

CRUCIAL EXPERIMENTS IN CLIMATE SCIENCE

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Computational experiments at the frontiers of our technological capabilities will require unprecedented community planning and coordination, essentially changing the way in which climate science progresses.

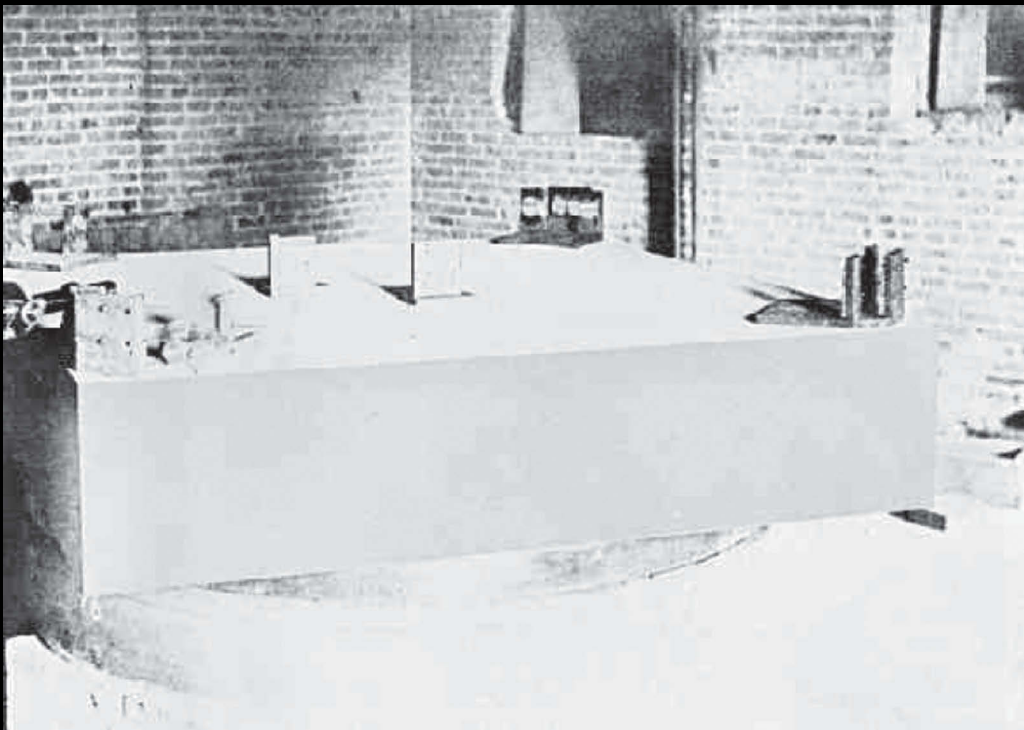


FIG. 1. The experimental setup of the Michelson–Morley experiments. This experiment rejected the aether hypothesis, opening the way for special relativity.

There is a delicate web of interactions among the different components of the climate system. The interplay among the time scales is quite intricate, as the fast atmosphere interacts with the slow upper ocean and the even slower sea ice and deep-soil and groundwater processes. Spatial scales are tightly connected too, as small-scale cloud systems, for instance, affect the large-scale energy balance. Furthermore, everything is connected by water in its various forms. Water flows easily from place to place and exchanges energy with the environment every time it changes phase. Evaporation, condensation, freezing, and melting processes must be taken into account and evaluated as accurately as possible. The past 40 years of climate simulation have made it apparent that no shortcut is ►

possible; every process can and ultimately does affect climate and its variability and change. It is not possible to ignore some components or some aspects without paying the price of a gross loss of realism.

Given the richness and intricacy of the climate system, stressing the interdependency and feedbacks, the sensitivity to small-scale processes and their effects, and the multiscale interactions and their far-reaching consequences, the full consideration of the climate system can be overwhelming. It is not clear how to consider the problem scientifically, that is, how to apply the scientific method to a system so inherently interconnected and so inseparable. This is the major challenge for climate dynamicists today.

A strict application of the scientific method requires a process of isolation of constituent subsystems and experimental verification of a hypothesis. For the climate system, this is only possible by using numerical models. Such models have become the central pillar of the quantitative scientific approach to climate science because they allow us to perform “crucial” experiments under the controlled conditions that science demands. Sometimes crucial experiments are recognized as such at the design phase, like the quest for the Higgs boson currently going on at the European Organization for Nuclear Research [Conseil Européen pour la Recherche Nucléaire (CERN)]. Other times it is only in historical perspective that some experiments are recognized as truly “crucial.” This was the case of the 1887 test by Michelson and Morley that rejected the hypothesis of the existence of the “luminiferous aether” (Tipler and Llewellyn 2003), an undetected medium through which light was deemed to propagate (see Fig. 1 on title page; http://quantumrelativity.calsci.com/Relativity/images/Michelson_Morley.jpg). Their result led to a reformulation of a physical theory of electromagnetic radiation and to special relativity and the invariance of the speed of light. “Crucial” experiments test competitive theories and the most successful one is finally selected.

Historically, science has progressed through the continuous interplay between theory and experiment, with hypotheses being initiated and challenged by new experimental observations. Up to the middle of the twentieth century, experiment and observation were restricted to the realm of what might be feasible in a physical experiment, effectively limiting the geosciences to observations without the capacity for controlled experiments. With the advent of the electronic computer, a third branch of scientific development—modeling—was added to theory and observation. John Von Neumann recognized the computer as the ultimate tool to investigate nonlinear problems like hydrodynamic turbulence, weather prediction, and climate simulation. Indeed, modeling has become invaluable in climate science, helping to elucidate the physical mechanisms that are important in coupled air–sea phenomena like El Niño–Southern Oscillation (ENSO), troposphere–stratosphere interactions like the quasi-biennial oscillation (QBO), and stratospheric sudden warmings (SSW). These are just a few of the prominent climate successes in the fusion of modeling to theory and observation. Numerical models have become our main investigative tool in climate science. Nearly a half century has passed since Lorenz (1967) wrote his famous monograph on the general circulation of the atmosphere absent a single model example. Given the complexity of climate, the investigation of climate science will probably rely more and more on numerical models.

The organization of this type of research has remained relatively stable, even if the complexity has steadily increased. Separate groups build the separate components of models, but basically climate science has stayed close to a “laboratory” style of operation, in which constructing and assembling models is like working in a small shop where everybody does a little bit of everything, like building a mechanical experimental apparatus.

The difficult challenge we face in climate dynamics is how to understand a complex, highly sensitive system. A number of strategies have been devised, relying on ensemble methods, accurate numerical descriptions, and completeness of processes and subsystems. Models have been extended to include more processes, with higher spatial resolution, and consequently shorter time steps. Nonetheless, the execution of new experiments requires a highly trained workforce using massive amounts of computational time and resources.

A new generation of computing systems will be composed of hundreds of thousands, perhaps millions, of processing elements and will enable

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numerical experiments on an unprecedented scale. The number of processors in these petascale systems is so radical that they may require new languages and a new programming paradigm. Numerical experimentation on these systems will accelerate climate research, but it will also require a change in the way modeling experiments are conceived and carried.

This paper suggests some components of the new level of organization and the method to design, select, plan, execute, and analyze numerical experiments on such complex computing and data management systems.

NUMERICAL MODELS AS EXPERIMENTAL TOOLS. To use ENSO as an example, Gilbert Walker first recognized the Southern Oscillation in his observational analysis in the early 1900s. The air–sea coupled nature of El Niño was revealed in the 1960s by the analyses of Bjerknes (1966). However, a theoretical understanding of the dynamics of the transition from one phase of ENSO to the next was still missing. That the transition mechanisms were related to oceanic equatorial wave propagation became apparent through the theoretical and modeling studies of Moore (1968), Anderson and McCreary (1985), Inoue and O’Brien (1984), McCreary (1976), Cane and Zebiak (1985), and Schopf and Suarez (1990). These works demonstrated the potential synergy among modeling, theory, and observations that permits hypotheses to be tested in isolation from the complexities of the natural climate system. Out of these efforts came the predictive capabilities of the Cane–Zebiak model and the understanding of ENSO phase transitions as a delayed oscillator. Further refinement of our understanding of ENSO evolution reduced modeling experimentation to the requisite accuracy with which air–sea coupling must be captured in comprehensive atmosphere–ocean general circulation models (AOGCMs). Even though the complexity of AOGCMs rivals that of the natural system, the great advantage of such fully coupled models lies in our ability to perform controlled experiments in such systems and the complete analyzability of the results. From comprehensive modeling studies, our scientific understanding of ENSO has grown to include the recharge–discharge paradigm (Jin 1997) and allows us to appreciate the importance of the eastern boundary stratus shield in maintaining both ENSO variations and the seasonal cycle of sea surface temperatures in the tropical Pacific.

Analogous developments occurred in the evolution of our understanding of SSWs. Charney and Drazin initiated theoretical ideas concerning the importance

of vertically propagating planetary waves and their absorption, and a complete theory eventually combined this work with the critical layer absorption mechanism of Booker and Bretherton (1967). This theory was proposed and tested mechanistically in a quasigeostrophic model by Matsuno (1971). As a consequence of this preliminary exploration of the understanding of the necessity of vertical-resolution and dissipative processes, both AGCMs and NWP models regularly began simulating and predicting SSWs from the early 1980s on (Boville 1984). A similar path led to the simulation of the stratospheric quasi-biennial oscillation: the early theory was developed by Holton and Lindzen (1972), laboratory modeling was accomplished by Plumb and McEwan (1978), and the full development within climate models was only recently accomplished by Giorgetta et al. (2006).

Because of the multiscale nature of climate dynamics, the impact of increasing the resolution of simulations afforded by increased computing power is often much greater than what might be expected by analysis of the truncation error. Higher resolution models can resolve new phenomena and thus account for the nonlinear interactions of these phenomena with the coarse-scale motions. A recent example has been the incorporation of sufficient ocean resolution to adequately simulate the tropical instability waves, which develop on the equatorial current in the Pacific. The signature of these waves is present in the sea surface temperature (SST), which modulates the atmospheric boundary layer stability, vertical mixing, and (consequently) the surface stress (Navarra et al. 2008). Simulation of this interplay in coupled models has decreased the systematic biases of the seasonal cycle of SST in the eastern equatorial Pacific and, consequently, reduced some of the biases in ENSO simulations (Jochum et al. 2005). Similarly, precipitation simulations improve whenever horizontal resolution increases in mountainous areas, better resolving the terrain-induced vertical motions. The improvement is seen not only locally but also downwind because of the more accurate advection of water vapor.

A final example of increased computational capacity helping advance science is in ensemble predictions and simulations. Prior to the 1980s, computational capacity was so limited that numerical models were integrated not only at marginally useful resolutions but also as a single realization of a weather forecast or climate simulation. Since the early 1990s, operational weather forecasts at both the National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF) have incorporated ensembles to

quantify the uncertainty of predictions and identify predictable signals in the state variables. Ensemble prediction has not only permitted advance warning of potential weather extremes like the Christmas Eve Lothar storm of 1999 by ECMWF (Shapiro and Thorpe 2004), but also allowed successful probabilistic seasonal predictions of the atmospheric effects of strong ENSO events. Such successes allow us to understand the role of initial data uncertainties and errors in forecasts as well as the inadequacies of our current models. Additionally, multimodel variants of ensemble techniques can maximize the skill in both weather and climate predictions (Krishnamurti et al. 1999). With the ability to span the range of both likely initial conditions and model physics uncertainty, we can optimize the utility of the weather and climate predictions by more accurately depicting their uncertainty.

NEW PHYSICS IN THE FUTURE. The essence of climate modeling in the twenty-first century is the dynamic interaction among components and among spatial and temporal scales. The prevailing view is that such a complex problem can only be adequately addressed with a hierarchy of models simulating the relevant processes on the appropriate scales. Models of the components of the climate system (global atmosphere, world oceans, cryosphere, land surface, and biosphere) have been developed almost exclusively in isolation from one another. Taken as a whole, these models include the processes that determine the evolution of climate components (large-scale fluid dynamics, turbulence and mixing, convection, radiation, land-surface hydrology, etc.). Some models include most of these processes; however, many other processes may be important (groundwater flow, atmospheric chemistry, biogeochemistry, marine and terrestrial ecosystems dynamics, weathering, etc.) and no single model incorporates all the relevant processes.

Each of the component models and the presumed model that incorporates all relevant components is based on physical laws developed through laboratory experiments and observations of nature. For example, the large-scale motions of the atmosphere and oceans are presumed to obey Newton's laws of motion and conservation laws for mass, energy, and momentum. When these laws are expressed mathematically, the equations describing the evolution of the system are typically nonlinear, coupled partial differential equations for which closed analytic solutions are not available. Therefore, the equations are represented with numerical approximations and integrated on high-speed computers.

Because the equations are complicated, and because the numerical solution methodology typically involves decomposing the spatial domains into small parts (grids) and solving the equations on each part separately, very sophisticated algorithms executed on high-performance computers are required. The available capability of the current generation of supercomputers limits the complexity, resolution, and integration duration of models.

The resolution requirements for accurate representation of biogeochemical cycles and biogeophysical processes have not been thoroughly investigated. However, it is clear that ecosystem models and atmospheric chemistry models are very sensitive to sharp gradients in the physical climate system, such as the thermocline in the upper ocean, the elevation and orientation of the land surface, or variations in precipitation (Denman and Gargett 1983). This suggests that accurate ecosystem simulation requires very finescale physical climate resolution.

Recognizing these issues, the World Climate Research Programme (WCRP) has recently adopted a new strategy for unifying its diverse research activities. This framework for a Coordinated Observation and Prediction of the Earth System (COPES; <http://copes.ipsl.jussieu.fr/>) is an ambitious, decade-long observing and modeling activity, with the ultimate objective of providing the soundest possible scientific basis for predicting the total climate system. The framework calls for an integrated approach in which the atmosphere, ocean, land, and cryosphere are considered in comprehensive models capable of assimilating weather and climate observations.

The continuum of prediction problems, from weather to climate and days to decades, will be addressed by a hierarchy of models that should become increasingly structurally similar to one another, merging eventually into "unified models" with common infrastructure and interchangeable parameterizations. This fact, when considered with the anticipated increasing international coordination of model development, integration, and analysis, implies that the modeling and model output data management challenges will be very large. The COPES framework calls for global models to be run with a "resolution of a few kilometers (as required for many practical applications), very large model ensembles to assess uncertainty, simulations of paleoclimates with fully coupled global climate models, and highly resolved regional models in response to the demand to develop adaptation policies and measures at the regional level" (World Climate Research Programme 2005). The increasing resolution, complexity, ensemble size,

and run duration of these climate prediction systems represent a fundamental challenge to the evolving capability of high-end computing.

Incremental refinements in weather and climate models yield incremental improvements. The dramatic increases in model fidelity proposed in the COPES vision will make possible fundamental breakthroughs in model design. Perhaps most importantly, it will be possible to resolve phenomena that are currently parameterized. For instance, cumulus convective and large-scale cloud processes are usually separately parameterized. At the kilometer scale, cloud microphysical models can unify these phenomena into a prognostic cloud-system submodel (Randall 2005; Randall et al. 2003).

In the middle atmosphere, there is a requirement to resolve the relatively fine structure of potential vorticity and the radiatively and chemically active species. Near the surface, the turbulent atmospheric boundary layer must continue to be parameterized, but with much more defensible schemes that depend on large-eddy simulation closure results with $O(10\text{ m})$ scale resolution or that realistically represent the stochastic nature of turbulence.

The details of orography, vegetation, and land cover are important for water resources and must be resolved. Near the surface of the ocean, turbulence in seawater, currently only represented in terms of thermally stratified flows, must also include the effects of salinity. Access to these scales in the 10 m to 10 km range will afford more realistic representation of atmospheric features (e.g., tropical cyclones), oceanic features (e.g., warm- and cold-core eddies), and land-surface characteristics (e.g., landscape-scale features and gradients) and the potential to improve prediction of severe weather, extreme weather and climate events, and large, long-lasting climate anomalies.

Trends in numerical weather prediction and climate simulation. There have been no revolutionary changes in numerical models of climate since their advent over 30 years ago. The models make use of the same dynamical equations, with improved numerical methods, and have comparable resolution and similar parameterizations. Over the past 30 years, computing power has increased by a factor of 10^6 . Of the million-fold increase in computing capability, about a factor of 1,000 was used to increase the sophistication of the model. Model resolution, the inclusion of more physical and biogeochemical processes, and more elaborate parameterizations of unresolved phenomena have all been modestly improved.

In the atmospheric component models, the horizontal resolution has quadrupled, and the number of layers has tripled. At the same time, models have increased in complexity through the addition of processes beyond the basic dynamics and thermodynamics of the atmosphere and ocean. For example, the inclusion of models of chemical reactions to simulate the creation and destruction of species in the atmosphere that may be radiatively active or that may interact with water vapor in the formation of cloud droplets, ice crystals, or raindrops is a relatively recent model development. The models used to simulate climate variability now include modules for atmospheric chemistry, atmospheric aerosols, land-surface vegetation and terrestrial ecosystems, the carbon and nitrogen cycles, and marine ecosystems.

The remaining factor of 1,000 increase in computing power was used for longer and more numerous runs of the numerical models. In the early 1970s, numerical weather predictions were extended to two weeks (Miyakoda et al. 1972). In the early 1980s, 30-day (Miyakoda et al. 1983; Shukla 1981) and in the early to mid-1980s 90-day climate simulations were attempted (Shukla et al. 1981; Kinter et al. 1988). In the mid-1980s, simulations of ENSO were made (Philander and Seigel 1985; Cane et al. 1986), and fully coupled general circulation models were used to predict interannual climate variations in the 1990s (Ji et al. 1994). Similar relative increases in model integration length have been made in paleoclimate and global change simulations. More numerous runs are primarily made to increase the ensemble size to provide a measure of the uncertainty in a given weather or climate forecast, and there have also been some experiments with very high-resolution models (Hamilton and Ohfuchi 2007).

These trends indicate that the problem of weather and climate modeling can be organized in terms of four dimensions: resolution, complexity, integration length, and ensemble size. Each of these competes for computational resources. (Some suggest that, because it also competes for resources, data assimilation represents a fifth dimension of this problem.) The current capability in high-end computing at any given time describes a boundary on what can be achieved in these four dimensions. However, there are some dependencies among the four dimensions. Some advances in complexity cannot be attempted until a certain threshold of resolution is achieved. One example is the full simulation of oceanic biogeochemical cycles, which requires resolving oceanic eddies.

High-end computing performance is expected to continue to improve. The peak speed of in-

dividual processors is expected to increase to ~30–50 gigaflops,¹ taking into account trends in chip design. Beyond that, the size limitations at the molecular scale will prevent further speedup unless radically new technologies become available. Future high-end systems can be expected to integrate well over 100,000 processors in a single system, assuming a higher degree of process parallelism than currently used.

It should be noted that weather and climate models, like other fluid dynamics applications, can be constructed to favorably scale to these numbers of processors at the very high resolutions envisioned in the COPES strategy (Oliker et al. 2005). However, the processors must be substantially faster than current technologies to overcome the superlinear scaling of operation count dictated by the Courant–Friedrichs–Levy stability condition.

Highly complex, high-resolution models can be expected to require $O(10^{17})$ operations per simulated day, which means that to achieve a 1,000-fold ratio of simulated time to wall-clock time, ~1-PF sustained capability [i.e., $O(10)$ PF peak performance] will be required. Assuming that 1-PF sustained performance can be achieved by 2011, then an ensemble of 30–40 members of a 17-km global hydrostatic AGCM coupled to an ocean general circulation model (OGCM), each with ~100 levels, or an ensemble of 25 members of a 5-km global nonhydrostatic NWP model coupled to an OGCM, each with ~100 levels, can be completed within a typical 3-wall-clock-hour supercomputing window.

If such advances can be made in the next 3–5 years, the progress beyond that can be even more exciting. One can envision that the weather and seasonal climate prediction model of 2015 will be a coupled global ocean–land–atmosphere–cryosphere model with a cloud-system-resolving atmospheric component, an eddy-resolving ocean component, both possibly on unstructured, adaptive grids, and a landscape-resolving land-surface component, fully initialized with the satellite-based, high-resolution observations of the global Earth system.

In order to have the necessary computational capability for seamless weather-to-climate, days-to-decades modeling in support of COPES objectives, it has been suggested that the WCRP encourage the development of an international strategy to address the gap between the scientific requirements for, and the availability of, high-end computational resources.

Such a strategy must articulate the scientific case for an international investment in breakthrough computing capability. The World Modelling Summit for Climate Prediction (<http://wcrp.ipsl.jussieu.fr/Workshops/ModellingSummit/index.html>) held in May 2008 in Reading, United Kingdom, under the auspices of the WCRP, World Weather Research Programme (WWRP), and International Geosphere–Biosphere Programme, advocated just such an international program (Shukla et al. 2009).

To achieve a seamless weather-to-climate prediction capability, such as is described by (Hurrell et al. 2009), will require substantial effort across all components of simulation-based research. Resources will have to be devoted to developing, porting, and optimizing weather and climate model application codes to achieve the necessary execution rate of simulation for the target computing architectures. Resources will have to be balanced with respect to computation, mass storage access, and postprocessing support for exabyte-volume datasets as well as visualization. Realizing the vision will also require attention to many aspects of high-end computing, including computing hardware (architecture, data storage and archival, networking, etc.) and software (operating systems, compilers, data management systems, and visualization tools), power, cooling, and infrastructure. Success will more likely depend on the development of new codes expressly intended for these high resolutions than on reengineering existing models. In addition, there is a significant requirement for highly skilled, well-trained human resources to support multiple models and modeling groups at remote locations.

Increasingly, century-long climate projection will become an initial-value problem requiring the current observed state of all components of the Earth system: the global atmosphere, the world oceans, cryosphere, and land surface (including physical quantities, such as temperature and soil moisture, as well as biophysical quantities, such as leaf area index, etc.) to produce the best projections of the Earth system and also giving state-of-the-art decadal and interannual predictions. The shorter time scales and weather are known to be important in their feedback on the longer-time-scale behavior. In addition, the regional manifestations of longer-time-scale changes will be felt by society mainly through the changes in the character of the shorter time scales, including extremes. For example, the well-known features of

¹ Computer performance in modeling applications is typically measured in floating point results per second (flops); a megaflop (MF) is 10^6 flops, a gigaflop (GF) is 10^9 flops, a teraflop (TF) is 10^{12} flops, and a petaflop (PF) is 10^{15} flops.

the climate that operate on interannual time scales, such as ENSO, are likely to be the agents of change in a greenhouse-warmed climate. Also, distributions in space and time of weather extremes, such as floods and tropical cyclones, are likely to be the most obvious (and costly) manifestations of global climate change.

A NEW PARADIGM—NUMERICAL MISSIONS.

Numerical missions. University departments and public and private nonprofit research laboratories have been at the forefront in the formulation and generation of numerical models for climate and weather. These developer groups have rarely been larger than 10–20 members each. Often, the entire effort has relied on even smaller subsets of dedicated scientists who personally took the responsibility to put together the models. This required an understanding of atmospheric and ocean dynamics and the equations describing them, extensive numerical capability, and of course programming knowledge. However, it is clear that we are approaching a point in which the amount of computer science knowledge required is getting to be more than what climate scientists can learn “on the side.” Weather services have already deployed software engineering groups to develop the special software. In the research/academic environment, this is not the case: models are still developed and maintained in a more casual way. The exception has been the development of community models that have been prepared by small groups and distributed to the larger community of users. Centralizing the development of the models has allowed more resources to be devoted to the software engineering and other model development needs that are not specifically climate or weather dynamics.

The usage of the models also has been very unstructured. Scientists typically have free access to the system that is limited only by the competition for resources among different projects. Students can work on their theses on the same system where large simulations are being performed.

Petascale computing is likely to change this situation. Numerical projects will separate into those too small to be worth implementing on a petascale system and those large and important enough to be critically dependent on the petascale system, because they cannot be done anywhere else [see the National Science Foundation (NSF) Petascale Computing Resource Allocations online at www.nsf.gov/pubs/2008/nsf08529/nsf08529.htm]. We are entering an era of “industrial computing” that will involve specialization, coordination, and detailed planning. Certain

tasks that have been traditionally performed by scientists, like executing and supervising the simulations on the machine, probably will be given to specialized parties and/or organizations, or possibly outsourced.

It is from these large experiments that we expect to gain the greatest advances in our knowledge of climate. They will be large, complex endeavors, dealing with data volumes and movement several orders of magnitude larger than today. They will have to be managed and selected carefully—spur-of-the-moment experiments may no longer be possible—and different expertise will have to be gathered for the planning, design, programming, execution, and analysis of these experiments. In fact, the process will look more like the development of a space mission: these computing experiments will be *numerical missions*. One example of such a numerical mission is described in Shapiro and Thorpe (2004). The improved organization will allow scientists to concentrate on science issues, freeing them from the technical task of final execution of the experiments.

We cannot expect that experiments on a petascale system will be repeated several times, and we cannot expect to have many experiments of this scale during the lifetime of a machine. It will be necessary to organize the scientific community to produce the ideas for the experiment, define the large collaboration necessary for their execution, and then select the most promising case on which to perform the experiments and analyze the results. Such a system is common in the astrophysical community for large telescopes or new space missions, and the same process has shaped the high-energy physics community, which shares large particle accelerators. In some sense, the petascale system is the equivalent of a large particle collider, and we need to update our organizational model to adopt this paradigm.

A possible scheme of research organization. The execution of these numerical missions will span several years, from concept to final analysis, and they will probably also need a decommissioning phase as the complex infrastructure built for experiment, data warehouses, storage, offices, and so on is disbanded and transformed into the structure necessary to maintain and service the data warehouses for the follow-up scientific exploitation, as is happening with the much smaller archives of the Intergovernmental Panel on Climate Change (IPCC) experiments stored at the Program for Climate Model Diagnosis and Intercomparison (PCMDI). The proposed science will have to be resilient, that is, capable of providing exciting and original results over several years. We envision several phases.

CONCEPT STAGE. In the concept stage, the core scientific idea for the experiment is described in a very short document and a preliminary estimate of human, computational, and financial resources is prepared. Unlike the current proposal process, the concept stage will have to show that there is sufficient scientific merit and innovation to justify the following detailed steps, the consortium expertise is well balanced and complete, and there are some plans for the governance of the consortium. The ideas will have to leapfrog the normal pace of discovery as the longer gap between concept, realization, and fruition will require proposals that will keep a peak research value for several years. For instance, a central issue like cloud-resolving simulations is probably a good candidate as they will open new physics that will provide new results for the entire lifespan of the project and beyond.

SCIENTIFIC CASE. If the concept of the experiment has been found appropriate for a petascale experiment, the consortium will have to prepare a detailed scientific plan. This phase is different from the previous one as the science and experimental plan must be described in detail, in particular with reference to the time development, and major milestones will have to be identified and described. An analysis of pitfalls and possible critical points will be performed, and contingency plans will have to be considered. Methods of analysis of the results and expected evaluation metrics have to be discussed and proposed. The consortium description has to be further extended, making sure that all relevant expertise necessary for the project and the analysis of the results is present.

TECHNICAL CASE. The technical feasibility of the proposed research is discussed next, involving the precise definition of the numerical experiments proposed in order to evaluate the computing resources, storage requirements, and data reduction strategies. These issues are seldom necessary in a typical agency proposal today, but they will need to be considered very closely in a petascale proposal. Data reduction strategies, for instance, are usually not contemplated in advance, but they are essential to guarantee that the data are made available to the analysis investigators in a tractable form.

DETAILED MULTIYEAR PROPOSAL. A detailed multiyear final implementation plan will have to be prepared for the final evaluation. The plan will include a detailed schedule, a list of deliverables, and milestones for the project. A detailed list of products and the timing of their availability will also be included.

The era of industrial computing. The changes that we have described will usher in a new era of calculation on such a large scale that it will be comparable to the transition from the artisan shop to the modern factory: it will be the era of industrial computing. Issues like quality control, procedure certifications, and data integrity will no longer be the subject of discussions by researchers, but they will be matters of procedural control and monitoring. It will free climate scientists from much of the engineering work that is now necessary in the preparation of the experimental apparatus they are using in their laboratory but that is hardly necessary to the core of climate science.

It will also create some new problems. It is unclear at this point if the field is going to need more software engineers and programmers or fewer as the computing power is concentrated in larger and fewer centers. A new professional figure may emerge who will maintain the laboratory and the experiment as the routine day-by-day simulations, developing along well-planned lines, may stretch for months or years. Questions about how such professionals will be trained arise without obvious answers.

It is difficult to predict the full evolution of our field, but it is likely that scientists will have to be linked in new ways to one or more of these large consortia. For example, researchers will want to try out ideas on smaller-scale computational platforms, with a clear path to scale up to the petascale systems. Educators also will need to have access to the systems and engineers so their students can be trained in how to design and execute experiments that make use of industrial computing.

The price will be longer preparation periods, longer planning sessions, and a less-flexible simulation strategy, with less room for errors and rerunning, because of the complexity and the cost of the large computing system. There will be the risk of experiments whose science is already obsolete when they enter the realization phase. The reason for the extensive planning and preparatory discussion is because of the complexity and scope of petascale computations. We expect that experiments will last 4–5 years from inception to decommissioning, which is somewhat shorter than the time required to prepare a satellite mission, since the actual infrastructure will be already in place.

Reproducibility will be a problem, given the essentially unique character of each numerical mission, and probably some degree of overall coordination will have to be found, either domestically or internationally. On the other hand, the science will be more transparent in the formulation of hypothesis and

numerical strategies, and it will also be more efficient as a single numerical effort will allow several investigations at the same time. Many diagnostics and special analyses will be performed on the same basic numerical experiment, as has been done for climate change experiments, for example, the diagnostic subprojects of the WCRP phase 3 of the Coupled Model Intercomparison Project (CMIP3) experiment for the IPCC Fourth Assessment Report (www-pcmdi.llnl.gov/ipcc/diagnostic_subprojects.php). Field experiments and satellite missions sometimes work along similar lines, putting several instruments on the same platform to share the cost and address several research issues at the same time. The price for improved efficiency is more planning and more community discussion to select the projects that will be finalized. The modeling community will have to find ways to improve the internal debate that leads to the selection of the projects. This is a delicate point, as the issue here is not to add more and more layers of forms and bureaucracy but to make sure that a thorough scientific evaluation takes place before the fact, rather than after the work is done, as often happens today.

The discussions conducted for the simulations needed for the IPCC assessments have already gone in this direction, but they are still examples of a loose coordination, rather than the tight coordination that will be required by the petascale machines. The transition is similar to what happened in astronomy when that community went from coordinating observations at different telescopes to creating a consortium for the construction of one larger instrument. Industrial computing and numerical missions will rely on that capability even more to allow climate science to address problems that have never before been attempted.

The global numerical climate community soon will have to begin a proper discussion forum to develop the organization necessary for the planning of experiments in the industrial computing age.

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