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Building Ocean Profile-Plankton Databases for Climate and Ecosystem Research

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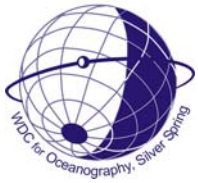

National Oceanographic Data Center

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ABSTRACT

We document the history and progress of two international ocean data management projects that have the goal of building the most comprehensive ocean profile-plankton databases possible. Such databases are crucial for scientific progress in determining the role of the ocean as part of the earth's climate system. These projects were initiated during the 1990s under the auspices of the Intergovernmental Oceanographic Commission. The "Global Oceanographic Data Archaeology and Rescue" project has the goal of locating (archaeology) and digitizing (rescue) historical oceanographic data that exist in manuscript or electronic media form that are at risk of loss due to media decay. To date this project has resulted in a doubling of ocean profile data for the pre-1991 period. The "World Ocean Database" project has the goal of encouraging the construction of global and regional oceanographic atlases and improved quality control procedures for oceanographic data. The *World Ocean Database 2001* and *World Ocean Atlas 2001* represent two of the most recent products of this project.

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1. INTRODUCTION

To determine the role of the world ocean as part of the earth's climate system and to develop climate system forecast capability for periods from months to decades, the international scientific community needs the most complete databases of historical oceanographic data possible. Many historical oceanographic data sets are not available to the international community because they exist only in manuscript form and are in fact at risk of loss to media decay and damage. There are also data in electronic form that are not generally available and are also at risk of being lost. This article describes projects initiated in the early 1990s to locate such data sets and to incorporate them into global or regional, comprehensive, integrated, scientifically quality-controlled database with all data in one uniform format.

These databases, and scientific products based on these databases, represent the infrastructure on which much ocean and climate research and assessments are now based. Specifically:

a) objective analyses of the data in these databases provide gridded climatologies that are used as initial and boundary conditions for ocean climate simulations and to verify simulations of the climate system. The data are used to prepare diagnostic studies, particularly for identification of interannual-to-decadal ocean variability. More recently these data are used as the input for ocean data assimilation efforts;

b) the international scientific community advises national and international bodies on such issues as climate change, *e.g.* the Intergovernmental Program on Climate Change (IPCC). Hence, the international oceanographic and climate communities should have access to the most complete electronic oceanographic data bases possible. Regardless of one's views about the origins of observed changes of the earth's climate system (anthropogenic, internal or natural), the scientific community needs the best scientific databases possible to perform scientific research on this topic;

c) substantial resources have been, and continue to be allocated, for national and international ocean and climate programs such as Tropical Ocean and Global Atmosphere (TOGA), World Ocean Circulation Experiment (WOCE), Global Ocean Ecosystems Dynamics (GLOBEC), Joint Global Ocean Flux Study (JGOFS), Climate and Global Change, Climate Variability and Prediction (CLIVAR) and for the establishment of a Global Ocean Observing System (GOOS). Planners of such programs should have access to all historical oceanographic data in order to optimize measurement strategies for these programs. Scientists analyzing data from such programs need historical data in order to study interannual-to-decadal variability. Operational forecast centers need historical data in order to perform quality control of synoptic data;

d) to understand fisheries variability, and to manage fisheries and other marine resources.

2. A BRIEF HISTORY OF OCEAN DATA MANAGEMENT

The science of physical oceanography can be considered to have started around 1902 with the formation of the International Council for Exploration of the Sea (ICES). ICES started as a consortium of western European countries with an interest in understanding the fluctuation of

fisheries of the northeast Atlantic. The titration technique used to determine salinity was developed around this time as well as the equation of state for sea-water. ICES coordinated and planned the work of oceanographic data collection. Less recognized is that ICES formally encouraged the international exchange of oceanographic data. This was done through establishment of a formal data publication series (Smed, 1968). As time progressed, oceanographic institutions established data archives. For example, in the United States the Woods Hole Oceanographic Institute and the Scripps Institute of Oceanography became archive centers for Mechanical Bathythermograph Temperature (MBT) profile data beginning around World War II. Data were stored in the form of handwritten cards containing both data and metadata.

National support for the development of oceanographic sciences grew in many countries after 1900 which led to the development of catalogues of oceanographic data. In the United States the National Academy of Sciences supported development of a catalogue, international in scope, of historical oceanographic data and of oceanographic institutions (Vaughn *et al.*, 1937) in order to encourage the development of the science of oceanography.

Establishment of the World Data Center (WDC) system occurred during the International Geophysical Year (IGY) in 1957-58 in order that scientific data gathered as part of the IGY be safely archived and accessible internationally without restriction. The World Data Center (WDC) System (Secretariat of the ICSU Panel on World Data Centres, 1996: http://www.ngdc.noaa.gov/wdc/wdcmain.html) operates under the auspices of the International Council of Scientific Unions, a non-governmental organization of scientific unions.

During the 1960s countries began establishing formal national oceanographic data centers to archive ocean data and provide services. These centers were organized internationally under the auspices of the Intergovernmental Oceanographic Commission (IOC) of UNESCO (Roll, 1979) to encourage the international exchange of oceanographic data and to support capacity transfer from developed to less-developed nations.

In 1993 the World Data Center for Oceanography- Silver Spring (then known as WDC-A for Oceanography and hereafter referred to as WDC-Silver Spring or just WDC) began, under the auspices of the IOC, the *Global Oceanographic Data Archaeology and Rescue* (GODAR) project. In 2001 the IOC initiated a *World Ocean Database* (WOD) project which is also led by WDC-Silver Spring. In the remainder of this paper we document the history and progress of these and related projects.

3. HISTORY OF THE GODAR PROJECT

Based on the knowledge of oceanographic scientists and data managers from the international community, it was clear in the late 1980s that substantial amounts of historical oceanographic data existed only in manuscript or analog form, or on obsolete electronic media. In addition, there were data in electronic form that were not available to scientists other than the principal investigator who made the original measurements. Such data were, and still are, at risk of being lost due to:

a. media degradation such as fading ink or magnetic fields;
b. obsolescence of devices to read such data from old media;

c. environmental catastrophes such as fires and floods;
d. the retirement of individuals who know how to access these data or know the metadata associated with these data that make them useable to other scientists;
e. simple neglect.

The idea of digitizing historical oceanographic data from manuscripts did not originate with the GODAR project. Several such efforts began with the advent of electronic computers. For example, the U.S. National Oceanographic Data Center (NODC) digitized substantial amounts of manuscript data after its establishment in 1960. What the GODAR project represents is the establishment of a formal, internationally organized effort to support such activities and to make available all data in a single, integrated database. The existence of a formal international project, such as GODAR, sponsored by a recognized intergovernmental body such as the IOC, not only provides coordination which helps avoid duplication of effort, but also can help in attracting national funding for participating countries.

In September, 1988 a workshop sponsored by the NOAA NODC and the NOAA Environmental Research Laboratories was held at NODC in Washington, D.C. Scientists and data managers from the U.S. and Canada held discussions on ocean data archiving and distribution. Following a suggestion by Sydney Levitus (Anonymous, 1988), one of the meeting recommendations was the establishment of a “Historical Data Validation Project” to “recover as much historical data as possible”. A second meeting was held at NODC in September, 1990. This meeting was supported by the U.S. Climate and Global Change (CGC) Program. Specifically, a report to the NOAA Panel on Climate and Global Change by the CGC Working Group on Data Management (chaired by Francis Bretherton, University of Wisconsin) had emphasized the importance of “data archaeology” for Global Change Research. In that report "Data Archaeology" was defined as “the reconstruction of past climate and other aspects of global change from existing data. It involves a mix of seeking out, restoring, evaluating, correcting, and interpreting past data sets. The word "Rescue" in this context refers to the effort to save data at risk of being lost to the science community by digitizing data along with accompanying metadata, incorporating these data into internationally available databases, and distributing these databases without restriction. The Panel Report recognized that researchers trying to study long-term ocean variability would have to wait decades for enough data to accumulate from new ocean observing systems to study decadal variability. At the 1990 meeting held at NODC, scientists and data managers from several countries and international centers including the Soviet Union, Republic of Korea, Japan, Chile, Australia, United States, and the International Council for the Exploration of the Seas (ICES) met to discuss the state of historical oceanographic data and in particular to discuss the loss of data due to media degradation. The meeting made a rough estimate that “approximately 50% of all the temperature profile data ever taken is not in the world’s data centers”. The results of the meeting led to the establishment of various national and international projects that are known generically as "Oceanographic Data Archaeology and Rescue" projects.

An international meeting known as the "Workshop on Ocean Climate Data" was hosted by NASA and NOAA at Greenbelt, Maryland, U.S.A (Churgin, 1992). The meeting was sponsored by the Commission of the European Communities (CEC), International Council of Scientific Unions (ICSU), World Meteorological Organization (WMO), International Council for Exploration of the

Sea (ICES), and the Intergovernmental Oceanographic Commission (IOC). As a result of the demonstrated progress of various national data archaeology and rescue projects, the workshop recommended the expansion of these projects to band together under the umbrella of an existing international organization.

As a result of the "Workshop on Ocean Climate Data", a proposal for a "Global Oceanographic Data Archaeology and Rescue" (GODAR) project was submitted by Sydney Levitus to the Fourteenth Session of the IOC International Data and Information Exchange Committee (IODE) meeting held in Paris, France during December, 1992. The IODE recommended to the IOC that this project be adopted as an IOC project. During the March, 1993 IOC Assembly meeting, the IOC adopted the proposal for a GODAR project. Sydney Levitus was invited to be Project Director, an invitation which he accepted.

4. WHY ARE OCEAN DATA MANAGEMENT PROJECTS NEEDED?

As this report documents, many oceanographic data were gathered before the advent of electronic computers. Earlier projects to digitize these data were incomplete. Oceanographic data have often been gathered for one specific purpose and then ignored. Recognition of the importance of the role of the ocean as part of the earth's climate system has resulted in a demand for historical ocean profile and plankton databases.

Even modern oceanographic measurements from a particular cruise or set of cruises may not be managed in what we consider to be an optimal fashion. What we believe is needed to facilitate oceanographic and climate research is a global, comprehensive, integrated, scientifically quality-controlled ocean profile-plankton database with all data in one, uniform format.

5. GOALS OF THE GODAR PROJECT

The GODAR project emphasizes:

a) Digitization of data now known to exist only in manuscript and/or analog form. This effort has highest priority of all activities;

b) Rescue of electronic data that are at risk of being lost due to media decay or neglect;

c) Ensuring that all oceanographic data available for international exchange are archived at two or more international data centers in electronic form;

d) Preparation of catalogues (inventories) of:

- i) data now available only in manuscript form;
- ii) data now available only in analog form;
- iii) digital data not presently available to the international scientific community;

e) performing quality control on all data and making all data accessible via the Internet and media including CD-ROM's and DVDs.

6. IMPLEMENTATION

From the inception of national and international ocean data archaeology and rescue projects at various centers, efforts were coordinated to avoid duplication of effort and to maximize the use of scarce resources. Joint activities include the exchange of data, data distribution plots, catalogue information about data holdings, and the exchange of scientists and data managers between centers. An emphasis on "rescue" and exchange of data occurring simultaneously was for two reasons:

a) some data are at risk of being lost forever if not saved immediately;

b) in order to demonstrate credibility, the project needed to demonstrate how quickly the project could act to make previously unavailable data accessible in electronic format.

Perhaps the most valuable technique to quickly describe data holdings is to produce data distribution plots and tables of the number of profiles on a year-by-year basis for each major measurement type. Levitus and Gelfeld (1992) did this for each of the major NODC digital archives. This work showed the distributions of NODC holdings for all countries combined. The GODAR project now prepares similar summaries on a country-by-country basis and distributes these electronically to data centers, scientists, and institutions in many countries. These summaries generate much interest and have resulted in the exchange of more information and data.

Physical, chemical, and plankton oceanographic data, as well as ancillary surface marine meteorological observations, are the specific types of data that the GODAR project focuses on. Initially, most data digitized, or otherwise rescued, have been physical parameters. Recently the rescue of sea level data from tide gauges has become part of the GODAR project.

A series of six regional meetings were held during the first several years of the GODAR project to survey the oceanographic data held internationally in both manuscript and electronic form. The first regional GODAR workshop was held in Obninsk, Russia, during May 1993. This meeting focused on datasets and activities in eastern and northern Europe. This region was chosen in particular because of the possibility of the loss of substantial data sets due to economic conditions in Eastern Europe. The report of this first regional GODAR workshop (IOC, 1993) gives some indication of the amounts of data that exist in manuscript form. For example, the Russian delegation reported the existence of data for approximately 450,000 Mechanical Bathythermograph (MBT) profiles and 800,000 Oceanographic Station (OSD) casts in manuscript form. Reports have been produced for each subsequent regional workshop (IOC, 1994a; IOC, 1994b; IOC, 1995; IOC, 1997; IOC,1999a) describing results of the workshop and in particular describing the amount of data held in manuscript and electronic form in each participating member state. The first phase of the GODAR Project culminated in an International Review Conference held in Silver Spring, Maryland during July 10-13, 1999. Seventy-five scientists and data center managers from twenty-five countries attended. The first phase of GODAR was deemed a success (IOC, 2003) and the workshop recommended the expansion of the project to include sea level data and geophysical data. Table 1 shows a list of all GODAR Workshops and the reports generated.

In 1999 a workshop (IOC, 1999b) sponsored by the IOC International Oceanographic Data and Information Exchange Committee (IODE) recommended formation of a special project to act as a focus for GODAR for countries bordering the western pacific under the title

"GODAR/WESTPAC" with the project office being located at the Japan Oceanographic Data Center (JODC).

In 1994, the European Union supported two pilot projects for developing concerted data management activities in the Mediterranean and Black Seas. These projects focused on the rescue and analysis of temperature and salinity profiles. These projects successively released the Mediterranean Ocean Data Base MODB (The MODB Group, 1996; Brasseur *et al.*, 1996), and MEDATLAS (MEDATLAS Consortium, 1997; Fichaut *et al.*, 1999). The latter database included the MODB data set with further quality checks of the observations. A new concerted action, MEDAR/MEDATLAS II started in 1998 for a 3-year period funded by the European Union's MAST program and was endorsed by the IOC as a GODAR project. This project aimed to develop regional sustainable data management capacity for the Mediterranean and Black Sea scientific and operational programs through data and information exchange, job training and workshops. The database and products resulting from the cooperation of 25 participants has been published on CD-ROMs (MEDAR Group, 2002). The long-term archiving of these databases is assured by several national data management systems. The released set of observations doubled the volume of available data compared to the previous project. It includes profiles for 12 bio-chemical variables in addition to temperature and salinity profiles, all fully checked for quality both automatically and visually, according to a common protocol based on international standards (MEDAR Group, 2001). It is notable that several countries that previously did not participate in the GODAR project were involved and that data never archived were released for public use. Gridded fields and maps have been produced using objective analysis methodology (Rixen *et al.* 2001). These results have been presented in many conferences and workshops with encouragement to continue the work to add new profiles and more parameters. However, the continuity of this cooperative data management is linked to the opening in call for tender, writing and approval of project proposals by the funding agencies, which has created a gap between successive database releases.

7. RESULTS OF THE GODAR PROJECT

Figure 1 is a comparison of the number of Ocean Station Data (OSD) casts (Bottle data) available from NODC/WDC in 1991 as a function of year for the 1900-1990 period compared to the OSD casts available as part of the *World Ocean Database* 2001. In 1991 NODC/WDC held data from 783,912 OSD casts for the pre-1991 period with the GODAR project adding an additional 1,050,509 casts. Most of the data acquired are from the post-World War II period when oceanographic expeditions expanded greatly in number. Similar figures are available for data from the other profile types maintained at NODC/WDC (Figures 2-4). The GODAR project resulted in the acquisition of data from 145,167 High Resolution Conductivity-Temperature-depth (CTD) casts for the 1967-1990 period compared to the 66,451 casts held by NODC in 1991; 610,345 Expendable Bathythermograph (XBT) temperature profiles for the 1967-1990 period compared to the 704,348 profiles held by NODC in 1991; 1,148,947 Mechanical Bathythermograph (MBT) temperature profiles for the 1941-1990 period compared to the 1,219,655 profiles held by NODC in 1991.

The global historical database of temperature data has increased by approximately 3.5 million profiles as a result of GODAR, and the GODAR workshops have identified on the order of another 1.5 million profiles that are in manuscript form. Thus it is clear that the international scientific

community now has access to a much more comprehensive ocean profile database than previously thought possible and that there will be additional historical data added in the future.

Figure 5 is an example of one of the data sets acquired as part of the GODAR project. It shows a submission by Japan of data from approximately 270,000 ocean station data profiles. These profiles represent data taken by the Japanese Fisheries Agency and Japanese Prefectural Fisheries Experimental Stations.

Data gathered as a result of the GODAR project have been made available on CD-ROM as well as the Internet. During the past eleven years NODC/WDC has published a series of global ocean profile-plankton databases. The *World Ocean Atlas 1994*, *World Ocean Database 1998*, and *World Ocean Database 2001* series each included all data acquired as part of the GODAR project. These databases also include real-time and delayed-mode data acquired through regular international exchange and special projects such as the Global Temperature-Salinity Profile Project (IOC, 1998) and modern data not distributed via the Internet which have been acquired as part of another IOC sponsored project known as the World Ocean Database (WOD) Project that we describe in the next section.

8. THE *WORLD OCEAN DATABASE* (WOD) PROJECT

In 2001 the IOC initiated a *World Ocean Database* project. The purposes of this project are to encourage the exchange of modern ocean profile-plankton data, develop regional and global databases and atlases, and to develop quality-control procedures for ocean profile-plankton data.

Modern data (post-1990) have been acquired as a result of this project and data from new instrument types have been added to the data available as part of the World Ocean Database series. Table 2 shows the progression of both the amount of "classical" data (*e.g.*, Ocean Station Data (OSD), High Resolution Conductivity-Temperature-Depth (HCTD), Expendable Bathythermograph (XBT) and Mechanical Bathythermograph (MBT)) available from NODC/WDC and the addition of data from new instrument types. Plankton data as well as data from moored buoys, drifting buoys, profiling floats, undulating ocean recorders (*e.g.*, towed CTDs), and instrumented marine mammals (Boehlert *et al.*, 2001) are now included in the *World Ocean Database 2001*. This includes many upper ocean temperature profiles that will help determine interannual-to-decadal variability of upper ocean thermal structure. For example Lysne and Deser (2002) compare the variability of the upper ocean thermal structure from an ocean general circulation model simulation of the Pacific Ocean with analyses of historical upper ocean thermal data. Figure 6 shows a time history of the number of ocean temperature profiles available from NODC/WDC as a function of time and includes the results of all projects described in this article.

As the size of the integrated global and regional databases increase it becomes feasible to begin characterizing the frequency distributions of ocean variables which is important for development of statistical quality control procedures. The state of quality control of historical oceanographic and synoptic ocean data needs to be improved. There has been little work done on this subject with the exceptions of work by Oguma and Nagata (2002), Levitus and Sychev (2002), and Oguma et al. (2003).

Several regional atlases have been prepared and published under the auspices of the WOD project. The subject of most of these deals with the oceanographic climate and variability of the subarctic seas (Matishov *et al.*, 1998; Matishov *et al.*, 2000; Sapohznikov *et al.* 2001; Berger *et. al.*, 2003, Markhaseva *et al*., 2002; Matishov *et al*., 2004).

9. BIOLOGICAL DATA

NODC/WDC has received many requests for ocean biological data during the past decade. These requests are to support specific missions such as missions to estimate sea surface chlorophyll from space-based platforms (*e.g*., SeaWIFS), determination of ocean biogeochemical cycles, and studies of marine biodiversity. Prior to 1998, NODC integrated databases did not include chlorophyll data nor plankton data. Data for these variables are now included in the *World Ocean Database* series. Approximately 132,000 OSD casts now contain chlorophyll profiles and there are 44,000 surface observations of chlorophyll from the French Ship-of-Opportunity Program, SURTROPAC (Dandonneau, 1992). The geographical distributions of these data are shown in Figure 7. The sea surface chlorophyll data have been used as internal boundary conditions for the analysis of surface chlorophyll estimates from the NASA Coastal Zone Color Scanner and SeaWIFS projects (Gregg and Conkright, 2002). Their results indicate that there are statistically significant gyre and basin scale changes in the distribution of plankton in the world ocean.

WOD01 contains over 106,000 plankton biomass observations, and over 700,000 taxonomic observations. As work continues to expand the plankton database, attention is focused on metadata requirements, quality assurance, and methods for incorporating data from different sampling techniques. In co-operation with numerous scientists and international groups (NOAA, 1997), NODC/WDC has identified key metadata requirements necessary for usefulness of plankton data, and is developing quality control and analytical techniques for these data. Figure 8 shows the state of the plankton recovery effort. More detailed information about the biological data can be found in the works by O'Brien *et al.* (2002a), O'Brien *et al.* (2002b), and Conkright *et al.* (2002b).

10. SEA LEVEL DATA

As noted above, since 1999 sea level data have been included in the GODAR project as part of the Global Sea Level Observing System (GLOSS). Substantial progress has occurred with respect to the location of, and digitization of, historical sea level data. Results of these efforts (and earlier efforts by Dr. Mark Luther) have recently been described by Caldwell (2003) which we summarize briefly. The goal of this GODAR sub-project has been to locate and digitize historical hourly records of sea level data measured by tide gauges. The hourly data rescued to date includes 372 years of data from 34 locations in 15 countries. The Japan Oceanographic Data Center has contributed data from tide gauges in the western Pacific however the majority of data are from countries in South and Central America. Many of these countries have contributed data and many data are from the archives of the former Coast and Geodetic Survey which is now part of the NOAA National Ocean Service.

11. SURFACE-ONLY MARINE OBSERVATIONS

Although not a formal part of the GODAR project some data centers have digitized surface marine observations from merchant ships and contributed them as part of the GODAR project. These data have been sent to the groups responsible for constructing the Comprehensive-Ocean-Atmosphere-Data-Set (COADS) where they have been incorporated into this database. Figure 9 shows the distribution of more than 420,000 sets of Chinese surface marine observations from Chinese ships that were digitized and contributed to the GODAR project by the Peoples Republic of China NODC.

12. DECLASSIFICATION OF NAVAL DATA

Ocean observations are made by numerous navies of the world. Many of these countries routinely submit all or part of their data to the World data Center system. During the past several years the IOC has issued Circular Letters requesting the declassification of naval oceanographic data. Argentina, Turkey, and Russia have declassified and made available additional oceanographic data in response to the IOC request.

13. PROBLEMS IN BUILDING A GLOBAL OCEAN PROFILE-PLANKTON DATABASE

The *World Ocean Database* (WOD) is a global, comprehensive, integrated, scientifically quality-controlled ocean profile-plankton database with all data in one uniform format produced by NODC/WDC-Silver Spring. The WOD has replaced earlier NODC/WDC profile databases. The latest version of this database known as *World Ocean Database 2001* (WOD01) and is comprised of data from 112 countries, representing 489 institutes, with data gathered by 3057 platforms (ships, buoys...) made during 55,000 cruises. For this reason we characterize WOD as a heterogeneous database. Although exact definitions are not possible we characterize a “homogenous” database as being composed of data from a few sensors, platforms, *etc.* For example, data from several satellites measuring the same variables.

Many problems are encountered in developing such a database. These include:

a) incorrect data or metadata submitted;
b) lack of critical metadata;
c) improperly formatted data submitted;
d) data submitted in many different formats but with each version slightly different from other versions.

It would not be an exaggeration to state that nearly every data set we receive has some type of problem associated with it. This requires manual intervention during processing and so the development of integrated profile-plankton databases is relatively labor intensive. The ocean profile-plankton databases we deal with are relatively small in size (<20 Gb) but require substantial effort to develop. This effort is justified by the effort it costs to make the original measurements and

the scientific utility of these databases and products based on these data as we document in the following two sections.

We are not implying that a "heterogeneous" database is any less difficult to construct or maintain then a "homogeneous" database. We simply mean that the problems are different.

14. ECONOMIC VALUE OF RECOVERED DATA

The text of this section first appeared in print in the work by Levitus *et al.* (1998) and more recently by Conkright *et al.* (2002a). Oceanography is an observational science and it is not possible to replace historical data that have been lost. From this point of view, historical measurements of the ocean are priceless. However, in order to provide input to a "cost-benefit" analysis of the activities of oceanographic data centers and specialized data rescue projects, we can estimate the costs incurred if we wanted to resurvey the world ocean today, in the same manner as represented by the WOD01 Ocean Station Data (OSD) profile archive.

The computation we describe was first performed in 1982 by Mr. Rene Cuzon du Rest, of NODC. We use an average operating cost of $20,000 per day for a medium-sized U.S. research ship (NSF personal communication) with a capability to make two "deep" casts per day or 10 "shallow" casts per day. We define a "deep" cast as extending to a depth of more than 1000 m and a "shallow" cast as extending to less than 1000 m. This is an arbitrary definition but we are only trying to provide a crude estimate of replacement costs for this database. Using this definition, WOD01 contains 1,800,000 shallow casts so that the cost of the ship time to perform these measurements is approximately $3.6 billion. In addition WOD01 contains 323,000 profiles deeper than 1000 m depth, so the cost in ship time to make these "deep" measurements is approximately $3.2 billion. Thus, the total replacement cost of the OSD archive is about $6.8 billion, a figure based only on ship-time operating costs, not salaries for scientists or any other costs. As previously noted approximately 610,000 XBT profiles have been recovered as part of the GODAR project. Assuming a present day replacement cost of $40/profile this represents amount $24 million dollars in data recovered.

15. SCIENTIFIC UTILITY OF OCEAN PROFILE DATA

We often receive questions about the importance and utility of historical oceanographic profile data. To respond to such questions we present Figure 10 which shows the history of scientific citations for some NODC/WDC ocean profile databases and products based on these databases. Based on the number of citations it is very clear that ocean profile databases and products based on these databases have had an enormous impact on scientific research during the past twenty years and will continue to do so in the future.

16. SCIENTIFIC PROGRAM SUPPORT FOR DATA ARCHAEOLOGY AND RESCUE

Data archaeology and rescue efforts have received widespread support not only for ocean data but for many other geophysical data (WCRP, 1995; WCRP, 1998).

17. DATA AVAILABILITY AND ACCESS

As part of its commitment to the scientists, institutions, and countries that have made these oceanographic data available, the GODAR project through NODC/WDC has made all data available on CD-ROM as well as on-line via the Internet from the NODC/WDC website (www.nodc.noaa.gov). Beginning with *World Ocean Database 1998* all data have been made available on-line.

The World Ocean Database products come with software conversion routines so that users of software packages, databases, and programming languages such as MATLAB, IDL, PC-Surfer, C, and FORTRAN can access the data. In response to user requests, we have defined the WOD01 format to be as 'self-defining' as possible so as to eliminate, or at least minimize, the need for any structural changes to the format when new data types are added. All code tables, documentation, and software containing metadata are available on-line as well as on the CD-ROMs which are used to distribute the WOD series. When a new database is released (every 3-4 years) users can acquire the new database or simply acquire data for those ocean stations that have been added or modified since the previous release. In addition, as corrections are made to the database after a release of WOD, users can acquire any modified data several days after the end of every month. There is a "Help Desk" and "Frequently Asked Questions" for the database available on-line.

Recently enhanced selection software (WODSelect) allows users to access data by specifying geographic area, observation dates, instrument type, measured variables, deepest measurement, country, ship/platform, project name, and institute. Data are made available in a Comma-Separated-Values format. WODSelect supports the goals of the IOC and WDC data exchange systems and the United Nations Framework Convention on Climate Change to "promote and cooperate in the full, open and prompt exchange of relevant scientific, technological, technical, socio-economic and legal information related to the climate system and climate change".

18. EDUCATION

The *World Ocean Database 2001* has been used to produce objectively analyzed climatological fields of the variables contained in WOD01. This product is known as *World Ocean Atlas 2001*. The analyses are performed on a one-degree grid at thirty-three standard depth levels for the world ocean between the sea surface and 5500 m depth. All of these fields plus observed one-degree square statistics of the number of observations, mean, standard deviation, and standard error of the mean for each variable and compositing period have also been computed. All of these fields are available on-line as digital fields and in the form of color figures (approximately 44,000 color figures are available). This product is know as *World Ocean Atlas 2001 Figures.* Numerous colleagues have informed us that these figures have proven valuable in teaching oceanography.

19. FUTURE WORK

Substantial amounts of oceanographic data have been identified as part of the GODAR and WOD projects that still need to be digitized and or transferred from aging electronic media to fresher media and incorporated into regional and global databases. Efforts will continue to digitize these data and make them available in future databases. The outlook for continued international cooperation is excellent. For example the Japan Oceanographic Data Center is in the process of digitizing data from approximately 10,000 Ocean Station Data casts for the WWII and pre-WWII periods. Data for additional variables such as tracers will be included.

20. ACKNOWLEDGMENTS

We acknowledge the contribution of many individuals, organizations, and countries to the projects described in this document. Scientists and technicians studying the world ocean have undertaken the task of collecting and processing the data. Oceanographic data centers and marine institutes have been particularly helpful through their participation in GODAR and WOD related projects. The staff of the NODC Ocean Climate Laboratory has been responsible for the construction of the *World Ocean Database* and *World Ocean Atlas* series. Dr. Iouri Oliouinine of the IOC was instrumental in guiding the senior author of this paper in the establishment and managing an international project such as GODAR. Mr. Peter Pissierssens has provided outstanding support as Dr. Oliouinine's replacement at the IOC. Dr. Ferris Webster provided support from the inception of the GODAR project. Mr. Greg Withee provided critical management support of the GODAR project, first as NODC director and then in other NESDIS management positions. Dr. John Knauss as NOAA Administrator was instrumental in establishing the NOAA ESDIM program which along with the NOAA Climate and Global Change Program provided, and continues to provide, financial support for data archaeology and rescue activities. The NOAA Climate and Global Change Program, the NOAA Earth Science Data and Information System Management Program (ESDIM), the NOAA Environmental Data Rescue Program, and the NOAA Climate Database Modernization Program have supported the work of the GODAR and World Ocean Database projects. NASA has contributed to the development of enhanced upper ocean thermal data sets. The European Community supported several regional GODAR meetings and Mediterranean data archaeology and rescue through its MODB, MEDATLAS and MEDAR/MEDATLAS II projects (contracts MAS2-CT93-0075-BE, MAS2-CT93-0074, MAS3-CT98-174 & ERBIC20-CT98-0103.

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Meeting Title	Location	Date	*IOC Workshop Report No.
IOC-CEC-ICSU-ICES Regional Workshop for Member States of Eastern and Northern Europe (Global Oceanographic and Data Archeology Rescue [GODAR] Project)	Obninsk, Russia World Data Center-B for Oceanography	May 17-20, 1993	IOC Workshop Report No. 88
IOC-SOA-NOAA Regional Workshop for Member States of the Western Pacific-GODAR-II (Global Oceanographic and Data Archeology Rescue (GODAR) Project)	Tianjin, China World Data Center-D for Oceanography	March 8-11, 1994	IOC Workshop Report No. 100
IOC-ICSU-NIO-NOAA Regional Workshop for Member States of the Western Pacific-GODAR-III (Global Oceanographic and Data Archeology Rescue Project)	Dona Paula, India National Institute of Oceanography	December 6-9, 1994	IOC Workshop Report No. 107
IOC-ICSU-CEC Regional Workshop for member States of the Mediterranean-GODAR-IV (Global Oceanographic and Data Archeology Rescue Project)	Valletta, Malta Foundation for International Studies, U. of Malta	April 25-28, 1995	IOC Workshop Report No. 110
IOC-ICSU-NOAA Regional Workshop for Member States of South America-GODAR V (Global Oceanographic and Data Archeology Rescue Project)	Cartagena, Columbia	October 8-11, 1996	IOC Workshop Report No. 127
IOC-ICSU Regional Workshop for member States of western Africa-GODAR VI (Global Oceanographic and Data Archeology Rescue Project)	Accra, Ghana	April 22-25, 1997	IOC Workshop Report No. 136
International GODAR Review Meeting	Silver Spring, Maryland	July 1999	IOC Workshop Report No.

* Workshop reports are available from : Intergovernmental Oceanographic Commission - UNESCO, 1 rue Miollis, 75732 Paris Cedex 15, France

Table 1. Summary of GODAR meetings.

Data type	NODC 1974*	NODC 1991 Global Ocean T-S Profiles (CD-ROM)	WOA94	WOD98	WOD01
Station data and low resolution C/STD profiles	425,000	783,912	1,194,407	1,373,440	2,121,042
High resolution CTD profiles	na	66,450	89,000	189,555	311,943
MBT profiles	775,000	980,377	1,922,170	2,077,200	2,376,206
XBT profiles	290,000	704,424	1,281,942	1,537,203	1,743,590
Moored Buoys	na	na	na	107,715	297,936
Drifting Buoys	na	na	na	na	50,549
Profiling Floats	na	na	na	na	22,637
Undulating Oceanographic Recorders	na	na	na	na	37,645
Autonomous Pinniped Bathythermograph	na	na	na	na	75,665
Total Stations	**1,490,000**	**2,535,163**	**4,487,519**	**5,285,113**	**7,037,213**
Surface only data** (cruises)	na	na	na	na	4,743**
Plankton Tows***	na	na	na	83,650	142,900

***Based on statistics in *Climatological Atlas of the World Ocean* (1982)

**** Surface data are represented differently in the database - all observations in a single cruise have been combined into one "station" with depth, value of variable measured and latitude, longitude, and Julian year-day to identify data and position of individual observations.

Table 2. Comparison of the number of stations by instrument type in WOD01 with previous NODC/WDC global ocean databases.

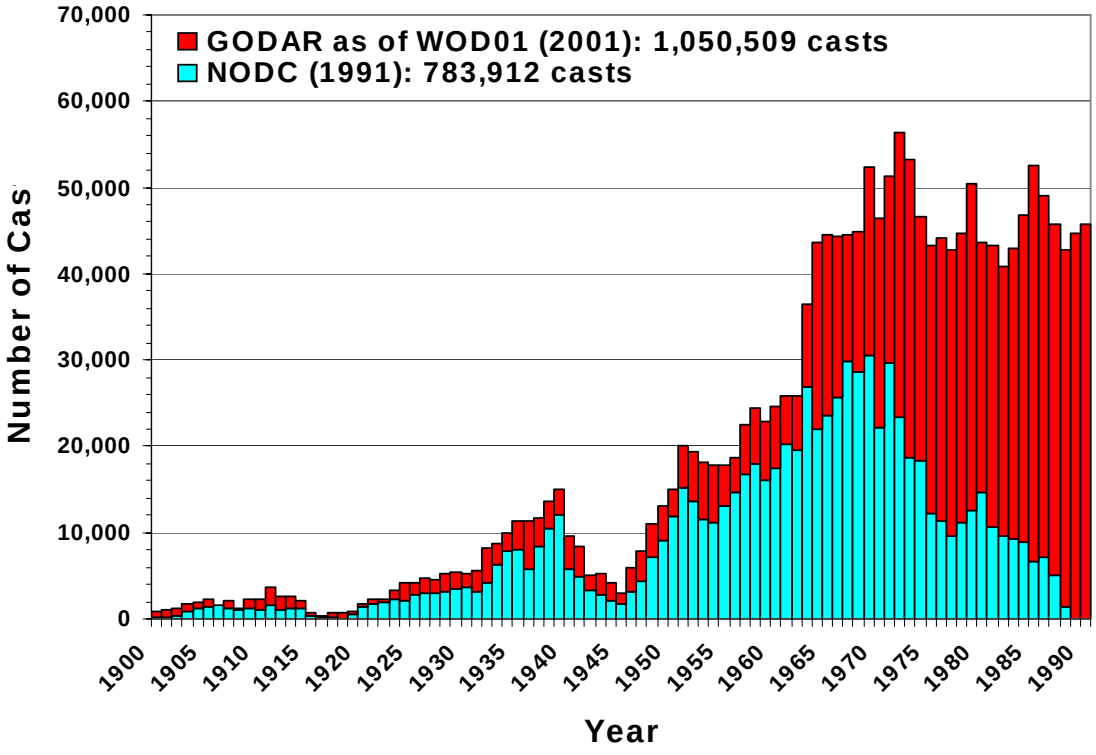

Figure 1. Ocean Station Data (OSD) recovered as part of the GODAR project for the pre-1991 period. Blue indicates the data held by NODC/WDC as of 1991 by individual years. Red indicates the data recovered by the GODAR project for these same years.

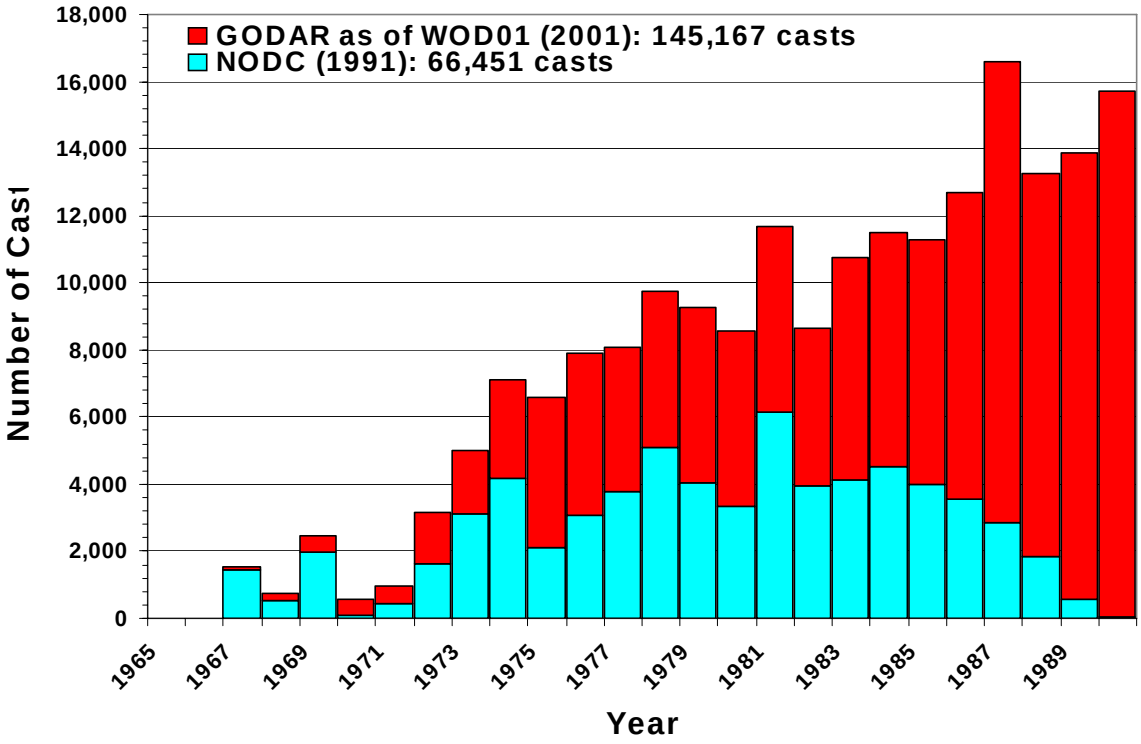

Figure 2. High Resolution Conductivity-Temperature-Depth cats (HCTD) recovered as part of the GODAR project for the pre-1991 period. Blue indicates the data held by NODC/WDC as of 1991 by individual years. Red indicates the data recovered by the GODAR project for these same years.

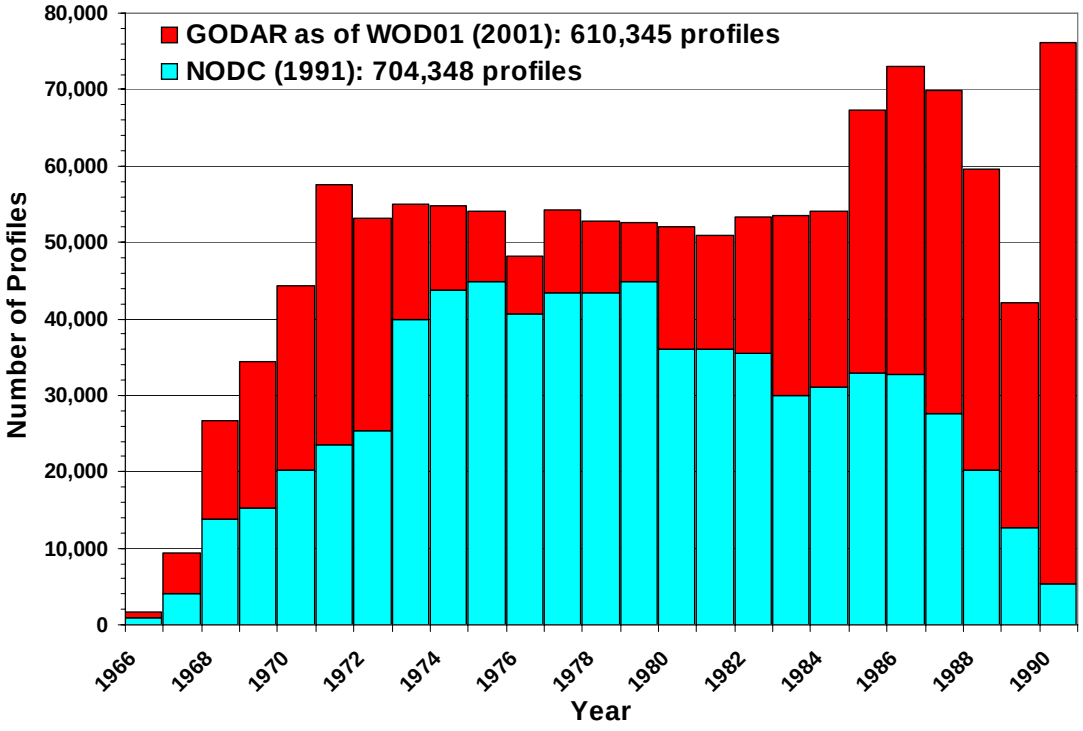

Figure 3. Expendable Bathythermograph profiles (XBT) recovered as part of the GODAR project for the pre-1991 period. Blue indicates the data held by NODC/WDC as of 1991 by individual years. Red indicates the data recovered by the GODAR project for these same years.

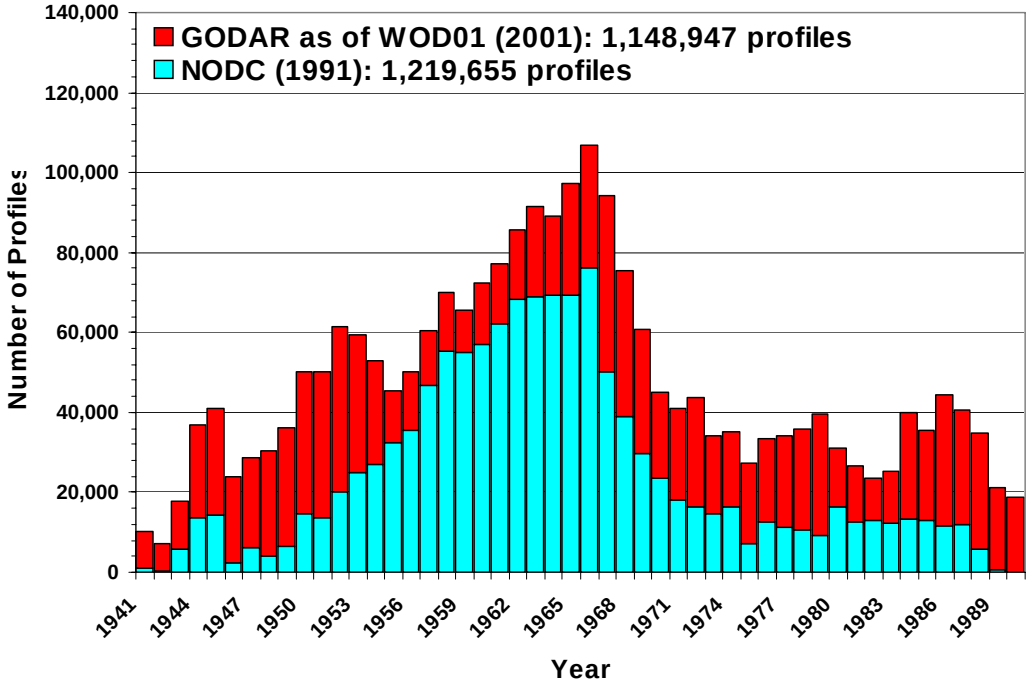

Figure 4. Mechanical Bathythermograph profiles (MBT) recovered as part of the GODAR project for the pre-1991 period. Blue indicates the data held by NODC/WDC as of 1991 by individual years. Red indicates the data recovered by the GODAR project for these same years.

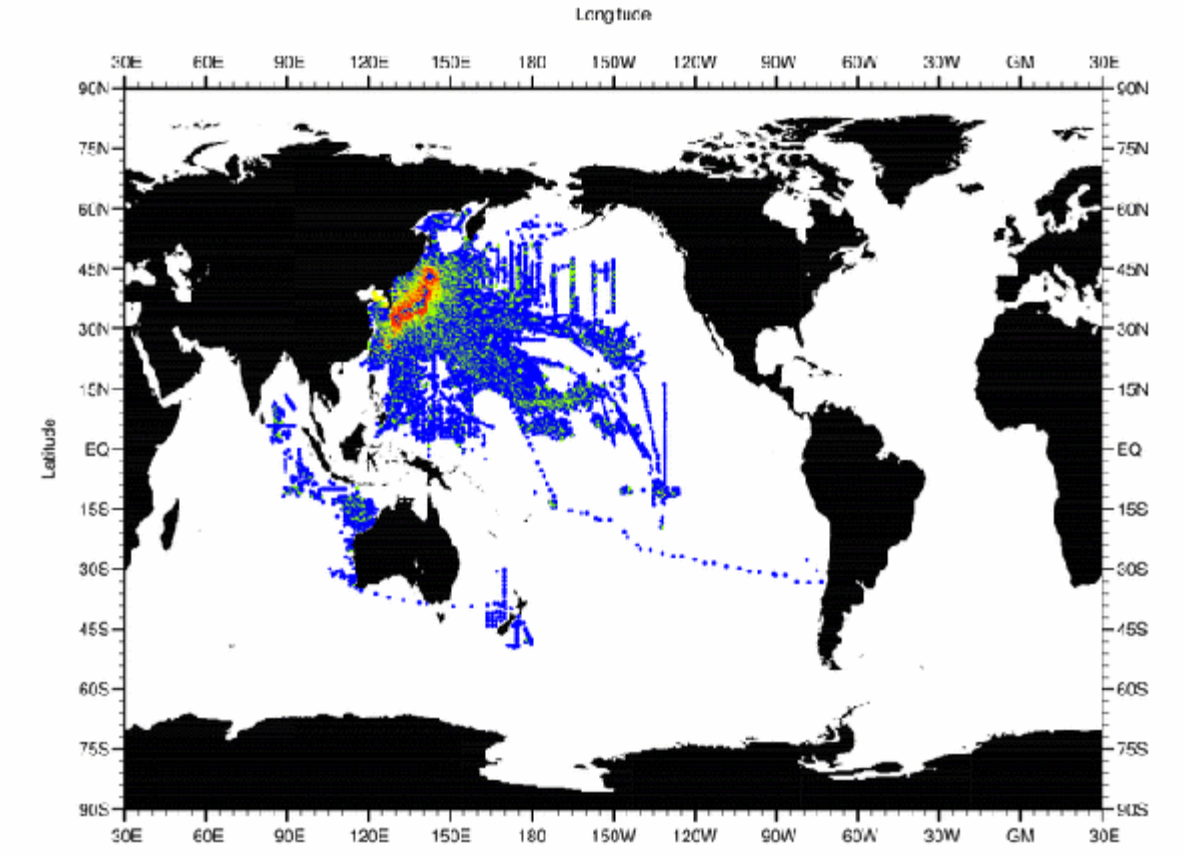

Figure 5. Japanese Ocean Station Data associated with the Japanese Fisheries Agency and Japanese Prefectural Fisheries Experimental Stations acquired as part of the GODAR project. A red dot indicates a one-degree square containing 41 or more surface observations, orange indicates 21-40, yellow indicates 6-20, green 2-5, and blue indicates a one-degree square containing 1 observation.

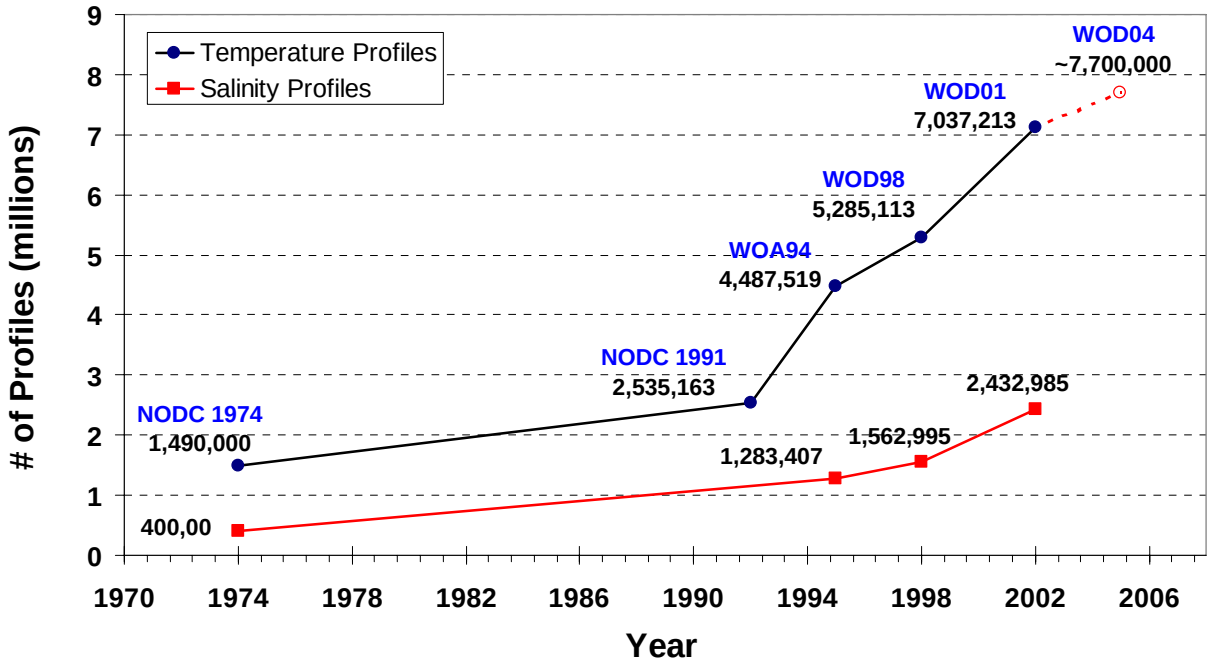

Figure 6. Growth of the NODC/WDC archive of temperature and salinity profiles as a function of time. The value for WOD04 is an estimate as of May 2005.

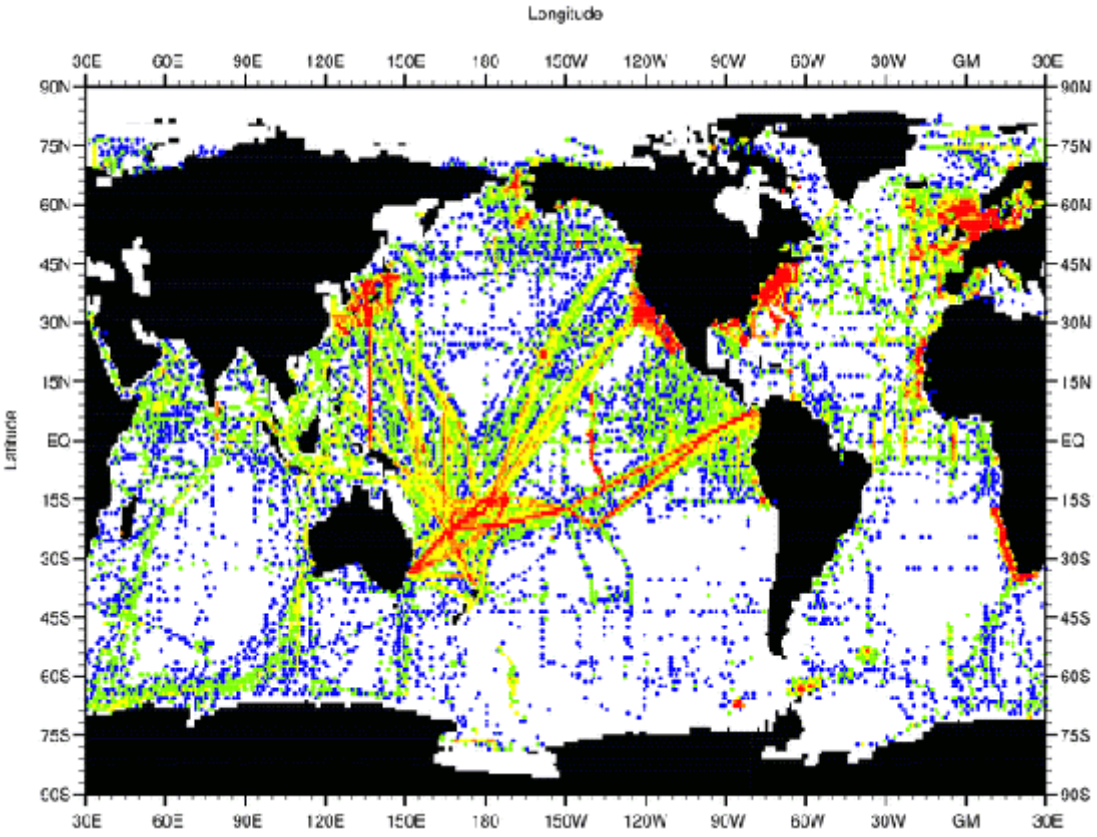

Figure 7. Distribution of chlorophyll profile data recovered by the GODAR project and surface-only chlorophyll data. Data made available by the French Ship-of Opportunity program (SURTROPAC). A red dot indicates a one-degree square containing 41 or more surface chlorophyll observations, orange indicates 21-40, yellow indicates 6-20, green 2-5, and blue indicates a one-degree square containing 1 observation.

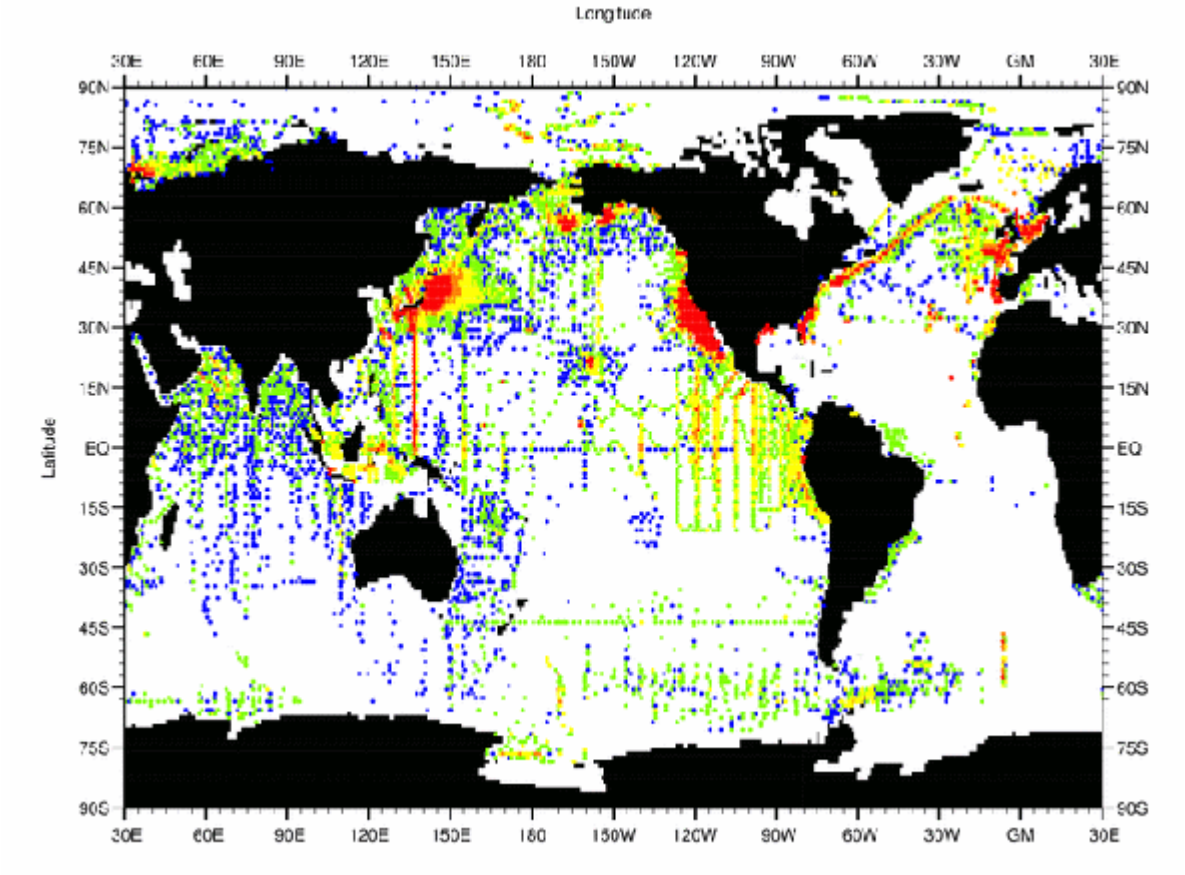

Figure 8. Distribution of plankton tows recovered by the GODAR project. A red dot indicates a one-degree square containing 41 or more plankton tows observations, orange indicates 21-40, yellow indicates 6-20, green 2-5, and blue indicates a one-degree square containing 1 tow.

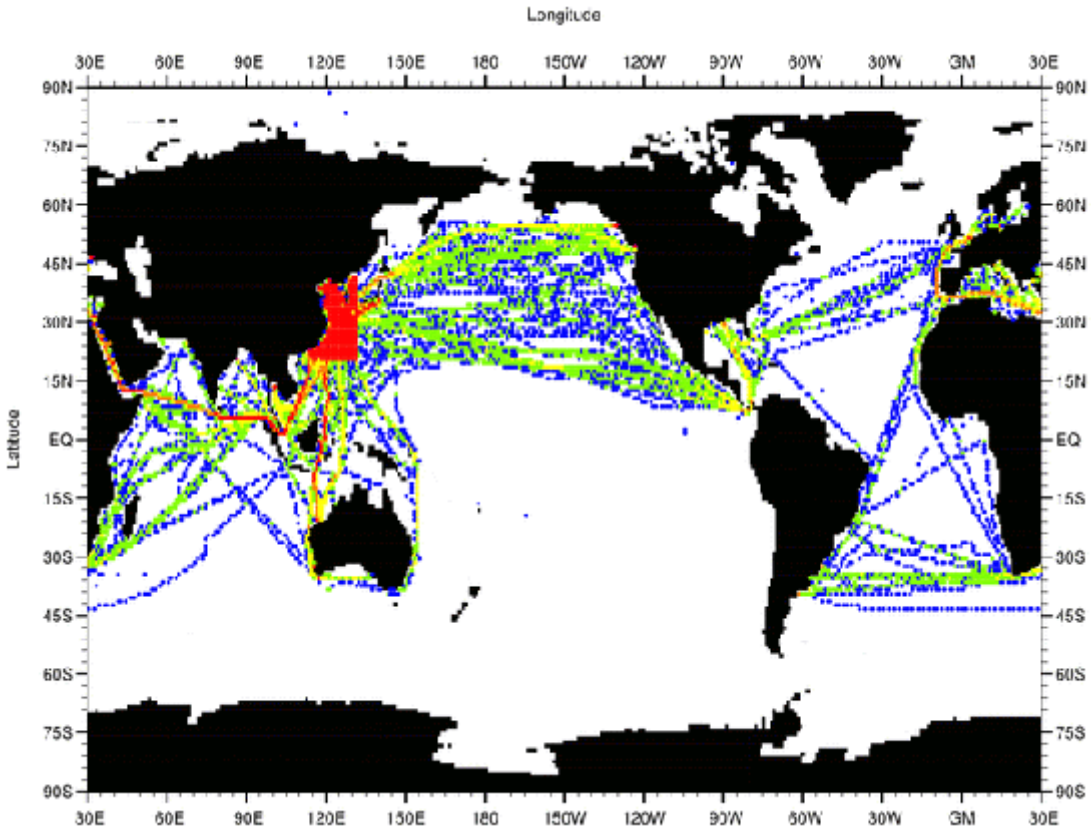

Figure 9. Distribution of surface marine observations made by People's Republic of China merchant ships contributed to the GODAR project. A red dot indicates a one-degree square containing 41 or more sets of observations, orange indicates 21-40, yellow indicates 6-20, green 2-5, and blue indicates a one-degree square containing 1 set of observations.

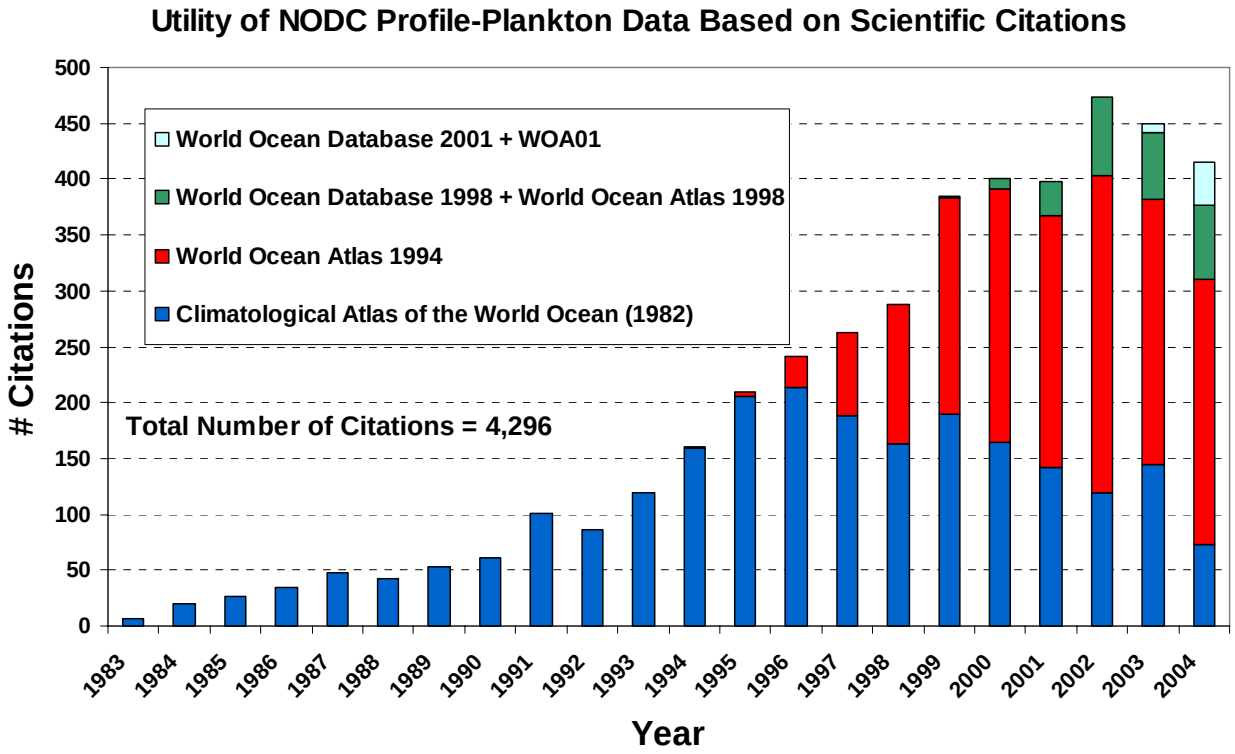

Figure 10. The utility of the NODC/WDC ocean profile-plankton archive as indicated by scientific citations of the databases and products generated based on these databases.

NOAA SCIENTIFIC AND TECHNICAL PUBLICATIONS

The National Oceanic and Atmospheric Administration **was established as part of the Department of Commerce on October 3, 1970. The mission responsibilities of NOAA are to assess the socioeconomic impact of natural and technological changes in the environment and to monitor and predict the state of the solid Earth, the oceans and their living resources, the atmosphere, and the space environment of the Earth.**

The major components of NOAA regularly produce various types of scientific and technical information in the following kinds of publications:

PROFESSIONAL PAPERS – Important definitive research results, major techniques, and special investigations.

CONTRACT AND GRANT REPORTS – Reports prepared by contractors or grantees under NOAA sponsorship.

ATLAS – Presentation of analyzed data generally in the form of maps showing distribution of rainfall, chemical and physical conditions of oceans and atmosphere, distribution of fishes and marine mammals, ionospheric conditions, etc.

TECHNICAL SERVICE PUBLICATIONS – Reports containing data, observations, instructions, etc. A partial listing includes data serials; prediction and outlook periodicals; technical manuals, training papers, planning reports, and information serials; and miscellaneous technical publications.

TECHNICAL REPORTS – Journal quality with extensive details, mathematical developments, or data listings.

TECHNICAL MEMORANDUMS – Reports of preliminary, partial, or negative research or technology results, interim instructions, and the like.

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