Observational Needs for Sustainable Coastal Prediction and Management

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Abstract

A number of successful coastal physical observing systems exist around the globe even though sustained ecosystem and biogeochemical observations are not as common yet. The need for considering the natural-human systems as interacting, integrative part of the Earth System is crucial for the day-to-day, sustainable management of the planet and this can only be done in a regional Earth System context. 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 producing effective decision-making tools for adaptive management of resources. The observational needs for global governance are being coordinated under GEOSS. Observational requirements for regional Earth System predictions and projections must serve model development, validation, and skill assessment, and are distinct from the global needs even though there are 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 in open and confined spaces, to satellites that monitor the Earth System at ever increasing details. The process understanding of the Earth System at the micro scale can be translated into predictive understanding and skillful predictions for sustainable management by merging these observations with Earth System models to go from global scale predictions and projections to regional environmental manifestations and mechanistic depiction of human interactions with the Earth System and exploitation of its resources. The observations in this context are akin to taking the pulse of the planet routinely to prescribe appropriate actions for participatory decision-making for sustainable and adaptive management of the Earth System and to avoid catastrophic domains of potential outcomes.

1. 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 (Lovelock, 2009, 1). 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. This is especially so in the context of coastal zones since ever increasing migrations to the coastal zone are having unique and unprecedented impacts on the Earth System. Prediction in this context carries a closer correspondence to reality than projection with an intrinsically larger uncertainty in the latter. I will focus on regional Earth System prediction keeping in mind that coastal zones are but a specific application of this concept. I will thus use the sustainable coastal management and adaptive management of a regional Earth System interchangeably.

A large number of coastal observing systems exist (see examples for the U.S. at http://www.csc.noaa.gov/cots/ and http://www.usnfra.org/) and despite the growing realization that monitoring more and more physical, biological, and chemical parameters is crucial, a more holistic approach is needed to consider the natural-human systems as continuously interacting components of the Earth System that are defining the future evolution of the Earth System itself and the time for reliable decision-making tools for sustainable management and for avoiding catastrophic regimes or tipping points in the future is upon the global human (Schellnhuber, 1998; Rial et al., 2004, 2,3). The main objective of this chapter is to provide the Earth System perspective for sustainable management of the coastal zones with a focus on the observational needs for delivering usable and skillful regional Earth System predictions and projections for decision-making. I am clearly starting with an *a priori* assumption that regional Earth System predictions and projections have the best potential for offering a decision-making tool under uncertainty (Murtugudde, 2009, 4).

1.1 Defining the Earth System

Schellnhuber (Schellnhuber, 1998; Schellnhuber, 1999, 2,5) 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 from where he appears to be watching the consequences of his actions weighing the consequences and corrective actions (Murtugudde, 2009, 4). The comprehensive piping diagram of the Earth System, the so-called Bretherton diagram (Schellnhuber, 1999, 5), illustrates the enormous range of spatio-temporal scales of interactive components we must deal with but this should also serve as the roadmap for integrated Earth System observations. This is clearly recognized in coordinating the global efforts under the Global Earth Observing System of Systems (GEOSS) which I will return to later. The critical new argument I would like to make is that future observational systems must be built on the interactive nature of the ecosphere and the anthroposphere and also must recognize that sustainable management will require that we do not forget the distinction between the global governance issues and the ‘place-based’ specificity of various regions, especially the coastal domains (Mitchell and Romero Lankao, 2003, 6). It is thus the interdisciplinary and process observations in addition to observing characteristic parameters or variables of the system (e.g., temperature, humidity, carbon, productivity, etc.) and the global and regional scales that I would like to emphasize here.

1.2 What is Sustainability?

Intuitively, sustainability simply implies the ability of one generation to use the resources without jeopardizing the ability of the future generations to access the same resources (Clark et al., 2003 7), while a mathematical form would state that the local rate of change for all the resources by all organisms be zero (Falkowski and Tchernov, 2003 8). The literature is quite vast on sustainability in various contexts and the need for institutional structures required to address the related research and practical issues including the intrinsically multi-disciplinary nature of the very concept (Gallopin, 2003, 9). Sustainability is essentially adaptive management with participatory decision making and learning-by-doing in the context of regional or coastal management (Gallopin, 2003; Kinzig et al., 2003; Murtugudde, 2009 4, 9, and 10).

Global governance issues under climate change are a major focus of the IPCC process but the basic issue of sustainable management of the Earth System offers two distinct scales of human control of the Earth System, viz., regional and global. Observational needs for sustainable management then must consider human actions and responses also at these scales, especially in the evolving coastal regions under multiple-stressors such as population growth, land use change, and eutrophication (Committee on Earth-Atmosphere Interactions, 2007 11). Schellnhuber (1998, 2) offers a few paradigms for such a control, at least to avoid the catastrophic domains where human existence is possible but subsistence will be miserable. He does offer a prioritized list to achieve sustainable development, as optimization (achieving the best Earth System performance), stabilization (achieve a desirable Earth System state), and pessimization (simply manage to avoid the worst Earth System states). The caveat of course is that putting these paradigms into operation via the Earth System Models is highly non-trivial but the task of avoiding catastrophes can not be abandoned (Kinzig et al, 2003; Committee on Earth-Atmosphere Interactions, 2007; Lovelock, 2009 1, 10, 11). As monumental a task as it is to provide useful and usable Earth System predictions with validation, uncertainties, and skill assessment, not attempting to build viable decision-making tools would be criminally negligent of the global human. Hence, it is imperative for us to consider the observational systems that will make this feasible and avoid overwhelming nature (Steffen et al., 2007 12).

1.3 Modeling the Earth System

The concept of Earth System modeling and prediction clearly evolved from the pioneering efforts in weather and climate prediction (Richardson, 1922; Phillips 1960; Nimias, 1968 13, 14, and 15). 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 (Kelly, 1979; Charney and Shukla, 1981; Cane et al., 1986 16, 17, and 18). The envelope of climate prediction continues to be pushed with new advances in decadal time-scale predictions (Keenlyside et al., 2008 19). 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 (Charney et al., 1975 20), and more recently, feedbacks from marine biogeochemistry and ecosystems (Ballabrera-Poy et al., 2007a; Huntingford et al., 2008 21, 22). Another major new direction of development of relevance to Earth System prediction was the early dynamic downscaling to regional scales (Dickinson et al., 1989; Giorgi and Bates, 1989 23, 24). Even as the spatial resolutions of the Earth System models improve with each IPCC assessment, they are expected to remain at ~10 Km scales for many years if not decades. It is evident that adaptive management of resources, especially coastal management issues, 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 through regional climate modeling has now been applied to various Earth System issues such as human health, agriculture, and water resources (Graham et al., 2001; Mearns et al., 2003; Giorgi and Diffenbaugh, 2008; 25, 26, and 27). The Earth System is indeed a system of systems and the regional specificity of the ecosphere and the anthroposphere must be seen as an integrated global Earth System with nested regional Earth Systems with their own idiosyncrasies. Coastal zones offer a unique set of human-nature interactions where the attraction of their services in terms of natural beauty, terrestrial and marine ecosystems, and so on, are the very reason for the stampede of new migrations and the uniqueness of the interactions between man and nature. In terms of observational challenges also, the coastal zones are unique for both remote and *in situ* techniques but also offer opportunities for driving technological innovations (Christian et al., 2006 28).

1.4 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 a 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/). Any skillful Earth System prediction must be reliably useful for decision-making, keeping in mind the holistic principles of sustainable management of the future trajectories of the Earth System evolution (Schellnhuber, 1998 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 (Liu et al., 2007 29). Observing these feedbacks themselves is very crucial for sustainable coastal management.

1.5 Observing the Earth System for sustainable management

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 (McPhaden et al., 2006 30). 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 Ocean Global Atmosphere-Tropical Atmosphere Ocean (TOGA-TAO) 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 (McPhaden et al., 1998 31). Sustained observational arrays are since established in the tropical Atlantic and the Indian Oceans (Bourles et al., 2008; McPhaden et al., 2009 32, 33).

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 (Schellnhuber, 1998; Cox and Nakicenovic, 2003; Biermann 2007; Dessai et al., 2009 2, 34, 35, 36). The need for sustained observations for continuously validating and assessing uncertainties in our Earth System models will need global and regional scale Earth System monitoring such as the Global Earth Observing System of Systems (GEOSS), being co-coordinated 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 Earth System 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 (Mitchell and Romero Lankao, 2003 37). 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), in 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 (Mitchell and Romero Lankao, 2003 37). 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.

2. Observations for sustainable coastal management

Instead of offering a shopping list of observations and data management-distribution strategies needed for sustainable coastal management, I will focus on an example of a practical application, viz., and regional Earth System prediction for human health, which is inseparable from the environment, water, and agriculture (Bell et al., 1993 38). This is an ideal example for considering the coastal zones since no other regions experience closer interactions between these three components of the Earth System. Even though the environmental connection to human health has been known since the time of Hippocrates (Franco and Williams, 2000 39), remarkably few mechanistic models have been developed to exploit weather and climate predictions for human health applications.

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 (Kelly-Hope and Thompson, 2008 40). 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 adapt to the advances in and needs for research and also to human feedbacks and modulating influences. 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. Note that I have deliberately mixed the observational platforms with the drivers (climate change, regional weather changes), and with processes (transmission), impacts (human health), responses (adaptation) and feedbacks (modulating influences). The motivation is to highlight again the integral nature of natural-human system and the need to avoid disciplinary boundaries in developing our observing systems.

2.1 Observing the natural-human system

The connections in Figure 1 are self-evident if one recognizes that 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 (McMitchael et al., 2003 41). 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 (Stewart et al., 2008 42). 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 (Stewart et al., 2008 42). Thus, using 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. Figure 1 is modified from (Murtugudde, 2009 4) to demonstrate that climate change indicators at global and regional scales are the targets of GEOSS and many of the local meteorological and related networks monitor the regional weather manifestations of climate change.

The concept I am emphasizing here is the need to think beyond the traditional platforms for observational instruments such as satellites, *in situ* moored, drifting, and robotic buoys, flux towers, volunteer ships, airborne manned and unmanned vehicles, and so on. These platforms will obviously continue to play foundational roles in our observational needs and will evolve to be more efficient, more accurate, faster, cheaper, and better. The data assimilative approaches to observational system simulation experiments (OSSEs), which have thus far been mainly disciplinary (Ballabrera-Pay et al., 2007b 43), have served well for optimizing observational systems and reducing or building in redundancies. The artificial dichotomy of disciplinary boundaries has been a handicap in sustainable coastal management (Lubchenco, 1998 44) and must begin to be shed even in the context of existing interdisciplinary observations (Dickey, 2003 45) to consider Earth System OSSEs. Defining the indicators to monitor the impact of natural-human interactions will thus be integral aspects of the observational system designs and the OSSEs will be ongoing exercises to attain adaptability in the observing system (Christian and Mazzilli, 2007 46). The latter is especially important to observe the feedback of the human system to the evolving natural system (Hibbard, 2007 47). The coastal observational needs in terms of the need to integrate the marine observations with the terrestrial and freshwater observations is already recognized (Christian, 2003 48) but we still have a long way to go in making it a monitoring of the natural-human system.

2.2 Observing the coast from microbes to man

It is now known that microbes modify the ocean environment (Rohwer and Thurber, 2009 49) and their influence cascades into ecosystem levels. Such a concept is not as obvious on land but it is known that the abundance and diversity of microbes in soil are just as large if not larger than the aquatic environments (Srinivasiah et al., 2008 50) and certain symbiont cyanobacteria in the terrestrial and marine biosphere produce neurotoxins (Cox et al., 2005 51). In the meantime, the science and technology of sequencing genetic make-up of living organisms and detecting them continue to grow by leaps and bounds (DeLong, 2009 52), including barcoding of floral and faunal DNA (Jakupciak and Colwell, 2009 53). This is an opportunity to drive technological innovation to not only using 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 (Janzen D. H. et al. 2009; Bowler et al., 2009 54, 55).

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 (Diaz and Rosenberg, 2008; Patz et al., 2004 56, 57). 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. What shape would such a regional Earth System prediction system take? As I stated earlier, there is no unique framework and regional specificity is crucial. One example of such a system is underway at the University of Maryland and I briefly describe it here, purely to provide the context for this entire discussion.

2.3 A prototype Regional Earth System Prediction for an Estuary

A nascent but quite a comprehensive effort on regional Earth System prediction is underway within the Earth System Science Interdisciplinary Center (http://essic.umd.edu) of the University of Maryland with dynamic downscaling of the seasonal to interannual climate forecasts and IPCC projections for the Chesapeake watershed with a regional atmosphere, watershed, and a regional ocean model. Routine forecasts of the Chesapeake airshed, watershed, and the estuary include seasonal predictions and decadal projections of such linked products as pathogens, harmful algal blooms, sea nettles, water and air quality, fisheries, dissolved oxygen, inundation and storm-surge, and so on. A prototype decision-making tool has been developed where the user can change the land use types (urban, wetlands, different crops, forests, livable habitat and smart growth concepts) and choose the time period of interest from the past, present, or the future to compute the nutrient loading in the Chesapeake Bay, dissolved oxygen levels, harmful algal blooms, sea nettles, fisheries habitat suitability, etc. The tool is being made fully 3-dimensional with the Google Earth and Google Ocean concepts to provide an integrated assessment and education tool for terrestrial and marine ecosystems and other resources. A unique, new approach is being attempted where specific users are being directly given the Earth System forecasts and the flow of information in their decision-making process is being monitored to obtain quantitative feedbacks. A larger context for this prototype effort is provided by a program called Climate Information: Responding to User Needs (CIRUN) which organizes workshops of users varying from agricultural to insurance sectors to national security (http://climateneeds.umd.edu), as a pioneering effort to drive a demand-pull for specific Earth System information instead of the old paradigm of supply-push where a vast number of model products are placed on the loading-dock hoping for users to pick them up, simply because modelers think they are useful (Murtugudde, 2009 4). The early returns on the use of our sea nettle forecasts by the recreational boaters are quite encouraging but we eagerly await the feedback from the watermen, river keepers, forest conservators, etc.

While most of the observational input into this prediction system has been for empirical modeling, validation, skill assessment and some optimization of parameters, efforts are underway to carry out physical and biogeochemical OSSEs with the ensemble transform Kalman filter techniques (Takemasa and Aranami, 2006 58). Natural-human system interactions are being considered in the health sphere by gathering environmental and pollution data along with mortality data to develop health indicators and more importantly, computational social science approaches to understand transmission dynamics of infectious diseases and environmental contributions (Ferguson, 2007; Lazer et al., 2009 59, 60). The motivation is to drive a health observation system to generate personalized, predictive, and pre-emptive Earth System information for human health. While the system is being built for the Chesapeake watershed, it is a prototype that can be implanted for any part of the world.

2.4 Model-data synthesis for sustainable management

It is the day-to-day management of the regional Earth System that will be crucial for global sustainability since global aggregation, which is meaningful for certain indicators such as greenhouse gas concentrations and global temperature increase, but most environmental stressors are local such as land cover change and the impacts also tend to be local such as human health (Patz et al., 2005 61). The ongoing saga of the swine flu clearly illustrates the natural-human system interactions in its full glory and the opportunity out of this potential disaster from the regional Earth System prediction is that there have been giant strides in improving process understanding of the natural-human system behavior (Vespignani, 2009; Cho, 2009 62, 63). We thus have a much better knowledge of what observations we need to capture these interactions.

The onus is on us to drive technological innovations for 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 (Stewart et al., 2008; DeLong, 2009; Jakupciak and Colwell, 2009 42, 52, 53). As stated above, novel advances in computational social science can capture transmission dynamics by using human movement and behavior 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 change, regional weather changes, resource distributions and allocations, population growth and movements and the associated cascades to human health must be a continuous feedback to the Earth System observation and prediction.

Much gets said about the need to effectively communicate the uncertainties in predictions (Allen et al., 2000; Stainforth et al., 2007 64, 65), but it is very crucial to ensure that data quality across disciplines is clearly understood and communicated in the sustainable management and regional Earth System prediction context (Costanza, 2007 66). The 'degree of goodness' as defined in (Costanza, 2007 66) will clearly not be uniform across disciplines in going from microbes to man and it is absolutely critical to establish the impacts of these differences on the information being extracted from these data and the synthesis of these data into models.

3. Concluding Thoughts

The conceptual framework I am offering is simply an extension of existing ideas. I am assuming 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 and these are also the best tools for sustainable coastal management. 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 but regional Earth System prediction will require additional regional specificities. 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 and its 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 and the natural-human system interactions. They will have to fully exploit these disparate data from every component of the Earth System, to reduce uncertainties and improve skills of our decision-making tools based on regional Earth System predictions.

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Figure Captions

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 behavior and their 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. Note that observations are not only necessary for physical, chemical, and biological parameters but also for processes and natural-human system interactions.

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 and so on. 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).**

Figure 1:

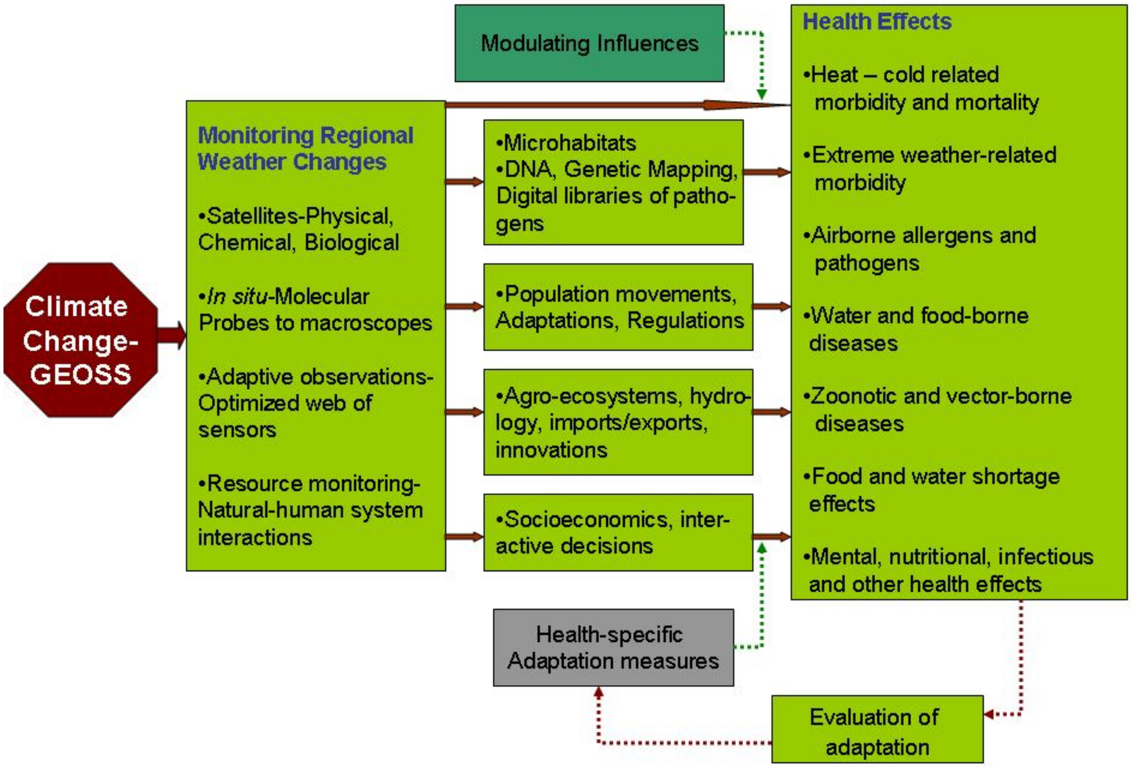
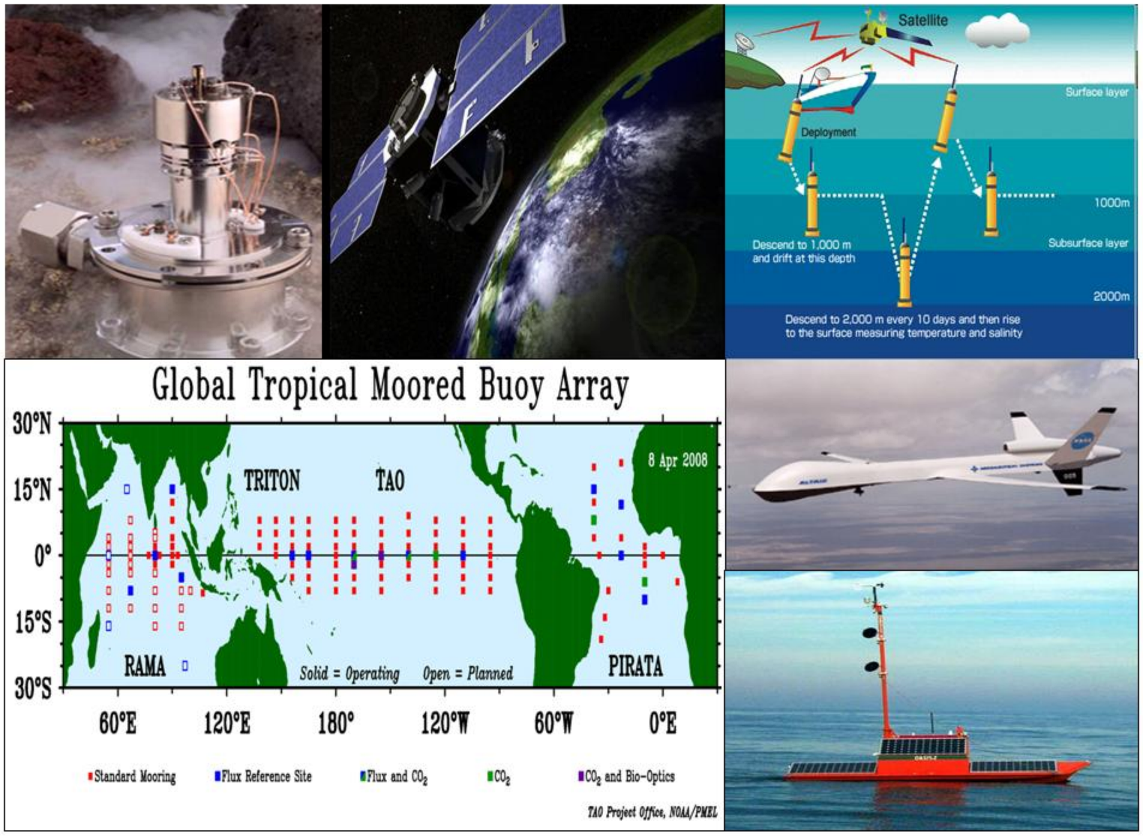

Climate Change-GEOSS
Modulating Influences
Monitoring Regional Weather Changes
•Satellites-Physical, Chemical, Biological
•*In situ*-Molecular Probes to macroscopes
•Adaptive observations-Optimized web of sensors
•Resource monitoring-Natural-human system interactions
•Microhabitats
•DNA, Genetic Mapping, Digital libraries of pathogens
•Population movements, Adaptations, Regulations
•Agro-ecosystems, hydrology, imports/exports, innovations
•Socioeconomics, interactive decisions
Health Effects
•Heat – cold related morbidity and mortality
•Extreme weather-related morbidity
•Airborne allergens and pathogens
•Water and food-borne diseases
•Zoonotic and vector-borne diseases
•Food and water shortage effects
•Mental, nutritional, infectious and other health effects
Health-specific Adaptation measures
Evaluation of adaptation

Figure 2:


Satellite
Surface layer
Deployment
1000m
Descend to 1,000 m and drift at this depth
Subsurface layer
2000m
Descend to 2,000 m every 10 days and then rise to the surface measuring temperature and salinity
Global Tropical Moored Buoy Array
30°N
15°N
0°
15°S
30°S
60°E
120°E
180°
120°W
60°W
0°E
TRITON
TAO
RAMA
PIRATA
8 Apr 2008
Solid = Operating
Open = Planned
Standard Mooring
Flux Reference Site
Flux and CO2
CO2
CO2 and Bio-Optics
TAO Project Office, NOAA/PMEL