focus on areas like auroral dynamics, storms, substorms, and radiation environments at different planets. The second initiative would focus on the end-to-end solar-terrestrial system. A prime example is the real-time global ionosphere campaign proposed by T. Fuller-Rowell (University of Colorado/NOAA Space Environment Center) to characterize global ionospheric variability as a function of season and geomagnetic activity. The campaign would reflect IHY priorities in several ways: it would cut across disciplines from solar to lower atmospheric physics, require data from many countries, address a global problem with high fidelity, have potential for discovery, and supply GPS systems to developing countries.

The suitability of global studies using widespread arrays of low-cost, ground-based instrument packages was echoed in other groups, notably in the working group on the heliosphere. Establishing a network of muon monitors and increasing neutron monitor coverage to gain latitudinal and longitudinal resolution were among the proposed possibilities. At the lowest end of the cost scale, J. Kasper described unique plans for thousands of low-frequency radio receivers. Like pixels in a snapshot, these could image the Sun and track evolving structures in the solar wind as they head toward Earth, while their Faraday rotation capabilities could map ionospheric parameters in unprecedented detail. Doing IHY science with widespread ground-based arrays has the added benefit of providing multinational educational opportunities. These would involve real-time data collection that could be incorporated into science programs around the globe.

The working group on the heliosphere also compiled a list of science questions concerning gaps in the overall understanding of our home star system, and designed potential IHY campaigns to address those questions. Primary among them is a three-dimensional study of the upcoming solar minimum compared to the previous minimum of opposite magnetic polarity. Using data from the existing spacecraft fleet, which constitutes a formidable heliophysical observatory, and working synergistically with the proposed network of small ground-based facilities, the study would create an unprecedented legacy data set completing the 22-year solar cycle. Another campaign would create a link to proposed atmospheric campaigns on the role of cosmic rays both in creating signatures of long-term climate variations and in controlling atmospheric parameters. A campaign to understand solar wind signatures of reconnection at the Sun would create a link to solar physics and reflect the theme of universal processes.

The theme of universal processes became the centerpiece of the report from the working group on the Sun. T. Forbes and S. Gibson summarized their efforts in a chart, shown in Table 1, that indicates processes common to an array of solar-related phenomena. In addition, the group proposed a number of potential IHY campaigns, some calling for much-needed coordination among existing ground-based observing facilities. For example, R. Moore proposed using the widely available H-α telescopes to address the perplexing problem of why some filaments fail to erupt.

All groups stressed the importance of working through existing programs like CAWSES (Climate and Weather of the Sun-Earth System) and groups like CEDAR (Coupling, Energetics, and Dynamics of Atmospheric Regions), GEM (Geospace Environment Modeling), and SHINE (Solar Heliospheric INterplanetary Environment), of maintaining existing spacecraft missions, and of promoting the development of comprehensive, long-term databases. All agreed to incorporate eGY as an intrinsic legacy tool. While the IHY will focus on campaigns that can be carried out during the celebratory year 2007, just as in previous international years, IHY activities will leave a foundation for future science and understanding.

Immediate follow-up to the workshop will include three special sessions at the 2004 AGU Fall Meeting on universal processes and structures, low-cost distributed instrument arrays, and education outreach opportunities.

The U.S. Planning Workshop for the IHY was held 20–22 April 2004 at the National Solar Observatory in Sunspot, New Mexico.

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The Ocean in a High CO_2 World

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It is now 25 years since the first papers appeared documenting by direct measurement the buildup of fossil fuel CO_2 in the ocean. In the past quarter century the situation has changed enormously. What was at first a controversial detection of a signal above a large natural oceanic background is now a huge and easily recognizable geochemical perturbation on a scale not matched for a large part of Earth's history. Earth's atmospheric concentration of CO_2 is now higher than experienced during at least the last 400,000 years.

The accumulated oceanic burden of fossil fuel CO_2 is now >400 billion metric tons. The net CO_2 gas invasion rate across the air-sea interface, driven by the growing global mean pCO_2 difference between air and sea, is now about 1 million metric tons CO_2 per hour, and the decrease in surface water pH is now about 0.1 pH units. The signal is detectable worldwide, and has penetrated to >1000-m depth. And simple extrapolations based upon well-recognized energy use scenarios, such as the Intergovernmental Panel on Climate Change (IPCC) IS92A "Business as Usual" projection, lead to oceanic pCO_2 levels of ~600 ppm, and a pH change of about 0.3, in the second half of this century with far greater changes possible in the future. Without the benefit of this massive disposal in the upper ocean of mankind's artifact of energy use, the world would face an overwhelming atmospheric CO_2 problem.

Yet the oceanic uptake blessing comes at a price, and that price may be paid by oceanic ecosystems facing changes in oceanic chemistry of unprecedented scale.

About 120 scientists met last spring at UNESCO headquarters, in Paris, under the auspices of the Scientific Committee on Oceanic Research (SCOR) and the Intergovernmental Oceanographic Commission (IOC) to review this problem, pose questions, and devise research strategies for the future. What are the possible oceanic consequences of no emissions control? Can oceanic iron fertilization strategies sequester significant quantities of CO_2? What might be the cost/benefit of direct deep-ocean CO_2 disposal as opposed to indirect surface disposal today? Finally, is the fundamental knowledge in place to provide wise counsel to society on these matters?

The Once and Future Context

M. Parry presented the projected climate impacts of no/some/much emissions control and sequestration (reflecting the wide range of policy options available), with a special focus on the impact of rising sea levels on human populations. J. Edmonds presented the daunting economic challenge of providing energy services throughout this century while reducing atmospheric emissions. L. Bopp reviewed the climate-driven physical changes projected for the ocean. Once change has occurred, it does not quickly go away. D. Archer noted that full consumption of fuel reserves will produce temperature and CO_2 changes from which the deep ocean will take 10^5 years to recover. The paleoperspective (E. Boyle) indicates that we are already beyond the still poorly understood 90 ppm glacial-interglacial CO_2 changes, and can soon enter a state not experienced on Earth for millions of years.

Can We Sequester CO_2 in the Ocean?

Two oceanic strategies have been proposed for ameliorating climate change. Iron fertilization (A. Watson) of high nutrient/low chlorophyll regions has been superbly demonstrated in a series of international field experiments, but the consequences of successful stimulation of phytoplankton growth give cause for concern. Little of the CO_2 fixed is transferred to great depth, one area of the ocean is robbed of nutrients at the expense of another, and undesirable side effects such as oxygen depletion and N_2O formation occur. Direct injection of CO_2 in the deep ocean will not result in oxygen depletion, but will change pH. P. Brewer showed recent in situ experimental results. However, under any imaginable scenario the quantities deliverable to the deep-sea by direct injection will be an order of magnitude less than the surface water CO_2 invasion from the atmosphere taking place today. Brewer recommended a novel series of Free Ocean CO_2 Enrichment Experiments (FOCE) to parallel the very large-scale Free Air CO_2 Enrichment Experiments (FACE) now well established on land, so as to assess the sensitivity of marine biogeochemical systems to CO_2 system changes, both from surface invasion and as part of any mitigation strategy.

The Impacts of High CO_2 Levels on Marine Ecosystems

H. Poertner presented knowledge of the impacts of higher CO_2 levels on marine animals and the limits on their adaptation, with invertebrates being more sensitive than fish. Responses include a trend toward metabolic depression, reduction of growth and reproduction, and enhanced mortality. It is possible that gradually decreasing CO_2 levels through geologic time have played a role in evolution, and that highly adapted animals such as squid, "the elite athletes of the sea," could face great challenges. Phytoplankton photosynthetically fix CO_2 but may not benefit from higher oceanic CO_2 levels, since there is already an abundance of CO_2 available for photosynthetic needs. Calcareous skeletal formation will likely be influenced by higher CO_2 levels, and U. Riebesell showed from elegant mesocosm experiments that many calcareous phytoplankton, which account for 90% of $CaCO_3$ fixation in the ocean, will form thinner skeletons and not thrive. CO_2 levels experienced today already contribute to this problem. Riebesell also proposed a series of FOCE experiments.

Coral reefs account for the remaining 10% of $CaCO_3$ fixation. Some 100 million people depend upon healthy reef systems, which provide a billion-dollar tourist industry. O. Hoegh-Guldberg reviewed the status of coral reefs today. The primary threat has been viewed as one of rapidly rising temperatures, with a 95% correlation of coral bleaching with thermal stress. Direct-controlled pH change experiments on natural reef systems have not yet been carried out, but large-scale aquarium studies have shown ~40% reduction in calcification at doubled CO_2 levels. The thermal and pH effects are expected to be additive.

The impact of slightly elevated CO_2 levels on growth, reproduction, and survival of calcifying invertebrates was examined by Y. Shirayama, who found clear evidence of reduced viability of sea urchins with even modest pH changes. Impacts on midwater plankton communities (L. Legendre) are as yet less well observed. Harmful effects on cardiocirculatory performance in fish at high CO_2 levels have been observed (A. Ishimatsu) with greater sensitivity in juveniles.

Intense natural sources of CO_2 have been found in the ocean, such as those emanating from volcanic vents, and these may serve as model systems (E. Vetter), although experimental control would be difficult.

Effectiveness of Intervention?

The changes described here are profound in scope, and we have little knowledge of their cumulative effect. Thus, discussion of intervention was approached with real caution. The potential for large-scale Feiron fertilization (H. de Baar, O. Aumont, A. Gnanadeskian) was found to be problematic for reasons given earlier. The vast Southern Ocean provides the largest potential target, and discussion focused on that. The analysis provided suggests that this is not a viable strategy. Direct deep injection (P. Haugan, J. Barry, B. Chen) was found to be viable for sequestering CO_2 from the atmosphere for ~500 years and moderating the CO_2 change that is already being experienced by upper-ocean ecosystems, but at the cost of intense local reduction of pH near the disposal site.

New Research Urgently Needed

If no intervention occurs, and atmospheric CO_2 levels proceed along the IS92A path and beyond, then by the twenty-second century we could see upper-ocean pH changes of >0.5 pH units, and the pH of the entire ocean lowered by >0.3 pH units (K. Caldeira). The consequences of this are far-reaching but largely unknown. The calcite saturation depth will migrate upward by 2 km, surface waters in the Southern Ocean will become undersaturated with aragonite by the end of this century (J. Orr), and viable coral reef systems will very possibly vanish.

There will be ecological losers on a very large scale. We may also find winners along the way, as animals that can tolerate a high CO_2 ocean will expand their range, but we cannot say whether any of these species will be those valued by mankind. The biogeochemical and ecological future of our ocean will be profoundly changed in ways that we do not understand.

The best scientific information available indicates that these impacts of a high CO_2 ocean are real, and are measurable today. They are additive to, but also distinct from, the much-debated effects of CO_2 on climate and will affect the ocean whether or not any particular temperature change occurs. A new set of research priorities was drafted based upon the findings of the meeting. These have been forwarded to meeting sponsors and appropriate national and international bodies. They are available at the Web site given below.

The symposium on The Ocean in a High CO_2 World was held on 10–12 May 2004 at UNESCO headquarters, in Paris, France.

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