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Disturbance indicators for time series reconstruction and marine ecosystem health impact assessment

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DISTURBANCE INDICATORS FOR TIME SERIES RECONSTRUCTION AND MARINE ECOSYSTEM HEALTH IMPACT ASSESSMENT

By

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DEDICATION

To

Dalia, my wife, for being patient during the many years of missed dinners, sleep and misplaced sense of priority. From now on, LIFE is first, all else can wait.

Kenneth and Roberta Sherman who taught me to attempt impossible things and then to learn from anticipated failure. They knew I would one day eventually make the impossible possible.

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PREFACE

The purpose of this dissertation is to outline the methods needed to develop a multidisciplinary systematically derived time-series data analysis system. This system is designed to improve understanding of the spatial and temporal extent and frequency of marine disease, morbidity and mortality events in coastal waters.

In 1995, I joined a group of investigators at Harvard University and collaborators at associated federal, state, and academic institutions interested in learning more about marine disturbance (HEED 1998). Their overarching question, "are disturbances getting worse as a result of global change, and what are the costs of the impacts?" is not directly addressed here. Rather, I designed an information system that may help answer those questions. Toward that end, I describe my contributions to this group called "Health Ecological and Economic Dimensions (HEED) of Global Change Program." While this dissertation is focused on my own contributions to the overall project, there are other important facets of the project, and these are discussed and referenced as appropriate to provide a contextual background for my own work.

The dissertation is based on three manuscripts as per the standards of the Natural Resources Ph.D. Program at the University of New Hampshire.

1) Sherman, B.H. 2000. Past Anomalies as a Diagnostic Tool for Evaluating Multiple Marine Ecological Disturbance Events. *Human and Ecological Risk Assessment*. CRC Press.

2) Sherman, B.H. 2000. Marine Ecosystem Health as an Expression of Morbidity, Mortality and Disease Events. *Marine Pollution Bulletin*. Pergamon.

3) Sherman, B.H. 2000. Marine Disease, Morbidity and Mortality, Toward a Baltic Sea Information System. Proceedings of the International Symposium on Fisheries Ecosystem Research and Assessments. Sea Fisheries Institute, Morski Instytut Rybacki. Gdynia, Poland. July 5- 6 1999 *Bulletin of the Sea Fisheries Institute*).

The following definitions and acronyms are more precisely defined and used within this document (in contrast to vernacular usage):

ANECDOTAL - casual or lay observations (considered valuable compared to no information).
ANOMOLY- perturbation from a normal state.
DISTURBANCE- Recognized anomaly (multiple discipline term).
EVENT- Multiple (co)occurrences involving different categories of entities - involving one or more major taxa or functional grouping in space or in time.
META-EVENTS - (multiple taxa and functional groups) multiple taxa cascades and or co-occurring morbidity/mortality. Also known as Major Marine Ecological Disturbances (Not to be confused with MMEDs where the leading 'M' stands for Multiple (below).
OCCURRENCE- observation(s) defined as unique in time and place -smallest space/time resolution.
TAXONOMIC- refers to Linnaean hierarchy.

The following abbreviations and acronyms are used more than twice in the text or accompanying CDROM containing the Appendices and are defined here for reference:

ArcView: ESRI GIS Software
ARIMA: Autoregressive Integrated Moving Average Analysis
CICEET: Cooperative Institute for Coastal Estuarine and Environmental Technology
COADS: Comprehensive Ocean-Atmosphere Data Set
CPI: Consumer Price Index
CZCS: Coastal Zone Color Scanner
El Nino: Warm Water Phase of ENSO cycle
ENSO: El Nino Southern Oscillation
EPA: Environmental Protection Agency
ESRI:Environmental Systems Research Institute
FEMA: Federal Emergency Management Agency
FES:Fisheries Economic Statistics
GIS: Geographic Information System
GIWA: Global International Waters Assessment
HAB:Harmful Algae Bloom
SD: Standard Deviation
HEED: Health Ecological and Economic Dimensions (Program)
IRI: International Research Institute
JAVA: Computer Programming Language
La Nina: Cool Water Phase of ENSO cycle
LDEO: Lamont Doherty Earth Observatory
LEXIS/NEXIS: Media Internet Search Tool
LME: Large Marine Ecosystem
MATLAB: Statistical Analysis Software
MMED: Multiple Marine Ecological Disturbance
NAO: North Atlantic Oscillation
NASA: National Aeronautics and Space Administration
Nino 3: Index of El Nino Conditions
NMC: Blended ship, buoy, satellite SST data
NMFS: National Marine Fisheries Service
NOAA: National Oceanic Atmospheric Administration
PC ORD: Ordination Statistical Software Program
PCA: Principal Components Analysis
PDF: Portable Document Format
PPTA: Precipitation Anomaly
PSP: Paralytic Shellfish Poisoning
SBA: Small Business Administration
SeaWiFS: Sea Wide Field of View Remote Sensing Color Sensor
SLPA: Sea Level Pressure Anomaly
SOI: Southern ocean Oscillation Index
SPT: Shellfish Poisoning Toxins
SSTA: Sea Surface Temperature Anomaly
Statistica: Statistical Analysis Software Program
USGS: United States Geological Survey
WS: Wind Speed

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ABSTRACT

DISTURBANCE INDICATORS FOR TIME SERIES RECONSTRUCTION AND MARINE ECOSYSTEM HEALTH IMPACT ASSESSMENT

by

Benjamin H. Sherman
University of New Hampshire, December 2000

A systematic reconstruction of Multiple Marine Ecological Disturbances (MMEDs) involving disease occurrence, morbidity and mortality events has been undertaken so that a taxonomy of globally distributed marine disturbance types can be better quantified and common forcing factors identified. Combined disturbance data include indices of morbidity, mortality and disease events affecting humans, marine invertebrates, flora and wildlife populations. In the search for the best disturbance indicators of ecosystem change, the unifying solution for joining data from disparate fields is to organize data into space/time/topic hierarchies that permit convergence of data due to shared and appropriate scaling. The scale of the data selects for compatible methodologies, leading to better data integration, time series reconstruction and the discovery of new relationships. Information technology approaches designed to assist this process include bibliographic keyword searches, data-mining, data-modeling and geographic information system design. "Expert" consensus, spatial, temporal, categorical and statistical data reduction methods are used to reclassify thousands of independent anomaly observations into eight functional impact groups representing anoxic-hypoxic, biotoxin-exposure, disease, keystone-chronic, mass-lethal, new-novel-invasive, physically forced and trophic-magnification disturbances.

Data extracted from the relational database and Internet (http://www.heedmd.org) geographic information system demonstrate non-random patterns relative to expected dependencies. When data are combined, they better reflect response to exogenous forcing factors at larger scales (e.g. North Atlantic and Southern Ocean Oscillation index scales) than is apparent without grouping. New hypotheses have been generated linking MMEDs to climate system "forcing", variability and changes within the Northwestern Atlantic Ocean, Gulf of Mexico and Caribbean Sea. A more general global survey known collectively as the Health Ecological and Economic Dimensions (HEED) project demonstrates the potential application of the methodology to the Baltic Sea and other large marine ecosystems. The rescue of multi-decadal climatic, oceanographic, fisheries economic, and public health anomaly data combined with MMED data provides a tool to help researchers create regional disturbance regimes to illustrate disturbance impact. A recommendation for a central meta-data repository is proposed to better coordinate the many data observers, resource managers, and agencies collecting pieces of marine disturbance information needed for monitoring ecosystem condition.

CHAPTER 1

INTRODUCTION

This work represents an *a posteriori* inductive approach for the reconstruction, assimilation and use of multiple data-types to determine the extent and frequency of major marine ecological disturbances linked to morbidity, mortality and disease events in coastal waters. The primary purpose of this work is to provide the methodological tools to guide the creation of hypotheses linking causes and consequences. Three manuscripts are included in this Dissertation. Each details how data-types from different disciplines can be merged to determine the extent and frequency of major marine ecological disturbances. Data, procedural, and analytical details are included as appendices in an accompanying CD-ROM. The methods discussed represent the first attempt in an effort to launch a major initiative in marine epidemiology. In these manuscripts marine morbidity, mortality and disease data are brought together in a single unified database and are defined as discrete phenomena with particular impacts and possible causes. The primary purpose of this work is to provide the methodological tools to guide the creation of hypotheses linking those causes and consequences. The U.S. National Research Council, U.S. Marine Mammal Commission, Intergovernmental Oceanographic Commission's Health of the Oceans and Coastal Global Ocean Observing System working groups have expressed a need for marine epidemiological assessments. The suggested methods of data collection, data transformation, calculation of anomalies, evaluation criterion and statistical analyses are described with these programs in mind. Some of the hypotheses generated for scholarly research are relevant to 1) climate and oceanographic forcing, 2) harmful algae bloom occurrence, and 3) disturbance regime characterization questions. The implications of the findings, why those findings are important, recommendations made, and needs for further study are presented in a concluding section of this dissertation, following the three papers.

Please note that in-depth exploration of any of the hypotheses discussed within this dissertation requires a broader cross-section of disciplinary collaboration than can be represented within a single author product. Important unpublished ideas and concepts herein described represent the contributions of a much larger academic community and credit is provided in the acknowledgements section or within parenthetical citations. Details described within this dissertation represent my distinct contribution to a larger effort in the following primary areas: program development, theory of integration, standards for data collection, standards for extracting data from source material, scale specificity in encoding data, data queries relevant for categorical analysis, temporal-spatial analyses, GIS manipulation, and iterative development. Where the theory, standards and implementation differ, additional information is provided.

This dissertation also represents a new approach in the design, construction and utilization of an information system. That information system is called the HEED (Health Ecological and Economic Dimensions) system, and was conceived at Harvard University in 1995 (HEED 1998). The primary scholarly contribution of this work is in the collection of marine disturbance data described within this document, its use to generate hypotheses, and preliminary findings related to ecosystem disturbance. Disturbance studies require long time series data collections, which are rare (Magnuson 1990, 1991; Roush 1995), making it necessary to scavenge available indicator and/or proxy data from multiple sources to evaluate large-scale and long-term patterns of disturbance. Information technologies (e.g. bibliographic search engines, geographic information systems, internet databases) have made it possible to collect scattered indicator information pertaining to marine disturbance. With a sufficient number of anecdotal observations derived from these sources, patterns have emerged that suggest common mechanisms or similar indicator response to exogenous forcing factors. By inspecting these patterns of response, some disturbance indicators appear more useful than others or serve as proxies (substitutes) for each other in a reconstructed time series.

Impact-based indices (emphasizing functional ecosystem roles) have been created and used to organize scattered and fragmented single species monitoring data (Paper 1, Figure 5). These indices in aggregate represent *Multiple Marine Ecological Disturbances* (MMEDs), an indicator of *Major* exogenous impact (Williams and Bunkley-Williams 1990, Epstein 1996; HEED 1998; Fisher *et al.* 1999, Harvell *et al.* 1999). MMED information once centralized provides more complete historical (e.g. time-series) information for a particular location than would be typically available to researchers or managers. This information may be used to facilitate exploratory analyses or to reveal local disturbance regimes (historically recurrent patterns of disturbance). Reflecting impacts from a wide range of possible sources, MMEDs are anomaly-proxies or indicators of an ecosystem's deviation from a healthy baseline (Likens 1992, Costanza *et al.* 1992, Haskell *et al.* 1992).

The methods described herein represent the first data "mining", data "rescue" effort meant to address both marine ecosystem health and disturbance questions. This dissertation describes the development of an internally consistent marine ecosystem health information system capable of supporting the needs of both academic researchers and resource managers. It makes use of derived keywords and queries designed to objectively and semi-automatically provide compatible information for retrospective analyses of particular places during given time periods. This dissertation is based upon the following Thesis:

> **Assimilated observational data extracted from multiple sources can adequately characterize functional marine ecological disturbances, reveal possible forcing factors, unanticipated impacts and contribute to ecosystem health assessments.**

This Thesis leads to the following hypothesis, which is evaluated using spatial, temporal and categorical criteria:

> **A large number of marine morbidity and mortality data once assimilated and analyzed will represent a non-random pattern relative to**

common categorical dependencies, and when these data are grouped into a smaller number of disturbance types, new information pertaining to common impact response to exogenous forcing factors will be revealed.

Six objectives to be met in testing this hypothesis are as follows:

1) Develop searches of review literature and systematic acquisition of available disturbance observational data.

2) Evaluate a nomenclature derived from a consensus of "experts" and standards for organizing and concatenating information of highly variable quality.

3) Create an information system to store, retrieve and display information appropriate to spatial, temporal and categorical queries.

4) Compare known disturbance relationships identified by the "experts" and supported within the published literature with relationships derived from the information system.

5) Evaluate the results of a functional automated classification versus the initial disciplinary classification system.

6) Demonstrate the utility of the information system by generating new hypotheses, confirming suspected relationships and assessing possible health/economic impacts from known forcing factors using automatically generated spatial/temporal/quality controlled aggregate marine disturbance indicators.

The methods to meet these six objectives represent a new tool for the assessment of ecosystem health using a specific set of disturbance indicators. The tool is not intended to be a complete compilation or robust assessment of such data, which can only come after a major, multifaceted and multi-principal investigator validation effort. However, given the preliminary analysis described in this dissertation, it should be possible to effectively develop and expand upon a fully validated data set and its applications. Insufficient data are available at present within the HEED database to conduct robust statistical analyses of the posed hypotheses. An outline is provided for how robust statistical analyses would provide inferential power of value to the marine, oceanographic, epidemiological, and resource economic research communities.

CHAPTER 2

METHODS

Because the project described exists at the intersection between disciplines, new methods were developed to address the aforementioned objectives. The methods include categorical data mining, data modeling, idea mapping, Internet data synthesis/distribution and statistical manipulation of this unique assembly of information. The methods presented were developed to serve as a set of research and management tools for use by a large research and decision-making constituency. An "expert" review group (CDROM, Appendix 1, Table A1) evaluated the HEED approach while it was developed.

Anomaly Approach

Central to the integration of information is the observation of anomalous occurrences of morbidity, mortality, and disease. Anomalies are defined as deviations from an established baseline in a particular time and place. Baseline conditions are modal, mean or follow pre-established dynamic changes as described by disciplinary "experts" (Orians 1975). If multiple disturbances can be detected in the same time and space, information "mined" from distributed sources of archived information can be used to connect or elucidate the relationships among the co-occurring disturbances.

With a list of initial keywords provided by disciplinary "experts" matched against the Library of Congress Cataloguing and Indexing keyword syntax, it was possible to "mine" the literature for relevant categorical information. Categorical "data-mining" can be viewed as a qualitative counterpart to the quantitative method for extracting pattern from large quantities of source data (see Fayyad *et al.* 1996, Hand 1998 for review of potentially useful quantitative methods). In this case, sources for data included journal articles, symposia, workshops, proceedings, books, government technical reports, semi-popular journals, unpublished manuscripts, selected institutional reports and research communications. The HOLLIS library reference system at Harvard University was used to search over 10,000 periodicals covering the period between 1945 and 1996 (refer to 1997 archived HOLLIS periodical list, http://www.harvard.edu). It was presumed that the searches conducted in 1995, 1996 and 1997 would capture the majority of historic publicly-available marine disturbance source material, and searches could be re-run periodically as new keywords, keyword strings, and indices were updated. Additional information was collected from Internet web pages, magazine articles, newspaper articles, news services, newspapers and television and radio transcripts using the Lexis/Nexis clipping service representing the period from January 1996 to August of 1998 (Lexis/Nexis Inc. periodical list, March 1998, maintained in Dayton, Ohio).

Five quality categories were associated with the source material obtained. The categories included: 1) key - primary citation for an occurrence with detailed data; 2) relevant - secondary citation for an occurrence including less detailed or very detailed data about some aspect of the occurrence, or occurrence referring to another citation; 3) review articles about types of occurrence, articles with some but not very detailed data (e.g. passing reference to an occurrence); 4) completely anecdotal or contextual information without spatial or temporal reference; 5) global, "other" - articles with usable data but outside of the study range or in need of validation. Each piece of source material was also given a rank based upon how certain, complete or reliable the information derived from the source appeared when entered into the database. Justification for this weighting of evidence is described within an extensive notes field.

Keywords are the foundation of the HEED inventory methodology, database, statistical associations and quantified results. Great care was made to assure that all derived associations could be reduced down to their fundamental keyword elements (and vice-versa). To retain some objectivity, keywords were accepted as researchers defined them within their published accounts; and considerable time was spent distinguishing between interpreted findings and basal observations per source as part of a quality ranking system. Once the keywords were defined and searches conducted, all metadata (data about the use of the keyword in context) were encoded within a relational database. Keyword groupings were derived using database queries designed to identify similar usage. The groupings were made discrete from each other, though the indicators comprising each of the groups are found to have overlapping attributes.

An "occurrence" within the database represents the most refined level of temporal resolution included within the database. An occurrence is defined as having a unique start-date, end-date and label (legend value if used in mapping). An algae bloom occurrence, for instance, is defined by its discrete time-span. If a red tide bloom of *Gymnodinium breve* occurred from March 10th to March 30th in three Florida counties that would constitute a single record. If the dates varied by a week from county to county (e.g. if the bloom were moving down the coast, recorded in each of 3 adjacent counties), then that bloom would be contained in three occurrence records. The discreteness of a 3 or more record red-tide bloom "event" would be recognized through aggregation of information using spatial and temporal database queries. Both date and place precision was assigned to all occurrence records for scale-constrained queries and later event derivation. With a list of all the types of occurrences gleaned from the literature, queries were written to aggregate like information. The aggregate grouping enables the database user to rapidly extract all the information about a particular class or occurrence type – fish kills, algae blooms, etc. (CDROM Appendix 3,4).

Spatially explicit locations based upon decimal latitude and longitude were obtained from the source literature entered into the database and extracted for mapping. The ArcView 3.1a software (ESRI, Redlands California) was used as the primary geographic information system (GIS). A World Wide Web interface was written in JAVA to allow remote researchers interested in hypotheses testing to interactively access data-sets, display, and map ten taxonomic groups of MMED data by area and year (CDROM Appendix 6). The ten taxonomic groups were chosen to represent the floristic and faunal disciplinary fields reporting disturbance occurrence.

Data Transformation

To evaluate relationships between climate and oceanographic variables, datasets never before brought together have been spatially and temporally referenced in conjunction with the MMED data. This data provides additional context for occurrence records. The available (environmental) data sets are transformed to match a common uniform (regularly spaced) yearly time series. The transformations degrade the quality of the more highly resolved data and introduce bias against disturbances (large area or/and short duration) that are expected to correlate with corresponding flora and faunal (a scale selection problem). These constraints limit correlative inferences.

Fisheries economic, basic meteorological and oceanographic time series establish a context for understanding anomalies (near continuous data) for particular locations. "Anomalies" are determined by observation of threshold conditions and magnitude deviation from a place specific average. If correlative statistics were to be run on the combined time-series, the baselines from which anomalies are calculated needs to reflect the same long-term changes experienced by disturbance sensitive organisms. A standard practice in time series analysis is to calculate the long-term mean for an entire series and determine anomaly from that baseline (Chatfield 1986). This practice becomes problematic in climate change scenarios and when extreme events toward the end of the record artificially raise the mean when evaluating anomalies prior to these extremes. To solve this problem, running means for periods of interest within each time-series may be calculated using a fixed moving window for significant anomalies to date. Tests were run on fisheries economic data using 10 year moving windows (CDROM Appendix 10). Experiments were conducted with the other data sets using similar techniques (e.g. sea level pressure and sea surface temperature anomalies were processed using four-year windows representing the period in between El Nino Southern Oscillation and North Atlantic Oscillation cycles, and the long-term historic values for precipitation are calculated by the National Weather Service. The moving window processes are yet to be fully validated). These standardization techniques prepare the near continuous time-series data for analysis in conjunction with the morbidity, mortality and disease (enumerated occurrences unique in space/time) data.

Disturbance Regimes

Through the use of the term "anomaly" -- common to all disciplines -- data from socioeconomic, ecological, and climatic fields of study were linked together in the database with explicit appropriate scaled spatial-temporal reference. For each of the 77 estuaries and embayments selected for place specific HEED review, Twenty-Nine locations (mostly within New England) were chosen to create combined temporal disturbance-regime plots (CDROM Appendix 7). Multiple marine ecological disturbance data were queried and enumerated by date representing all records indexed to the site. The combined data series, suggest that focused data mining at particular periods of time might reveal missing pieces of data presumed to correlate with the patterns of observation already present.

Methods for statistical analysis

There are two approaches in examining relationships between discontinuous or fragmentary biological observational data and the more continuous time-series data types: 1) exploratory and 2) statistical. The exploratory techniques are selected to examine the spatial, temporal and typological characteristics of the indicator data. These include principal components analysis, multidimensional scaling, relational database queries, geographic information system (GIS) spatial clustering tools, and satellite data/GIS overlay animations. This is contrasted with traditional hypothesis testing designed to verify *a priori* hypotheses about relations between variables (e.g., "There is a positive correlation between Sea Surface Temperature Anomalies and marine mammal stranding).

Exploratory data analysis (EDA) is used here to identify systematic relations between variables when there are no (or incomplete) *a priori* expectations as to the nature of those relations. Statistical methods are used to evaluate significant relationships if possible; however, categorical data findings used within this work should not be extrapolated beyond associative correlations because inexplicable and spurious correlations may also arise. With larger raw data sets from which to create MMED data, the resulting correlations will be more robust.

Correlation matrices were created for both the taxonomic and occurrence type records to discover associations and to crosscheck the "experts'" predicted groupings. For categorical analyses, queries were run to search the database and enumerate pairs of concept (events or legend field), taxon (ten groups) and scale (space/time) keywords to validate the manual classifications and objectively reduce 2021 individual keywords to a smaller number of functional categories (that may or may not reflect the original categories). The assumption was that the ten categories chosen by the "expert" group could be recreated along with the relationships identified in data modeling and idea mapping. Exploratory multidimensional techniques using principal components analysis (PCA) and ordination were used to rapidly determine if the ten taxonomic groups defined by the "experts" represent random groupings of functional disturbances or reflect a systematic pattern of keyword co-occurrence. A 140 occurrence-type keyword similarity matrix was created to analyze the enumerated pairings in contrast to the ten taxonomic keyword-pairing combinations found in Appendix 3 for expected patterns (CDROM Tables A3.1 and Table A3.2 respectively).

To deal with subtle or difficult to interpret standardized values, the deviation matrix was further transformed into binary form, the values above expectation were scored as 1 and values below expectation being scored as 0 (binary values are well suited for ordination). The validity of the original supposition that scale (an inherent pattern former) will meaningfully couple disturbance keywords and taxon, was examined by subjecting the binary matrix to principal component analysis (PCA and Brae-Curtis ordination, 3axis using PC-ORD and Statistica software packages). A similar ordination was run for space/time keyword matrices. Failure to observe "expert" defined relationships in the principal components ordinations would invalidate the original supposition that the HEED database can reproduce known relationships (defined by keyword pairs).

The primary assumptions implicit in the interpretation of the PCA results are as follows: The number of pairs are a reflection of relative, not absolute research effort; that the keywords reflect fundamentals of perceived disturbance impact, rather than fashion in editorial policy (Abrahamson *et al.* 1989) or bias in data entry; and that data transformation or selection through queries preserves taxon/keyword, scale/keyword relationships. Also it is understood that some records were missed because they did not have keywords coded in the database, that disciplines define some keywords uniquely and/or use different key words to describe the same concept, and that any unexplained correlations are representative of a conservative approach. A conservative approach is warranted because artifacts such as the founder effect (once picked indicator becomes a choice model due to precedence-not effectiveness) or editorial preference for some keywords will likely appear as signal even though both have little or nothing to do with disturbances but were coded into the database as a matter of policy.

Data for each year representing the sum total of events within each of the ten major taxonomic categories were queried from the database and plotted in an array (54 rows, 10 columns) (Paper 1, Figure 4). This yearly count data represents all data integrated from the Northwestern Atlantic, Gulf of Mexico and Caribbean Sea. Categorical information aggregated at this level of resolution provided the minimum number (sometimes less) of values needed for temporal analysis. Arrays were prepared for each of the 10 major taxonomic categories (Paper 1, Figure 4). Spearman rank order correlations were run for all the possible categorical relationships. Significant or surprising non-random associations among count data were noted. The findings from the correlation matrix were compared with the presumed relationships identified in the scalar and relational data modeling steps as a cross check of database design. For apparently significant and expected correlations, extended (standard) cross-correlation calculations were run to test the nature of the identified random pattern. While the data quantity and quality may not be suitable for more rigorous statistical analyses, this simple technique does provide a reference point that can guide future data collection.

A single PCA (1^{st} and 2^{nd} factors) plot was produced to examine spatial MMED relationships among the Northeastern states for which more detailed location data were compiled, and because these states are thought to share similar disturbance regimes (Synopsis of Results Section, Figure 29). The PCA plot was intended to test the supposition that adjacent regions respond similarly to temporal disturbances. Provided that adjacent states cluster together, it could be inferred, that their disturbance regimes may also be similar. In fact, many events observed do cross state boundaries and are coded in the database similarly, but rarely cross regional boundaries without significant seasonal lag (often picked up with yearly aggregate data analyses). To produce the spatial PCA, the "State/Province" keyword, taxonomic type (10 category) and month/year of occurrence were cross-tab queried (a query that determines a unique intersection between 3 variables) to produce a state/province integrated date matrix by enumerated event count data (Data table in CDROM Appendix 9).

Spatially explicit statistical analyses require better-collected data than represented by the MMED aggregate data. In the HEED database, data "happens" whenever somebody cares to mention what he or she saw as a distinct event. Findings of no significant occurrence are rarely if ever recorded and thus, no data versus "no-occurrence" cannot be distinguished. With few datapoints, similarity and dissimilarity associations are easily exaggerated by coincident-unrelated observation. Although this study is limited by the data presently available, this method can be revisited when more uniform data collection occurs.

To more fully understand the utility and potential of multiple marine ecological disturbance data, three papers appear in the following consecutive chapters. Each paper demonstrates a selective use of information technology for the reconstruction of historic marine disturbance event data. The first paper documents the increasing frequency of morbidity and mortality event observations in the North western Atlantic, Gulf of Mexico and Caribbean Sea, the second paper provides a survey of how such an analysis could be expanded to cover each of the Earth's fifty large marine ecosystems. The final paper proposes to apply these techniques to the Baltic Sea large marine ecosystem. In each of these papers, an outline is provided as to how "expert" consensus, spatial, temporal, categorical and statistical data reduction methods have or could be used to reclassify thousands of independent anomaly observations into eight functional impact groups. The eight groups, anoxic-hypoxic, biotoxin-exposure, disease, keystone-chronic, mass-lethal, new-novel-invasive, physically forced and trophic-magnification disturbances, are suggested measures of marine ecosystem health.

CHAPTER 3

APPLICATIONS OF THE HEED MMED APPROACH

Ecosystem Health Assessment in the Northwest Atlantic and the Margins of the Pacific, Atlantic, Indian Ocean Basins and the Baltic Sea

The three papers that follow constitute part of a series. In the first paper entitled "Past anomalies as a Diagnostic tool for Evaluating Multiple Marine Ecological Disturbance Events," emphasis is on the MMED methodology as a generic approach for rescuing potentially important data already collected in various funded, but uncoordinated studies. The paper is focused on methods to reconstitute the reported observations into a standard quality controlled multidisciplinary retrospective database that is designed for data recovery, synthesis, and hypothesis generation. Emphasis is placed on the utility of mining an existing repository (HEED) of widely scattered and fragmentary observations for their suitability in diagnosing anomalous events as components of MMEDs. The substance of the paper was presented at the Fifth Symposium of the U.S. Environmental Protection Agency's National Health and Environmental Effects Research Laboratory, entitled "Indicators in Health and Ecological Risk Assessment" Research Triangle Park NC, June 6-8, 2000.

The second paper of the series, "Marine Ecosystem Health as an expression of Morbidity, Mortality and Disease Events," is focused on the extension of the HEED MMED approach from the prototype case study in the Northwest Atlantic coastal region to a more global approach where the application may guide International funding of large marine ecosystem projects within economically developing parts of Africa, Asia, and Latin America. The emphasis in this paper is on the transferability of the methodology to enhance regional assessments of ecosystem health, with information that can contribute to improved ecosystem management practices and better international coordination of marine health information. The paper has been accepted for publication in a special issue of the Marine Pollution Bulletin.

The third and final paper in the series is entitled "A Prototype Methodology for the Assessment of Multiple Ecological Disturbance in the Baltic Sea Ecosystem." In this paper, the HEED MMED approach is focused on potential applicability to a single large marine ecosystem, the Baltic Sea. The paper outlines the HEED approach and may be useful to the eastern Baltic countries during the implementation of the Baltic Sea Large Marine Ecosystem (BSLME) project; sponsored by the Global Environmental Facility, World Bank, Helsinki Commission (HELCOM) and the International Council for the Exploration of the Sea (ICES).

CHAPTER 4

PAST ANOMALIES AS A DIAGNOSTIC TOOL FOR EVALUATING MULTIPLE MARINE ECOLOGICAL DISTURBANCE EVENTS

Sherman, B.H. 2000. Human and Ecological Risk Assessment. CRC Press

Paper 1: Summary

In the search for the best ecological and economic indicators of ecosystem change, a unifying solution for joining data from disparate fields appears as a general rule: Organize data into space/time/topic hierarchies that permit convergence of data resulting from shared and appropriate scaling. The scale of the data selects for compatible methodologies, leading to data integration and the discovery of new relationships. Information technology approaches include bibliographic keyword searches, data-mining, data-modeling and geographic information system design. The approach was used within the "HEED" study, which reconstructed historic marine disturbance events within the Northwestern Atlantic, Gulf of Mexico and Caribbean Sea. The object of the study was to retrospectively derive co-occurring Multiple Marine Ecological Disturbances (MMEDs). Disturbances include indices of morbidity, mortality and disease events affecting humans, marine invertebrates, flora, and wildlife populations. Correlations between the space/time occurrence, event coincidence, climate and oceanographic forcing are used to better define multiple marine ecological disturbance types. Systematic derivation of these types is part of diagnostic approach that can assist or guide marine ecological risk assessment.

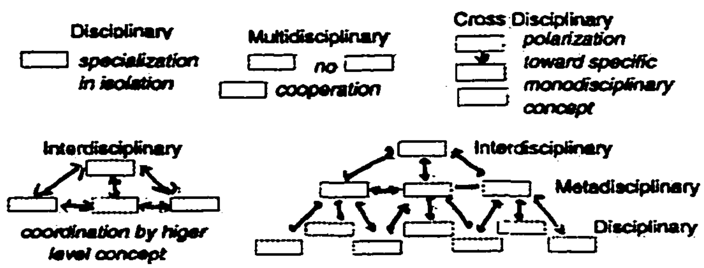
Paper 1: Introduction

Epidemics of marine disease, harmful algae blooms, fish kills, marine mammal and seabird mortalities, shellfish toxicity, anoxia, food web dysfunction, invasive species, human illness, beach closures and compromised seafood quality, are just a few of the disturbances and socioeconomic impacts presently motivating water quality management responses (Todd, 1994; Epstein, 1999; Sherman, 2000). Because these marine disturbance events are not easily isolated in space, monitored in real-time, or constrained within a single jurisdiction, a whole ecosystem perspective (large area / coarse resolution) is often taken to ascribe assessment criteria (Sherman and Duda 1999). An ecosystem perspective requires a researcher to choose a context or baseline, from which changes over time or anomalies and impacts are measured. Temporally, this perspective requires a retrospective assessment, often involving a literature review. Spatially, ecosystem work must match the scale of perceived impact, but remain large and coarse enough to capture potential forcing factors outside of the preconceived impact area (Levin 1992). Because the search for disturbance causality in an ecosystem can scale from organism physiology to climate system teleconnections (Bakun 1996), a wide range of historic information may be amassed representing many jurisdictions and the results of many disciplinary methods. Without an appropriate exploratory framework (e.g. hypothesis generating strategy and data reduction methodology) it is difficult to distinguish the rare but valuable insights at the intersection of disciplines from the more typical but limited view of a particular discipline.

It is no longer argued whether interdisciplinary methods are required for ecosystem assessments (Sherman 1994; Bertram and Stadler-Salt 1998; Duda and Cruz, 1998; NRC, 1999), but how best to assemble and reconcile information from disciplines. For example, a marine biologist, public health specialist and economist may each characterize the same event (e.g. harmful algae bloom) in a time and place. However, each will publish their observations in a different literature. A decade later, memory of that particular event may be lost or fragmented, however an interdisciplinary event-based data recovery strategy can be used to re-discover the same event from the separate individual accounts. Recovery of this and many other common event observations could provide an impact history quite distinct from the separate context and independent fragments recounted by a public health practitioner, marine biologist or resource economist from the perspective of their respective disciplines. A fuller context for any given event empowers an analyst to make better contemporary generalizations and perhaps to even discover possible mechanisms regarding causality or trends.

Sectorization, dividing the world into disciplines of study and administrative jurisdiction, has led to the fragmentation of earth sciences information. Ecosystem approaches require the reunification of information drawn from many disciplines and multiple administrative jurisdictions to select not only the most convenient indicators, but also the most representative indicators of ecosystem changing condition. Academia generally trains environmental scientists to sub-divide nature topically and, as a result, many ecosystem indicators are still topical taxonomic indicators (e.g. presence/absence of birds), not functional ecological indicators (e.g. ratio of ill to healthy birds). Jantsch (1976) illustrates a similar difference between topic and function when hierarchically describing the academic disciplines studying the world. His hierarchies describe the strength and extent of interaction among disciplines as a dysfunctional product of topical specialization, which leads to incompatible methodologies over time. Three general types of study emerge: disciplinary, multi-disciplinary and interdisciplinary (Fig. 1). Strict disciplines are fairly conservative when defining boundaries between their field and others. For them, boundaries are established by tradition and methodology. The strict topical disciplines when working within a single department comprise a multi-disciplinary unit. A multi-disciplinary unit may incorporate multiple discrete methods into a single study but this does not imply cooperation. Two or more multidisciplinary units working together are forced to reconcile those methods. At this point methods of research are altered to become transdisciplinary (interdisciplinary) or crossdisciplinary. Jantsch (1976) defines trans or interdisciplinary study as the integration of diverse disciplinary methods into entirely new methods. Transdisciplinary is the term applied to an individual whereas interdisciplinary applies to group work. Metadisciplines integrate multiple fields (e.g. botany and zoology to form landscape ecology). Functional classifications are by-products of an inter-, trans-, or meta-disciplinary process (Sherman 1994).

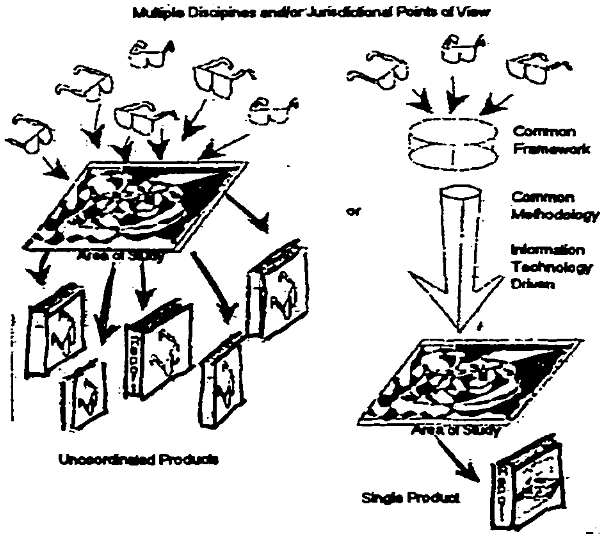
Figure 1. Schematic depiction of how a disciplinary approach using diverse topical methods divides the World and how the resulting fragmented data may be recovered through the creation of interdisciplinary methods emphasizing functional relationships rather than arbitrary disciplinary divisions (adapted from Jantsch 1976).



Jantsch's distinctions are not merely semantic, but indicative of research outcome if ignored. For instance, in environmental studies, project reports either "integrate" data among disciplines (interdisciplinary) defining an area or time period irrespective of discipline, or divide the subject matter into artificially separate disciplinary (topical) chapters merely held together by a binder. Occasionally, an editor, with transdisciplinary insight will summarize the material in introductory or concluding sections. Ecosystem approaches require a more fundamental and functional integration of information (Allen *et al.*, 1994). Technological tools now exist to make integration easier, particularly for bridging traditionally separate social, natural and physical sciences information. If an appropriate information technology framework or process is provided, interdisciplinary and multijursidiction ecosystem goals can be achieved. Information technology is used here as a catalyst to focus effort on a single integrated methodology.

A "summation" methodology, focused on marine epidemiology for example, is greater than its disciplinary components or "parts" (e.g. zoology, botany, climatology, oceanography, public health, resource economics, etc.) (Fig. 2). The present study demonstrates the use of a multidisciplinary database and data-mining system for cross-correlating environmental and biological sector driven observations into a systematic methodology for evaluation of functional ecological disturbances.

Figure 2



Sectorization of environmental science information, represented by glasses or points-of-view, grows from disciplinary specialization and yields uncoordinated products. Information technology, the filter or common methodology, focuses disciplinary points of view and produces a single unified product.

Recollecting Information

The majority of marine research results are found in at least one of thousands of scholarly publications, government documents or mass media reports. This conversion of the information acquisition process into an information dissemination process is largely a byproduct of 19th century science. This becomes increasingly less efficient as the number of electronic and traditional paper journals increases (Marshall 2000), and each individual information source captures a smaller fraction of the sum total of scientific research. Moreover, each publication outlet has its own peer review standard, an ever-changing consideration of quality data, and a segmented world-view (the byproduct of academic disciplines). For an individual consumer of information, it has become more difficult to derive the secondary benefit from research projects, as it is now very difficult to determine where, with whom and how environmental information is currently compiled. From the perspective of a researcher studying a particular patch of land or seascape, collecting all prior research products, irrespective of discipline and jurisdiction, from a given area during a stretch of time, remains a challenge. However, recovery of the information by-products from past studies is possible. One strategy is to focus on meta-data (data about data) and to extract this information from bibliographic archives. This can then direct efforts toward appropriate acquisition of the primary data itself. This literature/metadata mining strategy is expedited through an interdisciplinary process described within this paper. The process is designed to be expedient, cost effective, useful to resource managers, and to help generate new research hypotheses.

Metadata standards have evolved as an information technology necessity within the remote sensing and Geographic Information System (GIS) research community. GIS, for instance, allows data themes of a single spatial area to be joined to one another irrespective of the temporal period the data actually represent. Resource management agencies are increasingly reliant upon these technologies for primary data analysis. However, in the rush to use this information, data of different scales and qualitative types are commonly merged without explicit control or theoretical guiding principles to integrate information within the overlay process (Davis et al., 1991). By tracking the metadata, lineage and conversion methods and scales attached to the information layers, one can control error propagation and misuse (Johnston, 1998). Explicit analysis of metadata in an information-based research environment is useful because, at the least, insights can contribute to a feedback loop for improvement of the data collection process, identification of missing scales, and can enhance disciplinary/jurisdictional cooperation through data standardization (Fisher et al. 1999).

Anomaly Indices as Metadata

For ecosystem work, scientific metadata can be recovered to form environmental disturbance time-series by mining the articles and journals originally reporting research findings. Unfortunately the availability of pertinent disturbance indicator long time series data and information is limited, as science and resource management have shifted effort away from monitoring the unexpected (Wolfe *et al.*, 1987; Gross *et al.*, 1995). For marine scientists, ecosystem-based research has focused on "processes" such as seasonal dynamics and changes in community dynamics, and trophodynamic organization (Magnuson, 1990). These study types emphasize normal or generic conditions. Metadata characterizing these studies is of value, but the most pressing contemporary marine science questions come from the observation of unanticipated disturbances (non-normal conditions)(NRC, 1999). When a field researcher studying natural processes is confounded by a disturbance event, careful note of the anomaly is published. These publications become a meta-data trail to track down and possibly reconstruct an anomaly time-series. Tracking these anomalies through time can provide useful information for resource managers.

"Anomaly" is only a temporary classification within the academic literature, at least until the system is better understood. Climate forcing, species invasion, resource extraction and pollution are disturbances considered abnormal at first, until the threshold of novel observation is passed and the consequence of these persistent events leads to new ecosystem baseline conditions (Orians, 1975; Holling, 1986). However, until a system stabilizes around a new dynamic equilibrium, the marine ecologist's or data-miner's "canary" forewarning future ecosystem state-change are built upon these serendipitous, seemingly random anomaly observations. The observations could include large numbers of usually rare species, mass stranding of mammals, mortalities of fish or crustaceans occurring at the same time or separated by hundreds of miles. Multiple anomalies co-occurring within the marine environment, sometimes leading to a cascade of ecosystem changes, have been defined as multiple or major marine ecological disturbances

(MMEDs) (Williams and Bunkley-Williams 1990). Because of the need for retrospective analysis prior to magnitude classification, MMEDs are defined here as "Multiple" Marine Ecological Disturbances and major disturbances are defined as "meta-events" until proven to be major. Multiple anomalies, irrespective of the disciplines reporting the observations, form an anomaly index pertaining to the state of the ecosystem. At the very least, the index represents a science-based indicator of an ecosystem's behavior. Co-occurring anomalies (as functional indicators) can also provide early warning of ecosystem state-changes.

Tracking Anomalies

An anomaly is defined as a single event in a time and place manifesting in one or more occurrence reports from at least one or more publications. Disturbance observations reported might include a wide range of biological perturbations; regardless, an event was observed and was considered sufficiently extraordinary to merit publication (Mearns, 1985). The processes described are either physical or biological scale dependent events that decrease the life expectancy or kill species unfortunate enough to pass through space and time anomalies. (Figure 3). The fact that species respond to a disturbance phenomenon indicates that co-evolution or place-adapted characteristics make them good phenomenon sentinels for uncharacteristic ecosystem change. Conversely, repeated disturbances select for opportunists that thrive during anomalous times (Orians, 1975). Depending upon the frequency and duration of the anomaly, opportunists may reshape their environments to suit their needs at the expense of other flora and fauna; e.g. *Caulerpa taxifolia* (Meinesz, 1999), *Pfiesteria piscicida* (Burkholder, 1998).

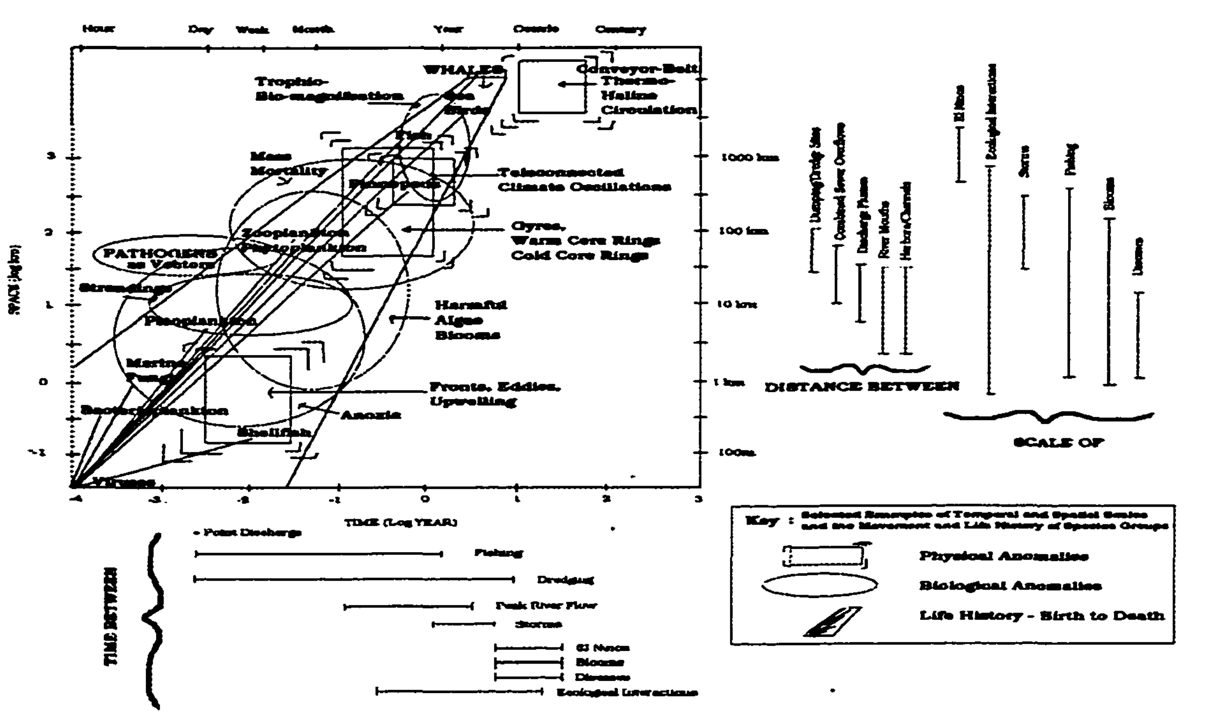


Figure 3. Characteristic Temporal and Spatial Scales for Disturbance Events. The species groups within the cone begin their average life history in the bottom left corner, and depending upon their ability to withstand the biological anomalies (ellipses) and oceanographic anomalies (rectangles) during their growth and maturation, they may live roughly as long the lines are long and move as far as the lines indicate. In brackets are anthropogenic and climate perturbations that may also influence survivability (adapted from NRC 1990).

The organisms involved in MMED events behave as indicators or sentinels of changes taking place within marine ecosystems and along their shorelines. Thus, reports of unusual occurrences merit more than a passing note in a journal or passing reference in a seldom read article; they may merit their own monitoring protocol. The business of science is to make better predictions (Allen and Hoekstra 1992), and to do this using retrospectively derived indicators requires scientific rigor. A systematic approach to anomaly occurrence investigation and MMED description is possible, but reconciling data reported from different observational scales (indicated in Fig. 3) becomes a challenge in developing anomaly indices.

There are a number of problems to overcome: 1) correlative or exploratory statistical methods often yield difficult or poorly explained multivariate relationships, occasionally connecting un-related variables. 2) Most monitoring data, meteorological, physical, economic, public health data, for example, are incompatible with respect to scale and resolution. Processing data to a normalized scale can easily mute the extremes in favor of normal distributions and thus important outliers or anomalies are lost. 3) Correlation of past coincidence information will not necessarily predict future occurrence. 4) There is little precedent to interpret the pooling of multiple species data into a single general anomaly time-series. 5) Anomaly datasets are comprised of findings that "something happened," whereas records that anomalies "didn't happen" rarely if ever exist. It is impossible, then, to distinguish between "no occurrences" or "no observation of occurrence." The fourth point introduces unacceptable uncertainty when testing hypotheses under adverse conditions using only retrospective data while the fifth point highlights the importance of compiling the most comprehensive data set possible in order to obtain robust statistical results.

Provided these five primary obstacles to MMED research using retrospectively derived anomaly indices are overcome, what might one do with an anomaly time series? The answer is relevant to pressing resource management questions. It would be of interest to determine how often rare events occur, what species or species combinations serve as effective indicators of these disturbances, the extent to which the occurrences are indicative of long-term trends and the relationships among causative variables. Moreover, if a pattern of these observations emerges, can future anomalies be forecast? What is the impact or damage from these events? Answers to these questions can be forthcoming from mining the metadata for emergent patterns (exploratory data analysis).

Managers occasionally rely upon methods less rigorous than Exploratory Data Analysis (EDA is a data mining method). Science itself is often considered just one view-point, sharing context with folk-wisdom, anecdotal accounts and economic practicality (Allen *et al.* 1994). Anomalies are recorded in all disciplines, however. The advantage provided to decision makers in meta-data mining of unified anomaly information is that what were once unrelated "non-science" observations are now folded into a single "anomaly" information system. As such, systematic mining of place/time specific anomaly information may create a more inclusive decision making environment. This is the unifying interdisciplinary product.

Northwestern Atlantic Case Study

A pilot effort to develop a rapid survey of possible connections and costs associated with marine disturbance types was initiated in 1995 by a group of investigators and collaborators at Harvard University and associated federal, state, and academic institutions (HEED 1998). The Health Ecological and Economic Dimensions (HEED) program convened a series of workshops in 1995, 1996 and 1997 to inventory observational morbidity, mortality and disease reports pertaining to: aquatic birds, coral and sponges, fish, harmful algae, human marine-related illness, mortalities and disease of marine mammals, molluscan shellfish and crustaceans, sea turtles, large invertebrates and seagrass. Seventy-seven rivers, estuaries, embayments, lagoons, cays, and harbors were selected to represent regional units within the Gulf of Mexico and United States eastern seaboard. In addition, the eastern coast of Canada, extending north to Labrador, and the Caribbean Sea, extending south to Venezuela were established as study boundaries. Global data and information located between regional units were also catalogued. More than 250 participating researchers provided data and bibliographic reference material to be later incorporated into a relational database and geographic information system (GIS). The HEED database was used to develop reporting standards, a classification system for disturbance events and a list of 2021 keywords to search over 10,000 assorted journal articles, symposia proceedings, workshop reports, books, semi-popular journals, manuscripts, and ultimately millions of anecdotal mass-media newspaper and wire-service reports for event information (Harvard University's HOLLIS cross-referenced bibliographic system and Lexis/Nexis Inc. (Dayton, Ohio) catalogues were used respectively).

Climate anomaly data and ecosystem structure data were compiled for the study area using Lamont-Doherty Earth Observatory's (LDEO) Climate Data Library (Blumenthal 1996,

1998) and NOAA's Office of Ocean Resource Conservation and Assessment National Shellfish Register of Classified Growing Waters (NOAA 1997), NOAA's Strategic Environmental Assessment Division's Estuarine Living Marine Resource program data (Nelson *et al* 1991, Nelson *et al.* 1992, Stone *et al.* 1994, Jury *et a.l* 1994), and Estuarine Eutrophication Survey data (Bricker *et al.* 1999). Nutrient data was derived from EPA and USGS sources compiled by Jaworski and Howarth (1996). Trophodynamic information was supported by the ECOPATH model and the UN Food and Agriculture Organization's statistics compiled by Pauly *et al.* (1998).

Public health data, including reports of illness and diseases of a marine origin, were obtained from state public health departments for each coastal Atlantic and Gulf of Mexico state (not all states responded). Contacts were made with researchers in resource economics, rural sociology, and other allied disciplines to compile a list of resource valuation studies undertaken in the bays and estuaries identified in the study region with particular focus on economic disruption in resource yields. Beach closures and other state public advisories were culled from the Natural Resources Defense Council's annual surveys. National datasets, including NOAA's fisheries economic statistics, those of the Federal Emergency Management Agency and individual state's Small Business Administration data, were useful; particularly, summaries of requests for financial assistance following catastrophic events.

A world-wide-web site with prototype interactive web-database was developed to facilitate data acquisition and categorization. This site also contained elements of an interactive Geographic Information System to facilitate data exploration. Links to a number of web tools were provided so researchers could validate their own data and better report events. For instance, data entry was aided by place/name lookup queries provided on the world-wide-web by the United States Geological Survey Geographic Name Information System (GNIS), Canadian Mapping Service and U. S. Defense Mapping Agency's (global) place name systems. These sites translate place names to latitude and longitude coordinates. With latitude and longitude and date, information can be "hot-linked" to online data servers such as the Lamont-Doherty Earth

Observatory marine atlas of the oceans and disease name registries located at the Smithsonian Institutions, National Ocean Data Center, and Centers for Disease Control. Other sources of data linked via the world-wide-web could include pictures of tumors or necropsy information, detailed descriptions of disease condition, abstracts and pertinent articles or related online references.

Twenty-Nine locations (mostly within New England) were chosen to create combined anomaly temporal disturbance-regime plots because of the availability of ancillary oceanographic data (Table 1). Decimal longitude and latitude (reported at the seconds of degrees resolution prior to conversion) were desired for all reported events.

Table 1. Time series data sources included Sea Surface Temperature Anomaly (SSTA) Sea Level Pressure Anomaly (SLPA), Wind Stress (WS), Paralytic Shellfish Poisoning (PSP), satellite data products including Coastal Zone Color Scanner and Sea Wide Field of View sensor data - CZCS and SeaWiFS).

Data desired	Data Obtained	Data Used	Time Scale	Space Scale	Use Constraint
SSTA	SSTA	SSTA	Monthly	2km	Rate in time not change in space
PPTA	PPT	PPT	Monthly	2km	Value not anomaly
Wind Stress	Wind Direction	W. Direction	Monthly	2km	Value not anomaly
SLPA	SLP	SLP	Monthly	2km	Value not anomaly
Ocean Color	CZCS	SeaWiFS	N/A	N/A	Representation unclear
Fisheries Econ	Fisheries Annual	Variability	Yearly	State	Only variability has meaning
Shellfish Econ	Yearly Harvest	Variability	Yearly	State	Only variability has meaning
PSP_Maine	PSP limited samples	Weekly/season	Monthly	1 km	Incomplete
PSP_Massachusetts	PSP limited samples	Weekly/season	Monthly	1 km	Incomplete and short duration
PO_4	Multi-year, avg.	Region	N/A	N/A	Wrong scales for processes
NO_3	Multi-year, avg.	Region	N/A	N/A	Wrong scales for processes
K	Multi-year, avg.	Region	N/A	N/A	Wrong scales for processes
NH_3	Multi-year, avg.	Region	N/A	N/A	Wrong scales for processes
SiL	Multi-year, avg.	Region	N/A	N/A	Wrong scales for processes
ENSO Index	Yearly	Integrated	Yearly	Ocean	Lag NINO 3
NAO Index	Winter/yearly	Integrated	Yearly	Ocean	Lag unknown

To capture the public awareness of events, and hence possible agency response to disturbances, news-media sources were also queried. This source material is more local in nature than many of the summary reports found within databases and often integrates suspected causes and environmental conditions more thoroughly than the conservative peer reviewed literature. Differing qualities of source material forced the assignment of ranking codes to all metadata entries. Because of questions of reliability, news-media data were assigned two codes: one based upon the type and perceived reliability of the publication, the second based on the proximity of the data to an expert source (e.g. direct observation by an expert, implied direct observation, unclear source of observation.) For purposes of data analysis, the more reliable peer-review historic data is examined separately from news-media data. The news media sources were most valuable in providing direct contact information regarding past events unreported within the peer review literature.

Scale was used in the HEED effort to optimally aggregate anomaly indicators and their proxies to construct major marine ecological disturbance (MMED) indices. Because anomaly, space and time are common themes across many disciplines, co-occurring anomalies (matched in space and time) permitted a rudimentary merger of different data types. Data models (Sherman 1994) helped to lump categorical data together, based upon similar scale, resolution, quality, and relationships (Tables 2,3). A data model (Tsischritz and Lochovsky, 1981) is a table developed prior to the creation of a relational database schema.

Tables 2 and 3. Examples of Data Models. (from Sherman 2000).

Table 2. **Pathogen Toxin Disease Model (a relational example)**

Taxonomic Indicator - report type	Pathogen keyword	Toxin keyword	Disease Keyword
Human- doctors reports, water proximity	*G.Breve*	Brevetoxin	Respiratory Distress
Shellfish - Mussel harvesting ban	*Alexandrium tamarensis*	Saxitoxin	Paralytic Shellfish Poisoning
Coral – Sea Fan decline report	*Asperillus spp.*	Fungal Infection	Gall Formation
Fish –Menhaden mortality report	*Pfiesteria piscicida*	Biotoxin	Ulcerative Mycosis

Table 3. **A Marine Disturbance Data Model (Scale-based coarse aggregate example)**

Some Indicators	Spatial Types	Temporal Types	General Parameters
Shellfish toxicity, Human illness & Harmful Algae Blooms (HABs)	Harbor, Estuary	High frequency Fast/acute	Biotoxins Storm pulses
Seagrass disease, Shellfish toxicity & HABs & Birds & Mackerel mass mortality	Bays and Sounds	Episodal Events Cyclic & Variable	Physical, Chemical, Biological combinatior
HABs & Pinnepeds Coral Reefs & Herring mass.mort.	Gulf, Seascape	Translates Downscale Threshold cascade	Oceanographic Forcing
HABs & Cetaceans & Sea Turtles (& = suggested correlation)	Wide-spread Large Marine Ecosystem	Lowest Frequency Slow/chronic	Climate Forcing Bloom Timing Seasonality shifts

By matching co-occurring and similarly scaled data, many described anomalies were collapsed into just a few major event types (methods included principal components analysis, cross-correlation matrices, and multiple regression) helping to create indices for evenly sampled data time-series or general taxonomic functional classes for episodic observational data. Multiple events, even if recorded by different observers for different purposes, if found to co-occur, when combined into indices provided ample sample sizes to test the power of the metadata relational database. If the data models for the co-occurring events appeared plausible, a single distinct disturbance event was formed from the multiple observations. This was the primary means of data reduction and determination of major versus minor events.

Data Integration

Although data were obtained at much finer temporal resolution (mostly monthly), the yearly level of aggregation was universal to all data types. Data for each year representing the sum total of events within each of the ten major taxonomic categories (Fig. 4) were queried from the database and plotted. This annual count data represents integrated disturbances within the Northwestern Atlantic, Gulf of Mexico and Caribbean Sea. Categorical information aggregated at this level of resolution provided the minimum number (sometimes less) of values needed for temporal analysis.

DATE	Public Health	Invertebrate	Mammal	Mollusc	Seagrass	Sea Turtle	HABs	Fish	Coral	Bird
1945	1						2			
1946							2			
1947							2			
1948										
1949							2	1		
1950										
1951							2	1		
1952										
1953										
1954	7									
1955	2						1			
1956	6	1					1			
1957	1			2						
1958	1	1								
1959	1			11			1			
1960	1			11						
1961	3			10			1			
1962	3			7	1		1			
1963	2			9					1	
1964	1			5						
1965							1	1		
1966	2						3	1		
1967										1
1968	1						9			
1969	1				1	1			1	3
1970							1			2
1971	17	1		2			25	8		

DATE	Public Health	Invertebrate	Mammal	Mollusc	Seagrass	Sea Turtle	HABs	Fish	Coral	Bird
1972	20	2		1	1		67	10		5
1973	9			1			15	1	4	
1974	6			1	1		45	6		1
1975	17				1		24	2	1	1
1976	20	8		10		1	74	21	3	
1977	12	1		1		2	19	3	5	
1978	11					1	6	1	2	1
1979	19		16	2			25	6	22	
1980	25	2	8	1		1	39	27	17	1
1981	20	1	1		4		10	3	13	1
1982	20	3	12	2	2	2	72	33	15	14
1983	28	29	6	7	3		69	25	55	28
1984	15	15		4	5		87	16	37	5
1985	21	2	2	16	6	5	93	11	1	7
1986	50	16	1	7	14	5	122	34	24	8
1987	70	3	25	23	8	4	201	39	124	9
1988	77	4		28	5	4	230	52	81	6
1989	36	7		15	4	4	162	43	18	25
1990	47	18	34	18	3	7	198	26	19	13
1991	21	19	2	26	1	6	147	55	8	7
1992	90	12	3	28	8	3	266	52	4	4
1993	44	5		22	3		145	22	8	17
1994	42	4	11	29	3	4	197	57	8	15
1995	54	7		13	9		180	81	28	9
1996	118	3	3			19	329	128	25	50
1997	24	1		8			39	13	10	
1998							3	1		

Figure 4. Matrix of Count Data by the Ten Major Taxonomic Categories for the Entire HEED Study Area. Zero values were assigned to cells for which there were no recorded observations. If variable effort in reporting were not a factor with these data, one would be able to distinguish between no data "zeros" and non-event "zeros". Data remain incomplete between 1996 and 1998.

It was found in the HEED study that frequency and duration of disturbances among different indicators led to a small set of repeated ecosystem responses. In the HEED database thousands of keyword combinations were reduced to 147 related disturbance types involving ten major taxonomic groupings, that when analyzed using principal components analysis, revealed eight semi-distinct disturbance types more ecologically relevant than the originally delineated ten taxonomic divisions: Anoxic-hypoxic, biotoxin-exposure, disease, keystone-chronic, mass-lethal, new-novel-invasive, physically forced and trophic-magnification disturbances (Fig. 5). These eight predominant impact types support the relationships anticipated from data modeling and confirmed by cross-correlation analyses (e.g. shellfish toxicity and human illness were associated in time and place as expected).

The eight marine disturbance types represent events that are acute, occurring within a short term span, (e.g. biotoxin exposure), protracted (evolving over time, as when fungi infect coral reefs and seagrasses), or chronic (e.g. tumor development, eutrophication). Other categories have specific correspondence to forcing factors (e.g. coral bleaching events and sea surface temperatures; population declines from climate variability and altered ecosystem dynamics). However, the majority of disturbance reports involve harmful algae blooms (HABs) as the indirect cause of morbidity (illness) and mortality. Because HABs can affect a wide variety of living marine resources and dramatically alter ecological relationships among species (Burkholder 1998), they are a leading indicator of marine disturbance, and thus, ecosystem health. Well-described anthropogenic impacts, such as oil/chemical spills, by-catch, dredging and errors in food preparation were excluded from the HEED database, unless relevant long-term or recurrent disturbance characteristics were defined. Direct human impact types are reviewed elsewhere (e.g. Sheppard 1998a,b,c), and much would be learned by merging direct and the more indirect impact databases.

Anoxic/Hypoxic Disturbance

algal bloom (anoxic)
algal bloom (anoxic?)
algal diatom bloom (anoxic?)
fish kill (anoxic)
fish kill (anoxic?)
invertebrate crustacean kill (anoxic)
invertebrate crustacean kill (anoxic?)
invertebrate kill (anoxic
mollusc bivalve kill (anoxic)

Keystone/Chronic Disturbance

algae macroalgae overgrowth
algal bloom (shading)
algal bloom (shading/wasting)
algal bloom (wasting)
bird reproductive failure
coral disappearance
coral neoplasia
human beach closing
human fisheries ban
human river closing
invertebrate decline
mollusc bivalve growth suppression
mollusc bivalve mortality (wasting)
mollusc bivalve reproductive failure
mollusc shellfish contamination
mollusc shellfish harvesting ban
mollusc shellfish harvesting ban (contamination)
sea turtle fibropapillomas
seagrass decline
seagrass decline (shading)

Disease Disturbance

algal mortality
bird disease (plague)
coral black band disease
coral rapid wasting disease
coral white band disease
coral white band disease (similar)
coral white plague type I
coral white plague type II
coral white pox
coral yellow blotch disease
fish disease
fish disease (toxic)
invertebrate crustacean disease
invertebrate crustacean shell disease
invertebrate illness
mammal dog illness
mammal pinniped distemper
mammal pinniped influenza
mammal sirenian virus
mollusc bivalve JOD
mollusc bivalve disease (MSX)
mollusc bivalve epizootic neoplasia
mollusc bivalve oyster dermo epizootic
mollusc clam QPX disease
sea turtle encephalitis
seagrass disease

New-Novel-Invasive Disturbance

List Truncated (includes too many categories

Mass-Lethal Mortality Disturbance

algal bloom
bird kill
bird mortality
coral destruction
coral mass mortality
coral mortality
coral ridge mortality
coral sponge destruction
coral sponge mortality
fish kill
fish mass mortality
invertebrate crustacean kill (unknown etiology)
invertebrate kill
invertebrate mass mortality
invertebrate mortality
mammal cetacean mass mortality
mammal cetacean mass stranding
mammal cetacean mortality
mammal cetacean stranding
mammal kill
mammal pinniped stranding
mammal sirenian mass mortality
mammal sirenian mortality
mollusc bivalve kill
mollusc bivalve mass mort.
mollusc bivalve mortality
mollusc gastropod mortality
sea turtle mortality
seagrass mortality

Trophic-Magnification Disturbance

bird disease NSP
bird mortality PSP
fish PSP
fish toxicity PSP
human ASP
human DSP
human Hepatitis A
human NSP
human PSP
human cholera
human disease
human gastroenteritis
human shellfish poisoning
human vibrio vulnificus
mammal cetacean PSP
mollusc shellfish harvesting ban ASP
mollusc shellfish harvesting ban DSP
mollusc shellfish harvesting ban NSP
mollusc shellfish harvesting ban PSP
mollusc shellfish toxicity ASP
mollusc shellfish toxicity DSP
mollusc shellfish toxicity NSP
mollusc shellfish toxicity PSP

Physcially-Forced Disturbance

coral bleaching
coral shut down reaction
coral sponge bleaching
fish cold kill
invertebrate cold kill
mammal cetacean cold kill
mollusc clam bleaching
sea turtle cold kill
sea turtle cold stunning
sea turtle egg destruction

BioToxin/Exposure Disturbance

algal bloom (red tide)
algal bloom (toxic)
algal bloom (toxic?)
algal bloom (toxicity unknown)
algal bloom (unusual red tide)
algal cyanobacteria bloom
algal diatom bloom
algal diatom bloom (toxic)
fish kill (toxic)
fish kill (toxic?)
human ciguatera poisoning
invertebrate crustacean kill (toxic)
invertebrate crustacean kill (toxic?)
invertebrate kill (toxic)
mammal cetacean mortality (toxic?)
mollusc bivalve kill (toxic)
mollusc bivalve kill (toxic?)
mollusc shellfish toxicity

bird mortality ASP
bird mortality NSP
fish lesions
fish toxicity ASP
human eye irritation
human memory loss
human neurological damage
human respiratory irritation
human seabather's eruption
human skin irritation
human swimmer's itch

Figure 5. Disturbance Types. The eight functional disturbance categories (box headers) better represent the 147 occurrence types (box-lists) than do the 10 taxonomic categories using semi-automated clustering procedures (From Sherman 2000)

Cross correlations among the ten taxonomic categories revealed anticipated temporal relationships among the following independent datasets: Harmful Algae Blooms and Shellfish (e.g. confirmation of biotoxin accumulation), Harmful Algae Blooms and Public Health (e.g. exposure and ingestion), Shellfish and Public Health (e.g. biotoxins/shellfish toxicity), Fish and Public Health (e.g. Ciguatera Fish Poisoning), Seagrass and Invertebrates (e.g. loss of habitat). An expected relationship between Marine Mammal health and Public Health Events was not found. Higher correlations than expected were identified between Seagrass and Public Health (this relationship has yet to be explained). These findings represent a first pass analysis of the HEED database's categorical relationships.

A more in-depth temporal analysis of cross-correlations among the 147 disturbance types revealed several statistically significant findings - yet to be fully investigated (Table 4):

TABLE 4.		Correlated Disturbance Indicators	Correlation Coefficient
Hepatitis A	vs.	Pseudo-nitzchia	0.812
Fish Lymphocystis	vs.	Aureombria	0.724
Human Gastroenteritis	vs.	*Vibrio damsella* and *Eurtoptiella*	0.707
Epizootic Neoplasia	vs.	Climate Cold Kill (sea turtles)	0.694
Synechococcus	vs.	Gannett Mortalities	0.687
Fish Lymphocystis	vs.	Eutreptia	0.624
Cladophora	vs.	*Aureococcus anophagefferens,*	0.526
Pfiesteria piscicida	vs.	Bottlenose Dolphin Mortality	0.488
Unidentified Dinoflagellate	vs.	Pfiesteria	0.484
Gull mortality	vs.	Dinophysis	0.466
Eutreptia	vs.	Aureumbria	0.451
Correlations in Time Not Necessarily Location			

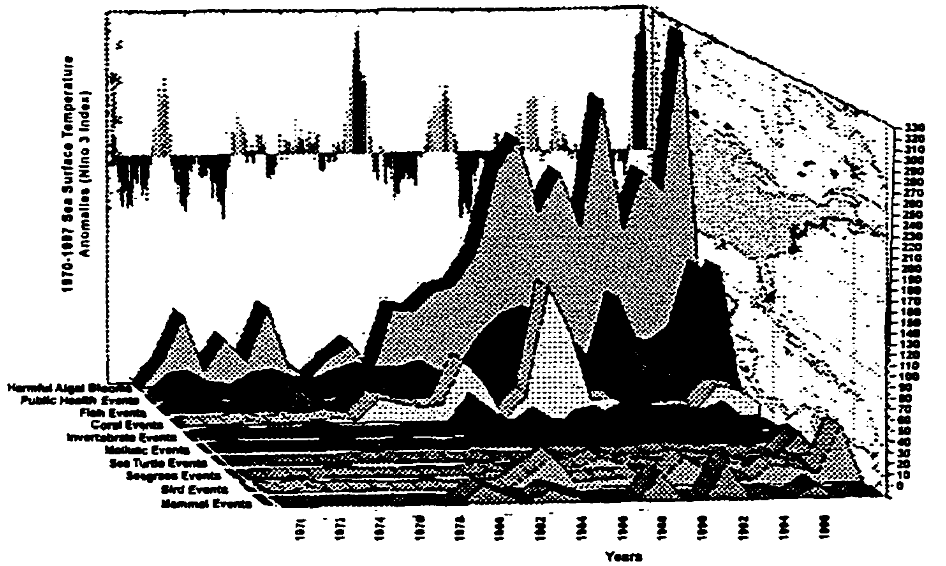
Many of the possible correlations in Table 4 may be artifacts of the data reporting process such that these independently observed disturbance events do not share a similar forcing factor (e.g. climate) or functional relationship. However, the possibility that one or more of these findings may actually represent a contribution to basic research or monitoring demonstrates the utility of the HEED meta-data system for hypothesis generation. A cross-check of metadata derived from the academic literature and an incomplete survey of news-media stories extracted using similar keywords also revealed unanticipated correlations. For example, in a 1987 article, Williams and Bunkley-Williams report that a series of large fish kills occurred off the coast of Venezuela and were reported in local newspapers in 1985. The HEED database not only captured those events, but also identified a similar large kill of coastal fishes from newspapers reporting similar events in Puerto Rico and the U. S. Virgin Islands in 1985. These events remain scientifically un-documented, because they were not of scholarly interest at the time. Retrospectively, the co-occurring disturbances appear to represent an important region-wide phenomenon, anecdotally referenced by Williams and Bunkley-Williams (1987). Now, the reports from different sources represent a single event awaiting validation within the HEED database.

HEED Data Mining Findings

One of the objectives of the HEED project was to retrospectively identify common forcing factors, particularly climate forcing, as the cause of morbidity, mortality and disease events. There is precedent for this type of varied source metadata investigation. Mearns (1985) conducted a review of Pacific marine fishes wandering north or south of their usual range. He concluded that the distribution of previously considered "rare" fish observations and unusual occurrences of marine organisms are commonplace, and that collectively (but not always) served as indicators of cool and warm oceanic disturbances associated with the El Niño Southern Oscillation (ENSO). Moreover, Mearns concludes that the pattern of unusual occurrences explain more than just decadal processes but a whole host of processes yet to be understood and likely are related to a large-scale oceanographic regime shift in the Pacific (McGowan et al. 1998; Brodeur and Ware 1995). An examination of the relationship between HEED MMED observations (representing a "whole host of processes") and marine climate anomalies is necessary to better understand climate forcing.

To examine large-scale forcing factors, occurrence reports were aggregated by year (1970 –1996) and consolidated into ten mutually exclusive taxonomic categories. The categories of observational count data were plotted relative to ENSO periodicity (Figure 6). These HEED results have encouraged further research into plausible mechanisms linking ENSO events with certain MMED events types.

Figure 6. Observations of Marine Disturbances within the Northwestern Atlantic Ocean, Caribbean Sea and Gulf of Mexico (data from HEED 1998).



Note that the compiled data depicted in figure 6 represent a general increase in awareness and reporting of anomalies for individual taxonomic groups. Interviews with the researchers and "experts" that made the original observations will be necessary to evaluate the difference between increased observational effort and increases in the appearance of disturbance over time. Harvell *et al.* (1999) conducted a survey of new and novel disease occurrences globally and concluded that increased observational effort during the last thirty years does influence the number of reports, but does not significantly influence inter-annual variability (e.g. coral bleaching world-wide responsive to sea surface temperature).

An interannual signal is apparent within the HEED data. Public health event reports, for instance, were most numerous during: 1972, 1976, 1982, 1983, 1985, 1990, 1993 and 1996. These years are coincident with strong El Niño events and/or drought conditions attributed to La Niña. Geographically, public health reports clustered in the Northeast, Florida and the Gulf States. Fish mortality data clustered in 1979, 1982-83, 1987, 1994, and 1997-98, and throughout the 1980s and 90s. The highest number of reported fish events occurred during El Niño years. Coral bleaching event reports and anomalously warm sea surface temperatures did co-occur. Bleaching reports occurred regardless of ENSO phase during the 1980's and 1990's. The diseases of invertebrates are clustered in Nova Scotia, Florida and the Caribbean and were coincidentally reported during the 1976, 1982-83, 1987-88, 1991-92 El Niño years.

Observation of multiple marine ecological disturbances (HEED 1998) and rare species outside of their geographic range during El Niño Southern Oscillation events (Mearns 1985) represents an additional tool or indicator of ecosystem change. Barber and Hayes (this issue), extend this concept further, suggesting that coral disease events may be indirectly related to the North Atlantic Oscillation (NAO) index due to iron-bearing dust blown from sub-Saharan Africa. They use aggregated anomaly data from Harvell *et al.* (1999) and HEED (1998) to describe a hypothesized increase in iron-dust-opportunistic pathogens and a climate regime shift in the mid-1970's corresponding with a shift in the NAO (a functional forcing relationship). The HEED MMED approach has also been found useful in large-scale global surveys (Sherman 2000) and may be applicable to smaller ecosystems like the Baltic Sea Large Marine Ecosystem (BSLME) (this issue) Agenda 21 project coordinated by the Global Environmental Facility, World Bank, Helsinki Commission (HELCOM) and the International Council for the Exploration of the Sea (ICES).

Relevance of Data Rescue

Increasingly, institutions are realizing that subscriptions to individual journals are decreasing as the number of publication outlets increase. Aware of the fractionation of the research communication process, federal agencies are revaluating the terms of grant research with a goal of encouraging better communication methods. Recent rules and requirements for some federal grantees now include careful documentation and reporting of meta-data associated with publication, transfer of all data to single standards based custodians, maintenance of copyright protection with the agency, and participation in indexing services to facilitate later data-mining efforts. The new requirements represent a change in valuation and priority concerning data and metadata. If data warehouses and data repositories are to be the future for information dissemination and communication as some have predicted (Marshall 2000) recovery of past research, development and monitoring investment should be a equally high priority. This is even more important as researchers retire with their soon to be lost data, older digital media decompose, and as existing institutional repositories become obsolete. These older information products form the backbone of the research community's collective memory and are increasingly the definitive record upon which new work is based. Mining of anomaly data can recover some of this prior marine research investment while addressing pressing contemporary resource management questions.

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CHAPTER 5

Marine Ecosystem Health as an Expression of Morbidity, Mortality and Disease Events

Sherman, B.H. 2000.. *Marine Pollution Bulletin*. Pergamon.

Paper 2: Summary

Over the last fifty years, national, international and private stewardship and conservation organizations have spent billions of dollars collecting marine ecosystem information. This remains divided among many custodians, scattered among thousands of published sources and, from a global perspective, is fragmentary in nature. It is argued that new resource management questions regarding coastal ecosystem health can be addressed through the recovery and data mining of this previously collected and often discarded information. A retrospective marine epidemiological approach was developed to demonstrate that marine morbidity, mortality and disease information is recoverable by keyword searching of academic journals and through the retrieval of publicly available digital and print-media information. Observational records compiled from disturbances occurring within the Northwestern Atlantic, Gulf of Mexico and Caribbean Sea confirm that anomalous marine morbidity and mortality events have increased in number and frequency during the last 30 years. A global approach is summarized for systematically reconstructing spatial and temporal disturbance indicator time-series using data mining and data reduction techniques. The techniques are applied to better understand factors causing disturbances among: aquatic birds, coral and sponges, fish, harmful algae blooms, human marine related illness, diseases and mortality of mollusks/shellfish/crustaceans, marine mammals, sea turtles, large invertebrates and seagrass. Over 300 named anomalous conditions were reduced

to 147 occurrence types and ultimately the following 8 functional impact groups were derived: anoxic-hypoxic, biotoxin-exposure, disease, keystone-chronic, mass-lethal, new-novel-invasive, physically forced and trophic-magnification disturbances. A survey of the large marine ecosystems of the world is made, to demonstrate a coarse but comparative view of the health of marine ecosystems. A new rapid global data/information collection and dissemination strategy is recommended.

Paper 2: Introduction

> *Errors of Nature, Sports and Monsters correct the understanding in regard to ordinary things, and reveal general forms. For whoever knows the ways of nature will more easily notice her deviations; and, on the other hand, whoever knows her deviations will more accurately describe her ways.*
>
> Francis Bacon (1620)

Red tides, bleaching of coral reefs, the stranding of marine mammals and mass mortality of fish and invertebrates have been observed for millennia. Aristotle, Homer (Iliad), Tacticus, and early European navigators were astute observers of these episodic phenomena (Baden *et al.* 1995) This century, the frequency, extent and duration of disturbances appear to be increasing (HEED 1998, Harvell *et al.* 1999). Over the past 40 years, reports of marine disturbance from around the world have filtered through academic publications, mass-media reports, and the archives of institutional stewardship agencies. However, these reports are fragmented from disciplinary sectorization, lack of coordination among research programs, overlapping national and local jurisdictional mandates and varied reporting standards.

Several groups have begun to characterize the health of entire coastal marine ecosystems (e.g. GESAMP 1990, NOAA 1993, NRC 1999) and to understand the pressures upon them, compare management techniques and guide better studies. Institutions are now designing new monitoring programs to collect ecosystem health information. National and international ecosystem health stewardship and conservation organizations have spent billions of dollars funding research and data collections relevant to ecosystem health questions. But, global scale marine ecosystem health information has not yet been consolidated (NRC 1995). Thousands of researchers have however, published studies describing anomalies among various taxonomic and indicator responses to a wide range of global disturbances. So, the potential exists to reassemble and characterize disturbance and impact information from published accounts and to reconstruct time series at a variety of scales to find common response patterns among multiple indicators.

Information technologies now allow mining of bibliographic archives, geographic information systems and Internet databases to re-collect scattered information. From observational accounts, patterns of response of some disturbance indicators appear to serve as proxies for each other in time. As collecting long-time series data for any single indicator is problematic (Magnuson 1990), reconstruction of historical time series by scavenging available indicator and/or proxy data provides a new information base to evaluate large-scale and long-term disturbance patterns. The purpose of recovering disturbance records is to match impact symptoms with exogenous factors. Epidemiologists use similar retrospective techniques to track public health problems. A marine epidemiological (marine ecosystem health) approach incorporates multiple techniques and the methods of many disciplines.

The methods summarized here represent a first approximation data mining- data rescue effort to address both marine ecosystem health and disturbance questions. Methods rely upon a basic knowledge species natural histories, as synchronized with, and/or responsive to ecological, climate and oceanographic variability. From such an understanding, a large number of reported anomalous marine morbidity and mortality observations can be placed within an information system and grouped to represent a smaller number of disturbance indicators reflecting common response to exogenous impacts. Impact-based indices (grouping indicators by co-occurrence in time and space) are used to organize scattered and fragmented species monitoring data. These indices measure *Multiple Marine Ecological Disturbances* (MMEDs) and are used to help define *major* impacts (Williams and Bunkley-Williams 1992). The centralized MMED information provides more complete historical (e.g. time-series) information than would be typically available to researchers or managers.

Scale Specification

Scale is used optimally to aggregate anomaly indicators to construct MMED indices. Point data (x,y sample locale), river, estuary, harbor, bay, state, drainage basin, province, nation, large marine ecosystem and their subdivisions are the spatial scales researchers associate with marine indicators. Observers use temporal sampling increments of hours to decades, often reporting conceptual divisions of time such as peak, duration, phase and seasonality (i.e. timing of phenological changes). Matching appropriately scaled data, many categories of data can be collapsed to fewer either creating indices (for evenly sampled data) or general taxonomic functional classes for observational data.

Episodic events involving the 10 major taxonomic divisions and the 10 regularly reported time series data types within Table 1, are globally available and provide a first impression of co-occurring anomalies associated with scale relative functional impacts (Figure 7). If multiple disturbances can be detected in the same time and space, mining of distributed sources of archived information elucidate the relationships among the co-occurring disturbances.

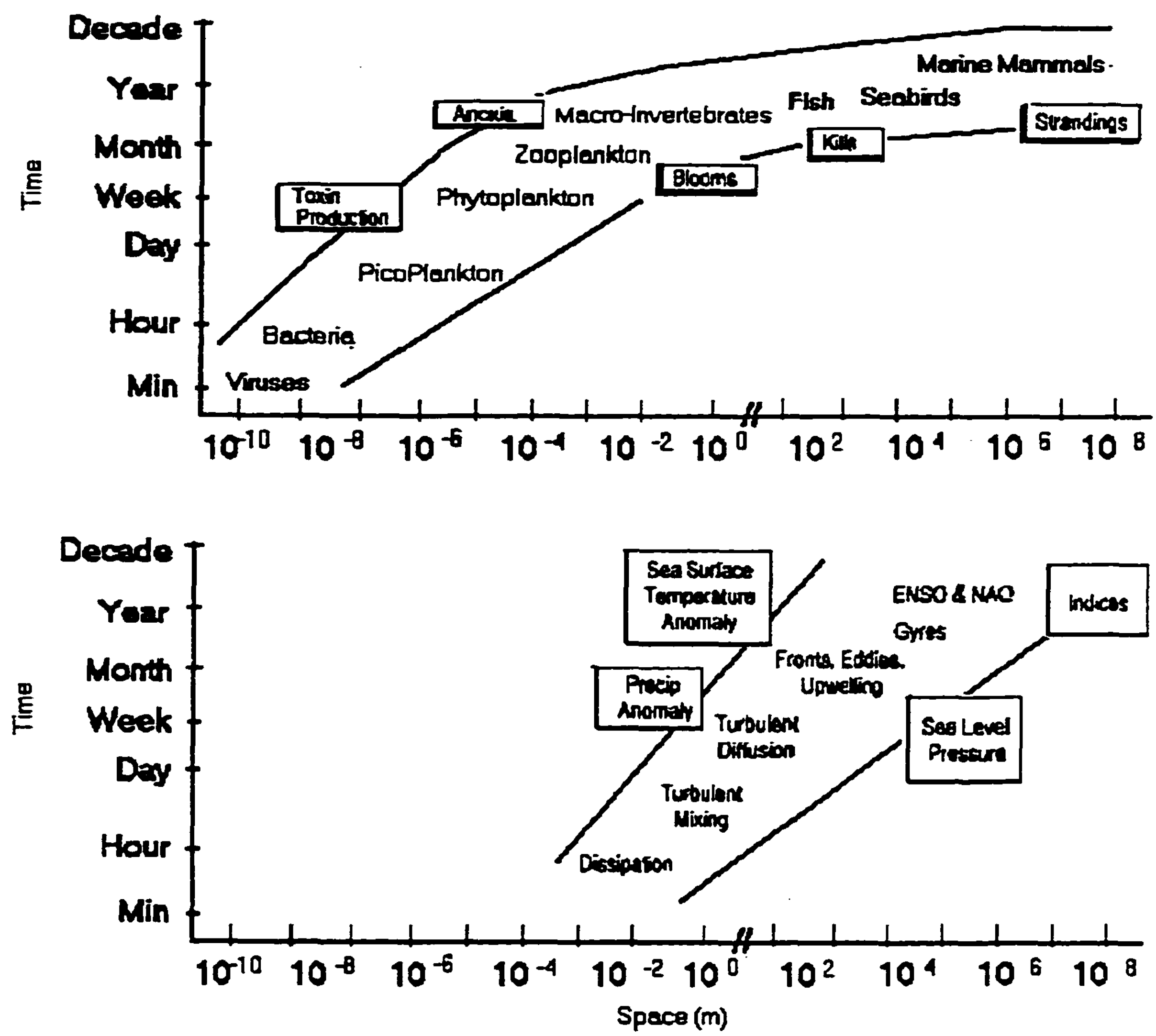


Figure 7. Some prescribed spatio/temporal scales associated with functional impacts within marine systems. The boxes within this figure are functional groupings of indices detected along a wide range of spatio-temporal scales (sliding along and in between the lines). Aggregate information from Linnaean taxonomic groups (top) or sets of processes (bottom) are the items between the lines. The likelihood of matching oceanographic or cliamate forcing (bottom log plot) with biological processes (top) is improved because the boxed functional groupings (both plots) are not fixed to a particular scale. Researchers may " float" (allen and Hoekstra, 1992) or slide the scale with each log-plot until forcing factor anomalies and possible impact category anomalies (from each log-plot) are matched in space-time. The log plot values and between the line elements are adapted from Murphy *et al.* (1988).

As anomaly, space and time are common descriptors for event data, co-occurring anomalies (matched in space and time) allow merger of different data types. Multiple events, even if recorded by different observers for different purposes, if found to co-occur may be defined as a distinct disturbance type (by characteristic behavior or components). Scale similarity and matching co-occurrence in space and time allows a fuller evaluation and tabulation of cost (to society) for each disturbance or anomaly type.

HEED Approach

A pilot effort to develop a rapid global survey of possible connections associated with marine disturbance types was initiated in 1995 (HEED 1998). The effort's information system is capable of helping researchers consolidate disturbance reports regionally and nationally, and could serve as a prototype of a global monitoring database for morbidity, mortality and disease. Marine health assessments like this bring together the expertise of multiple disciplines to: 1) recommend reporting standards for literature derived morbidity, mortality and disease events, 2) assess the integrity and coverage of monitoring data, and 3) recommend future data collection standards.

Survey Methods

The first step is to mine the literature for relevant categorical information. As an example, a literature search including journals, symposia, workshops, books, government technical reports, semi-popular journals, selected institutional reports, and research communications from 1945 to 1996 was conducted to populate a categorical database. Using keywords, the surveyors were able to extract meta-data (data about data) from 2127 published disturbance accounts. The source material ranged from key primary journal citations to reviews (secondary source citations) thence anecdotal accounts of anomalous events (partially verified information). Additional keywords taken from either the title, an author's list of keywords and abstracts of collated reference material were added to the pre-defined list of keywords until 2021 distinct marine disturbance keywords were cataloged to assist in future surveys. Of those keywords, 314 disturbance indicator types were classified and 246 pathogen toxin and disease combinations were derived. Well-described anthropogenic impacts, such as oil/chemical spills, by-catch, dredging and errors in food preparation were excluded unless relevant long-term or recurrent disturbance characteristics were defined. It is accepted that much could be learned by merging an anthropogenic disturbance and marine health impact database.

One of the most important features of literature and data mining exercises is to ensure that surveys are thorough and categorical classifications complete. Graphically tracking key concepts within the marine literature, establishing the epistemological evolution for defined disturbance groupings, is one way to evaluate thoroughness. The depictions are called Idea-maps (e.g. Figure 8), and these maps are created by backtracking citations until primary foundation-works for each disturbance type is identified.

Figure 8 Idea Mapping

<u>An Idea-map depicting a derivation of punctuated pioneer transport HAB disturbance type</u>

(Initiation Conceptual Model) Tester and Steidinger 1997, ←(Loop Current) (Tester et al. 1991), ← Conditioning (Steidinger 1975), ←Seasonality (Dragovich and Kelly 1966), ←Advection (Feinstein et al. 1955), ←(Current Transport) Maury 1859

To reduce the number of published disturbance types to a manageable number, spatial and temporal criteria can be applied using data models (Sherman 1994). Data models help lump categorical data together based upon similar scale, resolution, quality, and relationships. Scale groupings integrate presumed functional ecological categories (e.g. community, population, etc.) and lags or behaviors when disturbed (e.g. fast-acute, intermediate resilient, slow-chronic or cyclical variable and threshold cascade) using insight drawn from idea mapping.

Data Assimilation Methods

Place, time and type of occurrence represent the minimum information necessary for generating an observational report. Additional meta-data information about each event can be obtained from databases held by international, national, regional and local sources. Data may then be extracted for the following data types: sea surface temperature anomaly (SSTA), sea level pressure (SLP), wind stress (WS), precipitation (PPT), nutrients and other climate, oceanographic, health and economic data, Shellfish toxicity (PSP), fisheries economic variability, El Nino-ENSO and North Atlantic Oscillation-NAO indices, and merged with the biological disturbance data for correlative analyses. A variety of natural history reference sources describing the context of each place (e.g. bay, harbor, estuary, river) can be used to identify resident organisms and habitats anticipated to represent co-occurring biological anomalies. In this regard, the life history of species potentially present and the ramification of impact over time can be better understood even if biological observations are incomplete. To anticipate impacts from climate anomalies for instance, large quantities of data must be assimilated. Fortunately much of the necessary marine climate data is readily available from Internet-accessible world data centers (Blumenthal 1998).

The purpose of marine health literature surveys, data mining and development of physical, chemical, and economic anomaly databases is to retrospectively derive new time-series. Single species anomaly reports, and most types of biological monitoring data, when evaluated separately, rarely provide time series of sufficient length to evaluate trend or compare with other time-series. However, when co-occurring biological disturbance data are pooled together, a single MMED series representing temporal patterns of morbidity, mortality, and disease for particular places can be more usefully evaluated. Considered as ecosystem health incidences, observational anomaly data, once enumerated can also be standardized as a time-series. Combined anomaly time series representing place specific disturbance regimes provide a natural history of impact and response for specific locations (e.g. Figure 9).

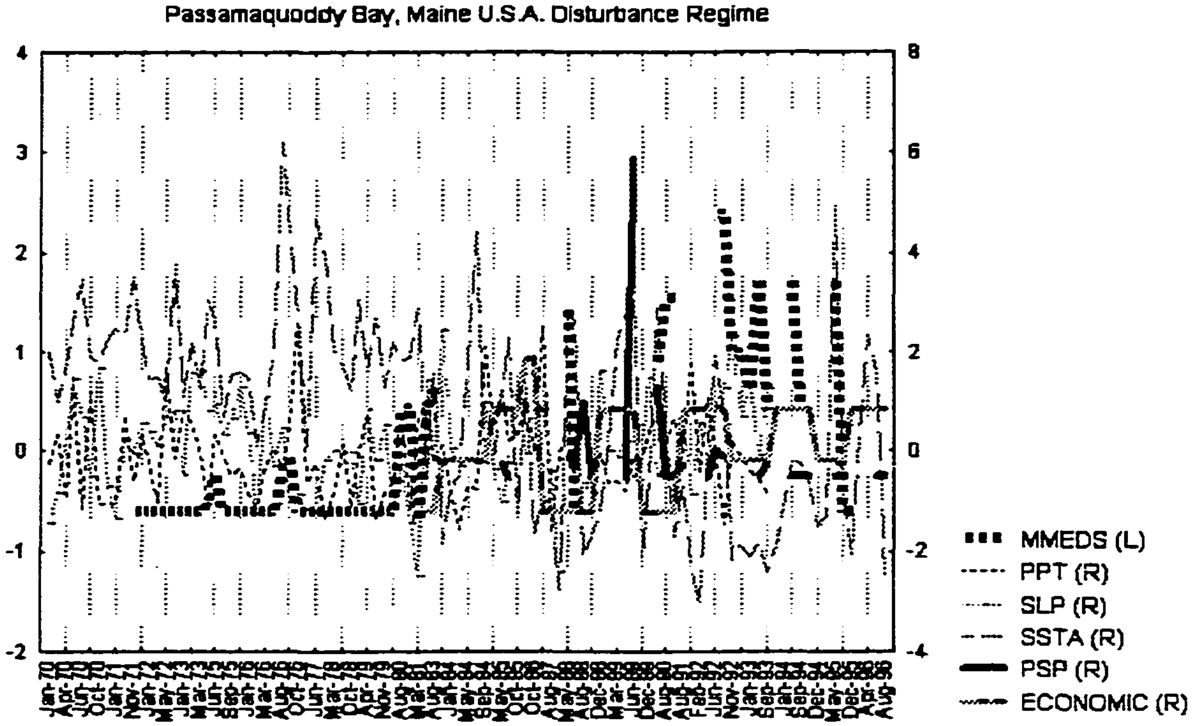


Figure 9. Disturbance Regime

Disturbance Type Derivation

Co-occurring biological anomalies reinforce the importance of particular events, point to periods of time where more intensive data searches ought to be conducted, and typically fill the gaps in incomplete monitoring series. For example, harmful algae bloom incidents, shellfish toxicity data, and reports of human illness from ingestion of shellfish biotoxins are often linked in time. In many cases, one of these health indicators can serve as a proxy for the other two within a time-series. Cross correlation analyses are helpful in determining quantitatively which disturbance indicators are related and which may effectively serve as proxies for each other.

Principal components analysis (PCA) and other multidimensional data reduction techniques provide another effective means of identifying categorical relationships (e.g. Hoekstra *et al.* 1991 for methodology). Semi-automated classification solutions are useful in situations when consensus among researchers is not achieved. Grouping of disturbance types using PCA appears to reflect scaling, common forcing factors, and/or synchronization in response to exogenous disturbance. The PCA provided here (Figure 10) was developed from the HEED (1998) survey data. The groupings classified using statistical procedures represent a reduction of thousands of keyword combinations and thousands of HEED database entries to a 147 related disturbance types that were further aggregated to form 8 combinations of disturbances representing the predominant impact characteristics reflected within the data models originally generated by the "experts."

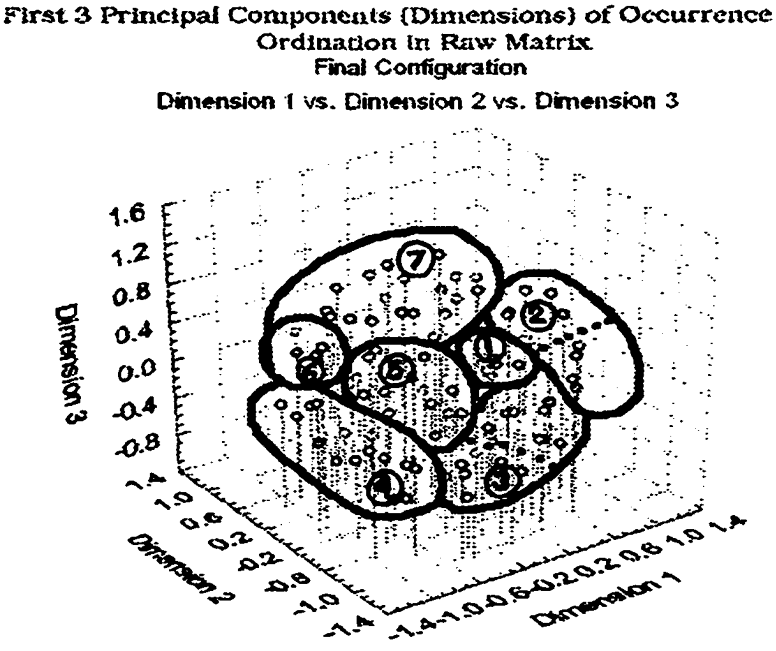


Figure 10. PCA of 147 Occurrence Types Within the HEED (1998) Database. The numbered labels represent interpreted clusters. Dotted lines represent possible subdivisions within the major clusters – noted as a "/" in the disturbance category title. The eight categories of disturbance are: 1) Anoxic-hypoxic, 2) Biotoxin/exposure 3) Keystone/chronic 4) Mass-lethal 5) Disease 6) Physically forced and 7) Trophic –magnification. 8) The New/Novel or Invasive category is comprised of elements from each cluster that, due to rarity within the database (reported only once per location), they were given their own class. The 8 disturbance categories are not mutually exclusive. A single observation can be part of any number of categories simultaneously.

Eight Categories of Disturbance

A first approximation global survey of morbidity, mortality and disease using the 8 functional disturbance categories is provided. The accompanying maps and lists of occurrence types are not meant as a comprehensive review of the health of the world's marine ecosystems, but rather suggest a starting point for a more complete survey. To illustrate the worldwide extent of available data or lack of survey information, large marine ecosystems (LMEs) are used for data aggregation (Sherman and Alexander 1989). Detailed global data, if available from the HEED (1998) survey, are also provided.

Many LMEs are stressed from the growing depletion of fisheries resources, coastal zone degradation from erosion and over-development, habitat damage, and excessive nutrient loadings and pollution from drainage basin effluents (Sherman and Duda, 1999). Using the 8 disturbance types as a guide, the health of the LMEs appearing in Figure 10 appear to be further impacted by the growing number of morbidity, mortality and disease events. Considerable effort will be required to quantify the frequency and extent of these impacts on the health of all 50 LMEs.

The eight marine disturbance types represent events that are acute, occurring within a short-time span, (e.g. biotoxin exposure), protracted (evolving over time, as when fungi infect coral reefs and seagrasses), or chronic conditions (e.g., tumor development, eutrophication). Other categories have specific correspondence to forcing factors (e.g. coral bleaching events and sea surface temperatures; population declines from climate variability and altered ecosystem dynamics). The majority of disturbance reports, however, involve harmful algae blooms (HABs) as the indirect cause of morbidity (illness) and mortality. Because HABs can affect a wide variety of living marine resources and dramatically alter ecological relationships among species (see Burkholder, 1998 for review), they are a leading indicator of marine disturbance, and thus, ecosystem health.

The documentary evidence systematically provided since 1972 indicates that HABs are increasingly problematic and their duration and numbers are increasing (Smayda and Shimizu 1993, Harvell *et al.* 1999). General explanations of why the frequency and distribution of HABs may have increased during the last three decades are given in Smayda (1990) and Harvell *et al.* (1999). Harmful algae blooms disturb ecosystems in three primary ways, through direct exposure of wildlife and humans to algal biotoxins, indirect exposure through the food chain and by contributing to hypoxic conditions that may lead to anoxia.

1) Bitoxin and Exposure Disturbances

The most harmful of the algae species produce potent toxins (biotoxins) damaging to many forms of marine life (Baden and Trainer 1993). Biotoxins cause mortalities of whales, dolphins, fish, shellfish and significantly impact commercial fisheries (NRC 1999). The toxic dinoflagellates (e.g., *Alexandrium, Gymnodinium, Pyrodinium, Dinophysis, Prorocentrum* genera) are responsible for a majority of major marine mortalities involving HABs. *Alexandrium* spp. mortalities involving fish, birds, and mammals (Armstrong *et al.* 1978, Geraci *et al.* 1989, White 1996) have been well documented. The less frequent toxic diatom blooms (e.g., *Pseudonitzschia*) are of particular concern, not only because of their impacts upon migratory waterfowl populations (Work *et al.* 1993) but also because of the severe debilitating illness of humans associated with the diatom biotoxins (Todd 1993). Diatoms such as *Chaetoceros, Skeletonema, Rhizosolenia* spp., or *dictyophytes* (Parry *et al.* 1989, Albright *et al.* 1993, Tester and Mahoney 1995) have spines that can become trapped in the gills and soft tissue of fish or shellfish. The resulting mechanical damage and respiratory impairment may lead to mortality. Cyanobacteria (e.g., *Anabeaena* ssp.) have been implicated in marine mammal mortalities (Nehring 1993). Cyanobacteria (*Trichodesmium erythraeum*) have also been shown to impair the feeding behavior of zooplankton (Guo and Tester 1994), damage coral polyps (Endean 1977), and may be involved in coral bleaching (Coles 1994). Cyanobacterial blooms have been associated with sponge mortalities and reduction in recruitment of spiny lobsters in Florida Bay (Butler *et al.* 1995), and are cited as problems in the Latvian portion of the Baltic (Thulin 1999).

In the Benguela Current, red tides have resulted in widespread mortalities of near-coastal populations of fish, shellfish, and crustaceans (Pitcher 1998). Along the Pacific Rim, mortalities of shellfish and finfish species, supporting growing mariculture industries, have been reported for the Gulf of Thailand subsystem of the South China Sea, where *Trichodesmium erythraeum, Noctiluca scintillans, and Ceratium furca* were the dominant toxic species (Pauly and Christensen 1993). Mortalities of bivalve and shrimp species supporting mariculture activities along the coast of China attributed to toxic red tides have been reported for coastal waters of the Yellow Sea and East China Sea LMEs (Chen and Shen 1999). Recent information indicates that since the 1970s the frequency and extent of toxic bearing red tide organisms have increased in the pacific coastal waters of China (She 1999).

Cyanobacteria biotoxins can cause tumors (Falconer and Humpage 1996) and have been implicated in chronic diseases of freshwater and estuarine animals (Phillips *et al.* 1985, Andersen *et al.* 1993). There is circumstantial evidence for a correlation between human shellfish poisoning and the co-occurrence of tumors, neoplasia and germinomas in bivalves (Landsberg 1995). Toxic benthic dinoflagellates (*Prorocentrum* spp.) can also produce tumor-promoting agents, like okadaic acid, that have been found within the fibroid tissue of dead green sea turtles (Landsberg 1998). Exposure to okadaic acid can occur through the consumption of macroalgae and seagrasses that provide substrate for *Prorocentrum*' growth (Fujiki and Suganuma 1993). Bears, raccoons, otters and birds that spend time in estuaries may also be at risk from biotoxin exposure. Cattle have been shown to be at risk from toxic cyanobacterial blooms in freshwater systems (Falconer 1993).

Direct exposure to biotoxins can arrest reproduction and feeding in shellfish, cause tumors in tropical fish (Landsberg 1998) and turtles, and respiratory irritation (Steidinger 1993) and neurocognitive disease in humans (Burkholder and Glasgow 1997; Grattan *et al.* 1998).

Respiratory irritation due to the aerosolized transport of toxic sea-spray in the vicinity of a bloom is considered a serious public health threat, and has resulted in numerous beach closures along the Florida coast (Landsberg and Steidinger 1998).

Exposure related disturbance impacts are not only due to algae blooms. The 1983 United States Environmental Protection Agency report "Health Effects Criteria for Marine Recreational Waters" describes several types of infections that can result from casual exposure to water. Gastroenteritis and hepatitis are the two most common swimming-associated illnesses. Other human impacts include: cellulitis - skin infection, conjunctivitis -- eye infection, otitis externa -- outer ear infection, swimmer's itch, seabather's eruption, jelly fish stings, and amoebicencephalitis (fresh water). While the duration of biotoxin and exposure related impacts are relatively short, long term ecosystem and use changes can result. Significant reports of toxins and exposure occurrences are usually tied to beach closures, and negative publicity in tourist related economies.

Biotoxin and exposure impacts occur with greater constancy once an ecosystem has become porous enough to allow entry and establishment to a large diversity of potential toxic and noxious species. The biotoxic species have evolved alleopathic offensive and defensive responses to out compete rival species (Baden *et al.* 1995). Evolutionary mechanisms, such as cyst formation and chemosensitive triggers, allow these same toxic species to more easily spread where disturbances are frequent and/or of sufficient magnitude to permanently carve these opportunists new ecological niches (Burkholder 1998). Mass mortalities and subsequent species substitutions eventually provide adequate benthic substrate supporting toxic biofilms and eventually displacement of predators and competitors so that once infrequent biotoxin and exposure disturbances become the new stable ecosystem configuration. Early indicators of threshold changes in ecosystem health from this disturbance type are the temporal periodicity of events and the magnitude of single events (Figure 11).

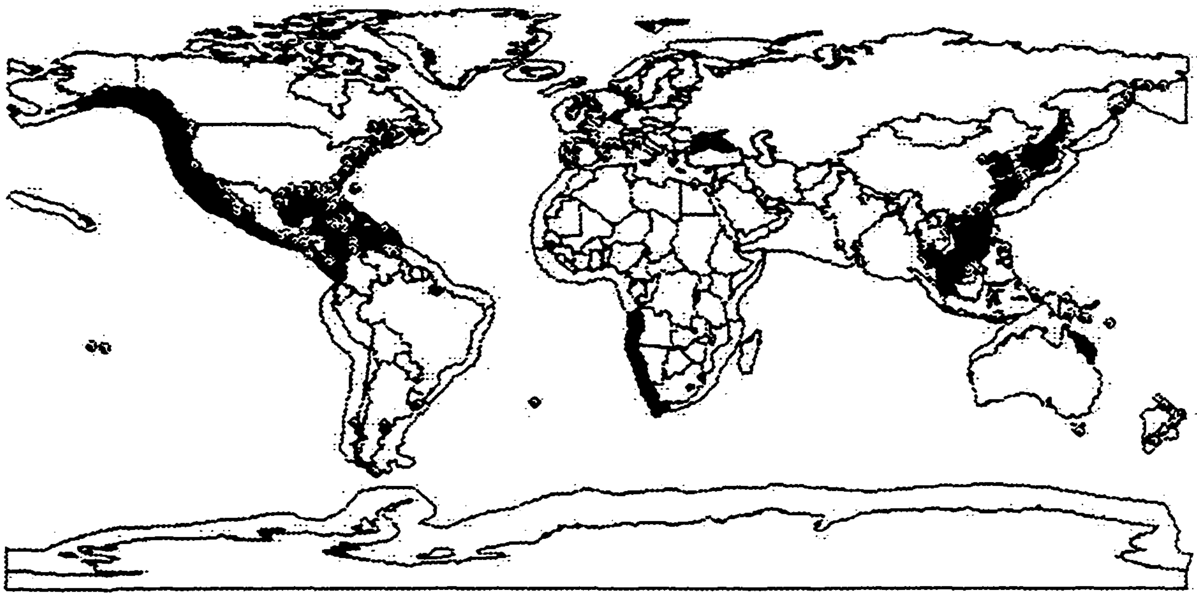


Figure 11.Map of biotoxin/exposure surveys.Within the 50 LMEs, shaded are regions where biotoxin and exposure disturbance types, including information on the distribution of reported harmful algae bloom events (dots) from 1945-1998, are available. The empty coastal polygons represent either insufficiently surveyed or unsurveyed regions. Biotoxin disturbances include algae blooms, cynanobacteria or diatom blooms that kill fish, invertebrates, mammals and humans. Exposure disturbances include mortality of birds associated with ASP and NSP toxins, lesions on fish or toxicity due to domoic acid, human eye irritation or memory loss or neurological damage or respiratory irritation or skin irritation (including swimmer's itch or seabather's eruption or jellyfish stings). These disturbance types are subsetted from a list of 147 types derived from the HEED (1998) rapid survey.

2) Anoxic/Hypoxic Disturbances

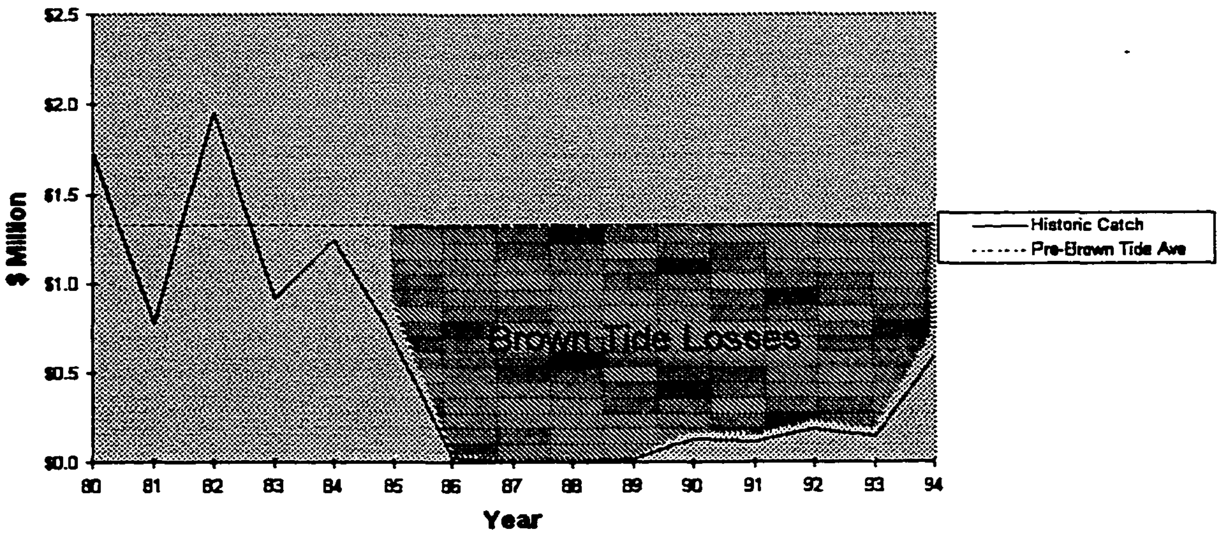
Blooms of non-toxic micro-algae and nuisance macro-algae are defined as harmful because they dramatically reduce sunlight penetration in the water column. Large blooms and excessive growth can also draw a substantial amount of oxygen from the water column at night during respiration. When spent cells decompose on the bottom even more oxygen is removed from the water column contributing to hypoxia (<0.02ppm oxygen) (Cosper *et al.* 1989). The ecological aftermath of most algae blooms is a temporary period of hypoxia, however, if blooms are frequent, near complete removal of oxygen (anoxia) from the water column can occur (Rabalais *et al.* 1999). Once a hypoxic disturbance regime is established, an anoxic trajectory is likely established due to shifts is species composition. Prolonged anoxia gives sulfur-reducing bacteria a foothold, which also accelerates mortality among benthic organisms. Subsequent deaths of fish and invertebrates provide more substrate for the decomposition cycle (Mahoney and Steimle 1979, Adnan 1989).

The magnitude of ecosystem impact from oxygen depletion can be quite significant. In the Black Sea, a region of approximately 35,000 km^2 of the northwest shelf is subjected to annual recurring hypoxic conditions leading to mass mortalities of benthos estimated at 60 million tons of bottom living animals, including 5,000 tons of fish between 1973 and 1990 (Zaitsev 1992). Seasonal mass mortalities are also observed in the southern Baltic Sea (Thulin 1999) and Gulf of Guinea (Ibe *et al.* 1998). Reports of massive fish kills including hake, have also been reported as the result of upwelling, blooms, and oxygen depletion in the Benguela Current (O'Toole 1998). In the Gulf of Alaska, plankton blooms leading to oxygen depletion have impacted fisheries and the economically important king crab (Epstein 1996) as well.

Seasonal occurrence of the hypoxic trajectory has been observed in the Gulf of Mexico since 1985. The hypoxic zone has grown as large as 18,000 sq. km encompassing as much as 80% of the water column (Rabalais *et al.* 1999). Turbid nutrient rich waters flowing into the Mississippi River and then the Gulf contain domestic sewage, agricultural and urban runoff drained from 41 percent of the United States. Since extreme flooding of the Mississippi river in 1993, the receiving waters within the Gulf of Mexico crossed a hypoxic threshold and the ecosystem has reorganized around a stable 7,000 square-mile anoxic "dead zone", off the Louisiana coast. The Gulf seafood industry has been heavily impacted, and that impact appears as anomalies within fisheries economic statistics (Prasad 1998).

Another mode of anoxic impact is from non-toxic "brown tide" algae (picoplankton), *Aureococcus anophagefferens* and *Aureoumbra lagunensis* for example (Cosper *et al.* 1987, Buskey and Stockwell 1993). During intense and persistent bloom conditions bio-deposition and microbial decomposition of the spent picoplankton cells draws the biologically available oxygen out of the water-column creating hypoxic and eventually anoxic conditions. In the short term, the quantity of picoplankton in the water column reduces bivalve filter-feeding activity, as these very small phytoplanktonic cells are poorly processed. Energy expended in filtration is not returned to the filter-feeders because of the comparatively low nutritive content of brown algae cells. Ultimately shellfish may starve (Tracey 1988). The brown-tides also reduce incoming sunlight, stressing aquatic macrophytes and arresting further oxygen production. Losses of seagrass meadows lead to a decline in egg hatching success of the red and black drum, and declines in zooplankton abundance (Draper *et al.* 1990). Combined with the high mortalities of shellfish, significant economic loss of important fishery resources can be attributed to brown tide events (Tracey 1988, Draper *et al.* 1990). The recurrent and persistent brown tides within the Peconic Bay of Long Island USA will be slow to recover because seagrass habitat, important for shellfish and fin-fishery recruitment was lost (Dennison *et al.* 1989, Tettlebach and Wenczel 1993). Tracked since 1985, the cumulative costs have been significant. The landings of scallops dropped from a value of $1.2 million in 1984 to a low of $2,400 in the last year of the recurring bloom in 1988 (Grigalunas and Diamantides 1996) (Figure 12).

Figure 12. Brown Tide losses in the Peconic of Long Island Sound



Fish kills due to hypoxia are the most commonly reported impact within the anoxic/hypoxic disturbance type, and have been used as indirect measures of ecosystem variability (NOAA, 1992). Beyond the regular seasonal oxygen depletion observed in shallow estuaries, mass mortalities of species due to hypoxia have also been used as early indicators of anoxic trajectories (Sindermann, 1996). There are also statistically significant relationships between the temporal co-occurrence of nuisance algae blooms and reported invertebrate, crustacean, and mollusc mortality events (HEED, 1998). Unfortunately, routine mortality reports are often lost or remain un-catalogued (Figure 13).

Recognizing the importance of eutrophication and the potential for anoxic trajectories, the Ministers of Environment representing North Sea adjacent countries set targets for 50% reduction of nutrient inputs based upon a single status report issued in 1994 (North Sea Task Force 1994). This proactive approach has become a topic for negotiation within the Oslo and Paris Commissions (OSPAR) (Reid 1999). The North Sea case is an excellent example of Environmental Ministers, as ecosystem stewards, acting in the best interests of marine ecosystem health, using indicator data.

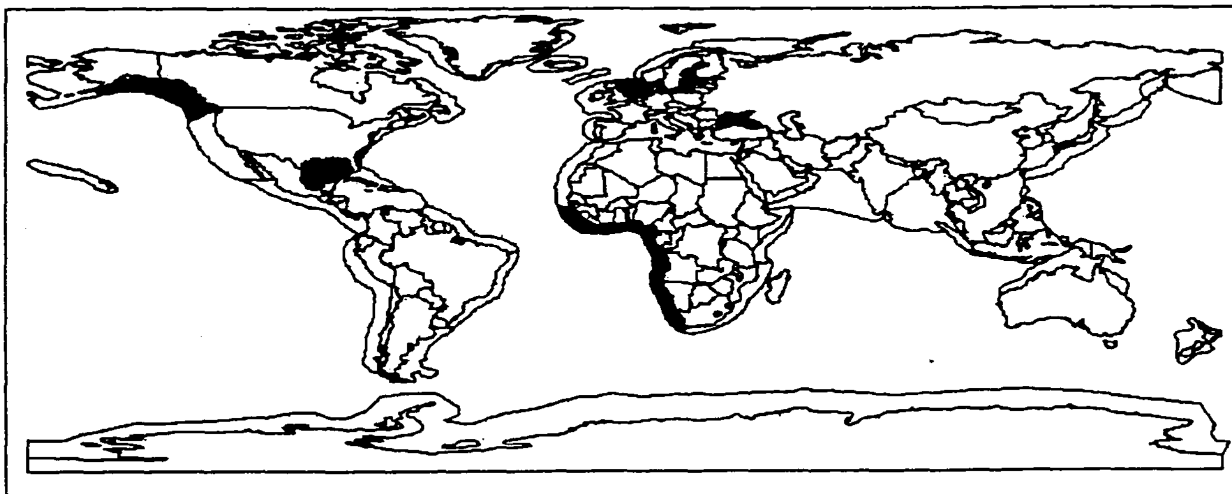


Figure 13. Anoxic/Hypoxic disturbance types. The shaded LMEs have been identified as having regionally accessible information regarding these data types (vs. insufficient/not surveyed empty polygons) for the years 1945-1998).

3) Trophic-Magnification Disturbances

A trophic disturbance is one that can be attributed to interspecies food-web relationships. Trophic disturbances increase geometrically as concentrations of toxins pass from one organism to another. Humans, at the top of the food chain, are particularly vulnerable and become sick from the consumption of foods harboring toxins assimilated during bloom events (Epstein, 1996). HABs affect human health primarily through the consumption of filter-feeding shellfish and fish that have bioaccumulated microalgal toxins. Several toxic dinoflagellates (e.g. *Alexandrium, Gymnodinium, Pyrodinium, Dinophysis, Prorocentrum sp.*), diatoms (e.g., *Pseudonitzschia sp.*) and cyanobacteria (e.g., *Anabaena sp.*) concentrated in shellfish tissue are harmful to humans (Shumway 1989, Steidinger 1993). Amnesic shellfish poisoning (ASP) from eating mussels contaminated with domoic acid (from the diatom *Pseudonitzschia sp.)* have caused short term and permanent amnesia due to the loss of brain tissue and, depending upon exposure, death from acute toxicity (Todd 1993). Illnesses in Canada in 1987 were followed by reports throughout the 1990's in California, Mexico, Spain, Korea and New Zealand. Seabirds have also been poisoned (e.g., Fitz *et al.* 1992; Sierra-Beltran *et al.* 1997). In the case of the November and December, 1987 Scotian Shelf outbreak of amnesic shellfish poisoning, *Pseudonitzschia delicatissima, var f. multiseries* bloomed in response to unusually high levels of nitrate-rich run-off complemented by stagnant and anomalous sea surface temperatures (Smith 1996). The blooming cells remaining within an unusually stable water column were able to produce significant quantities of Domoic acid.

More frequent and wide-spread are paralytic shellfish poisoning (PSP) events due to the ingestion of shellfish contaminated with *Alexandrium* sp. PSP acts on the nervous system (e.g. Price *et al.*, 1991) and though usually not fatal, human mortalities have been recorded in severe incidences. PSP has also been implicated in cases of bioaccumulation with the death of seabirds and marine mammals (Nisbet, 1983; Geraci *et al.*, 1989). PSP has a worldwide distribution, and dinoflagellate variants of *Alexandrium* co-occur in waters known to produce PSP. Significant reports of PSP include the Southeast, Northeast U.S shelves, Gulf of California, Mexico, California Current, Gulf of Alaska East and West Bering Seas, Caribbean Sea, Patagonian Shelf, Kuroshio Current, Sea of Japan, East China Sea, South China Sea, North Sea, Mediterranean Sea, Celtic-Biscay shelf, Arabian Sea, Indian Ocean. *Protogonyaulax tamarense* (a variant of *Alexandrium*), for instance, has been reported as the source of PSP from the ingestion of green mussels, *Perna viridis*, in the Gulf of Thailand (Piyakarnchana 1989; Piyakarnchana and Tamiyavanich 1979). PSP is caused by *Gymnodinum breve* in the Gulf of Mexico and periodically causes toxicity along the Southeastern U.S. Continental Shelf Ecosystem (Tester *et al.* 1993). *Gymnodinium catenatum* is associated with PSP in the Caribbean Sea, Iberian coastal LME, Pacific Central American Coastal LME, Southern Benguela Current, New Zealand Shelf. The dinoflagellate *Pyrodinium* has caused PSP in the Flores Sea, Philippines, South China, Coral and Bismarck Seas.

Neurotoxic shellfish poisoning (NSP) affects humans who have consumed shellfish contaminated biotoxins produced by *Gymnodinium* dinoflagellates. NSP is a significant problem in the Gulf of Mexico and recently, the eastern coast of Florida (Steidenger *et al.* 1999). Ingestion or inhalation of brevetoxins has also contributed to mass mortalities of manatees (*Trichechus manatus latirostris*) within Florida. Diarrheic shellfish poisoning (DSP) associated with *Dinophysis* has been reported coincident with eutrophication within the Norwegian Sea, North Sea, Celtic-Biscay Shelf, Mediterranean Sea and the Latvian portion of the Baltic Sea (Thullin 1999).

In the Caribbean, the toxic dinoflagellates Benthic *Gambierdiscus, Prorocentrum, Ostreopsis*, and *Coolia sp*. are associated with Ciguatoxic fish poisoning (CFP) (De Sylva 1994). CFP is passed from algae to grazers and eventually to large piscivores within an ecosystem. Tourists have a higher incidence rate of CFP due to their preferential consumption of barracuda and grouper. Carriers of the toxin were thought to be unaffected by CFP (Anderson and Lobel

1987). However, during the 1980 and 1993/94 reef mortalities and CFP disease outbreaks in Florida (Landsberg 1995), concurrent immunosuppression was often observed within the lower parts of the food chain associated with ciguatera-toxins (Landsberg 1998).

Chronic dietary exposure of animals to biotoxins can exert lethal or sub-lethal effects at all trophic levels, leading to impaired feeding, avoidance behavior, physiological dysfunction, impaired immune function, reduced growth and reproduction, pathological effects, or mortality (Lesser and Shumway 1993, Luckenbach *et al.* 1993, Wickfors and Smolowitz 1993, Burkholder 1998). Potential long-term effects of biotoxins on the health of aquatic animals may be expressed in terms of susceptibility to disease (immunosuppression) and in the development of neoplasia (Landsberg and Shumway 1998). Many of the possible effects and low dose impact of biotoxins are inadequately studied. Understanding the long-term impacts of sublethal, chronic effects (e.g., recruitment failure and subsequent loss of species within an ecosystem, reduced filtration of water masses and subsequent impacts on benthic-pelagic coupling) will require time-series monitoring (Landsberg and Shumway 1998).

Areas with clear trophic pathways for disturbance can also be conduits for bacteria and viruses. Zooplankton and phytoplankton serve as reservoirs for bacteria such as *Vibrio cholerae* (Colwell and Spira 1992). Studies in the Gulf of Mexico, Caribbean Sea, Indian Ocean, Humboldt Current and Gulf of Guinea suggest a viable trophodynamic transport mechanism for cholera (Epstein 1996, Colwell 1996, Lowenhaupt 1998). Trophodynamically acquired disease is a significant global issue. In aquaculture, feces from production provide ample nutrients for more frequent toxic blooms, antibiotics make harmful species more resistant (eg. samonellosis) and the combination of wider export, increased crowding and polluted water provide a perfect environment for epidemics (Todd 1994). Norwalk-type viral diseases, *E. coli*, shigellosis and cholera all of which can be passed through the food chain and as such, spread from one ecosystem to another (Todd 1994).

Trophodynamic disturbances affect more than just groups of species, but also the habitat supporting these organisms. Seagrasses and coral reefs, for instance, provide the habitat upon which other organisms build their homes, seek protection from predators, and consume for nourishment. Due to the highly productive nature of these systems, toxin production and bioaccumulation can be rapid given the number of food web connections in these highly productive areas. Wetlands and mangroves, also structural habitat, buffer against throphodynamic disturbances. When lost due to fuel wood shortages from cooking and smoking fish as in the Gulf of Guinea (Ibe *et al.* 1998) or removed, drained or flooded for agriculture and aquaculture, these systems become more vulnerable to disturbance (Pimm and Lawton 1998) speeding the recurrence of biotoxin harboring algae blooms. Wetland and mangrove ecosystems serve as Nature's "kidneys" by filtering nutrients, microorganisms, heavy metals and persistent organic pollutants. These structural habitats are self-organizing and self-perpetuating systems and as such, protect species from trophic disease by providing sufficient co-evolved biodiversity to keep disturbance causing organisms in check. Often damage to these critical habitats is the first step in a cascade of disturbances that can undermine ecosystem recovery.

Marine trophodynamic disturbances and habitat loss account for significant portions of lost Gross Domestic Product (Todd 1994). Indirect costs from marine morbidity, mortality and disease events are not surveyed for many maritime economies and for many LME regions impacted by trophic direct costs and losses are not calculated. Losses due to harvesting bans, hospital costs and monitoring and analytical services calculated for Canada, the Philippines and Japan and the United States during public health emergencies (1988 and 1991 respectively) were over a billion dollars (Todd 1994).

Figure 14 Trophic-magnification disturbances from 1945-1998 including HABs (circles) and the location of 1997-1898 Cholera epidemics (triangles). Shaded polygons are surveyed LMEs with data vs. open polygons representing LMEs unsurveyed or with insufficient information.

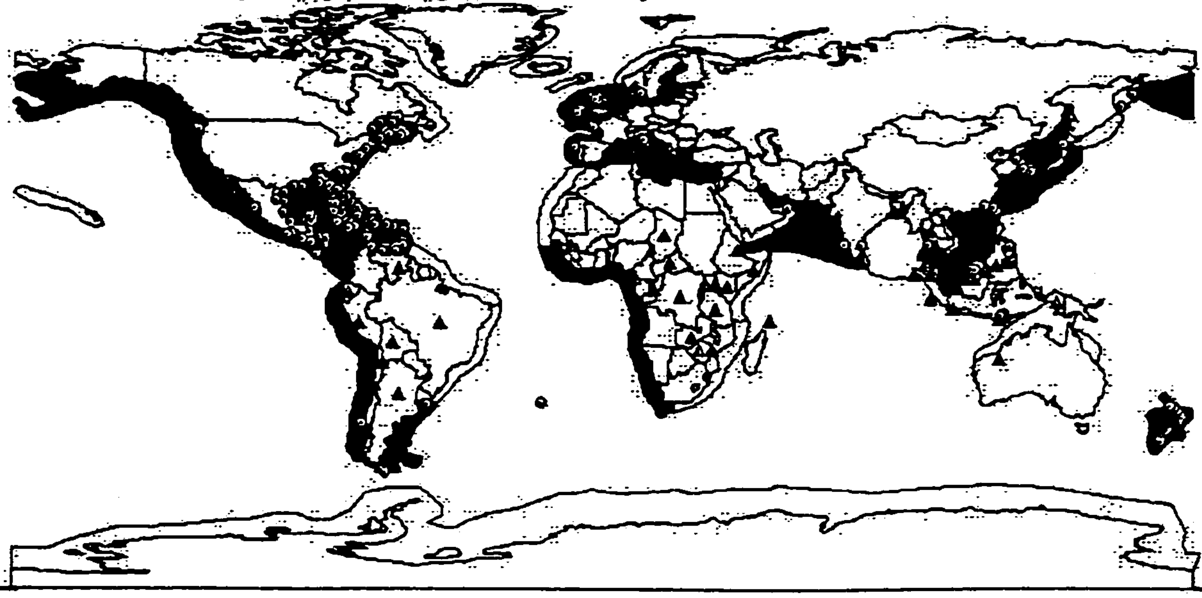
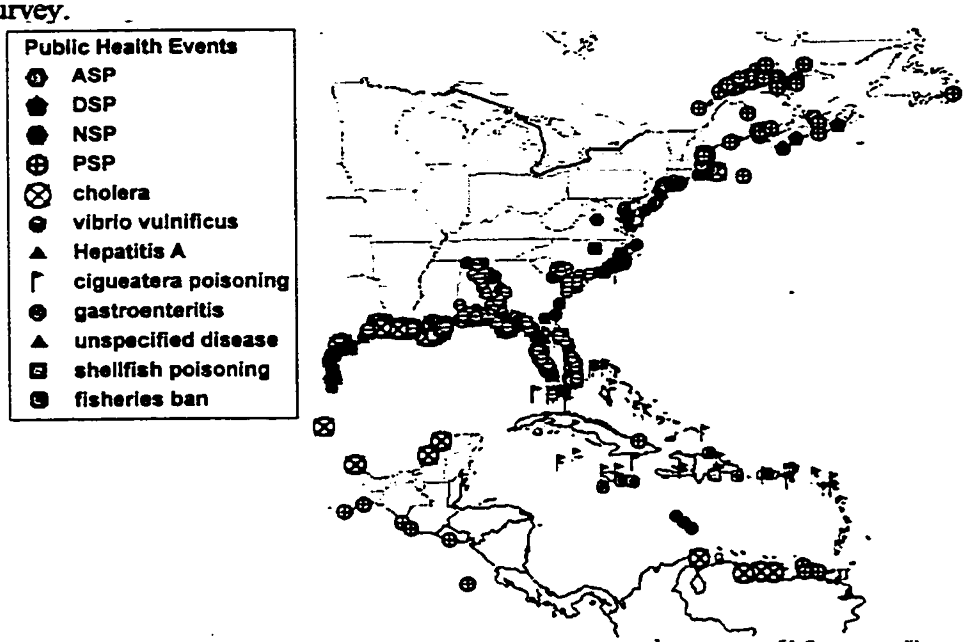


Table 5 ., Trophic Magnification Disturbance Type indicators subsetted from a list of 147 disturbance types.

bird disease NSP	human NSP
bird mortality PSP	human PSP
fish PSP	human Cholera
fish toxicity PSP	human human shellfish poisoning
human ASP	human vibrio vulnificus
human DSP	mammal cetacean PSP
hepatitis A	mollusc shellfish harvesting ban ASP, DSP, NSP, PSP
human gastroenteritis	mollusc shellfish toxicity ASP, DSP, NSP, PSP

Figure 15. North American view of public health trophic-magnification events from the HEED survey.



4) Mass-Lethal Mortality Disturbances

Mortality disturbance events include groups of occurrence reports clustered in space or time involving a single species or multiple species mortalities not yet attributed to a particular cause. In many cases the causative agents are unidentified harmful blooms. However these massive and widespread mortalities can be due to other factors. For instance, a significant and widespread black sea urchin (*Diadema antillarum*) mortality occurred in the Caribbean in 1983, coincident with El Niño conditions. Careful examination of the mass mortality, however, complicates a certain climate relationship. Hence this event is still classified as a mass mortality. Around the island of Jamaica, during that same time, a number of stresses combined resulting in the collapse of many reef species. Previous over harvesting of reef fish, cleaners of algae and detritus, led to algae overgrowth upon bleached coral reefs (already inundated by sediment and nutrient runoff). A disease, leading to the mortality of overcrowded sea urchin populations, also feeding on the algae, may have been a natural control on urchin overpopulation. This cycle has twice been observed with Canadian green urchin and kelp populations (Miller and Colodey 1983, Li *et al.* 1982). In the urchin case, because the mechanisms are unclear, they are best classified as mortalities until the climate and/or disease etiologies can be demonstrated. Mass mortalities of a species can push an ecosystem past threshold conditions to collapse and reorganize around a new stable state (Holling 1973). In Jamaica, macroalgal mats now smother the old reefs, and populations of all species, particularly fish, remain depressed. In this example multiple stresses contributed to threshold conditions (coral reef collapse), that subsequently affected the resilience of the entire island ecosystem (Lessios 1984). The mass mortalities are early indicators of restructuring.

Fish are the best monitored of those species apt to succumb to mass mortality. Anchoveta, herring, mullet, and other reef fish within the Caribbean at separate times have inexplicably died in large numbers. Catfish within the Gulf of Mexico and along the Northeastern Brazilian Shelf ecosystem have also mysteriously died in large numbers. Fish kills involving menhaden were prevalent in North Carolina's estuaries since the early 1980's (Noga and Dykstra, 1986). Yet it wasn't until 1991 that a possible causative agent, the extremely toxic dinoflagellate *Pfiesteria piscicida*, was found (Burkholder *et al.* 1992; Burkholder and Glasgow 1997). *Pfiesteria piscicida* is a small heterotroph (consuming plants and animals) with an extremely complex life cycle, and it has been implicated in shellfish mortalities, fish kills, ulcerated fish disease, and public health threats in North Carolina almost every year since its identification. However, it is extremely difficult to detect, leading to confusion over the leading cause of mortality. It is believed that *Pfiesteria* and *Pfiesteria*-like species weaken and cause mass morbidity in fish allowing opportunistic micro-organisms to secondarily cause the high mortalities (Landsberg *et al.* 1995, Burkholder and Glasgow 1997).

Mass mortality reports also have described deaths of brown pelicans in the Caribbean, marine mammal strandings in Peru, Chile, along the Caribbean, Gulf of Mexico, the Atlantic and Pacific U.S coastlines, the Azores, North Sea, and continental waters of China, New Zealand and Australia. Many reports do coincide with climate extremes, however, due to the wide diversity of possible causes and uncertainty of the percentage of populations involved, observational reports need to be followed by more in depth investigation.

5) Physically Forced (Climate/Oceanographic) Disturbances

Mortality events caused by shifts in climate or weather may be under-represented within the literature because many of these events are not viewed as anomalous. What distinguishes significant climate disturbances from normal interannual variability is the frequency of extreme events, extraordinary chemical and physical pulses, and subtle shifts in seasonality associated with regional climate change. These features can be viewed as anomalous because populations and communities of organisms adapted to specific tolerance ranges may be ill suited for the extremes and unable to escape or avoid impact (Bakun 1993). For threatened or endangered species, the consequences of lost feeding or breeding seasons due to climate irregularities can be significant. Some harmful bloom events have also been linked to changes in the behavior of water-masses and possibly oceanographic warming (Tester *et al.*, 1993, Fraga and Bakun 1993).

Of particular concern are coral bleaching events. Bleaching occurs when sea surface temperatures exceed 29°C. This has occurred for extended periods in recent El Nino years, far longer durations than reefs can tolerate, be resilient to, or recover from, following a temperature disturbance. The subsequent mortality of hard and soft corals over large areas of the world has fundamentally altered disturbance regimes within coral reef systems. The most severe bleaching ever reported has occurred around the central Indian Ocean islands of the Maldives, the Seychelles and Sri Lanka, and on the coasts and islands of India, Kenya and Tanzania. The bleaching in these areas has affected as much as 90% or more of the living corals and has led to localized species extinction (Hughes and Connell. 1999). Coral bleaching is being reported as a major marine disturbance, particularly devastating to the Great Barrier Reef (Pockley 1999). Bleaching has been reported with greater frequency worldwide. Reefs of the Arabian Gulf, Caribbean Sea, Indian Ocean, Java Sea, Mediterranean, entire Pacific Rim, Pacific Central American Coastal LME have been significantly impacted. In particular, reefs in Equador, Costa Rica, Columbia, Chile, Mexico, Florida Keys, Sargasso Sea, Bahamas, Bermuda, New Caledonia, Australia, Papua New Guinea, Philippines, Japan, Taiwan, American Samoa, and the Cook, Fiji, Marshall, Society, Tokelau, Tonga and Tuamotu, Palau, Solomon, Vanuatu and the Turks and Caicos Islands have all bleached in recent years. Within the Caribbean, bleaching has been followed by increased incidence of coral disease. The exact etiology of many of the coralline algal polyp mortalities and diseases are not known. Stresses other than water temperature appear to act synergistically with bleaching (Harvell *et al.* 1999). In both the Caribbean and Great Barrier Reef LMEs coral bleaching has the potential to be costly for both tourism and fishing (Wilkinson *et al.* 1999).

With dwindling populations of protected species, and the concentration of remaining healthy communities in a few protected marine reserves, unusually severe storms can now have a disproportional impact upon ecosystems. In this century, hurricanes Allen, David, Flora, Frederic, Andrew, Hugo in the Caribbean are responsible for a great deal of habitat destruction and mass mortalities of invertebrates, fish and the loss of seagrass meadows (HEED 1998).

To document climate variability impacts on ecosystem structure at large scales (hundreds to thousands of km) time series reconstruction strategies are needed (e.g. Chelton *et al.* 1982, Colebrook 1986, Hayward 1997, Polovina *et al.* 1995, McGowan *et al.* 1998). A notable example is the detection of a regime shift that affected much of the Pacific basin in the mid-1970s using reconstructed plankton, fish abundance, temperature and sea level pressure indices. Successful large area studies, like those involving the Peruvian anchovy can demonstrate that low-frequency trends in ecosystem structure can be correlated with co-occurring indices of atmospheric and oceanic physical structure (e.g., climate change indices) (Polovina *et al.* 1995, Hayward 1997). Hence, indices of weather and climate, once a relationship is understood, can serve as a proxy for species level indicator data and vice versa. This method has allowed researchers to extend and continue time series to better understand the natural history of climate variability and extremes (Guilderson and Schrag 1998).

Many climate influences are acting against a backdrop of long-term, global-scale environmental changes (Karl *et al.* 1997). These factors must all be considered in an integrated assessment. Some influences may be anthropogenic while others are "natural" in origin; and the changes occurring may be cyclic or random. If the climate regime is indeed changing -- as coral records and shifts in marine ranges now suggest (e.g., Barry *et al.*, 1995)-- the base-line upon which anomalies are measured will need to be modified. The long-term trends in ocean temperatures, tidal amplitudes, current patterns, ultraviolet radiation and freshwater runoff on marine communities and ecological processes will also require closer scrutiny.

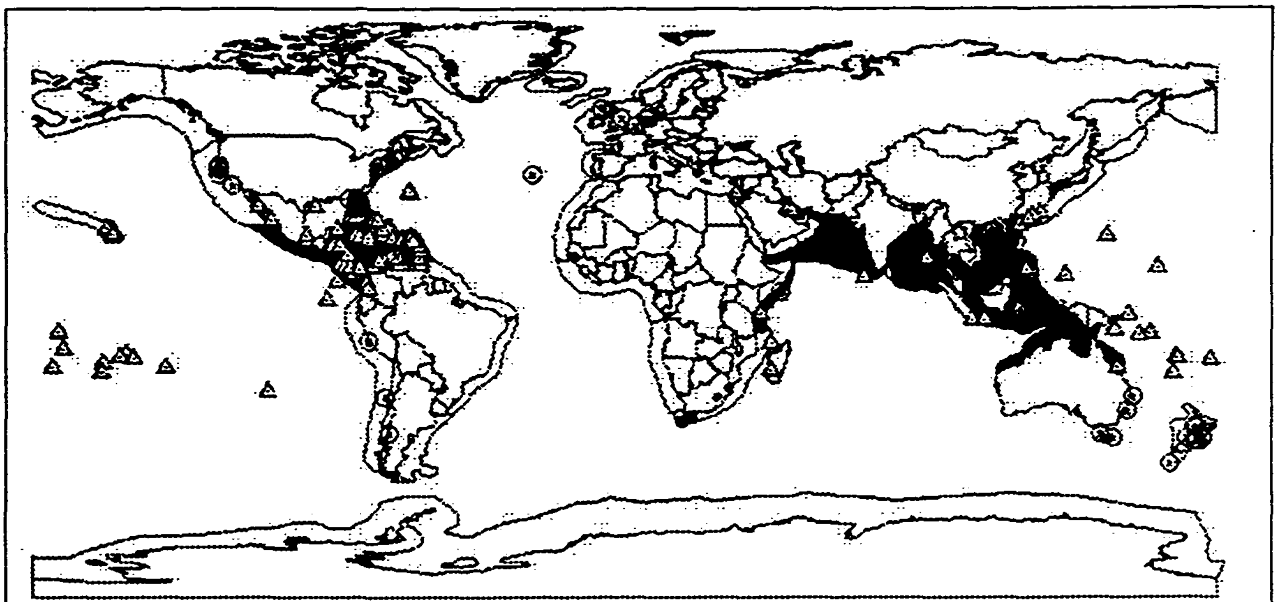


Figure 16. Physically forced disturbances. The 50 LMEs are outlined and those that are shaded have been identified as having regionally accessible information regarding these information types (vs. insufficient/not surveyed polygons). Also presented are data (triangles) representing coral bleaching and marine mammal strandings (circles) co-occurring with anomalous sea surface temperatures during the 1997-1998 El Nino year. Coral or sponge bleaching, coral shut-down reaction, fish or invertebrate or cetacean or sea turtle cold kills (clam bleaching and sea turtle cold stunning and egg destruction also included) are classified as physically forced-climate disturbance indicators (a subset of 147 disturbance types).

6) Disease Disturbances

For ecosystem health assessment, diseases are second only to harmful algae blooms as useful indicators for marine epidemiologists. Diseases are outcome measures reflecting feedbacks or perturbations with ecosystems. New diseases can emerge, and old ones resurge and undergo redistribution when the environment stresses an ecosystem and overwhelms the mechanisms providing resistance to the penetration and spread of pests and pathogens.

A high prevalence of morphological abnormalities (e.g. disease) in particular places and among multiple species is almost universally considered a straightforward indicator that the health of a particular system is suspect (Sindermann 1994). However, even with adequate time-series, it has been difficult to establish specific standards that define the quantitative degradation of particular habitats or regions over time. For instance, tabulation of crab and shellfish spots, pit formation on shells, deformed or missing points of the shell in "one-shot" surveys may tell us a lot about the prevalence of a particular disease, but fail to establish that trend over time (Butler *et al.* 1995). Even if a time-series were available, standard criteria for defining the relationships among multi-species disease incidence are needed.

Significant physical environmental anomalies can render entire populations vulnerable to infection and or replacement by more hardy competitors. Massive North Sea marine mammal kills in 1988, and dolphin die-offs in the western (1990) and eastern Mediterranean (1992) have been associated with several strains of morbilli (*phocine* distemper) viruses (Harvell *et al.* 1999). While pollutants (e.g., PCBs) may increase mammal susceptibility to infection, environmental changes particularly associated with El Nino conditions act as concentrators for ill animals, providing narrow migratory and feeding alternatives for stressed individuals and greatly increasing transmission among crowded populations.

The frequency and extent of impact from disease in marine mammals has increased many-fold (Harvell *et al.* 1999). Mass deaths involving agents such as morbillivirus, or influenza virus are becoming less "unusual mortalities" by those charged with responding to marine mammal mortalities (e.g. MMC 1998). In addition to the mass deaths, morbidity events of lesser magnitude are reported at a much greater frequency. The benefit of retrospective time-series reconstruction allows later reclassification once veterinary reports are evaluated and epidemiologists have established an etiology. Smaller scale events are now considered important outside of the veterinary sciences and increasingly, autopsy, necropsy and case reviews are found in a wider range publications (HEED 1998).

Diseases among migratory birds, like in their mammalian counterparts, represent similar trends. Outbreaks of disease among birds can occur for a variety of reasons. Migratory birds, often reliant upon small and ever shrinking oases and feeding grounds, crowd into areas where unhealthy conditions develop and diseases are easily spread (Friend and Pearson 1983, Friend 1987). Crowded, commercially-raised species, as evidenced by Hong Kong Avian flu and by several North American Duck Plague outbreaks can subject other species to unique stresses and risks. The 1997/98 ENSO event, altered food distribution patterns and severe weather heavily impacted both mammal and seabirds in several regions of the world (Duffy 1998, Epstein *et al.* 1998). Birds within the Gulf of Mexico, Caribbean and Eastern U.S. seaboard, for instance, are vulnerable to the same stresses that occasionally lead to outbreaks of illness and death in mammal populations (e.g. PCPs, POPs, pesticides). In these populations disease is an ecological opportunist (e.g., Mashima *et al.*, 1998; Daoust *et al.*, 1998. The pathogenesis and epizootiology of duck plague virus and other aquatic bird diseases are complicated and involve multiple strains of disease that vary in virulence but can effect multiple species across a range of age classes (Spieker *et al.* 1996). Unexplained outbreaks of a herpesvirus in ducks, geese and swans have been observed across the United States and Canada (Leibovitz, 1970). Better understanding of these complex outbreaks will require an integrated form of reporting that extends the entire length of migratory pathways.

Marine organisms exposed to disease, morbidity and mortality cross a wide range of taxonomic groupings from lethal coralline algal disease in tropical marine ecosystems to marine mammal mortalities from phocine distemper virus (PDV) in coastal waters of the North Sea and Norwegian Sea (Kennedy *et al.* 1988). Although incomplete, the geographic array of marine pathogens, disease outbreaks, and estimated mortalities assembled recently by Harvell *et al.* (1999) underscores the global extent of disease-related mortality events. Harvell *et al.* (1999) provides an abbreviated list of newly recognized globally distributed disease types involving a wide range of taxa. What distinguishes the significance in these disease accounts is the magnitude of mortalities caused by pathogens, not the increased effort in classifying the disease types. There will always be a background of increased reporting of classifiable diseases, but with impact specific criteria, trends in patterns of occurrence can be distinguished from improved observation.

The global epidemic of coral disease underscores the recent increased prevalence-theory. Black-band disease is now found throughout the Caribbean, Bay of Bengal, Sargasso Sea where no incidence had been observed or catalogued in photographs or film footage in prior decades. White-band disease is now found to have spread throughout the Caribbean including the United States and British Virgin Islands, Grenada, Guadeloupe, Honduras, Jamaica, Martinique, Netherlands Antilles, Nicaragua, Panama, St. Lucia, St Vincent, the Grenadines, Trinidad and Tobago, Bahamas and Bermuda. In each of these reef systems, disease incidences have spread and no prior records of incidence were observed (Goreau and Hayes 1994, T.Goreau, Global Coral Reef Alliance, unpublished data 1998). Similar trends have been observed with Red-band and Yellow-Band/Blotch disease in the Caribbean, Sea fan *aspergillus* disease in Columbia, Costa Rica, Panama, Trinidad and Tobago and Ridge mortality observed in Mexico. Rapid wasting disease in the Netherlands Antilles and coral neoplasia in Australian waters is now observed to be spreading to new areas.

Diseases spread from and among aquaculture facilities has become problematic in recent years (McGladdery 1998). Mass bivalve mortalities have resulted from transfer of infectious stocks (Fisher 1988). Shrimp viral diseases, though closely monitored, have also rapidly spread globally (Lightner and Redman 1998). Taura Syndrome, for instance, moved from a single shrimp farm in Equador to sites throught the Americas. Shrimp eating birds may be a vector. The Indo-Pacific hypodermal and hematopoietic necrosis virus regularly causes catastrophic epidemics within aquaculture areas and both wild and raised shrimp are susceptible (Lightner and Redman 1998). It is probably not a coincidence that incidences of disease occur in highly polluted areas (Sindermann 1996). The fish disease lymphocystis, as an example, appears to become problematic when heavy rains flush toxic chemicals into fisheries areas. Though the causative agent is a virus, the correlation with pollution has been demonstrated in many regions (Kinne 1993, Sindermann 1996, Williams 1992).

7) New, Novel Occurrences and Invasive disturbances

New or novel occurrences are defined as disturbances appearing for the first time in a species or within an area. This includes toxic or newly harmful toxic algae species or known harmful algae entering a new area and unprecedented mass mortalities among populations for which there are no previously recorded instances. The first instance of species invasions and significant changes in seasonality, distribution, and susceptibility of populations are also classified as new or novel occurrences.

Humans intentionally through aquaculture and often unintentionally, through ballast water, carry pathogens and vectors into areas where conditions allow spread and persistence of microbes, plant and animal opportunists. Where co-evolved pathogen host population relationships are absent, species are vulnerable to newly introduced disease. Human activity has not only increased the rate of spread of organisms but also changed the meaning of distance. Natural diffusion of genetic material had generally been local and gradual allowing species and ecosystems to adapt. But preferred routes or destinations, often between similar but geographically distant ecosystems, have made the World figuratively smaller. In one survey, 367 different species were identified in ballast water of ships traveling between Japan and Coos Bay, Oregon (Carlton and Geller 1993). Lockwood (1993) reports that 60 million tons of ballast water are discharged each year into 40 Australian ports. Hallegraeph (1993) was able to reconstruct the arrival of Japanese red tide dinoflagellates from captains' logs of ships anchored in Tasmanian waters. Well known biological invasions, such as the ctenophores (*Mnemiopis leidyi*), in the Black and Azov Seas (Travis 1993) are only a small part of a greater unmonitored, unregulated, and uncontrolled experiment waged in the coastal zone. Human casualties, from *Vibrio cholerae*, believed to be associated with shipping and South American seafood (Epstein 1999), and the movement of MSX, *Haplosporidium Nelsoni*, disease into New England Oyster populations only hint at the potential economic consequences and vulnerabilities faced by human assisted redistribution.

Tester *et al.* (1993) refer to a first occurrence of *Gymnodinium breve*, that bloomed during anomalous climatic and oceanographic conditions in North Carolina (USA) as a possible future indicator of algae redistribution due to larger climatic changes. Changes in distribution of organisms and concentrations of weakened hosts in smaller areas can lead to the evolution of new diseases. Duck plague virus first appeared in 1967, for instance, on Long Island, New York coincident with the development of farm breeding programs (Leibovitz, 1970). New or first occurrences of a pathogenic species in a location test the elasticity, and inertia of a marine ecosystem. The ease in which species invade is a measure of the porosity and vulnerability of the system to disturbance. Both anthropogenic facilitation and climatic changes have improved the odds for survival among new, novel and opportunistic pathogens and agents of disturbance.

Figure 17 New-Novel and Invasive Disturbance examples depicted by year of occurrence.

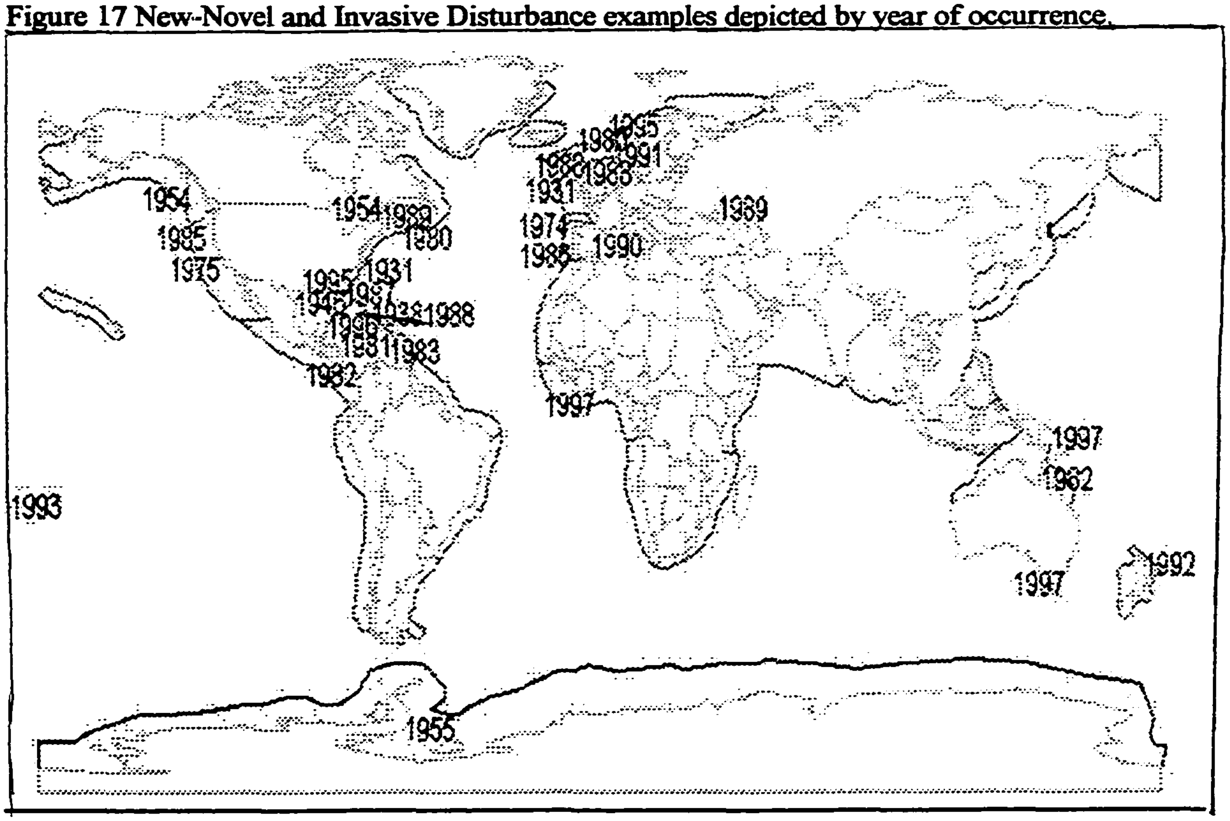


Table 6. Year, Species/Agent-Place for New Novel Invasive Disturbance Types from Harvell *et al* 1999.

1931 seagrass/slime mold-NAmerica, Europe
1938 sponges/fungus?-N Caribbean
1946 oyster/*Perkinsus*-Gulf Coast USA
1954 herring/pathogen-Gulf St. Lawrence
1955 seal/virus-Antarctica
1974 Flat oyster/*Marteilia*-NW Spain
1975 starfish/?-Western USA
1980 urchin/amoeba-NW Atlantic
1980 oyster/*bonamia* –Netherlands
1981 coral/bacteria
1982 coral/?-Central America.
1982 abalone/*Perkinsus* sp.- Australia.
1983 corals/bacteria?- Caribbean-wide
1983 scallop/*Perkinsus* -W Canada
1983 urchin/bacteria?-Caribbean-wide
1985 abalone/?-NE Pacific
1986 clam/*Perkinsus*-Portugal
1987 seagrass/slime mold-Florida USA
1988 scallop/protozoan-N Caribbean
1988 seals/virus-NW Europe
1988 porpoise/virus-NE Ireland
1989 scallop/*Perkinsus*-E Canada
1989 seals/virus-Lake Baikal
1990 dolphin/virus-W Mediterranean
1991 herring/pathogen-W Sweden
1992 kelp/?-NE New Zealand
1993 coralline algae/bacteria? -S Pacific
1995 urchin/nematode-Norway
1995 corals/fungus-Caribbean-Wide
1995 coral/bacteria-Florida USA
1996 coral/bacteria-Puerto Rico
1997 algae/fungus-Samoa
1997 pilchard/virus?-S Australia
1997 seal/virus-W Africa

8) Keystone-Endangered and Chronic Cyclical Disturbances

Howarth (1991) describes two general processes typically leading to ecosystem instability and collapse. Following a disturbance, these include 1) structural damage as the first noticeable impact. Subsequent disturbances can eventually impact and 2) change function or ecosystem critical processes. Individual impacts represent a low threshold for collapse due to inertia within the system. However, if disturbances are increasingly measured as rates or trajectories of change, increases or decreases in the amplitude and constancy of disturbance can be viewed as a chronic response to instability within ecosystems. The cycle leading to a chronic recurrence is known as a disturbance regime.

When disturbance becomes a regular feature of an ecosystem, the term anomaly must be redefined. At these periods of transition, a threshold is reached in the composition and function of the ecosystem. Under these circumstances an addition of a single significant perturbation can often lead to long-term significant changes. Ray (1996) uses the example of discontinuity/threshold in describing the reorganization of the Chesapeake Bay ecosystem. He defines oysters and oyster reefs as the keystone species. With their loss due to the spread of disease, overharvest and anthropogenic stress, the entire system reached a threshold where climatic variability shifted the ecosystem to a new stable state or configuration from which, the system has never recovered.

Stress favors domination by smaller organisms (Margalef 1975, Woodwell 1983, Odum 1985, Rapport *et al.* 1985, Gray 1989). Over time, these opportunistic microorganisms exert selective pressures on the most vulnerable, typically the endangered, rare or threatened, members of an ecosystem (Greve and Parson 1977). In this scenario, changes in silicate to nitrogen ratios can enable dinoflagellates to prosper at the expense of diatoms (Smayda 1990). Moreover, an abundance of smaller zooplankton predators feeding on the dinoflagellates can further alter a system by displacing large species. The smaller more gelatinous zooplankton can then prosper at the expense of fish larvae and adult fish unable to compete for food or effectively feed within the nekton are doubly impacted. It may be no coincidence that unhealthy systems are dominated by jellyfish (e.g. Black Sea; Mee 1992).

Chronic disease conditions are particularly important to monitor within endangered populations. Long term increases in neoplasia (cancer) incidences and other physiological ailments can be classified as chronic disturbances when they affect whole populations. Fibropapilloma incidences (including cutaneous papillomas and fibromas), on green seaturtles, *Chelonia mydas* (Herbst 1994) is an example of conditions that are now understood to be population wide increases. Cutaneous fibropapillomas develop over a long period of time and may play a significant role in turtle mortality (Williams 1992, Pinto-Rodriguez *et al.* 1995). These effects, when not fatal themselves, can lower immune system function, exhaust and generally debilitate the carrier. The condition increases susceptibility to entanglement, by-catch, starvation, vessel collision and other diseases (Williams *et al.* 1994). Visceral tumors in turtles, as in other species, can cause visual obstructions, organ dysfunction, potentially affecting buoyancy, digestion, cardiac function, and respiration (Herbst 1994). Surveys indicate that this disease was fairly rare prior to 1980, but in that year, the first documented outbreak in green turtles occurred, in the Cayman Islands and Florida's Indian River Lagoon (Herbst 1994). By late 1985, more than half of those captured in the Lagoon carried fibropapillomas (Williams *et al.* 1994), giving the first indication of an epizootic (wildlife epidemic). From 1982 onward, fibropapillomas rapidly increased in abundance around Florida, around Hawaii, and beginning abruptly in the mid-1980's, throughout the Caribbean (Williams 1992, Williams *et al.*, 1994). While 3-5 other species of turtles (including hawksbill and loggerhead) have been confirmed as new tumor hosts, the endangered green sea turtles remain the most heavily affected species (Williams 1991). Globally, green turtle fibropapillomas have now been reported in every major ocean basin in which the species exists (Herbst 1994), suggesting panzootic (animal pandemic) conditions of this chronic disturbance type (Williams *et al.* 1994).

The diversity of functional groups of species -- e.g., predators, prey, competitors, recyclers, scavengers and nitrogen fixers -- provide the buffers that dampen the impacts of stressors. Multiple species performing similar functions and tasks can provide "insurance" in case one or more keystone species decline (Ricklefs 1987, Pimm and Lawton 1998). Often, the first signs of significant structural and functional damage are the loss of the more stress sensitive species (Howarth 1989). The endangered or rare sensitive species are the biological indicators of disturbance, and presence or absence of these species can indicate a level of chronic disturbance within an ecosystem.

Whether bio-deposition changes the character of the sea floor through anoxia or biotoxins lead to tumor development in exposed wildlife, chronic disturbances are the most constant of the disturbance types. The aggregated disturbance indicators may be used to rapidly survey marine ecosystems and the eight general types of disturbance may provide a first approximation of the comparative health of coastal marine ecosystems.

<u>Network for Developing Standards and Achieving Consensus</u>

Determination of impact and ecosystem change is made by closely monitoring biological indicators, the condition of keystone species and co-occurring physical, chemical and ecological anomalies associated with disturbances. Unfortunately, it is rare for multiple monitoring systems spread among regions collecting dissimilar indicators, to provide either consistent temporal resolution or maintain consistency of data collection even within the same ecosystem (Gross *et al.* 1995). Academic, federal and state personnel working within the northern Gulf of Mexico serve as a notable exception. The Gulf of Mexico aquatic mortality network (GMNET) has developed multi-jurisdictional standards for data reporting and provides participants with regularly observed meta-data (data about data) reports. The shared meta-data and increased research communication has greatly reduced data comparison problems, redundancy in data collection, resolution and quality difficulties (Fisher *et al.* 1999).

As groups of managers and specialists create standardized methodologies for reporting MMED's, it becomes more important to provide an equally standardized means for exchanging information. A World Wide Web geographic information system (GIS) developed by the HEED (1998) Program, has allowed researchers, interested in hypotheses testing and managers interested in reconstructing disturbance regimes to interactively access data-sets to query anomaly and categorical data by space and time. The HEED system represents a demonstration of how information might be consolidated in a central location to explore standards and provide a common interface to research managers.

Climate, pollution and trophodynamic co-occurrence information have already been of value in assessing collateral impact from known disturbances (HEED 1998). Counts of the number of disturbance types (variety), their frequency in particular areas and raw numbers of occurrence can be used to better understand the natural history of marine disturbances and establish retrospective time-series reconstruction of past events. At present, the HEED database and GIS are most often used to describe known events in greater detail and to facilitate communication among researchers and resource managers. In the future, the internet-based marine disturbance data system can be linked to tissue and serum banks, tumor registries, disease image archives, museum specimen collections, and even be available to field veterinary response teams investigating events. Coupling field observation, data analyst recommendations and institutional monitoring provides the necessary components for a comprehensive marine epidemiological research system (Figure 18). The capacity for real time event reporting via the Internet is also under investigation.

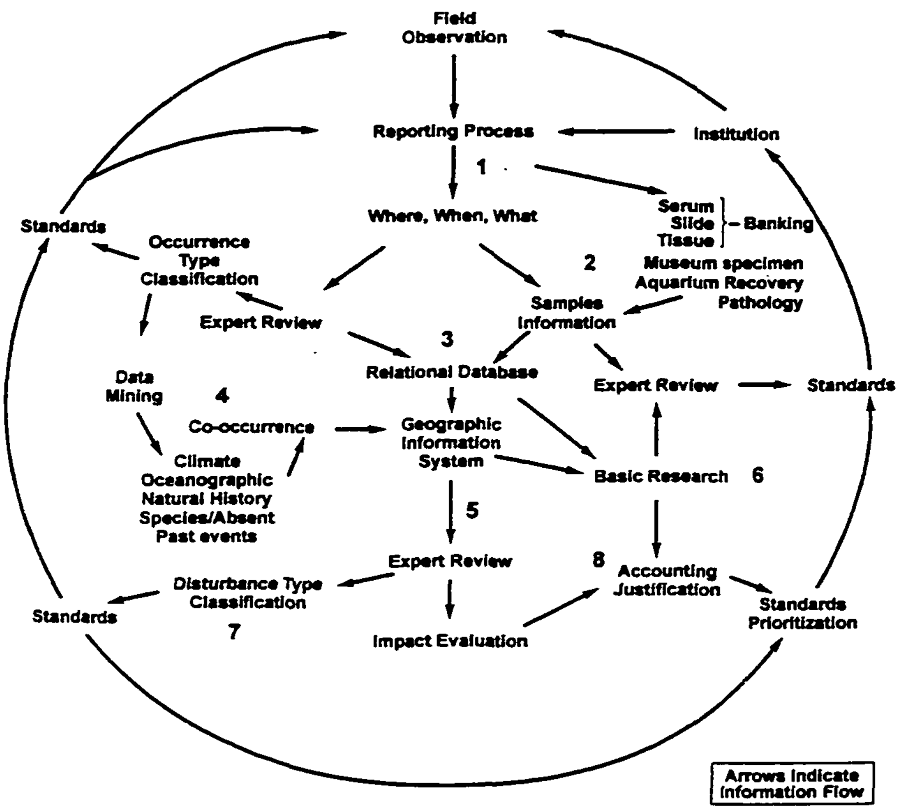


Figure 18. Information flows in a marine epidemiological information system. Field observations are part of a reporting process that records "where, what, when" information (1). If samples are taken they are sent to the appropriate laboratories and results and/or specimens are archived (2) and information regarding the unique laboratory custodian identification number is returned to a central relational database (3). Queries of the database generate occurrence type classifications, enable comparison of co-occurring anomaly data, and help extract ancillary life history and contextual information (including mass-media accounts if no other information is available (4). Output is provided in GIS format for expert review (5) and basic research exploration and hypothesis generation (6). The expert review process adjusts the disturbance type classification appropriately (7). Research scientists may use new insights gained from participating in quality control and observation to justify their efforts. Further analysis could reveal the cost of particular events that may even further justify the importance of the epidemiological information system approach (8). All steps, feedback to the generation of nomenclature and definition standards that ultimately may lead to the better reporting of observations taken in the field or new types of data collection or archiving by institutions.

Basis for Assessing the Health of Large Marine Ecosystems

Chronic illnesses, mass mortality and disease epidemics are being reported across a wide spectrum of marine taxonomic groups. Novel occurrences involving pathogens, invasive species and illnesses affecting humans and wildlife are globally distributed and appear to be increasing. These disturbances impact multiple components of marine ecosystems, disrupting the structural and functional relationships among species and the ability of systems to recover from natural perturbations. Climate change involving extreme events combined with human induced stressors may compromise an open-ecosystem or migratory population's resistance to opportunistic micro-organisms. Fungi, bacteria and viruses are quick to exploit the weak within a disturbed enclosed-ecosystem and eventually create suitable environments for continued proliferation. Assessments using a marine epidemiological approach can track these changes in ecosystem health (Epstein 1996).

Better understanding of the natural history of disturbance regimes requires the inventory and reconstruction of event time-series. Time series allow multiple marine ecological disturbances to eventually be classified as Major marine ecological disturbances (MMEDs). The number and frequency of MMEDs in a place can be used as indicators of a decline in ecosystem health and loss of essential services (e.g. economic, nutrient cycling). Reconstructing a natural history of these events and related environmental conditions facilitates a better understanding of the local, regional and global causes of disturbance. MMEDs can be mapped using geographic information systems to define spatial "hotspots" and temporal clusters of events (e.g., during El Niño events). Reconstructed time series have helped researchers identify eight general impact categories based upon the spatial and temporal dynamics of the observed disturbances. Assuming the appropriate observational meta-data information (noting source and quality) are available, resource stewardship agencies and research institutions can work on standards to better define regionally more appropriate or optimal indicators for characterizing each of the sub-disturbance types for ecosystem health assessment.

Data collected using a marine ecosystem health framework depicts an increase in the frequency, severity and geographic spread of MMEDs over the past several decades. These adverse biological events carry with them significant human health and economic costs. International institutions can use the ecosystem health framework presented in this chapter for assessing the health and consequence of disturbance within large marine ecosystems. Initial assessments could be followed by improved monitoring and surveillance followed by focused basic laboratory and field research. With new insight, early warning systems to enhance response capability to ecosystem health disturbances could be initiated, and coordinated mitigating actions taken, to address the underlying forcing factors leading to disturbance.

The combined HEED retrospective data mining and GMNET integrated multi-jurisdictional monitoring approaches could be applied beyond their present scales to include morbidity, mortality disease and comparative health assessments among the 50 large marine ecosystems.

Standard global characterization is particularly important due to the uncertainties surrounding the cause and consequence of marine disturbance and the unknown origin and distribution of many disturbance types. In many cases complex physical, chemical and ecological processes, for which mechanistic understanding is lacking, mask both human and climate influences. By taking a global, LME-scale perspective, natural, human induced impacts and the synergy of forcing factors resulting in marine disturbance can be better separated and understood. This will remain as an important challenge for marine science in the coming millennium.

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CHAPTER 6

A PROTOTYPE METHODOLOGY FOR THE ASSESSMENT OF MULTIPLE ECOLOGICAL DISTURBANCE IN THE BALTIC SEA ECOSYSTEM

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Paper 3: Summary

An approach is described for systematically reconstructing spatial and temporal marine disturbance regimes related to Baltic marine morbidity, mortality and disease events. The approach is compatible with the health module of the Baltic Sea's Large Marine Ecosystem initiative and consistent with implementation of the Baltic Sea Agenda 21 program. The approach is based upon a survey of disturbance events conducted in the Northwestern Atlantic Ocean, known as the HEED project. Eight general disturbance indicator categories are suggested for assessment of the health of the Baltic Sea ecosystem. These general disturbance types represent over 140 distinct impact categories and may be used to examine the relationship among impact causes, effects and costs from disturbances observed for the coastal and open waters of the Baltic coastline.

Paper3: Introduction

For the Baltic coastal margin, home to 40 million people, eutrophication, persistent organic pollutants, petrogenic contaminants, climate disturbance, overexploitation of fishery and other marine resources are potentially related to emerging diseases effecting both marine organisms and human populations (HELCOM, 1991). However, researchers have had difficulty tracking ecosystem change over time and it remains a challenge to isolate the causes of disturbances. Perception that the health of the Baltic has changed motivated decades of data collection, but these data are fragmented and scattered among thousands of reports, journals, and semi-public data repositories. It is argued that among the thousands of funded studies meant to address Baltic marine concerns, millions of Dollars, Kroners, Marks, Rubles and Zlotych have already been invested in collecting the right types of information, but the data have yet to be recovered for contemporary interdisciplinary cause and effect hypotheses (ICES, 2000).

The total impact of coastal degradation carries with it enormous financial costs due to loss of resources, recreational opportunities and costs of monitoring and remediation. The true costs have yet to be totaled. In selected studies, Todd (1994) and others have inventoried losses from morbidity, mortality and disease significant enough to affect the gross domestic product of many nations (Costanza et al. 1999). The key to recovering the impact or loss information within the Baltic region is to mine the results of already completed studies and to create or reconstruct the critical time-series suitable for tracking changes in ecosystem health. A prototype of this retrospective approach has been completed for the northwestern Atlantic along the coastal margin of North America, the Caribbean Sea and Gulf of Mexico (HEED 1998) (this issue). This paper describes the framework for a similar project to be conducted within the nine country Baltic Sea region (Figure 19).

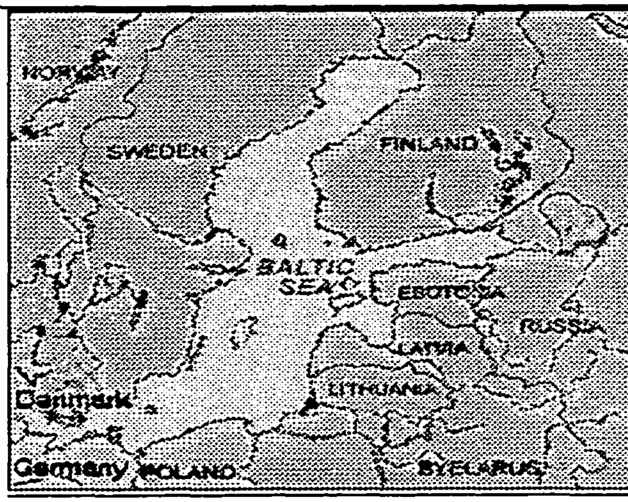


Figure 19. Baltic Sea Context.

A Standard for describing Baltic disturbance

There is a process for aggragating retrospective multiple ecological disturbance assessments. The first step, systematic compilation of a standards-based uniform information base, begins with a meeting of disciplinary experts representing physical oceanographic, marine biological, fisheries, public health and resource economic sectors. Each group invited to attend such a workshop is asked to bring bibliographic source material backing up their evidence of marine disturbance. This material is ultimately collated and entered as observational evidence into an interactive database with the capacity to reconcile location, time and type of disturbance event. The majority of synthesis activities at these interdisciplinary meetings center around reported results in the scientific literature, so called "gray literature", and anecdotal accounts offered by the expert community (all to be validated systematically). Database compilation is an ongoing process that begins with the simple classification and recording of pertinent marine disease morbidity and mortality anomalies in space and time.

For the northwestern Atlantic, a pilot effort to develop a rapid global survey of possible connections and costs associated with marine disturbance types was initiated by a group of investigators and collaborators at Harvard University and associated federal, state, and academic institutions (HEED 1998). The Health, Ecological and Economic Dimensions Global Change (HEED) program originally funded by the United States National Oceanic and Atmospheric Administration's (NOAA) Office of Global Programs and the U.S. National Aeronautics and Space Administration (NASA), developed an information system for acquiring and organizing that survey data (http://www.heedmd.org). The HEED information system is capable of helping researchers consolidate disturbance reports regionally and nationally, and could serve as a prototype of a global monitoring database for morbidity, mortality and disease events.

In the northwestern Atlantic workshops (HEED 1998), some classification problems surfaced. For example, researchers realized that description of fish kills varied widely within and between the literature of various disciplines. Once explicitly defined using the widest range of possible descriptions (number of fishs killed), researchers were able to narrow the list of possible observational descriptions and create translation look-up-tables to compare notes within and among disciplines and jurisdiction. These standard, gestalt definitions may then be coded into the database to create a baseline for type and magnitude of occurrence, while maintaining the original disturbance nomenclature associated with the field observers. Modern relational database structures maintain critical meta-data information regarding source, confidence and decision rules to allow future re-derivation of the nomenclature as understanding improves. For the Baltic, a similar process is undertaken in a literature review associating possible impact types, recorded for decades, into a new class of principal, secondary and tertiary driving forces controlling Baltic Sea variability in biomass yields (Kullenberg, 1986).

Baltic Sea Physical/Chemical Data Sources

The advantage of having a relational database lies with the capacity to query information to make new discoveries. Geographic Information Systems (GIS), built around database technology, permit spatial queries. For most regions of the world, spatial data is not present in a single place to permit those queries. Fortunately there is a digital spatial information infrastructure already in place for the Baltic Sea region. These information layers provide the base map or context for which all other spatial and temporal information can be associated. Langaas (1998) describes the Baltic Drainage Basin Project (BDBP), BALTEX , the BGIS and MapBSR GIS Internet initiatives in more detail, and the data for these information layers are provided on the following web sites http://www.grida.no/baltic/ and http://www.grida.no/infop/db1.htm.

Briefly, the Basic Geographic Information of the Baltic Drainage Basin (BGIS) database was coordinated by the Helsinki Commission (HELCOM), and funded by the Nordic Council of Ministers, the Finnish Environment Institute, Swedish Meteorological and Hydrological Institute, Swedish Space Corporation, GRID-Warsaw and GRID-Arendal. These data custodians have pooled their database information into a seamless Geographic Information System (GIS) format compatible with the UN Economic Commission of Europe statistics data sets and globally available satellite remote sensing and digital spatial information reference material. This is an unprecedented achievement in a region this size and involving diverse jurisdictions. The information layers include coastlines, administrative boundaries, rivers and lakes, roads, settlements, topography, population, land use, and ecological carrying capacity (Sweitzer *et al.* 1996). The Baltic Sea Experiment (BALTEX) project was conceived to identify eutrophication sources and possible effects along the coastal margin of the Baltic Sea. The BALTEX layers provide critical process information in comparison to the static GIS base-map information layers (Raschke, 1994). The project charted prevailing climate, hydrographic, and physical/chemical flows within the region to examine fate and transport concerns. The models permit trajectory analyses and trace backs, which may be useful in identifying harmful algae bloom initiation, public health vulnerabilities, and the origin points of stranded marine mammals. The Baltic Drainage Basin Project (BDBP) conducted by the Beijer Institute and Department of Systems Ecology, Stockholm University, and GRID-Arendal, Norway provides an information layer relevant to point and non-point source detection for materials entering into the Baltic Sea (Gren *et al.*, 1996 and Jansson *et al.*, 1996). With these information layers, vulnerable populations can be associated spatially and temporally with possible changes in patterns of harmful algae blooms, and distribution of pollutants that have led to marine mortalities.

For a Baltic assessment of disturbance "costs" associated with physical forcing (e.g. climate, oceanography, etc.), many of the critical marine information layers have not yet been unified into the multi-nation digital product and remain the proprietary products of individual research institutions and nations. However, the precedent provided with past data unification efforts will likely allow the Baltic countries to take the lead in this research and science based assessment applications area. Selected American examples of such information layer integration include merger of bathymetry, hydrography, sea surface temperature, salinity, dissolved oxygen, nutrient fields, sea level pressure and ocean color datasets. These datasets were combined for the northwestern Atlantic project (HEED 1998).

Rather than wait for the compilation of comprehensive physical, chemical and environmental data within the Baltic region, an interim strategy is recommended. Many of these data layers are available in a coarse format from a single source compiled using the United States' standards for global exchange of coverage datasets. The coarse data have been valuable to the global climate change community, and although resolution is less than ideal, climate forcing and disturbance can be associated with observed marine disturbance events. The HEED (1998) study, for example, found a possible relationship between the North Atlantic Oscillation and shifts of marine populations resulting in morbidity and mortality. The coarse data product called the World Ocean Atlas (Levitus, 1994; Levitus and Boyer 1994) is available from a set of 13 CD-ROMs from the U.S. National Oceanic an Atmospheric Administration's National Ocean Data Center. It includes information covering the Baltic Sea at 2km to 5km resolution varying from yearly time series data to composites of average seasonal values compiled from a blending of twenty years of infrequently collected data and satellite measurements. Process models, including processes documented within the Baltic help fill data gaps where neither sea-truth nor observational records exist. Large portions of these datasets are available on the Internet as a byproduct of global climate change modeling efforts (Blumenthal 1996, 1998). Precipitation datasets and stream flow are other data sources valuable for examining disturbance patterns. Weather stations associated with the World Meteorological Organization network and national programs regulating impounded water (typically used in agriculture and power generation) may be among the best sources for climate time series within the Baltic region.

A powerful application of the information from the BDBP study may come from economic data associated with eutrophication (not yet available in digital form). Together with National statistical sources and UN Food and Agricultural Organization (FAO) statistics recording biomass yield, it may be possible to isolate the cost of particular disturbance events as linked with nutrient loading and determine the loss to commercially valued fisheries retrospectively. In a Long Island Sound, NY USA example, such a technique successfully linked blooms of brown-tide organisms with financial losses associated with the loss of shellfish fisheries. Follow-up surveys documented the financial impact to fisheries dependent communities. The association of dollar loss and the disturbance events has motivated policy action in that region (Grigalunus and Diamantes, 1998).

Baltic Sea Ecological Data

Methods quantifying speciation, distribution and abundance of phytoplankton, zooplankton and macro-invertebrates have been reconciled among several of the data collection organizations studying the Baltic Sea (HELCOM 1991). A precursor to an integrated Baltic Sea disturbance information system is the determination of what constitutes an anomaly from this collection of baseline biological resource data. For instance, the Finnish Institute of Marine Research provides data on an algae blooms via an Internet monitoring website. Their "Alg@line" database and mapping system is regularly updated with bloom information as provided by the

Finnish and Swedish coastguards, Seascouts, Stockholm Archipelago Foundation, Finland's Environmental Administration and Swedish Meteorological and Hydrological Institute (FIMR, 2000). This sea-truth information provides a basis for calibrating satellite remote sensing algorithms necessary for the correct interpretation of remotely sensed imagery. Compared against the baseline survey data provided by the intercalibrated regional resource surveys (e.g. HELCOM 1991), it may be possible to extend the Finnish observational chlorophyll bloom dataset to evaluate overall Baltic Sea algae bloom variability. A variability index defines the difference between normal and abnormal conditions, based upon historical precedent, and hence harmful blooms can be distinguished from ordinary peak biomass blooms.

Non-native species have moved into or been introduced into the Baltic Sea and many are considered invasive (Leppakoski 1984). A database of invasive species is kept by the Centre of Systems Analysis, University of Klaipeda , Lithuania (Kautsky and Kautsky, 2000). There are too many marine institutions holding anomalous marine biological resource data, potentially impacted by algae blooms and invasive species within the Baltic to adequately survey within this brief review. Algae blooms were the leading indicator of morbidity and mortality of marine flora and fauna within the HEED (1998) Northwestern Atlantic and global surveys. To begin an assessment of ecological disturbances within the Baltic, a focused inventory of biological indicators, and data custodians for the respective data, is needed.

Disturbance Data

The most challenging aspect of integrating land and marine interface layers for marine disturbance descriptions involves the precise naming of coastal units in the vernacular language of the respective nations contributing to the observational records (e.g. common names vs. map names of stretches of beach associated with recreation or fishing). Also, wetland boundaries, difficult to map due to their seasonal variability, should be regarded as one of the more important types of thematic coverage needed for a multipurpose Baltic geographic information system. With these physical base map layers and oceanographic time-series data in place, a context is formed for the disturbance or anomaly data mined from the literature. To examine ecological disturbances, spatial and temporal parameters must be consistent among all the physical time-series. In the peer reviewed literature, observational anomalies are reported as associated with a particular parcel of marine area designated with a particular name. Rarely are coordinates or polygons ascribing the extent of an incident defined. As such, it is necessary to use lookup tables to translate a place name to the center point of a minimum mapping unit (expressed in seconds of latitude and longitude. Point data (x,y observation locale) are reported at a variety of spatial scales including: river, estuary, fjord, harbor, bay, province, drainage basin, nation, large marine ecosystem and subdivision spatial designations. Daily to decadal temporal increments may also include time-divisions such as peak, duration, phase and seasonality (timing of phenological changes) in addition to the standard start-date, end-date necessary for an event record. To address the mismatch between differently scaled data, many observational event descriptions (categories) may be collapsed to a lesser number through the creation of indices (for evenly sampled data) or general taxonomic functional classes for observational data (Table 7). Biological anomaly data, in general cover all the major taxonomic divisions that are typically observed as vulnerable to disease and appear as coastal mortalities.

Table 7. In the Northwestern Atlantic, ten general taxonomic classes of disturbance observation (discrete in space and time) were correlated with time-series measurements (near continuous) representing significant pressures upon those indicators. Note: Coral and Sea turtle events are not relevant within the Baltic. In this table, anomaly time series from the U.S. National Ocean Data Center, World Meteorological Organization, U.N. Food and Agricultural Organization, World Health Organization in addition to National time series are suggested for the Baltic region.

Morbidity, mortality and disease count data	Time-series data indices for anomaly matching
1. Aquatic birds events,	1. Shellfish poisoning toxin (Resale Industry)
2. Coral and sponge events,	2.Climate indices (ENSO/NAO - NODC)
3. Fish events,	3.Sea level pressure (NODC)
4. Harmful algae booms,	4.Sea surface temperature anomaly (NODC)
5. Human marine related illness,	5.Precipitation anomaly (WMO)
6. Mortalities and disease of marine mammals,	6.Wind stress/direc. (Navy, Harbor Masters)
7. Mollusk shellfish and -crustacean events,	7.Fisheries economic statistics (FAO)
8. Sea turtle events,	8.Public health statistics (WHO)
9. Large invertebrate mortality,	9.Discharge/dumping reports (Env. Ministries)
10. Seagrass disease and loss	10.Beach closures (Ministries of Health)

Through the use of the term "anomaly" -- common to all disciplines – observation data from socioeconomic, ecological, oceanographic, public health and climatic fields of study can be linked together in the database using spatial-temporal queries to draw together appropriately scaled data. Normalized temporal disturbance-regime plots are used to present this information graphically (Figure 2). Multiple Marine Ecological Disturbance data (MMEDs), an index of all biologically significant events, may be compiled into a single category enumerated by date to represent a disturbance regime indexed to a particular location. The index is necessary because there is rarely sufficient morbidity and mortality information available for a single taxonomic category in a particular place to create a meaningful time series. Many of the morbidity and mortality events are in fact correlated (Sherman, 2000). Thus, disturbances can serve as proxies for one another.

In the HEED study, for instance, human illness records were related to shellfish toxicity and harmful algae blooms. When public health records were unavailable, the shellfish toxicity records helped in the search for incidents of gastroenteritis - representing possibly undiagnosed cases marine-related illness. The proxy technique not only helps identify known association, but has also been helpful in correlating disturbance observational data yet to be documented within the peer-review literature. For hypothesis formation, MMEDs become a powerful inferential tool. The north Atlantic marine disturbance workshops resulted in the formation of data-models (Sherman, 1994) that clearly documented known and unknown relationships among morbidity, mortality and disease data. A typical data model, for instance, demonstrates a relationship between pathogen, host, toxin, and disease. The data models were tested for regional locales by plotting the combined series to depict regional disturbance regimes. This was done with all data, extending from 1945 to 1998. Realistically, there was only sufficient intercomparative information for the last 20 years. Figure 19 depicts a sample graph with this data plotted from 1970-1996 for Passamaquoddy Bay, Maine USA. Time series plots like Figure 19, while incomplete, suggest that focused data mining at particular periods of time might reveal missing pieces of expected pattern observed where data are present and where proxy data might be present.

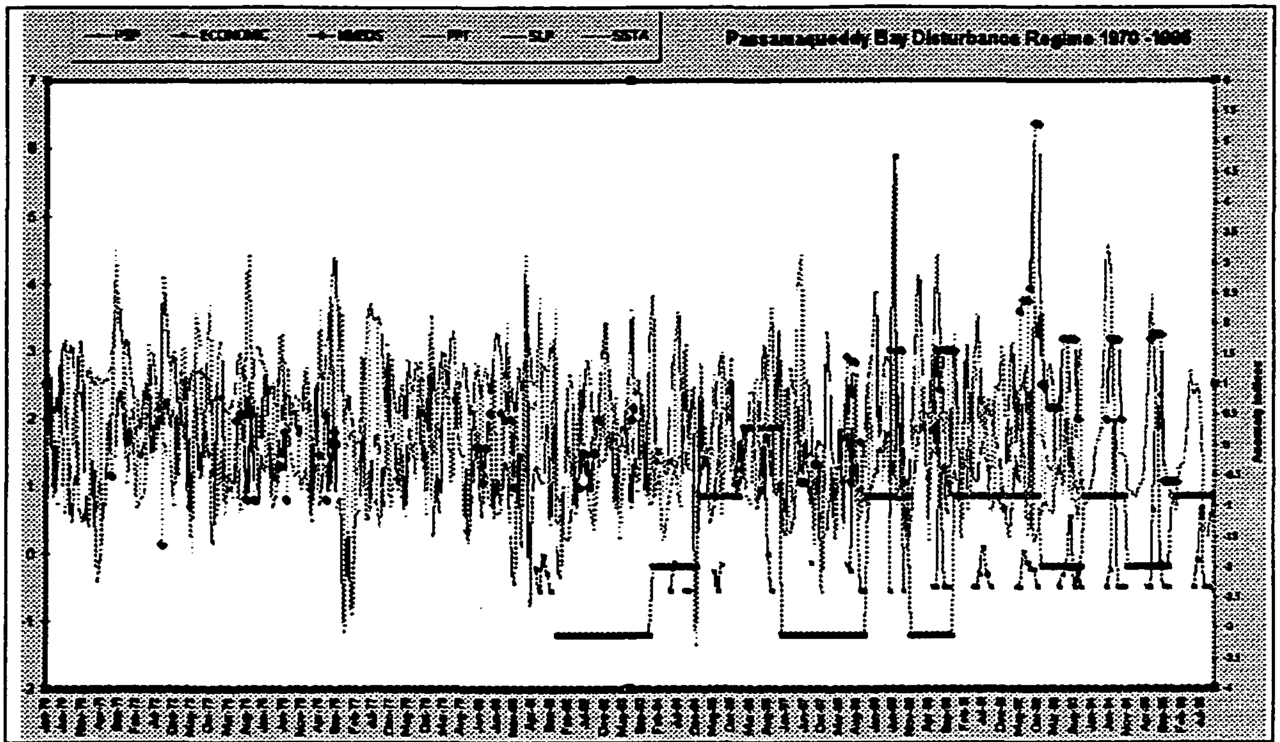


Figure 19: Combined time series plots help fill visual data gaps from incomplete records and provide a more complete representation of disturbance regimes. Depicted here is an example of Passamaquoddy Bay, Maine, U.S.A, showing the occurrence of several types of combined disturbance patterns. MMED occurrences are displayed as points along-side paralytic shellfish toxicity (PSP) values, an index of economic variability, sea surface temperature anomalies, standardized precipitation values and sea level pressure indices. The predominant MMED factors in this region are blooms of the biotoxin producing *A. tamarensis* dinoflagellates resulting in shellfish-bed closures due to PSP.

Marine health assessments like the HEED (1998) effort bring together the expertise of multiple disciplines to: 1) recommend reporting standards for literature derived morbidity, mortality and disease events, 2) assess the integrity and coverage of monitoring data, and 3) recommend future data collection standards. To find anomalous occurrence reports, the marine literature may be searched systematically using pre-defined marine disturbance keywords recommended by experts. Events missed in the literature of one field do often appear from recursive searches in other fields.

Survey Methods

The first step in marine ecosystem health survey is to "mine" the literature for relevant categorical information using keywords. As an example, in the HEED (1998) program, a literature search including journals, symposia, workshops, books, government technical reports, semi-popular journals, selected institutional reports, and research communications covering the years 1945 -1996. Using keywords, the surveyors were able to extract meta-data (data about data) from 2127 published disturbance accounts. The source material ranged from key primary citations in refereed journals to review literature (secondary source citations) to anecdotal accounts of anomalous events (partially verified information). Additional keywords taken from either the title, an author's list of keywords and abstracts of collated reference material were added to the pre-defined list of keywords until 2021 distinct marine disturbance keywords were cataloged to assist in future surveys. Of those keywords, 314 disturbance indicator types were classified and 246 pathogen toxin and disease combinations were derived. Within the Baltic there will likely be many more types due to linguistic differences to be reconciled. Well-described anthropogenic impacts, such as oil/chemical spills, by-catch, dredging and errors in food preparation were excluded from the HEED (1998) health survey, unless relevant long-term or recurrent disturbance characteristics were defined. Direct human impact types, particularly important within the Baltic (including persistent organic pollutants) are reviewed elsewhere (e.g. Sheppard 1998a, 1998b, 1998c), and it is accepted that much would be learned by merging an anthropogenic disturbance and marine health impact databases.

As a feasibility study, mass media reports including newspapers, television and radio transcripts and other archived and searchable international accounts could be mined using a subset of keywords. The occurrence reports from mass media sources like LEXIS/NEXIS Inc. (Dayton Ohio, USA), used in the HEED global survey, may provide a quick list of newsworthy occurrences to be referenced against the peer review and government sources. Mass media accounts are advantageous (although often inaccurate) because scientists and observer information are misunderstood, manipulated or misquoted. At the least, the articles referenced in a database may represent a public awareness data layer highlighting major events and provide follow-up contacts to obtain more accurate event information.

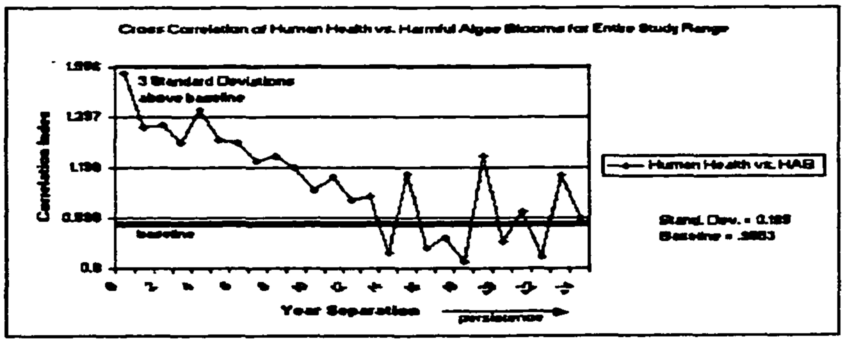
One of the most important features of literature and data "mining exercises" is to ensure that the surveys are thorough and categorical classifications' complete. Graphically tracking key concepts within the marine literature, establishing the epistemological evolution for defined disturbance groupings, is one way to evaluate thoroughness and to develop consensus within expert communities. The depictions are called "Idea-maps" and these maps are created by backtracking citations until primary foundation-works for each disturbance type are identified.

To reduce the number of literature derived disturbance types to a manageable number, spatial and temporal criteria can be applied using data models (Sherman 1994). Data models help lump categorical data together based upon similar scale, resolution, quality, and relationships. Scale groupings integrate presumed functional ecological categories (e.g. community, population, etc.) and lags or behaviors when disturbed (e.g. fast-acute, intermediate resilient, slow-chronic or cyclical variable and threshold cascade) using insight drawn from idea mapping.

For apparently significant and expected correlations among time series, extended (standard) cross-correlation calculations may be run to test the nature of the relationships. While there are no rules for interpreting association with this type of anecdotally reported data, cross correlation provides guidance as to which and how strongly categories are correlated and where more data exploration could be focused. Cross-correlation measures the joint variation of two parameters. It also provides a measure of the persistence of the dependence (the correlation peak's width in year to year comparisons) and the lag-time between the variation of two parameters (the offset of the correlation peak from same year comparison- zero time delay).

For the data examined in the HEED study it was presumed that there was no long-term (multi-year) interdependence. Consequently, cross-correlation coefficients were expected to become stable with random fluctuations about a mean value (Zar 1984). This did not happen for Public Health (PH) and Harmful Algae Bloom (HAB) events. Only data compared during the same year (year separation 0) represent a significant correlation (3 SD above baseline). Persistence from year zero in the HAB data series compared to subsequent Public Health years (1-12), although representing a form of serial autocorrelation, is not interpreted as significant, and by year 13, random oscillation around a baseline or mean occurs. More data will be needed to evaluate serial autocorrelation structures to separate signal from noise. In this example human health was the leading variable as compared against HABs forming a correlation idex, although, the cross correlation test is a symmetrical test (Figure 20).

Figure 20. Symmetric Cross Correlation of Human Health versus Harmful Algae Blooms. Plotted are the coefficients of cross correlation (called an index because data were standardized) from 1971-1996 representing 25 years of successive yearly comparison.



Coefficients were computed for 25 years time periods to provide a measure of a baseline and standard deviation (SD) encountered. The zero time-delay cross-correlation coefficients are considered statistically significant when they differ from the modal-mean by more than three (3) SDs. While the data quantity and quality may not be suitable for more rigorous statistical analyses, this simple technique does provide a reference point that can guide future data collection.

Calculation of the cross-correlation coefficients for each category-year pair tested synchronicity among categorical elements. Significantly high cross correlation (approaching 3 standard deviations from the "random-noise" baseline) when compared to mean values derived from comparison of a single year to any of the subsequent years represented non-random co-occurrence in time. The reason why a multiple year lag-effect remained, although not statistically significant, is not fully understood. It has been hypothesized that once a HAB disturbance regime initiates, it persists within a location for a number of years, and could negatively impact human health for many years (even when HAB events are no longer recorded).

An evaluation of all harmful algae bloom data versus all public health data is presented here to demonstrate large scale non-random association among these two independently collected categories of data, brought together within the HEED database for the first time. A coefficient of correlation using the Spearman Rank Order correlation routine (StatsSoft 1999) for the years 1945 through 1997 was .91 (Figure 21). A subset of data for the years 1971 through 1996 were extracted representing 25 years of Human Health events and HAB events. The 25-year subset representing the annual number of occurrences of harmful algae blooms and public health occurrences were evaluated using this technique. The cross correlation between HAB and public health occurrence data is statistically significant, 3 standard deviations removed from random background noise levels) (Fig. 21). The high rank order correlation (.91) indicates that there is a relationship between harmful algae blooms and public health occurrences throughout the study period and range (entire HEED study area). This indicates that for every x value, there is a y value reflecting an equally high or low value for each year. The cluster of points near (0,0) represent either missing data for years in either categories (often present at the beginning of record collections) or observed non-occurrence data (the two zero value types cannot be distinguished). Monthly or seasonal data would more accurately reflect associations than the yearly data depicted in this graph and were unavailable in sufficient quantity to perform the cross-correlation analyses. As more data are entered into the HEED database, this technique can eventually be implemented within each bay or estuary, at a variety of time intervals more appropriate to the mechanisms linking categories together. Any significant measures of correlation at this level of resolution will help determine which categories are closely associated and synchronous in response to exogenous forcing, and also which indicators might usefully represent the behavior of other indicators (proxies).

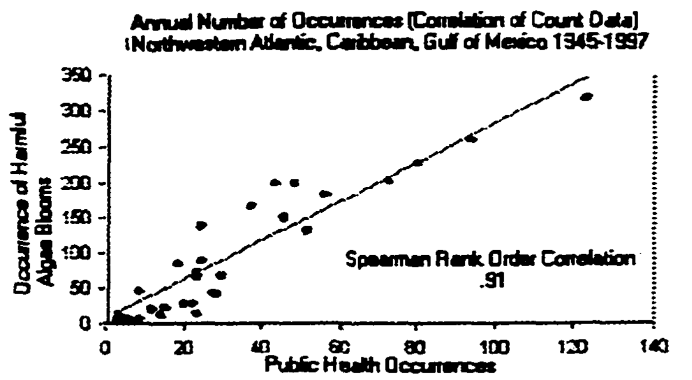


Figure 21. Cross correlation scatter plot representing a comparison of unique space/time count data of occurrence reports (x,y) 1945-1997 for public health and harmful algae blooms.

Monthly or seasonal data would more accurately reflect associations than the yearly data depicted in Figures 20 and 21 and were unavailable in sufficient quantity to perform further statistical tests. This may be the case in the Baltic region as well. As more data are entered into a database, the technique can eventually be applied to each fjord, bay or estuary, at a variety of time intervals more appropriate to the mechanisms suggested within the data models. Any significant measures of correlation at coarse resolutions will help determine which categories are closely associated and synchronous in response to exogenous forcing, and also which indicators might usefully represent the behavior of other indicators (proxies).

Other exploratory techniques useful in examining associations include principal components analysis (PCA), ordination, and auto regressive integrated moving average (ARIMA) time series analysis These techniques can help reduce thousands of database entries to a few meaningfully related disturbance types. Combinations of statistically derived disturbance variables are a crosscheck of the "expert" assigned event-type classification depicted in data models. Those resulting disturbance categories can be given names based upon their predominant impact characteristics.

Eight MMED categories were derived based upon a global cross-section of HEED data (Table 8). These disturbance types represent events that are acute, occurring within a short-time span, (e.g. biotoxin exposure), protracted (evolving over time), or chronic conditions (e.g., tumor development, eutrophication). Other categories have specific correspondence to forcing factors (e.g. coral bleaching events and sea surface temperatures; population declines from climate variability and altered ecosystem dynamics). The global survey documented 147 disturbance types. Almost all of these may be usefully applied within the Baltic Sea, although not all 147 disturbance indicator types comprising these eight categories are present within the Baltic. For each coral reef type, for instance, removed from the global list, a Baltic Sea disturbance type such as Anasakis parasite infestation of herring (e.g. Sweden) or beach closure due to eel mortality (e.g. Poland) could serve as a substitute. A Baltic Sea specific keyword list would guide a new category derivation. Examples of the eight types, their use, and the 147 general disturbance indicator types are discussed more fully in Sherman (2000).

Table 8. Eight Disturbance Types with Example Indicators (categories are not mutually exclusive)

Biotoxin/Exposure (e.g. toxic algae blooms, human gastroenteritis)
Anoxic/Hypoxic (e.g. nuisance blooms, Baltic cod/hypoxia)
Trophic Magnification (e.g. tainted shellfish, piscavor tumors)
Mass Mortality (e.g. M74 salmon aquaculture losses, flatfish mortalities)
Climate Forcing (e.g. North Atlantic Oscillation and storm damage)
Disease (e.g. herring lymphocystis, morbillivirus, phocine distemper virus)
Novel and Invasive Disturbances (e.g. Ballast water discharge)
Keystone and Chronic Disturbance (e.g. colonial waterbird mortalities, seasonal eutrophication)

In addition to the increasing movement of invasive species and the spread of disease, the majority of global disturbance reports involve harmful algae blooms (HABs) as the indirect cause of morbidity (illness) and mortality. Because HABs can affect a wide variety of living marine resources and dramatically alter ecological relationships among species (Burkholder, 1998), they are a leading indicator of marine disturbance, and thus, ecosystem health. For the Baltic, it is recommended that close attention be paid to HABs and organic pollutants as outlined within the Health of The Oceans (HOTO) panel of the United Nations Environmental Program (HOTO 1999).

A Baltic Prototype

As groups of managers and specialists create standardized methodologies for reporting MMED's, it becomes more important to provide an equally standardized means for exchanging information. A World Wide Web geographic information system (GIS) developed by the HEED (1998) program, has allowed researchers interested in hypotheses testing and managers interested in reconstructing disturbance regimes to interactively access data-sets to query anomaly and categorical data by space and time (Figure 22). Precedent provided by the sharing of information layers via the Internet within the BDBP, BALTEX and BGIS programs is encouraging. A marine disturbance information system built upon such a GIS foundation serves as a prototype for how information might be consolidated in a central location to explore standards and provide a common interface to research managers. In the future, the internet-based marine disturbance data system can be linked to human disease and wildlife morbidity and mortality through tissue and serum banks, tumor registries, disease image archives, museum specimen collections, and even be available to field veterinary response teams investigating events. Coupling field observation, data analyst recommendations and institutional monitoring provides the necessary components for a comprehensive marine epidemiological research system.

Figure 22. A Prototype Baltic Sea Internet Information System

The HEED system demonstrated how climate, pollution and trophodynamic co-occurrence information has already been of value in assessing collateral impact from known disturbances (HEED 1998). Counts of the number of disturbance types (variety), their frequency in particular areas and raw numbers of occurrence can be used to better understand the natural history of marine disturbances and establish retrospective time-series reconstruction of past events. The capacity for real time event reporting via the Internet would be the next logical step.

Volunteer Anomaly Observers

Obtaining real-time reports of disturbance presupposes a network exists to relay anomaly information into a Baltic Sea information system. Electronic mail and mass-media fora already link parts of the possible marine disturbance community. However these sources of information cannot substitute for a dedicated network of volunteer coast-watchers. To overcome the difficulty of collecting anomaly data retrospectively and thus not knowing the difference between reported non-occurrence and lack of data collection, a network of Baltic coast-watchers is proposed. Academic researchers, interested members of the public and even young people and college students could enter topical information compatible with the MMED standards as part of their educational curricula. The participants would enter data into online spreadsheet columns referenced to place and date. Information could include sampling points, closest meteorological station reference ID and extracted data from that station, stream gauge data, national discharge and toxic release inventory data (if available), nearest marine biological laboratory, contact information for various topics, satellite overpass information, and perhaps even portions of volunteer monitoring network data (Table 9). Volunteer data collection projects have been successfully tied into mainstream professional research programs in the United States (Lee 1994). Quality assurance and quality control (QA/QC) of that data could be integrated into routine college level instruction, and moreover, graduate student oversight of the QA/QC procedures would provide a hierarchical level of participation extending from school age children to senior faculty. The Internet makes this process feasible, and increasingly computers and Internet connections are reaching libraries and educational institutions.

The resultant Internet base-map data layers would complement the GIS and database information provided by marine scientists and public health officials, but have much greater spatial and temporal resolution. Reporting could be a real-time feature of the system. In areas offshore where ferries and ships of opportunity do not collect transect information and within coastal data-poor regions, citizen training to obtain measurements from personal watercraft, bridges and coastal bays, harbors and rivers with public access could at the least capture some information regarding anomalous mortality events. Circulation modeling and satellite time-series could be used to derive approximate origin points. Some precedent for such an effort has already been established within the Baltic. Students from 25 schools representing Estonia, Denmark, Finland, Latvia, and Lithuania sections of the Baltic coast participated in the first Coastwatch Baltic Sea Project (BSP) funded by the UNESCO regional schools project by filling out questionnaires for portions of the coast (500m sections) (Kristian, 1999).

Table 9. Field Measurements trained volunteers could collect and contribute to a highly resolved Baltic Sea GIS

Physical coastal measurements	Coastal *in situ* Chemistry	Biological Information Desired
Stream gauge statistics Meteorological Station - Nearest sampling time- in synchrony with satellite overpass Place specific volunteer data Wind direction and velocity Wave height and direction Tide-stage Cloud cover- Sun angle time of day Radiometric spectral reflectance pole held measurements Global Positioning System data Precipitation extremes (storms) 30 days	Secci disc Light penetration Turbidity Temperature (surface and bottom) Water depth Pole radiometer data Salinity Oxygen Silicate Nitrate Phosphate	Seaweed litter, Submerged Aquatic Vegetation Chlorophyll - water for phytoplankton Net zooplankton -bongos Bait shop reports on species abundance and availability Fisherman reports from the docks on conditions Shellfish benthos settlement on bricks Disease normal vs. abnormal Fecal coliform counts Shellfish hepatitis, hospital reports Mussel watch Mammal sightings/stranding networks Audubon society bird counts

Disturbance Reconstruction

Chronic illnesses, mass mortality and disease epidemics are being reported across a wide spectrum of marine taxonomic groups. Novel occurrences involving pathogens, invasive species and illnesses affecting humans and wildlife are globally distributed and appear to be increasing (HEED 1998, Harvell *et al.* 1999). These disturbances impact multiple components of marine ecosystems, disrupting the structural and functional relationships among species and the ability of systems to recover from natural perturbations. Climate change involving extreme events combined with human induced stressors may compromise an open-ecosystem or migratory population's resistance to opportunistic micro-organisms. Fungi, bacteria and viruses are quick to exploit the weak within a disturbed enclosed-ecosystem and eventually create suitable environments for continued infestation. Assessments using a marine epidemiological approach can track these changes in ecosystem health (Epstein 1996).

Better understanding of the natural history of disturbance regimes requires the inventory and reconstruction of event time-series. Time series allow multiple marine ecological disturbances (MMEDs) to eventually be classified as major disturbances (Meta-Events). The number and frequency of Meta-Events in a place can be used as indicators of a decline in ecosystem health and loss of essential services (e.g. economic, nutrient cycling etc. see Costanza and Haskell, 1992 for review). Reconstructing a natural history of these events and related environmental conditions facilitates a better understanding of the local, regional and global causes of disturbance. MMEDs can be mapped using geographic information systems to define spatial "hotspots" and temporal clusters of events (e.g., during El Niño events). Reconstructed time series have helped researchers identify eight general impact categories based upon the spatial and temporal dynamics of the observed disturbances. Assuming the appropriate observational meta-data information (noting source and quality) are available, resource stewardship agencies and research institutions can work on standards to better define regionally more appropriate or optimal indicators for characterizing each of the sub-disturbance type for ecosystem health assessment.

These adverse biological events carry with them significant human health and economic costs. International institutions can use the ecosystem health framework to assess the health and consequences of disturbance within large marine ecosystems. Improved monitoring could follow initial assessments, perhaps even using the surveillance data from volunteer disturbance observers, followed by focused basic laboratory and field research. With new insight, early warning systems to enhance response capability to ecosystem health disturbances could be initiated, and coordinated mitigating actions taken, to address the underlying forcing factors leading to disturbance within the Baltic.

Basis for assessing the health of the Baltic Sea ecosystem

Concerned about the potential and limits of the Baltic Sea's carrying capacity, the region's Prime Ministers and their environmental ministries agreed to a series of collaborative marine science and management assessments brokered under the United Nation's Agenda 21 program. The Baltic Agenda 21 program has been an international instrument for governments to work together on common resource issues and the development of a thirty-year vision for future sustainability.

Among the assessments to be conducted in support of the Baltic 21 initiative, is the Baltic Sea Large Marine Ecosystem (BSLME) project (ICES, 1999; Thulin, 2000). The BSLME project is an ecosystem-based effort to introduce innovative methodologies for assessing the changing states of the BSLME, and implementing actions that consider whole ecosystem effects and recommend actions that maximize socioeconomic benefits from the goods and services of the Baltic Sea. The objective of the BSLME, project is to overcome the present short-term sector-by-sector activities to manage resources and improve environmental conditions with due consideration of the multiple interactions between resource use, human intervention, and environmental quality and variability.

An approach has been outlined to systematically reconstruct spatial and temporal disturbance regimes through the recovery of metadata and construction of a Baltic Sea Information System in accord with the Baltic Agenda 21 and the BSLME projects. The approach is based upon a survey of morbidity, mortality and disease occurrences defined retrospectively as events within the Northwestern Atlantic Ocean, Gulf of Mexico and Caribbean Sea using a set of keywords and an index of space/time co-occurrence developed during the HEED (1998) study. A survey of large marine ecosystems (Sherman 2000) conducted using the same keywords has identified a set of 8 disturbance types distributed globally. It is hypothesized that these eight types of disturbance will be found within the Baltic Sea. However, the specific occurrence types comprising each of the eight disturbance types will need to be defined specifically. With a Baltic observational anomaly information system, a new set of Baltic-specific keywords may help identify the distinctive patterns of marine disturbance and clarify the cause of unusual morbidity, mortality and disease events observed with greater frequency among Baltic Sea marine populations.

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CHAPTER 7

SYNOPSIS OF RESULTS

Database Integration

In the HEED project, meta-data from 2,127 published disturbance accounts were extracted for every item inventoried during the data acquisition stage. The source material ranged from key primary citations in refereed journals to review literature (secondary source citations) to anecdotal accounts of anomalous events (partially verified information) (CDROM, Appendix 12). Additional keywords taken from either the title, an author's list of keywords and abstracts of collated reference material were added to the pre-defined list of keywords until 2021 distinct marine disturbance keywords were cataloged to assist in future surveys. Of those keywords, 314 disturbance indicator types were classified and 246 pathogen toxin and disease combinations were derived to describe relationships (CDROM, Appendices 2,3).

The 2021 distinct marine disturbance keywords were queried and paired with twelve general taxonomic groups (10 categories) representing 7 specified Kingdoms (double counting variants), 80 Phyla, 82 Classes, 154 Orders, 145 Families, 311 Genera, 483 Species/ Subspecies designations, and 529 common name variants (CDROM, Appendix 4). When the database was further queried to produce combinations of keyword/taxonomic pairs, Over 300 observation types were reduced to 147 by adding count data using the Spatial / Temporal Data Models (Data Models are rule based scale matching lists). Further Reduction of 147 occurrence types to 88 by adding count data for the algae group into a one of several bloom classes was considered an acceptable aggregation by the "expert" reviewers (for the legend event descriptors). The taxonomic correlation matrix and PCA/Ordination steps helped reduce 88 to 8 general forms of direct and indirect marine disturbance impact (Paper 2).

The database was used to make simple queries related to observational trends. An issue to address was that of using the database to generate new hypotheses and confirm known occurrences.

Some HEED results have already been confirmed by local "experts." Three examples follow:

> "Reports of gastrointestinal and neurological diseases associated with HABs, bacterial and viral infections increased during the 1980s and again during the 1990s. Beach and shellfish closures have become increasingly common during the 1990's" (Personal Communicaiton, Dr. Lora Flemming, University of Miami, 1997).

> "Large fish kills occurred in the mid 1970s, early and late 1980s and mortalities persisted throughout the 1990s. Each instance co-occurs with sea surface temperature and precipitation anomalies, but not all anomalies have co-occurring fish kills. Biotoxins from the ingestion or presence of blooming dinoflagellates and bloom-associated anoxia are the major causes of fish mortality." (personal communication, Dr. Daniel Baden, University of North Carolina, Wilmington 1997).

> "Geographically, marine mammal mortalities have clustered in the Northeast, in southern Florida, around Galveston Texas and in areas affected by harmful algal blooms (HABs). Anomalous sea surface temperatures, HABs, and viral agents have been found to co-occur with marine mammal mortalities in previously undocumented ways." (Personal communication, Dr. James Mead November 1998, Smithsonian Museum of Natural History).

Hypothesis Generation

In addition to confirmation of known events, exploring associations within the database has generated new hypotheses of previously unknown relationships. Four prototype examples are provided below. These examples each represent major applications of the HEED database, to be developed by the author and others in future studies.

1) ENSO. The 10 categories of taxonomic unique observational count data were plotted relative to ENSO periodicity (data from HEED 1998). These HEED results have encouraged further

research into plausible mechanisms linking ENSO events with certain MMED events (Figure 23). Note that the compiled data depicted in Figure 23 represent a general increase in awareness and reporting of anomalies for individual taxonomic groups. Interviews with the researchers and "experts" that made the original observations will be necessary to evaluate the difference between increased observational effort and increases in the appearance of disturbance over time and for each disturbance type used for aggregation.

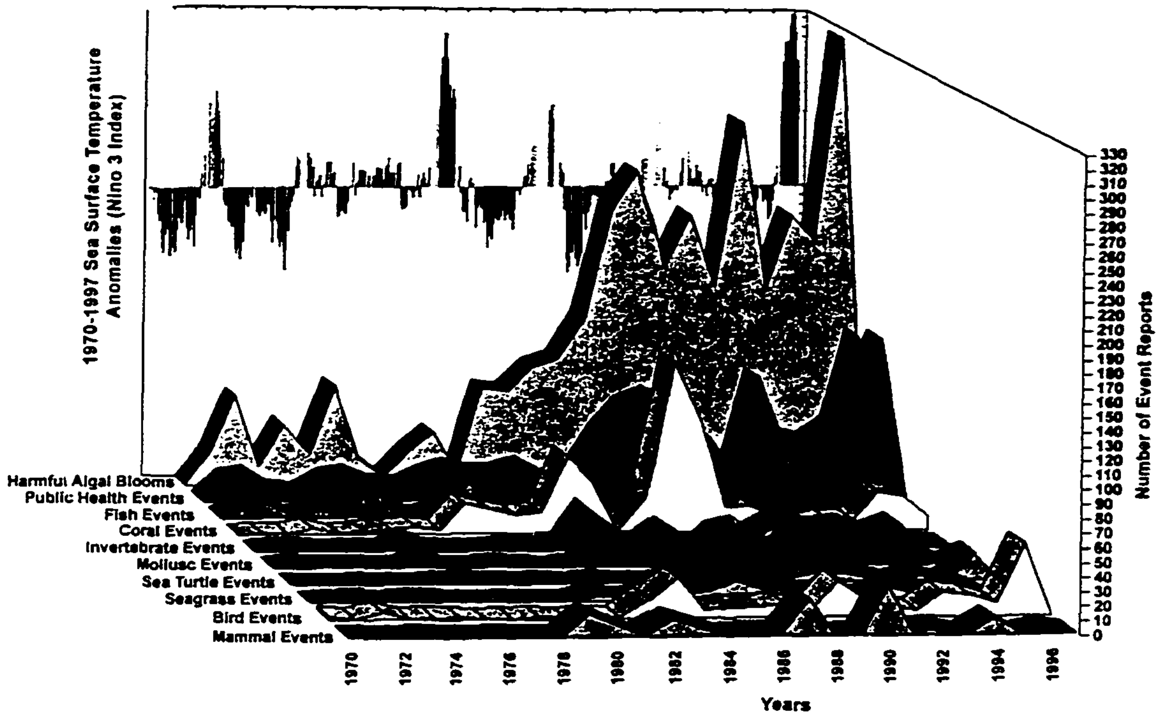


Figure 23. All of the event reports (unique by place and time) were summed by year (front) and divided into non-mutually exclusive taxonomic category (left) and plotted with respect to each other and the El Niño/La Niña anomalies (Nino 3 index- back). Public health event reports, for instance, were counted and reports were highest during: 1972, '76, '82/83, '85, '90, '93 and '96. These years are coincident with strong El Niño events and/or drought conditions attributed to La Niña. Geographically, Public health reports clustered in the Northeast, Florida and the Gulf States. Fish mortality data clusters in 1979, 1982-83, 1987, 1994, and 1997-98, and throughout the 1980s and 90s, with the highest number of reported events occurring during El Niño years. Coral bleaching event reports and anomalously warm sea surface temperatures did co-occur. Bleaching reports occurred regardless of ENSO phase during the 1980's and 1990's. The diseases of invertebrates are clustered in Nova Scotia, Florida and the Caribbean. Diseases of invertebrates were reported during the 1976, 1982-83, 1987-88, 1991-92 El Niño years (Graph reproduced from HEED 1998, the map (right, back) depicts the entire dataset's density of observations in red).

2)<u>NAO.</u> Figure 24 depicts all MMED anomaly data summed into a single series and presented along-side NAO, rainfall, and dust data. The increase in observations represented within the HEED dataset (starting in the mid 1970's, Figure 25) suggests that the North Atlantic Oscillation known to cause changes in rainfall over the Sahel in Africa and to lead to increases in iron-rich dust transport in the Caribbean and Western North Atlantic, may also benefit opportunistic pathogens and harmful algae which have led to a greater number of MMED observations.

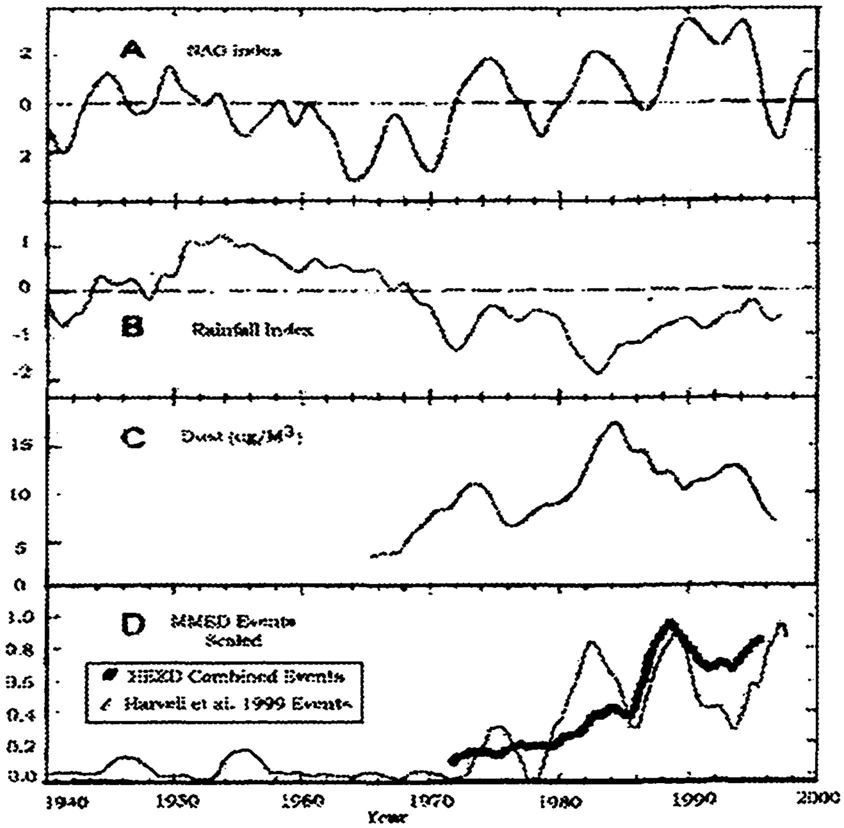
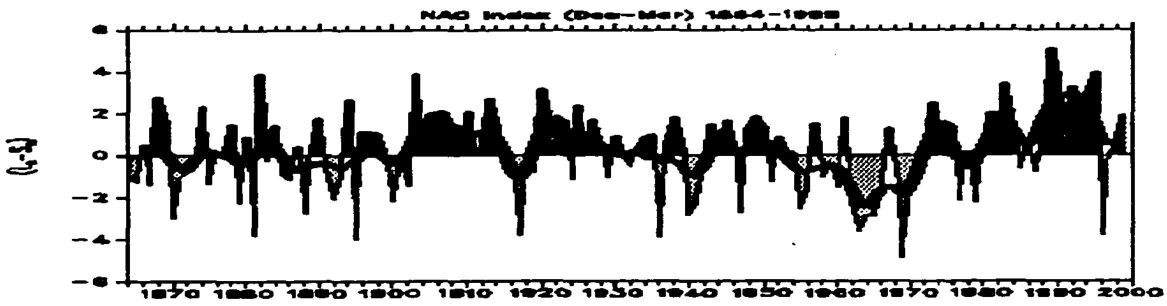


Figure 24. Correlation of NAO, Rainfall, Dust and MMED events (Graphs A,B,C appear in Hayes et al., 2000). Harvell *et al.*(1999) events refer to a subset of events collected from HEED 1998 and others over a much longer period of time but with less quality control compared to the HEED data (Graph D). Note the phase shift in the NAO 1971-1995 (Graph A, and in the 2 graphs below) and coincident changes in the respective series (B,C,D).

Figure 25 NAO 1970's phase shift (image from Tom Karl, National Climatic Data Center 2000).



3) <u>HABs.</u> Figure 26 is an illustration of the timing of harmful algae bloom occurrence compared to the timing of peak biomass in particular estuaries. The data were brought together to address a speculative hypothesis presented in Smayda and Shimizu (1993) suggesting that HABs occur at times when high biomass diatom blooms subside. The estuary-specific biomass data were extracted from Cebrian and Valiela (1999) and the HEED database was queried by month and place for HAB data. Using the HEED data, Smayda's speculative hypothesis can be investigated in more detail. The results suggest that HABs occur opportunistically when "normal' (mostly diatom) biomass is low. The implication is that environmental factors and disturbances occurring at the transition between seasons may promote the occurrence of harmful algae blooms otherwise kept in biological and chemical "check" during peak biomass periods.

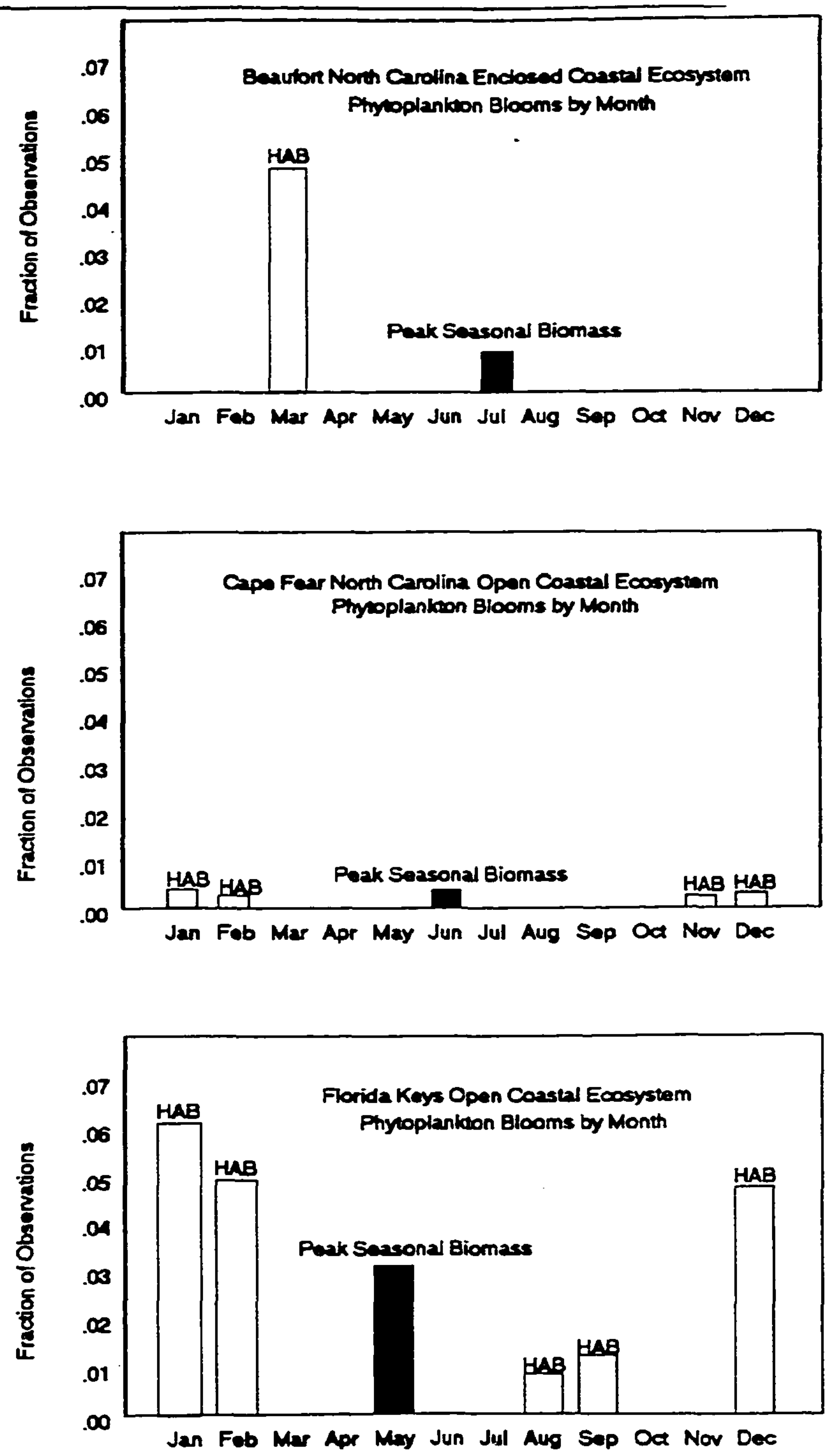


Figure 26. HAB Timing. These graphs depict the sum of all harmful algae bloom occurrence observations and peak biomass event observations per average month, January – December (1945-1998), versus the fraction from total of all observations – a measure of observational effort (height). Although effort does differ, HABs (mostly dinoflagellates) do appear to occur at different times of the year than the peak biomass blooms (mostly diatom) in these selected ecosystems. Much more data will be required to fully evaluate Smayda's hypothesis in these and other coastal waters.

4) <u>Long Island Scallops.</u> Grigalunas and Diamantides (1996) having interviewed "scallopers" suggest that scallop revenue declined as a result of persistent brown tides occurring in Peconic Bay of Long Island, NY. The blooms were associated with the commercial extinction of the fishery. HEED data brought together both the economic harvest values from the National Marine Fisheries Service Statistical database and HAB records to better substantiate T. Grigalunas' MMED hypothesis (Figure 27) (personal communication University of Rhode Island Dept. of Resource Economics 1996).

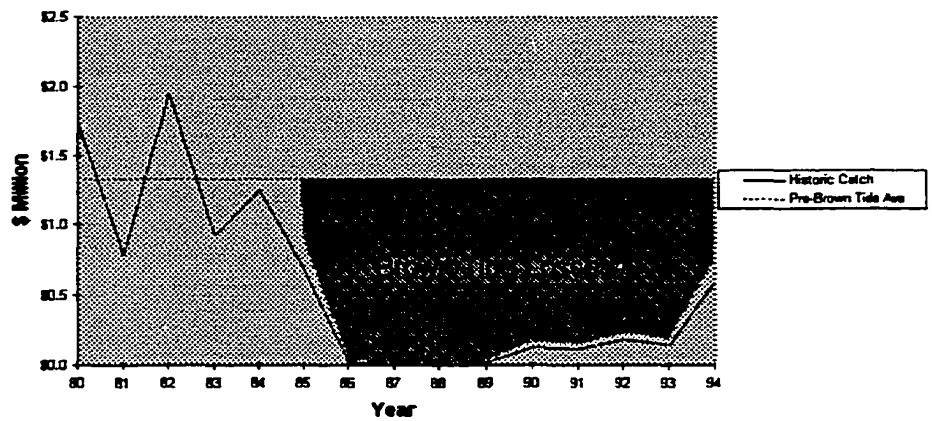


Figure 27. Peconic Bay and Long Island Shell Fisheries Decline. A series of chronic and persistent brown tides occurred from 1985 to 1989. Hypoxic and anoxic conditions led to the reduced recruitment and delayed recovery of these shellfisheries. The cost in millions of dollars can be calculated from NMFS long term statistics adjusted for the time-value of money (Consumer Price Index) and the price per bushel of shellfish located in adjacent (unaffected) growing regions.

<u>General Relationships</u>

Correlation matrices were produced (Figure 28) representing expected relationships among the following independent datasets: Harmful Algae Blooms and Shellfish, Harmful Algae Blooms and Human Health, Shellfish and Public Health, Fish and Public Health, Seagrass and

Invertebrates. An expected relationship between Marine Mammals and Public Health Events was not found. Higher correlations than expected were identified between Seagrass and Public Health.

For the significantly correlated data, and groups of data presumed to be related based upon data modeling, manual cross correlation confirms that there are no persistent correlations when factors are separated by multiple years from 1971-1996. An illustrative example is HAB/Human-health. The year-to-year persistence found in the HAB/Health database suggests the data may be serially auto correlated in the same manner between categories (Paper 3).

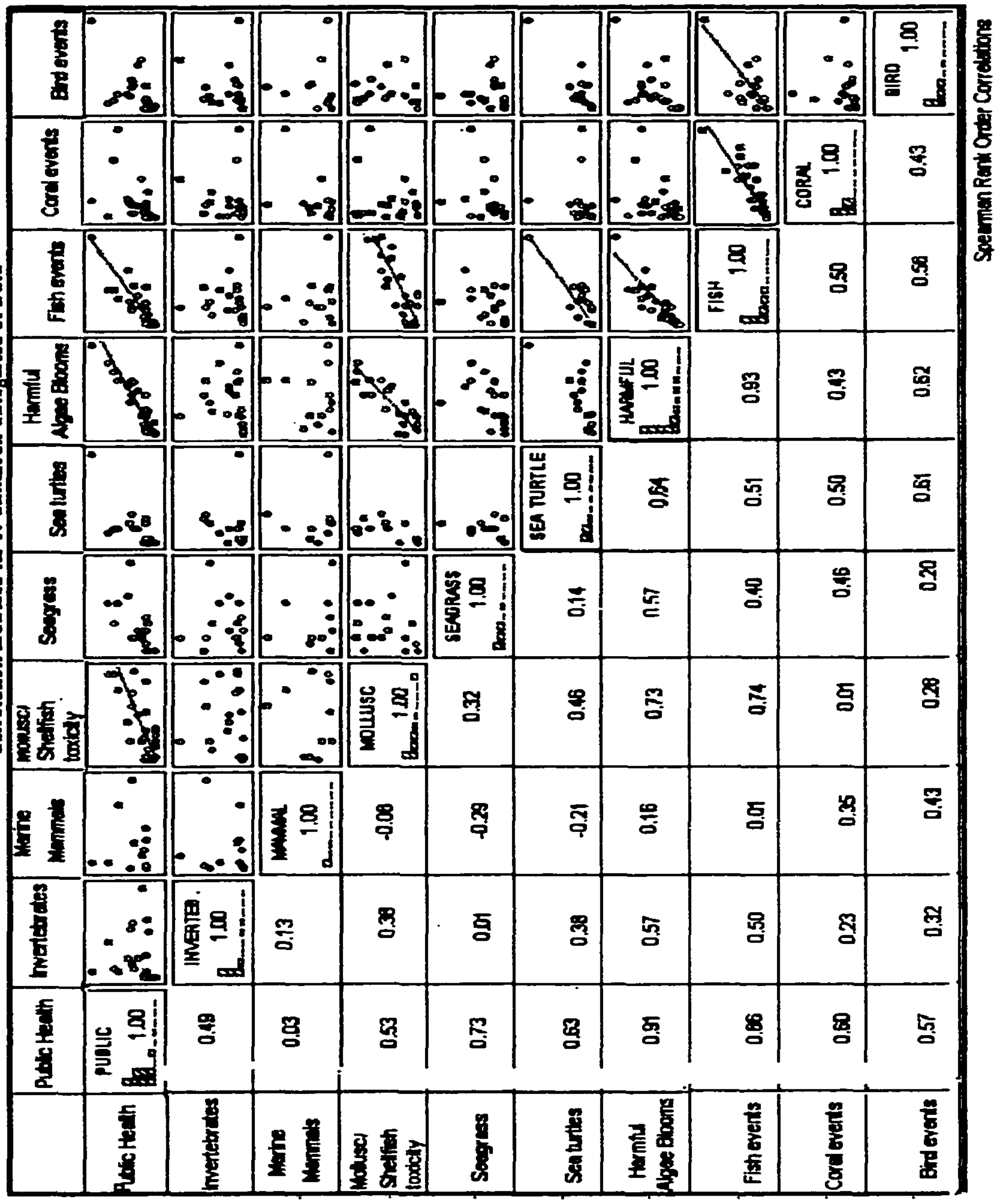
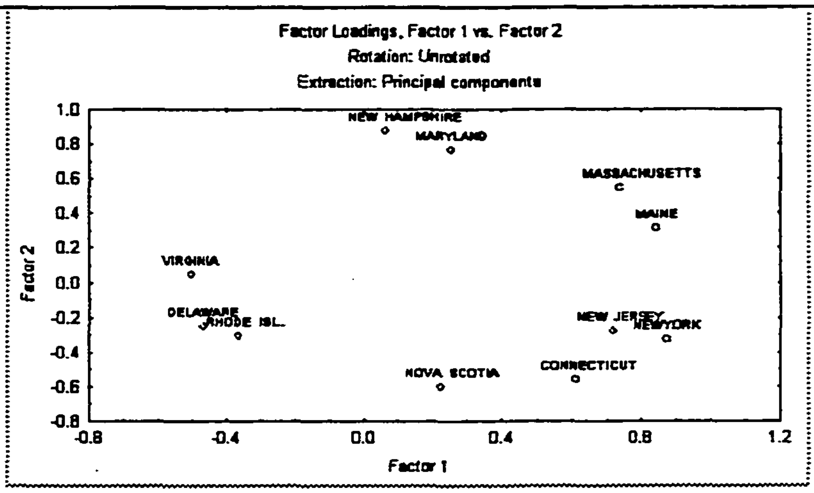


Figure 28. Linnaean "Expert" (Ten) Categorical Associations 1945-1996. Identity matrices are read like graphs. The intersection of the categories labels listed at the left and at the top (turn page to read) correspond to the axes of the mini-cross-correlation graphs (dot scatter plots) and also the correlation coefficients (number values) at the intersection of category labels (bottom left hand side of page and top of page). Frequency histograms depicting number of data points are on the diagonal with values of 1.0 for correlation coefficients because the same category data is compared against the same category data. The axes for each "graphlet" are the number of occurrences from 1945 to 1996 at the yearly level of aggregation for unique observational data. Each point has 2 coordinates (x,y) in which x is the number of occurrences for a year and y is the number of occurrences for y axis for the same year. Statistically significant associations are depicted with best-fit lines. In rank-order correlation, the number of similar high/low points in a series weights the correlation coefficients. Statistica's (Statsoft 1999) Spearman Rank Order Correlation statistic was used to compute the values portrayed (not all high coefficients are significant due to insufficient sample sizes). A cross-correlation index value for each intersected "graphlet" was calculated by hand to confirm that the automatically generated correlations represent the associations depicted above.

As expected, states that are proximate to each other tended to cluster together in the Principal Components Analysis (Figure 29). Exceptions include the New Hampshire/Maryland group and Nova Scotia. At this point, the reasons why Rhode Island clustered with Delaware and Virginia rather than clustering with Connecticut, New York and New Jersey are unclear. However, the raw data (CDROM Appendix 9) indicate that fortuitous temporal correlations with the small numbers of occurrence data points can greatly skew the PCA results. With a more complete database, the PCA results will be more robust.



Principal components Eigenvalues:

% Total Variance	Cumul. Eigenval	Cumul. %
88.96179	9.785797	88.96179

Figure 29. PCA (1st and 2nd factors) showing regions with similar disturbance regimes (raw data in Appendix 9).

Currently little information exists on the short and long term interactions among multiple disturbances in spatial pattern, frequency intensity or effects of multiple disturbance on regional scales on terrestrial and marine ecosystems (Landres *et al.* 1999; Duda and Cruz 1998). According to Landres *et al.* (1999) and Ricklefs (1987) further understanding of local ecological communities requires understanding at broad spatial and temporal scales that encompass a "regional – historical viewpoint". The HEED approach for examining the frequency and extent of multiple disturbances using a wide range of spatial and temporal scales is responsive to the expressed interest of : 1) applied ecologists for implementing ecosystem level management practices (Christenson *et al.* 1996), and 2) the interest on the part of national and international agencies to improve present conditions relative to biodiversity loss, climate change, spread of invasive organisms and disease, and degradation or overexploitation of coastal waters (GIWA 1999).

General Methods Questions Remaining

With additional statistical analyses made possible by a more a comprehensive data set, a number of questions could be addressed: 1) Can species-level morbidity and mortality data be used to define major marine ecological disturbances as distinguished from multiple marine ecological disturbances across a wide range of taxonomic groupings and a hierarchy of spatial/temporal scales, in the absence of information regarding relative magnitude of events? 2) Can marine disturbance hot-spots or areas particularly vulnerable or sensitive be identified simply using spatial/temporal co-occurrence? 3) What areas of the world are best represented with which types of disturbance characterizations and which are the best indicators for particular disturbance types? 4) Have there actually been shifts in the seasonality of harmful algae species or the periodicity of blooms and/or have researchers left important distributional and bloom data unpublished? 5) What are the extrinsic and intrinsic forcing factors that tie similarly scaled co-occurring disturbances together? 6) What are the implications of merging multi-taxon data into a single MMED category?

A fully operational HEED information system will allow researchers the freedom to explore data and relationships without being limited by their preconceptions of complexity and a need to first explain the mechanistic relationships among their observations. The system was not designed to supplant hypothesis testing, but rather guide researchers to potentially interesting questions. Once a relationship is found, there is ample opportunity to practice hypothesis testing. The problem in disturbance ecology is that one cannot begin at the reductive stage to discover a general pattern (Allen and Hoekstra 1992).

Applications of the HEED Ecosystem Health Approach

One objective of marine research programs is to provide the data needed to detect changes in ecosystem condition over time and to learn what causes those changes. Separating natural from anthropogenic variability in coastal systems is important, as are separating the effects of local (e.g., point source), regional (e.g., non point source and harvesting) and large-scale (e.g., global climate change) forcing. The HEED approach, because it focuses on impact first and causality second, provides a framework to decide which MMEDs are the best indicators of changing ecosystem health, and which causes are part of natural processes versus those induced by human intervention. In three separate publications, the HEED MMED approach is proposed as a guide for ecosystem health assessment in the Northwest Atlantic and the margins of the Pacific, Atlantic, Indian Ocean Basins and the Baltic Sea. In large-scale assessment efforts, data from satellite sensors will most likely provide better information about physical and chemical dynamics. However, these tools require sea truth for calibration. A distinct advantage of the HEED system is the accommodation of a wide range of spatial and temporal scale biological anomaly data to correlate with remotely sensed data.

CHAPTER 8

GENERAL CONCLUSIONS

The central tenet of this dissertation's framework is that "mining" of distributed sources of archived information can connect or elucidate the relationships among multiple and co-occurring (same place, same time) disturbances. The keyword data "mining" and "expert" informed approach led to the creation of a unique marine epidemiological information system for disturbance evaluation. The hypothesis that: "A large number of marine morbidity and mortality data once assimilated and analyzed will represent a non-random pattern relative to common categorical dependencies" was supported. Another part of that hypothesis: "when these data are grouped into a smaller number of disturbance types, common impact response to exogenous forcing factors will be revealed" was supported quantitatively using categorical correlations and qualitatively using temporal and spatial criterion.

The hypotheses generated with the HEED data using qualitative and exploratory data analysis techniques were a byproduct of the initial evaluation of the HEED information system, methodologies and study design. Quantitative analyses of the suspected synchronous MMED data and exogenous forcing factor variability, presented in graphical form in this dissertation, will be necessary prior to publication of meaningful and significant results. The HEED system will complement the quantitative analyses by providing information on data compatibility, quantity and quality. Each of these issues was considered necessary to support the meaningful explanation of patterns inferred.

Seven major findings specifically support the hypothesis statements and address the following Thesis:

> **Assimilated observational data extracted from multiple sources can adequately characterize functional marine ecological disturbances, reveal possible forcing factors, unanticipated impacts and contribute to ecosystem health assessments.**

1) The correlation analyses indicate that aggregated taxonomic categories within the database respond similarly to inter-annual (temporal) variability. HABs and human health, HABs and Fish events, HABs and shellfish toxicity were found to correlate as expected. Human health and fish events were also found correlated to a lesser degree. This may be because human health and fish events are secondarily related by their similar response to HAB biotoxins. Ciguatoxic Fish Poisoning (CFP), a human malady, has been found to also damage the health of fish (Landsberg 1995). The more direct CFP association, due to human consumption of food-chain biomagnified toxin, may involve a lag effect that mutes a stronger temporal correlation.

2) Because non-random patterns emerged from the analysis of grouped Linnaean marine count data, it is presumed that many of these disturbance indicators may be used interchangeably. The cross-correlation analysis method examined this supposition over time. The non-random patterns of co-variance among Human Health and HAB categories (the grouped pair with the highest coefficient of correlation) demonstrated some persistence in multiple year comparisons. One may speculate that regions with co-varying public health and HAB events may have persistent seasonal disturbance problems that have been picked up as inter-annual signal. Spectral analysis of these cross-correlated time series data would help quantify these more qualitative temporal categorical findings.

3) When the various impact categories were lumped into a single MMED category and examined within a single Large Marine Ecosystem, adjacent states that were presumed to share similar disturbance regimes clustered together. An unanticipated finding was that Rhode Island and New York, both impacted by the same brown tide event, did not cluster together. Rhode Island clustered instead with Delaware, which shares similar oceanographic and episodic disease occurrence type. Further investigation of sea surface temperatures, salinity and circulation during the event-periods in question may better support the category/time clustering of spatial areas. The first approximation LME findings represent another possible disturbance analysis methodology to be explored using the HEED data. Caution should be exercised in extrapolating from clusters appearing in principal components space. The MMED occurrence-timing-spatial PCA can help generate hypotheses among logical groupings, but investigation of clusters such as the New Hampshire and Maryland cluster may inappropriately redirect efforts.

4) The multidimensional scaling (PCA and Ordination) analysis of occurrence types did not support the "expert" supposition that occurrences would cluster according to Linnaean taxonomic groupings, but rather clusters of occurrences reflect similar functional response to disturbance. Though the results were different than expected, the eight derived categories did represent both the cross-correlations found from categorical analyses and similar spatial and temporal scaling of impact response. Both the Linnaean taxonomic categories and the functional impact categories have been found useful in organizing and summarizing a large amount of categorical data. A prospective marine epidemiologist may choose between the Linnaean hierarchy to investigate Genera specific novel occurrence and disease types or the functional impact classification to evaluate the ramifications of disturbances. In both cases, the HEED information system provides a standardized repeatable classification nomenclature. The eight derived

functional disturbance categories (Paper 1, Figure 5), at present, are aggregate indicators of *Multiple Marine Ecological Disturbances (MMEDs)*. Provided that further statistical analyses support the robustness of the groupings in comparative regional analysis (CDROM Appendix 9) and by similar temporal coherence within each group (proposed in CDROM, Appendix 8), these eight categories will be used to define *Major Marine Ecological Disturbances(Meta Events)*.

5) The ability to link different anomaly datasets together within the HEED information system through queries of spatial and temporal coordinates held in common provides a context for local disturbance hypothesis testing (bay, harbor, estuary). Although more systematically collected base line and magnitude information will be required to apply the eight functional categories to disturbance regime reconstruction and assessment, qualitative graphical confirmation of co-varying combined Linnaean MMEDs, oceanographic, economic and climate data sets at the bay/month level of resolution are promising preliminary findings (even if sample sizes are presently too small to test the strength of those relationships). The derived disturbance groups may accurately reflect species' synchronous life histories, interdependence, and/or response to spatial and temporal forcing factors. Categorical correlation and cross-correlation results open the possibility of substituting one similarly responding occurrence type for another (proxy data) if complete data sets for particular information types remain unavailable. Further searches of locally held unpublished data for particular locations could be used to verify the utility of the proxy approach at these scales prior to the initiation of disturbance-monitoring systems. Following a recoding of the database to reflect the eight derived disturbance categories, regional disturbance regimes, oceanographic and climatological forcing factors as well as fisheries economic impacts can be better evaluated. The collapse of the oyster shellfishery in Long Island Sound and the Peconic Bay estuary using the aggregated anoxic/hypoxic category, and the evaluation of seasonal occurrence

of HABs relative to peak biomass periods in many bays are preliminary examples of the use of HEED approach in hypothesis confirmation.

6) The common indicator response identified among multiple large marine ecosystems likely reflects exogenous forcing from large-scale climate, oceanographic and ecological factors (or some synergistic combination of those factors with unevaluated anthropogenic pressures). This was demonstrated through the graphical annual depictions of ENSO and NAO MMED co-variations. Alternative explanations such as coincidental aggregation of many smaller scale processes with similar outcomes and reporting effort biases are unlikely, on an inter-annual scale, to reflect so consistently and precisely the variability observed. New hypotheses regarding the mechanisms leading to co-variation have been facilitated.

7) The patterns qualitatively identified in this dissertation reflect the strength and importance of incorporating diverse observational and even anecdotal disturbance data into study designs. The assimilated observational data extracted from multiple sources can adequately characterize functional marine ecological disturbances and reveal possible forcing factors. The methodological tools and the examples summarized here represent an approach that can be applied to any coastal region of the world and the approach, not limited to marine systems may be used for terrestrial, limnological and epidemiological resource management applications (Sherman, 1994; Epstein *et al.* 1999). The most fundamental result of this work is the demonstration that the HEED system by its design, provides more than the sum of the information it contains.

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