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Digital Earths Lighthouse Activity

The Digital Earths Lighthouse Activity (DE-LHA) aims to facilitate the research required to build quantitative frontier climate information systems and to support the international community engaged in developing and implementing them. The success in building climate information systems that enable society to answer critical questions depends on major advances in at least three areas: modeling of the global climate system at scales that resolve phenomena that are key to societal decision making, the fusion of models and observations through data assimilation systems for climate and the full integration of quantitative models of human interactions with the changing climate in the information system infrastructure.

Earth System Modeling and Observations (ESMO) Core Project

ESMO takes a seamless and value-chain model-data-observation approach across Earth system components, fundamental and applied disciplines, time and spatial scales and infrastructures. It aims to optimize model development, establish new prediction systems, innovate observing systems, improve climate data eco-systems and connectivity, advance data assimilation and digital-twin frameworks. This framework will enable the formulation of WCRP modeling and observational requirements to observe, understand and predict the climate system.

WCRP is co-sponsored by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of UNESCO and the International Science Council (ISC), see www.wmo.int , www.ioc-unesco.org and council.science.

Disclaimer

Executive Summary

A new generation of ultra-high-resolution, kilometer-scale, climate models are appearing. There has been enormous progress over the last few years in ultra-high resolution modeling. This new class of coupled models is working at the scale of weather models. Many modeling groups can now run season-length global atmosphere-only simulations, or sea ice and ocean models at kilometer-scale grid spacing. Multi-decadal regional climate simulations at continental-scales are now feasible. First results of simulations of a year or longer with coupled kilometer-scale models are also emerging. Current throughput of such ultra-high-resolution simulations indicates that multi-decadal simulations are within reach. These new global earth system models also come with tremendous challenges, such as operating in the atmospheric turbulent gray zone, spinning up slow-varying processes in the land and ocean, large computational costs, and immense output data volumes.

The km-scale modeling workshop took place at the National Center for Atmospheric Research (NCAR) in Boulder, CO in October 2022. The workshop had about 65 in person attendees, and another 30 who participated in virtual breakout sessions. The goals were to bring people from different communities together: different spheres of the earth system (land, atmosphere, ice, ocean) and different scales (regional to global, weather to climate). There were extensive breakout discussions. The topics covered were related to (a) Critical science questions for k-scale models, (b) Key technical challenges for such systems and (c) Organization of the k-scale modeling section of the Digital Earths Lighthouse activity. Recommendations are summarized here and the discussion behind them noted in the full report.

Scientific Issues

Results from more than 10 global km-scale atmospheric models and 3 different ocean/sea-ice models were presented at the workshop. There was discussion of atmospheric processes (including deep convective motions) as well as ocean and ice processes, and critical land processes. Recommendations centered on collaboration with GEWEX GASS on understanding shallow and deep convective behavior, as well as extratropical behavior. Developing collaborations with mesoscale regional climate modelers and global climate modelers was highlighted. Ocean and ice groups showed high resolution models permitting eddies and even leads in sea ice. Teaming up with CLIVAR's ocean model panel and relevant CLiC sea-ice groups for process understanding is desirable. For the land surface, much of the emphasis was on advancing hydrology modeling for global and climate purposes. Teaming up with existing efforts such as GEWEX GLASS and Global and Regional Hydroclimate projects was discussed as critical. In all these efforts, the concept of a Process Intercomparison Project (PIP) across scales of space and time was floated as a key way to make progress. Another key question was whether global km-scale models are needed, or if regionally refined or regional models are sufficient. This requires understanding to what extent high resolution processes feed back on teleconnections and the general circulation.

Technical Issues

Running and analyzing km-scale models creates enormous (exascale) challenges. Collaboration on use of exascale computing architectures (with accelerators) is encouraged, as well as sharing best practices on infrastructure for models and analysis, which was discussed extensively. Data volumes in space (and high frequency in time) require a new model for analysis. Several approaches were identified to reduce data volumes and are being explored including minimal output sets, 'streaming' output to temporary storage, and compression of saved data. All approaches will likely need to be used. Data volumes also change how users can interact with the data for analysis, and a new paradigm is needed so that data can be analyzed in-situ without copying or moving it. Federating access to common tools at data centers was discussed. This option has a benefit of enabling low-bandwidth access to the data to possibly many users, including those in the global south. Many of the new analysis tools are open-source and community developed. These efforts should be supported (open source is not free), and in particular, the workforce for infrastructure, computing and software engineering and development should be supported and cultivated.

Organizational Issues

Finally the participants discussed organizational issues and how the Digital Earth Lighthouse Activity could move forward. A list of modeling centers for global and regional km-scale models is being developed. The WCRP has a strong role to play as an honest broker in facilitating communication and analysis of models, as well as fostering development. There was support for guiding Process Intercomparison Projects (PIPs), which can be developed from key science issues (atmospheric deep convection, ocean eddies, etc). There was also a desire for a working group of km-scale model developers to share information, similar to WGCM and WGNE. The overlap is strongest with WGNE. But km-scale is a slightly different set of models and foci, different infrastructure issues, and a more exploratory, research activity. Discussions with WGNE, WGCM, and ESMO on the appropriate fora should be started. There is also a need for a clear link with applications, which will require more interactions and discussions with CORDEX and the Regional Information for Society (RIfS) WCRP Core Project.

Future Activities

Immediate next steps were also discussed. One was developing the PIP concept around interested communities. Another was to attempt to get communities together by coordinating meetings of relevant WCRP and ESMO groups, e.g. for a common week in a common location, perhaps starting in 2024. Along with this, a hackathon and tutorial on km-scale models could be planned, also for 2024.

Contents

1. Introduction

Climate models aim at simulating the flow of energy and water across the ocean, land, atmosphere and ice caps, but their typical coarse grid spacing of O(100 km) introduces the need to parameterize key processes, which creates a source of long-standing model errors and uncertainties. Due to the advancement in computer technologies, a new generation of ultra-high-resolution climate models are appearing. There has been enormous progress over the last few years in ultra-high resolution modeling. Many modeling groups can now run season-length global atmosphere-only models at kilometer-scale grid spacing. Several efforts are also advancing for km-scale ocean and sea-ice models. Multi-decadal climate simulations at continental-scales are now feasible. Many modeling centers are actively developing ultra-high-resolution global coupled earth system models that leverage advances from other modeling communities such as sub-mesoscale ocean eddy models. Current throughput of such ultra-high-resolution simulations indicates that multi-decadal simulations are within reach.

These models allow simulation of the global earth system at a few kilometers that resolve the dominant modes of energy transfer as well as the cycling of water across the land, atmosphere, ocean and ice cap, closer to first principles. This new class of coupled global (and regional) models is working at the scale of limited temporal weather models. These new earth system models also come with tremendous challenges, such as operating in the atmospheric turbulent grey zone, large computational costs, and immense output data volumes.

2. Scope and goals

The km-scale modeling workshop took place at the National Center for Atmospheric Research (NCAR) in Boulder, CO in October 2022. The aims of the workshop were to:

- Bring very high-resolution modelers of different communities (atmosphere, ocean, land, ice but also global and regional) and sub-components (physics and diagnostics) together.
- Raise awareness of common and unique scientific and computational issues faced by the various communities when moving to ultra-high-resolution.
- Discuss the applications and use of ultra-high resolution global models by identifying things that we already know do not work or that we anticipate not to work.
- Share current progress in simulating various spheres at ultra-high-resolution and in coupling them.
- Identify key challenges and joint community tasks that can be achieved within one- to two-years

The workshop had about 65 in person attendees, and another 30 who participated in virtual breakout sessions. The meeting was a mix of invited and contributed talks, with extensive time for breakout groups. Talks were recorded
(https://www.youtube.com/playlist?list=PLsqhY3nFckOHU-L6lxgf-oEgA-Eus_bA3)

The breakout groups were constant over 4 days, and featured discussion of the same set of questions for each group, enabling them to take a deep dive into the questions and expand upon them.

The main themes discussed in the breakout groups were related to (a) Critical science questions for k-scale models, (b) Key technical challenges for such systems and (c) Organization of the k-scale modeling section of the Digital Earth Lighthouse activity. The breakout sessions and plenary discussions were used to also discuss potential future activities, leading to some recommendations on how to proceed with the k-scale modeling focus area of the Digital Earth Lighthouse Activity. These discussions are synthesized in this document.

Meeting Website: https://www.mmm.ucar.edu/events/workshops/wcrp

3. Scientific Issues

As highlighted above, the workshop had a strong focus on identifying and discussing scientific issues in each model component as well as in the coupled modeling systems when applying the models with resolutions of less than 5 km. We report the major outcomes of these discussions in this section. We begin the discussion by briefly summarizing some of the results reported in the various invited and contributed papers presented at the workshop. Here, we focus on major achievements as well as emerging issues when simulating individual spheres as well as the coupled climate system at km-scale.

The workshop was presented with results from more than 10 global km-scale atmospheric models, of which about a handful have begun coupled simulations, usually at somewhat coarser resolution. Results from at least 3 different ocean/sea-ice models were also presented. While all the 10+ atmospheric models naturally also contain land-surface models, there was very little focus on understanding land-surface processes in the simulations. There was, however, significant focus on the role of land-surface processes in several of the presentations using regional km-scale models, which ranged from the role of orography to the inclusion of ground water in the simulations. This highlights the potential benefits from uniting research efforts in the global and regional modeling communities, one of the major recommendations of this workshop.

It was evident throughout the workshop that the explicit (as opposed to parameterized) representation of deep convection in the **atmosphere** in km-scale models has major benefits for the model behavior. However, there is still an open question whether any parameterized deep motions are necessary at these scales. In particular, the simulation of rainfall shows marked improvements, both in rainfall intensity distributions and the simulation of the diurnal cycle with explicit (or mostly explicit) treatment of deep convection. The simulation of tropical weather phenomena, from tropical cyclones to tropical waves, to the evolution of the Madden-Julian Oscillation also show noticeable improvements when compared to coarser resolution models.

Another common issue reported was the large diversity in the structure/mode of deep convection simulated by the models. While some groups reported a prevalence of somewhat unstructured “blobby” convection near the grid-scale, others reported too strongly organized systems emerging frequently.

Recommendation: *We recommend investigating the causes for the variety of deep convective behavior in the models in collaboration with the GEWEX GASS activity.*

There are good attempts in the current atmosphere models to try to represent key extratropical weather regimes that create severe impacts (wind, rain/snow, icing). Examples were shown of simulation of squall lines, mesoscale convective complexes and extratropical cyclones. Many of the models (even global NWP models) are still struggling with these key extreme weather features. There is a long history of simulating these features at km-scale in mesoscale models.

Recommendation: *The workshop identified the lack of analyses of extratropical phenomena as a major current gap in the analysis of the global km-scale models and recommends research efforts to be directed to this area. Global model groups (and even regional climate groups used to 10-25km) should team up with experienced mesoscale modelers working at these km-scales.*

Despite the great progress, several common issues for future research clearly emerged from all modeling groups. First, the treatment of low clouds likely requires major attention. This is a critical issue for the traceability of climate models. While mid-latitude continental weather phenomena have gotten a lot of attention at these scales from regional weather forecasts, there has been little work on shallow marine clouds. Several groups reported a poor simulation of the trade-wind regions. Here, the simulation of shallow convective clouds was highlighted as a major concern. Two different approaches to this issue were reported. Some groups maintain the shallow convection parametrization of the coarse-resolution parent model, while others expect a unified turbulence parametrization to simulate shallow convective clouds. Neither of these approaches is currently successful. It was noted that shallow boundary layer turbulence parameterizations are necessary until `eddy permitting' 3D turbulence can take over at scales well below 1km (100-250m).

Recommendation: *We recommend making the improvement of the simulation of boundary-layer clouds at km-scale, which is a "gray-zone" scale for these clouds, a near-term priority. We recommend exploring a close connection to the very experienced process groups in the GEWEX GASS community and the Large Eddy Simulation community to address this issue.*

The workshop saw several presentations on km-scale simulations of the **oceans and sea ice**, both in forced and coupled mode. Most of the coupled results presented were at 0.1 degree (10km) ocean resolution with only a few coupled models having been run at higher resolution. There is clear evidence that the eddy-richness of the ocean at resolutions of 0.1 deg or higher improves several of the long-standing issues in ocean models. There is also evidence that current approaches to the treatment of sea-ice will likely work at km-scale, although several presentations highlighted the need for a rethink once resolutions higher than 1 km are used. Several presentations also highlighted benefits from coupling ocean wave models to the systems, including the reduction of model biases when doing so. There were early indications that offsetting the costs of doing so can potentially be achieved through machine-learning techniques. While the overall results presented were impressive, the analysis of the underlying processes in km-scale ocean and sea-ice models clearly requires additional efforts.

Recommendation: *Forge a closer relationship of the km-scale ocean and sea-ice modeling community with the emerging coupled modeling efforts through engagement with existing groups (such as CLIVAR's Ocean Model Development Panel and the relevant CLiC groups) and bring a focus to a process-based understanding of the km-scale simulations.*

The **land** modeling community had only a very limited representation at the workshop. It remains somewhat unclear whether this is a reflection of the size of the community thinking about km-scale modeling of the land or whether the timing and location of the workshop hindered participation by that community. One hypothesis is that the global land surface modeling community works on science questions important for climate, and these are related to carbon and biogeochemical cycling, rather than hydrology for example. What is clear is that land-surface processes, in particular hydrological aspects, require urgent attention for them to be suitably represented in km-scale models. It was evident from several of the presentations that while the need for parametrization at km-scale is somewhat reduced in the atmosphere and ocean, the processes treated increases for the land surface as processes that can be neglected at coarse resolution become important once the landscape and orography are better resolved. Chief among these is 3D exchanges of water in the land surface at multiple scales: catchment-scale hydrology must be able to move water horizontally, across grid boxes and in regions of topography and vegetation canopies. There was evidence from regional modeling studies that the feedback to the atmosphere of including such processes can be large. Overall there was evidence that the regional land modeling community and the hydrology community is ahead of the global land climate community in recognizing the importance of and implementing new processes in the models. This creates an opportunity for new collaborations.

Recommendation: *Engage with existing land modeling efforts (such as in GEWEX GLASS and GHP), and Regional Hydroclimate Projects (RHPs) to establish a recognizable effort in km-scale modeling of the land for inclusion in climate models.*

Several groups presented first early results from global coupled simulations at km-scale from which the above recommendations are derived. The workshop recognized these as major technical and scientific achievements towards km-scale climate modeling in the future. Many of the improvements and issues reported for the component models translate into the coupled simulations that exist so far. There is strong evidence for a better representation of variability at sub-annual timescales in the atmosphere, ocean and sea-ice, such ocean eddies, sea-ice leads and ridging and tropical atmospheric waves. A major emerging issue is that the mean model climates show large biases, similar to those reported at coarser resolution. This is not unexpected at this early stage, as very little effort at studying their causes and addressing the processes involved has so far been possible. However, the existence of these biases prompted the workshop participants to call for deeper investigations of their root causes as well as a discussion of the necessary model experiments to study and address them (see below).

Recommendation: *To address the issues above and to connect the communities engaged in km-scale model development with those studying processes in the various spheres, the workshop proposes to instigate a range of* ***Process Intercomparison Projects (PIPs).*** *One key feature is that such groups should have a cross-scale dialog of models and observations from global km-scale models to regional and limited area models, and from in-situ to satellite data and assimilation methods. Another is to focus on understanding processes and their interactions at these scales. Each of these projects should focus on identifying and improving the representation of key processes in km-scale models that have been linked to the overall model errors. We note that the identification of those processes requires significant research in itself. The definition of the PIPs should be grass-roots driven but requires structures for groups to interact on a regular basis (see below in* ***Organizational Issues*** *for suggestions).*

While there was general consensus that the elimination of the parametrization of deep convection in the atmosphere constitutes a major advance in our ability to model the atmosphere, there was significant discussion on what constitutes the **main purpose of using km-scale models**. The workshop agreed that while the capability of km-scale models to better treat convection had been demonstrated (e.g., better rainfall intensity distributions), there were many open scientific questions as to how this capability enables an improved simulation of synoptic and larger scales, up to the general circulation. There was significant evidence for such improvements in the tropics (better waves, MJO, Tropical Cyclones, etc). It is an open question how the better representation of tropical phenomena affects the extra-tropics via wave propagation of waves that have their origins in the tropics, and via the global teleconnections that emanate from diabatic sources in the tropics. If the improvements in processes do not feed back onto the general circulation, then perhaps simply regionally refined km-scale domains are more appropriate.

Recommendation: *More efforts should be made to investigate how better representing convection and other processes in the land, ocean and ice at km scales actually feeds back onto the larger scale circulation beyond the tropics and how it improves the simulation of climate phenomena as well as weather scales in the models. These processes could be foci for different PIPs.*

There was significant discussion about **experimental designs** that enable the analysis of model behavior and the resolution of any issues identified across the various spheres. The workshop noted that the current approach of running global simulations for as long as possible is unlikely to be effective and a hierarchy of modeling approaches and experiments ought to be developed to use the computational resources available effectively in developing better models. Some concrete recommendations included the use of regional models (or regionally refined global models) to focus on specific phenomena, the development and use of cheaper, idealized modeling frameworks (akin to Single Column Modeling for low-resolution GCMs), the strong alignment of model simulations with recent field campaigns both in space and time, and the development and sharing of common model evaluation tools (see also the Technical Issues Section).

Recommendation: *The workshop suggested for the groups involved in km-scale development to build on the DYAMOND experience and jointly develop experiment and evaluation frameworks that are shared across the community and that allow for the use of a model hierarchy in model evaluation and development. The recommendations below are designed to help facilitate this.*

4. Technical Issues

4.1. Computational speed and efficiency

The emergence and development of km-scale models is closely linked to advances in high-performance computing (HPC). Emerging exascale HPC systems will provide the computational power to run coupled global km-scale earth system models at sufficient speed needed for climate applications. However, many of the current modeling systems are not equipped to efficiently leverage the heterogeneous exascale HPC architectures that will rely on accelerators such as Graphic Processor Units (GPUs). Most of the major model development centers have ongoing projects to refactor (Randall *et al.* 2022) or rewrite (Fuhrer *et al*. 2018, EAMxx) existing model code to more efficiently run on next generation HPC systems. Model speedups between a factor of 3 to 10 are achievable. Closer collaborations between modeling centers and sharing of ported code such as shared model physics would accelerate this technological transition. During this transition period, efficient protocols that allow the transfer of model developments between CPU and GPU versions of a model have to be developed. There are some additional efforts using languages other than FORTRAN (C++, Julia), and better compatibility of code elements across languages is desirable: it is difficult for any model group to write and maintain all its own code.

Another bottleneck in running km-scale ESM is the coupling of different earth system components with each other. Each component has different optimal grid configurations – e.g., hydrologic models need high resolution in steep topography while atmospheric models ideally run on homogeneous grids – making coupling these components computationally expensive. Current solutions to this problem are to run all earth system components on the same grid (Randall et al. 2022) or to reduce the coupling interval to speed up the integration. Future research should focus on advancing the development of community numerical methods, tools and coupling infrastructure to allow more flexibility in building km-scale ESM.

Recommendation: *Encourage collaboration and sharing of (a) techniques and experiences for new architectures (like GPUs), (b) collaboration on coupling infrastructure and even (c) sharing and common development of ported code (such as shared model physics).*

4.2. Data volumes

Managing and analyzing the large amount of data that are produced by km-scale ESMs is a major scientific challenge (Overpeck *et al*. 2011, Schär *et al*. 2020). Km-scale models can provide much more localized data than traditional climate models, which are of great interests to stakeholders and impact researchers. Additionally, km-scale models are more realistically simulating high-frequency events (e.g. downpours), resulting in the demand to save data at higher temporal frequencies (e.g., hourly and sub-hourly).

There are three primary approaches that help to manage the increasing data volume. First, the best way to reduce the output volume is to only save variables that are needed for offline model analyses. This demands in depth considerations of the output variable list before simulations are started and iteratively reviewing the variable list to optimize it during each major modeling effort. Coordinated research projects such as CORDEX created such output lists that can be used as reference (CORDEX, 2022). Second, running model diagnostics (e.g., the calculation of CAPE), and analyses (tracking features at high temporal resolution) online during the model integration can significantly reduce output requirements. For km-scale models, one concept being developed by DESTINE in Europe is to 'stream' the data to a hybrid memory/storage system where it can be operated on for a period of time by other applications running diagnostics, impact models or archivers. Third, compressing the output data can reduce the data volume by orders of magnitude. How to optimally compress earth system data is an ongoing research effort, should be informed by the analysis needs, and has to be tailored to the distribution of variables to achieve optimal results. For example: many variables need only lossy compression, and the time for decompression may slow down analysis.

The size of km-scale model output inhibits the existing model evaluation paradigm of downloading the data to a local analysis server. Model output should rather be analyzed at the location of the data, which is the approach used to analyze data from the DYAMOND project. However, no data center is currently equipped to provide such computational resources to the wider research community and the need for an international data and analysis center that would provide sustainable access to km-scale climate model output was discussed. Such a center would mitigate current inequalities in the accessibility of high-resolution climate model and observational datasets that exclude particularly researchers in the global south from participating in cutting edge research. An alternative to such a global center is to create an international alliance of existing data centers that would allow joint data and analysis access. Many centers now have front end web-based Interactive Development Environments (IDEs, e.g. 'JupyterHub' servers: https://jupyter.org/hub) to their data access, and allow a 'local community' of users access. So a user could get several logins to access data at several centers. Perhaps such access to front end IDEs (which are secure) could be 'federated' to registered users in other centers, similar to the eduroam network for wireless access. This would be of particular benefit for users from under-represented groups.

Recommendation: *Encourage and facilitate access and initial analysis of km-scale model output at the location of the data. Discuss federating access to web-based development environments to facilitate cross model investigations and reduce duplication of effort. Also to support users from under-represented groups.*

4.3. Data Analyses

Even with access to sufficient storage and state-of-the-art analysis systems, analyzing the large data volume from km-scale models is still challenging. Many modeling systems are using unstructured grids, which complicates data analysis and comparison with observations. Additionally, parallelized evaluation programs are needed to allow exploratory data analysis. Projects such as Raijin (Raijin 2022) are hoped to mitigate some of these challenges in the near future. However, programs that are essential to analyzing large gridded datasets such as xarray in Python (Hoyer and Hamman, 2017) often have no long-term funding and might be discontinued in the future, which makes developing sustainable model evaluation tools difficult. Coordinated investment in human resources to develop open source analysis tools would be valuable.

The development and analysis of km-scale models also require novel analysis approaches that are tailored towards process based understanding of model performance rather than analyzing climate mean states. Such approaches partly exist in the NWP community and could be further developed in close collaborations by leveraging model evaluation packages such as NOAA's Model Diagnostics Task Force (MDTF)-Diagnostics package, DOE's Coordinated Model Evaluation Capabilities (CMEC) effort, NCAR's Model Evaluation Tools (MET) and the DKRZ easy.gems projects.

Recommendation: *Continue and sustain support for development of open-source data analysis tools to ensure that there is a toolkit for km-scale model analysis. Continue to share and coordinate such tools. Facilitate sharing of best practices for analysis. Digital Earth can also help by making a list of available tools and by identifying missing capabilities.*

4.4. Workforce

Developing km-scale ESMs is at the cutting edge of multiple disciplines including high-performance computing, software development, data science, data visualization, and natural science. Successfully developing such cutting-edge models demands highly interdisciplinary research that can only be established in stable research environments and by providing competitive salaries. It also requires substantial investments in model development and novel approaches to reward such contributions in the scientific community since they typically result in less publications than model applications.

While this workforce for model development is advancing mostly in developed countries, the data and analysis can be more easily shared. Web-based analysis of large datasets enables researchers without physical access to high-bandwidth connections the ability to do cutting edge analysis. Furthermore, some km-scale modeling efforts are emerging regionally in countries outside of the OECD, and they could be encouraged by sharing of analysis tools. Coordinated tutorials in accessing and analyzing km-scale model output could be of great value outside of just modeling centers, and grow and diversify the workforce.

Recommendation: *Continue to invest in the human workforce for model infrastructure. Ensure that data set access and open source analysis tools are freely available and can be used in the easiest way possible to grow the scientific workforce around the world. Not everyone can run the models. Many more researchers can be helped to access, analyze and use the output to benefit society.*

5. Organizational Issues

The need to develop km-scale models is at the heart of WCRP strategy (e.g. see https://www.wcrp-climate.org/news/wcrp-news/1859-future-climate-modeling-workshop)

During the workshop we heard from the many modeling centers now actively developing km-scales models across different timescales and spatial domains. Many of these are already aligned with WCRP activities under the Earth System Modeling and Observations core project (ESMO) the Digital Earth Lighthouse Activity (DE LHA) and more widely across WCRP (e.g. CORDEX) including both global and regional modeling activities;

As part of the workshop and extending beyond it, we compiled a list of global and regional climate modeling efforts at scales of 5km or finer. These activities are concentrated in developed countries, but not exclusively. Figure 1 shows representation from the US, Europe, China, Japan, Argentina and South Africa. Twenty one different modeling efforts were identified. Twelve are global, and the rest are regional climate modeling efforts. The workshop brought together representatives from about two-thirds of these model groups in person or virtually.

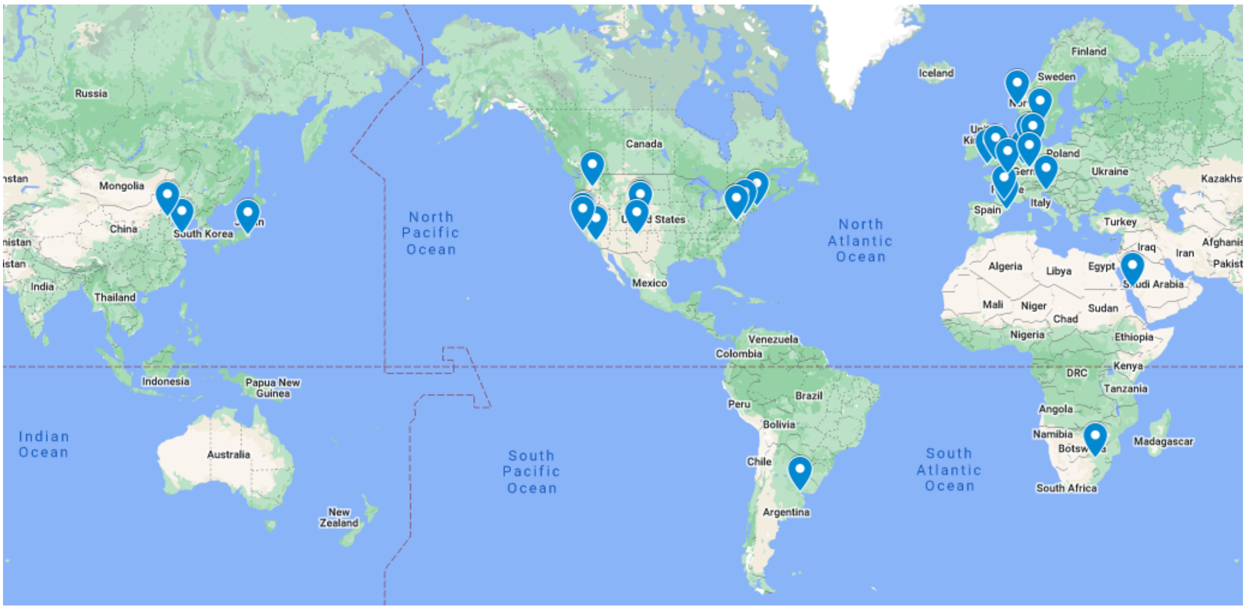

Figure 1: Map of self-Identified locations of Km-scale (5km or finer resolution) global and regional models, either coupled or single components of the Earth System

This workshop discussed the value of better coordination of these efforts, including the type and benefits of coordinated intercomparisons that are appropriate at the current point for km-scale models. Some clear principles emerged;

- Most groups would value a well-designed intercomparison to provide a platform for scientific exploration of common problems, range of uncertainty and to provide a concrete evidence base on the added value of global km-scale models relative to different benchmarks.
- WCRP has a valuable role to play as an 'honest broker' to facilitate an impartial intercomparison enabling a model-agnostic, inclusive approach cutting through hyperbole.
- Design of intercomparison should be flexible to include both global and regional domains and range from process understanding (e.g. idealized modeling) to coupled modeling with both explicit and parameterized convection. Emphasis is on the evaluation of the process rather than standard metrics of performance (e.g more of a Process Intercomparison Project or 'PIP')

Recommendation 1*: Take forward initial ideas for design of PIP from workshop breakout groups and facilitate grass-roots organization of cross-scale groups around topics/regions/phenomena.*

The km-scale modeling community would value a forum under WCRP for engagement and discussion of the proposed PIP and wider scientific and technical issues. This has parallels with the existing WGCM (Working Group on Coupled Modeling) for traditional climate models and WGNE (Working Group on Numerical Experimentation) for forecast models. However, km-scale models overlap both groups, and are central to neither. It was felt that at least initially a joint focused group of km-scale models in collaboration with WGCM and WGNE would allow more rapid progress with a particular focus on representation of both global and regional km-scale model developers.

Progressing the many technical issues outlined above on computational speed/efficiency, data volumes, data analyses could benefit from a specific focus on Infrastructure in such a group. This has parallels with the WGCM Infrastructure panel (WIP), with slightly different issues and the two would need to work closely together.

Recommendation 2*: Propose a new WCRP WG with representation from global and regional km-scale model developers to be coordinated with WGCM and WGNE. DE LHA and ESMO co-chairs to agree on the best current home and lifetime of such a group. Discuss with WGCM and WGNE and especially the modeling groups on WGNE and WGCM the appropriate arrangements.*

The initial focus of a km-scale working group will be on building the scientific evidence for km-scale modeling in particular how convection at local scales feeds back onto the larger synoptic scales for both weather and climate. However the workshop also saw the need for a clear link to application of km-scale models for users (e.g. through the WCRP Regional Information for Society core project (RIfS))

Recommendation 3*: DE co-chairs to work with CORDEX and RIfS co-chairs to ensure strong engagement between the relevant groups.*

6. Future Activities

Recent large initiatives, both in Europe and in the US, are pushing and supporting the development of kilometer-scale simulations. With several groups now being able to conduct kilometer-scale simulations on the full Earth, as demonstrated through the DYAMOND intercomparison project, the community either developing or using such simulations is rapidly expanding and will continue to expand. As a downside, many meetings with a focus on high-resolution modeling have been organized, without much coordination, overloading everyone's calendar. Besides dedicated sessions at societal annual meetings (like AGU and EGU) and meetings of projects funding kilometer-scale modeling, we note the yearly convection-permitting climate modeling workshop, the PAN-GASS meeting, this meeting, the model hierarchies workshop, the yearly WGNE workshop on systematic errors in weather and climate models or the yearly DYAMOND workshop.

Recommendation 1: *Starting in 2024, work with the WCRP and ESMO to try to combine meetings in one main yearly one-week meeting for those efforts focused on or related to kilometer-scale modeling. Reserve specific days of that meeting for individual communities attending the meeting to meet separately.*

Kilometer-scale models are developed on the northern hemisphere reflecting the geographical distribution of exascale computing resources. At least within Europe and the U.S., there is a strong effort to not only make the data publicly available, but to entrain scientists from non-modeling institutes to use such data. This happens through the organization of summer schools and hackathons. Organizing international hackathons has three main advantages. First it forces modeling institutes to think about how to share the data, how to develop efficient workflow strategy and to communicate this. This has for instance leads to easy.gems (https://easy.gems.dkrz.de), a user-driven site for documenting ways to analyze kilometer-scale simulations. Second, it attracts young scientists to the field. Third, hackathons build upon specific cases (or questions or common model issues) that are investigated by a group of people. Those cases could be used as seeds for PIPs then proposed to the wider community.

Recommendation 2: *Organize a hackathon and tutorial, targeting PhD and PostDocs. Starting perhaps in 2024.*

As noted above, PIPs may be organized to foster the development and use of kilometer-scale simulations. The design of PIPs should take into consideration lessons learned from past intercomparison projects. First the DYAMOND intercomparison projects were very successful because it didn't have too many requirements on the modeling groups concerning experiment design and output requirements. Second, a bottom-up approach, as used in PAN-GASS with motivated individuals proposing a project that is motivated by their interests/findings, tends to work better than a strongly constrained structure, especially since different types of models will be used. Finally, in the past, intercomparison projects have either targeted regional modeling groups or global modeling groups. But at least concerning intercomparison projects on specific regions, those regions are also automatically simulated by global models.

Recommendation 3: *Provide support and space for individual PIPs to develop. Include output of global models when conducting intercomparison projects on specific regions. The process could start with a series of webinars on topics of interest to a sub-set of model groups, make sure they are 'diverse' with participation from different types of models, and see what organically grows.*

7. Recommendations

The recommendations above are complementary and overlapping, and we summarize them here. They provide a potential roadmap for the Digital Earth Lighthouse Activity to accelerate progress towards Digital Earths and to grow the community to be more diverse than it is now by expanding access and helping train new scientists from a broad range of locations.

7.1. Scientific Recommendations

- Modelers that currently work on developing novel km-scale models (global and regional) should engage with and learn from established weather and climate mesoscale model developers. The Lighthouse Activity should help form teams that bring these groups together.
- Key science issues for the atmosphere (the most developed area) include: The organization and intensity of deep convection at 1-4km, representing shallow convection at 4km-100m, extratropical storms. It is important that development efforts are coordinated with GEWEX GASS.
- Interesting work on km-scale oceans and sea ice is emerging. The appropriate scales to simulate these systems are different from the atmosphere. We recommend that the ocean and sea-ice communities engage with CLIVAR Ocean Model Development Panel and CLiC for process understanding.
- km-scale models could significantly improve hydrology simulations: for example, catchment-scale lateral flow of ground water and coupling to water fluxes at the surface have been shown to improve the representation of land-atmosphere coupling and surface climate. A path exists to engage with existing land modeling efforts (GEWEX GLASS and GHP), and Regional Hydroclimate Projects (RHPs) to improve the representation of hydrology in km-scale land models.
- Much of what global km-scale models are aiming for can be done or supported by regional models. Downscaling aspects of global km-scale modeling can be provided by or supported by regional models. The community should investigate, together, how better representing processes at km scales actually feeds back onto the larger scale circulation and must be treated globally to improve the simulation of climate & weather phenomena. In addition, the value of using global models to provide a baseline for regional (and regionally refined) km-scale models and their ability to help improve global models should be explored.

7.2. Technical Recommendations

- There are significant technical challenges for km-scale models, and interesting solutions are emerging. We encourage collaboration and sharing of techniques for (a) new architectures (like GPUs), (b) coupling infrastructure and even (c) ported code (such as shared model physics).

- The large data volumes drive a need to access and analyze km-scale model output at the location of the data. This provides a way to make such models broadly available and get more eyes on them for development. The community could discuss federating access to web-based development environments (facilitates cross model investigations & users from under-represented groups).
- The use of open-source analysis tools is rapidly improving the ability to use large data volumes and to share knowledge. Open source is not free: someone needs to develop and maintain it. The community should continue and sustain support for the development of open-source data analysis tools. Digital Earths can also help by making a list of available tools and encouraging collaborations, as well as by fostering development of new tools and standards that enable international collaborations, discovery etc., around the globe, by helping to federate data analysis centers.
- The community should continue to invest in the human workforce for model infrastructure to encourage the best minds wherever they are to contribute to development and analysis

7.3. Next Steps

- Digital Earths LHA should encourage cross-scale Process Intercomparison Projects (PIPs) around topics/regions/phenomena. PIPs should be 'diverse' with participation from the observational community and different types of models, and see what organically grows (nurtured by the WCRP). This can start with discussing some of the key science issues identified.
- The Digital Earths LHA should engage with WGCM and WGNE to develop a similar forum for km-scale models that fall between the groups. This should have representation from global and regional km-scale model developers and thus also requires DE to work with CORDEX and RIfS co-chairs to ensure strong engagement between the relevant groups.
.
- Work with the WCRP and ESMO to try to combine modeling meetings (starting 2024) in one main yearly one-week meeting for km-scale modeling. Reserve specific days of that meeting for individual communities attending the meeting to meet separately.
- Organize a hackathon and tutorial, targeting PhD and PostDocs, on a bi-yearly basis. Starting perhaps in 2024 (See meeting above). Coordinate with other regional/national efforts

Annex 1 - Agenda

Monday, 3 October

Moderator: Andreas Prein

0900-0915 Welcome and Logistics

0915-0945 ESMO, the Digital Earths Lighthouse activity and Workshop Goals - **Christian Jakob), Andrew Gettelman, Cath Senior**

0945-1030 Coupled k-scale modeling – Challenges and opportunities – **Cathy Hohenegger**

1030-1100 Coffee Break

1100-1145 Progress and challenges on making regional climate change simulations at km-scale - **Nikolina Ban**

1145-1230 Progress and challenges on high resolution Atmospheric modeling with NICAM **Daisuke Takasuka**

1330 Lunch

Moderator: Andrew Gettelman

1330-1415 **Contributed Talks** (12+3 min each)

- ECMWF Km-scale modeling effort for the development of a Digital Twin of the Earth - **Benoit Vanniere**
- Prototyping Convection-Permitting Global Weather and Sub-Seasonal Forecast with the NOAA Unified Forecast System - **Fanglin Yang**
- Global large eddy simulations and their collaboration with detailed observations based on vertical atmospheric motions - **Masaki Satoh**

1415-1430 **Breakout Sessions Introduction - Christian Jakob**

1430-1530 **Breakout Session 1**

1530-1600 Coffee Break

1600-1730 **Contributed Talks** (12+3 min each)

- K-Scale Project: Exploiting a global-to-regional seamless modeling strategy in the UK to advance research and applications across timescales - **Huw Lewis**
- The Navy Earth System Prediction System: Version 2 Developments - **William Crawford**
- Very high resolution coupled climate modeling with unstructured ocean model - **Nikolay Koldunov**
- The emergence of the mesoscale in Global Storm Resolving Models - **Pier Luigi Vidale**
- Using ARM Observations to Evaluate Simulated Mid-Latitude and Tropical MCSs Across the Grayzone of Convection - **Andreas Prein**
- Mean-state GCM biases are a predictor of precipitation biases in dynamical downscaling - **Stefan Rahimi**

1730-1900 Icebreaker

Tuesday, 4 October

Moderator: **Andrew Gettelman**

0900-0945 Towards the Predicted Ocean – Ideas from FIO models coupled with ocean surface waves - **Zhenya Song** (Virtual)

0945-1030 Sea ice at the flow size scale: Is it time for new modeling approaches? **Martin Losch** (Virtual)

1030-1100 Coffee Break

1100-1145 Challenges of high resolution for land modeling - **Martin Best**

1145-1230 **Contributed Talks (12+3 min each)**

- Ultra-high resolution atmosphere modeling in E3SM - **Aaron Donahue**
- Simulations With Earth Works - **David Randall**
- K-Scale: Assessing the added value of explicitly modeling convection within a very-large tropical domain compared with the nested LAM approach - **Richard Jones**

1230-1330 Lunch

1330-1500 **Breakout Session 2**

1500-1530 Short Plenary: Reflections and new questions from the breakout group discussions so far

1530-1600 Coffee Break

Moderator: **Cathy Hohenegger**

1600-1730 **Contributed Talks** (12+3 min each)

- Three-Dimensional Structure of Convectively Coupled Equatorial Waves in K-scale MPAS Aquaplanet Simulations – **Rosimar Rios-Berrios**
- Toward Process-Resolving Fully-Coupled Arctic Climate Modeling and Prediction - **Mark Seefeldt**
- Hydrometeorology and terrestrial hydrology across Alaska: a high-resolution coupled land-atmosphere modeling system - **Andrew Newman**
- Moving land models towards actionable science: A novel application and multi-objective optimization of the Community Terrestrial Systems Model across Alaska and the Yukon River Basin - **Yifan Cheng**
- A Hydroclimate Project over the United States, Integrating Ultra-High-Resolution Modeling and Observational Strategies to Create a Regional Digital Earth - **Timothy Schneider**
- Sub-seasonal Predictability of Rainfall over the Kingdom of Saudi Arabia - **Hari Prasad Dasari**

Wednesday, 5 October

Moderator: Andreas Prein

0700-0830 **Online breakout session 1**

0900-0945 Findings and insights from the DYAMOND project - **Tomoki Miyakawa**

0945-1030 Progress and challenges around high-resolution Earth System Prediction - **Steve Yeager**

1030-1100 Coffee Break

1100-1145 Modeling ice sheets at ultra-high resolution - **Helene Seroussi** (Virtual)

1145-1245 **Contributed Talks** (12+3 min each) Participants

- The CORDEX perspective on the ultra-high resolution modeling - **Silvina Solman** (Virtual)
- Towards an energy consistent coupling of the height-based Model for Prediction Across Scales Atmosphere (MPAS-A) dynamical core with the pressure-based Community Atmosphere Model (CAM) physics packages - **Peter Lauritzen**
- Data Assimilation for Climate Aneesh Subramanian RRTMGPxx: a portable radiation code for ultra-high-resolution modeling - **Benjamin Hillman**

1245-1345 Lunch

1345-1500 **Breakout Session 3**

1500-1530 Short Plenary: Reflections and new questions from the breakout group discussions so far

1530-1600 Coffee Break

Moderator: Christian Jakob

1600-1730 **Contributed talks** (12+3 min each)

- NASA GEOS-ECCO-MITgcm sub-10 kilometer coupled modeling, some early results and plans - **Chris Hill**
- Progress towards global cloud-permitting greenhouse warming simulations - **Sun-Seon Lee**
- Enhanced large-scale atmospheric circulation response to Gulf Stream SST anomalies in CAM6 simulations with 14-km-resolution regional refinement – **Robert Jnglin-Wills**
- Development of a global km-scale atmospheric model for centennial scale simulations - **Olivier Geoffroy**
- Analyses of added value for heavy rainfall and strong wind in convection-permitting climate simulations over Germany -**Michael Haller**
- Improving Earth System Models via Hierarchical System Development - **Michael Ek**

In parallel: Online Breakout Session 2

Thursday, 6 October

Moderator:	**Cath Senior**
0700-0830	Online breakout session 3
0900-0945	Computational challenges and opportunities for ultra-high resolution Modeling - **Oliver Fuhrer** (Virtual)
0945-1030	Data challenges for ultra-high resolution modeling - **Milan Klöwer** (Virtual)
1030-1100	Coffee Break
1100-1145	AI (f)or high-resolution models **? Laure Zanna** (Virtual)
1145-1215	**Contributed Talks** (12+3 min each)

- EarthWorks: The Computational
- Challenges of building an end-to-end,
- GPU-enabled km-Scale Modeling System **- Richard Loft**
- Addressing the Software Engineering
- Challenges within the EarthWorks Project -**Sheri Mickelson**

1215-1315	Lunch
1315-1500	**Breakout Session 4**
1530-1600	Coffee Break
1600-1700	**Breakout Group report preparations**

Friday, 7 October

0900-1030	Breakout group reports - **Chairs and Rapporteurs**
1030-1100	Coffee break
1100-1230	Workshop synthesis and wrap up -**Christian Jakob**, **Andrew Gettelman, Cath Senior**
1400-1700	Workshop report outlining session (By invitation)

Annex 2 - Acronyms

CliC	Climate and Cryosphere (WCRP)
CLIVAR	Climate and Ocean Variability, Predictability and Change (WCRP)
CMEC	Coordinated Model Evaluation Capabilities
CORDEX	Coordinated Regional Climate Downscaling Experiment
CPU	Climate Policy Uncertainty
DE LHA	Digital Earth Lighthouse Activity
DKRZ	German Climate Computing Center (Deutsches Klimarechenzentrum
DOE	Department of Energy
DYAMOND	DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains
ESM	Earth System Model
ESMO	Earth System Modeling and Observations (WCRP)
GCM	General Circulation Model
GEWEX	Global Energy and Water Exchanges (WCRP)
GASS	Global Atmospheric System Studies (GASS) Panel (GEWEX)
GHP	Greenhouse Gas Protocol
GLASS	Global Land-Atmosphere System Studies (GLASS) Panel (GEWEX)
GPUs	Graphic Processor Units
HPC	High Performance Computing
IOC-UNESCO	Intergovernmental Oceanographic Commission of UNESCO
ISC	International Science Council
LHA	Lighthouse Activity
MDTF	Model Diagnostics Task Force
MET	Model Evaluation Tools
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
PIPs	Process Intercomparison Project
RHPs	Regional Hydroclimate Projects
RIfS	Regional Information for Society (WCRP)
UNESCO	United Nations Educational, Scientific, and Cultural Organization (UN)
WCRP	World Climate Research Programme
WGCM	Working Group on Coupled Modeling (ESMO)
WGNE	Working Group on Numerical Experimentation
WMO	World Meteorological Organization

Annex 3 - References

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