EMERGENT TECHNOLOGIES CONVERGE TO BRING THE GLOBAL OCEAN TO SCIENTISTS, ENGINEERS, EDUCATORS, POLICY MAKERS, AND THE GENERAL PUBLIC

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Abstract: Driven by solar and internal geothermal energy, the complex processes interacting within the global ocean constitute the ‘flywheel’ of our planetary life-support system; it is the massive volume of the ocean that drives long-term weather and short-term climatic variations across the seas and onto the continents. Entirely new approaches to understanding the complexity, power, and vagaries of this ‘oceanic modulator’ are arising from the rapid implementation and use of submarine cabled networks that will provide unprecedented electrical power and bandwidth to thousands of increasingly sophisticated robot-sensor systems distributed throughout full-ocean environments. Partly triggered by the advent of a growing number of these cabled research systems, oceanographers are benefiting from a host of ***emergent*** technologies largely driven by communities external to the world of ocean sciences. Important developments include: robotics, biotechnology, cloud computing, *in situ* chemical and genomic sensors, digital imaging, nanotechnology, serious gaming, new visualization technologies, computational simulations and data assimilation, seismo-acoustic tomography, and universal access to the Internet. Far more powerful than any one of these emerging technologies will be the ***convergence*** of the ensemble. As these rapidly evolving capabilities are integrated into sophisticated, remote, interactive operations, a pervasive human telepresence throughout entire volumes of our, once ‘inaccessible’, global ocean will be realized. Such capabilities will be required to meet the onset of immense environmental and societal challenges in the coming decades that can only be addressed through optimally informed international collaboration.

1. A GRAND CHALLENGE

Historically oceanographers have gone to sea in ships to study limited portions of the ocean for short periods of time. We have utilized satellite systems for surficial imaging and for limited bandwidth communications (Iridium), extending the reach and duration of research in the oceans. But the grand challenge in the Ocean Sciences for the coming decades will be the need to successfully design and aggressively implement novel strategies and innovative infrastructures to dramatically increase our rate of discovery and understanding of the complex interactions operating throughout the volume of the ocean basins**.** [Figure 1]

We must deliver these next-generation approaches fast enough and well enough to provide confident anticipation of short- and long-term ocean-generated threats to society. These approaches must also provide the basis for predicting, well in advance, positive and negative impacts of potentially non-linear "tipping points" in our planetary ecosystem resulting from shifts in the dynamic behavior of the oceanic system. In a timely manner, we must also create the ability to reassess the recoverable living and non-living resources distributed throughout the oceans and the under-lying seafloor.

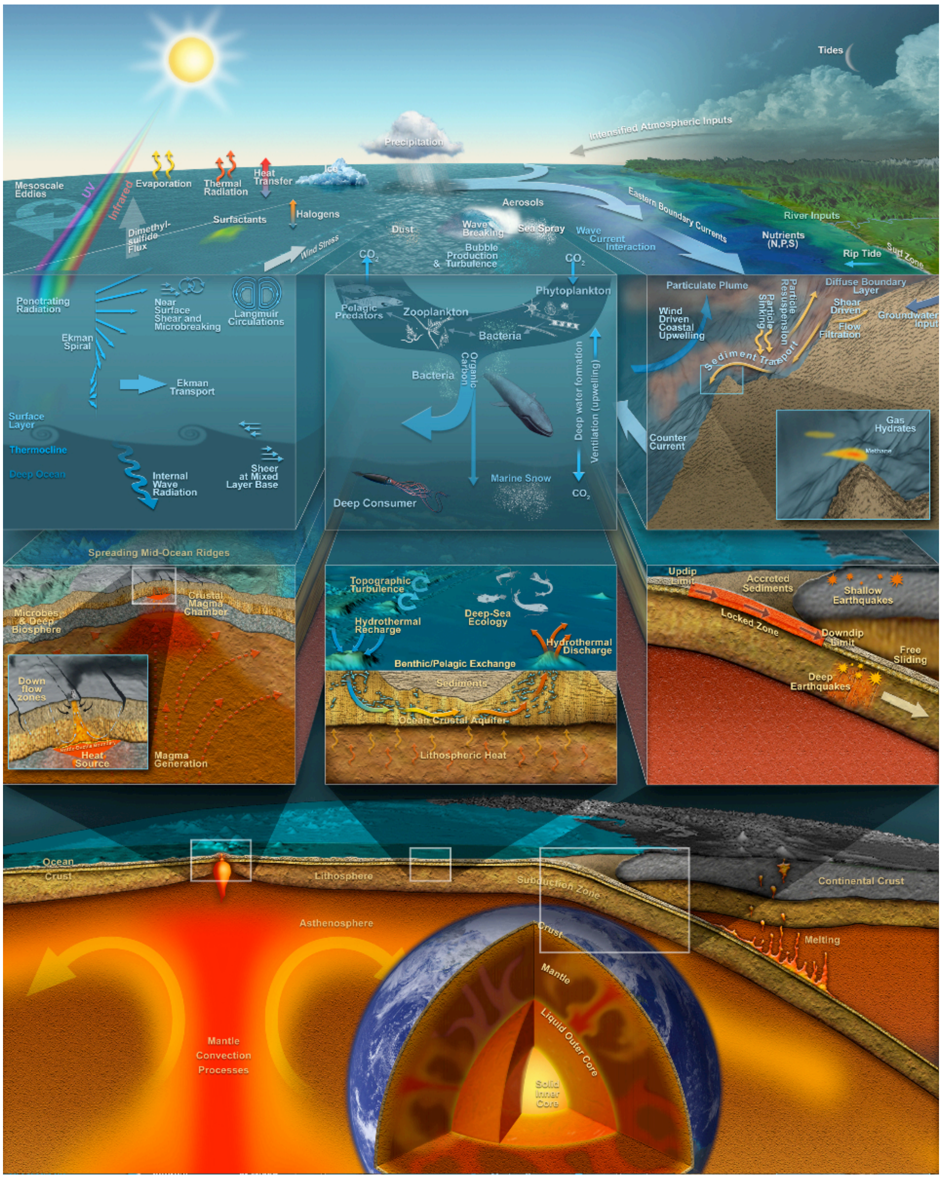

Figure 1. A major part of the challenge of studying the global ocean well enough to predict its long- and short-term behavior lies in the fact that the entire system of interacting physical, chemical, and biological processes have co-evolved over the past 4 billion years. This complex system of many hundreds of interacting processes is the 'flywheel' of our planetary life support system. Until the advent of humans as a major environmental agent, this system was dominated by two energy sources: solar energy from without, and geothermal energy from within. Only by establishing permanent and highly interactive, volumetric telepresence within this system will we come to understand it well enough to forecast its behavior with fidelity. Electro-optical cables can be the backbone for this next generation capability.

Illustration designed by John Delaney and Mark Stoermer; created by the Center for Environmental Visualization (CEV) for the NEPTUNE Program.

2. SOCIETAL PRESSURE AND OCEANIC IMPACTS

By 2030 there will be a billion more people on the planet, with another billion arriving in the following two decades. These projections impart an urgency to under-standing and harnessing the oceans. Arguably, humans will eventually have to learn to "manage" the entire planet; but we do not now have the insight, the knowledge, or the wisdom to do so. The next two to four decades must be spent preparing for the time when we will have no choice but to confront this awesome responsibility. Realistically, Earth is a 'water-world' – we must learn its secrets; living on the continents, we are not well positioned to do so. Yet, because seawater is effectively opaque to electromagnetic radiation, the oceans are very difficult to explore. It is easier to map the moon or Mars with satellite laser-altimeters than it is to map the seafloor.

It was whimsically asserted in the midst of the space program, that we knew more about the moon's behind than we knew about the ocean's bottom. In some ways this is still true, but the era of exploring the spatial distribution of major features in the ocean basins (and on the moon) is mostly past. Our focus now is more on exploring the time domain, meaning that we must understand the **behavior** of the ocean to anticipate the unexpected. In this regard, the ocean basins are still the last physical frontier on Earth. Not only do they episodically deliver devastating impacts on human society, they harbor potentially vast mineral and bio/microbial wealth that is virtually unexplored in some respects. Further, the patterns of ocean circulation and changing sea-surface temperature distributions correlate closely in time with ever-shifting patterns of drought and flooding on the continents. It is therefore not surprising that the dynamic behavior of the ocean is linked directly to patterns of food growth and famine on the adjacent continents; we must learn to understand and predict all of these linkages in both time and space.

3. 4-D HUMAN TELEPRESENCE, GLOBAL CONNECTIVITY

Simple monitoring of the ocean using traditional technologies is no longer sufficient. Moving to the next level of understanding and predictive modeling requires interactive capabilities projecting four-dimensional human telepresence across entire volumes of the ocean from the atmosphere to well within the seafloor. We must be able to detect significant behavioral excursions, both expected and unexpected, within the volume of the ocean basins, and we must be able to reconfigure our sensing/measurement modalities to fully, quantitatively, and adaptively characterize all the processes unfolding within these energetic phenomena.

Success in this endeavor will be a computation- and communication-intensive challenge. As it succeeds, it will require massive storage/archiving activities, supplemented by facile global transport of vast, ever-growing amounts of data from the natural environment, and from increasingly sophisticated model simulations, to globally distributed users. Scientists, policy makers, and citizens linked by the Internet will become increasingly engaged in our ocean as it becomes more and more accessible to all.

4. AMPLIFYING TECHNOLOGY SPIRALS

Ocean Science is rapidly becoming a beneficiary of the **convergence** of a host of powerful, exponentially evolving, **emergent** technologies driven by widely diverse technical and economic forces essentially external to the world of ocean research. These cutting edge capabilities include, but are not limited to, very high bandwidth communications, nanotechnology, biotechnology, information technology, *in situ* genomic analysis, remote mass spectrometry, computational modeling, imaging technologies, and robotics. More powerful than any single technology will be the progressive *integration* of all these enabling capabilities into highly sophisticated systems designed to conduct challenging remote operations in novel ways. The potential of these next-generation ocean science research and operational systems to function independently, or nearly so, under harsh and remote conditions will rapidly transform human capacity to conduct sustained, comprehensive studies of entire ecosystems using a volumetric telepresence that is not now possible.

The term "eco-genomics" has been coined to anticipate the technologies that have continued to evolve at an exponential pace following the completion of the Human Genome Project. The amount of time for, and the cost of, sequencing a genome have dramatically decreased in the past 10 years, as has the size of the equipment necessary to complete the analysis. Pioneering efforts using derivative capabilities in the actual ocean have been tested and are expected to be in routine use within 5 years. The Nobel Prize in Physics this past year was awarded for work leading to digital imaging that is revolutionizing our capacity to capture both motion and still imagery with a fidelity and visual acuity that rivals or exceeds human vision.

Full application of these and other data-intensive sensing techniques within the global ocean would be impossible without the other element recognized by the Nobel Committee for Physics, optical communication. Derivative research has opened the entire planet to high bandwidth communications. The potential to incorporate semiconductors into more conventional fiber transmission systems holds the potential to dramatically enhance the effectiveness and flexibility of utilizing fiber in the oceans to conduct science and enhance education. The initial vision embodied in Moore's Law regarding the exponential doubling capacity of integrated circuits for computers can be seen as an analogue to other emergent technologies.

In the hands of innovative scientists working with inspired engineers many of these technologies will be used to leverage the effectiveness of the many others. The fact that numerous technologies are evolving in an exponential manner may be the basis for suggesting that the ensemble will evolve even more rapidly. The bottom line is that provision of bandwidth and power via submarine cables may optimize next-generation science in the ocean basins by fully capitalizing on a full suite of emergent technologies [1, 2, 3]. The recent use of cables for ocean science is an early phase of a trend toward world-wide networks of cables, both dedicated *and shared*, throughout the global ocean, to vastly enhance human telepresence in a fashion heretofore unimaginable.

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5. OCEAN COMPLEXITY - NATURAL LABORATORIES

Understanding the complexity, the dynamics, and the resilience of the ocean reservoir is central to achieving the capacity to address increasingly urgent issues of population expansion and environmental devolution. Over the next several decades, researchers will not be able to encompass the entire global ocean with equal focus and coverage. We must carefully select key representative ocean volumes for intensive study of interlinked major and minor processes comprising the full scope of oceanic complexity.

Interactive, distributed sensor networks using novel technologies can create large-aperture "natural laboratories" employing real-time experimental control over the entire 'laboratory' volume. Fixed and mobile assets distributed throughout a given volume, all communicating via the Internet at nearly the speed of light, can allow constant surveillance of, and response to, a wide spectrum of physical, chemical, and biological processes interacting within key portions of the ocean system. Cabled laboratories will extend unprecedented power and bandwidth to a wide range of interactive real-time sensors, instruments, and robots that can carry out routine experiments, or be programmed to investigate emergent events like erupting volcanoes, major storms, fish stock migration patterns, or progressive environmental anomalies such as ocean acidification or low oxygen 'dead' zones. These new capabilities will empower many investigators to push the envelop on high creativity and bold exploration of the time-space domain within a number of natural systems. Selected volumes of the ocean will be captured within such natural laboratories, allowing many hundreds of experiments to be conducted simultaneously in the a well-documented framework [4].

Initial approaches must simultaneously and comprehensively study all levels of ocean dynamics within these selected volumes in sufficient detail to allow prediction of any and all transient, or steady state, outcomes using experimentally vetted computational simulations and models. This approach requires that dozens of experiments be conducted for decades to document, model, and eventually predict essential interactions operating within these dynamic volumes. Results of such experiments must then be progressively integrated into simulations of even more complex global ocean systems in anticipation of specifying the ocean's ultimate behavior well into the future.

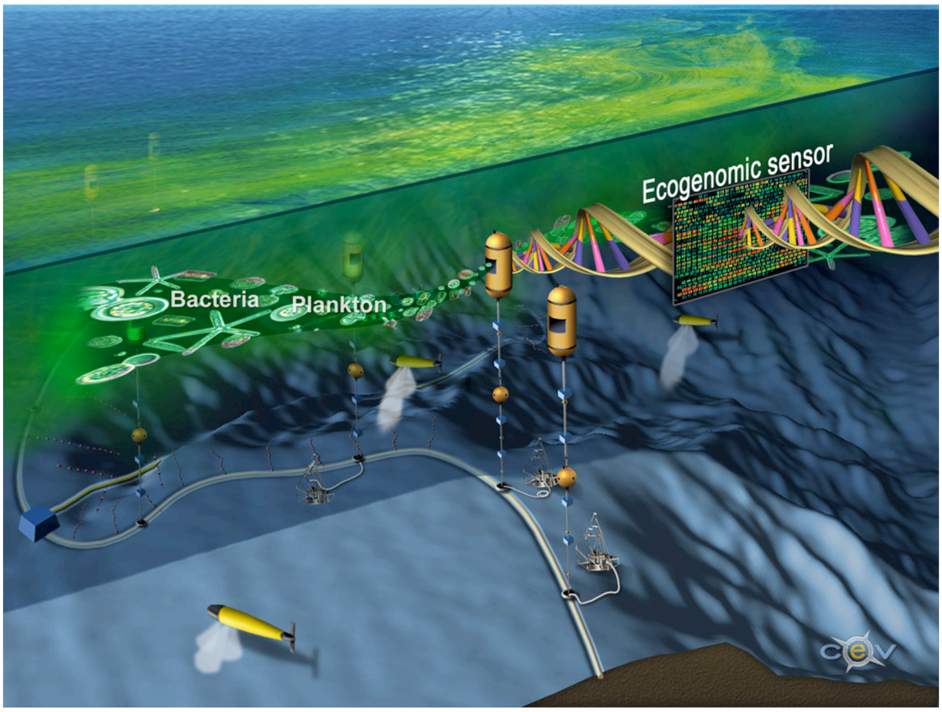

Figure 2. A vision of the type of next generation application that might flow from the incorporation into oceanographic research strategies of a rapidly evolving **in situ** *genomic analysis capability within selected volumes of the ocean. This capability will launch a revolutionary shift in the manner in which we study ocean systems using on-demand genomic analyses of living communities that dominate the base of the oceanic food chain, and can vary widely depending on the environmental conditions.* Scientific concept by Ginger Armbrust; graphic design by Mark Stoermer for CEV.

Cables can uniquely support widely distributed or densely packed 3-D arrays of sensors distributed *in situ* so that the information available is transmitted from many locations simultaneously – a powerful check on the most sophisticated ocean simulation models. All data must be fully archived (with metadata), indexed in time and space, for extensive analysis by scientists across the world, many of whom may not have been directly involved in the original collection. [5]

6. BROADER POTENTIAL - CABLED HUMAN PRESENCE IN THE SEA

Cabled infrastructure is but one piece of the marine research infrastructure needed in the coming decades. Cabled undersea networks may be thought of as the first "interstate" highway that brings growth and discovery by linking and enhancing existing tools such as University-National Oceanographic Laboratory System (UNOLS) research vessels, satellites, autonomous underwater vehicles (AUVs), gliders, and unmanned aerial vehicles (UAVs). For example, more effective use could be made of UNOL's vessels as single research platforms *and* as service platforms for tending experimental sites within the volumetric footprint of a cabled suite of sensor arrays. Another example might include enhanced use of existing data platforms (ships, satellites, AUV's, gliders, UAV's) for identifying areas worthy of rapid response or sustained observation. Similarly, cabled infrastructure could serve as a "data port" for many mobile assets to plug in and transmit massive

Figure 3. An artist's depiction of a fully automated seafloor analytical laboratory within an active submarine hydrothermal system. Operated serially, or in parallel, by different remote science groups on land using the power and bandwidth provided by industry standard electro-optical cables. Real-time analysis, **in situ** *specimen dissection, and complex experiments can be conducted on any and all materials flowing through the environment of this volcanically driven ecosystem containing exotic microbial fauna. Full operation of such an environmental laboratory will require integration of many emergent technologies discussed in the text. A system of this type, and a host of others, will become commonplace as the emergent technologies are increasingly integrated into next-generation forms of human tele-presence in the oceans.* Scientific concepts by John R. Delaney; graphic design by Mark Stoermer for CEV.

amounts of data from the open ocean to be quickly analyzed in the “cloud" computing environment, then returned to the mobile asset and used for near-real time mission updates or validation. Although the installation cost of cabled infrastructure is not cheap, when considered over a 25-year lifetime, maintenance costs are low, as are data transmission costs, and when viewed as cost per observation, because of the band width, cabled infrastructure is a surprising bargain. [6]

7. GLOBAL PROBLEMS *REQUIRE* INTERNATIONAL SOLUTIONS

Over the coming decades, many nations for many reasons will implement cabled sensing systems in offshore extensions of their territorial seas, continental shelf-slope environments, and Exclusive Economic Zones. As these powerful new forms of integrated marine infrastructure become more sophisticated and the data become routinely accessible, the Internet may emerge as the most powerful oceanographic research tool on the planet [5]. In response to unexpected, but energetic transient events in ocean environments, rapid reconfiguration of key sensor arrays linked to the Internet via submarine electro-optical cables will allow us to image, measure and respond to energetic and previously inaccessible episodic phenomena. These events may include catastrophic natural events such as erupting volcanoes, large submarine mass wasting events, big earthquakes, giant storms as well as progressive environmental anomalies that include ocean acidification, hypoxia events resulting in “dead zones”, and harmful algal blooms

Like the atmosphere, and outer space, the oceans do not belong to any single nation, yet we are all dependent on them. To address some of the changes induced in the global ocean system will require high levels of international collaboration. Because submarine cabled communication systems now bind the international community together, it is fitting that these remarkable products of private industry emerge as an integral part of the solution to one of the major questions confronting our global society: How does the planetary life support system actually work?.

8. REFERENCES

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