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The National Association of Marine Laboratories: A Connected Web for Studying Long-Term Changes in U. S. Coastal and Marine Waters

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Abstract. Long-term time-series measurements provide data that test specific hypotheses or suggest new avenues of study. Such studies are widely acknowledged as important for differentiating the influence of human activities from natural background variability. Several long-term research or monitoring programs are active in coastal and marine environments around the world and serve as models for development of new studies. The spatial array of U.S. coastal laboratories is suitable for resolving latitudinal trends and for many types of comparative studies. However, establishing a network of coastal laboratories focused on long-term monitoring and research problems presents special challenges in setting research priorities at appropriate scales, in data management, and in coordination of the scientific effort. The National Association of Marine Laboratories (NAML) is uniquely positioned to promote long-term studies among networks of its member institutions. The NAML can play an effective role in publicizing the importance of long-term studies, in providing access to expertise in this type of research, and in promoting its continuance for periods longer than the length of individual scientific careers.

Preface

"The goals of NAML are to:

—advance the wise use and conservation of marine and coastal habitats and resources;
—encourage and support the recognition of the unique role of coastal laboratories in competent environmental research, academic and outreach education, and public service;
—promote efficient information exchange, constructive cooperation, and productive coordinated effort among member institutions;
—provide a contact and forum for efficient exchange of information and utilization of expertise between member institutions and governmental agencies."

National Association of Marine Laboratories promotional brochure, *circa* 1990

Introduction

Long-term measurements of ecological and physical phenomena are, arguably, the most valuable data we collect for understanding how the world works and how it changes over time, whether naturally or under the influence of human activity. Examples of such data are few but very well-known, and they have been the foundation of research in which the dynamics of processes contributing to environmental changes are measured. Studies conducted under the rubric of "global change" can probably all be related in some way to the continuing, nearly 40-year-long collection of atmospheric CO_2 data initiated by Keeling in 1958 at the Mauna Loa Observatory in Hawaii (Keeling *et al.*, 1976). The broadscale fishery and climatic events modeled by Sharp and McLain (1993) would have been difficult to describe without the long-

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term measurements of the "southern oscillation" in the equatorial Pacific Ocean by Troup (1965). Such climate-driven events in the ocean or on land simply cannot be understood unless they are put into the long-term context (Peterson *et al.,* 1995; Plaut *et al.,* 1995). Thus, natural processes or phenomena that change with time—whether slowly or rapidly, periodically or irregularly—cannot be documented reliably from a single field expedition; in such cases, repeated oceanographic measurements are imperative. Time-series studies are also ideally suited for the documentation of complex natural phenomena that are under the combined influence of physical, chemical, and biological factors [*e.g.,* the recognition of acid rain at Hubbard Brook by Likens *et al.* (1977)]. The valuable legacy of many other long-term biological studies is aptly noted in several recent publications (*e.g.,* Champ *et al.,* 1987; Spellerberg, 1991; Kramer, 1994; Leigh and Johnston, 1994). Data derived from the few other extant long-term oceanic time-series provides ample incentive and scientific justification for establishing additional study sites (Wiebe *et al.,* 1987).

Given the immense value of carefully constructed time-series measurements, how can the diverse group of American coastal laboratories—geographically separated, only partially connected through meetings, telephone, facsimile, and electronic mail, physically different and with vastly different monitoring and research capabilities—be organized for long-term monitoring in the coastal and marine environment? What role can the National Association of Marine Laboratories (NAML) play in facilitating this important task?

This paper identifies several aspects of long-term studies that should be considered before a coordinated monitoring and research effort can be promoted or facilitated by the NAML organization and undertaken by groups of coastal laboratories. We indicate some problems that might be addressed by a coordinated effort organized with NAML support and recommend some potentially viable approaches. Several current model programs with similar goals in place are examined as case studies. Lastly, we propose several types of activities that the NAML organization can do to initiate the coordination process.

Some Considerations

Both scientific and logistical considerations influence the establishment of any long-term time-series measurement program. Foremost among these are site selection, choice of variables to be measured, sampling design, and sampling frequency. Equally important is the assessment of the desired accuracy and precision, which strongly influences the choice of the analytical method to be used for a given candidate variable. Other project design considerations include the availability of suitable reference materials, the hierarchy of sampling replication, and knowledge of the magnitude of mesoscale horizontal variability for data collected at a fixed geographical location, *i.e.,* whether values measured for variables are similar or greatly different at nearby stations. In addition, common methods must be employed to ensure that data collected will be strictly comparable.

Long-term time-series research programs present special problems for scientists in general (Strayer *et al.,* 1986) and for marine scientists in particular (Tabata, 1965; Wolfe *et al.,* 1987). Besides sufficient funding to maintain these costly programs and their attendant personnel management and logistical concerns, there have been misconceptions and thus negative attitudes among some scientists and funding agencies about the value of "environmental monitoring" (Karl and Winn, 1991). Experience has shown that antecedent data collection is necessary and worth the investment, as it is impossible to presage the types of interesting hypotheses that emerge over time from monitoring efforts. It is also very important that every program incorporating time-series observations be fully integrated into experimental and theoretical frameworks and involve scientists of the highest caliber. Finally, many ecological processes are complex and involve time lags, threshold effects, and both positive and negative feedbacks. Consequently, the effects of these processes on populations and habitat variability may not easily be revealed through simple statistical analyses of observations. Effective data assimilation and modeling are clearly vital to the long-term success of these monitoring programs. Thus whether conceived of as valuable for their future broadscale applications, or as a means of answering more local questions, long-term studies have had, and will continue to have, ever greater implications for science and society.

What Types of Studies Are Appropriate for Collaboration Among Coastal Laboratories?

Many topics are suitable for hypothesis-driven questions: *e.g.,* the effects of changing land use patterns and their point source and diffuse inputs on water, sediment, and habitat quality; the effects of large-scale removal of higher trophic levels (fishes) on ecosystem dynamics; sea level rise impacts on coastal habitats; and our abilities to better define biogeographic boundaries in the context of physical and climatic processes on broad spatial scales. Individual coastal laboratories might also be expected to have very different degrees of "pollution," and this could be the variable of interest.

In terms of long-term monitoring, many approaches are possible, including such relatively easy things to measure as surface water temperature and salinity or even *E. coli* counts. What we don't have are data on processes

that can be linked and compared across habitat types represented at each laboratory's location. A simple measurement of surface water BOD (biological oxygen demand) integrates several dynamic processes with implications for water quality and coastal ocean health. The same can be said for something like Secchi disc depth measurements taken wherever the water is, for instance, ten meters deep. Such observations could be linked with data from other governmental agencies that monitor stream and river flows with broad implications for measuring erosional losses on a national scale.

In terms of long-term research, there are an equally large number of possibilities. The best approach would be to assemble teams of laboratories with unique and comparable capabilities to examine local or regional questions. For instance, those with strong plankton sampling capacities could look at representative taxa and measure their lipid content and body burden of pesticides or their rates of pesticide uptake. This could lead to an examination of pesticide degradation rates, for example. Those labs with strong capabilities in chemistry might create a matrix of spatial and temporal observations on nutrient concentrations with a look towards the capacity of the coastal region for absorbing those types of human impacts. Even labs with only modest capabilities in these areas could at least contribute samples to the mainstream labs for whatever question was under study.

The following example illustrates the immense power of long-term collaborative networking. Determining the rates at which bacteria use dissolved organic matter in waters of differing salinity does not require a long-term study. However, determining the relative amount of bacterial biomass in coastal waters as a function of periodic fresh water discharge requires a much longer period of data collection. If the question is whether the bacterial response is similar at all latitudes, then a spatial array of observations is necessary. This is because the magnitude or scale of the riverine discharge may be different at each coastal site, and the pattern of discharge may also differ due to timing of storm events. Higher latitude sites may have a prolonged period of runoff in the springtime, whereas seasonality in runoff volume may be subdued or absent at tropical sites. Obviously a coordinated effort among latitudinally dispersed facilities such as coastal laboratories would be required to approach this type of study, whether to look at bacterial contamination of coastal waters in a public health sense, or to answer related questions about rates of nutrient regeneration or sediment input as they change through time.

The example above also points to one of the unique aspects of the NAML membership—the organization includes an inherently beneficial spatial array of coastal laboratories having latitudinal and other gradients (*e.g.*, watershed size, population density, etc.) along our coastlines. No ship or cruise plan can possibly duplicate what could be done synoptically within the NAML organization. The potential for new knowledge derived from cross-site comparison of common data sets is enormous. This is but one of many advantages (Table I). Unfortunately, not all laboratories are equally capable of participating in a coordinated long-term study (Table II). The mere size of coastal laboratories (and their highly correlated annual budgets) partially reflects the scale of operations that each can support, but the critical aspect for any laboratory is the long-term component of the activity. Even adequate funding cannot assure continuity of trained personnel to perform the measurements or of the required intellectual leadership.

Data Management—A Critical Requirement

Many institutions with long-term studies underway are successful because they have site continuity and integrity, staff stability with relatively low turnover, a commitment from their higher administration to maintain the long-term effort, and science-driven questions that the long-term data are designed to address. These attributes have been extolled previously by Wolfe *et al.* (1987), but the issue of data management was only partially addressed by these authors.

Table I

Aspects of U.S. coastal laboratories that are favorable for creation of a coordinated long-term program of monitoring and research

A.	Location
	Present on all coasts in all coastal states
	Cover a broad range of latitude and longitude
	Comprise diverse habitat types: open coast, sheltered bays, estuaries, coral reefs, clear and turbid waters, hard and soft-bottoms, deep and shallow waters, etc.
	Accessible by land and air as well as by sea
	Under varying degrees of anthropogenic stress: tourism, industry, aeolian deposition, etc.
	Can include large lake systems
B.	Physical Plant
	Docks & piers provide easy access to shallow coastal waters
	Boats provide access to nearshore habitats
	Analytical equipment in place for a variety of physical and/or chemical and biological measurements
	Archival space for samples may be available
	Communications facilitites: phone, fax, e-mail, newsletters
	Meteorological capabilities for weather observations
C.	Personnel and Technical Staff
	Highly skilled or specialized people who know the local fauna, flora, and conditions
	Taxonomic expertise
D.	Resources
	Private, local, state, federal funding available
	Volunteer helpers from local area
	Partnerships with various interests

Table II

Aspects of coastal laboratories that impair their abilities to perform long-term projects

A. Location
Study sites may be difficult to access on a frequent or regular basis
Seasonal weather patterns may preclude observations
B. Physical Plant
Maintenance of critical facilities (especially meteorological stations)
Loss of facilities to storms or other disturbances
No capability for sample storage
No data management capabilities
C. Personnel and Technical Staff
Lack of personnel or lack of skilled personnel
Normal turnover and training of replacements
Competition with other job obligations
D. Resources
Lack of funds to purchase necessary supplies
Changing priorities, reductions in force
Partnerships dissolve
Failure of leadership

Data management is an integral part of long-term studies, a component that becomes more important and often more demanding of resources with time. As a study progresses and the data and its attendant metadata (documentation describing the data) accumulate, quality assurance routines and data management requirements grow as well. Hardware, software, and storage devices reconfigure and require updating every two or three years. Unfortunately, these costs preclude effective data management at many smaller coastal laboratories. However, the lack of sufficient funds to perform data management will not be a tenable argument in the future because (1) external funding will be tied to demonstrated, effective data management procedures; (2) data management costs can be included in proposal budgets; (3) data management, if creative, can be done inexpensively; and (4) the long-term benefits outweigh the costs.

In a coordinated long-term study or monitoring project involving several institutions, some laboratories will be able to perform effective data management, while others will not. A possible and obvious solution is to centralize data management at a few institutions (or even a single site) having the necessary infrastructure and communication capabilities to do the job while providing associated decentralized access throughout the network. Without attention to data management on-site or at such a centralized facility, a coordinated long-term research or monitoring program for coastal laboratories is doomed to failure.

One model for the management of standardized data collected at several different sites is the Centralized Data Management Office (CDMO) of the National Estuarine Research Reserve System (NERRS). Research at the 22 individual reserves in this program is managed locally by personnel at marine laboratories from throughout the nation and Puerto Rico. As part of a system-wide, long-term environmental monitoring program (the NERRS National Monitoring Program), each reserve site collects water quality data (dissolved oxygen, temperature, salinity, nutrients, etc.) with mechanized data loggers deployed *in situ* at locations representative of problem areas. For example, the water collectors may be positioned in small tributaries that drain agricultural basins or in areas whose waters have a high residence time. Data are downloaded to computers at each site where individual reserves are responsible for quality assurance, quality control, and documentation. Data and metadata are then transmitted electronically to the CDMO computer hub for storage, graphic representation in standard formats and scales, and other standardized manipulations. Each data-generating site has access to its own data or data from any other site, *i.e.*, it is a shared database. The centralized network office of the Long-Term Ecological Research (LTER) program works basically the same way, except that data are not collected with the same instruments at the same frequency, and no two sites may be collecting all of the same types of data (Franklin *et al.*, 1990). The U.S. Joint Global Ocean Flux Study (U.S. JGOFS), on the other hand, has a distributed data management scheme (Brown, 1992).

Another issue—data ownership (Wakefield, 1995)—is handled in the LTER network by giving data generators exclusive rights to publish their own data for an appropriate, agreed upon period, at which time it becomes available to the public. The exclusive period is usually one or two years but can be quite variable in length, depending upon site and investigator needs. It is one year for both U.S. JGOFS (core data sets only) and the NERRS National Monitoring Program. The latter has a formal data ownership and dissemination policy that allows a one-year exclusive period for principal investigators (D. Porter, pers. comm.). This mechanism ensures that file cabinets and personal computers do not fill up with data that will eventually be lost, but enforcement of the policy and promulgation of timely publication requires a dedicated effort by principal investigators and data managers at each LTER site as well as by those at the LTER network office. Having a standardized data collection protocol would reduce the need for extensive on-site data management, as a centralized database compiled using common methods would be accessible to all.

Which coastal laboratory would be willing and able to perform this task for a NAML-organized network? Because the NAML membership is regionalized, one or two laboratories in each region could perform data management activities for any group of laboratories in the region having similar data collection needs. Coastal laboratories could also organize across regions for specific research

questions. This presumes, of course, that the regional group of laboratories can agree to attack a question requiring standardized collection of data over a long time period. This aspect itself is probably a more difficult issue to resolve than mere data management, but as Nixon (1996) points out, coastal and marine laboratories may have to approach coastal zone management issues on a regional basis if they are to survive.

Establishing Appropriate Long-Term Research Priorities

In thinking about the sorts of coastline-scale long-term questions that should be approached through monitoring studies, it is appropriate to reflect on why there are so many different coastal and marine laboratories in the first place. The roles of these institutions are as varied as their sizes and locations, but a common thread is their local, regional, or national community service as a way to advance education, research, and public outreach (see Preface; *Am. Zool.,* 1988). Every laboratory touches at least some aspect of these services, and their locations historically have also provided each a "sense of place," a concept developed more thoroughly by Tenore (1996). Therefore, we should ask ourselves how the long-term collection of data can fit within the broader mission of coastal and marine laboratories to serve the public. These services are provided in both direct and indirect ways.

Direct service involves such things as K-12 teacher educational programs about marine ecology, advice on disease prevention to managers of shrimp ponds or oyster farms, coordination with county council members about siting problems for local industries or municipal sewage outfalls, or involvement in management decisions concerning health-related closure of public beaches or shellfish beds.

Indirect service comes from basic research activities that have applied outcomes. For instance, the results of long-term studies on nutrient fluxes within a watershed can be applied to management of runoff in local soil management districts. Studies on larval recruitment can be applied to decisions about when to open or close fishing or shellfishing seasons (*e.g.,* DeLancey *et al.,* 1994). Thus the real challenge is to establish a set of hypotheses that can be tested only at the regional or national level that will have implications for the public good. The public is not always willing to wait for answers to long-term questions, but they (and funding agencies) will respond positively as long as coastal laboratories—through NAML—put effort into effective public communication about the intrinsic value of their research. An editorial in *Science* bolsters this view (Woolley, 1995), and a recent workshop designed to establish program objectives for the newly created NOAA Coastal Services Center in Charleston, South Carolina, clearly identified issues for study which the public will embrace.

Time and Space Domains: The Matter of Scale

The coastal ocean exhibits natural time and space variability on many scales, ranging from millimeters to kilometers, seconds to decades, or more. Establishing only a single time-series sampling site eliminates from further consideration the important spatial component of habitat variability. But an interconnected web of otherwise independent geographical sites, as could be organized by the NAML, could provide critical data on both the space and time components of coastal or oceanic variability.

Therefore, once again the matter of observational scale—spatial and temporal—becomes relevant (Williams, 1984; Livingston, 1987; Levin, 1992; Giller *et al.,* 1994). Melding spatial and temporal variability in an ecological or physical research project is a fairly routine matter (Mann and Lazier, 1991). The more difficult task is dissecting and differentiating among the effects of space and time upon our results. Studies that examine scale in either domain are fairly recent arrivals in the marine science literature. Large-scale patterns were frequently the result of wholesale extrapolation based on too few sampling stations. Classic examples are the early work on zooplanktonic biomass distribution patterns in the Pacific Ocean (*e.g.,* Vinogradov, 1970) and early maps of primary production in the sea by Koblentz-Mishke *et al.* (1970). All this guesswork about patterns has changed now: synoptic observations at increasingly larger spatial scales and over increasingly longer time periods are almost viewed as routine with the help of satellites, moored instrument platforms, acoustic tomography, and dataloggers of all types. The computer "revolution" that has enabled us to assimilate, portray, interpret, and understand massive amounts of data has indeed revolutionized our capabilities for examining scale and pattern (Platt and Sathyendranath, 1988).

Another important issue in long-term, time-series studies is consideration of how long is "long-term," and how long is data collection necessary and sufficient to test a particular hypothesis. A decade-long data set can be used to assess interannual variability but will have little success in resolving the effects of quasi-periodic phenomena like the El Niño—Southern Oscillation that has temporal scales of 4–7 years. As Green (1984) so aptly states, our science has hopefully matured enough to accept that some critical problems will simply require long-term research investments.

What have we learned about scale? Both the size of the study area and the duration of an experiment can affect the data and thus our view of the phenomenon under study. Moreover, this relationship holds whether the in-

vestigation involves an individual organism, a population in a patch, an area large enough to link patches via dispersal mechanisms, an entire biome, or a biogeographic range of diverse habitat types. Disturbance events affecting each scale are likely to be of longer duration as the study area increases in size; *e.g.,* tornadoes as opposed to hurricanes. Whether emergent properties related to scale at the community level are sufficiently well-known that we can generalize from them is still open to debate, because each interacting population within a community may be operating at a distinctly different scale whose dimensions have been defined evolutionarily. Therefore scale effects depend on the nature of the question under investigation. As we continue to examine processes at various scales in the sea—currently being done in the National Science Foundation's U.S. Joint Global Ocean Flux Study (Fig. 1)—we can expect new properties to surface and new principles to emerge. A comprehensive understanding of natural habitat variability and the ability to resolve natural from human-induced change is likely to require several decades of observations. In addition, the temporal scale of planned observations must match the spectrum of available resources—both fiscal and intellectual. The question of scale remains a worthwhile, testable target for every discipline in the aquatic sciences that can easily be attacked with long-term studies at coastal and marine laboratories.

Other Programs in Place: A Unique Role for the NAML

There are several long-term research or monitoring programs in place throughout the world: *e.g.,* France's National Research Project on Coastal Zones (PNOC, 1995), and many in the United Kingdom (Spellerberg, 1991; Gamble, 1994). Some have evolved from small-scale efforts whereas others have been conceived as long-term investments from their inception. Long-term data have been collected in European countries for much longer than elsewhere, but the more recent efforts have, with a few notable exceptions, been better organized conceptually and managerially [*e.g.,* LTER (1993), and LMER (Hayden *et al.,* 1991); EPA (1994a, b); NERRS (1992; Crosby and Beck, 1995)]. The widespread media reporting of global warming, ozone thinning, sea level rising, coral reef bleaching, seals dying, and climate-related coastal erosion is helping to position us, at just the right time, to contribute to managing our long-term investment in preserving oceanic, neritic, and coastal habitat.

We must not compete with other efforts in progress or underway. Similarities among the goals and working group recommendations for creating ILTER (International Long-term Ecological Research) programs, for enhancing communications among members of the Ecological Society of America (Colwell, 1995), and other ideas about linking non-coastal biological field stations with coastal laboratories in a national network (Lohr *et al.,* 1995) should form a strong basis for, and justification of, any coordinated long-term program that results from efforts of laboratories in the NAML membership.

A Contrarian Viewpoint

Although the Internet is available globally now, it does not provide the only appropriate or useful means of forming coordinated links among marine laboratories for research and monitoring purposes. Therefore, as software and hardware technologies improve, other mechanisms for linking laboratories should also be sought (*e.g.,* satellite-based, real-time video communications). This challenge is not trivial, because so many technological decisions will need to be made (beyond the difficult scientific questions) about the standardization and structure of data collection, physical storage devices, information dissemination modes, user fee support, and other data management issues. What would be the cost of getting every laboratory properly calibrated to measure salinity and temperature routinely and to contribute time-series measurements to a centralized (or distributed) database? Will the effort to coordinate such a diverse group of laboratories be worthwhile? Can any laboratory afford to divert and refocus already scarce resources towards participation in a networked long-term monitoring or research program? How soon might new monies become available for such programs as this?

A few examples may shed light on the immensity of such an exercise. The LTER budget (with many fewer sites than NAML has laboratories) is about $10 M per year. The LMER budget is about half that, and the NERRS budget is less, about $4 M. Therefore, a NAML-scale program might cost about $10 M at a minimum. How many funding sources would be needed to accumulate such a sum? These are easily asked questions, but absent a coordinated plan, answers are not defensible.

At least one formal group, the Mid-Atlantic Regional Marine Research Program, has examined some of these technical problems with a view toward creating a coordinated regional data management plan (Antech Systems, 1995). The Atlantic States Marine Fisheries Commission has published results of a workshop held specifically for coordinating use of extant long-term bottom trawl survey data (some since the early 1970s) for fisheries management (Berger, 1994). It is instructive, therefore, to ask what the NAML can (or should) do beyond these more local or regional efforts. Should we pursue anything on a national scale? Have we maximized the amount of science being done per unit effort, or is there room for redirection?

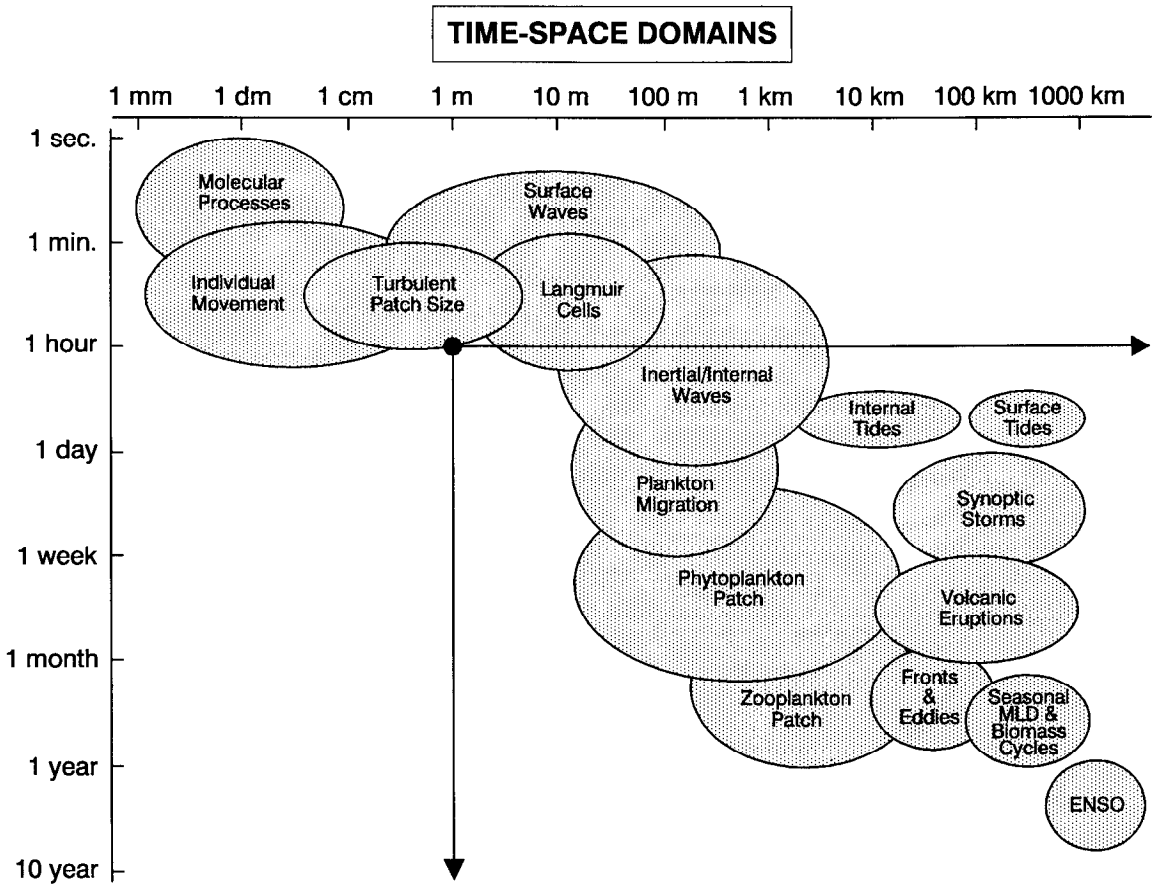


Figure 1. Temporal and spatial domains of various physical and biological processes in the sea (adapted from Dickey, 1990).

Role of the NAML in Organizing a Network of Laboratories

Perhaps the first action item for NAML is to initiate and organize a survey of the long-term, time series parameters currently being measured at coastal laboratories. Information should include why the measurements are being made, their methodologies, sampling locations, measurement frequency, study duration, and the types of quality control measures in place.

The NAML organization should also establish a registry of experts on various aspects of long-term studies to provide advice to laboratories and other groups preparing to engage in time-series types of measurements. Such advice might include specific information on data management and data dissemination as well as on methods for ensuring high quality measurements. The thrust of this registry would be not only to provide advice, but also to enable an assurance that environmental policy decisions and management actions resulting from monitoring activities can be based on the highest quality data and trend information.

The length of many important time-series measurements will exceed the length of the scientific careers of individual scientists who initiate them. The NAML, through networking and consensus, should advocate continuance of these efforts whenever these motivated scientists retire. This will, of course, require substantial leadership and support for long-term efforts, and the NAML can promote the rationale by showcasing some long-term data sets that have had a significant impact on science and society. Previously cited examples of the CALCOFI (California Cooperative Fisheries Investigations) data sets linking ocean warming and a major decline in zooplankton abundance (Roemmich and McGowan, 1995a,b), the long-term plankton records for the North Atlantic showing climatic trends on biota (Gamble, 1994), and familiar freshwater lake cleanup success stories like Spirit Lake (Larson, 1993) and Lake Washington (Edmondson and Lehman, 1981) all provide fodder for that rationale.

The serious effects of overfishing, whether on George's Bank cod or oysters in Chesapeake Bay, also provide an opportunity for the NAML to promote the utility of long-term studies by showing how they provide the data nec-

essary to discover these disturbing trends. The popular press has a willing and receptive audience for such accounts (*e.g.*, Parfit, 1995; Safina, 1995), and we must seize the opportunity to promote the NAML's role in producing these long-term studies of discovery and in keeping our citizens informed through research, education, and outreach.

There is a clear need for long-term, high resolution time series measurements of key environmental and biological variables at strategic locations in representative systems. Given their diverse capabilities, the NAML's coastal laboratories have great potential for long-term and large-scale monitoring and research. However, until a coordinated network is established, much of this potential will never be realized. This is the organizational challenge that faces the National Association of Marine Laboratories.

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