Climate and ecosystems of high northern latitudes are now changing so rapidly that their comprehension and predictability have become strong priorities for Earth system research (e.g., Hinzman et al. 2005; Wang and Overland 2009). These changes differ markedly from those inferred from many current global climate models, and there are considerable limitations in our understanding of high-latitude climate sensitivities (Rind 2008). Reasons for these inadequacies may reside along interfaces and coupling channels of the total system, including biogeochemical, ecosystem, and human components that are not included in most current climate models. Furthermore, a unique opportunity now exists to apply outcomes from observational studies undertaken during the International Polar Year (IPY) 2007–09 to improve understanding of physical–biogeochemical–ecological–human interconnectivity in the Arctic using complex system models. These factors provided the motivation for this community workshop, held by the University of Quebec at Montreal (UQAM), International Arctic Research Center (IARC), and Swedish Meteorological and Hydrological Institute (SMHI). Meeting deliberations focused on the future configuration, development, and implementation of high-resolution, integrated environmental system models of the Arctic and surrounding regions.

The meeting explored possibilities for international collaboration in the development of regional Arctic system models (ASMs). They are being developed in several countries and have been identified as agents for understanding physical–biogeochemical–ecological–human interconnectivity of high northern latitudes. ASMs are rapidly evolving from coupled, regional climate models to include sophisticated biogeochemistry, marine and terrestrial ecosystems, atmospheric chemistry, and aerosols. Some researchers are also looking to incorporate glaciers, ice sheets, hydrates, and human-system components into ASMs within the next five years.

ASMs can generate a unique spectrum of limited-domain model states with varying complexity to target important coupling paths affecting variability and rapid change. ASMs are also an ideal platform for downscaling global climate projections so that human–environment interactions can be nested within Earth system simulations. These noteworthy features have stimulated a growing network of regional Arctic modelers to forge stronger ties.

The previous Arctic System Modeling Workshop, sponsored by IARC, was held in Boulder, Colorado, in May 2008. It culminated in a blueprint for a community ASM (CASM) to resolve finescale Arctic processes and to develop and improve upon methods used for global Earth system modeling near the poles (for workshop participants, deliberations, and
outcomes of the 2008 meeting, see online at www.iarc.uaf.edu/workshops/2008/arctic_system_model_08). CASM would be a high-resolution (1–10 km), nested entity of a global coupled ocean–sea ice–atmosphere–terrestrial model, focusing on Arctic problems with a 5-yr timeline for the concurrent simulation of boreal biogeochemistry, marine and terrestrial ecosystems, atmospheric chemistry, and aerosols. A longer time horizon is anticipated for the coupling of glacier, ice sheet, nonbiogenic gases, hydrate models, and human-dimensions modules (see Fig. 1). A key focus of the project would be the use of CASM for probabilistic downscaling of global model projections to help understand Arctic change, variability, and complexity. It would provide an open-source platform for cross involvement of observationalists, regional and global modelers. However, the best way to incorporate international involvement in this U.S.-driven proposal remained unclear at the Boulder meeting.

Montreal workshop organizers posed several questions to meeting delegates on how best to coordinate several parallel ASM efforts, including CASM. Would it be worthwhile to establish an international committee to facilitate regular intercomparison of different ASMs? Would this help identify common problems in simulating the Arctic system? To what extent is international collaboration desirable and feasible in the development of ASMs and their component models? How can ASMs be used to better quantify uncertainty in future environmental scenarios of the Arctic, and how can we improve the way we communicate these projections to civil planners, indigenous groups, defense analysts, and industry?

Representatives from groups in the United Kingdom, Canada, Denmark, Germany, Norway, Sweden, and the United States briefed the Montreal meeting. They covered topics on recent developments in coupled regional Arctic modeling, Arctic assimilation, uncoupled global modeling with Arctic-focused grids, model evaluation projects, and emerging modules and model components (a list of participants, the agenda, and presentations for the 2009 meeting are available online at www.iarc.uaf.edu/workshops/2009/arctic_system_model_09). These reviews highlighted omissions in current-generation regional coupled models that are especially relevant to the future direction of regional Arctic system modeling: rapid retreat of ice sheets and glaciers will significantly impact the Arctic but are missing entirely from coupled simulations; ocean ecosystems simulated in regional models are configured as biogeographically specific mechanisms potentially incompatible with boundary conditions from global models; atmospheric particulates and photochemistry were missing from all models represented at the meeting despite their relevance to cloud physics, soot deposition, and pollution monitoring; albedo-changing dynamic vegetation models are in their infancy and only one important biogeochemical flux (carbon) was represented in simulated high-latitude terrestrial ecosystems; and, though it remains a distant possibility for inclusion in ASMs, methane release through permafrost degradation and ocean floor geochemistry could alter projections of Earth’s future greenhouse gas budget. Also, numeric tools for comprehending human–environment interactions in the Arctic are underdeveloped. However, these “human dimension” modules are crucial for communicating societal impacts and model uncertainties to decision makers. These challenges provided context for discussions on scientific strategy.

There was strong consensus that regional, high-fidelity Arctic models must soon extend beyond purely physically based coupled regional climate simulations to incorporate sophisticated chemistry and ecosystems. Regional Earth system models have been advocated by many researchers (e.g., Giorgi 1995; Leung et al. 2003), and workshop delegates agreed that the resolution offered by ASMs will make them a useful tool for developing and refining polar parameterizations for future global Earth system models. However, caveats were voiced by several scientists at both the Boulder and Montreal meetings about the key purpose of developing numerical tools for investigating the Arctic: foremost, our ability to answer questions about high-latitude environments rests in tools that explain
interconnectivity rather than those that simply increase resolution inside set geographic boundaries. The list of prospective model additions in the previous paragraph all demand high resolution, but many will also introduce nonlinearities that will be difficult to fully comprehend in global coupled simulations. For this reason, there is a growing trend to analyze complex planetary phenomena using a mix of sophisticated, global models and simplified process integrations (e.g., Merryfield et al. 2008), and this is where ASMs are most likely to contribute significantly to Arctic research: They offer a platform to break down complexity using a spectrum of model states ranging from uncoupled, mesoscale, reduced-physics integrations to one-way, nested, regional coupled models using both low and high resolution, finally leading to analysis and inclusion of processes in global simulations. Therefore, meeting participants agreed that the key to an integrated understanding of the system is flexible ASM configurations that can be tailored to individual science questions.

ASMs also provide a unique ability to downscale information from global simulations to understand human–environment interactions. Economic modeling was presented to the workshop that placed a value on Alaskan infrastructure changes based on climate model projections. This demonstrated the benefit of a closer alliance between human-dimension researchers and regional Arctic modelers, and there was consensus that human-system module development should receive greater attention, especially in the areas of economics, fisheries, and subsistence living. This integrated approach to the study of climate impacts would provide better capabilities for quantifying the likelihood of possible changes in these sectors. A strong push was made to designate several pilot projects for interactive coupling with ASMs, of which one concept seemed best prepared: the modeling of Arctic water resources, influenced by and feeding back to hydrologic pathways in coupled, regional simulations.

With the outcome of these discussions in hand, two key recommendations were made at the Montreal meeting. First, several nations with strong Arctic interests are moving quickly toward ASMs and there is an informal and growing network of research groups involved in the field. This network offers great potential to spearhead future developments, and it should be supported by regular workshops targeting common problems in constructing and coupling emerging model components and understanding the Arctic system as a whole. A grass-roots committee formed by those most actively involved in model development should coordinate the network. Second, an ASM synthesis hub should also be established at an international research institute. This could take the form of an internet portal that would facilitate centralized sharing of model output, ASM evaluation methods, and tailored observational datasets to help identify common model deficiencies. It could also provide tools to help use ASMs to target prime locations for in situ instrument deployments, addressing chronic Arctic undersampling.

As a result of the Montreal meeting, the final component of the draft CASM plan first penned at the 2008 Boulder meeting was also decided. A framework for international collaboration has been established and has been incorporated into the community ASM science plan (Roberts et al. 2010). It is anticipated that researchers working toward an open-source community model will join the already sizable international network represented in Montreal, working to create new tools to understand and communicate complexity, variability, and change in the Arctic.

ACKNOWLEDGMENTS. The authors gratefully acknowledge the contributions of 166 researchers who have organized, participated in, and reviewed reports from the
ASM workshop series. We also thank the National Science Foundation Office of Polar Programs (OPP 0652838), the Canadian Foundation for Climate and Atmospheric Sciences, Study of Environmental Arctic Change for Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies (SEARCH for DAMOCLES), and the International Arctic Science Committee for financially supporting the Montreal workshop. Thanks to Jennifer Moss for assisting in the preparation of Fig. 1 and supporting online material.

REFERENCES


