Earth System Science and the second Copernican revolution

Raghu Murtugudde

An elegant definition for the Earth System was put forth by Schellnhuber as consisting of the ecosphere and the anthroposphere, where the ecosphere includes all natural spheres such as the geosphere, atmosphere, cryosphere and the biosphere. Human being has evolved into a dominant anthroposphere with his impact on the functioning of the Earth System so dominant now that a new geologic period called the Anthropocene is underway. As the global human is beginning to realize his dependence on the ecosphere for future survival, global governance is being contemplated for navigating the future evolution of the Earth System. For all denizens of planet Earth, it is absolutely crucial to attain development to be more in harmony with the ecosphere and use natural resources sustainably. A critical component of ecosphere–anthroposphere balance will depend on the education of future generations. A careful planning of higher education is called for to achieve such development to not only produce a globally aware workforce but also train Earth System scientists who are ecospheric doctors and surgeons capable of monitoring the pulse of the planet, diagnosing the ailments, and devising the remedies needed for sustainable functioning of Gaia's body.

Keywords: Anthroposphere, Copernican revolution, Earth System Science, ecosphere.

SCHELLNHUBER[1] compares the evolution of understanding of human body over the last several millennia to the more recent expositions on the functioning of the Earth System, especially as a potentially self-regulating Gaia[2]. He further notes that the invention of the microscope and the telescope in the 17th century which allowed Copernicus to show that Earth was not the centre of the universe and also essentially initiated the culture of individual research and invention leading up to the industrial revolution. The contrast with the 20th and the 21st centuries is remarkable in terms of going into space and looking back at the complexities of Earth as a system and visiting other planets and even leaving the solar system. More importantly, 'big science' is here in terms of the Intergovernmental Panel on Climate Change (IPCC) leading global negotiations of actions needed to adapt to and mitigate the impacts of climate change, attributed to human actions (IPCC 2007). Schellnhuber terms this era of big science and the investigation of physiology of the Earth System as the second Copernican revolution.

Global governance issues being dealt with by IPCC and the UN in general, span the gamut from food and energy security to human health and place climate issues at the forefront of human existence, raising serious concerns about continuing with business as usual in the way the global human consumes natural resources. Especially in a natural resource-limited country with a rapid population growth like India, this Earth System functioning is a quintessential question of survival for most citizens. Developing countries now face a unique opportunity for innovation in education, science and technology to leapfrog the follies of unplanned growth achieved by the developed world. More importantly, it raises fundamental questions about the way we should be educating the newer generations as every human action begins to intimately interact with the functioning of the planet that hosts us. The focus of this perspective is to offer a roadmap for Earth System Science education and speculate about the best way to foster interdisciplinary education to train a globally aware workforce that will extend safe regimes of human existence on our planetary home by constantly seeking and maintaining pathways for sustainable development.

In its most simplistic, motherhood sense, sustainability is the ability of one generation to use the resources without jeopardizing the ability of the future generations to access the same resources[3]. A mathematical definition of sustainability would require the local rate of change for all the resources by all organisms to be zero[4]. These elegant and yet impractical definitions highlight the educational challenge for Earth System Science. Considering that sustainability as a goal would require many strategies

Raghu Murtugudde is in the Earth System Science Interdisciplinary Centre, Department of Atmospheric and Oceanic Science, University of Maryland, College Park, MD 20740, USA.
e-mail: ragu@essic.umd.edu

to accomplish the goal and the tactics to implement the strategies will have to focus on adaptive management with participatory decision making and learning-by-doing as the mode of operation from regional to global scales[5]. Our education system must thus prepare future generations to function within this paradigm, highlighting the imperative to create teachers, technocrats, bureaucrats and policy wonks that can communicate across disciplinary and cultural boundaries to navigate human–natural system interactions and decisions on the sustainability highway.

Educational imperatives

A detailed piping diagram of the Earth System was given by Fisher[6] and Schellnhuber[1] in the Bretherton diagram. Bretherton diagram is an excellent map of the complex feedbacks in the planetary machinery and an indicator panel for physical and social sciences needed as the foundation for Earth System Science education. The new educational paradigm must be based on the new intrinsic fact of the anthropocene[7,8] that all human actions leave an imprint on the Earth System. The awareness education about the Earth System thus has to start at as early an age as possible. Needless to say, increasing course-work for elementary to middle school curricula is neither necessary nor a panacea and may in fact be counter-productive.

Earlier the better

My suggestion would be to expand education to include more nature trips for elementary and middle school students and simple measures such as installation of weather stations in every school. Simply noting various weather parameters every day over a few years and trying to understand the concept of environmental variables such as temperature, humidity, winds and rainfall amounts will lead to an ingrained instinct to pay attention to the world around and the interpretation of data over a few years collected by their own hands will provide the solid foundation needed for Earth System analysis as a way of life. A sense of synthesis and elementary steps towards research can be instilled by engaging students in activities such as taking photographs of the insects and vegetation and documenting the biodiversity. It will also provide an enormous database for a census on ecosystem biodiversity for all the regions of the country. Similar efforts can be driven to create databases of environmental variables, air and water quality, and with appropriate engineering innovation of hand-held bacterial counters, even digital libraries of pathogens in indoor and outdoor spaces and waterbodies including genetic fingerprints[9], all collected by students as volunteers doing field studies and gaining practical knowledge of the Earth System and our interaction with nature. Open houses in centres of higher learning such as the Indian Institute of Science can be modelled after similar successful efforts at various institutions such as the University of Maryland or the Lamont-Doherty Earth Observatory of Columbia University (http://www.marylandday.umd.edu/). Tens of thousands of students and parents would visit the various departments and laboratories to experience many hands-on experiments and learn about the research; more importantly about the numerous educational and career options that exist. The interdisciplinary nature of Earth System Science can be woven as a theme from the natural–human interactions that occur every minute of every day. How does climate affect the weather in terms of temperature, heat waves, rainfall, humidity, etc.? How has climate and the monsoon variability over millions of years affected human evolution? How do these weather conditions affect which microbes survive and which pathogens may re-emerge and how do zoonotic, anthroponocic, water and vector-borne diseases depend on the weather? How do people spread diseases? How do computer scientists and mathematicians combine their fields of expertise in tracking diseases via computational social science? How can engineers provide a tool for a water inspector to test the rivers, streams, lakes and other waterbodies for bar-coding the DNAs of the pathogens that reside in those waterbodies? How can a chemical engineer monitor air and water quality not only in homes, schools and office buildings, but also on trains and planes? How can a doctor be given environmental information so that he can track his patient's health along with the weather factors and pollution that may be important in determining the remedies? How can saving energy and reducing the use of plastic be beneficial to the environment and make our existence more harmonious with nature? Clearly, a large number of normative, strategic, operational and analytical questions can be enlisted[10] to find ways to generate learning methods that are practical and fun without increasing work loads for teachers and students. This is also the way to allow the new generation of students to continue to grow up to be engineers, doctors and so on, but also carry a high-level of awareness about the Earth System that they depend on for their future.

It is critical not to provide simply negative messages about the impending doom and gloom of global warming but let the young minds grow up with imagination and exciting possibilities to be what they dream to be and yet be the stewards of the environment (see ref. 11 for the African perspective). It is also paramount to enlighten their minds about Earth System Science not just being another degree with another line of working for a living but it being a unique new choice in applying science, engineering, medicine, economics, journalism and law to environmental issues as in environmental science, environmental medicine and so on.

Educating the ecospheric doctors

The need for Earth System Science as a field of study was espoused many decades ago[12] but the concept of Earth as a system was evident in the writings of Vernadsky as far back as the 1920s[13] even though the concept of the physiology of Earth was made famous by Lovelock[2] as Gaia, a self-regulating biological entity. Much has been said about the best way to foster interdisciplinary education[14], so I will not spend too much space on that thought. India has already recognized the need for Earth System scientists and has initiated many efforts to train professional Master's level students to meet the expected employment market demand (S. Nayak, pers. commun., 2010). The efforts outside India have focused on a series of new courses based on global change and environmental sciences (see ref. 14). This is clearly a straightforward and apt response to address the need and the opportunity.

The Earth System Mandala: In the spirit of the Bretherton diagram, the educational map for Earth System Science can be represented as shown in Figure 1. Clearly, this is hardly comprehensive in terms of the vast interdisciplinary nature of the issue at hand. However, it is a schematic way to consider the educational imperative. Disciplinary physical and biological sciences are the bases for understanding the functioning of the planetary machinery. Natural–human interactions can only be understood from economical and sociological sciences and must be combined with disciplinary sciences and understanding to address the various Earth System issues such as sustainability, geoengineering, adaptation and mitigation. Potential impacts of anthropogenic activities and the need for solutions offer unique new opportunities

Figure 1. The Earth System Mandala is a schematic for the various disciplinary and interdisciplinary fields of education in Earth System Science. More importantly, the curricula for every field of study must provide a minimum level of awareness of natural–human system interactions and their impacts on the functioning of the Earth System.

for education in innovations and understanding from genetics to nanotechnology to Earth System Science from alternative energy to environmental medicine.

The anthroposphere is at the centre of the Earth System and professional degrees in Earth System Science itself will obviously have to focus on the land, atmosphere, ocean, biosphere, cryosphere and the geosphere. All this education must train a workforce that will be able to address the global governance issues from the mundane global Earth System monitoring, carbon cap and trade, and international negotiations to the much more daunting job of finding safe trajectories and accessible and inaccessible domains of safe planetary operation. The most crucial would be to apply the educational structure, engineering innovations and monitoring, and process understanding at all levels to grow a cadre of Earth System forecasters to generate skillful predictive information for interactive decision-making and day-to-day management of resources for sustainability.

Earth system scientists: Professional degrees focused on practical training will obviously focus on what the market is expected to demand in terms of expertise and could range from weather and climate forecasters for specific applications from resource management to agriculture to human health, observationalists to monitor air and water quality, wind and solar radiation for energy production, regional modellers for downscaling weather and climate for interactive decision-making and adaptive management, parks and river keepers, ecosystem managers, forecasts for insurance and reinsurance industries and so on. The scope of the education has to then span the basics of weather and climate, climate change and sustainability together with the socio-economics of user needs and stakeholder engagement which are often underestimated. This is crucial for avoiding the old paradigm of 'loading dock' approach where various models and empirical products are supplied on websites and are expected to be simply loaded up on to trucks by users who need them[15]. More and more evidence emerges everyday on the need to engage users and develop a feedback process to render the climate information useful and the newly emerging concept of climate services[16] offers a framework for optimizing institutional and educational investment for meeting these needs.

Research needs take this a step further in training social, economic and physical scientists to explore the natural–human system interactions in the spirit of the century of the environment we have entered where environment is at the centre-stage of everything from ecological systems to social justice to national security[17]. More importantly, any future investments in education, training of the workforce and institutional infrastructure for climate services in India must consider the past lessons on putting blind faith in unproven modelling frameworks and the actual benefits realized by the various sections of the population[18,19]. Much thought should also be given to avoiding reinventing the wheel by importing or accessing as much of the external expertise in global modelling and focus on dynamical and statistical regional downscaling for sustainability with a focus on education, research and training in generating linked products in the sense of Earth System prediction for agriculture, water, human health, energy, transportation, biodiversity and sustainability[9,15]. Regional specificities must also drive not just the education and training for a monitoring system but also the technological innovation and engineering and implementation[20,21].

Second Copernican revolution and India: The most significant way in which India can innovate educating its future generations is to propagate the second Copernican revolution to match the pervasive influence of the century of the environment. Scepticism about global warming, especially the attribution to anthropogenic activities, will continue but the impact of pollution on human health and water will be an easy case to make. The greatest triumph will be to use the opportunity to capture new markets in education, energy, food, transportation and so on, with innovative approaches by creating a work force that is fully aware of the second Copernican revolution that is underway. This is distinct from the work force that has core education in Earth System Science. This will consist of engineers, doctors, physical and social scientists, technocrats and bureaucrats who are experts in the impact of the environment on their respective fields and related societal and economical sectors and will be able to apply and adapt their expertise to seek solutions, drive inventions and create employment and capture niche markets to fill the needs as they emerge in response to changing climate and related cascades in the functioning of the Earth System.

The new demands of having this work force on the educational system will be to break down the barriers and allowing students in one discipline like molecular biology to work with the faculty in Earth System Science for a thesis or a chemical engineer to work with an ecologist or a geneticist to work with food scientist on nutrigenetics and its role on an individual's health, or a mathematician to work with a computer scientist on computational social science and so on. Clearly, the combinations are infinite and the liberalization of the disciplinary boundaries will require nimble administrative structure that will allow committees to be formed for Ph D students from as many disciplines as necessary and research fields as far removed as needed. Clusters of thesis and projects should be designed to address end-to-end problem's solutions; for example, instrumentation, mathematical and theoretical modelling for integrated assessment of microbes-to-man, physics-to-fish-to-fishermen-to-fishing fleets-to-markets, from genes-to-genomes-to-genetics-to-medicines, and so on. As the initial experiments prove to be successful by the quality of the projects and dissertations and the applications of proposed solutions, students can be allowed to cross institutional boundaries and float from being a student at one institute to doing research at various institutes as required by the laboratory facilities, field studies, and advice from various experts at other national or international and governmental or non-governmental institutions.

The goal must always be to identify and satisfy needs from intellectual curiosity to institutional and socioeconomic needs to military–industrial and governmental mandates to deal with the adaptation to and mitigation of climate change impacts. This will set India apart in leading the second green revolution as in green technology and green solutions; food security being but one small part of the new green revolution.

Concluding thoughts

Whether one believes in climate change and the human impact or not, and despite the uncertainty in the potential impacts of increasing greenhouse gases in the coming years and decades, the train of global actions for global governance is already on the move. Since every living thing on the planet is already on this train, not responding to the impending potential impacts of climate change is akin facing backwards to pretend as if the train is not moving. It is imperative for the global human to do all he can to avoid the unacceptable solutions for the functioning of the Earth System. And this requires an educational system that will train the coming generations to clearly identify the undesirable domains of Earth System evolution and find solutions to avoid those pathways. I have provided my own perspectives on some of the essential elements to accomplish this daunting task. I would reemphasize that this also offers the biggest opportunity of the entire human history on this planet where the spaceship is safe only if every rider is safe just like an airplane cannot be made any safer for the first class than the economy class. Rich and poor countries are together on this shared journey and India can do well to devise an educational system to exploit the opportunities and train a workforce to lead the innovation required to find these solutions for the safe functioning of the Earth System on this journey.

1. Schellnhuber, H. J., 'Earth system' analysis and the second Copernican revolution. *Nature*, 1999, **402**, C19–C23.
2. Lovelock, J. E., *Gaia: A New Look at Life on Earth*, Oxford University Press, Oxford, UK, 2000, p. 147.
3. Clark, W. C., Crutzen, P. J. and Schellnhuber, H. J., Science for global sustainability: toward a new paradigm. In *Earth System Analysis for Sustainability* (eds Schellnhuber, H. J. *et al.*), The MIT Press, Cambridge, MA, 2003, pp. 1–28.
4. Falkowski, P. and Tchernov, D., Human footprints in the ecological landscape. In *Earth System Analysis for Sustainability* (eds

Schellnhuber, H. J. *et al.*), The MIT Press, Cambridge, MA, 2003, pp. 211–226.
5. Gallopin, G. C., What kind of system of science (and technology) is needed to support the quest for sustainable development? In *Earth System Analysis for Sustainability* (eds Schellnhuber, H. J. *et al.*), The MIT Press, Cambridge, MA, 2003, pp. 367–386.
6. Fisher, A., One model fit all. *Mosaic*, 1988, **19**, 52–59.
7. Crutzen, P. J. and Stoermer, E. F., The 'Anthropocene', *Global Change Newsl.*, 2000, **41**, 17–18.
8. Steffen, W., Crutzen, P. J. and McNeill, J. R., The Anthropocene: are humans now overwhelming the great forces of nature? *Ambio*, 2007, **36**, 614–621.
9. Murtugudde, R., Regional Earth System prediction: a decision-making tool for sustainability? *Curr. Opin. Environ. Sustain*, 2009, **1**, 37–45.
10. Schellnhuber, H. J., Discourse: Earth System analysis – the scope of the challenge. In *Earth System Analysis – Integrating Science for Sustainability* (eds Schellnhuber, H.-J. and Wenzel, V.), Springer, Heidelberg, 1998, pp. 5–195.
11. Philander, S. G., Where are you from? Why are you here? An African perspective on global warming. *Annu. Rev. Earth Planet Sci.*, 2009, **37**, 1–18.
12. Lawton, J., Earth system science. *Science*, 1965, **292**, 1965.
13. Ghilarov, A. M., Vernadsky's biosphere concept: a historical perspective. *Quart. Rev. Biol.*, 1995, **70**, 193–203.
14. Johnson, D. R., Ruzek, M. and Kalb, M., Earth System Science and the Internet. *Computers and Geosciences, Special Issue: The Year 2000 Challenges*, 2000, **26**(6), 669–676.
15. Shapiro, M. *et al.*, An earth-system prediction initiative for the 21st century. *Bull. Am. Meterol. Soc.*, 2010 (in press).
16. Miles, E. L., Snover, A. K., Binder, L. C. W., Sarachik, E. S., Mote, P. W. and Manuta, N., An approach to designing a national climate service. *Proc. Natl. Acad. Sci. USA*, 2006, **103**, 19616–19623.
17. Lubchenco, J., Entering the century of the environment: a new social contract for science. *Science*, 1998, **279**, 491–497.
18. Lemos, M. C. and Dilling, L., Equity in forecasting climate: can science save the world's poor? *Sci. Publ. Pol.*, 2007, **34**, 109–116.
19. Dessai, S., Hulme, M., Lempert, R. and Pielke Sr, R., Do we need better predictions to adapt to a changing climate? *Eos*, 2009, **90**, 111–112.
20. Murtugudde, R., Observational needs for sustainable coastal prediction and management. In *Management and Sustainable Development of Coastal Zone Environment* (eds Ramanathan *et al.*), Springer, 2010 (in press).
21. Murtugudde, R., Observational needs for regional earth system prediction. In Proceedings of the OceanObs09: Sustained Ocean Observations and Information for Society (eds Hall, J. *et al.*), ESA Publication WPP-306, 2010.

ACKNOWLEDGEMENTS. The Chesapeake Bay Forecast System was funded by NOAA. This perspective was motivated by Prof. Prosenjit Ghosh and coerced by Prof. A. G. Menon. I am indebted to my host, the Indian Institute of Science, Centre for Atmospheric and Oceanic Science, and the Divecha Centre for Climate, for this opportunity. Tony Busalacchi, Steve Halperin and Clarissa Anderson have always provided constructive criticisms and guided the shaping of my views.

Received 8 April 2010; revised accepted 12 May 2010