The need to include fully coupled regional Human System models with Earth System models in order to study Climate Change and Sustainability

A White Paper submitted to the
Workshop on Mathematical Challenges for Sustainability
DIMACS Center, Rutgers University, November 15-17, 2010

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This White Paper is most related to Theme 2 and Theme 4.[1]

Fully Coupled Models vs. One-Way Coupling

The interaction between human and natural systems has been typically studied in a one-way coupled fashion, i.e., one component as input, the other responds. Examples of this one-way coupling approach include demographic projections used to predict demand for natural resources (water, energy), and natural disasters triggering human migration patterns. In the real world, both the human and natural components of the Earth system are fully coupled, meaning that their coupling is bi-directional, not a one-way coupling. For example, the atmosphere and the ocean are coupled in both directions, and the important chaotic phenomenon of El Niño-Southern Oscillation (ENSO) is the result of an instability of the coupled ocean-atmosphere system. By contrast, until the late 1990's, atmospheric and ocean models used to be coupled in a "one-way" mode: the atmospheric models would be affected the sea surface temperature (SST) but could not change it, and the ocean models would be driven by the atmospheric wind stress and surface fluxes, but could not change them.

[1] ***Theme 2: Human-Environment Systems as Complex Adaptive Systems***
"we will focus on the dynamics, both endogenous and in response to outside disturbance, of coupled Human-Environment Systems (HES)".
Theme 4: Managing Human-Environment Systems for Sustainability
"The planet faces enormous sustainability challenges… For example, given current trajectories, it has been predicted that society will have to double food production in the next 40 years to keep pace with demand, while reducing pollution impacts on aquatic ecosystems and reducing the rates of biodiversity loss associated with land-use change and overfishing. An improvement in well-being within this ambitious scenario would require improved livelihood opportunities for the poor and a shift in human behavior among others toward goals that seek well-being through a less consumptive lifestyle. This would necessitate radical changes in the management of human-environment systems for sustainability… For example, such shifts in human behavior may arise more readily if risks associated with various responses can be defined in an appropriate probabilistic framework and presented so as to most effectively provide general public appreciation of the trade-offs involved in various management actions."

Such “one-way” coupling cannot represent the positive and negative feedbacks and the delayed feedbacks that take place in nature and which produce the ENSO instability. Cane et al. (1986) developed the first prototype of a two-way coupled ocean atmosphere model, and with this model Zebiak and Cane (1987) were able for the first time to predict El Niño several seasons in advance. Current climate models have since switched to fully coupled atmosphere-ocean-land-ice. More recently biosphere systems are also being fully coupled, with changes in vegetation not only being able to affect climate through changes in albedo and soil moisture, but also the type of vegetation that grows in a region can change depending on the local climate [Zeng et al., 1999, Porporato *et al*., 2001, Sternberg *et al*., 2002].

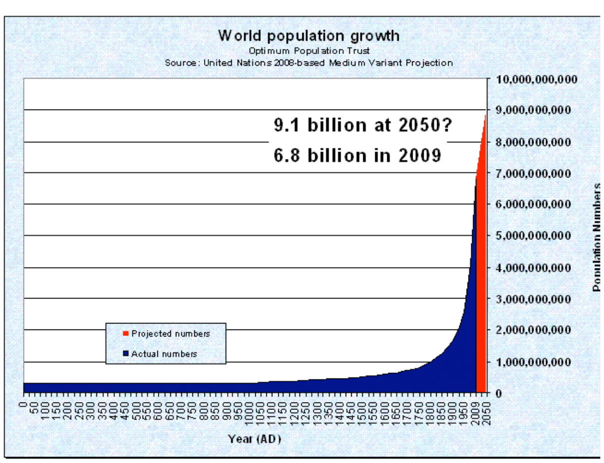
It should be noted that realistic coupled models are considerably harder to develop than one-way coupled models because there is much more freedom for the coupled model to drift away from reality. For example, with a one-way coupling, the atmosphere can see the ocean sea surface temperatures (SST) but it cannot change it, so that the SST anchors the atmosphere within realistic limits of temperature. In a two-way coupling, by contrast, the temperatures of the coupled atmosphere-ocean system have much more freedom to drift away. This requires more careful modeling in order to develop realistic solutions. At present fully coupled climate models have been developed to the extent that they are now realistic, and there is general agreement among climate modelers that full coupling is essential in order to have a realistic climate system.

The human system in some ways now dominates the natural system, with, for example, the vast majority of large mammals being domesticated. Most of the land that can be cultivated has already been devoted to agriculture, and the production of grain has increased by 250% between 1950 and 1985, allowing the population to double during that period. This “green revolution” was made possible by the use of vast amounts of fossil fuels to fertilize, irrigate and mechanize agriculture. The human economy has grown even faster than the population, since *per capita* GNP has also grown (Fig. 1). Humans are influencing the climate through both emissions of greenhouse gases (GHG), and use of natural resources (e.g., land, water, minerals). In fact, population growth is a primary driver of every environmental challenge that threatens sustainability: generation of GHGs, other pollutants and toxic waste; depletion of resources, including water, oil, fisheries, topsoil, etc.; resource wars and civil conflicts; malnutrition and world hunger; lack of resources for education and health care, especially in poor countries; best farmland converted to urban and suburban sprawl; waste disposal and need to find more landfill space; species extinction.

Unfortunately, in some contexts, population has become a “*taboo*” subject. For example, a study by the London School of Economics concluded that per dollar spent, family planning reduces four times as much carbon over the next 40 years as adopting low-carbon technologies, so that it is cost effective and should be a primary method to reduce emissions. Nevertheless, there was no discussion on population or family planning in the UNFCCC’s 15th Conference of the Parties (COP15) held in Copenhagen last year, nor it appears to be in the next meeting (COP16) to be held in Mexico in December 2010. This reluctance to discuss population and climate may now be changing, as evidenced by the decision of the UK Royal Scientific Society to launch a two-year new population study related to climate.

Given the prominent role that population and human activity have in driving climate change, it seems that Earth System models should be also fully coupled with Human System models if we want to be able to simulate more realistically climate change and sustainability. This need is particularly well expressed in a recent Science paper by Liu et al (2007) that includes the NOAA Administrator (J. Lubchenko) as one of the authors. The abstract states that “Integrated studies of coupled human and natural systems reveal new and complex patterns and processes not evident when studied by social or natural scientists separately. Synthesis of six case studies from around the world shows that couplings between human and natural systems vary across space, time, and organizational units. They also exhibit nonlinear dynamics with thresholds, reciprocal feedback loops, time lags, resilience, heterogeneity, and surprises. Furthermore, past couplings have legacy effects on present conditions and future possibilities.”

There are now several economic models coupled to rather simple Earth System models, sometimes known as Integrated Assessment Models (IAM). One of the models in this class is the MIT Integrated Global System Model (IGSM) (Prinn et al., 1999, Sokolov et al., 2003), which has a model of anthropogenic emissions including 16 regions, with 7 non-energy sectors and 15 energy supply sectors in each region. The MIT IAM has been widely used and it can estimate uncertainties (Webster et al, 2003). Another widely used IAM model was created at the Joint Global Change Research Institute (JGCRI, PNNL/UMD, Kim et al., 2006). It has recently been used to show the importance of assigning value to all sources of carbon transferred to or from the atmosphere, and not just to fossil fuels. IIASA has also developed an IAM known as MESSAGE (Riahi et al., 2007). The National Institute for Environmental Studies of Japan has developed an IAM known as AIM/CGE (Xu and Matsui, 2009), and a study by Matsumoto and Matsui (2010) also concluded that high carbon prices are essential to abate emissions faster, and that although this policy reduces GDP growth, the differences in its growth rate are small. The US Electric Power Research Institute has developed a Model for Evaluating Regional and Global Effects of greenhouse gases (GHG) policy (MERGE), described in (EPRI, 2009) as sufficiently flexible to explore views on a wide range of contentious issues: costs of abatement, damages of climate change, valuation and discounting. However, as with the Netherlands Environmental Assessment Agency IMAGE model (Bouwman et al., 2006), these IAMs are not fully coupled, the population demographics components are not interactive with the rest of the model.



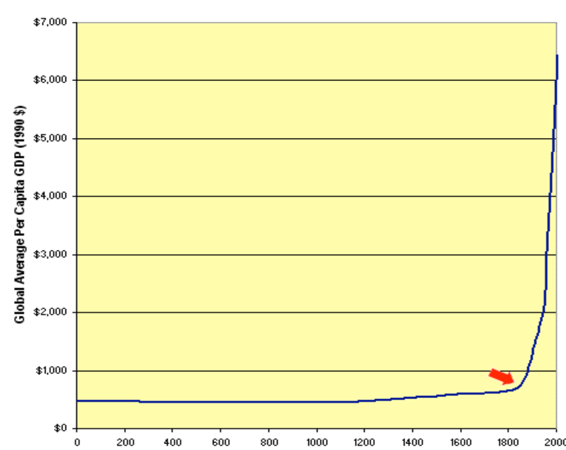


Figure 1. Left: World Population Growth, estimated by the UN after 2009 (medium growth). Right: Globally averaged per capita GDP.

Since human activity has profound effects on the Earth System, and since the Earth System creates significant constraints and effects on the Human System, we propose that Human System regional/country models should be coupled with the Earth System models to better simulate these effects, gain an improved understanding of the range of feedback and response dynamics of the coupled human-earth system and arrive at a quantitative tool that can be used for next-generation decision making and development of policies towards sustainability. Otherwise, the lack of coupling between the Human and Earth Systems eliminates absolutely crucial feedbacks and will necessarily lead to "surprises" (Liu et al., 2007).

This raises the interesting issue of *how* to model the Human System so that it is fully coupled with the Natural System, and not with a one-way coupling as several current IAM models with external population input. It should be explored to what extent these models can be also fully coupled with population models. One approach that can address this challenging modeling problem is System Dynamics (SD). The economic components of the above mentioned IAMs, being based on the Neoclassical Economic approach to modeling, are primarily general equilibrium models. We propose that the chaotic tendencies, nonlinearities and multiple feedbacks found in complex adaptive systems are more realistically modeled using SD modeling.

An early example of this approach was used by Meadows et al, (1972, "Limits to Growth" and "30 Years Update", 2004). A recent comparison shows good agreement with what actually happened 30 years after the study was completed (Turner, 2009). Nevertheless the Limits to Growth model has some serious deficiencies, the most important being that the whole world population and economies are lumped together, so that regional/country characteristics, policies, migrations, etc. cannot be accounted for.

To model the human system with a SD modeling approach with regional submodels would have several advantages:
1) It can be relatively simple to design and couple with the natural system.
2) Using regional or country submodels allows for consideration of the impact of government policies, migration, and disturbances such as HIV, as well as the regional vulnerabilities associated with sea level rise, erosion, etc.
3) It would be possible to create estimation of risk by using a probabilistic approach based on ensemble techniques, now widely used for weather and climate prediction.

Figure 2 is an example of the type of components and two-way interactions that a coupled Human-Earth system would have.

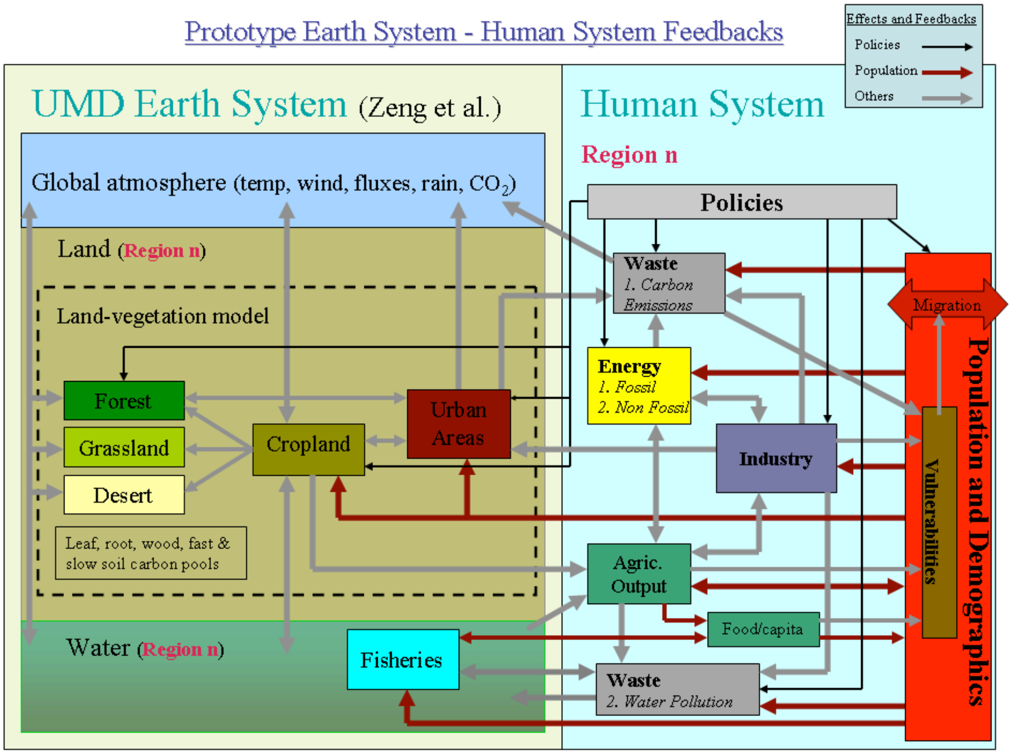


Figure 2: Schematic of the components and two way interactions of a prototype Earth model (left) coupled with regional human models (right).

The full coupling of Human System Models with Earth System Models will bring new mathematical, computational and scientific challenges, including all the chaotic results of nonlinearities, the possibility of more solutions drifting away from reality, and the problem of parameterizing the effects of government policies. The vast space of possible solutions needs to be explored, including some solutions that may have characteristics that are non-intuitive.

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