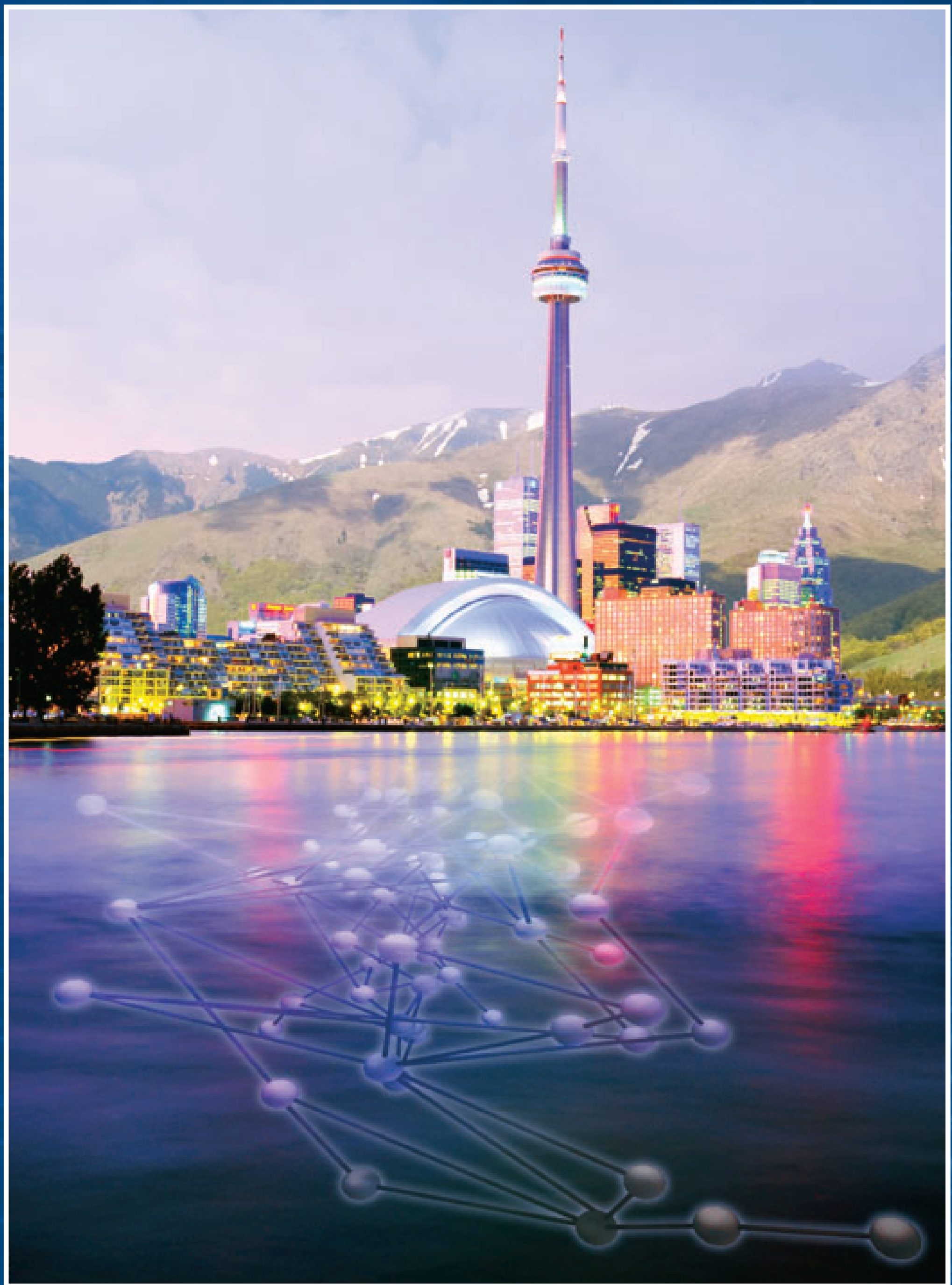
Grand Challenges *of the Future* for Environmental Modeling

In the Setting of NSF's Environmental Observatories Initiatives



M Bruce Beck, Principal Investigator

White Paper

GRAND CHALLENGES OF THE FUTURE FOR ENVIRONMENTAL MODELING

Report of the NSF Project (Award # 0630367)
May 2006 - May 2008

M B Beck

Warnell School of Forestry and Natural Resources
University of Georgia, Athens, Georgia 30602-2152

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This *White Paper* has been written solely by the Principal Investigator, who must accordingly assume the customary full responsibility for the views expressed and for any errors and omissions. The overall form of the *Paper* was fashioned initially through an opening Project Workshop held at the University of Arizona, Tucson, Arizona, May 16-17, 2006, and discussions thereafter of the Workshop's outcomes. Design of the Workshop and oversight of subsequent discussion of its outcomes in settling the design of this *White Paper* were the responsibility of an Advisory Committee, whose membership was as follows.

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Grand Challenges of The Future For Environmental Modeling

In the Setting of NSF's Environmental Observatories Initiatives

Foreword

Together with the oncoming environmental cyber-infrastructure,[1] including novel sensors and sensor technologies, the Environmental Observatories (EOs) of the National Science Foundation (NSF) share the collective ambition of bringing unprecedented streams of observations to bear on Environmental Science in the decades to come. Mathematical and computational models are intrinsically generic entities, cutting across specific, disciplinary boundaries, in particular here, those of the Observatories in the Ocean Sciences (ORION), Ecology (NEON), Hydrology and Environmental Engineering (WATERS Network). What new opportunities for research might these EOs bring about for environmental modeling, especially where those opportunities benefit greatly from the cross-cutting, collaborative, integrative style of model building?

This *White Paper* sets out thirteen Grand Challenges of the future for environmental modeling in response to that question. The same grand challenges are also set out in the *Synopsis* of this Paper, which is available as a separate document at www.modeling.uga.edu/EOModels and which can be read as an extended Executive Summary of the present document. Both the *Synopsis* and this *White Paper* introduce and discuss each challenge in the same format: of the context and foundations of — hence, the justification of — why each should have been identified as a challenge in the contemporary research scene; followed by expression of the challenge itself; with then a discussion of some indicative lines of possible responses to the challenge. While composition of this *White Paper* has been prompted by the EO initiatives, our grand challenges have been evolving over the years, and will endure into the future, irrespective of the substantial current commitments to plans for realizing the ambitions of the Observatories. They therefore merit significant consideration as matters for further research in their own right.

Our thirteen challenges span the three domains of:

> ***Science***, predominantly so, and especially in respect of bringing together thinking and research from across the above disciplines, and indeed from beyond them (reaching notably into the biomedical sciences);
>
> ***Policy***, given the vital role of computational models in decision support for environmental stewardship; and
>
> ***Society***, in view of the great, contemporary debate over sustainable development of the biosphere.

Motivated by NSF's EO initiatives, nevertheless, this *White Paper* is concerned to assess how those initiatives, with all their technical innovations in monitoring and sensors, as well as the prospective environmental cyber-infrastructure, have collectively: (i) created entirely novel and unexpected challenges; (ii) accelerated our approach to identifying and defining otherwise less swiftly emerging challenges; or (iii) significantly changed our opportunities for successfully responding to long-standing, recalcitrant challenges of the past several years, if not decades.

[1] The Engineering Research Plan for the WATERS Network defined a cyber-infrastructure in the following terms (WATERS, 2007a): "A cyberenvironment [cyber-infrastructure] is an integrated system for automated collection, storage, retrieval, and analysis of data accessible by multiple parties through a Web portal. It includes various tools for real-time collaboration with other remotely based researchers and provides access to the monitoring information collected by an observatory's field facilities, as well as historical and other relevant data. Analytical (e.g., statistical), modeling, and visualization tools needed to conduct engineering analyses are provided within the system. An operational cyberenvironment also could include control and feedback systems for decision-making and management."

Four recommendations are made. They are intended to be generally indicative of the mix of strategies that might eventually be deployed for developing and implementing specific responses to specific challenges. Especially important in this will be the determined pursuit of more than a superficial appreciation and cultivation of the "people skill-set" required for the conduct of inter-disciplinary research. The recommendations of this *White Paper* are also intended to complement, not duplicate, recommended actions now emerging from the science and education plans of the EOs themselves. There are two recommendations of a more specific nature, however:

(i) The procedures of Observing System Simulation Experiments (OSSEs) should be applied sooner rather than later in designing the Observatories, and certainly *before* their construction; and

(ii) Having now brought together the community associated with this cross-cutting theme of environmental modeling, the fruits of that effort should not be allowed to dissipate through lack of support for its *active* promotion and management in the future.

Passive management, or management "by default", in contrast, will not be a successful strategy for responding to what we are about to express as the grand challenges of the future for environmental modeling.

Preface

How to Use this White Paper

The length of this *White Paper* may be both striking and off-putting to the reader. We offer the following advice, therefore, on how to make the most of the work invested in composing it.

The following *Executive Summary* largely comprises expression of the ***Grand Challenges*** and ***Recommendations*** (exactly as they appear in the main body of the *Paper*). These are linked together with just the minimum of logic necessary to convey an impression of the coherent whole.

A separate *Synopsis*, wherein the logic generating the coherent whole is provided in a more expansive, but nevertheless succint, form, is available for downloading at www.modeling.uga.edu/EOModels.

In the main body of the *White Paper*, we have placed lengthier background, illustrative, or exemplary material in boxes. This material is entirely integral to our justifications for singling out the various ***Challenges***, or to indicating possible lines of responses to them. The purpose of setting such material aside in this manner, however, is to allow the reader to focus on following the overall logic of the *White Paper*, yet in more detail than in the *Synopsis*.

Finally, some words must be offered on the matter of what is understood as a model. Any logical "if"-"then", or like, rule of (mental) reasoning could constitute a *model*. Belief Networks (BNs), for example, are formally organized stacks of such rules, realized in encoded, algorithmic form and manipulated on the computer for deducing outcomes from premises and assumptions. The distinction is a fine and subtle one, however, between where mental reasoning should cease, because of the danger of inconsistent and erroneous reasoning with too many such rules, and computations be commenced with a formal, numerical BN model. It is less subtle in the case of a differential equation as the model. Most, if not all, models would, or should, have begun in this way, through the rules of mental reasoning, before the arrival of differential calculus, or when puzzling for the very first time over how an algal cell grows and divides. In Environmental Science, we have come to equate a model with a set of differential equations, even though it is self evident that other forms of model, such as agent-based models, are now prominent objects of study and manipulation on the computer.

"Model", as used herein, will signal anything that has passed beyond the fine and subtle line of mental reasoning into numerical manipulation on a computer. But while this implies that any form of model along the continuum from BNs to partial differential equations will come within the purview of this *White Paper*, it is acknowledged that models as sets of differential equations are the predominant form of model of concern and discussion. It could be argued, of course, that it should be the purpose of the Environmental Observatories and the environmental cyber-infrastructure to propel the evolution of any model of an environmental system along this continuum towards differential equation forms.

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Executive Summary

MOTIVATION

The National Science Foundation (NSF) is supporting the development of three major Environmental Observatory (EO) initiatives, in the Ocean Sciences, Ecology, and Hydrology-*cum*-Environmental Engineering. Modeling, and the mathematical problems and methods it encompasses, provides a natural language for communication across the various disciplines contributing to the EOs. With this in mind, NSF supported a Workshop in May, 2006, in Tucson, Arizona[2], to begin assessing the views of the environmental modeling community on how it might collectively contribute to the success of the planned EOs. Design of the Workshop and overall design of this *White Paper*, duly informed by the proceedings of the Workshop, were the responsibility of a Committee of sixteen scientists and engineers, chaired by M Bruce Beck of the University of Georgia. The content of the *White Paper* has subsequently been developed from an extensive review of the contemporary literature. The result is a set of ***Grand Challenges*** — their origins, context, and possible lines of enquiry in response to them — for the future of research into Environmental Modeling.

CONTEXT

Environmental models, as we have come to know them over the past half century — as predominantly digital computer realizations of differential-equation solvers — are not going to "go away", no matter how much some members of the Environmental Science community might wish it so (Pilkey and Pilkey-Jarvis, 2007). Great tension between empiricist and theorist is present in the heated contemporary debate over whether climate change influences hurricane intensity and *vice versa* (Mooney, 2007). Such is the stuff indeed of popular fiction (Crichton, 2004). Models are destined to become ever more complex, tending towards Virtual Realities. That progression, however, will not expunge uncertainty. In response to Moorcroft's question (Moorcroft, 2006), we are still some distance, perhaps considerable indeed, from a "predictive science" of the biosphere. And people and policy-makers *will* use models, for good (NRC, 2007) and ill: to shape environmental policy to the likes of their special interests, or repel, oppose, or delay unwanted policy, and in what are called scientifically untenable ways (Pilkey and Pilkey-Jarvis, 2007).

The environment, the biosphere, are just too complex for us to reason through the needs of Policy without models. Yet the more complex the models themselves become, paradoxically the less they may be trusted by the public, and the greater the surprise (to some) when models fail to account for what comes to pass in actuality, as they surely will. Climate models inevitably have incomplete structures and the various alternative models tend to have similar model structures. Consensus can seem stronger and more brightly illuminated than it ought, while significant unknowns and possibilities at the periphery of our understanding and vision are left to lurk in the shadows (Oppenheimer *et al*, 2007).

Some, examining the use of models for forecasting in the domain of Environmental Science, from their perspective in business and econometric forecasting, go so far as to charge this (Green and Armstrong, 2007):

> The forecasts in the [2007 IPCC WG1] Report were not the outcome of scientific procedures. In effect, they were the opinions of scientists transformed by mathematics and obscured by complex writing. Research on forecasting has shown that experts' predictions are not useful in situations involving uncertainty and complexity. We have been unable to identify any scientific forecasts of global warming. Claims that the Earth will get warmer have no more credence than saying that it will get colder.

Models, then, have joined the armory of Policy Foresight and Science, but as a two-edged sword: *Models à la Mode — the Promise and Peril of Integrated Environmental Modeling*, as Clarke entitled his 2004 paper (Clarke, 2004) for the Foresight and Governance Project of the Woodrow Wilson International Center for Scholars (Washington, DC).

[2] Original material for the Workshop can be found at www.modeling.uga.edu/EOModels

THE CHALLENGES

Challenge # 0: *Models and the Growth of Knowledge*

Neither Environmental Science nor modeling has been the object of sustained enquiry by philosophers of science. If there has been any philosophy of environmental modeling, it has been one of: as computational capacity grows, so larger sets of equations may be solved simultaneously, hence — all else being equal — we shall have models that are ever better approximations of the truth of the matter. We ask, then, as a ***Grand Challenge*** arching over the entirety of this *White Paper*:

> ***How does knowledge grow through the deliberate development, evaluation, and use of a computational model? What, in fact, should be a proper, sound philosophical basis for employing models, by design, in this context of basic scientific discovery; and how can the community of environmental modelers contribute to the construction of these philosophical foundations?***

Challenge # 1: *Global Issues of Science*

Beyond the customary view of them as formal archives of constituent scientific hypotheses, models can be exploited in a more active manner:

> ***Given the proposed Environmental Observatories (EOs), how can we design and employ models for the identification of important scientific questions in Environmental Science, with the accompanying potential for basic scientific discovery, in particular, at the interfaces between — and in the interstices amongst — the various disciplines within that Science?***

Such questions of a *global* scientific nature, associated expressly with modeling, are defined *not* in the sense of "extending over the entire globe", but in the sense that they can only be perceived and addressed when a (reasonably complex) model of the multi-disciplinary *whole* has been assembled from the mono-disciplinary, sub-model *parts*.

Challenge # 2: *Role of Cyber-infrastructure in Addressing Global Issues*

Delving more deeply into the computational mechanics of responding to ***Challenge # 1***:

> ***What kinds of software platforms within the environmental cyber-infrastructure will be necessary for supporting extensive, heuristic experimentation with a model's structure, i.e., in facilitating experimental "rewiring" of its constituent hypotheses and their interconnections in the assembly of the whole, while the inter-disciplinary community of environmental scientists works at formulating and resolving core science questions in the interstices amongst the constituent disciplines?***

How, for example, could the environmental cyber-infrastructure — as the complement of the manual labors of the scientific analyst under ***Challenge # 1*** — increasingly automate coverage of all the gaps amongst the disciplines, so that the potential discovery of significance is not overlooked? At the same time, how could it facilitate discrimination of the singularly key from the plethora of potentially spurious constituent hypotheses of which the multi-disciplinary whole of the model has been composed?

Challenge # 3: *Universal Science Issues and Process Mechanisms*

We know that variations across scales of observation and simulation are crucial to understanding and stewarding biodiversity and resilience of behavior in environmental systems:

> ***Is there a unifying and uniquely distinctive approach to the use of models in exploring issues of scale, and cross-scale interactions, along each of the three dimensions of (i) time, (ii) space, and (iii) biogeochemistry, where this last manifests itself across scales from molecular biology up to all the chemical and biological species comprising whole ecosystems?***

Challenge # 4: ***Universal Science Issues of a Biological Nature***

We may be forgiven for believing we live in a "biological age". All of the "Recommended Immediate Research Investments" of the NRC's 2001 Report on the *Grand Challenges of Environmental Sciences* (NRC, 2001) relate to ecology. Hence:

> ***What breakthroughs are needed in order to develop a more effective and complete paradigm of modeling biological processes — common to the ocean sciences as much as to terrestrial ecology or biological wastewater treatment — across all scales: from molecular biology to whole ecosystems, and including mimicking of the intelligence and metabolism of individuals in a population, their movement through an environment, and their interactions with other individuals, as a function of that intelligence and metabolism?***

What novelty might then be unleashed by turning insights, acquired from working with the Individual Based Models of ecological and social systems, towards study of the predominant physics and differential-equation models of Hydrology and the Ocean Sciences?

Challenge # 5: ***Applied Mathematics and Generic, Dynamical Systems Properties***

While there is the scope for significant rewards to be returned from bringing together the various disciplines of the EOs through the devices of modeling, so the community of environmental modelers should be assiduous in ever looking outwards from the confines of their own collective discipline:

> ***Building on the shoulders of the various mathematical theories of catastrophe, chaos, and complexity — but with the ambition to go beyond these — what new insights into the generic and fundamental dynamic properties of the behavior of systems can be obtained from the deliberately orchestrated*** **in situ** ***observation of the behavior of many specific environmental systems and the modeling thereof? In particular, how can the rich experience of elucidating these generic features from studies of whole ecosystems, indeed social-ecological systems, be productively interfaced with exploration of the novel properties of dynamical systems behavior yet to be discovered in the study of cellular metabolism, self-repair, and self-replication? How can coordination of relevant research across all of the Environmental Observatories uniquely accelerate such development? Looking towards*** **Challenge # 12,** ***how can the community of model-builders in the Environmental Sciences best be organized so as to benefit as much as possible from novel developments in modeling in general, as they arise in, for example, the quite disparate disciplines of the biomedical sciences, social sciences, cognitive sciences, artificial intelligence, and artificial life?***

How, in other words, might study of the behavior of *specific* environmental systems contribute to the development of *generic* theories about the behavior of dynamic systems?

Challenge # 6: ***Observatory Network Design and Operation***

We know well enough the merits of Observing System Simulation Experiments (OSSEs). Their future use in the design of the EOs constitutes the rare exception of being a specific recommendation of this *White Paper*. But what of the subsequent stages in the life cycles of the Observatories, for which we ask:

> ***Given a mature complex of environmental cyber-infrastructure and sensors, with — crucially — both an ever-alert monitoring and horizon-scanning facility and in-depth capacity for real-time processing of information and production of knowledge, what kinds of novel, model-based computational schemes of adaptive environmental sampling will be needed to enable rapid re-targeting of observing capacity for on-line probing of, and experimentation with, systems behavior?***

The cyber-infrastructure of Mahinthakumar *et al* (2006) — inspired by the emergence of "Dynamic Data Driven Applications Systems" (DDDAS; Darema, 2005), and intended for threat-response in public, potable water supply systems — is one instance of the vision implied in answering such a question.

Challenge # 7: *System Identification*

This, which is to say, model calibration writ massively more richly, is pivotal in reconciling observation with theory. As a problem it has been long-standing and inadequately treated, and largely, but not entirely so, because of the historic absence of adequate streams of field data. The unresolved, but engaging, tension between empiricists and theorists in Mooney's 2007 popular-science book *Storm World*, provides every reason for why our community should be drawn to this challenge:

> ***Under the expectation of massive expansion in the scope and volume of field observations generated by the Environmental Observatories coupled and integrated with the prospect of equally massive expansion in data processing and scientific visualization enabled by the future environmental cyber-infrastructure, what radically novel procedures and algorithms are needed to rectify the chronic, historical deficit of the past four decades in engaging complex models (VHOMs)[3] systematically and successfully with field data for the purposes of learning and discovery and, thereby, enhancing the growth of environmental knowledge?***

The environmental cyber-infrastructure holds out the promise of supporting the "tinkering paradigm" from ***Challenge # 2***, of rewiring at will the constituent hypotheses assembled in the model. Scientific visualization and animation of the conceptual structure of the model — not its input or output data fields — can be expected to be a necessary part of realizing this intellectual support.

Challenge # 8: *Predictive Science and Uncertainty*

Taking a lead from the question that is the title to his paper (Moorcroft, 2006), "How Close Are We To a Predictive Science of the Biosphere?", this *White Paper* enquires:

> ***Recognizing the inevitably flawed and uncertain conceptual foundations of many environmental models — while acknowledging the possibility of natural features of biological acclimation, even evolution, over a longer-term horizon, especially in response to the introduction of invasive species, and the high likelihood of continual adaptation in the behavior of many types of environmental system — how are structural error/uncertainty and structural change in these models to be identified, quantified, rectified, and accounted for (in the propagation of prediction errors and the making of decisions)? What new schemes of generating environmental foresight will be needed to cope with these challenges?***

And to some considerable extent, the rejoinder to Moorcroft's question can be found in Oppenheimer *et al* (2007), who in their turn question the value of premature consensus around climate change assessments, when in truth structural error/uncertainty in models seems both inevitable and to be guarded against.

Challenge # 9: *Assimilating Data and Processing Information in Real-time*

To be able to conduct the affairs of science and environmental engineering in "real-time" is recognized as a major opportunity for the community of environmental modelers. It is in keeping with the general quickening of the pace of things, as a manifestation of contemporary society. Under the EO initiatives, employing models and signal-processing algorithms in real time has all the thrill of conquering some final technical frontier:

> ***In a world of increasing inter-connectedness and instantaneous communication, environmental vulnerability, and infrastructure systems fragility — subject in all probability to higher-amplitude extreme events, natural disasters, terrorist threats, and the like — how best can the expected innovations in cyber-infrastructure***

[3] Very High Order Models.

and sensors under the Environmental Observatories programs be used in developing models and real-time data-processing and forecasting algorithms: for the on-line detection of faults, failures, anomalies, and the weak signals portending imminent dislocations in system behavior; and for orchestrating/guiding rapid counter-measures for enhancing and resuscitating/reviving damaged system functioning, system survivability, and resilience?

Whereas ***Challenge # 6*** asked how might models be used to inform the deployment and re-deployment of observing capacity in a built, operational EO, ***Challenge # 9*** is now different. The challenge is one of reconstructing coherent, homogeneous fields of variables internal to the model: in particular, from all manner of heterogeneous observing platforms and devices; and, in principle, across the dimensions of time, space, *and* biogeochemistry. In this — as opposed to many of the preceding ***Challenges***, wherein questions of a biological or ecological nature tend to predominate — studies tied to the relevant physical attributes of Hydrology and Oceanography are expected to continue to be in the vanguard of responses.

Challenge # 10: Management and Decision-support

In the measured prose of any report from the National Research Council, we find acknowledgment of a turning away from the prevailing view of models as "truth-generating machines" towards an outlook embracing other perspectives, most notably that of the model as a "tool", such as a hammer or screwdriver, designed to fulfil, in particular, the predictive tasks of supporting regulatory, environmental decision-making (NRC, 2007). In more colorful terms, van der Sluijs (2007) introduces the image of uncertainty as the "monster" at the interface between Science and Policy — monstrous in the sense of confusing what were previously kept strictly separate, i.e., the objectivity of Science and the subjectivity of value systems. This *White Paper* asks, therefore:

Under the prospect of lengthy and costly social negotiation and legal discourse over policy formation, wherein the placing of trust by various stakeholders in the models underpinning that policy is crucial, and where it has come to be recognized that the needs of model evaluation and peer review for conventional research science are different from those of regulatory science, what new methods of evaluating the alternative models designed to fulfil the predictive tasks of policy formation, decision-support, and management for environmental stewardship are urgently needed? How is the uncertainty associated with both the model and the decision-making context to be handled computationally and what new algorithmic and procedural developments will this warrant?

Challenge # 11: The Long View: Towards Sustainability of the Built Environment

Since the greatest debate of our times is the "sustainability debate", with its significant implications for the design and operation of the built infrastructure at the interface between Man and Environment (most conspicuously so at the urban centers of socio-economic activity), how best should the Environmental Observatories be deployed and, more specifically, what kinds of models should be developed in order to promote a better strategic alignment of the study of urban metabolism with that of ecosystem services, all within the web of global biogeochemical cycles? How too, in the widest of possible terms, can innovations in information and communication technologies (ICT) — as realized in the environmental cyber-infrastructure — lead to tangible gains in reducing the unsustainability of current patterns of socio-economic behavior?

It is easy to imagine mathematical programming and optimization to have been made for charting a course towards sustainability of the built environment: find those policies and technologies maximizing the rate of departure from unsustainability, subject to their satisfying the constraints of being {environmentally benign}, {economically feasible}, and {socially legitimate} — the triple bottom line. A fine line indeed separates what of human nature, preferences, and values should be approximated and manipulated by a model and what should rightly remain in the space of public debate and democracy.

A simulated life-time of *your* simulated self with *your* personal/private preferences, undergoing forms of learning and negotiation with other simulated beings over aspirations for less unsustainable futures, is in prospect. Environmental modeling, and those who construct and use models, may increasingly be drawn into the unfamiliar territory of unusual and novel questions of ethics.

***Challenge # 12*: Community Structure**

Looking across the ***Grand Challenges*** now expressed, each calls for investments in changing habits of mind as much as in equipment, computing, specialized field campaigns, and so on. We ask therefore:

> ***What steps can the community of model-builders in the Environmental Sciences take to pre-empt and reduce to a minimum the still readily apparent scope for re-inventing the "wheels" of modeling in contemporary research across the various disciplines of the EOs? How can our community best be organized so as to benefit as much as possible from novel developments in modeling in general, as they arise in, for example, the quite disparate disciplines of the biomedical sciences, social sciences, cognitive sciences, artificial intelligence, and artificial life? More broadly, how should the community of modelers best work with the community of primary field scientists to promote the development of models for basic scientific discovery at the interfaces amongst multiple disciplines? In the light of universal and ever-more urgent calls for profound changes in the manner in which the next generation of scientists and engineers is educated, trained, and formed — all of which calls focus on "inter-disciplinarity" — what special role can models serve in meeting these needs?***

RECOMMENDATIONS

Two general and then two specific recommendations follow.

***Recommendation # 1*: Within Community Orchestration: Substance Not Form**

Models, as the *lingua franca* for communicating amongst the Ocean Sciences, Ecology, Hydrology, and Environmental Engineering, are integral to our becoming inter-disciplinary.

> ***Having brought a significant proportion of the community together, through a Workshop, and now — by virtue of the literature reviewed herein — this* White Paper*, it would be a missed opportunity not to provide the wherewithal for the continuing active maintenance, development, and scientific prosperity of the modeling community under the EO initiatives.***

Inasmuch as not all of us have the talents for becoming an astronaut or brain surgeon, not everyone is suited to engaging fully and effectively in inter-disciplinary work, including when the object of enquiry is the development and application of models. Substance, as in recognizing and cultivating an appropriate set of "people skills", may be more important than the organizational and administrative form of community orchestration.

***Recommendation # 2*: Cross-Community Communication: Attaining The Bigger Picture**

The mathematical methods of modeling, like the software and algorithms of an environmental cyber-infrastructure, can seem opaque and impenetrable when radical inter-disciplinarity and cross-communication are called for, between the technical expert and the technically lay person, even when seemingly so little as the divide between the field science and the modeling must be bridged. The oft-heard plea to "Let the data speak for themselves" is revealing of the attitudes of other professional scientists towards modeling and modelers.

Given that modeling cannot proceed in a vacuum, detached from reality, case studies and case histories should be prepared and packaged in forms designed to serve the ever-present need of the modeling community to build and maintain fruitful relationships with a variety of other communities — of philosophers, scientists, engineers, scholars, policy-makers, and the public — in developing the beginnings of responses to the Grand Challenges.

Environmental modeling has now a history of at least four decades to look back upon. This is long enough for us to discern the significance — or otherwise — of models: from their role in the philosophy of science and the growth of knowledge, to that in the successive and "jerky" exchanges between Science and Policy, such as those recorded in Dennis (2002) and Schertzer and Lam (2002). The very struggles within our own community, to attain that strategic sense of the "big picture", should facilitate its articulation in a variety of more comprehensible forms for a variety of audiences. It is time to engage in such struggles.

Recommendation # 3: Models for Design/operation of the EOs

Given the maturity of Observing System Simulation Experiments (OSSEs), and their obvious potential role in the design of all the Environmental Observatories, investment in the work needed to respond to this facet of Challenge # 6 is recommended. In seeking progress on a variety of fronts, however, such investment should be directed beyond the pragmatic needs of EO design, for example: to furthering the social and professional aspects of bridging any divides between the field-science and model-building communities; and to propelling OSSEs as much as possible beyond the current state of their art.

As generally understood in an OSSE, simulation is based on sets of differential equations as representations of the observed system's behavior. Developing schemes of OSSEs founded upon the Individual Based Models (IBM) typical of Ecology appears to remain as yet an essentially untouched domain of research.

Recommendation # 4: Training the Next Generation

Having argued a case in favor of the special role of models, as the* lingua franca *of inter-disciplinary research, we recommend investigating the merits of complementary alternatives to vehicles such as NSF's Integrated Graduate Education Research and Training (IGERT) schemes for the purpose of training the next generation of environmental modelers.

We would not want to pursue any alternative, however, without a systematic prior assessment of how young researchers mature to become leaders of inter-disciplinary thinking.

CONCLUSION

Models need data for their evaluation. Essentially, we wish to know whether the model approximates well enough the behavior of the real thing. Imagining a future with High Volume High Quality (HVHQ) streams of data emanating from the Environmental Observatories is to look beyond a "nonlinear" break with the terms and conditions under which Environmental Modeling has labored in the past. Reconciling Very High Order Models (VHOMs) with the HVHQ data of the EOs, in the workspace of the future environmental cyber-infrastructure attuned to provoking new knowledge, has thus the air of a ***Grand Challenge*** that is *primus inter pares.*