol particles; 4) Long-term monitoring and field campaigns; 5) Aerosol-cloud-climate-biosphere interactions, 6) Air quality, and 7) Arctic research. He is recognized as a highly cited scientist (since 2014, by Thompson Reuters) and has received Aerosol Foundation Award for multidisciplinary research (2022), the Vaisala Award (2013) for his contributions on combining state-of-the-art science and instrument development; He is also a receiver of Science and Technology in Society Future Leader Award from New York Academy of Sciences. He serves as the PI of Biogenic Aerosols–Effects on Clouds and Climate (BAECC), a multiplatform research campaign to elucidate the role of secondary aerosols to clouds, supported by U.S. Department of Energy. He is a board member of the PACES initiative, and is actively involved in coordinating EU projects including iCUPE, ACTRIS IMP, and RI-URBANS.

Dr. Juerg Luterbacher is a Professor of Climatology, Climate Dynamics and Climate Change, and former Director of the Department of Geography at the University of Bern, Switzerland where he also received his PhD. From 2020 to 2024, he was the Director of Science and Innovation and Chief Scientist at the World Meteorological Organization (WMO). He served as an elected member of the Scientific Advisory Board appointed by UN Secretary-General Guterres and is a member of the Academy of Sciences and Literature/Mainz, Germany. Dr. Luterbacher has shown outstanding leadership across a wide spectrum of climate science, contributing significantly to the development of a holistic Climate–Earth System approach. He co-developed and implemented the PAGES research strategy on past climate for Europe, the Mediterranean, and Asia, focusing on the last 2000 years. He was also a High-Level Advisory within the OECD Group on Losses and Damages and is a Member of the Climate Change on Earth Observations for Climate Change Impacts on World Heritage Cities/UN Flexible Mechanism. He was a Lead author of Chapter 5, "Information from Paleoclimate Archives" of the 5th IPCC Assessment Report. He has authored over 200 peer-reviewed scientific publications and has repeatedly recognized as a Thompson Reuters Highly Cited Researcher in the field of Geosciences. He is currently the coordinator of the Horizon Europe Project MedEWSa (www.medewsa.eu).

Dr. James W. Hannigan is a Project Scientist at the Atmospheric Chemistry, Observations and Modeling Lab at the National Center for Atmospheric Research, USA. He has more than 30 years' experience in infrared spectroscopy and remote sensing of the atmosphere. He applies these techniques to observe trace atmospheric constituents, enabling a better understanding of trends in long-lived species that affect climate and stratospheric ozone and shorter-lived emissions from biomass burning, anthropogenic pollution, and volcanic activity that impact air quality. He has developed trace gas instrumentation for airborne observations and participated in many field campaigns spanning from the Antarctic to the North Pole. Currently, he operates three ground-based stations within the Network for the Detection of Atmospheric Composition Change (NDACC) located at Pituffik, GR, Mauna Loa HI and Boulder CO. Dr. Hannigan serves as Co-Chair of the NDACC Infrared Working Group and has been a member of the Steering Committee since 2004, which coordinates more than 70 remote sensing sites worldwide. NDACC data are publicly available and widely used for understanding global trends, determining changes related to emissions or atmospheric dynamical perturbations, and validating satellite observations. He is also an advisor to CREGARS section of ACTRIS and conducts research supported by both the U.S. NSF and NASA.

Prof. Markku Kulmala, Academician, leads the Institute for Atmospheric and Earth System Research (INAR) at the University of Helsinki. He is active in international initiatives to establish and enhance comprehensive, continuous measurement networks all around the world, with a focus on addressing the complex interactions between air quality and climate change. Prof. Kulmala is a world leader in atmospheric aerosol science and one of the founders of "terrestrial ecosystem meteorology". His research encompasses the SMEAR field stations and GlobalSMEAR network, forming the backbone of a global observational infrastructure. His work spans theoretical and experimental aerosol physics, atmospheric chemistry, observational meteorology, biophysics and the intricate feedback between the biosphere, aerosol, cloud, and climate. Prof. Kulmala has established a comprehensive research program that integrates long-term atmospheric observations, global modelling and deep theoretical and experimental insights into air quality-climate interactions. Prof. Kulmala is the Foreign Member of the Chinese Academy of Sciences, a council member of the World Academy of Sciences (TWAS), and a member of six other prestigious academies. He has received more than ten major international awards and holds nine honorary doctorates and professorships.

ORCID

Hanna K. Lappalainen http://orcid.org/0000-0003-3221-2318
Alexander Baklanov http://orcid.org/0000-0002-5396-8440
Jaana Bäck http://orcid.org/0000-0002-6107-667X
Silja Häme http://orcid.org/0000-0002-3763-0407
Tuukka Petäjä http://orcid.org/0000-0002-1881-9044
Jürg Luterbacher http://orcid.org/0000-0002-8569-0973
James W. Hannigan http://orcid.org/0000-0002-4269-1677
Markku Kulmala http://orcid.org/0000-0003-3464-7825

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