AIMES 2.0: TOWARDS A GLOBAL EARTH SYSTEM SCIENCE

Geologists, biologists and other scientists are no strangers to the interlinked nature of Earth's complex adaptive systems. Now, Earth-system researchers need to consider adding social systems to their complex webs of research. **Sander van der Leeuw** examines how one IGBP programme is working to do so.

Earth is a complex place: the planet is composed of oceans, deserts, forests, animals, microbes, volcanoes and more, and everything interacts to create a whole. Now, add human structures to that list: governments, the Internet, social movements, individual desires. Those, too, are complex, interacting systems. And these two worlds – the natural and the human-made – are meshed together in a cyborg whole.

Over the last century or so, humans have increased their impact on the natural environment so much that they cannot be left out of the picture. No wonder, then, that the next step for Earth-system science, and for the many interdisciplinary researchers who work in that field, is to incorporate economics, governance and other human and social dimensions into their work.

A major section of the IGBP known as AIMES (Analysis, Integration and Modeling of the Earth System) will pursue this goal, by expanding beyond the natural and life sciences that composed Earth-system science until now.

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Field work

For more than a decade, AIMES 1.0 has developed the field of Earth-system science. From this perspective, the planet is a coupled system of interacting physical, chemical and biological components; together, these components produce planetary-wide effects that are beyond their own individual dynamic forces. Changes wrought by the ocean's circulation patterns, for example, such as the El Niño–Southern Oscillation in the Pacific, have repercussions for weather patterns half a world away, in this case changing rainfall patterns in Europe. And the rapid accumulation of greenhouse gases in the atmosphere, due to human energy consumption, causes the Earth's polar icecaps to melt and sea levels to rise.

This perspective slowly became mainstream in global environmental change research, partly due to the success of AIMES; its forerunner, the Global Analysis, Integration and Modeling (GAIM) project; and its partner projects, for example, the World Climate Research Programme (WCRP) and the World Global Climate Model (WGCM). The GAIM project initiated serious efforts to model the carbon cycle involving a number of international teams. AIMES 1.0 has been instrumental in extending this approach to include the physical components of the climate system, from soils to water cycles to the atmosphere, as well as couplings to the biological components of the land and ocean carbon cycle, such as fisheries and coral reefs (Friedlingstein *et al.* 2006). As a result, the next Intergovernmental Panel on Climate Change (IPCC) report will include such coupled models.

More recently, AIMES sparked a dialogue between climate modellers and socioeconomic researchers to ensure greater consistency in IPCC's assessment process (Hibbard *et al.* 2007). This discussion highlighted the dual nature of the pressing challenges we face: climate change, financial crises, food security, pandemics, and energy availability and sustainability are symptoms of our geographic interconnectedness at a global scale on the one hand, while on the other hand, these challenges are topically interconnected as well – energy needs are connected to food and water security, and both are affected by climate shifts and

NASA/NOAA/GSFC/Suomi NPP/VIIRS/Norman Kuring financial markets, for example, as well as by government policies.

The dialogue also highlighted the pervasiveness of information and communication technologies in all human and societal endeavours (Helbing 2013). Because of our interconnectedness – through the Internet and our decision-making structures – nations and cultures increasingly must share the burden of these challenges. However, interconnectedness also provides a new universe of tools for research and engagement.

Taking on risk

These interconnections – both our planet's connected systems and our own societal links – are gaining more attention. But another aspect of how we understand global systems has received less attention: the changing nature of risks.

Ever since the Neolithic era began about 10,000 years ago, the nature of risks has slowly shifted from the environment to society. Over the past two centuries in particular, human activities have irrevocably changed planet Earth; our impacts are now so widespread that we dominate many aspects of the Earth system's dynamics. Hence, our major risks are no longer natural ones that are predominantly external to society, but social risks that are considered internal to society. In the process, societal dynamics and interventions in the environment have driven the Earth system to some of the limits of its safe operating space.

With global interconnections, as Helbing (2013) argues, more links between different parts of the Earth system and human societies substantially increase the probability of "risk cascades": local events that are in themselves seemingly minor can now lead to major global crises. The current global financial crisis amply demonstrates this kind of risk cascade, and the increased probability of such chain reactions also applies to potential pandemics, sea-level rise due to greenhouse gas emissions, and other challenges.

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These trends – more interconnections that lead to risk cascades – show the need for a new focus on future outcomes, in scientific research as well as for policy and society. The nature of human risk perception also adds to the urgency of this shift. Human interventions tend to be based on a very limited knowledge of the many complex processes involved in a challenge. Thus, we often are unaware of many risks that may be the consequences of our interventions.

Moreover, whereas humans generally mount interventions in response to relatively frequently observed phenomena, such interventions also have long-term effects on a system. Over time, therefore, risk patterns shift: frequently perceived short-term risks get fixed, only to give rise to unknown longer-term risks. In our daily lives, we as individuals focus on short-term risks and tend to ignore long-term ones (such as climate change), and our governments do the same. Because of this "risk bias", we have a hard time assessing the full effects of our actions, let alone their many-faceted impacts on the very complex real world (van der Leeuw 2010).

Because of the gulf between the perceived dimensions of a problem and any unperceived effects, the domain of unintended consequences always grows faster than our knowledge. While we think we know more about a system, we actually understand less because the system has disproportionately changed due to our actions. In the evolution of all social-environmental dynamics, there thus comes a point where a society is overwhelmed by the unintended and unanticipated consequences of its own actions – a "tipping point" that puts a society into crisis.

Arguably, this shift in risk spectrum is at the root of the various crises we are experiencing today. Our empirical, reductionist approach to science seems to have blinded us to unanticipated consequences: current scientific methods reduce the complexities of the Earth system to the point that a "clear" (but necessarily incomplete) explanation of phenomena emerges.

The trial-and-error methods of problem-solving that evolved from our current approach to science are inadequate to deal with issues facing today's rapidly changing global system. Over the past half-century, the recognition that many phenomena are complex (adaptive) systems has convinced us as Earth-system scientists that we need to adapt our thinking and approach. We require unprecedented amounts of information to drive new analytical and computational approaches and new tools to understand the multi-dimensionality of such complex systems across many scales in time and space. We need to ask fundamentally different questions, transforming both the conceptual/theoretical and epistemological foundations of the natural and social sciences.

Making a change

This shift moves the emphasis away from learning **from** the past towards learning **for** the future. Instead of studying "origins", "explanation" and "causality", research should move towards studying "emergence" and "anticipation". Rather than reducing the number of dimensions, research must enhance the complexity of our understanding through modelling and the design of multiple potential futures (van der Leeuw *et al.* 2011). These shifts will allow us to improve our ways of dealing with unanticipated consequences and to become

pro-active rather than **re**-active.

In response to this challenge, AIMES 2.0 economists and social scientists are arguing for a Global Earth System Science that aims to holistically study systems like the Internet, urban centers and how they are networked, the financial system, human health and more, all at a global scale (Finnigan 2003, Helbing 2013, Jaeger *et al.* 2013). This Global Earth System Science should extend the "Complex Adaptive Systems" perspective beyond the natural world to the social domain. Socio-environmental processes should be studied as an integral part of this new way of thinking, in order to develop evidence, concepts, and questions concerning the Global Earth System to help practitioners to reflect on their experiences and to assess possible consequences of their actions.

Such research should be designed to be truly global in three different senses: **physically**, looking at the Earth system in its entirety; **intellectually**, fusing all relevant approaches and disciplinary contributions to consider the topic holistically; and **demographically**, considering and ultimately engaging the whole human population. To achieve these goals, Global Earth System Science should combine advanced modeling and forecasting technologies with conversations that bridge the gap between science and society. AIMES 2.0 will embrace such a Global Earth System Science approach.

A central goal of Future Earth, the next embodiment of IGBP's work (see news story on p. 6), is to develop intensive, continuous, iterative exchange with societal stakeholders and decision-makers to stimulate public policy and societal responses. AIMES 2.0 will embrace that goal and will also promote an intellectual fusion between disciplines, to develop the insights that practitioners need.

The project will focus on questions that are core to the Future Earth initiative. These questions include determining the states and trends of key environmental processes and components, such as biodiversity, soils and more. Human-driven change and the social foundations of sustainable development need to be clarified, such as population growth, consumption habits and available technology. How do these fit into human wellbeing, equality, health, education and security?

To address these core concerns, AIMES 2.0 will consider the approaches, theories and models that will allow us to explain and, where possible, to anticipate the functioning of the Earth's socio-ecological systems. How do we understand the interactions between them, make projections for the future, and anticipate critical thresholds? These questions require determining the risks of crossing regional to global thresholds and planetary boundaries, which might induce tipping points and social-environmental crises due to global environmental change.

With these new tools and a new way of thinking, we hope to identify the patterns, trade-offs and options for equitable and sustainable use of resources and land. We need to ensure sustainable access to food, water, clean air, energy and materials for current and future populations. With that in mind, we have to consider the implications of climate change – for food, water, health, human settlements and ecosystems. The main question now will be how humans might adapt to climate change and find ways to harness the ecosystems services we have, in order to soften impacts of climate shifts in the future.

We need to find the links between biodiversity, ecosystems, human wellbeing and sustainable development. We expect that this approach will simultaneously rejuvenate the science, energise the scientific community, enlarge it by more directly involving new disciplinary communities, and contribute in a major way to solving some of the challenges that our global society faces in the 21st century. ▮

Global Risk Networks

Data-driven approaches have allowed Earth-system scientists to illustrate the strong connections in global networks, as Dirk Helbing of the Swiss Federal Institute of Technology in Zurich wrote in a recent perspective in *Nature*. Models inspired by the human nervous system, for example, or nuclear chain reactions that might lead to a "human time bomb", where one imploding node sets off explosions down interconnected pathways, show both the good and the bad of our tightly linked networks. Models can include economic inequality, wars, biodiversity, organised crime, air pollution and even the slowing growth of the Chinese economy.

Global Earth System Science should combine modelling and forecasting with conversations between science and society.

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