Climate Modelling User Group [CMUG]

Deliverable 1.2

Earth Observation for Climate Foresight Report

Centres providing input: All CMUG partners and Science Leads from multiple ECV projects

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Contents

1. Executive summary

This report provides an overview and selected examples of the relevance of Earth Observation (EO) data in assessing human and natural influences on the climate system and how improved Earth Observations could help respond to these influences in terms of minimising and addressing any adverse consequences and maximising the benefits of an improved understanding of the system. It considers high-level drivers of EO data requirements, including in the context of international agreements on climate change, sustainable development, disaster risk reduction and biodiversity. It then provides examples of where EO data and research are contributing to climate information and services relevant to the monitoring, understanding and prediction of the climate system and then where further data generation and research activities would support and enhance this contribution. These examples are drawn from the work and experience of scientists involved in the European Space Agency (ESA) Climate Change Initiative (CCI). Finally, conclusions and recommendations are drawn from these examples and summarised below.

The examples provided in the report demonstrate that EO data and research generate information relevant to international and national policies and action on climate change directly, e.g. from monitoring greenhouse gases to detecting trends in the cryosphere and sea levels, and indirectly through their role in improving understanding, modelling and forecasting of the Earth System. Information is also produced that is relevant to monitoring ecosystems/biodiversity and progress towards Sustainable Development Goals (SDGs). The contribution to improved forecasting has significant value in several contexts, generating information useful in many sectors of the economy, building climate resilience, adapting to climate change and managing climate-related risks. EO data and research also have the potential to generate vulnerability and exposure indices which could further add value in these contexts. Finally, combining EO data and modelling generates more complete information about the evolution of the Earth System and is used in the attribution of climate trends, events and impacts, again highly relevant to policies and action on climate change.

The specific examples provided of future activities that would broaden the contribution of EO data and research fall into five categories: new observations; continuity in and improvement of existing observations; integrating Essential Climate Variables (ECV)s, modelling and in-situ observations for applications; modelling and climate science; and building capability. Work on new observations should include generating global long-term climate data records (CDRs) for precipitation and other aspects of the hydrological cycle (rivers and wetlands), land and sea vegetation and ecosystems and carbon aerosols resulting from fires. Work on existing observations should focus on continuing existing good practice in maintaining continuity in satellite measurements with suitable overlaps between new and retiring satellites whilst enhancing the efforts to improve and further homogenize the CDRs and characterise their uncertainties and assess inter-ECV consistency.

Combining ECV data with modelling is already generating more complete characterisation of the state and evolution of the Earth System and improvements in the ability to model all components of the system (atmosphere, ocean, land, cryosphere). This provides the ability to monitor and simulate the key Earth System cycles of carbon, energy and water which would have a very broad range of applications and could be improved by integrating the ECV data with models of the full Earth System rather than its components. For example, for the carbon cycle this would facilitate enhanced monitoring and predicting of emissions and mitigation actions whilst generating useful information on important contributors to the cycle such as terrestrial and marine ecosystems and permafrost systems. Similarly, energy and water cycle monitoring and modelling generate key information on, in particular, likely future warming levels, many climate hazards, water availability and the cryosphere. Thus, generating this integrated climate information and modelling should be a focus for a future EO data and research activities.

Finally, with these future EO data and research activities aimed at generating information and services for a wide range of applications, dialogue is needed between the providers of the information and services and the actors and stakeholders applying them to establish a clear understanding of requirements and applicability. This requires these communities to integrate their knowledge and expertise and thus building their capability to engage effectively in the dialogue and to understand relevant details of the available knowledge, information and services. This will be key to ensure sustainability of any services built on the outcomes of the research.

2. High-level drivers of requirements for EO data in climate change science and services

The main international demands for generating and undertaking research on climate-relevant Earth-Observation (EO) data are driven by requirements from climate policy (on monitoring, adaptation, loss and damage and mitigation), sustainable development, disaster risk reduction and assessments of biodiversity and ecosystem services. These data and the related research are also relevant to a range of climate-relevant economic activities. The diagram in figure 1 below sets out these high-level drivers and components of these to which EO data and research are relevant. It also summarises various EO data and research activities and how these link into the components and other activities required to generate and integrate the information to meet the requirements.

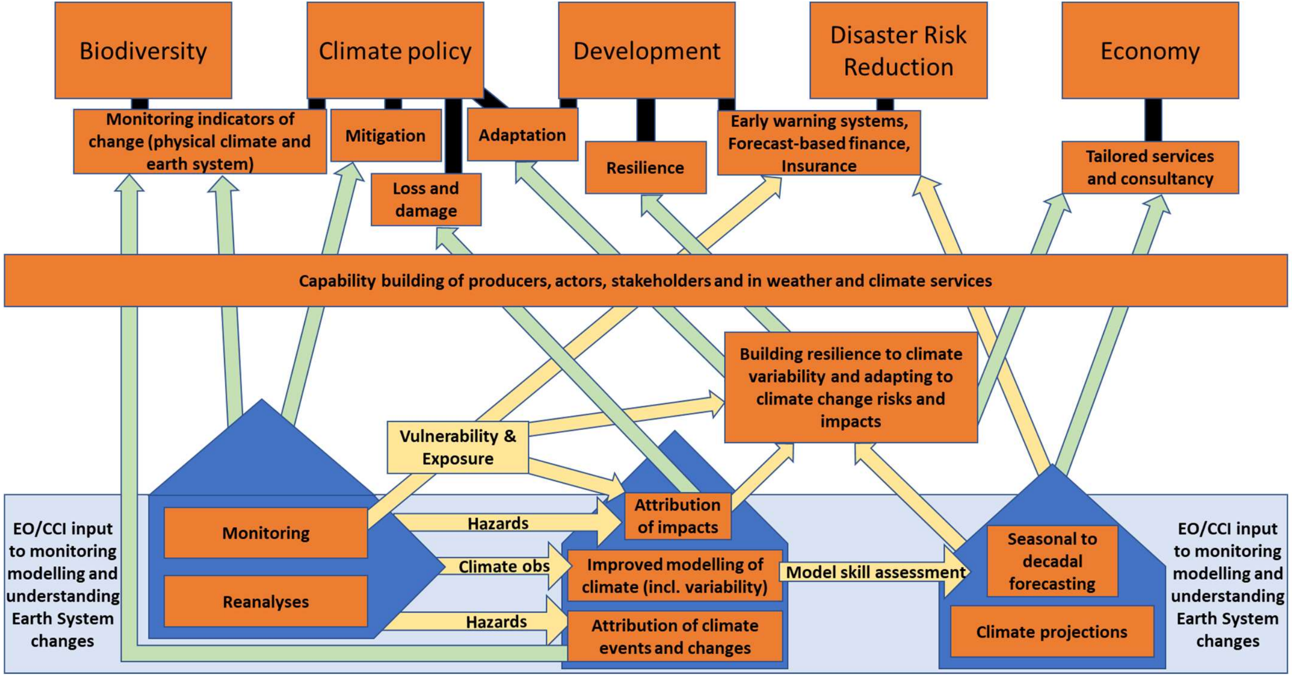


Figure 1: High-level drivers of Earth Observation (EO) data for climate and their connections to EO data products and research. The main high-level drivers are shown in the top row with components of these in the row below linked by black bars to the relevant drivers. The bottom row (within the light blue rectangle) describes relevant products and research directly involving EO data and those where EO data are integrated with models to generate new information on, or improve the forecasting of, changes in the Earth System and its weather and climate. These are clustered into three blue boxes: on the left, representing the generation of data; in the middle, representing the application of these data with models to either understand the drivers of changes or to improve the models themselves; and on the right, representing the use of the models in generating forecasts and climate projections. The green arrows represent information directly relevant to the component it points to, either from all of the activity contained in the blue box or from one of the constituent activities if the arrow emanates from the orange box describing the activity. The yellow arrows represent information flow between the blue and/or orange boxes in the bottom row or where multiple inputs contribute to the activity or component in one of the orange boxes above. The yellow box containing "Vulnerability & Exposure" indicates EO data on the vulnerability and exposure of people or systems at risk which is relevant to the three activities in the orange boxes the emanating arrows point to. The lower of the two orange boxes between the upper and lower rows represents the integration of information from the orange and blue boxes below which can be used for resilience building and adaptation. The upper box of these two indicates that in order to integrate the products and focus the research from the activities below into the components above requires efforts to build the capability of the producers, actors, stakeholders and in the related weather and climate services involved in this integration.

Climate policy is driven by the processes and bodies of the UN Framework Convention on Climate Change (UNFCCC) which are supported by the assessments of the Intergovernmental Panel on Climate Change (IPCC). The IPCC assessments require relevant indicators of the causal factors of climate change (e.g. greenhouse gas emissions and atmospheric concentrations) and the related changes in the physical climate system (e.g. warming, sea-level rise) and their impacts in natural and human systems (e.g. drought, wild-fire, flooding). The UNFCCC Paris Agreement and other instruments encourage activities to minimise and respond to these changes and impacts, i.e. both mitigation and adaptation actions, and requires countries to report on the monitoring of these. Mitigation actions can also have natural and human system impacts which require monitoring; and adaptation actions require information about the vulnerability and exposure of systems at risk (e.g. crops in drought-prone areas or settlements in flood-prone areas). Many of these activities, from understanding the Earth's climate system to climate change impacts and options for adaptation to these, require the use of models for which Earth Observations are crucial in evaluating their representation of climate processes and their ability to simulate and predict the climate. Thus, many areas of climate policy require EO data and research.

Progress towards the Sustainable Development Goals (SDGs), developed under the UN's 2030 Agenda for Sustainable Development, will all be influenced by climate change and conversely achieving them will contribute to the aims of the Paris Agreement (Gomez-Echeverri, 2018). In particular, attaining the goals will require building resilience to climate-related hazards, e.g. to improve food, water and energy security, health outcomes, infrastructure and communities. This will require information on the hazards themselves (e.g. heatwaves, poor air quality, flooding, droughts), both on their current likelihood and intensities and forecasts of these over coming days to seasons (or longer, e.g. in the case of multi-year drought). It will also require information on indices of vulnerability and exposure in affected systems which are key determinants of the severity of any impacts in these systems. Thus, many of the EO data and research requirements derived from climate policy, from monitoring of hazards to assessing vulnerability and exposure of natural and human systems at risk, are relevant to the SDGs. Also, attaining the Goals often requires overcoming complex problems which need to be understood in depth to ensure that these data and research are relevant and used to solve the problems. This requires significant capability to be built amongst the users and producers of relevant knowledge (i.e. about the affected systems as well as the data and research) which will need to be shared and integrated to generate this understanding and options for action. Finally, economic activity which enhances the prosperity of affected people and communities (e.g. through improved agricultural productivity or generating renewable energies) can also be relevant to the SDGs through contributing to building capability and enhancing adaptive capacity (and thus reducing vulnerability), and again EO data and research can contribute to this.

Closely linked to both attaining the SDGs but also adapting to climate change are the international efforts to address risk under the Sendai Framework for Disaster Risk Reduction (DRR). Understanding the risks and how to reduce them, including through appropriate reconstruction, require the same elements of monitoring of and information on hazards, vulnerability and exposure (e.g. Voigt et al., 2016) as well as the ability to forecast the hazards (and knowledge on the skill of these forecasts). These underpin the required early warning systems as well as some of the other response measures such as forecast-based finance, adaptive social protection and index insurance schemes. In addition to being directly relevant to DRR, these systems/schemes are also often components of climate change adaptations. Finally, information from the monitoring of disaster-related climate impacts and the effectiveness of adaptations to reduce these is relevant to the Global Stocktake and an assessment of Loss and Damage, both important components of the Paris Agreement.

A final area of international activity which involves monitoring of the Earth System involve the assessments of the International Panel on Biodiversity and Ecosystem Assessments. EO data and research are again relevant here, and these assessments have significant relevance to or overlap with the activities described above. For example, satellite retrievals of fluorescence data over land and ocean colour can be used to quantify land photosynthetic and ocean biological activity respectively. More generally, Essential Biodiversity Variables are being identified by the Biodiversity Observation Networks of the Group on Earth Observations (GEO-BON), see e.g. Navarro et al. (2017).

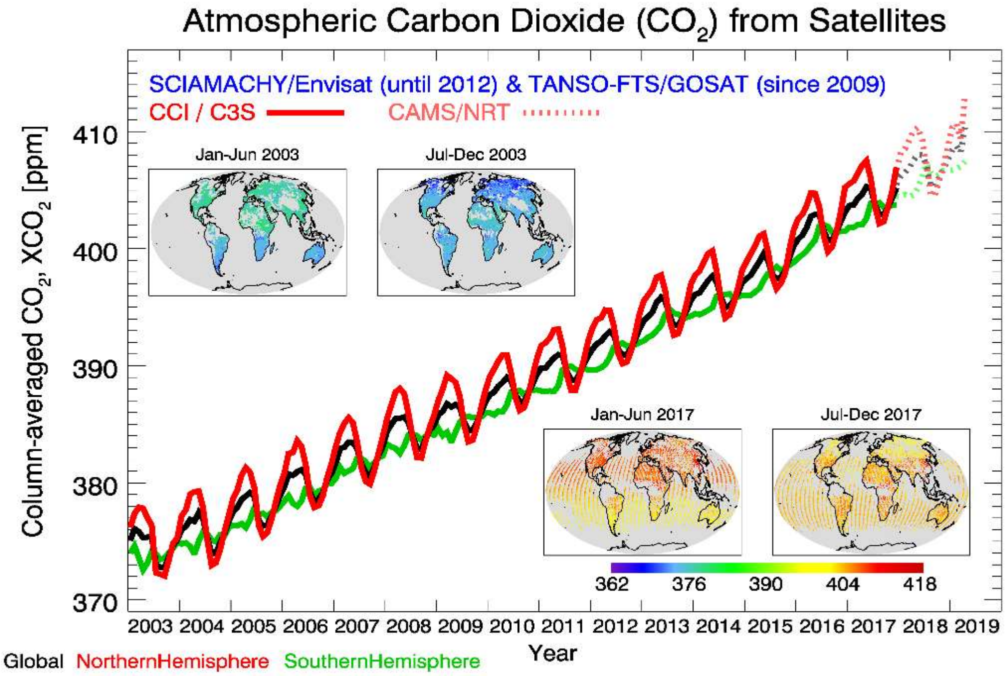
In addition to requirements derived from the above international policy drivers, there are many climate-sensitive sectors of the economy (e.g. agriculture, water resources, infrastructure, insurance) which would benefit from improved forecast and climatological information. Many EO data have a central role in verifying and improving the models used for weather and seasonal forecasting and climate change projections. Thus, they help to quantify and enhance the benefit that weather forecasts bring in warning of and avoiding the impacts of disruptive weather. Similarly, their application in seasonal forecasting can benefit the many developing country regions which apply these in planning their agricultural and other climate-sensitive activities. Also, EO data are increasingly used for index-based weather/climate insurance in the agricultural sector in developing nations (opening up affordable, objective insurance to food growers in the face of drought and other risks) which require long-term records of EO observations that are stable and quality-assured (e.g. Hochrainer-Stigler et al., 2014, Valverde-Arias et al., 2020). EO data and research could provide this directly through enhancing the quality or range of information in addition to facilitating indirectly through generating better forecasts from improved and/or more comprehensively validated models. Another sector, which is specifically linked to climate change through mitigation and to the SDGs through SDG 7 on affordable and clean energy, is that of renewable energy. In this case EO data and research can be of use in planning solar or hydropower, wind-energy or biofuels or in evaluating and improving the models used to forecast relevant weather and climate variables which are required in the operational use of these energy sources.

3. Climate information and services requiring EO data and research

EO data comprise a set of variables that characterise the Earth's climate system, including physical, chemical or biological quantities. A standard set of key variables, known as Essential Climate Variables (ECVs), are defined by the Global Climate Observing System (GCOS, an international agency co-sponsored by UN and other international organisations) as relevant to understanding and predicting variability and change in the climate system and underpinning efforts to adapt to, mitigate and address the consequences of associated risks. Most ECVs are a collection of several related geo-physical variables, called ECV products (e.g. Sea Ice ECV products includes sea-ice concentration, extent/edge, drift, and thickness). ECV datasets are generated by combining information from and performing relevant research on historical, in-situ and remotely sensed datasets. The European Space Agency (ESA) Climate Change Initiative (CCI) plays a significant role in developing and enhancing ECV datasets, with EUMETSAT and the Copernicus Climate Change Service (C3S) two other European institutions also having important roles. The examples provided in this and the following section are drawn from the work and experience of scientists working in CCI projects. In this section the examples demonstrate how EO data can be used to monitor, understand, simulate and predict variability and change in the climate system. In the following section they describe technical details of activities and research required to generate the data for these purposes related to specific situations, e.g. improving the monitoring of greenhouse gases relevant to the Global Stocktake or improving the quality and resolution of reanalyses for enhanced understanding of the climate system and for evaluation of climate models.

a. Monitoring, reanalyses and process studies

Carbon dioxide (CO_2) and methane (CH_4) are the two most important anthropogenic greenhouse gases (GHGs). Thus, they are key variables to monitor both to understand the human influence on the climate system and to track mitigation responses to reduce their emissions as required by the UNFCCC Paris Agreement and its 5-yearly Global Stocktake. The most important of these is CO_2 (Fig. 2) which is one of the 7 WMO and GCOS global climate indicators which motivated work by ESA and EU to set up an operational GHG monitoring system. This included detailed requirements for CO_2 and CH_4 EO data products being formulated in the ESA Climate Change Initiative (CCI) User Requirements Document (URD, http://www.esa-ghg-cci.org/?q=webfm_send/344) and in the corresponding Target Requirements Document (TRD) of the Copernicus Climate Change Service (C3S). These are very demanding, especially with respect to accuracy, as even small biases can result in significant errors of the derived surface fluxes, and to account for the many sources which are highly variable and concentrated in relatively small areas thus requiring frequent observation with high spatial resolution.



Contact:Michael.Buchwitz@iup.physik.uni-bremen.de Figure:3-May-2019

Figure 2: Timeseries and maps of atmospheric CO_2 as retrieved from the satellite instruments SCIAMACHY/Envisat and TANSO-FTS/GOSAT. The quantity shown is XCO_2, i.e., the column-averaged dry-air mole fraction of CO_2 in parts per million (ppm). Year 2003-2017 data have been generated for and made available by the Copernicus Climate Change Service (C3S, https://climate.copernicus.eu/). The EU-funded C3S performs the operational continuation of the ESA Climate Change Initiative (CCI) GHG_cci project (http://www.esa-ghg-cci.org/). Recent data (dotted lines) show the (preliminary) near-real-time product generated for the Copernicus Atmosphere Monitoring Service (CAMS, https://atmosphere.copernicus.eu/). Details see "European State of the Climate 2018 / Headline Climate Indicators / Greenhouse Gases" (https://climate.copernicus.eu/greenhouse-gases).

The Ocean plays a central role in Earth's climate. It has absorbed about 93% of the extra energy from the enhanced greenhouse effect and 30% of anthropogenic carbon dioxide (CO_2) from the atmosphere. It is therefore essential to monitor it, to assess changes in sea surface salinity, temperature, wind/wave forcing leading to possible changes in air-sea exchanges and in ocean circulation, thus potentially modifying the role of the Ocean in the Earth's climate.

Globally applicable EO data are also increasingly sought after to fill data gaps in current SDG monitoring. An example of where EO data can play a key role is in the monitoring and forecasting of climate in urban areas. More than half the world's population live in cities, and "sustainable cities and communities" is the focus of SDG 11. Recent heatwaves around the world have highlighted the vulnerability of some communities to climate change, with people in poor areas of cities particularly at risk. Studies, such as Dousset et al (2011), have found that higher than normal surface temperatures can lead to increased mortality rates. EO monitoring can be merged with urban databases to identify districts at risk and thus supply criteria for adaptation strategies in urban planning, such as increasing green spaces. Incidents of water-borne diseases have been associated with ocean heat waves (Baker-Austin et al. 2016).

EO data have proven helpful in generating information on climate sensitive sectors such as agriculture, water planning and irrigation management, fire risk management, fisheries, aquaculture and many more disciplines and industries. For example, monitoring of soil moisture can provide information relevant to managing water demand and irrigation. Also, forestry and agriculture use the Normalized Difference Vegetation Index (NDVI) and Leaf Area Index (LAI) to monitor how crops evolve over the season and EO data provide crop area estimates, crop stress indices, productivity assessments and yield models across a range of time scales. In particular, systematic yield estimation and the effect of the stress factors on the yield can be provided from EO data through combining temporal trajectories of agricultural development and information for detecting the onset and severity of drought (Anderson et al 2011). For the latter, when water is a limiting factor the resultant decrease in transpiration can be deduced from the consequent increase in the surface temperature of the canopy. LAI has also been used to demonstrate the greening (and, in some areas, browning) of vegetation over a large part of the globe (Munier et al. 2018), a subject of active research (including attributing the causes of these trends).

Closely linked to direct monitoring of climate (-influenced) variables is the generation of reanalyses comprising comprehensive and consistent long-term data records of how weather and climate have changed over the period under consideration, typically of several decades. This is achieved by applying data assimilation to integrate observations available from a variety of data sources together into a state-of-the art model that describes one or more components of the climate system, e.g. the atmosphere and land surface. The result of this data-model integration is a comprehensive, complete, temporally continuous, physically consistent and homogeneous dataset of variables. The advances of recent years on both the parameterisation of physical processes in climate models and the way observations are characterised and exploited make modern reanalyses useful for climate studies and as such they are referred to as climate reanalyses. The latter are reanalyses that produce datasets with the same characteristics of Climate Data Records (CDRs), i.e. time series of measurements of sufficient length, consistency, and continuity to enable study and assessment of long-term (i.e. multi-decadal scale) climate variability and change. Climate reanalyses have two main properties: they rely on quality-controlled observational data, i.e. only observations of proved quality are assimilated, and cover a long temporal period. As such, climate reanalyses play a central role in assessing how and how much the climate system has changed. Observations are at the core of a reanalysis as they can affect the reanalysis' quality and limit/increase its ability in reproducing the evolution of the climate system. For re-analyses that are continuously updated (e.g. ERA5) it is preferable that the long-term stable observation records used in the core of the reanalysis are also available with sufficient timeliness to be used in generating the updates.

Finally, EO data can be used in understanding and constraining key earth system processes which can then be applied to develop representations of these in climate models and provide lines of evidence useful for generating key metrics of global or regional climate change. One example is climate sensitivity (the change in global average surface temperature generated by changes in the radiation budget in the earth system, e.g. by increasing greenhouse gases) which is a crucial property of the climate system. This is relevant to determining atmospheric concentrations (and thus allowable emissions) of greenhouse gases consistent with global warming targets and then the influence of these on a wide range of atmospheric, land surface and ecosystem indices, e.g. extreme temperatures, water availability and plant productivity. In a recent comprehensive assessment of lines of evidence constraining climate sensitivity, Sherwood et al. (2020) noted both the importance of EO data, and the need for maintaining these into the future, "to better constrain climate feedbacks and the physical processes responsible for them." They then observe: "Continuing cloud and radiation observations from both passive and active sensors will reduce uncertainty in feedbacks inferred from inter-annual variability and identify whether the feedbacks exhibited through trends to the emerging warming are consistent with current understanding. However, progress requires maintaining observations that are in danger of disappearing at the end of current satellite missions. High-quality in-situ observations will also help constrain key process uncertainties not amenable to satellite observations."

b. Attribution and modelling of variability and change in climate and the Earth System

Earth observation data will continue to be a key component for evaluating climate models and for characterizing and attributing climate variability and climate change, both directly and via their role in generating climate reanalyses as described above. The following ongoing activities require EO data and research to facilitate progress in our understanding of the climate system and evaluating models of the system:

- Maintaining continuous and long timeseries: EO timeseries are essential for detecting long-term changes in climate and for attributing these changes to human interference outside the range of natural variability. For a robust detection and attribution, continuous and long timeseries are indispensable.
- Characterizing model quality: Earth observations and reanalyses are crucial for evaluating climate models, both in terms of the quality of the representation of individual processes within the models and

their overall ability to simulate and be used in the attribution of drivers of global and regional climate and Earth System variability and change. Given natural climate variability, a simple EO data-model simulation comparison will never be able to completely characterise model errors as EO data are just one realization of how the climate evolved under natural variability. However, comparing statistics of both will clearly identify errors in the model's climatology of the variable in question.

- Providing gridded fields at high resolution: 2-dimensional gridded EO data without spatial gaps are ideal for evaluating climate model. Because substantial increases in CPU capacity allow climate modellers to run global climate models at unprecedented spatial and temporal resolution, the EO data and reanalyses need to keep pace with the increased resolution. For example, the recent reanalyses generated by ECMWF, ERA5, has increased resolution significantly compared to the earlier ERA-Interim product. This allows the evaluation of global and regional climate models on small spatial scales with substantial internal variability which is relevant for providing information on, e.g., climate extremes to stakeholders and the public.

c. Seasonal-to-decadal forecasting

Seasonal-to-decadal forecasting is an aspect of climate science of high priority for society due to its immediate application. It brings together the climate prediction, modelling, observational and services communities. It has shown great potential to inform society and decision-makers in climate-sensitive sectors such as agriculture, energy production and tourism.(e.g. Vaughan et al., 2019). There have been recent advances in forecasting at these timescales leading to promising levels of skill in predicting the large-scale drivers of sub-seasonal, seasonal and multi-annual climate variability as well as their consequent local climate impacts (e.g. White et al, 2017). To further improve climate predictions there is however a need for enhancing aspects like their initialization stage through the use of more sophisticated assimilation techniques combined with the most up-to-date observational datasets, the validation of the forecast systems and the generation of user-relevant products.

ECVs are essential for these purposes and some (such as SST, SSS and Sea Ice) are already in use and have proven to be invaluable (Blockley and Peterson, 2018). For example, assimilation of sea ice thickness products has shown important benefits for seasonal prediction and assimilation of SSS in a coupled model has been shown to potentially improve ENSO forecast (Hackert et al. 2020). In the case of decadal predictions, the use of the ECVs has been more limited because long hindcasts are required to assess forecast quality and generate bias adjustments. However, the recent availability of increasingly longer datasets has been a significant step forward in this respect. New ECVs with additional information from the different components of the climate system, such as land (e.g. land surface temperature, soil moisture), cryosphere (e.g. ice sheets) and ocean biogeochemistry (e.g. ocean colour) are becoming equally important now that the community is able to perform more complex simulations with Earth System Models (ESMs – climate models which additionally contain components representing e.g. the biosphere, carbon cycle, atmospheric chemistry, etc). It is in this context where ECVs can trigger substantial gains in knowledge and ability to generate ground-breaking climate information. For example, ECVs of fire related products (i.e. burned area and biomass) contribute significantly to the validation of both wildfire models and the verification of retrospective predictions and bias adjustment of forecasts performed with them (e.g. Turco et al., 2018). GHG related ECVs such as XCO_2, for example, can be used to evaluate highly uncertain components of ESMs such as the carbon cycle (e.g. Lauer et al., 2017). The inclusion of other products (like aerosols) as boundary conditions can also boost the predictive capacity of ESMs and help in attribution of regional climate changes.

Another example with a regional focus and with links to health-related SDGs is the application of seasonal prediction systems and EO data to forecasting outbreaks of infectious diseases. A current research project is integrating historical EO, hydrological and dengue fever data in Vietnam with hydrological and dengue models to calibrate a system to be used with seasonal forecast data to provide seasonal forecasts of dengue fever outbreaks (Figure 3). The project aims to build resilience to climate change by providing early warning systems to mitigate health impacts from increased rainfall and flooding expected in the future. This provides a good example of the importance of integrating globally available EO data (e.g. land surface temperature, NDVI, soil moisture) with relevant regional datasets of physical (e.g. streamflow) and impact variables (e.g. incidence of dengue fever) with seasonal forecasts of meteorological variables to generate forecasts of a societally-relevant impact.

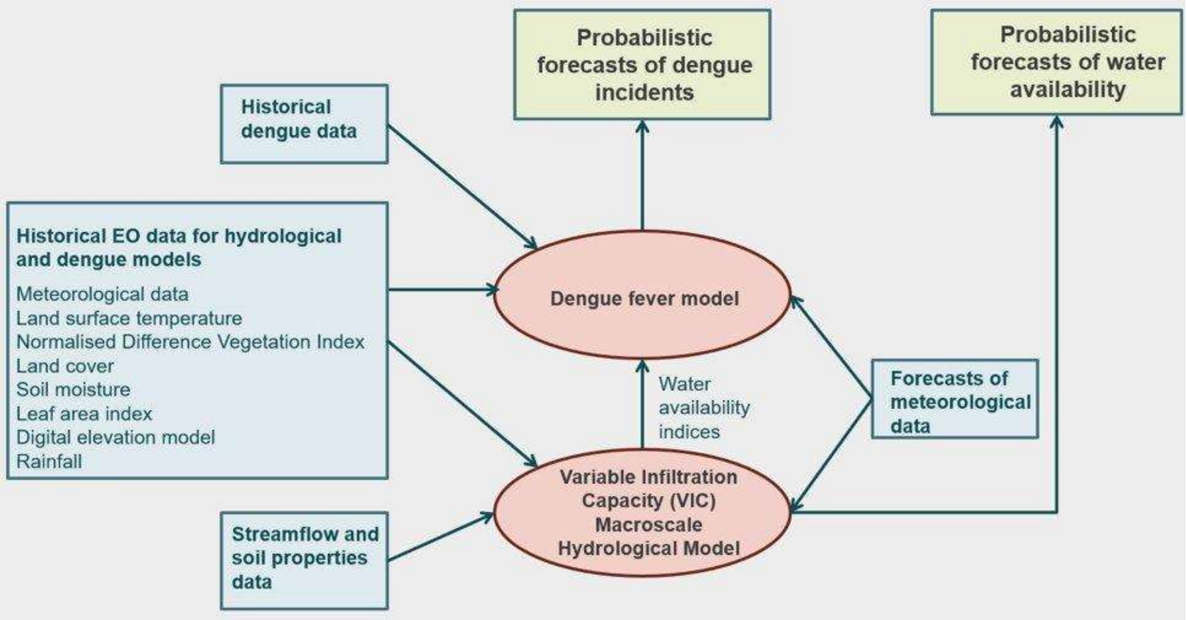


Figure 3: Schematic diagram of the data inputs and modelling systems being used to develop seasonal forecasts of dengue fever and water availability in Vietnam for the UK Space Agency D-MOSS project

Finally, as noted above, ECVs can serve as well to better constrain observational uncertainty during all stages of climate information generation (Popp et al. 2020). It is only by fully considering observational uncertainty that robust estimates of the information quality can be formulated, which is a fundamental aspect for the users. For the climate community, quality assured long-term satellite data records with reliable uncertainty estimates in ECVs such as clouds or sea ice are also key to improve the representation of certain processes in the models, e.g. via improved parameterizations, in particular over regions of important systematic biases which can compromise the predictive skill locally, and beyond via associated teleconnections.

4. EO activities required to enable and deliver the climate information and services

The previous section described examples of how EO data can be used to monitor, better understand, simulate and predict variability and change in the climate system. In this section technical details of some activities and research required to generate the data for these purposes related to specific situations using examples from the work and experience of scientists working in CCI projects.

a) Monitoring, reanalyses and process studies

o New and improved quality ECVs and ECV products

Research and Development (R&D) is critical to integrate data from new and future sensors into the long-term ECV records. The Copernicus Sentinels provide a recent and growing source of high-quality data which should be fully integrated into CDRs both to maximise their utilisation and to extend and ensure continuity of the records. For example, an objective of the Sentinel-3 mission is to provide climate quality observations for sea and land surface temperatures as well as ocean colour. CCI+ is ensuring data from the first units A and B contribute to the associated CDRs. Follow-on units (C and D) will replace these long-term and R&D beyond CCI+ will be needed to ensure seamless continuity. In addition to follow-on units for existing Sentinels there are six Copernicus candidate missions (new Sentinels) which could be new sources of climate data over the coming decades. Some of these could provide EO data to specifically address mitigation and adaption strategies. For example, the Land Surface Temperature Mission (LSTM) would provide observations for climate services on agriculture and urban monitoring. Data from this mission would contribute to information on hazards, such as droughts and heatwaves, with vulnerability indices required to be developed.

Key phenomena that would have significant societal benefit if well-observed are the variability of and long-term trends in precipitation. However, the episodic and patchy nature of precipitation makes it a particular challenge for all observing systems, both ground and satellite based. The number of missions directly (via radars) measuring precipitation is relatively small, and indirect inferential methods each have a range of strengths and weaknesses though the example of using satellite based Sea-Surface Salinity to complement the spatio-temporal sampling of precipitations events (Supply et al. 2018) demonstrates their potential. The societal and scientific value of maximising the length, consistency, stability and resolution of precipitation observations is extremely strong, and so pursuing further research to generate these observations should be a priority.

Data on atmospheric CO_2 and CH_4 are currently generated operationally via the Copernicus services C3S (primarily for climate applications) and CAMS (primarily for monitoring, reanalysis and forecasting applications), see Figure 2. However, these operational services do not include R&D required, for example, to generate appropriate data products from new satellites. Some of this work is happening in the ESA CCI GHG project and also the EU-funded projects CHE and Verify are undertaking research into monitoring CO_2 emissions and the use of this in country-level reporting to the UNFCCC. These activities will need to be continued and built upon in order to ensure that the UNFCCC's Global Stocktake process will provide the comprehensive and high-quality reporting of GHGs required by the Paris Agreement.

Ocean colour is currently the only window into the ocean biosphere at synoptic scales, and the data from Sentinel missions are crucial to providing reliable, climate quality data on the distribution of phytoplankton in the ocean, and for computation of marine primary production. Novel algorithms are also emerging, for distinguishing different types of phytoplankton in the ocean, thereby contributing to our understanding of marine biodiversity. In combination with the ESA Biomass mission and related initiatives, we now have the wherewithal to study biologically-mediated carbon cycle over land and ocean, at the global scale, and over the long time scales essential for disentangling signals of climate change from natural ecosystem variability.

Despite the importance of CO_2 and CH_4 as the prime causes of global warming, our knowledge about their various natural and anthropogenic sources and sinks still has significant gaps. An appropriate understanding of these, and how they will respond to a changing climate, is critical for reliable climate prediction and assessing the potential for mitigation to meet climate policy targets. Satellite observations of CO_2 and CH_4 contribute to a better understanding of their location and dynamics using methods such as inverse modelling. However, information is also required on land-cover change, forestry, wetlands, permafrost and ocean ecosystem productivity which are important sources and sinks. Many of these components are currently observed or can be derived from EO data (the situation of permafrost is described immediately below) but clearly the key is for these to be of sufficient quality and to be able to be combined to allow accurate monitoring and prediction of GHG emissions and concentrations at national to global scales.

Permafrost monitoring is challenging as it is a sub-ground phenomenon. This applies to monitoring in situ as well as with EO data. The climate signal provides an integrated measure of changes in surface conditions, specifically temperature and snow properties. These are the main input parameters for modelling permafrost. To ensure gap free records, EO data are combined with reanalyses. This specifically demands reliable reanalysis records across the Arctic, Antarctic and in mountain regions (all of which are challenging to generate reliable observations for due to issues with sensors, lack of in situ observations and models). To further improve the quality, land-surface characterization that serves as a suitable proxy for soil properties (such as presence of peat) which determine heat transfer is needed. Crucial regarding Arctic permafrost and the fate of carbon is landscape heterogeneity which needs to be addressed with suitable satellite data and eventually considered in climate modelling (Swingedouw et al. 2020). As snow records (specifically spatial resolution and global availability of snow water equivalent) from EO data do not currently meet the requirements of permafrost modelling, information on vegetation height is required to allow modelling of snow redistribution. Although landcover information exists globally from many sources, including CCI, surface descriptions (with respect to soils as well as vegetation physiognomy) which meet the needs of permafrost modelling still do not exist. The requirements in thematic content can be met with EO data (as demonstrated at local to regional scale), but these exceed the level of detail usually addressed at global level due to following international standards which are inadequate for the purpose of permafrost monitoring. Vegetation height in high latitudes also represents a proxy for non-forest above ground biomass, a component of the carbon cycle not yet addressed by EO data for the entire Arctic and also very important for wildfires, particularly during boreal summer.

Surface state information (frozen/unfrozen; also considering presence/absence of snow) has been identified as an independent measure to assess the potential distribution of permafrost. It overcomes the need for gap filling as it is derived from microwave data but it is limited in spatial resolution. Developments in downscaling and integration into permafrost modelling are required to obtain benefit from such alternative sources. Thawing of mountain permafrost is a potential source of serious hazards (rock fall and related debris flows) threatening life and infrastructure (e.g. Haeberli and Gruber, 2009). So far, EO based observations of mountain permafrost and the effects of its thawing are only in its infancy (e.g. terrain displacement from InSAR).

There are many useful land-surface variables relating to vegetation that could be obtained from EO data. One key variable, Leaf Area Index (LAI), was not an ECV addressed by the CCI programme but a prototype is being produced by C3S. The EO data for the 1980s' and 1990s' decades that can be used to estimate LAI consist of AVHRR data. The historical AVHRR suffer from a lack of on-board calibration (Molling et al. 2010). This generates uncertainties that can prevent sufficient overlap from one AVHRR series with another one. This is detrimental to the homogenisation work that needs to be done to produce a CDR. Given this situation, a way forward could be to use Vegetation Optical Depth (VOD) that can be derived from the same microwave observations already used for the soil moisture ECV (e.g. Fernandez-Moran et al., 2020). The soil moisture CDR is mainly based on active and passive microwave observations at C-band and X-band (Dorigo et al. 2017) and with L-band is used in land surface model assimilation (Kumar et al., 2020) and L-band VOD data link to above-ground biomass (e.g. Mialon et al., 2020). VOD at C-band and X-band is linked to leaf biomass and hence to LAI (Zribi et al. 2011, Momen et al. 2017, Vreugdenhil et al. 2017). The ratio of LAI to VOD is proportional to the Specific Leaf Area (SLA). SLA is a key parameter in land surface models. It is often assumed to be a constant value. In reality, SLA may present a seasonal cycle (Brisson et al. 2005) and may change very rapidly (e.g. for wheat during the stem elongation phase). SLA may also present decadal and multi-decadal changes related to nitrogen supply and to the CO_2 fertilization effect. Hence VOD could be used to consolidate existing LAI estimates, and to support attribution studies involving LAI. In addition, the status of vegetation with respect to the phenological cycle/growing season could be derived from combining vegetation indices with satellite-derived temperature records.

As noted above EO data are being used in current SDG monitoring but there are still many gaps. For example, the majority of countries did not report on the proportion of ambient water bodies with good quality (SDG6.3.2) in the last data drive (2017). In future, more elements of the water cycle will need to be described: river hydrology and inundated (wet)lands related to risks of drought and floods and consequent disease vectors are one example. In the coastal region, elements such as seagrasses and corals support essential livelihoods for which global records do not currently exist. In this context, UNEP are looking, for the next data drive, to the Copernicus Land Monitoring Service (CLMS) data on water quality to fill the current gaps in reporting. The logical next step is that historical records on the same water quality variables will be requested which is an area of active research within the ESA CCI Lakes project. This project will also generate lake hydrology variables related both to water availability/scarcity and hazards (floods and relevant diseases) though linking these to services will require further investigation. In addition, to provide more robust and complete information, data on other variable components in the water catchments, notably rivers and snow water equivalent in mountainous regions, will be required which would also require additional research. Outputs from this would then be very relevant as the basis of future C3S and CLMS products, e.g. for a range of hydrological applications such as hydropower planning and water availability for irrigation.

Some GCOS ECVs (e.g. the Sea Ice ECV) are a collection of geophysical variables (ECV products), that might require widely different EO data sources and techniques. For the Sea Ice ECV, many more variables are required (e.g. snow-depth, age, melt-pond coverage, type, lead fractions, albedo…) than have been covered in CCI so far (i.e. sea-ice concentration, thickness, and to a lesser degree motion/drift), or in other sustained research initiatives. These variables mostly rely on EO data and techniques that are not those needed for concentration (microwave radiometry) and thickness (altimetry), including optical imagery for melt-ponds and leads, and scatterometry for ice type. Prototype algorithms and time series exist for many of these additional variables, as well as the required FCDRs, but R&D efforts are required to mature these towards high-quality climate data records, and later transferred to operational services. As well as these additional variables, future efforts for the Sea Ice ECV could make better use of L-band radiometry time series (SMOS, SMAP, ...) and scatterometry. There will also be a need to develop climate-specific algorithms for the potential Sentinel Expansion Polar Mission(s) (CIMR, CRISTAL, ...) to achieve climate consistency with past ESA, EU and/or third-party missions. At the other end of the timeline, in the "pre-satellite era" (<1978), precursor satellite missions (e.g. ESMR Nimbus-6, or SHF Meteor-Priroda) could be better exploited to extract highly valuable snapshots of the past state of the polar regions. Access to these early satellite data will require Data Rescue actions, liaising with the US and Russia.

- **New and improved assimilation and reanalyses**

Observations are critically important in generating reanalysis products, as the former can affect the quality and consistency of the latter. One of the limiting issues is that the Global Observing System (GOS) was never designed for climate studies and for long-term climate variability assessments, but rather for weather forecasting. Ideally, the GOS would provide long-term, well-characterised, comprehensive and consistent observations. With the increased work towards creating Earth System Models (ESMs) with progressively higher level of complexity and coupled components, reanalysis systems are also becoming progressively more complete and comprehensive. With that, there is an increased need to observe and monitor all components of the climate system, i.e. the atmosphere, and its composition, the land, biosphere, ocean, and cryosphere.

Ongoing technical developments in improving assimilation include coupling of the atmosphere and ocean surface properties (sea surface temperature and sea ice concentration in particular) to better capture the impacts of air-sea interactions. Reanalyses are most useful when they addresses multi-decadal periods of time, and in this context, data rescue, reprocessing and improvement of satellite data from the 1960s to 1980s is an important priority, since for vast areas of the climate system these may be the only observational constraints to inform the trajectory of a re-analysis model. Valuable EO data historic archives are in danger of degrading or being lost (particularly archives of regional direct downlinks, some still in analogue format), and, as well as simply preserving the data, effort should be invested to reprocess and make more usable these unique, irreplaceable datasets.

The current land reanalyses for terrestrial surfaces such as ERA-Land and ERA5-Land consist of performing an offline simulation of terrestrial variables using an atmospheric reanalysis (e.g. ERA5). They do not integrate satellite-derived observations into land surface models. For example, ERA5-Land has a prescribed Leaf Area Index (LAI) annual cycle for each grid-cell (Boussetta et al. 2013). As a result, LAI is often not consistent with the simulated soil moisture and surface energy, water and carbon fluxes. Advanced Land Data Assimilation Systems (LDAS) able to assimilate various land ECVs such as LAI and surface soil moisture (e.g. Albergel et al. 2017) need to be used to produce land reanalyses. Another advantage of the advanced LDAS is that the assimilation of vegetation-related variables can be used to improve the analysis of the root-zone soil moisture, which is a key variable for water resource assessment and for assessing trends in the terrestrial hydrological cycle. Finally, data assimilation could also help consolidating a transfer function relating Vegetation Optical Depth to LAI.

More specifically, future reanalyses should include simultaneous estimation of atmospheric constituents and cloud variables, in particular as it will be a great advance to include observations from the visible part of the spectrum into reanalyses. At the moment meteorological reanalyses at best only partially include cloud observations. In order to be able to use reanalyses as reference datasets, it will be necessary that all relevant ECVs are analysed and constrained by observations. Capabilities have been developed to include cloud observations in assimilation but have not been fully exploited yet. Reanalyses of atmospheric constituents such as aerosols should be performed simultaneously with meteorological reanalyses to benefit from fully coupled ESMs. The provision of individual aerosol species instead of a total Aerosol Optical Depth (AOD) would also be beneficial as different reanalysis systems may have different capabilities. Observations related to atmospheric composition should be reprocessed to extract the maximum amount of information also from older datasets/sensors using the most recent algorithm versions.

- **Source / sink attribution of climate/air quality relevant trace gases**

In addition to monitoring particularly important greenhouse gases, such as CO_2 and CH_4, black carbon or absorbing aerosols should also be monitored as they also have a warming effect. While aerosols that have a cooling impact on the global radiation budget such as sulphate have decreased in recent years thanks to stricter air quality measures, carbonaceous aerosols are on the rise (e.g. Boreddy et al, 2018). They are an important component of atmospheric particulate matter (between 20% and 50% of the total aerosol mass, Kanakidou et al, 2005; Putaud et al, 2010) and absorb solar radiation, thus contribute to warming the atmosphere. Biomass burning aerosols connected to fire activity have increased due to enhanced activity possibly connected with climate change. Long-term trends of carbon concentrations in aerosols are important for investigating trends of the impacts of combustion sources, as well as to have a baseline for modelling future scenarios of radiative forcing. Nevertheless, there is a lack of long-term studies of carbon content in aerosols because these measurements are generally not included in national air quality standards and, therefore, are not continuously monitored in environmental monitoring networks. It is of paramount importance to monitor these species on a global scale. Current and future satellite missions and related research projects should consider addressing the problem of source/sink attribution of relevant atmospheric constituents.

b) Attribution and modelling of variability and change in climate and the Earth System

- **Application of monitoring and reanalysis to modelling and for vulnerability and exposure (for attribution)**

EO research on the most likely real evolution of an observable generates reliable reference data on climate variability and change both for climate scientists and for public communication. In order to detect and (in combination with modelling) attribute climate trends from these EO data, and use them to evaluate climate model simulations, any signal or difference must be clearly identifiable as outside the uncertainty range in these observations. It is thus important to characterise these observational uncertainties and they should ideally be based both on ensembles from a single product (different parameter range, different retrieval algorithms), and from multi-product ensembles. To increase confidence uncertainty estimates from EO data should be traceable through all calibration and comparison steps, combining the uncertainty and confidence of each. A compilation of the observational products for analysis and use in model evaluation is being developed through the Obs4MIPs initiative (https://esgf-node.llnl.gov/projects/obs4mips/) which should be further pursued.

EO CDRs are generally not fed directly into climate models but are used in those representing other components of the climate system, e.g. hydrological or glaciological models, as part of model evaluation or cross ECV consistency exercises or to enable detection or attribution of trends in climate-driven systems. Some of this activity is happening through the Climate Research Group members of the CCI ECV projects (with some coordination by CMUG through its Climate Science Working Group) but with a greater focus on integrating information across ECVs larger overarching questions could be addressed. With such climate system component models increasingly being incorporated into Earth System models (both global, e.g. CMIP6 ESMs (Eyring et al., 2017), and regional, e.g. Lewis et al., 2019), research focused on monitoring the dynamics of these components using multiple ECVs would generate valuable results for evaluating these models for the benefit of environmental prediction across a range of locations and scales.

In addition to EO data being used to detect climate or Earth System changes and attribute these when combined with modelling, they have the potential to generate observations of other physical variables and systems. These can be used in the context of the attribution of impacts which requires information on the exposure and vulnerability of the impacted system (e.g. James et al., 2018) that such observations could provide. For example, the impact of heat extremes or flooding in an urban environment will depend on such factors as the extent and density of urbanisation which would determine important variables such as the number of people or structures exposed to the hazard. Thus, to be able to determine what the impact of a specific event is attributable to, all of these factors need to be taken into account. In the case of the examples given, EO data could be used to calculate trends in urbanisation which, alongside information on trends in extreme climate hazards, could provide evidence of whether the severity or likelihood of a particular event has been affected by either climate or socio-economic trends (or both), generating important information for building resilience or adapting to future impacts caused by these climate hazards.

- **New ECVs and cross-ECV budget/cycle analysis for model evaluation and process-based constraints**

As noted above, ECVs have significant potential to improve understanding of Earth system processes and thus application of relevant EO data can be used to assess of robustness of model simulations and projections and guide work on model improvement. For example, permafrost extent and ground temperature data are required at adequate temporal resolution and spatial coverage to evaluate climate models. A key issue for process understanding is the availability of a representative soil description. This applies to the combination of the land surface temperature and snow ECVs for retrieval of the permafrost ECV (as described earlier) as well as for land surface modelling and subsequent evaluation. Snow insulation and unfrozen water effects are further key issues for climate modelling. Thus, in addition to the permafrost ECV's value for model evaluation, the process understanding work would naturally suggest areas of cross-ECV activity. This includes the need for surface descriptions which would involve information on land-cover, on vegetation height in high latitudes (which would also represent a proxy for non-forest above ground biomass relevant to the carbon cycle in the Arctic) and the application of snow data in permafrost modelling. Ensuring consistency with observations of these variables, either as prescribed or predicted, in climate models and then the ability of these models to simulate their variability and change, could provide valuable information on their fitness-for-purpose and confidence in any simulated trends or projected changes.

Other key aspects of the global climate system which should be well represented in climate models are the global and regional Earth System Cycles of energy, water and carbon. Global observations of ECVs over seasonal and multiannual timescales covering the oceans, land surface, cryosphere and atmosphere can be synthesized to make significant progress in accurately quantifying these cycles. A "stocktake" of these observations will constrain the energy and water exchange fluxes and storage within models and help to quantify model bias, improve process representation, and improve model capability in predicting climate change responses. This could also reveal key gaps and uncertainties in the Global Climate Observing System and recommend approaches to closing these.

c) Seasonal-to-decadal forecasting

- **ECVs suitable for initial conditions and assimilation for seasonal and decadal predictions**

A key requirement for seasonal forecasting is that the initialisation of the re-forecasts (also known as hindcasts) is consistent with that of the real-time forecasts, otherwise the calibration of the forecasts becomes invalid. Reanalysis datasets are often used to generate initial conditions for long-range predictions. However, changes in the global observing system over time or in the way ECVs are obtained can cause unphysical structures in the reanalysis time series that affect the quality of the long-range predictions. This is particularly so in the case of atmospheric composition and land-related variables. Figure 4 clearly shows that with an incorrect vertical distribution of stratospheric volcanic sulfates, diagnosed from comparison with observations of atmospheric aerosols, the temperature response at 30hPa from a seasonal system is not well represented after major volcanic eruptions (in this case that of Mt Pinatubo in 1991).

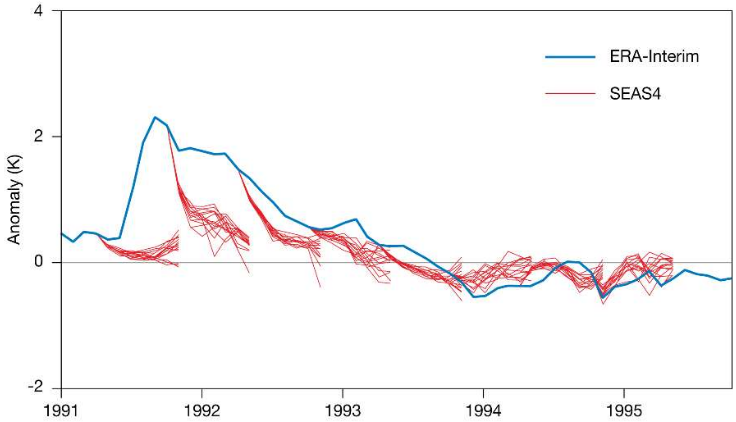


Figure 4: Stratospheric temperature at 30 hPa from ERA-Interim (blue) and the ECMWF System 4 Seasonal System (SEAS4) after 6 months. The response after the Mt Pinatubo eruption is not well captured due to incorrect vertical distribution of volcanic sulphates.

- **New/improved ECVs for initialization of additional components of the climate system (e.g. atmospheric composition, land, cryosphere, ocean biogeochemistry)**

Seasonal prediction systems are being used to generate global hydrological predictions which tend to be less constrained and calibrated in those river catchments that do not have reliable observational data available. In this context, EO missions able to provide information about the level of rivers and lakes would be extremely valuable. Even more valuable would be combined satellite/hydrological model based estimates of river flow or river surface current, especially if these were at high spatial resolution and absolute accuracy.

d) Building capability

The previous section and sub-sections above have included examples where EO data and research are being or could be used to generate climate information and services. An important aspect of these activities, and a requirement for their effectiveness, is for them to include opportunities to bring together the users (and related stakeholders), communicators and producers of the information or services so there is clear understanding of the requirements and applicability of these. Generating this understanding will, in general, require producers to be aware of and comprehend the context in which the information/services will be applied which could include a wide range of issues from how familiar stakeholders are with climate variables or concepts such as probability to how information is communicated to the technical details of the required indices and their spatial and temporal attributes. In turn, users will need to understand issues such as the robustness and accuracy of information they want to apply as well as being clear on the details of what they are being supplied with and how it should or should not be used. Also, climate services will often involve people acting to facilitate the understanding of users/stakeholders and producers and related flows of information and knowledge so will need to be aware of and understand these issues as well. In many cases, these different actors will have some understanding of some of the issues involved though often this will be incomplete and involve areas of expertise which they are unfamiliar with or are outside their usual fields of responsibility. As a result, much of the required understanding or detail of the EO data and research needed and how it is then used as climate information or in services will only be clarified if the related activities allow for interaction and iterative development and learning between the various communities. This is clearly demonstrated in current work developing climate information distillation and effective climate services and involves building capability amongst all actors involved.

In the context of EO research relevant to climate information and services, this leads to a range of implications. In the research programmes themselves, if some of the outputs are expected to be relevant to a certain target region or sector then researchers should engage with stakeholders involved in the communication or application of these outputs. This would require project staff, including some researchers, to have or build capability to engage effectively with the stakeholders to gauge their understanding and requirements of the outputs. This could happen in the context of engagement with policy/practitioner forums or through projects having dedicated case studies, e.g. taking the research outputs into specific climate service context or into a climate resilience or adaptation application. There would then likely be a requirement to build capability in these stakeholders to develop their understanding further and ability to interpret and apply the outputs and thus ensuring sustainability of any services built on the outcomes of the research. In this context the activities under the GMES (Global Monitoring for Environment and Security[1]) and Africa initiative for EO services in Africa may be good to build on.

e) Fitness for purpose of EO products for climate and Earth System research applications

To ensure fitness of purpose of EO products requires significant interaction and collaboration between those involved in developing and deploying applications with Earth observers. For example, frequent exchange of information and needs between EO data generators and providers and climate modellers through workshops, conferences and joint projects is key for the required interaction and joint effort to better understand the Earth system, how to model it and then to use subsequent models for predicting its behaviour.

In addition, rapid provision of EO data through easy access will increase their use substantially. In the case of climate modellers, they require open-source access to data in NetCDF format with the EO data located on a single platform such as ESGF to be easily to download. As noted above, this is already occurring via the obs4MIPs initiative with another example being "input4MIPs" which collates and makes available boundary condition and forcing datasets for climate models (https://esgf-node.llnl.gov/projects/input4mips/). Accessing multiple observational products is currently complicated and time-consuming and needs to be facilitated to make the use of these products as smooth as possible. This is especially important for quick detection and attribution studies on climate extremes.

5. Conclusions and recommendations

Earth Observation (EO) data and research play a critical role underpinning climate change research and providing information relevant to international and national policies and action on climate change. The information is also relevant in other international and national fora, from monitoring progress on the sustainable development goals and ecosystem health to developing exposure indices for managing climate risk to generating climate services relevant to many sectors of the economy. The examples provided in the preceding sections both demonstrate this and where further EO data and research activities could enhance this role. Focusing on the latter, the rest of this section summarises these examples of possible future activities in five categories: new observations; continuity in and improvement of existing observations; integrating ECVs, modelling and in-situ observations for applications; modelling and climate science; and building capability.

New observations

Precipitation is a fundamental variable of the climate, of direct relevance to socio-economic and ecological systems and a key component of the hydrological cycle. Eumetsat's CM-SAF is coordinating the development a prototype precipitation climate data record (CDR) due for release in 2021 (sponsored by NASA, NOAA, JAXA, Eumetsat, CNES, ISRO, and DoD through the Global Precipitation Measurement initiative, gpm.nasa.gov) and generating a global, long-term, high quality CDR for precipitation should be a major focus of future EO research. Other aspects of the hydrological cycle which would benefit from developing new EO datasets include river flow and water levels and wetlands (to complement existing research on lakes, snow and glaciers), providing improved monitoring or forecasting of relevant SDGs and hydrological sensitive systems such as agriculture and energy. Other components of the earth system for which new observations would be of value include land and sea vegetation and ecosystems. In particular, vegetation optical depth (and the linked quantity of specific leaf area) would provide longer higher quality records of land vegetation and new observations of seagrasses and corals would generate information relevant to ecosystem and carbon cycle monitoring and livelihoods of coastal populations. Finally, carbon aerosols resulting from biomass burning, forest fires etc are an important component of the atmospheric energy budget and comprehensive and high-quality observations of these would improve the calculation of and reduce the uncertainty in the anthropogenic radiative forcing of the climate.

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[1] https://africa-eu-partnership.org/en/projects/global-monitoring-environment-and-security-gmes

Continuity in and improvement of existing observations

General requirements that are considered key aspects for a climate observing system (see also the GCOS Global Climate Monitoring Principles, https://gcos.wmo.int/en/essential-climate-variables/about/gcos-monitoring-principles) include:

1. Have suitable period of overlap between new and old satellite systems adequate to determine inter-satellite biases and maintain the homogeneity and consistency of time-series observations.
2. Provide continuity of satellite measurements (i.e. elimination of gaps in the long-term record) for already observed variables.
3. Generation of quality controlled Fundamental Climate Data Records (FCDRs) and associated meta and calibration data.
4. Comprehensive characterisation of uncertainty in the ECV products.
5. Sustain operational production of priority climate products.
6. Reprocess observations regularly to improve and homogenize the available datasets.
7. Assessment of the consistency between related ECVs.
8. Develop long-term data preservation strategies.

Operational programmes such as C3S address item 5 but do not provide resources for the R&D aspects, some of which are addressed by ESA's CCI programme. However the continuity of these important R&D aspects needs to be ensured, e.g. to maximize the information content provided by the addition of appropriate data products from new or not yet included satellites and deal with (potential) problems with existing satellites such as degradation or remaining satellite-to-satellite inconsistencies. R&D requires expert knowledge and ensuring its availability implies seamless continuation with long-term commitments and sufficient funding. Keeping experts in the team is a mandatory requirement to be fulfilled to address the important and challenging R&D aspects for generating a high-quality climate information service.

One example is continuing and enhancing sea and land surface temperature observations to generate a high-quality global surface temperature dataset critical for monitoring global warming, to provide input into multi-ECV research on Earth System components, budgets and cycles and provide information on hazards, e.g. in urban environments. Another important surface variable of the climate system is sea-ice and though certain properties are well-observed (extent, thickness, to some extent drift) there are others (e.g. snow depth, melt ponds, type/age) which could be generated by new R&D on and rescue of existing data sources. Finally, improved information on other land-surface variables such as land-use/cover and vegetation could provide important information on exposure of human and natural systems to climate hazards relevant to risk reduction and monitoring and attribution of climate impacts.

Another important example is continuing and improving the monitoring of GHGs, crucial to the Global Stocktake and country reporting required by the UNFCCC Paris Agreement. The current C3S products do not include data from OCO-2, TanSat and Sentinel-5-Precursor, which have the potential (along with the planned Copernicus CO_2 Monitoring (CO2M) mission) to address the issue of heterogeneity of the sources. Continuous R&D is needed to maintain and achieve the highest possible data quality and information content. This is currently addressed to some extent by the ESA CCI GHG project but these activities need to be continued in the future including to deal with degradation and other issues related to currently used satellites. It is also important to maintain or establish a close working relationship between the satellite data provider and data users, especially those who use the data in combination with inverse modelling in order to obtain information on surface fluxes. This capability was a focus of the initial GHG-CCI project and building stronger links with the user and stakeholder communities in the future should be a focus to ensure that the EO data can be exploited to their full potential.

Integrating ECVs, modelling and in-situ observations for applications

In addition to the important activity of generating the best products with the best algorithms or filling time series from current and previous satellite sensors, a future EO-based program should also focus on "integrated" climate information (often cross-ECV) products serving specific needs of the broader communities of interest. In particular this implies that future activities should include the integration of modelling applications using the ECVs. This also implies there should be a focus on defining what are the key science questions and then addressing these using a combination of EO data with modelling and field observations.

Linked to the previous example of monitoring GHGs and fluxes of these is generating information on their sources and sinks and including calculating the budget of the full carbon cycle. This requires more accurate and detailed information on land-cover change, forestry, wetlands, permafrost and the ocean carbon cycle which has applications in monitoring country-level GHG emissions and mitigation actions, regional ecosystems and evaluating the representation of these processes and systems in earth system models. The latter is crucial for establishing confidence in future projections of warming and carbon budgets required to meet specific global warming targets as well as ecosystem impacts.

One of the processes relevant to the carbon cycle and also various climate change impacts is permafrost. Generating information on permafrost requires data on multiple ECVs to be integrated with modelling and more research is required for this to be sufficiently detailed and accurate for monitoring trends. This research could also be applied to validate the representation of permafrost in earth system models and ensuring consistency with the multiple ECVs required would build further confidence in the models. This would improve detection and attribution and projection of changes in relevant hazards and impacts such as permafrost degradation and its implications for infrastructure, or rockfalls in mountainous regions (as well as improving confidence in projected warming and carbon budgets).

Modelling and climate science

There are many other such processes and cycles which require combining ECVs derived from satellites and in-situ data with modelling to improve monitoring and their representation in earth system models. These include global or regional hydrological cycles as referred to previously, global and regional energy and carbon cycles and glaciers or ice-sheets. In all cases, improved monitoring and quantification of these would allow increased confidence or suggest areas for improvement in the models as well as potentially identifying gaps and uncertainties in the observing system, e.g. in regions with specific challenges such as mountains and the poles.

An important application of models and ECV data is their use in generating reanalyses, comprehensive multi-decadal timescale representations of the evolution of the climate system constrained by the data. Previously these have focused on individual system component, such as atmosphere or ocean, or have been used to generate e.g. land-surface “reanalyses” from a land-surface model driven by atmospheric reanalysis data. Consistency in the results from these reanalyses would be significantly improved if the coupling between system components, e.g. atmosphere and the ocean, was included or terrestrial variables were assimilated into the land-surface model generating the land-surface reanalysis. Recent technical developments have allowed some initial exploration of these ideas but significantly more research is required to fully develop them and demonstrate their value. The very widespread use of current high-quality atmospheric and oceanic reanalyses (e.g. ERA5) in climate (modelling) research supports pursuing this research. Finally, there are still improvements that should be sought within the component analyses, for example more comprehensive inclusion of atmospheric constituents and cloud observations would improve the consistency of atmospheric reanalyses.

Along with detection and attribution of trends in EO data, a significant application is in the evaluation of climate models, for example in the application of ESMValTool to assess the performance of the CMIP5 and CMIP6 ensembles (e.g. Lauer et al., 2017). For all these applications it is essential to quantify the errors in the data. As EO data are often generated from multiple processing and/or sources of observed quantities, generating traceable error estimates improves confidence in the overall quantification. For these data and error estimates to be easily accessible and applicable by climate researchers, comprehensive data documentation and delivery systems are required such as the current Obs4MIPS project . This also requires good data practices by the data producers and is facilitated by the use of common format and standards. All of these activities significantly increase the ease of use and reach of the data and thus it is important that they continue to be supported.

Building capability

The future activities suggested above are focused on generating climate information and services which have the potential for a wide range of applications, from climate research to attributing trends in impacts to assessing risks from climate variability and change. In order to realise this potential a dialogue is required between the users (and related stakeholders), communicators and producers of the information or services so there is clear understanding of the requirements for and the applicability of these. In many cases, these different actors will understand, to an extent, some of the issues involved though often areas of expertise which they are unfamiliar with or are outside their usual fields of responsibility will be involved. These issues can be overcome by interaction and iterative development and learning between the various communities. This implies that if EO data and research are to be relevant in a specific region or sector then projects generating these should engage with stakeholders involved in their communication or application. Thus some project staff, including researchers, need to have or build capability to engage effectively with the stakeholders to gauge their understanding and requirements of their outputs. Similarly, it is likely that capability would need to be built in these stakeholders to develop their understanding further and ability to interpret and apply the outputs. This would likely require some or all of the following activities, policy/practitioner forums, dedicated case studies in project to take research outputs into specific climate service context or into a climate resilience or adaptation application, and would be important to ensure sustainability of any services built on the outcomes of the research.

Summary

The conclusions and recommendations above are drawn from a set of examples and experience from researchers involved in CMUG and some other CCI projects. As a result, the recommended new EO data and research activities should be considered as illustrative and far from comprehensive with respect to the general requirements identified in section 1. However, all have merit and some are clear priorities; precipitation, improved monitoring and modelling of GHGs and the global carbon cycle and of surface temperature. In addition, it is clear that different categories of activity are required:

1. underpinning work of developing new observations and maintaining/enhancing current observations;
2. integrated multi-ECV and modelling work focused on important processes/system component and earth system cycles;
3. technical work on collating, documenting and disseminating data products including assessments of their uncertainties;
4. work defining project/programme outcomes involving interactions between and building capability of stakeholders involved in using, communicating and producing the information or services.

Clearly, a comprehensive EO research programme would involve all of these activities. Individual projects may focus their research activities on the first or second categories (or may need to include both, e.g. if work on a specific system required new/enhanced observations) but should certainly include the other two.

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7. Glossary

Terms	
Data assimilation	Observations directly influence the model initial state taking into account their error characteristics during every cycle of a model. This is used for reanalysis, NWP, which includes seasonal and decadal forecasting.
Model validation	Observations are compared with equivalent model fields to assess the accuracy of the model. This can be on short time scales for process studies or long time scales for climate trends.
Climate monitoring	This describes the use of a satellite only dataset to monitor a particular atmospheric or surface variable over a period > 15yrs to investigate whether there is a trend due to climate change.
Initialisation	To initialise prognostic quantities of the model with reasonable values at the beginning of the simulation but do not continuously update.
Prescribe boundary conditions	Prescribe boundary conditions for a model run for variables that are not prognostic (e.g. land cover, ice caps etc).
Accuracy	Accuracy is the measure of the non-random, systematic error, or bias, that defines the offset between the measured value and the true value that constitutes the SI absolute standard.
Stability	Stability is a term often invoked with respect to long-term records when no absolute standard is available to quantitatively establish the systematic error – the bias defining the time-dependent (or instrument-dependent) difference between the observed quantity and the true value.
Precision	Precision is the measure of reproducibility or repeatability of the measurement without reference to an international standard so that precision is a measure of the random and not the systematic error. Suitable averaging of the random error can improve the precision of the measurement but does not establish the systematic error of the observation.
Acronyms	
(A)ATSR	(Advanced) Along Track Scanning Radiometer on ERS -1&2 and ENVISAT
AVHRR	Advanced Very High Resolution Radiometer
BADC	British Atmospheric Data Centre
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite
CCI	Climate Change Initiative
CCMVAL	Chemistry-Climate Model Validation Activity
CDR	Climate Data Record
CMC	Climate Modelling Community
CMIP5	Climate Model Intercomparison Project-5
CMUG	Climate Modelling Users Group
COSP	CMIP5 Observation Simulator Package
CSAB	Climate Scientific Advisory Board
DAAC	Distributed Active Archive Centres
ECV	Essential Climate Variable
EGU	European Geophysical Union
ENSO	El Nino- Southern Oscillation
ERA	ECMWF Reanalysis
ERBS	Earth Radiation Budget Satellite

ERRMERG	Error of merged dataset
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FCDR	Fundamental Climate Data Record
FOAM	The Fast Ocean Atmosphere Model
GCOS	Global Climate Observing System
GPS	Global Positioning System
GSICS	GCOS Satellite InterCalibration System
HIRS	High resolution Infrared Radiation Sounder
IGOS	Integrated Global Observing Strategy
IPCC	International Panel for Climate Change
ISCCP	International Satellite Cloud Climatology Project
LAI	Leaf Area Index
MACC	Monitoring Atmospheric Composition and Climate
METAFOR	Common Metadata for Climate Modelling Digital Repositories
NAO	North Atlantic Oscillation
NWP	Numerical Weather Prediction
OSTIA	Operational Sea Surface Temperature and Sea Ice Analysis
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PDO	Pacific Decadal Oscillation
SAGE	Stratospheric Aerosol and Gas Experiment
SSAOB	Single sensor accuracy for each observation
SSEOB	Single sensor error for each observation
SSM/I	Special Sensor Microwave Imager
SST	Sea Surface Temperature
TCDR	Thematic Climate Data Record
UMARF	Unified Meteorological Archive and Retrieval Facility