Observational Needs for Regional Earth System Prediction

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1. Abstract

While the IPCC will continue to lead Earth System projections for global issues such as greenhouse gas levels and global temperature increase, high-resolution regional Earth System predictions will be crucial for adaptive management of resources. The focus here is on the day to day management of the Earth System which necessarily narrows the spatial scales down to the order of meters. Observational requirements for regional Earth System predictions must serve model development, validation, and skill assessment, and are distinct from the global needs with many overlaps. Technological innovations will have to meet the scientific demand to produce instruments from molecular probes to exploit the ever evolving genetic-level understanding, to nano-technology for *in situ* monitoring of the environment, to satellites that monitor the Earth System at ever increasing details. The observations must monitor the pulse of the planet routinely to prescribe appropriate actions for participatory decision-making to sustainably and adaptively manage the Earth System and avoid catastrophic domains of potential outcomes.

2. Introduction

The urgency of actions needed for avoiding the tipping points in the functioning of the Earth System is now becoming more and more obvious. The main objective here is to highlight the observational needs for regional Earth System predictions and projections, where such predictions and projections are assumed *a priori* as the main decision-making tools for sustainable management of the Earth System. Schellnhuber [1, 2] has led the efforts to provide the overarching definition for the Earth System as being comprised of the ecosphere and the anthroposphere. The ecosphere here is the geosphere-biosphere complex and includes the more well-known components such as the ocean, atmosphere, cryosphere, etc. along with the biosphere, whereas the anthroposphere puts man at the helm whose actions are responsible for the current evolution of events [3]. The observing systems of the future will have to consider the integral and interactive nature of the Earth System.

3. Modeling the Earth System

The concept of Earth System modeling and prediction clearly evolved from the pioneering efforts in weather and climate prediction [4, 5, 6]. Climate forecast has taken a complex trajectory compared to weather prediction since climate has many modes of variability such as the monsoons and the El Niño-Southern Oscillation (ENSO), with their own spatio-temporal scales and predictabilities [7, 8, 9]. The envelope of climate prediction continues to be pushed with new advances in decadal time-scale predictions [10]. The natural evolution of climate modeling towards Earth System models was motivated by some of the most fascinating Earth System feedbacks, such as the potential role of bio-physical feedbacks on droughts over Sahara [11], and more recently, feedbacks from marine biogeochemistry and ecosystems [12, 13]. A major development of relevance to Earth System prediction was the early dynamic downscaling to regional scales [14, 15]. Even as the spatial resolutions of the Earth System models improve, they are expected to remain at ~10 Km scales for many years if not decades. It is evident that adaptive management of resources demand Earth System information at the order of 1 Km or less and the only way to reach these goals is via dynamical and statistical downscaling. Dynamical downscaling has been applied to various Earth System issues such as human health, agriculture, and water resources [16, 17, 18].

4. Earth System Prediction

While there is no unique approach to an Earth System modeling framework, the International Geosphere Biosphere Project (IGBP), DIVERSITAS, the World Climate Research Program (WCRP), and the International Human Dimensions Program (IHDP) have created the new Earth System Science Partnership focused on energy and carbon cycles, food systems, water resources and human health as the most critical issues for human well-being (http://www.essp.org). Along these lines, the WCRP launched a new strategic framework for Coordinated Observation and Prediction of the Earth System (COPES), which lists the following as one of its aims; to facilitate analysis and prediction of Earth system variability and change for use in an increasing range of practical applications of direct relevance, benefit and value to society (http://wcrp.ipsl.jussieu.fr/). A realistic Earth System prediction must immediately focus on quantitative forecasts for decision-making, keeping in mind the holistic principles of sustainable management of the future trajectories of the Earth System evolution [2]. The enormity of the task is daunting considering the complexity of the interactions and feedbacks between humans and natural systems with the coupling dependent on space, time, and organizational structures [19].

5. Observing the Earth System

The most well-known mode of climate variability, viz., the El Niño-Southern Oscillation (ENSO), with its global reach offers an excellent analogy for Earth System interactions and a set of predictable targets with applications from agriculture to fisheries to human health [20]. As the gold-standard for successful climate prediction, ENSO also offers one of the best examples of the role of observations in improving process understanding and translating it into successful predictions. The Tropical Atmosphere Ocean array of moored buoys in the tropical Pacific combined with a number of satellites offered a clear demonstration of how well-coordinated and integrative observing systems do lead to routine, operational and usable climate and Earth System predictions [21]. Sustained observational arrays are since established in the tropical Atlantic and the Indian Oceans [22, 23].

The question of uncertainties in Earth System predictions at both short and long time-scales are crucial with the former requiring quantitative measures of skill in addition, whereas projections of future trajectories of the Earth System at longer time-scales will need to offer a more solid understanding of the known unknowns or irreducible uncertainties [2, 24, 25]. The need for sustained observations for continuously validating and assessing uncertainties in Earth System models require global and regional scale Earth System monitoring, the former being co-coordinated under the Global Earth Observing System of Systems (GEOSS) by the Group on Earth Observations (GEO; http://www.earthobservations.org/index.html). The stated vision for GEOSS is to realize a future wherein decisions and actions for the benefit of human kind are informed by coordinated, comprehensive and sustained Earth observations and information. The GEO plan defines nine societal benefit areas of disasters, health, energy, climate, water, weather, ecosystems, agriculture and biodiversity which is nearly comprehensive enough for the monitoring and nowcast-forecast vision of Earth System prediction models.

Hard decisions on management and policy will be made by experts in ‘soft’ sciences with the some of the softest information coming from the ‘hard’ sciences such as climate physics. Reliability of the climate and Earth System information can be enhanced and more quantifiable success can be achieved at regional scales and shorter lead-times (days to seasons) for high resolution regional Earth System models with the boundary conditions provided by the global Earth System models. The advantages of local and regional understanding of natural-human system interactions or the “place-based” Earth System predictions and decision-making are evident in a number of success stories [26]. The observations for regional Earth System prediction must begin to consider the monitoring of the natural system as it is constantly being kicked around by the human system. The Earth System does span the range from microbes to man and while one should be skeptical of models, it is imperative to remember that the situation is clearly not as rosy as modelers tend to believe but neither is it as hopeless as social scientists assume.

6. Observations for Regional Earth System Prediction

Instead of offering a shopping list of observations needed for regional Earth System prediction, it is worth considering an example of a practical application, viz., and Earth System prediction for human health, which is inseparable from the environment, water, and agriculture [27]. The traditional approach or the old paradigm of climate prediction for human health tends to find correlations between climatic variables and disease incidences, outbreaks, or indicators that are precursors to an outbreak [28]. However, climate change is expected to alter not only the environmental conditions but also population growth and movement which will clearly affect the transmission dynamics of any disease we can think of. The impacts of global change are clearly manifest in global indicators such as temperature and sea level rise but the impacts on humans are often associated with local changes in weather, ecology, hydrology, etc. Any observational system that purports to be a part of the prediction system for human health must capture the linkages from climate change to human health with the intermediate steps of microhabitat selection by the relevant microbes, transmission dynamics, socioeconomics, and adaptation measures. A succinct way to illustrate the potential range of observations for this one particular application can be illustrated by a schematic shown in Figure 1.

The ultimate reliability and success of a prediction system will depend on filling the gaps in mechanistic linkages from changes in climate to human health [27, 29]. Climatic variables such as temperature, precipitation, humidity, and the frequency of their occurrences via changes in extreme events will affect human health through associated changes in ecological responses and transmission dynamics with a whole host of socioeconomic and demographic factors exerting many complex modulating influences [29]. The role of the microbial contamination pathways can be exemplified by considering the example of human infections by toxic algal blooms in the marine or lacustrine environment. The algae or the microbes in these water-bodies exploit a microhabitat for their own competitive edge and not to genetically render themselves toxic or virulent to humans since infected persons do not necessarily return to the water-body to provide feedback to the microbes [30]. Thus, a climatic habitat index has severe limitations in forecasting the incidences or toxicity of such harmful algal blooms or pathogen levels without also considering the genetic, chemical, and biological factors, the microbial contamination pathways, human behavior and exposure. It is now known that microbes modify the ocean environment [31] and their influence cascades into ecosystem levels. This is an opportunity to drive technological innovation to not only use acoustic and other techniques to monitor the food webs and biomass but also include monitoring of DNA and RNA on observing platforms such as Argo or have miniaturized probes that go from genetics and genomics to ecology to human health and all other aspects of Earth System prediction [32, 33].

The levels of most of the harmful algae and pathogens are related to human activity such as agriculture, waste water treatments, and land use change [34, 35, 36]. Combined with the fact that coasts continue to get denser in human occupation and sea level continues to rise, the ocean observing systems can not be designed in isolation anymore. More importantly, these disparate observations have to be integrated into Earth System models, especially in the high resolution regional Earth System models [16, 27].

Technological innovations must drive creations of global digital libraries of air and water quality including pathogens and their genetic information and also instrumentation so that decision-makers on the ground carrying detectors such as hand-held bacterial counters or optimally distributed web of sensors that monitor environmental factors and bacterial levels can instantly validate the Earth System forecasts against the digital libraries [27, 30]. Novel advances in computational social science can capture transmission dynamics by using human movement and behavior [37, 38] which should drive macro-scale human ecological observations as a part of the Earth System monitoring. The prediction models must be effective decision-making tools for specific mitigation and adaptation measures and response training such that the evaluation of the impacts of policy and management decisions in modulating climate and regional weather changes, resource distributions, population movements and the associated cascades to human health must be a continuous feedback to the Earth System observation and prediction.

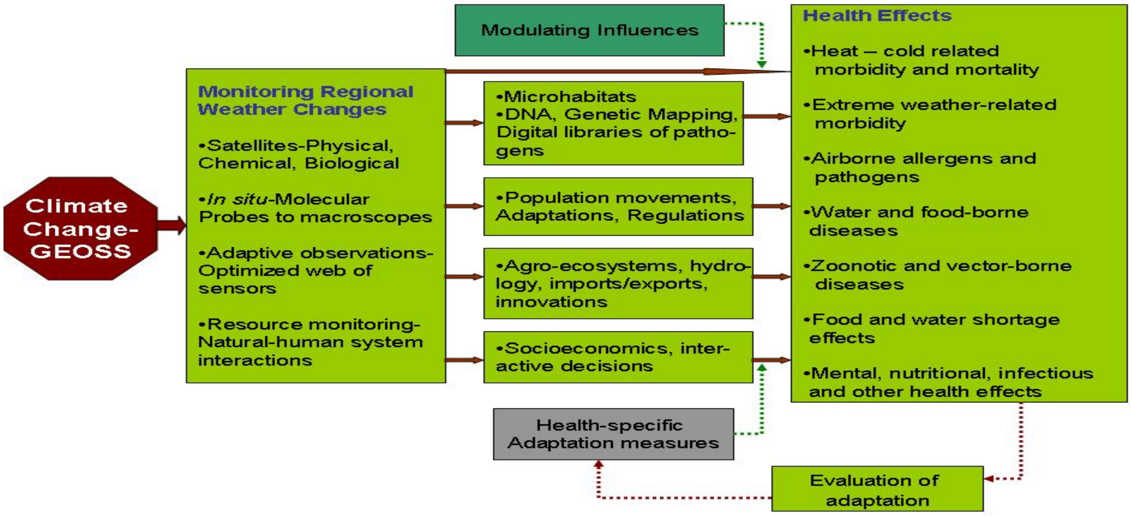

Figure 1: Schematic of linkages from climate change driver to human health to illustrate the need for interdisciplinary observations. A comprehensive and integrated approach to monitor the Earth System at regional and local scales will have to capture the natural-human system interactions to be able to provide effective decision-making tools based on regional Earth System predictions and projections for human health. Similar pathways exist for other Earth System components and resource managements.

7. Concluding Thoughts

The conceptual framework I am offering starts with the assumption that high resolution regional Earth System models offer the best hope for effective decision-making tools to adaptively manage the Earth System under climate change pressures. This presents a monumental challenge but an unprecedented opportunity to develop integrated Earth System observation strategies and drive technological innovation. I am further advocating that the global Earth System observational needs which are being effectively coordinated under GEOSS, will need to be complemented by regional Earth System monitoring. Figure 2 depicts it as a drive towards miniaturization of instruments needed to capture the details at the microbial level which have always been important but now will need to be resolved to understand the consequences of climate change on microbial dynamics and their feedback to the natural-human system interactions. In addition to the traditional observational platforms, observations in more and more details with smaller and smaller instruments will play a major role and they will need to observe not just the physical, chemical, and biological parameters and processes but also human ecology.

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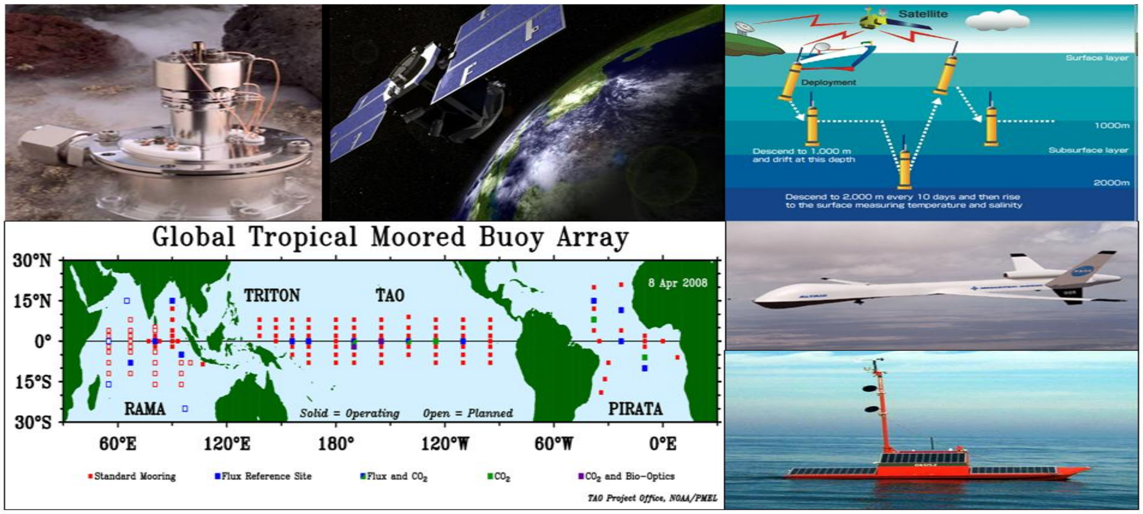

Figure 2: Observational systems for regional Earth System prediction and monitoring will obviously rely on the traditional platforms such as satellites, moored and drifting buoys, unmanned aerial vehicles, flux towers, etc. New innovations will most likely involve miniaturized detectors that will not only monitor environmental variables in the open and indoor spaces but also record genetic level information to facilitate understanding, modeling, and prediction of Earth System interactions from microbes to man. Top left corner shows a 4 inch tall mass spectrometer as an example of miniaturization (**http://aemc.jpl.nasa.gov/activities/mms.cfm).**

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