Version date: 11 June 2021

Explaining and Predicting Earth System Change

Executive Summary

Following a large-scale international effort, climate predictions for the coming five years are now issued operationally by the World Meteorological Organization (WMO) and offer great potential to develop climate services. While statistical skill has been established in retrospective forecasts, there is an important need to understand and attribute the drivers of predicted signals to gain further confidence in the forecasts.

On multi-annual to decadal timescales climate is influenced by many factors including internal variability and external forcing from greenhouse gases, aerosols, ozone, solar variations, volcanic eruptions, and land use changes. Attribution of multi-annual changes in the climate system can in principle be achieved with climate model simulations of the responses to the different forcing factors. However, there is mounting evidence that models may underestimate atmospheric circulation signals. Hence large ensembles are required to diagnose the modelled responses, and comparison with historical observations is needed to assess and calibrate the model simulations.

This Lighthouse Activity proposes an ambitious plan to:

1. Assess and improve persistent errors in climate models and re-analyses of historical observations.

2. Build an integrated operational capability to attribute and predict multi-annual to decadal changes in the climate system and provide quantitative attribution statements to support WMO forecasts and State of the Climate reports.

3. Establish a methodology for assessing the adequacy of and recommending improvements to observational networks and modelling systems to capture early indicators and the full evolution of these changes in the climate system.

4. Provide quantitative assessments of current and future hazards, underpinned by robust process understanding.

5. Seek to maximise the value to users of the advances achieved, e.g. through development of an international open-access multi-model archive of seasonal-to-decadal hindcasts and forecast data, and through case studies employing co-design of decision-relevant products.

A key component of (2) will be large ensemble single forcing simulations of the historical period. These do not currently exist and will require support from funding agencies.

1. Description of the Activity

The formulation of robust policies for mitigation of, and adaptation to, climate change requires quantitative understanding of how and why specific changes are unfolding in the Earth System, and what might happen in the future. Quantitative explanation of observed changes – through robust process-based detection and attribution – is also fundamental to specification of confidence in climate assessments, predictions and projections. However, the capacity to deliver these capabilities is very immature. The WCRP Lighthouse Activity on Explaining and Predicting Earth System Change (EPESC) is intended to address this gap.

The overarching objective is: ***To design, and take major steps toward delivery of, an integrated capability for quantitative observation, explanation, early warning and prediction of Earth System change on global and regional scales, with a focus on multi-annual to decadal timescales.***

Some examples of changes of interest include: the “hiatus” in global mean surface temperature rise that was observed in the 2000s; the rapid warming of the North Atlantic Ocean that occurred in the 1990s; changes in phase of the Interdecadal Pacific Oscillation; persistent marine heatwaves such as in the North Pacific during 2013-16; and persistent droughts such as in the Sahel during the 1970s and 1980s. This Lighthouse Activity (LHA) is concerned both with events that have multi-annual to decadal duration and also with understanding how regional-scale changes on these timescales influence the characteristics of hazards (e.g. storms) occurring on shorter space and time scales. Changes in atmosphere and ocean circulation, and the impacts of these changes, are of particular interest because of their importance in shaping hazards and because current capabilities to explain and predict changes in circulation are especially immature.

We have found it useful to organise the scientific challenges and opportunities around three major themes with associated working groups, as follows.

Theme 1: Monitoring and Modelling of Earth System Change

Tighter integration between the global climate observing system and the climate modelling community is necessary to address a number of interrelated challenges. These include (i) understanding and quantifying the uncertainty in key climate metrics, focusing on interannual to decadal climate variations; (ii) providing a quantitative framework for designing or optimizing an observation system suitable for detecting and monitoring interannual to decadal climate variations; and (iii) understanding and overcoming persistent Earth System model and re-analysis biases through the use of comprehensive estimation methods that bring modelling and (re-)analysis closer together and lead to a better usage of the diverse, heterogenous observing networks underlying the Global Climate Observing System (GCOS).

The joint consideration of observation and modelling challenges provides a conceptual framework for identifying major gaps and opportunities for progress in both monitoring and observing Earth System variability and change. The benefits of this tighter integration will first be explored by focusing on a number of specific case studies. These case studies will be used to develop a systematic methodology that can be applied subsequently to assess a wider set of events.

Theme 2: Integrated Attribution, Prediction and Projection (including early warning and the potential for abrupt change)

Multi-annual forecasts are now routinely issued on the WMO Lead Centre for Annual to Decadal Climate Prediction website and in the WMO Global Annual to Decadal Climate Update (GADCU). However, improved understanding and attribution of predicted signals is needed to gain further confidence in the forecasts. The objectives of Theme 2 are (i) to establish and apply attribution methodologies to help explain multi-annual to decadal changes in the climate system and (ii) to design and build an operational capability using these attribution methods. Outputs of this system will be integrated with forecasts issued by WMO.

Theme 3: Assessment of Current and Future Hazards

The goal of Theme 3 is to understand (i.e., explain), quantify and predict (or project) changes on multi-annual-to-decadal timescales in the characteristics and statistics of weather and climate hazards (such as: tropical and extratropical cyclone frequency, intensity and paths; drought duration and severity; floods; heatwaves; cold air outbreaks). Major objectives are: (i) quantifying the current likelihood of specific weather and climate hazards (ii) quantifying changes in weather and climate hazards on multi-annual to decadal timescales; (iii) understanding the processes connecting changes in hazards to natural and anthropogenic drivers of climate variability and change; and (iv) advancing capabilities to predict and project changes in hazards.

2. Relevance to the World Climate Research Programme (WCRP)

The WCRP Strategic Plan for the coming decade highlights four Scientific Objectives, three of which speak directly to objectives of this Lighthouse Activity. ***Fundamental understanding of the climate system*** (objective 1) and ***prediction of the near-term evolution of the climate system*** (objective 2) are at the heart of this LHA's effort to explain and predict multi-annual to decadal-scale Earth system change. These efforts require a full, integrated assessment of our observational and modelling capabilities that cross component (ocean, atmosphere, land, ice) and disciplinary boundaries, and help push forward the capabilities of prediction and uncertainty quantification for multi-annual to decadal timescales.

Furthermore, this LHA will ensure that advances in fundamental understanding of Earth System change are targeted to meet the needs of decision-makers facing climate-related risks and opportunities. Societal benefits to be delivered by this LHA include early warning of significant global and regional scale changes in the climate system, and quantification of current and future hazard risk on regional scales. The benefits of this new actionable information will be enhanced through co-development with diverse stakeholders (e.g. governments, businesses, public), and thereby offer a major contribution to WCRP's efforts to ***bridge climate science and society*** (objective 4).

3. Research Priorities (including "Scope of the Activity" and "Gaps in knowledge and expertise")

Three cross-cutting foci connect the work of the separate thematic elements of this LHA. First, the development of a capability to observe, explain, and predict changes in the Earth System requires the ***tight integration and coupled usage of observations and models***, including characterization and quantification of uncertainties. Evaluation of model skill and prediction system effectiveness requires observational datasets that capture the phenomena of interest. Just as observations can be used to confront models and determine their skill, models can be leveraged as tools to inform the design of efficient, targeted observing systems. We envision an interactive workflow between model and observing system improvement, as both represent incomplete knowledge reservoirs. Similarly, identification of causal factors and processes leading to large-scale climate regime shifts or changes in regional hazard risk require integrated usage of both observations and modelling systems.

Secondly, initial steps to develop a capability to observe, explain, and predict Earth System change will focus on a small number of compelling ***case studies*** targeting climate "anomalies" or "events" that have occurred in recent decades. Through these case studies, we will seek to develop a systematic approach across all three Themes to identify causal factors shaping these events, and to assess the potential for predictions of the events themselves and, where relevant, their impacts on hazards.

Finally, we envisage that ***large ensembles of single-forcing experiments*** will inform the activities at the heart of each of the themes. For example, they will be valuable to characterise fingerprints of the responses to different forcing factors that can inform observing system design (Theme 1), quantitative process-based attribution (Theme 2), and understanding the drivers of changing hazards (Theme 3).

Theme 1: Monitoring and Modelling of Earth System Change

The requirements of this LHA for Earth System models and observational systems currently present a number of inter-related knowledge and capacity gaps. These include: (i) persistent biases in Earth System model simulations; (ii) an under-utilization of the wide array of observational data collected today under the Global Climate Observing System (GCOS) and the Global Ocean Observing System (GOOS) for climate model calibration; (iii) a disconnect between Earth System reanalysis efforts and climate modelling efforts, and/or data assimilation efforts that are not necessarily targeting major needs (e.g., initial condition estimation versus model parameter calibration); (iv) sparse observational sampling of various elements of the Earth System, which warrants extra care in using the observations that do exist in the context of modelling; and (v) simple, ad-hoc approaches to dealing with the combined stream of uncertainties from observations and models. The proposed activities will establish closer ties between GCOS assets, climate model development and assessment efforts, and data assimilation systems to address some of these inter-related issues. For example, improved usage of available observations could help alleviate some climate model biases through comprehensive climate model calibration efforts.

Initial activities to expose and address the issues outlined above will be targeted towards a few case studies of recent climate anomalies. These case studies will address a number of scientific questions including:

- How early were these “events” recognized as such and how well were they monitored by different elements of GCOS (and GOOS, in particular for the ocean, where sparse sampling remains a major issue)?
- How well did “models” do in representing these events, in particular Earth System/climate models and Earth System reanalyses?
- How well were the underlying metrics observationally constrained? (E.g., regional vs. global heat content anomalies; global mean values as small residuals of large regional variations; climate anomalies at the margins of the polar ice sheets; …)
- Do current observations lend themselves to enabling mechanistic understanding of anomaly propagation/evolution, in particular observational coverage of “upstream”/precursor processes that led to the “events” of interest?
- What methods could inform quantitative observing system design to address questions, such as: What should be measured and where? How many observations are sufficient? What are optimal combinations of different observing networks (satellite and in-situ)?

The observing networks that operate under GCOS/GOOS can play a major role in this approach. For such case studies, the value of these networks could be assessed, major gaps (as well as potential “redundancies'') identified, and observational requirements formulated. We are not proposing specific observations (such as clouds, sea ice, precipitation, etc.), but subsume these to the discussion of relevant metrics of interest.

Another important objective is the development of calibration and uncertainty quantification (UQ) strategies around existing or emerging models. We envision approaches of model emulation or surrogate modelling. Quantifying uncertainties of global and regional changes in relevant climate metrics, based either on observations, models, or synthesis/data assimilation products, remains a great challenge, in part because of the computational complexity of the underlying problem. An activity could develop frameworks and workflows that will account jointly for uncertainties in observations (instrument error, representation error, sampling, ...), models (parametric errors, structural model errors, …), and assimilation strategies (to the extent that they exist) into comprehensive uncertainty propagation flows that seek to combine these error sources, and, for example, propagate them onto specific target metrics relevant to climate diagnostics. Coordination with efforts that are developing novel modelling infrastructures, such as the Digital Earths LHA, will be crucial.

Theme 2: Integrated Attribution, Prediction and Projection (including early warning and the potential for abrupt change)

On multi-annual to decadal timescales climate is influenced by a range of factors including internal variability and radiative forcing from greenhouse gases, anthropogenic and volcanic aerosols, solar variations, land use changes and ozone. Climate model simulations are essential to disentangle the relative roles of these different factors. However, climate models are imperfect, and currently available simulations do not take into account the latest estimates of, and uncertainties in, the various radiative forcings. Developing an operational attribution capability therefore requires two stages:

1. Critical assessment of the ability of models to simulate internal variability and responses to radiative forcings. A key outcome of this stage will be recommended corrections to eliminate, reduce, or adjust for model errors.

2. Operationalization of attribution simulations using the latest estimates of radiative forcings and uncertainties, and application of corrections diagnosed in stage 1.

Taken at face value, large ensemble historical simulations suggest a dominant role for internal variability in regional climate change on decadal timescales (Deser et al., 2020). However, there is mounting evidence that climate models may underestimate atmospheric circulation signals in seasonal (Eade et al., 2014, Scaife et al., 2014, Baker et al., 2018), interannual (Dunstone et al., 2016) and decadal (Athanasiadis et al., 2020; Smith et al., 2020) predictions, and in historical simulations (Zhang and Kirtman, 2019; Sévellec and Drijfhout, 2019; Klavans et al., 2021). Consequently, attribution is complicated by the possibility that models may not properly represent the relative roles of internal variability and external factors (Scaife and Smith, 2018).

Ultimately models need to be improved so that they do not underestimate atmospheric circulation signals. In the meantime, a potential way forward is to diagnose the response to individual forcing factors from the mean of large ensembles, and then to assess their relative roles by scaling to reconstruct the observed historical record and treating the residual as internal variability. Such single forcing experiments have been proposed by the Detection and Attribution Model Intercomparison Project (DAMIP, Gillett et al., 2016). However, they are generally low tier and have not been completed by many modelling centres; those centres that have completed such experiments typically included only a few ensemble members. Hence, a key objective of Theme 2 is to develop large ensembles of single forcing historical simulations (LESFs).

Analysis of the LESFs will provide scaling factors for the different forcings and hence corrections for the model simulations. However, further work will be required to assess their robustness and whether historical corrections continue to be valid for operational predictions. This will likely involve detailed analysis of recent case studies, assessment of observational uncertainties, and exploration of possible non-linear interactions between the responses to different forcings.

Operationalization of attribution simulations will require real time estimates of individual forcings together with uncertainties. Theme 2 will therefore identify sources of forcing information and assess how quickly the information will be available.

The operational attribution system developed by this Lighthouse Activity will ideally be an international collaboration involving several models. Hence potential contributors will be identified and the infrastructure for coordinated attribution will be established.

Theme 3: Assessment of Current and Future Hazards

There are many knowledge gaps in quantifying the impacts of natural and anthropogenic drivers on hazards. Due to the limited length of reliable observational records and the relatively rare occurrences of many types of hazards, it is often challenging to identify significant trends and to distinguish internal variability from responses to anthropogenic forcing. Our current ***capability to explain hazard changes*** is also limited due to a lack of process understanding about how drivers of large-scale change may affect hazards. One example is the debate on whether Arctic warming impacts midlatitude extreme weather (e.g. Barnes and Screen, 2015). In general, hazards or weather/climate extremes are often regarded as the tail of the distribution of the climate system, and strong theoretically-based constraints do not exist for most types of hazard.

Our current ***capability to predict and project hazard changes*** is limited due to several factors: i) many types of hazards are related to mesoscale, or even convective-scale processes (such as tropical cyclones and tornadoes), or closely tied to the coupling between different components of the climate system (such as the role of land-atmosphere interaction in droughts or heat waves), which global models do not represent well; ii) large inter-model spread exists in predicted and projected climate changes on the regional scale, which is due to differences in model formulation (e.g. physics parameterizations and resolution); iii) climate models often have large biases in representing the regional distribution of hazards, and this leads to the deficiencies of the models in capturing the impacts of climate changes on hazards even if a model predicts the regional climate change skillfully; iv) signals related to anthropogenic forcing are often weak compared to internal variability; and v) balanced initialization of coupled prediction systems is major challenge due to model biases, technical difficulties and lack of observations.

A gap also exists between the research and user communities regarding multi-annual to decadal prediction products that are ***feasible, useful, usable, and beneficial***. One example is tropical cyclones. Although research has demonstrated the predictability of basin-wide statistics of tropical cyclones, users are often more interested in landfalling tropical cyclone statistics. There is likely a middle ground, and ***co-design between researchers and users is needed*** for it to be identified. Another dimension is related to a lack of systematic assessments of the skill of climate forecasts for different regions, variables, averaging times, and spatial scales. Users frequently do not have targeted skill assessments for their applications. This can be partly addressed by efforts to provide open forecast archives of raw model outputs with common formats and variables that allow all models to be processed in the same way.

While observations provide us with a window into regional hazard risk, observations alone are insufficient to understand natural and anthropogenic drivers of hazard modulation. They may lack sufficient spatio-temporal coverage and, more importantly, offer only a single realization from which the compounding effects of different drivers are hard to disentangle. Model experiments are therefore essential. ***The computational challenges are particularly severe*** because ***large ensembles*** are needed to simulate the likelihood of specific hazards (e.g. extreme events) under specific boundary conditions, yet ***high resolution*** is also required to simulate the hazards (e.g. tropical cyclones), and their interactions with larger scales, with sufficient fidelity. This will therefore be an area where ***collaboration with innovations developed in the Digital Earths LHA*** are likely to be especially important.

A range of experimental designs will be useful to make progress with the challenges in this Theme, including: hindcast datasets to quantify current risk (e.g. Thompson et al., 2017); coupled single-forcing experiments (as described in Theme 2); large ensemble atmospheric General Circulation Model (GCM) experiments, possibly including regional downscaling (e.g. Mizuta et al., 2017; Imada et al., 2020), and targeted nudging experiments. While atmospheric GCM experiments cannot fully address predictability, they are nonetheless helpful to quantify natural and anthropogenic contributions to changing hazards (e.g., Watanabe et al., 2014), e.g. the regional risk of heavy precipitation (Imada et al., 2020).

Activities within this Theme will focus on:
1. Research to link large-scale drivers to local hazards,
2. Quantifying current and future risk of hazards using large ensembles,
3. Assessing predictability of changes in hazard risk, and
4. Attributing changes in hazard risk to internal or external climate drivers.

We envisage an initial focus on understanding the multi-annual to decadal variability of specific hazards, such as tropical and extratropical cyclones, heat waves, cold air outbreaks, droughts, and heavy precipitation/floods. One or more case studies of recent events or changes in the large-scale atmospheric circulation regime will be chosen, in collaboration with the other themes, for focused investigation.

4. Deliverables and Outcomes

Reflecting achievement of our central objective the ultimate outcome of this LHA will be:

> ***A design of, and major steps toward delivery of, an integrated capability for quantitative observation, explanation, early warning and prediction of Earth System change on global and regional scales, with a focus on multi-annual to decadal timescales.***

Other headline deliverables will include:

- Case studies of multi-annual-to-decadal changes in the climate system assessed from the perspectives of all three LHA themes.
- Contributions to WMO Annual-to-Decadal Forecast and State of the Climate reports focused on the attribution of multi-annual to decadal changes in the climate system.
- Quantitative assessments of the current risk of specific hazards and future risk under defined scenarios, supported by process-based understanding of the drivers of changing risk.
- Improved capabilities for prediction of multi-annual to decadal changes in the climate system and their impacts on hazards, based on improved models, initialization approaches, ensemble design and process understanding.
- Development of an international open-access multi-model archive of seasonal-to-decadal hindcasts and forecast data.
- Demonstration of the user value of the advances above through case studies employing co-design of decision-relevant products.

Additional interim and theme-specific deliverables will include:

Theme 1

- Critical analysis of the role that observations play in constraining key climate phenomena as represented in climate models and Earth System reanalyses.
- Recommendations on novel and/or quantitative approaches to inform the design of observing systems in support of Earth System modelling frameworks.
- Analysis frameworks for quantification of the full range of uncertainties in reanalyses as well as climate predictions.
- Improved methods to initialize Earth System models for multi-annual to decadal prediction.

Theme 2

- Critical analysis of models and development of techniques to improve or correct model errors.
- Operational attribution simulations using latest estimates of radiative forcings and uncertainties.
- Advances in process-based attribution of multi-annual to decadal changes in the climate system.
- Progress in resolving the signal-to-noise paradox in predictions of atmospheric circulation change.
- Providing a coordinating role on developing systematic skill assessments for annual to decadal forecasts.

Theme 3

- Internationally coordinated large ensemble numerical experiments to quantify the impact of natural and anthropogenic drivers on changes in regional hazards.
- Advances in process-based attribution of multi-annual to decadal changes in hazards.

5. Engagement and Co-design

Successful delivery of this LHA will require close collaboration with many different groups within WCRP and, in addition, a smaller number of key external partners. An overview of potential collaboration opportunities is provided in Table 1. In the following paragraphs we highlight some of the most important collaborations we envisage.

Collaboration between Theme 1 and the newly formed WCRP Earth System Modelling and Observations (ESMO) Core Project will help advance the objectives of both activities. Similarly, Theme 3's objectives overlap substantively with the My Climate Risk Lighthouse Activity and the Regional Information for Societies (RifS) Core Project: collaboration and/or joint membership will be considered. Collaboration with the Digital Earths LHA will be important for all three themes.

There is also potential for collaboration with Safe Landing Climates in areas such as early warning of possible rapid change (or "tipping points") and the use of observations to constrain long-term projections.

Concerning ***external engagement***, specific priorities by theme are:

- Theme 1: GCOS and GOOS
- Theme 2: WMO (State of the Climate reports and Annual-to-decadal Climate Updates)
- Theme 3: WWRP; Risk management communities, Future Earth

There are also opportunities to engage with major national and international programmes such as d4PDF, iHESP, Copernicus and the EU Destination Earth initiative.

Engagement with funding agencies will be essential to achieve the ambitions of this LHA. This engagement needs to explore the common interests between the priorities of specific agencies and the goals of the LHA.

EPESC working group		WCRP Homes	Grand Challenges	Other LHAs	WCRP Projects	External Partners
1	**Monitoring and modelling Earth System change**	Models & Data; CLIVAR; GEWEX; SPARC; CliC	Climate Sensitivity, Carbon Feedbacks, Melting Ice, NTCP	Digital Earths, Safe Landing Climates	CMIP	GCOS, GOOS
2	**Integrated attribution, prediction and projection**, including early warning and the potential for abrupt change	CLIVAR, GEWEX, SPARC, CliC, Models & Data (WGSIP)	Near-term climate prediction (NTCP)	Digital Earths, Safe Landing Climates (e.g. emergent constraints)	CMIP (especially DAMIP and DCPP)	WMO (annual-to-decadal update)
3	**Assessment of current and future hazards**	CLIVAR, GEWEX, SPARC, CliC, RifS, Models & Data	Extremes, (+ Water, Sea-level change and coastal impacts)	My Climate Risk, Digital Earths	CMIP Global Extremes Project (GEP)	WWRP

Table 1: A summary of areas of common interest, and hence collaboration opportunities, with other WCRP activities and (in the rightmost column) potential external partners.

6. Implementation, Including Timeline

Following acceptance of the initial Lighthouse Activity Science Plan (estimated timeframe: August 2021), the Lighthouse Activity Scientific Steering Group will begin drafting an Implementation Plan, coupled with a series of inception activities:

- Publication of Science Plan (submission fourth quarter 2021; currently targeting the *Bulletin of the American Meteorological Society*);
- Virtual workshop on attribution of multi-annual to decadal changes in the climate system (22-24 September 2021);

- Publication of perspective article based on outcomes of the September 2021 workshop (submission likely second quarter 2022); and
- Selection of key case studies, informed by presentations and discussions shared during the workshop (fourth quarter 2021).

Additional activities currently being investigated to grow the community include a series of webinars, panel discussions, or competitions focused on scientific needs of the three Themes. Such a series could include jointly sponsored events with other Lighthouse Activities and/or WCRP Core Projects.

The Implementation Plan will be submitted to the WCRP JSC by the end of 2021, with the goal of launching the activity in earnest early in 2022. Launch activities will centre on the initiation of case study efforts in each of the working groups. Within the first year these efforts should yield insights into:

- Attribution of causal forcing factors, event evolution and early indicators of the case study onset (Theme 2);
- Assessment of the ability of the current observing system to capture these early indicators and monitor the evolution of the event (Theme 1);
- Recommendations for observing system improvements to fill gaps identified in the above assessment (Theme 1);
- Assessment of the hazard risks associated with the case study events (Theme 3); and
- Assessment of the ability of models to simulate the full evolution of the case study event, including identification of relevant model biases and illustrations of methods to reduce these biases through improved process representation and/or model calibration (all themes).

An in-person meeting of the LHA science team during the second or third quarter of 2022 will help build momentum and ensure success.

Within the first five years we aim to have:

- Established methodologies for novel case study application;
- An international open-access multi-model archive of seasonal-to-decadal hindcasts and forecast data;
- Improved capabilities for prediction of multi-annual to decadal changes in the climate system and their impacts on hazards, based on improved models, initialization approaches, ensemble design and process understanding; and
- Quantitative assessments of the current risk of specific hazards and future risk under defined scenarios, supported by process-based understanding of the drivers of changing risk.

Proposed Management of the LHA

Figure 1 shows a proposed management structure for our LHA, with a Working Group for each of the three themes reporting to an overall Scientific Steering Group (SSG). We anticipate that the individual working groups may develop distinct ways of working and collaborating with other WCRP activities and external partners.

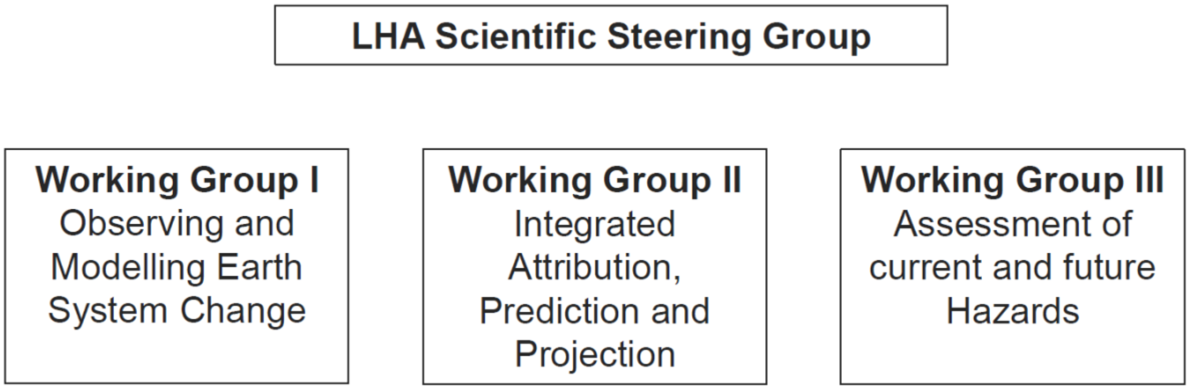

Figure 1: Proposed management structure of the Lighthouse Activity.

Evolution of the LHA Science Team membership

Initial membership of the Science Implementation Team will largely overlap with membership of the Science Plan Development Team, with the current group expected to remain involved at least through the end of 2021. Co-chairs of the LHA and co-leads of each of the Working Groups will remain in place. These eight individuals will form the core membership of LHA SSG, with others added from the WG teams to help balance gaps in expertise and representation. During the final quarter of 2021, we will develop an LHA membership evolution plan informed by JSC feedback on the Science Plan and JSC plans for the WCRP Implementation Plan.

7. Requirements

Resource requirements have not yet been scoped; we consider this a task for the Implementation Plan. As noted in Section 5, engagement with research funding agencies will be essential to realise the ambitions of this LHA.

8. Budget

In the near term, EPESC is planning to organise a core SSG face-to-face meeting in 2022. This would facilitate discussions on the case study efforts and other early priorities for each of the working groups.

A series of webinars will also be organized and, depending on the platforms and tools provided by the WCRP Secretariat, some indirect financial resources may be necessary, in case there are charges to the use of such licenses.

Also, competitions that would improve capabilities for attribution and prediction of multi-annual to decadal-scale climate drivers could be organised in 2023 with prize money, similar to other competitions that have been run at WMO. Additional resources that would complement prize money provided by WCRP may need to be identified for such an event.

Specific workshops for each of the themes described in this plan will also be organised within the first few years, and the EPESC Science Team will actively try to involve other LHAs and core projects for the joint organisation of these events. For these workshops, financial resources would be directed mainly to early career scientists.

9. Communication and capacity exchange

The Explaining and Predicting Earth System Change webpage will be hosted by WCRP, following the template for all the LHAs. It will serve as a point of reference for all EPESC members as well as the wider WCRP community.

Working together with the WCRP Secretariat, EPESC members will be encouraged to share new opportunities to engage with other projects, and internal and external partners. The webpage will also have a compilation of the latest scientific articles relevant to EPESC objectives.

10. Risks

- Lack of funding to address the research challenges. Key mitigating action here is engagement with funding agencies.
- Insufficient engagement by the research community. Mitigating action is proactive strategies to engage, e.g. through webinar series, workshops, etc.
- Potential gaps in expertise. Mitigating action is adequate scoping of scientific needs and recruitment of additional members for the Science Implementation Plan. Needs for training could also be considered in collaboration with the WCRP Academy.
- Difficulties with external collaborations, e.g. GCOS. Mitigating action is early engagement with desired collaborators for rapid identification of their priorities. If those priorities are not well-aligned with priorities of the LHA, timelines may need to be adjusted or alternative collaborative organizations may need to be identified.

11. Authors

Member	Role	Affiliation	Country	Representation
Rowan Sutton	EPESC Co-chair	NCAS/University of Reading	UK	
Kirsten Findell	EPESC Co-chair	GFDL/NOAA	USA	GEWEX
Anca Brookshaw	Co-lead WG1	ECMWF	UK	ESMO
Doug Smith	Co-lead WG2	UK MetOffice	UK	
Frederic Vitart		ECMWF	UK	

Jochem Marotzke		Max Planck Institute for Meteorology	Germany	
Lijing Cheng		Institute of Atmospheric Physics, Chinese Academy of Sciences	China	CLIVAR
Markus Donat		Barcelona Supercomputing Center	Spain	ESMO
Masahide Kimoto	Co-lead WG3	National Institute for Environmental Studies	Japan	
Patrick Heimbach	Co-lead WG1	University of Texas	USA	CliC
Shoshiro Minobe		Hokkaido University	Japan	CLIVAR
Michael Ek		UCAR	USA	GEWEX
Scott Osprey	Co-lead WG2	Oxford University	UK	SPARC
Lin Wang		Institute of Atmospheric Physics, Chinese Academy of Sciences	China	SPARC
Sandy Lucas		NOAA	USA	
June-Yi Lee		Pusan National University	South Korea	
Leandro Díaz		University of Buenos Aires	Argentina	YESS
Matilde Rusticucci		University of Buenos Aires	Argentina	
Zhuo Wang	Co-lead WG3	University of Illinois	USA	WWRP
James Risbey		CSIRO	Australia	

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