ESMO – Earth System Modelling and Observations

Strategic Plan and Governance

2022–2030

(June 2022 draft version)

ESMO is sponsored by the

World Climate Research Programme (WCRP)

ESMO Strategic Plan 2022 - 2030

ESMO coordinates, advances, and facilitates all modelling, data assimilation and observational activities within WCRP, working jointly with all other WCRP projects and providing strategic connections to related external programs. It follows a seamless and value-chain approach across all Earth system components, disciplines, and scales. The modelling and observational activities under ESMO are central to the provision of science-based climate information to support adaptation planning and decision-making, local and regional climate impact assessments, and national and international mitigation and adaptation policies. Such information advises a wide range of stakeholders about how and why the climate is changing and what that will mean for societies, economies, livelihoods, and ecosystems. Understanding, adapting to, and mitigating climate change requires taking a holistic perspective on our Earth system. The strong interplays between carbon, energy and water cycles are just one well-known example of the globality in climate research. An immediate consequence of these complex interconnections is that the monitoring, modelling, and analysis of the various climate components need to be carried out in a consistent and coordinated manner.

ESMO objectives

The ESMO Strategic Plan is based on three scientific objectives that will underpin and integrate the next decade of climate science modelling, data assimilation and observational activities (Figure 1). The objectives are informed by the most pressing shortcomings in our ability of monitoring, predicting, and projecting the climate system from days to centuries and from local to global spatial scales with an aim to advance the core capabilities of the programme. The objectives are:

(1) Advancing predictions and projections of the Earth system on time scales from weeks to centuries via a model-observation integrating framework.

(2) Improve monitoring, understanding, and attribution of climate system changes and impacts with robust uncertainty quantification through the synthetic use of models and observations.

(3) Advancing and harnessing emerging technologies in modelling and observations.

Each of the above objectives requires an internationally coordinated, integrated, and consistent framework combining global Earth system observations, data assimilation and modelling. Through the above objectives, ESMO will contribute to our understanding, predictive skills, and improved projections across all components of the climate system.

Many individual aspects of the three objectives are already being addressed in the WCRP core projects, Light House Activities (LHAs) and Working Groups (WGs). For each objective, ESMO will provide coordination on specific priority topics and activities chosen according to the most pressing needs of the community and the capabilities and mandate of ESMO. These activities have the potential for strong collaborations across WCRP, obtaining rapid results and benefits and addressing the cross-cutting science questions highlighted below.

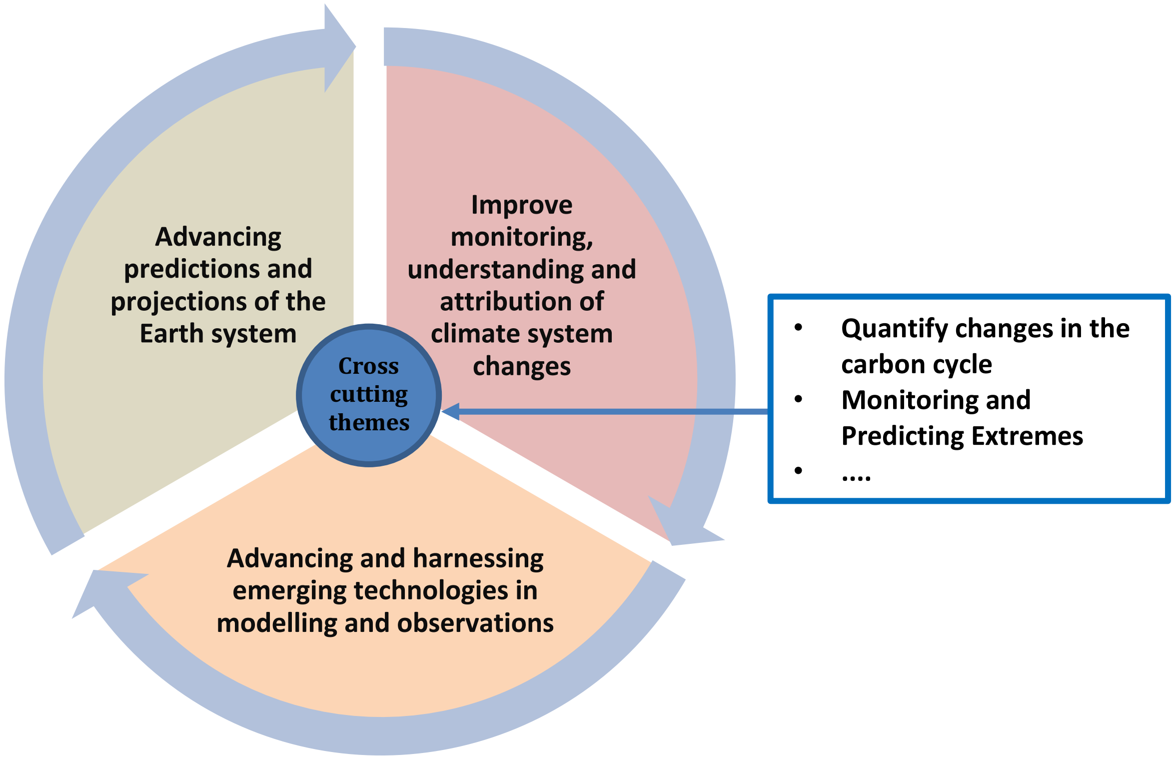

Figure 1: ESMO objectives and Initial cross-cutting themes.

Cross cutting science themes

ESMO will identify a number of cross-cutting science themes that will strongly benefit from the coordinated model-observation framework. We are here identifying two initial cross-cutting themes that are central to the WCRP scientific objectives. The first cross-cutting target is to quantify changes in the carbon cycle across timescales and in response to natural and forced change. This cross-cutting theme is part of the wider WCRP focus on changes in water, energy, and carbon cycles, but also entails a range of scientific issues across the ESMO objectives. The second cross-cutting theme will focus on meteorological, oceanic, and hydrological extreme events at a global scale and their improved monitoring and predicting. This second cross-cutting theme will be closely developed with the Global Extremes Platform that sits under RIfS. ESMO will continue to develop further cross-cutting themes as the project and working groups evolve.

ESMO partners

Recognising the broad and ubiquitous nature of modelling and observational activities within WCRP, ESMO will form connections and partnerships with all WCRP Core Projects and Lighthouse Activities (LHAs) with the goal to enhance and advance the total capability. ESMO will aim to act as a modelling and observations focal point for collaborations with external partners such as regional and global research and operational groups, as well as observational coordination bodies.

Within WCRP, ESMO will establish or build on strong collaborations and cross-cutting activities with the observational and modelling panels and working groups of the core projects and LHAs. Such collaborations will ensure efficient communication across WCRP constituencies and communities and remove fragmentation and duplications. The cross-cutting activities will help to advance existing WCRP modelling, data assimilation and observational efforts and connect them within an integrating framework under ESMO. This will also provide clear bridges to support activities in other core projects (e.g., the Global Extremes Platform in RIfS, cross-WCRP focus on water-energy-carbon cycles). Another focus will be on sharing data, knowledge, and opportunities within WCRP with a particular attention to data equity, including for the developing world

External partners of ESMO include, but are not limited to, the Global Climate Observing System (GCOS); the Global Ocean Observing System (GOOS); the CEOS/CGMS Working Group Climate (WG Climate); the World Weather Research Programme (WWRP) and the Global Atmosphere Watch (GAW) of the World Meteorological Organization (WMO); Future Earth; and the Global Carbon Project.

ESMO will work closely with the GCOS Steering Group and panels to support GCOS in its role of assessing the status of global climate observations and producing guidance for its improvement. By establishing strong and strategic links, ESMO will help to ensure that WCRP's observational needs are integrated into GCOS periodic releases and help to sustain provision of observations inclusive of access systems and analysis tools. Links to the Committee on Earth Observation Satellites (CEOS)/ Coordination Group for Meteorological Satellites (CGMS) Working Group on Climate (WG Climate) will allow ESMO to provide input to the space agencies on all issues related to climate monitoring from space.

ESMO will foster the collaborations of all its WGs with internal and external partners. The WG on Numerical Experimentation (WGNE) reports to the WMO Research Board and will continue to play a critical role, alongside the other modelling WGs, in supporting the development of seamless modelling capability across timescales from weather to climate, jointly with WWRP and GAW. Within WCRP, WGNE will sit under ESMO governance and cross-cutting activities will strengthen the collaboration with other WGs (WGCM, WGSIP).

ESMO will also connect to broader stakeholders including the United Nations Framework Convention on Climate Change (UNFCCC), the Intergovernmental Panel on Climate Change (IPCC), the Global Framework for Climate Services (GFCS) and implementing initiatives such as the Copernicus Climate Change Service (C3S), and WMO operational entities.

Objective 1 - Advancing predictions and projections of the Earth system

The first objective focuses on improved predictive skills of the evolution of the climate system on time scales from weeks to centuries. While Earth System Models (ESMs) are the key tools for the provision of science-based climate predictions and projections, an integrative framework making use of Earth system observations and data assimilation practices is needed to ensure fitness for purpose of models to address an ever-expanding suite of applications. In this context, the use of satellite data needs to be strengthened, as its potential has not been fully exploited to date.

Earth System Models have become more comprehensive and realistic over recent decades but remaining fundamental scientific and technical challenges must be overcome if they are to fully realize their potential to improve scientific understanding and benefit society. Physics and resolution improvements have delivered reduced systematic errors across time and space scales, although such progress has been painfully gradual in practice. Many of these biases have persisted across multiple model generations and are relatively well known (cf. WGNE systematic error workshops and survey), so continued benefit will be gained through renewed focus on “properly” reducing these errors.

A fruitful new direction that could serve as a pragmatic “bridge” for improving model fidelity in the near term, is to apply in the model equations tendency bias corrections derived from data assimilation increments to represent “missing” tendencies, e.g., due to imperfect model physics or finite resolution. This technique has thus far been shown to reduce systematic errors in several models and can improve the skill of initialized predictions by reducing skill degradations caused by systematic errors. In addition, this method can be applied selectively to identify geographical sources of model systematic errors. Further development and broader uptake of this approach could greatly benefit climate model applications and could contribute to identifying the sources of errors.

A related need is to use observations and reanalysis to quantify model fidelity in standard and accessible ways, as has been the focus of various existing efforts. The consistency of observations (e.g., across components of the Earth system) is a prerequisite for their successful use in modelling evaluation. This applies to the evaluation of historical simulations, e.g., from CMIP experiments, process evaluation, and the use of observational datasets for data assimilation from medium-range weather to decadal forecasts. As a first step, observational requirements for the analysis of the Earth system in the context of modelling need to be provided in consistent and comprehensive manner. Furthermore, quantifying uncertainties in observational changes and error sources will give a better context to both improve and evaluate models. If gridded datasets from reanalyses are used for verification and calibration of model output, multi-reanalysis combinations can provide improved state variables and uncertainty estimates, such as discussed under Objective 2.

The various components of ESMs need different levels of initialization depending on their governing spatio-temporal scales. In particular for the ocean, land surface, soil, and ice sheets, special initialization procedures are necessary as the comparably slow processes in these compartments lead to a much more pronounced dependency on the initial state. One possible approach to create realistic initial conditions for a component is to perform a spin-up run with the external forcing provided by an existing reanalysis. Another possible approach would be to apply a data assimilation cycle to the spin-up to accelerate the convergence of the component’s model state towards a realistic representation.

Representation of the water cycle and specifically improving the representation of organized tropical meso-scale convective systems and heavy precipitation is a fundamental challenge for weather and climate models. This entails a range of scientific issues such as interactions between the convective systems and large-scale circulation or cloud-aerosol interactions. Accurate modelling of these inter-connected processes has been shown to require ultra-high resolution global and regional models (km-scale) which will need to be developed and integrated within a traceable hierarchy of weather and climate models.

Earth system models do not have yet a sufficient representation of the physical and biogeochemical processes that govern climate-carbon feedbacks. This is particularly true for terrestrial ecosystems with state-of-the-art CMIP6 ESMs currently missing key processes such as soil carbon dynamics in permafrost, or drought induced mortality in tropical forests. For marine ecosystems key uncertainties include the response of the carbon cycle under multiple environmental stressors such as warming, deoxygenation and acidification. Long-term monitoring of these processes in order to support the evaluation of key developments of new parameterizations in ESMs is critically needed to help reduce uncertainties in future projections. On a decadal timescale, changes in atmospheric CO_2 are modulated by major variability modes in the climate system. Such effects can hide signals of emission changes, decarbonization measures and potential CO_2 removal strategies posing large challenges for detectability and verification of decarbonization policies.

Climate projections with ESMs are usually done with prescribed socio-economic emission scenarios resulting in a large spread on climate projections. A new alternative approach of adaptive scenarios is more in line with the United Nations Framework Convention on Climate Change Paris Agreement global stocktake process where countries emission targets are being revised on a regular basis. In a similar way, adaptive scenarios assess the warming simulated by ESMs at given time intervals and adapt the emissions for the next simulation years to ensure the desired warming level by the end of the overall simulation period. This new approach is extremely attractive as it would allow direct quantification of the remaining carbon budget and its uncertainty for a given climate target.

Objective 1 - Methods and Activities

Many of these challenges are already being addressed in the modelling WGs and observational panels that sit under ESMO and in other core projects and LHAs. These range from process understanding and development of component models (e.g., GASS within GEWEX) to assessment, intercomparison and evaluation of ESMs (e.g., CMIP within WGCM). Here we highlight some specific priority topics that we feel ESMO is particularly well-placed to address and that would yield rapid results and benefits to the modelling community and the broad user community that relies on model results. These include activities focused on model improvements via the reduction of systematic errors (a-d), the use of reanalysis and data assimilation (e-f), the coordination of observational activities in the context of modelling (g-i), as well as links to external partners (j).

a. ESMO-wide surveys of model development teams on their top concerns for model errors and shortcomings to prioritize problems on which to focus. This continues the longstanding WGNE activity.
b. Activities aimed at increasing the visibility, uptake, and understanding of the benefits of the tendency bias correction method (e.g. via a dedicated intercomparison projects).

c. Continue to develop well-designed, international model intercomparison projects (e.g., to target specific model errors related to applied parametrizations and to test the performance of and need for certain model components).
d. Coordination of work on interpreting and optimizing the value of multi-model, single model, and large initial condition ensembles.
e. Coordinate activities on the use of reanalysis and data assimilation for model initialization.
f. Conduct multi-reanalysis combinations to provide improved variable and uncertainty estimates for the use of model verification and calibration.
g. Develop near-term prediction systems including the carbon cycle in support of verification and monitoring activities.
h. ESMO co-ordinated global survey of observational needs to support model evaluation that goes beyond ECVs.
i. Unifying simulated observation techniques for model-data comparisons, e.g., enabling comparisons to data at radiance level.
j. Linking Research-to-Operations, through better integration of current and future activities across WCRP and WWRP communities.

ESMO's approach will be to promote and integrate work within ESMO WGs, other core projects and LHAs and hold a relatively small number of inclusive but targeted and focussed workshops, possibly recurring at intervals of two years or so, to exchange cutting-edge ideas and to jump start collaborative community efforts toward meeting specific objectives. These might be particularly effective if including groups that might not normally interact (e.g., weather and climate modelers) and targeting Early Career Researchers (ECRs).

Objective 1 - Outcomes

Top level outcomes of the activities under this objective are to 1) identify, attribute, and reduce model systematic errors across systems and to 2) enhanced skill of S2S and I2D prediction and climate projections for decades to centuries. In detail, the envisioned outcomes include:

- Recommendations on the use of model configurations for different applications.
- A traceable hierarchy of weather and climate models.
- Early warning capacity for weather and climate extremes and associated risk.
- Improved prediction skill and reduced model biases through application of tendency bias corrections derived from assimilation increments.
- Quantify impacts of model deficiencies on analyses and forecasts.
- Improvements in representation small scale processes, e.g., tropical convection and its organization.
- Best practices and a common understanding of observational uncertainties among the observation and modelling communities.
- Quantification of observational needs for modelling derived in a consistent way across all parts of WCRP at a global level.

These link strongly with objectives and WGs under the LHAs Explaining and Predicting Earth System Change and Digital Earths.

Objective 2 - Improve monitoring, understanding and attribution of climate system changes

Bringing together information from observations and models in coupled systems is critical for capturing and attributing the past evolution of the Earth system. Such knowledge will allow for a better understanding not only of the characteristics, but also of the impacts of climate change. Key aspects of this objective are a robust signal detection supported by consistent uncertainty quantifications in observational and reanalysis data sets.

Data assimilation is a traditional approach to obtain estimates of the state of a dynamical system. Therefore, it is often employed to generate monitoring data sets such as reanalyses in order to provide optimal retrospective time series as a synergy of model and observational information. With respect to Earth system approaches, the existing data assimilation methods have to be developed further, i.e., extended, and adapted. A special focus has to be given to the consistent representation of the different spatial and temporal scales that govern the processes in the various compartments of the Earth system. Therefore, adapted data assimilation approaches must be able to identify appropriate spatio-temporal structures near the interfaces of compartments in order to control information transfer across interfaces while at the same time retaining physical consistency in each compartment.

Monitoring products such as reanalyses have to be temporally consistent over long periods of time to be able to draw meaningful conclusions on changes of the mean state or its variability, e.g., detecting and analysing the effects of climate change. This requirement is, however, in conflict with the ever-changing observing system landscape which introduces jumps or artificial drifts in the reanalysis. Intensified homogenization efforts for observational time series and their utilization in the next generation of reanalyses are required.

A key element of future reanalyses will be the characterisation of uncertainties associated with the reanalysis's outputs. Some reanalyses made an important advance towards this goal by providing an uncertainty estimate based on an ensemble of realizations or a multi-model reanalyses ensemble. Systematic components of reanalysis uncertainties remain unknown and are a significant contribution to the uncertainties in quantities averaged over long-time scales or over large spatial scales. Estimating and validating this component of the uncertainty, in the production of a 'benchmark' reanalysis, will require in particular satellite observations with very well characterised, and small, uncertainties. Further, a strong collaboration of reanalysis producing centres is needed in order to foster exchange of data and knowledge and to define common standards for the evaluation and inter-comparison of reanalyses.

Physical consistency is a top priority for the combination of measurements and for their use in coupled systems to provide a holistic view of the Earth system. Further, quantifying uncertainties in observational changes and error sources will give a better context to improve and evaluate models. In addition, knowing the uncertainty in climate trends and variability is arguably as important as to understand the trends themselves, in order to avoid incorrect inferences or optimistic levels of confidence in conclusions drawn from observations. The combined use of observations, e.g., in determining energy budgets, requires consistent methodology to determine uncertainty estimates for the contributing variables. While only systematic errors are important for long-term changes, the determination of uncertainty estimates for observations should consider all effects on measurements that cause error.

Simulation based Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs) can determine accuracy, cost-efficiency, and viability of existing and proposed observations within various model designs. Thus, they will inform the design of observing systems that support input data for variational approaches including sensitivity studies, passive monitoring activities, as well as nudging techniques for observationally constrained evolutions of simulations and reanalyses. Such experiments also contribute to process understanding studies as well as detection and attribution of long-term climate changes. These activities will be jointly developed with The Explaining and Predicting Earth System Change (EPESC) LHA and the Global Extremes Platform.

Understanding the fate of anthropogenic CO_2 emissions in the climate system is critical to quantify current and future climate change. Thus, long-term monitoring of all relevant processes (e.g., ecosystems and interfaces) in order to detect their changes under current anthropogenic perturbation, is required. The Global Climate Observing System provides the authoritative source of Essential Climate Variables (ECVs), but these do not currently include a comprehensive overview of all carbon cycle variables. The omissions are both for processes not currently considered (e.g., lateral flows) and different use cases for a specific variable (e.g., point source monitoring versus synoptic country scale monitoring). Recent new emphasis on cycles in GCOS, have opened an opportunity for ESMO to establish an active interface with GCOS especially on carbon observation requirements.

Another important aspect is a coherent global carbon cycle reanalysis that extends back to 1990 or earlier to provide the recent past baseline of interest for policy options. Such reanalysis would need to be a fully coupled land-ocean-atmosphere carbon cycle reanalysis to be used for assessments of carbon cycle evolution and policy implementation in the next 15-25 years. The time horizon required will be able to benefit from relevant space-based observations for ocean-land and atmosphere component over the full period which should considerably advance the data assimilation potential of the reanalysis itself.

Another important aspect is the extension of current reanalysis systems with coherent estimates of the global carbon cycle back at least to 1990 to provide the recent past baseline of interest for policy options. In order to be used for assessments of carbon cycle evolution and policy implementation in the next 15-25 years, this would need a fully coupled modelling and data assimilation approach with respect to the land-ocean-atmosphere system. In the envisioned time horizon such a reanalysis will be able to benefit from relevant space-based observations for ocean-land and atmosphere components.

Objective 2 - Methods and Activities

a. Efforts on homogenization of observational data sets used as time varying boundary forcings for reanalyses and models ensuring best consistency with the observations and temporal consistency. They should be extended as far back as possible and include uncertainty estimates that could readily be propagated by the model into other variables.
b. Promote the continuous curation of observation-space data sets of in-situ observations as input to data assimilation in reanalyses applications including data rescue, quality control, integration into collections, and inclusion of most recent observations.
c. Implementation of a joint community effort on coordination of OSEs and OSSEs for climate.

d. Develop a common understanding of observational and reanalysis uncertainties via promotion of common vocabularies, concepts, and standards for documenting known error effects.
e. Establish a framework for enhanced exchanges among reanalysis producers with respect to the provision of observations as well as to implement common standards for evaluating and inter-comparing reanalyses with an application-oriented focus.
f. Develop methodologies and tools for handling observational uncertainties, e.g., for binning uncertainties that are correlated across space and time.
g. Organisation of observation inter-comparison projects to identify and correct systematic errors, e.g., uncertainty quantification activity in ocean datasets.
h. Implementing metrology concepts to quantify uncertainty in observational data sets at different time and space scales.
i. Coordinate the solicitation and collection of observational requirements for carbon cycle monitoring across all of WCRP to be provided to GCOS for consolidation in the overall observing system requirements and advocacy.
j. Establish a strong interface to the space agencies though the CEOS/CGMS Working Group on Climate to provide guidance on the needs of the WCRP research community for space-based observation (e.g., of the carbon cycle and atmospheric composition).
k. Promote the need for a coherent fully coupled land-ocean-atmosphere Carbon Cycle reanalysis of the recent past. 1990.

New and revitalized efforts on observations and reanalysis under ESMO will be required to deliver many of these activities. Joining up of work with GCOS and WWRP will be vital to success.

Objective 2 – Outcomes

Top level outcomes of the activities are 1) improved monitoring and forecasting capabilities of the Earth system with enhanced methods for robust signal detection and uncertainty quantification and 2) advanced data assimilation methodology for climate. These link strongly with objectives and WGs under the LHAs Explaining and Predicting Earth System Change and Digital Earth as well as WWRP-DAOS.

- Data selection, understanding of their requirements, and curation of datasets.
- Written guidance on how to derive meaningful observational requirements in support of GCOS and expert groups advising agencies in ground-based network design or the definition of a space mission.
- Education of the upcoming generations of climate scientists to data assimilation.
- Provision of improved climate information for adaptation, serving societal needs.
- Facilitated exploitation of interface observations, and co-design of observing system.
- Improved quantification of budgets in the energy, fresh water and specifically carbon cycles.
- Observations and products become increasingly fit-for-purpose for ESMO science.

Objective 3 - Advancing and harnessing emerging technologies in modelling and observations

New and emerging technologies will impact all methods of operation in climate science including aspects of Earth system modelling, new approaches in data assimilation and interpretation as well as innovative observations. For instance, machine learning techniques can be exploited across the whole climate science and services chain, from observational quality control and model development to data assimilation and post-processing. Objective 3 aims at supporting and advancing the applications of such new technologies by the WCRP community.

Advanced modelling efforts seeking to represent the global Earth system in ever finer detail are targeting cloud-resolving, km-scale resolutions. Such simulations require advanced computing and software architectures and generate immense amounts of data that must be stored, analysed, and served to the scientific and climate impacts communities. Emerging technologies such as machine learning will likely become indispensable for mining and interpreting this data. The challenges of distilling scientific understanding from model outputs will only magnify, so that hierarchies of weather and climate models, including simple low-order models, will continue to serve as vital points of reference.

There is clear potential to apply machine learning methods to post processing of model output for bias correction to enable use of predictions for services and societal applications across timescales from sub-seasonal to decadal. Neural networks have become a focus in this regard, allowing for complex non-linear dependencies to be exploited. While the results of the post-processing are likely enhanced through these approaches, the synthesis of multiple observational networks, spatio-temporal generalizations and downscaling efforts can also be easily implemented.

With the rapid development of advanced technologies, new modelling approaches are emerging such as integrating machine learning into model formulations. Recent results show that machine learning-based models are capable of competing with or outperforming existing dynamical models to forecast large-scale spatial patterns of precipitation. They are also able to better calibrate and merge multi-model ensemble prediction output. A major challenge is to include such new approaches not only within individual components but also across the various scales and components of the climate system. Other modelling challenges focus on technical issues such as exascale computing and coding, input/output and memory issues, debugging, and data formats.

With respect to observations, new technologies and data products become more and more important driven by requirements for precise, high resolution and consistent observations of a growing number of climate science relevant variables. New types of observing platforms are expected to be increasingly used, e.g., surface or sub-surface gliders and bottom-based observing platforms in the field of ocean science. Satellite technology is also changing rapidly with the development and advancement of small, low-cost satellites. Through their technological innovation, such small satellites enable entirely new architectures for a wide range of applications in climate science. Their greater flexibility and affordability will allow for testing new innovative components and products and provide greater interoperability with ground-based sensors.

Climate science observations can also benefit from citizen science contributions, which most often take the form of image interpretation or collection of in situ data. Both approaches can be highly useful for the calibration and validation of remotely sensed images. Engaging non-professional volunteers in scientific studies will enable the collection and interpretation of climate relevant information on a larger scale. Current challenges focus on data quality issues and on the question of how to engage citizen participation in the longer term. Truly integrated climate monitoring systems with data contributions from and embedded feedback for citizens have the potential to strengthen the role citizen science in climate research.

Focused support is needed for technical infrastructure including data access systems such as obs4MIPs and ESGF, cloud-based model evaluation tools, observation simulators, standard observation-based diagnostics tools, and requirements of new observational data for near-real time systems. ESMO will harness emerging technologies in collaboration with the LHA Digital Earth and related initiatives such as European Destination Earth in order to substantially raise the technological capabilities to model, monitor and simulate natural phenomena and related human activities. These activities will develop a range of computer and data access services specific to Earth System observations and modelling including the provision of hosted data processing in cloud infrastructure. In addition, there are substantial operational capabilities available that are currently under-utilised for research activities.

Objective 3 - Methods and Activities

Key activities will focus on ways of strengthening sustainability of technical systems for working with observations and model outputs and harnessing emerging technologies for climate modelling and research bringing best practice from research and operations closer together.

a. Application of machine learning to develop physically constrained, scale-aware, and ideally stochastic parameterizations for subgrid-scale motions and fluxes informed by observational and modelling “big data”.
b. Application of machine learning for post-processing of initialized climate prediction for services and societal applications across timescales from sub-seasonal to decadal, including forecast product creation, verification, and calibration.
c. Application of exascale computing and data management. Help facilitate dialogues connecting climate modellers, software engineers, and hardware designers to proactively enhance mutual understanding of the climate community’s evolving needs and the developing tools needed to realize them.
d. Promote and inform science applications involving new sensors and citizen science
e. Coordination of unification of data to common data types for rapid comparison.
f. Promote interoperable forecast model databases that allow verification and calibration of model output across all time scales
g. Share best practices and knowledge on data policy, protocols, and standards via coordinated web-based tool
h. Provide a communication platform for tools for bringing models and observations together.
i. Establishes partnership engagement with technical panels in WCRP, Destination Earth and other related activities inside and outside WCRP inclusive operational entities.

Objective 3 – Outcomes

Top level outcomes of the activities under Objective 3 are 1) Stronger engagement of the weather and climate modelling communities with emerging technologies, 2) Promotion of innovation in observations such as robotic platforms and new sensors, 3) Advancing model-data fusion through interoperability frameworks and smart data bases and 4) Support and broadened application for sustainability of data and modelling infrastructure. These link strongly with objectives under the Digital Earths LHA.

- Human capacity building and promotion of co-design of projects between climate and computer scientists.
- Strengthening sustainability of technical systems for working with observations and model outputs (e.g., data access systems such as obs4MIPs, ESGF; new observational data for near-real time systems; cloud-based model evaluation tools; observation simulators, standard observation-based diagnostics).
- Promotion and wider use of the file/data standardization and archive/dissemination infrastructure developed for CMIP across WCRP.
- Verification metrics and bias-correction strategies enhanced and tailored to stakeholder needs.
- Multi-model databases including cloud computing and big-data python-based software frameworks.

ESMO structure

ESMO brings together WCRP scientists and partners to plan and take part in activities targeting the scientific priorities described under objectives 1 to 3. All activities under ESMO are overseen by the ESMO Scientific Steering Group (SSG) which has the overall responsibility for planning and guiding the work of the Core Project. The ESMO International Project Office supports the SSG and the wider ESMO community in their work and is the main point of contact for ESMO.

ESMO consist of various Working Groups (WGs), some of which have existed for a longer time and some of which are in the process of being formed. Co-chairs and memberships of the WGs are appointed by the SSG. Co-chairs of the WGs will be ex-officio members of the SSG to ensure consistency in science direction

There are four modelling and prediction WGs that contribute to ESMO's science plan and develop the various components of modelling in WCRP:

- Working Group on Coupled Modelling (WGCM). WGCM oversees CMIP through the joint governance of the CMIP panel and the WGCM Infrastructure Panel (WIP) and is supported by the CMIP International Project Office (CMIP-IPO)
- Working Group on Subseasonal to Interdecadal Prediction (WGSIP).
- Working Group on Numerical Experimentation (WGNE), jointly supervised by WCRP and the WMO research Board.
- Sub-seasonal to seasonal Prediction Project (S2S), jointly supervised by WCRP and WWRP. Phase II of S2S will conclude in December 2023. Discussions with WWRP and the S2S leadership have started in order to identify the best approach to retain the S2S community within WCRP.

There is one reanalysis task team that contributes to ESMO's science plan.

- Task Team for Intercomparison of ReAnalyses (TIRA).

The role of and activities under this task team will be revised to include all data assimilation aspects in the future. The task team will be converted to a WG.

There is one project on observational aspects that contributes to ESMO's science plan.

- Observations for Model Intercomparisons Project (Obs4MIPs).

Two additional observational WGs will be established in the near future.

- WG on Observational Requirements within WCRP (WGOR)
- WG on Systematic Errors in observational Data (WGSED)

All working groups will contribute to all three ESMO objectives with some WGs being the main contributors. In Table 1 the major internal contributors and the main internal and external partners are listed for each of the three ESMO objectives.

Objective	**Main internal contributors**	**Main internal partners**	**Main external partners**
Advancing predictions and projections of the Earth system	WGCM, CMIP, WGNE, WGSIP, S2S Obs4MIPs, WGOR	GSOP, OMDP, GLASS, GASS, CCMI, SNAP, EPESC, Digital Earths	WWRP, GCOS, GOOS, GAW, WG Climate, Future Earth
Improve monitoring, understanding and attribution of climate system changes	TIRA, WGSED, WGOR	S-RIP, TUNER, GDAP? EPESC, Digital Earth, Reanalyses.org	Global Carbon Project, WG Climate
Advancing and harnessing emerging technologies in climate science research	WGNE, WGCM, CMIP (WIP), WGSIP, TIRA, WGSED?	Digital Earth,	EU Destination Earth

Table 1. Main internal contributors as well as the main internal and external partners for the ESMO objectives.

ESMO Governance 2022 - 2030

The activities of ESMO are governed by the ESMO Scientific Steering Group (SSG) that guides the formation of ESMO's scientific program in consultation with the WG co-chairs. The ESMO SSG consists of scientists representing modelling, data assimilation and observations across all climate-related disciplines in atmospheric, oceanic, hydrological and cryospheric sciences. In addition to monitoring and shaping the course for ESMO, the SSG briefs the Joint Steering Committee (JSC) of WCRP on progress made within ESMO. The organizational structure of ESMO consists of standing working groups that advance science and carry out organizational tasks.

The International ESMO Project Office (IEPO) is responsible for the overall ESMO management and co-ordination. The IEPO supports all ESMO activities by planning meetings, implementing research goals, and producing a semi-annual newsletter to keep the ESMO community informed. The IEPO is the major communication channel and the primary point of contact for those wishing to participate in, contribute to, or learn more about ESMO activities.

ESMO Scientific Steering Group: Terms of Reference

The ESMO SSG is led by two Co-Chairs elected by the SSG and approved by the WCRP JSC. The SSG has up to 12 members (including the Co-Chairs) elected by the SSG and approved by the WCRP JSC. Terms of the ESMO SSG members will follow the "WCRP guidelines on membership". The SSG meets annually together with the chairs of the ESMO working groups. Partners, and other experts can be invited as needed. A public part of each SSG meeting is typically accompanied by a closed session where budgets and confidential matters are discussed, and relevant decisions made. The annual meetings are supplemented by more frequent meetings of the SSG, as needed.