

ADDRESSING THE COMPLEXITY OF THE EARTH SYSTEM

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Integration of physical, biogeochemical, and societal processes would accelerate advances in Earth system prediction.

Earth system science addresses natural and human-driven processes affecting the evolution and ultimately the habitability of the planet. We must recognize that the Earth system encompasses interactions among the atmosphere, ocean, ice, land, biochemistry, and humanity. Humanity has advertently and inadvertently perturbed the entire system, with both positive and negative consequences. Thus, the accelerated development of a monitoring and prediction system that integrates physical, biogeochemical, and societal processes is essential if we are to provide quantitative information that can initiate and guide the mitigation of, and adaptation to, future changes in the Earth system. This paper illustrates the crucial role of the biosphere in a complex, integrated Earth system prediction framework. As noted in Shapiro et al. (2010), effectively predicting the evolution of the full Earth

system in a way that embraces the next frontier of socioeconomic and environmental applications demands international commitment and coordination.

THE ROLE OF THE BIOSPHERE. The biosphere is the “life zone” of Earth system. It is composed of living beings and their multi-way interaction with the geophysical and biological elements within the lithosphere (solid Earth), hydrosphere, and atmosphere. Until recently, the biosphere was primarily studied within the context of its response to geophysical influences, with less attention to the feedback of biospheric processes on weather and climate. However, this is beginning to change with new components of land cover, including urban areas (e.g., Oleson et al. 2008) and fire (e.g., Golding and Betts 2008), being implemented in the global models.

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Many active biogeochemical feedback systems exhibit highly nonlinear behavior. Changes of system dynamics can be initiated by both natural and human activities. These changes can be abrupt “tipping points” between significantly differing states of the Earth system that society might not want to transgress (Steffen et al. 2003; Lenton et al. 2008; Rockström et al. 2009). The biosphere is also intertwined in the geochemical cycling that can contribute to natural and anthropogenic contributions to climate variability and change. The examples below illustrate this for anthropogenic changes in global nitrogen and ocean carbon cycles.

THE ROLE OF NATURAL AND REACTIVE

NITROGEN. As recently as the 1960s, the production of reactive nitrogen (N_r) was primarily controlled by natural processes (lightning, microbial activity). Today, the amount of N_r in the biosphere is overwhelmingly produced by anthropogenic activities, primarily from the industrial production of fertilizer and combustion of fossil fuels (Galloway et al. 2008). The human production of N_r fertilizers has massively increased food production. By contrast, the shortage of nitrogen-based fertilizer in many developing countries has contributed to food insecurity, the degradation of land fertility, and societal conflicts. Excess anthropogenic N_r interacts with the hydrologic and other biogeochemical cycles and ultimately can contribute to direct effects on climate (e.g., through increased production of the greenhouse gas N_2O), indirect effects on climate (e.g., through the carbon cycle), and environmental and human health (e.g., by altering water and air quality). There is still much to be understood about the magnitude of these effects. The transformation of N_r to, for example, nitric acid or NO_x contributes to total greenhouse gases and thereby increases atmospheric radiative forcing. Furthermore, stratospheric ozone declines from reactions with N_2O (Solomon et al. 2007). Both natural and human-produced N_r contribute to the global production of NO_x , with fossil fuels and other human activities contributing over twice (33 TgN yr^{-1})¹ that of natural ($8\text{--}13 \text{ TgN yr}^{-1}$) sources (Denman et al. 2007).

There are strong linkages between the N and C cycles; for example, increased N_r can increase CO_2 uptake in Northern Hemisphere forests (Magnani et al. 2007). Furthermore, excess N_r contributes to the loss of terrestrial biodiversity (Stevens et al. 2004; Bobbink et al. 2010) and a variety of pollution

problems including aquatic eutrophication (Galloway et al. 2008; Vitousek et al. 2009; Schlesinger 2009). Atmospheric transport of anthropogenic nitrogen accounts for approximately one-third of the open ocean’s external (non-recycled) nitrogen supply and up to 3% percent of the annual new marine biological production (Duce et al. 2008). We acknowledge that inland seas, lakes, rivers, streams, and ponds are likely to have some impact on nitrogen movement across landscapes, but there has been little research to date that addresses the continental or global movement of nitrogen as controlled by these processes. The interactive effect of disturbances in the land and ocean nitrogen cycle on regional and global climate through perturbations in the carbon cycle are in the early stages of implementation in Earth system models (ESMs) (Thornton et al. 2009). To highlight the importance of nitrogen, and its relationship to carbon, Jain et al. (2009) indicated that the simulated effects of nitrogen limitation influenced the spatial distribution of the estimated sources and sinks of CO_2 , and Thomas et al. (2010) estimated that nitrogen deposition could increase global tree carbon storage by $0.31 \text{ Pg carbon yr}^{-1}$.

A major priority is to optimize the use of nitrogen to promote food security while at the same time minimizing its harmful environmental and climate impacts (see www.initrogen.org). ESMs should incorporate the complexity of the effects and feedbacks of disturbances in the nitrogen cycle on land, in the atmosphere, and in marine processes, including impacts on climate.

CARBON DIOXIDE INTERACTIONS IN THE ATMOSPHERE–OCEAN SYSTEM.

The observed increase in atmospheric carbon dioxide (CO_2) concentrations accounts for only 55% of the CO_2 released by human activity since 1959. The remaining atmospheric CO_2 is taken up by plants on land and by the oceans (Denman et al. 2007). The dissolution of atmospheric carbon dioxide is primarily controlled by temperature and salinity in surface ocean waters. As CO_2 dissolves in surface waters, pH is decreased, or ocean acidification can occur. If pH decreases sufficiently, aragonite (a meta-stable form of calcium carbonate produced by marine organisms to make their solid shells) becomes soluble. Parts of the southern oceans could become corrosive to aragonite by as early as 2050–60 (Orr et al. 2005). These ecosystem dynamics are in the early phases of implementation in global models (Le Quéré et al. 2009). Model development that captures such carbon cycle dynamics can provide insight into, for example,

¹ TgN refers to 1012 grams, equivalent to 106 tons of nitrogen.

how the functionality of coral reefs and other marine ecosystems might be accelerated or degraded (e.g., Guinotte et al. 2003).

Ocean biology (i.e., ocean color via phytoplankton) affects the depth of penetrating solar radiation in the ocean, which in turn influences the sea-surface temperature, which impacts the ocean–atmosphere coupling and, for example, the amplitude and phasing of El Niño–Southern Oscillation (ENSO) (Timmermann and Jin 2002). For example, global ocean model experiments, using an ocean general circulation model coupled to an ocean biogeochemistry model (Manizza et al. 2005), suggest that at mid and high latitudes, the trapping of solar heat flux by phytoplankton pigments warms surface temperatures by up to 1.5°C and reduces penetrative heat flux, thereby cooling subsurface temperatures by up to 0.5°C in spring and summer. Furthermore, at high latitudes, model results suggest that the sea-ice cover is reduced by up to 6% in summer because of the radiative warming of the sea surface temperature by phytoplankton (Manizza et al. 2005).

BIOSPHERE–CLIMATE INTERACTIONS IN THE AMAZON. There is paleoclimatic evidence of savanna replacing parts of the forest in the Holocene (Mayle and Power 2008), providing a legacy of change for these biomes. The ecosystem of the Amazon basin plays an important role in regional-to-planetary interactions with the weather and climate. Model studies have tested the hypothesis that two stable ecosystem states can emerge in the Amazon basin: rainforest or savanna (Oyama and Nobre 2003; Salazar et al. 2007). Today’s energy and water balance within the Amazon basin is driven by rainforest vegetation, albedo, and evapotranspiration. Shapiro et al. (2010) discuss Saharan aerosol natural fertilization of the Amazon rainforest as one control of the energy balance described here. The external forcing of climate change by deforestation (Sampaio et al. 2007) could transition the stable forest into another stable state of forests and savanna (Nobre and Borma 2009), radically altering the energy balance of the region. Surface energy and hydrology balances modulate the strength and location of organized convective cloud systems over the Amazon rainforest, which in turn affect the strength and location of the intertropical convergence zone (ITCZ). The associated changes in the tropical convective heating and momentum flux modulate the intensity and location of the Northern and Southern Hemispheric subtropical jet stream, affecting midlatitude and polar weather patterns (Brunet et al. 2010).

Climate model simulations show that changes in the Amazon basin biosphere affect surface temperature and precipitation as far away as North America, Africa, and the Himalayas and, in turn, influence the African and Asian monsoons (Nobre et al. 1991; Gedney and Valdes 2000; Werth and Avissar 2002; Nobre et al. 2009). In this way, changes in one region can reverberate throughout the entire Earth system.

EARTH SYSTEM MODELS. Current prediction systems should be extended to include impacts on society, specifically on water, food, health, and air quality. This can be done in the next decade by using existing (or improved) models that deal with the interfaces between climate and water, climate and agriculture (crop), climate and food, climate and energy, and climate and diseases. To address issues beyond the physical weather/climate system, the community is developing ESMs ranging from fully coupled atmosphere–ocean general circulation models (AOGCMs) to simplified ESMs of intermediate complexity (EMICs) to explore numerical simulations of the coupled biophysical, biogeochemical (e.g., carbon cycle), and climate system (Randall et al. 2007). These models include climate interactions for ocean and land carbon cycle dynamics, with work underway to implement additional processes (e.g., marine ecosystem, terrestrial biogeography, urban land cover; Oleson et al. 2008) and surface hydrology and socioeconomic sectors such as agriculture, industry, energy, and health. Data assimilation for *coupled* ESMs that include carbon cycle dynamics—a key research challenge—will also provide a predictive context for assessing the value of observations and identifying and optimizing the observation systems required for sustained monitoring and improved prediction from days to decades (e.g., Sacks et al. 2006; Shapiro et al. 2010; Brunet et al. 2010). Another key challenge for next-generation ESMs is to incorporate human interactions such as socioeconomics and land use. To date, no fully coupled models exist.

Such a unified ESM system (Fig. 1) could play a key role in assessing risks and identifying potential hazards and opportunities for society.

A complex Earth system model couples the physical climate system with biogeochemical cycles (e.g., carbon cycle, atmospheric greenhouse gases and chemistry, aerosol microphysics, ecosystem dynamics, and hydrology, including anthropogenic influences). It encompasses key physical, biological, and chemical interactions. The introduction of such complex processes is a challenge that can only be met if key processes are integrated with observations and

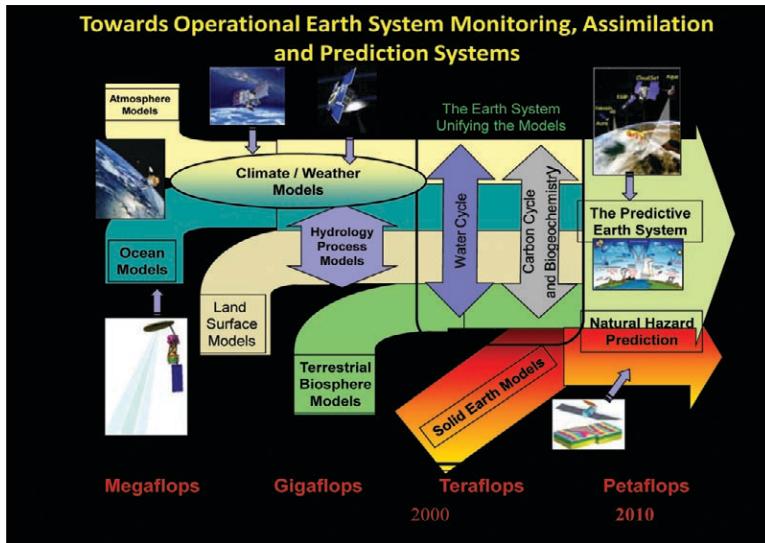


FIG. 1. A conceptualization of the diverse elements of a complex Earth system analysis and prediction system, and the computational requirement for assimilating observations and forecasting the atmosphere, ocean, and land. Investments in high-capacity computers are crucial to combine the diverse interacting components at high spatial resolution and so provide a dynamic view of the complex evolution of the Earth system. Linking ESM to hazard prediction models will provide insight into how climate change (e.g., sea level rise) might interact with other aspects of the geophysical system (Shukla et al. 2010).

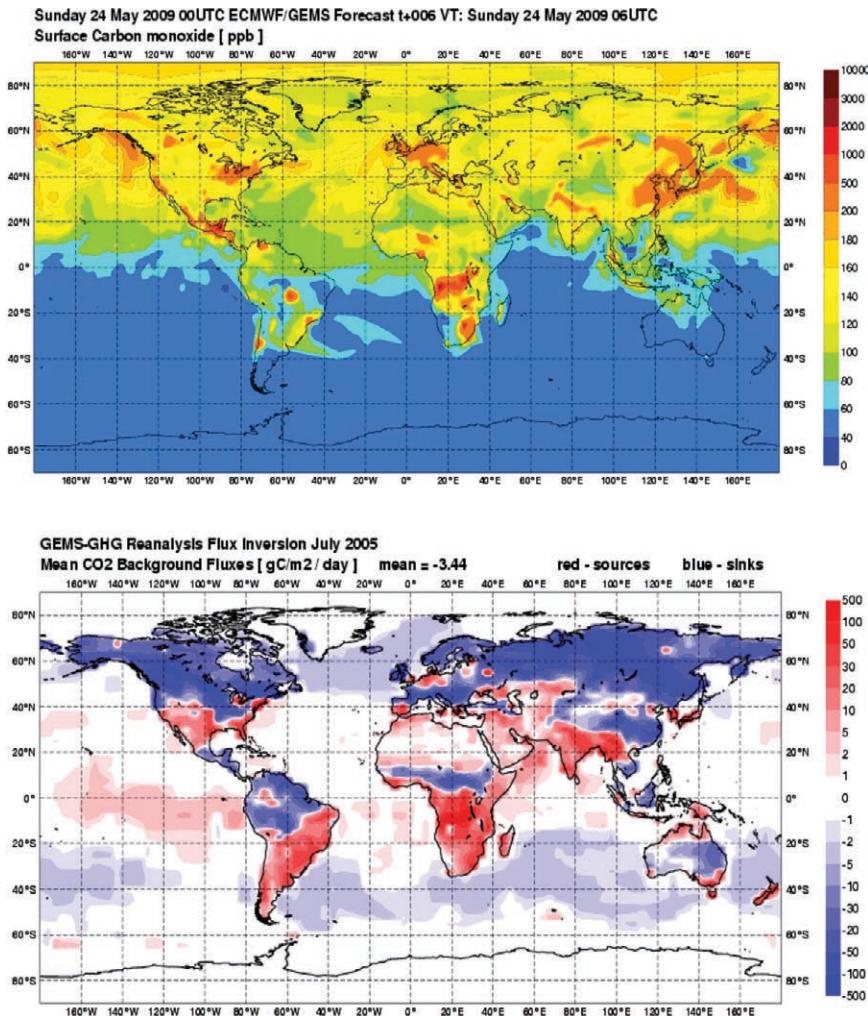


FIG. 2. (top) Predicted global distribution of carbon monoxide surface mixing ratio (ppb) by the ECMWF (EU-funded GEMS Project) with an assimilation of space observations. (bottom) Monthly mean exchange surface flux of carbon ($\text{gC m}^{-2} \text{day}^{-1}$) derived from atmospheric CO_2 observations by the AIRS and atmospheric transport calculated using winds from the ECMWF reanalysis. The atmospheric transport has been computed by the general circulation model of the Laboratoire de Météorologie Dynamique at a resolution of $2.5^\circ \text{ lat} \times 3.75^\circ \text{ lon}$, nudged to the ECMWF analyzed winds. The CO_2 atmospheric reanalysis is in the form of 6-hourly two-dimensional mean concentration fields in the free troposphere, where the AIRS CO_2 weighting function peaks.

measurements from synoptic (e.g., remote sensing) data, field campaigns, and laboratory studies for appropriate (e.g., scale and process) representations in global models.

One challenge facing the global climate modeling community is to provide insight into extreme climate and weather events to bridge the gap between seasonal and interannual events and help understand near-term (e.g., next 30 years) climate dynamics (Meehl et al. 2009). This is being addressed through

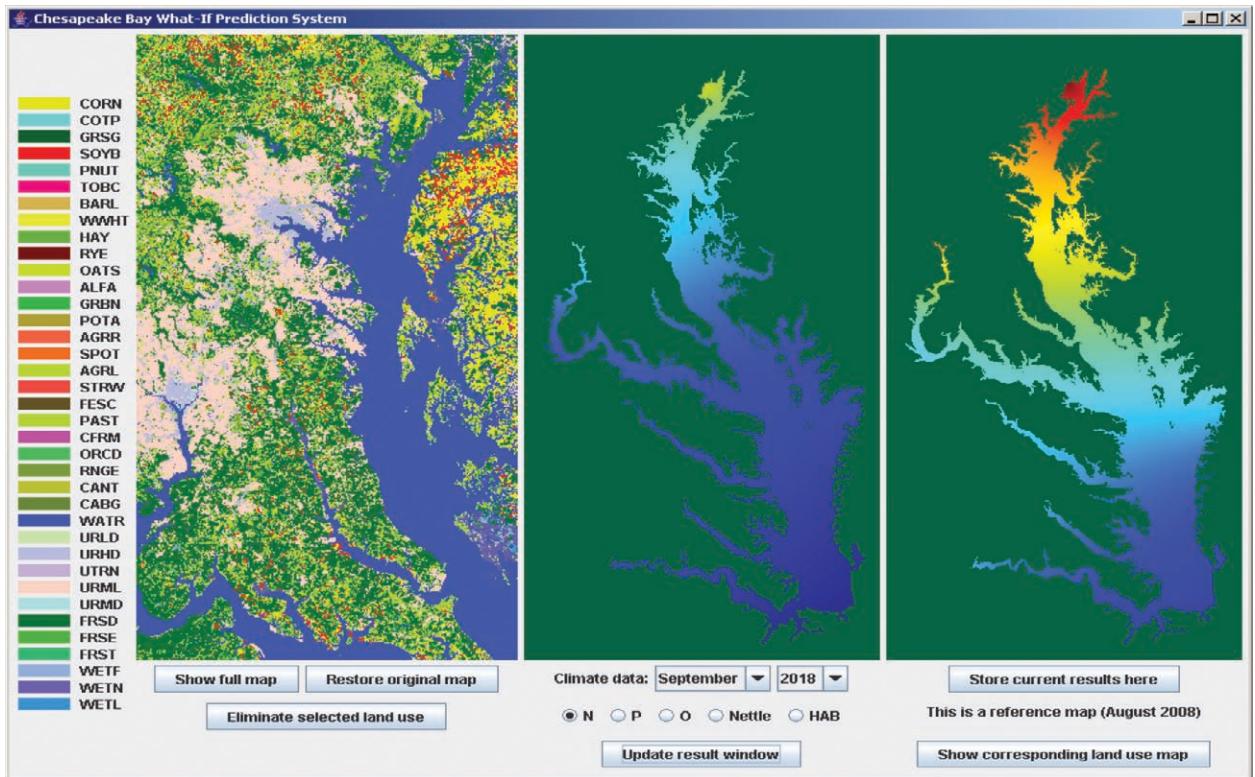


FIG. 3. The CBFS System Decision Support Interface, depicting (left) the land cover/land use types at a 30-m resolution incorporated into the coupled ocean–atmosphere–land–ecosystem model of the Chesapeake Bay watershed, (middle) changes to nitrogen loading to the bay if all runoff from poultry farms is remediated by 2018, and (right) current nitrogen concentrations in the bay.

a coordinated decadal prediction experiment for the upcoming Intergovernmental Panel on Climate Change’s (IPCC’s) Fifth Assessment Report (AR5) (Taylor et al. 2009). Some models will run with land systems at increased spatial resolution ($0.5^\circ \text{ lat} \times 0.5^\circ \text{ lon}$). The objective of this experiment is primarily to evaluate model skill. We anticipate, however, that model results will provide statistical insight into possible extreme events for the next three decades and into climate over the next several decades. The results also will narrow uncertainties in near-term climate predictions (Hawkins and Sutton 2009).

A noteworthy accomplishment in short-timescale Earth system prediction is the implementation of the Global and Regional Earth System (Atmosphere) Monitoring Using Satellite and In-Situ Data (GEMS) Monitoring Atmospheric Composition and Climate (MACC) project coordinated by the European Center for Medium-Range Weather Forecasts (ECMWF). The ECMWF now issues daily regional and global predictions of atmospheric composition (see <http://gems.ecmwf.int/>). Such products help reveal the vulnerability of the population to air pollution, particularly in cities. They provide information on the

term evolution of biogeochemical cycles in a changing climate (e.g., the carbon cycle). An example of the predicted global distribution of a reactive gas such as carbon monoxide (CO) is shown in Fig. 2. In the case of carbon dioxide, ECMWF assimilates observations from the Atmospheric Infrared Sounder (AIRS) into their model. Global budgets of carbon dioxide have been derived by inverse modeling. Figure 2 also shows the monthly average surface exchanges of CO_2 estimated for July 2005.

Another example of a regional Earth system model (Fig. 3) is the Chesapeake Bay Forecast System (CBFS) developed at the University of Maryland’s Earth System Science Interdisciplinary Center (Murtugudde 2009a,b). Chesapeake Bay is experiencing environmental changes and is likely to continue to do so over the next several decades given its exposure to sea level rises, past changes in land use and land cover changes, and increasing population density (Constantin de Magny et al. 2009). A question facing decision makers in the region is how to prepare for and adapt to these changes. Using downscaled, coupled land–atmosphere–ocean–ecosystem models, combined with remotely sensed observations, the CBFS provides

integrated Earth system analyses and predictions of the bay and watershed. This information system enables policymakers, urban development planners, and natural resource managers, as well as a variety of private users, to make decisions involving timescales from days to decades.

COUPLING THE HUMAN SYSTEM TO THE NATURAL SYSTEM.

Introducing interactions between the natural (physical, chemical, biological) and human (economic, social, political, cultural) systems represents a major challenge in the development of Earth system prediction/projection systems. The first steps have been taken by introducing prescribed emission scenarios in climate models (Nakicenovic and Swart 2000) and developing impact models that support decision processes. Impact assessment models (e.g., Carter et al. 2007) focus, for example, on water management, agriculture development, food production, epidemiology and other health issues, air quality, urban dynamics, demographics, and population migration. A major step forward will be to couple such models with climate and even weather models, especially to address regional issues. Detailed economic, energy, and land use models should gradually replace prescribed emission scenarios in climate models.

The development of integrated prediction systems for the seasonal-to-decadal timeframe must become

a major objective of the operational prediction centers with engagement of the academic research community and, if successful, will be a key focus for the climate services being established in different countries. Such prediction systems should account for human actions and provide the information needed to reduce the vulnerability of societies to predicted high-impact environmental events.

A conceptual modeling framework that accounts not only for the influences of human actions on natural systems as historically done through proxy (e.g., greenhouse gas emissions, land cover changes) but also for the impacts of environmental services on human welfare and health will need to be developed (Fig. 4). What complex Earth system prediction models will not easily capture is the essence of feedback from political and social decision-making into the integrated prediction/projection modeling systems. Before such feedbacks are incorporated into prediction/projection modeling, they will first be addressed in assessment models. At the same time, new paradigms will be developed whereby social science information will be included in detailed predictive ESM. Exploring, for example, the possible integration of agent-based approaches (e.g., Gilbert 2008), modeling that emphasizes autonomous individual processes or entities acting on simple behavioral rules and thus generating a complex system, or other methodologies describing the evolution of complex systems should be envisaged.

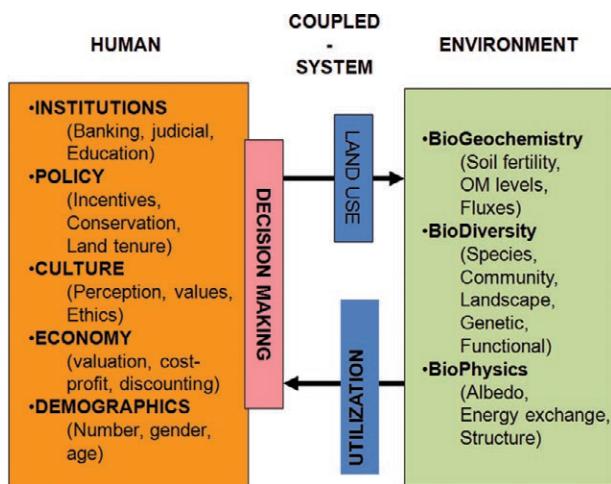


FIG. 4. An example of a model of a coupled human-environmental system that accounts for the influences of one subset of human actions (land use) on the natural systems and for the role of environmental goods and services for human welfare (utilization). [While “culture” is listed as a separate factor in this list, it is worth emphasizing that culture is a pervasive factor that also shapes institutions, economy, science, etc. (Proctor 1998).]

CONCLUSIONS.

We have suggested that future efforts in multidisciplinary Earth system modeling should include i) the development of global Earth system analysis and prediction models that account for physical, chemical, and biological processes in a coupled atmosphere–ocean–land-ice system; ii) the development of a systematic framework that links the global climate and regionally constrained weather systems and the interactions and associated feedbacks with biogeochemistry, biology, and socioeconomic drivers (e.g., demography, global policy constraints, and technological innovations) across scales and disciplines; and iii) the exploration and development of methodologies and models that account for societal drivers (e.g., governance, institutional dynamics) and their impacts and feedbacks on the environmental and climate systems. The latter is a particularly grand challenge because human behavior is not easily represented within the framework of present-day physical prediction systems. However, it is increasingly recognized that humanity is capable of perturbing the entire Earth system, hence the need for collaboration

between natural and social scientists to explore ways of integrating societal processes into present and future ESM, if the latter are to provide quantitative information to use to mitigate and adapt to future changes in the Earth system.

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