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WORLD OCEAN DATABASE 2013

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

The oceanographic databases described by this atlas series expands on the *World Ocean Database 2009* (WOD09) product and its predecessors. We have expanded by including substantial amounts of both recent and historical data not previously available. Earlier NODC/WDC oceanographic databases, and products derived from these databases, have proven to be of great utility to the international oceanographic, climate research, and operational environmental forecasting communities. In particular, the objectively analyzed fields of temperature and salinity derived from these databases have been used in a variety of ways. These include use as boundary and/or initial conditions in numerical ocean circulation models, verification of numerical simulations of the ocean, as a form of "sea truth" for satellite measurements such as altimetric observations of sea surface height among others. Increasingly, nutrient fields are being used to initialize and/or verify biogeochemical models of the world ocean. In addition, NODC/WDC products are critical for support of international assessment programs such as the Intergovernmental Program on Climate Change (IPCC) of the United Nations.

It is well known that the amounts of carbon dioxide in the earth's atmosphere will most likely double this century compared to the CO_2 level that occurred at the beginning of the Industrial Revolution. It is necessary that the scientific community has access to the most complete historical oceanographic databases possible in order to study climate change and variability, ecosystem response to climate change, and for other scientific and environmental problems. Data gathered at great expense should be available for future use

In the acknowledgment section of this publication we have expressed our view that creation of global ocean databases is only possible through the cooperation of scientists, data managers, and scientific administrators throughout the international community. In addition, I thank my colleagues at the Ocean Climate Laboratory (OCL) of NODC for their dedication to the project leading to publication of this atlas series. Their commitment has made this database possible. It is my belief that the development and management of national and international oceanographic data archives is best performed by scientists who are actively working with the data.

The production of oceanographic databases is a major undertaking. Such work is due to the input of many individuals and organizations. We have tried to structure the data sets in such a way as to encourage feedback from experts who have knowledge that can improve the data and metadata contents of the database. It is only with such feedback that high-quality global ocean databases can be prepared. Just as with scientific theories and numerical models of the ocean and atmosphere, the development of global ocean databases is not carried out in one giant step, but proceeds in an incremental fashion.

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September, 2013

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This work was made possible by a grant from the NOAA Climate and Global Change Program which enabled the establishment of a research group, the OCL, at the National Oceanographic Data Center. The purpose of the OCL is to prepare research quality oceanographic databases, as well as to compute objective analyses of, and diagnostic studies based on, these databases.

The international exchange of oceanographic data occurs between countries, under the aegis of the International Data and Information Exchange Committee (IODE) of the Intergovernmental Oceanographic Commission (IOC) and the International Council for Exploration of the Sea. Data is exchanged on a non-governmental basis under the aegis of the International Council of Science (ICSU) which operates the World Data Center System. The data made available as part of this atlas include data acquired as a result of the IODE/IOC Global Oceanographic Data Archaeology and Rescue (GODAR) project. At NODC/WDC, data archaeology and rescue projects have been supported with funding from the NOAA Environmental Science Data and Information Management (ESDIM) Program and NOAA Climate and Global Change Program. Support for some of the regional IOC/GODAR meetings was provided by the MAST program of the European Union (EU). Also, the EU MAST program supported the MEDAR/MEDATLAS project which collected, processed, and distributed data for the Mediterranean Sea which are included in WOD13. The NATO sponsored TU-Black Sea project resulted in substantial amounts of data that have been incorporated into this atlas.

We acknowledge the scientists, technicians, and programmers who have submitted data to national and regional data centers as well as the managers and staff at the various data centers. Our database allows for the storage of metadata including information about Principal Investigators to recognize their efforts.

We thank Charlotte Sazama for her assistance in locating historical and recent data for inclusion in this database. John Relph provided outstanding help in advising on web security for the online version of this atlas and database. The OCL acknowledges the help received over the last several years from colleagues in other NODC divisions.

The OCL expresses thanks to those who provided comments and helped develop an improved *World Ocean Database 2013* (WOD13) product. Any errors in WOD13 are the responsibility of the Ocean Climate Laboratory.

A special acknowledgement to Syd Levitus, who retired as head of the Ocean Climate Laboratory in June of this year. His dedication to preserving ocean data, careful quality control, and public dissemination of the data has inspired the OCL staff and spurred research and data projects around the world. WOD13 is his last contribution as head of the OCL, although he will continue his oceanographic research. His leadership will be greatly missed.

CHAPTER 1: INTRODUCTION

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ABSTRACT

This atlas describes a collection of scientifically quality-controlled ocean profile and plankton data that includes measurements of temperature, salinity, oxygen, phosphate, nitrate, silicate, chlorophyll, alkalinity, pH, pCO_2, TCO_2, Tritium, Δ^{13}Carbon, Δ^{14}Carbon, Δ^{18}Oxygen, Freons, Helium, Δ^{3}Helium, Neon, and plankton. A discussion of data sources is provided.

1.1. INTRODUCTION

1.1.1. History

The World Ocean Atlas 1994 (WOA94) represented the first database and analysis product of the National Oceanographic Data Center (NODC) Ocean Climate Laboratory (OCL). WOA94 included vertical profiles of six variables including temperature, salinity, oxygen, phosphate, nitrate, and silicate as well as objective analyses of these variables at standard depth levels. World Ocean Database 1998 (WOD98) updated WOA94 to include additional data for these six variables as well as data for additional variables such as chlorophyll, nitrite, pH, alkalinity and plankton as well as high-resolution CTD (conductivity-temperature-depth) and high-resolution XBT (expendable bathythermograph) profiles. Products derived from this database, such as objective analyses of the variables that comprise WOD98 were made available as a separate atlas and CD-ROM series entitled World Ocean Atlas 1998 (WOA98). World Ocean Database 2001 (WOD01) included data from new instrument types such as profiling floats, Undulating Ocean Recorders (e.g., towed CTDs), and Autonomous Pinniped Bathythermographs (instrumented Elephant Seals) as well as additional data for existing instrument types. World Ocean Database 2005 (WOD05) contained data from new variables (tracers) and from one new instrument (gliders). World Ocean Database 2009 (WOD09) continued to add historical and recent ocean profile data, with the new wrinkle that data were updated online every three months. These updates included preliminary quality control, while the release of WOD09 contained the final quality control, which included manual as well as automated steps.

This new release is known as World Ocean Database 2013 (WOD13) and contains a substantial amount of historical and recent data not previously available as part of the fully quality-controlled WOD series with final quality control flags included. For WOD13, the number of standard levels was increased from 40 to 138 to provide finer vertical resolution. As with our previous work, users can obtain the latest information on WOD013 (e.g. Errata sheet, Frequently Asked Questions and Updates) via the NODC Home Page, (click on World Ocean Database). The purpose of this atlas is to describe the WOD13 database and show the historical distributions of profiles made using the various instrument types included in WOD13 as well as some specific variables that comprise WOD13. This provides users with basic information about the data in the historical ocean profile archives of NODC/WDC. In addition we point users to web sites that represent sources for some of the data sets included in WOD13.

In this atlas, "WDC" stands for the World Data Center for Oceanography, Silver Spring which is collocated with NODC. WDC was formerly known as "WDC-A for Oceanography". More information about the World Data Center System can be found here .

1.1.2. Goals for World Ocean Database 2013 (WOD13)

Our goal in developing and distributing WOD13 is to make available to anyone, without restriction, the most complete set of historical ocean profile data and plankton measurements possible in digital form along with ancillary metadata and quality control flags.

As with earlier versions of NODC/WDC databases, the data contained in WOD13 will find use in many different areas of oceanography, meteorology, and climatology. Whether studying the role of the ocean as part of the earth's climate system, conducting fisheries research, or managing marine resources, scientists and managers depend on observations of the marine environment in order to fulfill their mission. Oceanography is an observational science. Because of the importance of understanding climate variability and climate change, it is necessary to study the role of the ocean as part of the earth's climate system (IPCC, 1996; WCRP, 1995).

WOD13 is a product based on data submitted to NODC/WDC by individual scientists and scientific teams as well as institutional, national, and regional data centers. A major contribution of NODC/WDC to the field of oceanography has been to provide centralized databases where all data and metadata are in the same format. This has allowed investigators such as Wyrtki (1971) and Levitus (1982) to construct atlases that have proven to be of great utility to the scientific research and the operational forecasting communities.

1.1.3. Data Organization

Data in WOD13 are organized using the following operational definitions:

Profile: A set of measurements for a single variable (temperature, salinity, etc.) at discrete depths taken as an instrument is being dropped or raised vertically in the water column. For surface-only data, the profile consists of measurements taken along a horizontal path. For moored buoys and drifting buoys, the instrument does not move vertically in the water column, so a profile is a discrete set of concurrent measurements from the instruments placed at different depths on a wire attached to the buoy.

Cast: A set of one or more profiles taken concurrently or nearly concurrently. Meteorological and other ocean data, e.g. Secchi disk data, are also included in a cast if measurements were taken concurrently with the profile(s). Observations and measurements of plankton from net-tows are included if taken concurrently or in close time proximity to profiles. If there are no profiles in close proximity, a net-tow by itself will constitute a cast. Each cast in the WOD13 is assigned a unique cast number. If the cast is subsequently replaced by higher quality data, the unique cast number is inherited by them. If any alteration is made to a cast, this information is noted in comments to the monthly database update, referenced by the unique cast number. For surface-only data in dataset SUR, a cast is defined as a collection of concurrent surface measurements at discrete latitudes and longitudes over an entire cruise (see definition of cruise below). Latitude, longitude and Julian year-day values are included with each set of measured oceanographic variables.

Station: A particular geographic location at which one or more casts are taken.

Cruise: A set of stations is grouped together if they fit the "cruise" definition. A cruise is defined as a specific deployment of a single platform for the purposes of a coherent oceanographic investigation. For an oceanographic research vessel, this deployment is usually well-defined with a unique set of scientific investigators collecting data for a specific project or set of projects. In some cases different legs of a deployment with the same equipment and investigators are assigned different cruise numbers, as per the investigators designation. In the case when merchant ships-of-opportunity (SOO) are used for data collection, a cruise is usually defined as the time at sea between major port calls. Profiling floats, moored buoys, and drifting buoys are assigned the same cruise number for the life of the platform. For surface-only data in dataset SUR, a cast and cruise are the same, except for 27 cruises which were split into 2 casts each due to the large number of sets of measurement (> 24,000).

In WOD13, a cruise identifier consists of two parts, the country code and the unique cruise number. The unique cruise number is only unique with respect to the country code. The country code is usually assigned based on the flag of the data collecting ship. If the platform from which data were collected was not a ship, (e.g. a profiling float, drifting or moored buoy), the country of the primary investigator or institute which operates or releases the platform is used (See Johnson *et al.*, 2013; Appendix for a list of country codes. Note that under an international effort to standardize codes, WOD has switched from IODE country codes to ISO country codes.) For data for which no information on country is present, a country code of 99 is used. For data for which there is no way to identify a specific cruise, a cruise number of zero (0) is used.

All data grouped as cruise are listed under one unique country code/unique cruise number combination. It is possible to get all bottle, high-resolution Conductivity-Temperature-Depth (CTD), bathythermograph (BT), and towed-CTD data for a cruise using one unique cruise identifier. However, there are still cases for which BT data have a different cruise identifier. It is an ongoing project to match these BT data with the correct bottle and high-resolution CTD data.

Accession Number: A group of stations received and archived at the U.S. NODC. Each collection submitted to NODC is given a unique “accession number”. Using this number, a user can get an exact copy of the original data sent to NODC as well as information about the data itself (i.e. metadata) from NODC through the Accession Tracking Database (ATDB). Cruises are not always subsets of accession numbers, as data from the same cruise may have multiple accession numbers. Each cast has an associated accession number (with a few exceptions). If data from a cast is replaced by higher quality data, the accession number will reflect the new source of the data while the unique station number will remain unchanged. If a profile for a variable not previously stored with a station becomes available, the profile will be added to the existing station, and a variable-specific accession number will be added to the station to record the source of the new profile.

Dataset: All casts from similar instruments with similar resolution. For instance, all data acquired by bathythermographs (BTs) which are dropped over the side of a ship on a winch and recovered reside in the MBT dataset, all CTD data collected at high vertical depth resolution (relatively small depth increments) are stored in the CTD dataset. For convenience, each dataset is stored in a separate file in WOD13.

1.1.4. Datasets

The WOD13 datasets group together data acquired in a similar manner. So, bottle data and low vertical resolution CTD casts are grouped together since bottle casts often include temperature and salinity measurements from CTDs only at the depths at which bottles were tripped. High resolution CTD data are stored in a separate dataset because of their high volume. The low-resolution version of the data is often available as well, in casts which include bottle data. Cases where high and low-resolution CTD data are available in different datasets are identified in the data themselves.

The WOD13 datasets are briefly described below and in more details in followings chapters. A list of datasets in WOD13 is shown in Table 1.1.

The three-letter notation for each dataset is the abbreviation used for the naming of the output data files. Note that not every particular instrument used for data acquisition has a dedicated separate dataset to hold the data, and that the three-letter dataset notation does not always reflect all diversity of instrumentation used for gathering the data found in the dataset. More detailed data descriptions and relevant oceanographic information can be found in chapters 2-16 of this document, and in the bibliographies and references provided for each chapter. For a description of the instrument codes as well as for other codes embedded in the data format, see Johnson *et al.* (2013).

The WOD13 database includes oceanographic variables measured at "observed" depth levels as well as interpolated to a set of 138 "standard" depth levels. All climatic fields in the atlas are produced based on "standard" depth levels data. Note that the 40 standard depth levels used in previous versions of WOD are all among the 138 standard depth levels used in WOD13, to provide continuity.

Table 1.1. Instrument types in the WOD13

DATASET	SOURCE
OSD	Bottle, low-resolution Conductivity-Temperature-Depth (CTD), low-resolution XCTD data, and plankton data
CTD	High-resolution Conductivity-Temperature-Depth (CTD) data and high-resolution XCTD data
MBT	Mechanical Bathythermograph (MBT) data, DBT, micro-BT
XBT	Expendable (XBT) data
SUR	Surface only data (bucket, thermosalinograph)
APB	Autonomous Pinniped Bathythermograph - Time-Temperature-Depth recorders attached to elephant seals
MRB	Moored buoy data from TAO (Tropical Atmosphere-Ocean), PIRATA (moored array in the tropical Atlantic), MARNET, and TRITON (Japan-JAMSTEC)
PFL	Profiling float data
DRB	Drifting buoy data from surface drifting buoys with thermistor chains
UOR	Undulating Oceanographic Recorder data from a Conductivity/Temperature/Depth probe mounted on a towed undulating vehicle
GLD	Glider data

OSD Dataset – Ocean Station Data, low-resolution CTD, low-resolution XCTD, plankton tows

i) Ocean Station Data

Ocean Station Data has historically referred to measurements made from a stationary research ship using reversing thermometers and water samples collected from bottles tripped at depths of interest in the water column. The water samples are analyzed to measure variables, including water salinity, oxygen, nutrients (phosphate, silicate, nitrate plus nitrite), chlorophyll, pCO_2, TCO_2, and tracers (Tritium, Δ^{13}Carbon, Δ^{14}Carbon, Freons, Helium, Δ^{3}Helium, Δ^{18}Oxygen, and Neon) concentrations. The two most commonly used bottle types are the Nansen and Niskin (see Chapter 2.)

ii) Low-resolution CTD data

Conductivity-Temperature-Depth (CTD) instruments are a combination of a pressure sensor (measured pressure is converted to depth), a resistance temperature measurement device (usually a platinum thermometer), and a conductivity sensor used to estimate salinity. CTDs are usually mounted on a metal frame and lowered through the water column suspended from a cable. The frame is often used to hang bottles for collecting water samples. Low-resolution here refers to a limited number of temperature and/or salinity measurements made along the vertical profile. Usually, but not always, these measurements are recorded at the depths at which bottles are tripped to collect water samples. This dataset also include data from the older Salinity-Temperature-Depth

(STD) instruments - the precursor to the CTD. About 5.6% of all data in the OSD dataset are listed as containing temperature and/or salinity data measured by CTD/STD (see Chapter 3.)

iii) Low-resolution Expendable CTD (see description below under CTD, Chapter 5.)

Plankton tow – net tows or bottle casts from which plankton counts and/or biomass observations were taken (see Chapter 14.)

CTD Dataset – High-resolution CTD (CTDs and XCTDs recorded at high depth/pressure frequency)

i) High-resolution Conductivity-Temperature-Depth (CTD) data

High-resolution CTD data consist of temperature and salinity profiles recorded at high frequency with respect to depth or pressure. These records are usually binned (averaged) in 1 to 5m depth interval mean values by the data submitter, although some means are calculated using smaller depth intervals. Often the high-resolution CTD cast has a low-resolution counterpart in the OSD dataset with accompanying measurements from bottle samples. In these cases, both the high-resolution CTD and the OSD data have a marker identifying these data as coming from the same station ('hi-res pair' - second header code # 13 in the WOD native format). High-resolution measurements of dissolved oxygen, chlorophyll (from a fluorometer), and beam attenuation coefficient (BAC) from a transmissometer are also included in this dataset when available. Note that in many cases the dissolved oxygen and chlorophyll data are uncalibrated and not of high quality. Information on whether these variables are calibrated is not usually supplied by the data submitter (see Chapter 3.)

ii) High-resolution Expendable Conductivity-Temperature-Depth (XCTD) data

Expendable Conductivity-Temperature-Depth (XCTD) probes are similar to XBT instruments (described below) - they are a torpedo-shaped device attached to a spool of copper wire. Along with the thermistor found in the XBT, a conductivity sensor is used to estimate salinity. XCTD instruments are produced by Sippican, Inc. (Sippican, U.S.A.) and The Tsurumi Seiki Co., Ltd. (TSK, Japan). The standard XCTD has a manufacturer-specific drop-rate equation error (Johnson, 1995; Mizuno and Watanabe, 1998, Kizu *et al.*, 2008). Depth corrections for both manufacturers are incorporated in the standard level dataset. Air dropped and submarine discharged XCTDs have no known drop-rate problems. XCTD casts make up less than 1% of the CTD dataset. Data from XCTD instruments are included in the CTD dataset (see Chapter 5.)

XBT Dataset – low and high-resolution Expendable Bathythermographs

Expendable Bathythermograph (XBT) probes are torpedo-shaped devices attached to a spool of copper wire. The instrument is launched over the side of a moving ship, from an airplane, or from a submarine. Temperature is estimated by measurements of the resistance in a semi-conductor (called a thermistor), The information is sent back to the command unit for recording over the copper wire. Depth is calculated as a function of time since launch using a manufacturer-supplied equation. When the wire has unspooled, the copper wire breaks. XBTs have been deployed since 1966. There are currently two manufacturers of XBTs: Sippican in the United States, and TSK in Japan. (A third manufacturer, Sparton, is no longer in business.)

Seaver and Kuleshov (1982) and Heinmiller *et al.* (1983) reported a systematic error in the recorded depths for XBT drops. Hanawa *et al.* (1995) published depth corrections for XBT types T-4, T-6, and T-7. Kizu *et al.* (2005) published revised drop-rate equations for T-5 XBTs manufactured by TSK (T5 probes manufactured by Sippican do not have a drop-rate problem). More recently, there has been a great deal of research into year-dependent fall-rate and temperature biases, spurred by a paper by Gourestki and Koltermann (2007).For more information on these studies, please see Chapter 4 and this webpage on XBT fall-rate bias.

The recommended practice for exchanging and archiving XBT data (UNESCO, 1994) states that these data should not be corrected or altered so as to provide a known base for a user to then apply necessary depth correction. In 1996, both TSK and Sippican began distributing software which used the amended depth equation as the default. In the WOD13 XBT dataset, all data prior to January 1, 1996 are assumed to have depths as calculated with the original manufacturer's depth equation, unless otherwise noted, in keeping with established convention. For data taken on or after January 1, 1996 to the present, no assumption is made about the depth equation used. The data are marked as either using the original manufacturer's depth equation, the amended depth equation, or unknown depth equation, based on information provided by the data submitter. There are more than 78,000 XBT temperature profiles taken since January 1, 1996, for which no drop-rate equation information is available. The present database applies all listed corrections only during the interpolation to standard depth levels. The observed level XBT data are not altered in the released WOD13. However, users can obtain observed level XBT data with any of 11 published XBT corrections applied.

PFL Dataset – Profiling floats

Profiling floats are platforms drifting at a predetermined subsurface pressure level in the water column, rising to the surface at set time intervals. Pressure, temperature, salinity, and sometimes dissolved oxygen measurements taken on the ascent or previous descent are transmitted to the designated satellite. Most profiling floats are now operated as part of the Argo project (http://www.argo.ucsd.edu/). Profiling float data were taken mainly from the Global Ocean Data Assimilation Experiment (GODAE, http://www.usgodae.org/) server, with smaller contributions from WOCE and GTSPP (see Chapter 6.)

MBT Dataset – Mechanical Bathythermographs, Digital Bathythermographs (DBT), and Micro-bathythermographs (μBT).

i) Mechanical Bathythermographs

Mechanical Bathythermographs (MBT) were developed in their modern form around 1938 (Spilhaus, 1938). The instrument provides estimates of temperature as a function of depth in the upper ocean. Earlier versions of the instrument were limited to making measurements in the upper 140 m of the water column. The last U.S. version of this instrument reached a maximum depth of 295 m. MBTs recorded temperature as a function of depth by scratching a line on a smoked glass plate with a stylus. Pressure was determined from a pressure-sensitive tube known as a Bourdon tube. MBTs could be dropped from a ship moving at low speed. The accuracy of an MBT is about 0.3°C (see Chapter 7.)

ii) Digital Bathythermographs

A bathythermograph (developed in Japan) digitally records depth-temperature pairs as it is lowered in the water column. These instruments were used mostly by the Japanese in the mid-1970s and the 1980s in the Pacific Ocean, and less extensively by the Canadians in the North Pacific and North Atlantic (see Chapter 8.)

iii) Micro-Bathythermograph

Bathythermographs designed to record depth-temperature pairs at high vertical or temporal resolution (see Chapter 13.)

MRB Dataset – Moored buoys

Moored buoys are platforms which are anchored or otherwise stabilized to measure oceanographic and atmospheric data in a small area around a fixed geographic location. Measurement devices are suspended at subsurface levels from a chain attached to the buoy. Temperature is measured using thermistors. Salinity is measured using conductivity sensors similar to those in standard CTDs. The moored buoy dataset includes data from the Tropical Atmosphere-Ocean (TAO) buoy array (in the tropical Pacific), the TRITON buoy array (in the western tropical Pacific and Indian Ocean), the PIRATA buoy array (in the tropical Atlantic), MARNET buoys and light-ships (in the North Sea and the Baltic Sea). The data in WOD13 from the TAO, PIRATA, and most of the TRITON buoys are daily averages acquired from the TAO webpage. The remainder of the TRITON buoys, the MARNET buoys and light-ships data were acquired from the Global Temperature and Salinity Profile Project (GTSPP,) database (see Chapter 9.)

DRB Dataset – Drifting buoys

Drifting buoys are platforms which are advected by ocean currents. Drifters may be moved by either surface currents or at predetermined (usually shallow) depths. Drifting buoy data included in WOD13 were acquired from the GTSPP database, from the Japanese Arctic Buoy program archive, and from the Woods Hole Ice-Tethered Profiler program. The GTSPP data are from the subset of oceanic drifting buoys which have multiple subsurface temperature measurement devices (thermistors) suspended from a chain, the others are ice drifters with profilers attached. For more information on the ocean drifting buoys, See Project Nopp Drifters page or The GDP Drifter Data Assembly Center page (also see Chapter 10.)

UOR Dataset – Undulating Oceanographic Recorders (Towed CTDs)

Undulating Oceanographic Recorders are specific types of oceanographic vehicle which are towed behind a vessel while ascending and descending in the water column, recording temperature, salinity, and other variables at high vertical and horizontal resolution (see Chapter 11.)

APB Dataset – Autonomous Pinniped Bathythermographs

The Autonomous Pinniped Bathythermograph (APB) dataset contains data collected by elephant seals with instruments attached to their bodies. Temperature and salinity profile data are recorded when the animals dive to feed, and are transmitted via satellite upon surfacing (see Chapter 12.)

GLD Dataset - Gliders

The glider dataset contains data collected from reusable autonomous underwater vehicles (AUVs) designed to glide from the ocean surface to a programmed depth and back while measuring temperature, salinity, depth-averaged current, and other quantities along a sawtoothed trajectory through the water (see Chapter 15.)

SUR Dataset – Surface-only data

Surface-only data are either data collected using some type of bucket, or by ship-mounted thermosalinographs. These data are not the focus of WOD13. WOD includes only selected surface datasets which contained data from specific time periods and ocean areas which were not otherwise well covered by profile. Note that a "cast" here refers to an entire cruise of surface-only measurements (see Chapter 14.)

Meteorological and Sea state measurements data

All datasets in WOD13 are loaded with the meteorological and sea-state data collected during oceanographic casts and submitted as part of the metadata. This information (when available) is stored in secondary header of each station in WOD13. Detailed information on parameters, their counts, and their distribution among the datasets is shown in Table 1.2.

1.1.5. Economic and scientific justification for maintaining archives of historical oceanographic data: the value of stewardship

Oceanography is an observational science, and it is impossible 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 WOD13 Ocean Station Data (OSD) dataset.

The computation we describe was first performed in 1982 by Mr. Rene Cuzon du Rest, of NODC. We use an average operating cost estimate of $20,000 per day for a medium-sized U.S. research ship 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 coarse estimate of replacement costs for this database.

Using this definition, WOD13 contains approximately 2.8 million shallow casts so that the cost of the ship time to perform these measurements is approximately $5.6 billion. In addition, WOD13 contains 0.4 million profiles deeper than 1000 m depth, so the cost in ship time to make these deep measurements is approximately $4.2 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, technicians, or any other costs.

1.1.6. Data fusion

It is not uncommon in oceanography that measurements of different variables made from the same sea water samples are often maintained as separate databases by different principal investigators. In fact, data from the same oceanographic cast may be located at different institutions in different countries. From its inception, NODC recognized the importance of building oceanographic databases in which as much data from each station and each cruise as possible are placed into standard formats, accompanied by appropriate metadata that make the data useful to future generations of scientists. It was the existence of such databases that allowed the International *Indian Ocean Expedition Atlas* (Wyrtki, 1971) and *Climatological Atlas of the World Ocean* (Levitus, 1982) to be produced without the time-consuming, laborious task of gathering data from many different sources. Part of the development of WOD13 has been to expand this data fusion activity by increasing the number of variables that NODC/WDC makes available as part of standardized databases.

1.1.7. Distribution

WOD13 is distributed on-line in three formats: Climate and Forecast (CF) compliant netCDF, comma-separated value (csv), and legacy ASCII.

We have included software conversion routines so that users of software packages, databases, and programming languages such as MATLAB, IDL, GS-Surfer™, C, and FORTRAN can access the data in WOD13. In response to user requests, we have created the WOD13 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 or instrument types are added or increases in data precision occur. We do not envision any substantial changes to our present data format. Note that data are also available through WODselect in Climate and Forecast (CF) compliant netCDF and in a comma separted value (csv) format.

1.2. COMPARISON OF WOD13 WITH PREVIOUS GLOBAL OCEAN PROFILE DATABASES

Table 1.3 shows the amount of data available from different dataset types that were used in earlier global oceanographic analyses. During the past four years, the archives of historical oceanographic data have grown due to special data management and data observation projects (see Section 3.1), as well as due to normal submission by scientists and operational ocean monitoring programs. With the publication of WOD13, there are now approximately 12.8 million temperature profiles and 5.4 million salinity profiles (as well as other profile data and plankton data) available to the international research community in a common format with associated metadata and quality control flags. There has been a net increase of about 3 million temperature profiles, or 40%, since publication of *World Ocean Database 2009.*

1.3. DATA SOURCES

The oceanographic data that comprise WOD13 have been acquired through many sources and projects as well as from individual scientists. Some of the international data exchange organizations are described.

The International Council for the Exploration of the Sea (ICES) was established in 1902 and began collecting and distributing oceanographic data at that time.

The International Oceanographic Data Exchange (IODE) activities of the Intergovernmental Oceanographic Commission (IOC) have been responsible for the development of a network of National Oceanographic Data Centers in many countries. This network greatly facilitates international ocean data exchange. The IOC was established to support international oceanographic scientific needs including data exchange on an intergovernmental basis (UNESCO, 1979). Additional information about IODE can be found on their web page.

The World Data Center System was set up during the International Geophysical Year under the auspices of the International Council of Scientific Unions (ICSU, 1996; Rishbeth, 1991; Ruttenberg and Rishbeth, 1994). Contributions of data from scientists, oceanographic institutions, and countries have been sent to WDC for Oceanography, Silver Spring since its inception. There are two other World Data centers for Oceanography. WDC for Oceanography, Obninsk (formerly WDC-B for Oceanography) is located in Russia and WDC for Oceanography, Tianjin is located in China. Additional information about the World Data Center System can be found on the following web page, hosted by the National Geophysical Data Center located in Boulder, Colorado.

Table 1.2. Meteorological and Sea-state parameters stored in the WOD13.

Variables	**OSD**	**MBT**	**XBT**	**CTD**	**MRB**	**Total**
Bottom depth (m)	1,720,643	615,999	457,760	465,218		*3,259,620*
Water color (Forel-Ule color scale)	282,109	12,412	476	10,000		*304,997*
Secchi disk visibility depth (m)	446,737	12,150	452	14,944		*474,283*
Wave direction (WMO 0877)	360,534	30,005	30,587	6,822		*427,948*
Wave height (WMO 1555)	228,123	114,322	50,568	24,813		*417,826*
Sea state (WMO 3700)	570,029	478,174	53,969	29,851		*1,132,023*
Wind force (Beafort Scale)	604,615	14,444	3,264	3,945		*626,268*
Wave period (WMO 3155 or NODC 0378)	133,298	34,385	40,819	15,508		*224,010*
Wind direction (WMO 0877)	1,242,924	653,670	156,191	51,571	494,299	*2,621,216*
Wind speed (in knots)	607,232	673,374	157,098	56,132	499,361	*1,993,197*
Barometric pressure (millibar)	761,775	338,204	29,534	69,301		*1,198,814*
Dry bulb temperature (°C)	1,148,663	622,892	139,625	59,471	530,374	*2,501,025*
Wet bulb temperature (°C)	231,664	495,850	51,969	37,461		*816,944*
Weather condition (WMO 4501 and WMO 4677)	655,166	514,896	45,925	39,889		*1,255,876*
Cloud type (WMO 0500)	363,125	25,589	14,328	24,424		*427,466*
Cloud cover (WMO 2700)	706,432	524,097	28,596	42,779		*1,301,904*
Horizontal visibility (WMO 4300)	102,627	185,593	863	23,409		*312,492*
Reference/Sea surface temperature (°C)	23,384	1,171,291	117,066	391		*1,312,132*
Absolute air humidity ($g\ m^{-3}$)	95,550	1,768		677		*97,995*
Sea surface salinity		2,556	11,656			*14,214*

Table 1.3. Comparison of the amount of data in WOD13 with previous ocean databases.

Dataset	NODC (1974)[1]	NODC (1991)[2]	WOA94	WOD98	WOD01	WOD05	WOD09	WOD13
OSD [3]	425,000	783,912	1,194,407	1,373,440	2,121,042	2,258,437	2,541,298	3,115,552
CTD [4]	na	66,450	89,000	189,555	311,943	443,953	641,845	848,911
MBT [5]	775,000	980,377	1,922,170	2,077,200	2,376,206	2,421,940	2,426,749	2,425,607
XBT	290,000	704,424	1,281,942	1,537,203	1,743,590	1,930,413	2,104,490	2,211,863
MRB	na	na	na	107,715	297,936	445,371	566,544	1,411,762
DRB	na	na	na	na	50,549	108,564	121,828	154,900
PFL	na	na	na	na	22,637	168,988	547,985	1,020,216
UOR	na	na	na	na	37,645	46,699	88,190	88,190
APB	na	na	na	na	75,665	75,665	88,583	1,427,610
GLD	na	na	na	na	na	338	5,857	103,798
Total Stations	**1,490,000**	**2,535,163**	**4,487,519**	**5,285,113**	**7,037,213**	**7,900,349**	**9,155,099**	**12,808,409**
Plankton				83,650	142,900	150,250	218,695	242,727
SUR [6]	na		na	na	4,743	9,178	9,178	9,289

[1] Based on statistics from *Climatological Atlas of the World Ocean* (1982).
[2] Based on NODC Temperature Profile CD-ROM.
[3] WOD13 OSD dataset includes data from 121,763 low-resolution CTD casts and 1,489 low-resolution XCTD casts.
[4] WOD13 CTD dataset includes data from 5,985 high-resolution XCTD casts.
[5] WOD13 MBT dataset includes data from 80,325 DBT profiles and 5,659 Micro-BT profiles.
[6] Surface data are represented differently than profile data in WOD13 – all observations in a single cruise are combined into one "station" with zero depth, values of measured variables along with latitude, longitude, and Julian year-day to identify and locate individual sets of observations.

1.3.1. IOC Global Oceanographic Data Archaeology and Rescue Project

NODC and several other oceanographic data centers initiated “data archaeology and rescue” projects around 1991. Based on the success of these projects, in 1993 the Intergovernmental Oceanographic Commission (IOC) of UNESCO initiated the Global Oceanographic Data Archaeology and Rescue (GODAR) project with the goal of locating and rescuing oceanographic data that are stored in manuscript and/or digital form and are at risk of being lost due to media decay. The international scientific and data management communities have strongly supported this project. Results from the first phase of this project were described by Levitus *et al.* (1994). With the publication and distribution of WOD13, approximately 3.7 million temperature profiles have been added to the historical archives of oceanographic data since the inception of various national data archaeology and rescue projects and the IOC/GODAR project in 1991, and the NODC/WDC ”Global Ocean Database Project” in 1996. The status of these projects to date has been described by Levitus *et al.* (1994), Smolyar *et al.* (2004), and Levitus *et al.* (2005).

1.3.2. World Ocean Database Project

In 1995 the World Data Center for Oceanography, Silver Spring initiated a project entitled “Global Ocean Database” with support from the NOAA Earth System Data and Information Management (ESDIM) program. This project was instituted because it was recognized that there are substantial oceanographic data in digital form at oceanographic institutes around the world that, while not at risk of being lost due to media degradation or neglect, have not been submitted to the WDC system. WDC for Oceanography has begun requesting institutions to transfer their entire ocean profile and plankton archives to WDC for Oceanography. After receipt at NODC/WDC, the data in these databases are compared to existing data holdings and duplicates and near duplicates are eliminated before data are added to the NODC/WDC archives.

The response to WDC requests for data has been excellent. In some cases, part or all of the data submitted by institutions already exists in the NODC/WDC archive and database. However, often there are large numbers of casts that were thought to be in these databases that were in fact not present. In addition, there were large number of Ocean Station Data casts for which the NODC/WDC databases had temperature and salinity data but not data for other variables (e.g., chlorophyll, nutrients, etc.). These additional data were merged in with the profiles from the existing stations. There were also cases for which the NODC/WDC databases had data only at standard or selected levels. We replaced these data profiles with the corresponding observed level profiles.

In 2001 the IOC initiated the World Ocean Database Project. The goals of this project are to encourage more rapid exchange of modern oceanographic data and to encourage the development of regional oceanographic databases, regional quality control procedures for oceanographic data and regional atlases.

1.3.3. Near-real time data sources

The Global Temperature-Salinity Profile Program (GTSPP) (Searle, 1992; IOC, 1998) is a project sponsored by the Intergovernmental Oceanographic Commission to develop databases of temperature-salinity profiles reported in "real-time". WOD incorporates XBT, XCTD, CTD, glider, and pinniped data from GTSPP. Users wanting GTSPP data directly can acquire the data over the Internet via the NODC website or by contacting the NODC user Services group.

Tropical moored buoy data from the TAO/TRITON array (McPhaden *et al.*, 1998) and the PIRATA and RAMA arrays were obtained from the Pacific Marine Environmental Lab (PMEL). Users wanting the complete TAO/TRITON/PIRATA/RAMA buoy database comprised of data that have had the benefit of additional PMEL processing and quality control, can find instructions for acquiring these data via the Home Page of PMEL.

Profiling floats from the Argo program were obtained through the Coriolis Global Data Assembly Center. Users wanting the most up to date Argo data and quality control should obtain their data via Coriolis web-site.

1.3.4. International Research Projects Data

Data from the WOCE DVD version 3.0 (CTD and OSD profiles) are included in WOD13. Some WOCE XBT profiles are also part of WOD13. Data from the Joint Global Ocean Flux Study (JGOFS) and the Global Ocean Ecosystem Dynamics (GLOBEC) are also included, as are data from the Climate Variability (CLIVAR) project. Many of these data were obtained through the CLIVAR and Carbon Hydrographic Data Office (http://cchdo.ucsd.edu/)

1.3.5. ICES Contribution

The International Council for Exploration of the Sea (ICES) has collected data from participating countries for many years. ICES data are included in WOD13.

1.3.6. Declassified Naval Data Sets

As a result of the end of the Cold War, the navies of several countries have declassified substantial amounts of oceanographic data that were formerly classified, in some cases at the request of the Intergovernmental Oceanographic Commission. It should be recognized that some navies have policies of declassifying substantial amounts of data in real-time or with relatively short time delays. For example, the U.S. Navy has contributed approximately 435,000 mechanical bathythermograph (MBT) profiles and the U.S. Coast Guard approximately 217,000 MBT profiles to the NODC/WDC databases. Recent U.S. Navy data have been acquired from the U.S. Navy MOODS database. Also, the Australian Navy reports profile data in real-time including data from their Exclusive Economic Zone (EEZ).

1.3.7. Integrated Global Ocean Service - Volunteer Observing Ship programs

Since the pioneering work of Mathew Maury beginning in 1854, there have been programs in existence to gather meteorological and oceanographic data from merchant ships. These ships are sometimes referred to as Voluntary Observing Ships (VOS) and the programs called Ship-of-Opportunity Programs (SOOP). During the 1970's, the U.S. (Scripps Institute of Oceanography) and France (ORSTOM, New Caledonia) began a SOOP program that focused on the deployment of XBT instruments from VOS platforms in the Pacific Ocean (White, 1995). This program expanded to include the Atlantic and Pacific Oceans and is now supported by NOAA Ship-of-Opportunity Program. Several countries are conducting SOOPs or have conducted them. These programs are coordinated internationally by the World Meteorological Organization (WMO) and the Intergovernmental Oceanographic Commission (IOC). A description of the status of many of these programs can be found in the report, IOC (1989). As described in this report, Australia, Canada, Chile, Germany, Japan, United Kingdom, and Russia have conducted such programs in addition to France and the U.S. A summary of the status of the system is given by Joint IOC-WMO Committee for IGOSS (1996).

1.3.8. NOAA Ship-of-Opportunity Program (SOOP)

The NOAA SOOP program acquires surface meteorological data and XBT profiles from instruments placed on Volunteer Observing Ships participating in the program. The automated system for acquiring and transmitting these data is known as SEAS (Shipboard Environmental Acquisition System). Data are transmitted via satellite and eventually stored at NODC/WDC. Approximately 20,000 XBT probes are deployed each year as a result of this effort.

1.3.9. SURTROPAC

The SURTROPAC program is a French Ship-of-Opportunity Program that uses Volunteer Observing Ships (VOS) to make measurements of sea surface temperature, salinity, and chlorophyll (Dandonneau, 1992). These data are in the SUR dataset in WOD13.

1.3.10. Underway CO_2

Surface measurements of pCO_2 and TCO_2 have been included from SOOP programs (Murphy *et al.*, 2001; Zeng *et al.*, 2002) and research cruises (Inoue and Sugimura, 1998; Keeling *et al.*, 1965; Murphy *et al.*, 1995; Takahashi *et al.*, 1980; Wanninkhof and Thoning, 1993; Weiss *et al.*, 1992; Wong and Chan, 1991; Wong *et al.*, 1995).

1.4. QUALITY CONTROL FLAGS

Each individual data value and each profile in WOD13 has quality control flags associated with it. A description of these flags and general documentation describing software for reading and using the WOD13 database can be found in Johnson *et al.* (2013). WOD13 also includes Quality Control Flags assigned by data submitters. There are both Type I and Type II statistical errors (for normal distributions) associated with these flags. There are some data that have been flagged as being questionable or unrepresentative when in fact they are not. There are some data that have been flagged as being "acceptable" based on our tests which in fact may not be. In addition, the scarcity of data, non-normal frequency distributions, and presence of different water masses in close proximity results in incorrect assignment of flags. Oguma *et al.* (2003; 2004) discuss skewness of oceanographic data.

The obvious advantage of flagging data is that users can choose to accept or ignore all or part of the flags assigned to data values. The most important flags we set are based on unusual features produced during objective analyses of the data at standard levels. This is because standard statistical tests may be biased for the reasons described above. Data from small-scale ocean features such as eddies and/or lenses may not be representative of the large-scale permanent or semi-permanent features that we attempt to reproduce with our analyses and may cause unrealistic features to appear. Hence, we flag these data, and other data that cause such features, as being unrealistic or as questionable data values.

It is important to note that an investigator studying the distribution of mesoscale features in the ocean will find data from such features to be the signal they are looking for. As noted by Levitus (1982), it is not impossible to produce one set of data analyses to serve the requirements of all possible users. A corollary is that it is also impossible to produce one set of quality control flags for a database that serve the exact requirements of all investigators. As data are added to a database, investigators must realize that flags set for certain criteria being violated in an earlier version of the database may be reset solely due to the addition of new data which may change the statistics of the region being considered. Even data that have produced unrealistic features may turn out to be realistic when additional data are added to a region of sparse data. Conkright *et al.* (1994) present the objectively analyzed field of silicate at 1000 m depth using all silicate data available as part of WOA94 and using only data flagged as being acceptable. There are noticeable differences.

1.4.1. Levels of Quality Control

Different oceanographic variables in the WOD13 datasets have various levels of quality control performed to them. Those oceanographic variables in datasets used for calculating climatological means had the highest level of quality control. This included all preliminary and automatic quality control checks and subjective checks performed in evaluating the quality of the resultant climatological fields. The automatic checks included minimum/maximum range assessment for 28 ocean areas at 102 standard levels.

Values of temperature in all datasets except APB received the highest level of quality control. Likewise, values of salinity received the highest level of quality control for all datasets except APB.

Values of oxygen, phosphate, silicate, and nitrate concentrations in the OSD dataset received the highest quality control. Values of phosphate, silicate, and nitrate concentrations are only present in the SUR dataset.

Oxygen data in the CTD and PFL datasets received a lower level of quality control. Since these data were not used to calculate climatologies subjective checks were not performed on them. After calculation of climatologies using oxygen data from the OSD dataset only, the newly calculated five-degree statistics (mean and standard deviation) were used to perform a standard deviation quality control check on oxygen in the CTD and PFL datasets. The reason for not using the oxygen data from the CTD dataset is that many of these oxygen data are not calibrated. Oxygen sensors for profiling floats are still a developing technology.

Chlorophyll, pH, and alkalinity values received a lower level of quality control than oxygen for the CTD and PFL datasets. There are no chlorophyll, pH, or alkalinity climatologies calculated for WOA13, so no standard deviation checks were performed. All other checks were done as for oxygen in the CTD and PFL datasets.

A lower level of quality control was done on pCO2, DIC, Tritium, Helium, Δ3Helium, Δ14Carbon, Δ13Carbon, Argon, Neon, CFC-11, CFC-12, CFC-113, and Δ18Oxygen concentrations. Only initial range checks were applied to these variables in the OSD dataset. These ranges, a single minimum and maximum for all oceans were taken from the WOCE Data Reporting Requirements (WOCE Publication 90-1 Revision 2).

Beam Attenuation Coefficient (BAC) data in the CTD dataset was subject to this lowest level of quality control as well. The minimum and maximum values were set by A. Mishonov.

For more information about the quality control procedures, see Johnson *et al.* (2013).

Plankton data have a different set of quality control detailed in Chapter 16 of this document as well as Johnson *et al.* (2013).

1.5. OUTLOOK FOR FUTURE ACQUISITIONS OF HISTORICAL OCEAN PROFILE AND PLANKTON DATA AND INTERNATIONAL COOPERATION IN THE "WORLD OCEAN DATABASE PROJECT"

Substantial amounts of historical ocean data continue to be transferred to NODC/WDC for archiving and inclusion into databases. The outlook for our ability to continue increasing the amount of such data available to the scientific community is excellent. Based on the positive results of the IOC/GODAR project and the World Ocean Database Project, we have requested the continued cooperation of the international scientific and data management communities in building the historical ocean data archives. There is a particular need for high-resolution CTD data to resolve smaller scale features in the vertical and thus provide objective analyses of variables at greater vertical resolution than present. Examination of the distribution of high-resolution CTD profiles presented in Figure 3.2 and by Boyer *et al.* (2002) documents the lack of such data for global scale analyses. There is a need for additional historical chlorophyll, nutrient, oxygen, and plankton data so we can improve understanding of ocean biogeochemical cycles.

Improving the quality of historical data and their associated metadata is an important task. Corrections to possible errors in data and metadata is best done with the expertise of the principal investigators who made the original observations, the data center or group that prepared the data, or be based on historical documents such as cruise and data reports (however, one has to also consider that these documents may contain errors). The continuing response of the international oceanographic community to the GODAR project and the Global Ocean Database Project has been excellent. This response has resulted in global ocean databases that can be used internationally without any restriction for studying wide variety of environmental problems.

As the amount of historical oceanographic data continues to increase as a result of international cooperation, the scientific community will be able to make more and more realistic estimates of variability and be able to place confidence intervals on the magnitude of temporal variability of the more frequently sampled variables such as temperature

1.6. LAYOUT OF THE REST OF THIS DOCUMENT

The rest of this document, Chapters 2-16 describe in more detail the oceanographic instrumentation used to collect the data which are contained in WOD13 and the nature of the measurements themselves. Chapter 2 describes the OSD dataset, with an emphasis on Ocean Station Data. However, not all chapters neatly fit into one dataset. For instance, Chapter 5 is about the XCTD data, which are spread over the OSD and CTD datasets. Chapters 7, 8, and 13 all details the data which are collected by different instruments and stored in the MBT dataset.

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CHAPTER 2: OCEAN STATION DATA (OSD), LOW-RESOLUTION CTD, LOW-RESOLUTION EXPENDABLE XCTD, AND PLANKTON

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2.1. INTRODUCTION

Data from Ocean Station Data (OSD) casts have historically referred to surface and sub-surface oceanographic physical, chemical, and biological measurements at depths of interest in the water column (*i.e*., profiles) made from sea-going research ships using a variety of water samplers. Data that are in the OSD dataset are also frequently referred to as "bottle data" and the entire OSD collection may be alternatively referred to as the "Bottle Dataset". Here we adopt the general term OSD to refer collectively to low vertical resolution spacing between samples profiles, serial (discrete) water column measurements (bottles, buckets), plankton (bottles, net-tows), to relatively low vertical resolution Expendable Conductivity-Temperature-Depth (XCTD), and to relatively low vertical resolution Conductivity-Temperature-Depth (CTD) data in the *World Ocean Database 2013* (WOD13**)**. High vertical resolution Conductivity-Temperature-Depth data are in the CTD dataset. Salinity-temperature-depth (STDs) and CTDs were introduced about the mid-1960s. As a result many data from the mid-1960s and even from later years were archived at relatively low vertical resolution. These low depth resolution data are stored in the OSD dataset as opposed to the high-resolution CTD dataset. Low-resolution here refers to a limited number or a subset of measurements as a function of depth or pressure. At a minimum, these low-resolution CTD and STD measurements are recorded at the depths at which water samples have been collected and usually data at some additional depths are recorded.

The OSD dataset include a number of the most frequently measured *in situ* physical, chemical, and biological oceanographic observations as a function of depth or pressure. We believe that the OSD dataset provides the most comprehensive collection of unrestricted access discrete oceanographic observations available to date totaling 3,115,552 casts covering the years 1772 to 2012 (Figure 2.1). The description that follows is a general note on the data in the OSD dataset.

2.2. COMMONLY USED LOW AND LARGE VOLUME WATER COLUMN SAMPLERS

Most of the historical seawater samples of the ocean's water column in the OSD dataset were obtained from oceanographic research cruises occupying a number of selected oceanographic station geographic locations (sometimes called hydrographic stations) along generally pre-selected cruise tracks. For each station, discreet water samples from the ocean surface to some selected depth of the water column were obtained by means of a variety of specially designed sampling water bottles of different volumes depending on the target measurements. Some of the early historical oceanographic measurements of the water column were collected by means of wood or metal buckets.

Water sampling collection and analysis is a labor intensive process and many types of water sampling devices have been invented since the early days of oceanographic research. The Nansen and Niskin bottles are probably the most commonly used water samplers to date for the serial collection of relatively small volumes of seawater (about < 10 liters). Nansen bottles, commonly used prior to the late 1960s, were invented by Fridtjof Nansen in 1910. These are cylindrical pressure-resistant metal containers (usually made of brass) with plug valves at each end that allow the collection of small volumes of seawater (about < 1.5 liters) at selected depths in the water column (Sverdrup *et al.,* 1942). The Nansen bottles often included two or more specially designed protected and unprotected mercury-filled glass reversing thermometers inside a small metal case exposed to the water column attached to the outside of each bottle. These thermometers allowed the estimation of the *in situ* temperature and pressure at which each bottle closed in the water column. The Nansen bottles were generally replaced by the Niskin bottles in the late 1960s. Niskin bottles helped minimize some of the problems associated with the collection of Nansen bottle samples (Worthington, 1982). Niskin bottles are cylindrical pressure-resistant plastic containers (to minimize contamination between the bottle and the water sample) with rubber spring-loaded end-caps that allow the collection of a variety of volumes of seawater (about 1.2 to 10 liters). Niskin bottles are frequently mounted around a circular rosette sampler metal frame with the capacity to hold as many as 36 bottles. The bottles can then be closed at any depth or pressure by an electrical command from deck or from preset depth (pressure) values. When the closed Niskin bottles are brought back on deck, water samples can be collected from each bottle and then analyzed for different seawater constituents. The rosette frame may include a CTD and other automated sampling sensor instruments (*e.g.*, fluorometers, transmissometers, *etc.*).

The majority of the most commonly analyzed constituents dissolved in seawater in the OSD dataset were obtained from a relatively small sample volume of seawater. The most commonly analyzed constituents in seawater have been salinity, dissolved oxygen, and the major dissolved inorganic nutrients: nitrate, silicate, and phosphate (Table 2.1). Many additional chemical constituents such as trace metals and transient tracers have been measured with the emergence of more precise and clean chemical measurements and sampling techniques. For example, large volumes of seawater are needed for the analysis of chemical constituents in trace concentrations present in seawater such as isotopes (*e.g.*, argon-39, kripton-85, and carbon-14). Present day analytical techniques for measuring kripton-85 in seawater, for example, require a sampling volume of about 1200 liters (Smethie and Mathiew, 1986; Key, 1994; Smethie, 1994). The Gerard-Ewing samplers were first used during the Geochemical Ocean Sections Study (GEOSECS) program in the early 1970s (Bainbridge, 1980; Craig, 1972; 1974; Craig and Turekian, 1980) and subsequently used during several research cruises such as the Transient Tracers in the Ocean (TTO, Williams, 1986), South Atlantic Ventilation Experiment (SAVE, Smethie and Jacobs, 1992), and World Ocean Circulation Experiment (WOCE) programs. Below we describe briefly the main features of the Nansen and Niskin bottles.

2.3. VARIABLES AND METADATA INCLUDED IN THE OSD DATASET

The OSD dataset includes the most frequently measured *in situ* physical (*e.g*., temperature, salinity), chemical (*e.g*., dissolved and particulate geochemical tracers. dissolved gases), and biological (*e.g*., chlorophyll and plankton) historical oceanographic observations as a function of depth or pressure. Table 2.1 lists the nominal names, number of profiles for each measured variable (or stations in the case of plankton data), and sampled years. Each oceanographic station data record may contain simultaneous profiles of one or more of these variables as a function of depth or pressure obtained during one or more casts. The user can extract data from the OSD dataset both at observed depths and at nominal standard depth levels.

The observed level measurement values in the OSD dataset are the data submitted by the data originator converted to the WOD data format as a function of depth or pressure. All data in OSD are in WOD nominal units (Table 2.1). The profiles at standard levels in the OSD dataset are the measurements submitted by the data originator vertically interpolated to selected depth levels. The profiles include quality flags for observed and standard depth level data (Johnson *et al.,* 2013).

Physical variables such as temperature, salinity, and hydrostatic pressure are conservative parameters which define the equation of state of seawater (*e.g.*, Millero and Poisson, 1981). By conservative variables we mean measurements which are not affected directly by biochemical processes.

Temperature measurements have been obtained by means of manual (*i.e.*, visual readings of temperature from reversing thermometers) and automated (*i.e.*, digital recordings of temperature from STDs and CTDs) sensor instruments. Temperature measurements have been obtained following several International Temperature Scales (ITS) definitions dating back from to early 1900s (*i.e.*, ITS-1927; ITS-1948, ITS-1968) to the ITS-1990 (Preston-Thomas, 1990). Temperature data in WOD13 nominal units are in the scale the measurements were reported in by the originator of the data.

Salinity measurements have been obtained by manual (*e.g.*, chemical titrations, chlorinity to salinity formulae, refractometers, salinographs, inductive salinometers, *etc.*) and automated (*i.e.*, conductivity to salinity from CTDs) methods. For the past few decades, bottle salinity sampling and analyses are normally conducted to calibrate the conductivity to salinity measurements of CTDs. Salinity measurements have been obtained using reference standard seawater samples of known salinity (within uncertainty). In 1978 the practical salinity scale (PSS-1978) was adopted defining salinity in terms of electrical conductivity ratio (UNESCO, 1981; Lewis and Perkins, 1981; Culkin and Ridout, 1998). Under the PSS-1978 definition, salinity measurements are dimensionless (Millero, 1993). Seawater standards provide a means to facilitate the inter-comparison of ocean salinity measurements against samples of known electrical conductivity ratio (UNESCO, 1981; Mantyla, 1980; 1987; 1994; Culkin and Smed, 1979; Aoyama *et al.,* 2002; Kawano *et al.,* 2005). More recently, the concept of absolute salinity anomaly has been introduced to compute absolute salinity values in terms of salinity values using the PSS-78 definition (McDougall *et al.*, 2009). In all cases, WOD13 salinity data are not corrected for “standard sea water” changes (Mantyla, 1994) or converted to any salinity scale other than the scale the measurements were reported in.

Low-resolution CTD profiles present in the OSD dataset may be associated with high-resolution CTD profiles in the CTD dataset. This is done so that users of the OSD dataset have access to CTD values collected at the same time and depth or pressure that water samples are collected and to maintain a more or less concise size for the OSD dataset. Similarly, users of the CTD dataset may have access to low vertical resolution profiles for other variables (Table 2.1).

Geochemical variables such as dissolved oxygen (O_2), major dissolved inorganic nutrients (reactive phosphate, nitrate, nitrite, and silicate or silicic acid), carbon species (alkalinity, dissolved inorganic carbon, partial pressure of carbon dioxide) and pH are non-conservative variables. Their concentrations result from diffusion and advection of waters with varied preformed concentrations, by biogeochemical processes, and by atmospheric inputs (Redfield *et al.,* 1963; Sarmiento *et al.,* 1998; Falkowski *et al.,* 1998; Broecker and Peng, 1982).

The WOD13 includes nitrate plus nitrite (N+N) and nitrate data only. The concentrations of N+N and nitrite are often estimated by photometric analyses where in one case nitrate is measured indirectly by effectively reducing nitrate to nitrite while in the other only nitrite is measured (Strickland and Parsons, 1972; Atlas *et al.,* 1971; Whitledge *et al.,* 1986; Gordon *et al.,* 1993). The concentration of nitrate is then obtained by difference between the estimated concentrations of N+N and nitrite. It is important to note that data reported as nitrate in the WOD13 should be used with caution because it is difficult to verify that the nitrate data are N+N or nitrate. When reported by the originator of the data, WOD13 includes metadata information about whether the labeled nitrate measurement is reported as N+N data. Historical dissolved inorganic carbon (DIC), alkalinity (ALK), partial pressure of CO_2 (pCO_2), and pH data in WOD13 not always include information about the methods, instruments, and scales used (Millero *et al.,* 1993a, 1993b; Ramette *et al.,* 1977; Robert-Baldo *et al.,* 1985; Bradshaw and Brewer, 1988; Byrne and Breland, 1989; Dickson, 1981; 1984; 1993; DOE, 1994). When reported, modern geochemical data include additional metadata including the use of certified reference materials (CRM) and scales.

Table 2.1. Measured variables present in the Oceanographic Station Data (OSD) dataset.

Parameter [nominal abbreviation]	Reporting unit (nominal abbreviation)	Number of profiles (sampled years)
Temperature [T]	Degree centigrade (°C)	2,851,770 (1772-2012)
Salinity [S]	Dimensionless or unit less	2,382,296 (1873-2012)
Dissolved oxygen	Milli-liter per liter (ml l^{-1})	899,424 (1878-2012)
Phosphate	Micro-mole per liter (µM)	576,397 (1922-2012)
Silicate	Micro-mole per liter (µM)	438,675 (1921-2012)
Nitrite	Micro-mole per liter (µM)	309,909 (1923-2012)(1)
Nitrate	Micro-mole per liter (µM)	353,454 (1925-2012)(1)
pH	Dimensionless or unit less	248,793 / 248,066 (1910-2011)
Total Chlorophyll [Chl] unless specified	Micro-gram per liter (µg l^{-1})	215,192 (1933-2012)
Alkalinity	Milli-equivalent per liter (meq l^{-1})	71,737 (1921-2011)
Partial pressure of carbon dioxide	Micro-atmosphere (µatm)	3,358 (1967-2007)
Dissolved inorganic carbon	Milli-mole per liter (mM)	18,321 (1958-2011)
Tritium	Tritium Unit (TU)(2)	1,933 (1984-2003)
Helium	Nano-mol per liter (nM)	2,443 (1984-2003)
Delta Helium-3	Percent (%)	2,436 (1985-2003)
Delta Carbon-14	Per-mille (‰) deviation	1,260 (1987-2003)
Delta Carbon-13	Per-mille (‰) deviation	1,075 (1991-2003)
Argon	Nano-mol per liter (nM)	75 (1993-1993)
Neon	Nano-mol per liter (nM)	1,410 (1987-2001)
Chlorofluorocarbon-11	Pico-mole per liter (pM)	15,279 (1982-2011)
Chlorofluorocarbon-12	Pico-mole per liter (pM)	15,255 (1982-2011)
Chlorofluorocarbon-113	Pico-mole per liter (pM)	5,294 (1990-2011)
Delta Oxygen-18	Per-mille (‰) deviation	675 (1991-2008)
Pressure	Deci-bar	163,863 (1890-2012)
Plankton taxonomy and Biomass	Various units	242,727 (1900-2012)(3)

Table 2.1 Notes:
(1) Profile count includes 21,055 profiles of Nitrate + Nitrite (N+N) minus 2,053 profiles that reported both N+N and Nitrate concentrations.
(2) One tritium unit (TU) equals 1 tritium atom in 10^{18} hydrogen atoms.
(3) Plankton count refers to the number of stations casts (see Plankton Chapter).

The dissolved O_2 concentration is often analyzed following various modifications of the Winkler titration followed by end-detections by visual, amperometric, or photometric methods (Winkler, 1888; Carpenter, 1965; Culberson and Huang. 1987; Knapp *et al.,* 1990; Culberson *et al.,* 1991; Dickson, 1994). Carpenter (1965) outlined a whole bottle titration method that minimized the amount of error that was introduced during the O_2 titration from the volatization of iodine and the difference between the titration end point and the equivalence point. It is worth noting that the CTD dataset contains high-resolution O_2 data obtained from electronic sensors mounted on the CTD rosette frame. For example, polarographic O_2 electronic sensors estimate seawater O_2 concentration by estimating the flux of oxygen molecules per unit time that diffuse through a permeable membrane. The PFL dataset also contains a number of relatively high-resolution O_2 profiles. These high-resolution O_2 profiles obtained by electronic sensors can be subject to sensor drift problems resulting in relatively lower data quality than O_2 profiles which have been obtained by chemical analysis of discrete water samples. The CTD O_2 data are often calibrated using discrete O_2 measurements of the water column (Owens and Millard, 1985). For these reasons, the O_2 profiles in the CTD and PFL datasets are kept separate from the O_2 profiles in the OSD dataset.

Dissolved noble gases and tracers help in the interpretation of how ocean surface properties are transmitted into the ocean's interior, the dynamics of ocean circulation, biochemical cycles, ocean-atmosphere interactions, and to help infer paleotemperatures (Broecker and Peng, 1982). The OSD dataset includes noble gases such as neon, argon, and helium. The distributions of these gases are useful, for example, to further our understanding of the ocean circulation and air-sea gas flux interactions (Schlosser, 1986; Weiss, 1971; Broecker and Peng, 1982). The distributions of transient tracers provide estimates of oceanic ventilation rates; a measure of water mass spreading rates from the surface to the ocean interior. Specifically, transient tracers such as bomb-fallout radionuclides and natural isotopes function as "clocks" recording the elapsed time since a parcel of water was last in contact with the oceanic surface layer (Schlosser *et al.,* 1991; Jenkins, 1982; 1987; Jenkins and Rhines, 1980; Östlund and Rooth, 1990). For example, tritium was delivered to the atmosphere as a result of the atmospheric thermonuclear weapon tests in the late 1950s and early 1960s. Chlorofluorocarbons are man-made gases with high greenhouse potential (Bach and Jain, 1990). Their time history within the water column provides important clues regarding the oceanic uptake of atmospheric gases (Bullister and Weiss, 1988; Smethie, 1993; Weiss *et al.,* 1985; Haine *et al.,* 1995). There is a large number of freons produced and dissolved in the ocean. The most commonly sampled freons (chlorofluorocarbon, CFC) in the ocean are CFC-11, CFC-12, and CFC-113. CFCs were used worldwide as refrigerants, propellants, and cleaning solvents. The temporal evolution of the CFC concentrations in oceanic waters is essentially controlled by the atmospheric record. Most of the transient tracer data in the OSD dataset were collected starting with the GEOSECS program in the early 1970s, and later as part of WOCE program in the 1990s.

OSD chemical data received at the National Oceanographic Data Center (NODC) are reported by originators of the data in a variety of concentration units that may differ from the WOD standard units (Table 2.1) and the international system of units in oceanography (UNESCO, 1985). When originator's units differ from a set of adopted WOD common units, the data are converted from the originator's units to a common set of concentration units to facilitate the use of the WOD data. For example, originator's chemical concentration units reported in per-mass units were converted to per-volume units assuming a constant density of seawater equal to 1025 $kg \cdot m^{-3}$ (*e.g.*, an arbitrary choice). Chemical concentration units reported in mass-per-volume basis were converted to mole-per-volume units using the standard element atomic weights of 1989 (CRC, 1993). Dissolved oxygen originator units reported in molar-per-volume units were converted to volume-per-volume (ml-per-liter) using a molar volume of O_2 of ~22.392 liters-per-mole. This molar volume is only slightly smaller than the ideal gas volume (22.4 liters-per-mole) by about 0.04% (Garcia and Gordon, 1992). Though some chemical data in the OSD dataset are expressed in per-volume units, it is useful to express chemical concentrations in per-mass units that are temperature and pressure independent.

In the near future, the standard units for all WOD variables which are now per volume will become per-mass.

In addition to the observed data (profiles as a function of depth of each sampled variable), OSD casts include additional information (commonly referred to as “station header information”) such as, but not limited to, ocean surface conditions (*i.e.*, wave direction and height, sea state), meteorological observations (*i.e.*, cloud cover and type, visibility, wind speed and direction, barometric pressure, dry and wet bulb temperature), water color and transparency (*i.e.*, Secchi disk depth), originator’s information about the data collected (instrumentation, methods, units, quality flags, stations and cruise labels, institutions, platforms, principal investigators, *etc.*). Johnson *et al.* (2013) describes the WOD13 cast header information and data format. We refer collectively to this information as station metadata. The cast metadata included in the OSD dataset are not meant to substitute in whole or in part data for information included with any oceanographic cruise data reports or scientific manuscripts which may be associated with any particular OSD subset. Metadata are included in the OSD dataset as a means to quickly identify additional information about the measurements that may be available with each cast. Metadata are included with each OSD cast in the form of header information when metadata were included with data received at NODC. The biogeochemical data in the OSD dataset have been measured using a variety of manual and automated analytical methods. It is beyond the scope of this work to describe the evolution and intercomparison of the uncertainty, precision, and accuracy of historical oceanographic chemical measurements. Not all data received at NODC contain complete metadata information.

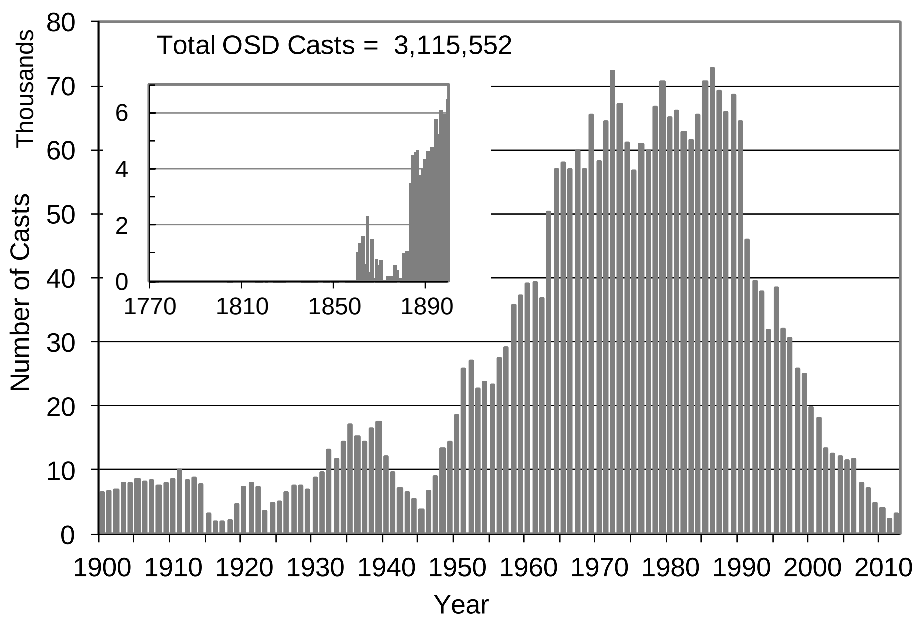

Figure 2.1. Time series of the number of OSD casts in WOD13

It is difficult to estimate the precision and reproducibility of the historical chemical data in part because (1) there has not been a generally accepted set of standard international analytical oceanographic methods; (2) there has been a continuous availability over time of new or improved analytical techniques for the sampling and determination of the concentration of dissolved and particulate constituents in seawater; (3) there is the practical difficulty of periodic comparison of the precision and accuracy of oceanographic data collected by oceanographic institutions worldwide. At present, we are not aware of a suitable monitoring program for the systematic comparison of analytical instruments, measurements, and certified reference standards used by international research institutions or universities to collect oceanographic observations. Some major international oceanographic sampling programs have adopted sample and measurement protocols such as the WOCE and the Joint Global Ocean Flux Study (JGOFS) programs. These protocols are believed to provide relatively consistent high-quality measurements. In the past few years certified reference materials (CRMs) of known chemical concentrations have been used for the analysis, for example, Dissolved Inorganic Carbon and Alkalinity (DOE, 1994) or Dissolved Inorganic Carbon (Dennis A. Hansell per. Comm.). It is generally believed that adoption of CRMs facilitates the interlaboratory comparison of measurements collected by different observing systems oceanographic systems. Farrington (2000) provides a summary of advances in chemical oceanography for the 1950-2000 period.

2.4. OSD DATA COVERAGE

The sampling coverage of the OSD variables is worldwide and for some variables spans several decades (Tables 2.1 and 2.3). The number of OSD casts added to WOD has increased greatly since 1974 (Figure 2.4, however, the coverage for each variable is nonuniform in space or time (Table 2.2, Figures 2.5-2.28). The largest numbers of oceanographic profiles present in the OSD dataset consist of temperature, salinity, and dissolved oxygen measurements. This nonuniformity of the number of profiles can be attributed to different reasons. First, historical oceanographic cruises typically sampled individual or a limited suite of tracers to deduce specific physical, chemical, biological or geological aspects of the ocean. In other words, oceanographic cruises in general have a specific research goal which may require sampling of a limited number of variables. Second, the sampling and analysis of biochemical variables is quite more labor intensive when compared to temperature or conductivity measurements obtained by CTD instruments.

2.5. PARAMETERS AND METADATA NOT INCLUDED IN THE OSD DATASET

The WOD includes data for other biochemical variables not available as part of the WOD13 release. These variables were not released as part of the WOD13 because a minimum of data quality control was not performed on these measurements. The variables not present in the WOD13 include dissolved and particulate organic carbon, nitrite, total phosphorus, ammonia, various chlorophyll pigments, and primary production. In addition, the NODC maintains a database of originator's data files and documentation as part of the Ocean Archive System (OAS). Users of the WOD13 can retrieve the original data as sent to NODC. It is worth noting that in some cases, data received at NODC may include measured variables which were not digitally stored in the WOD (*e.g.*, trace metals, organic compounds, *etc*.). Information about these variables is maintained in the OAS and available via the NODC Geoportal.

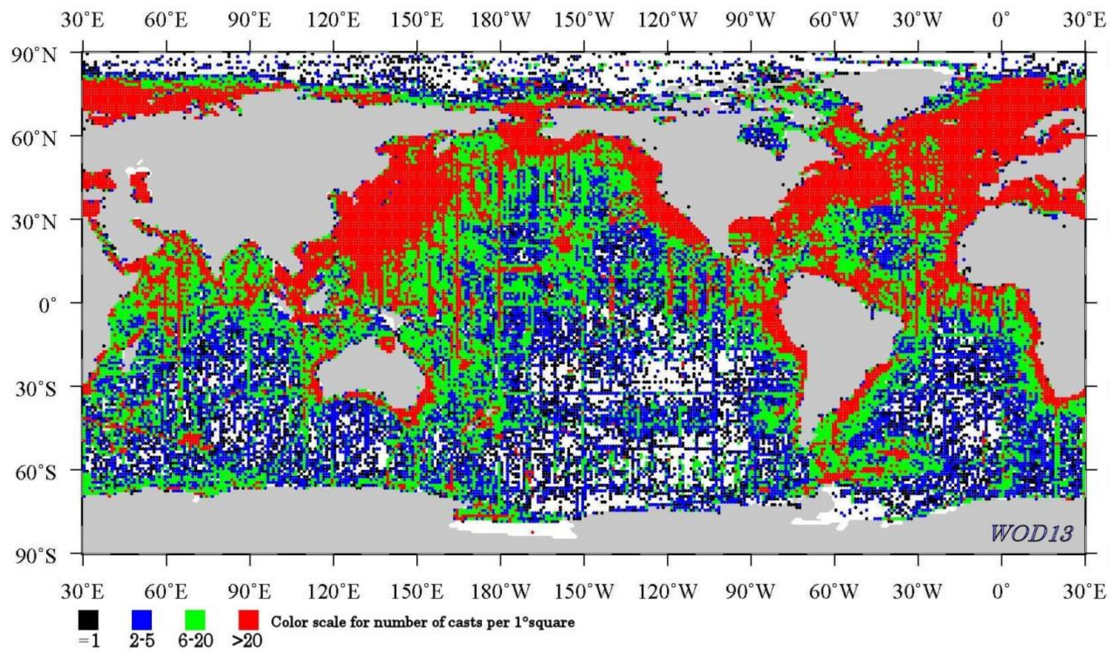

Figure 2.2. Geographic distribution of OSD casts in WOD13

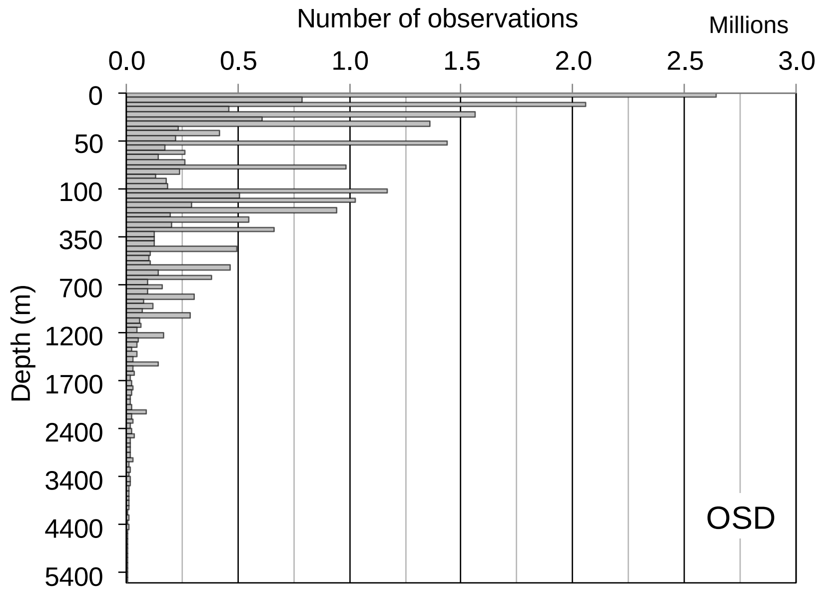

Figure 2.3. Distribution of OSD data with observations within the vertical interpolation limits of each standard level (see Johnson *et al.* 2013).

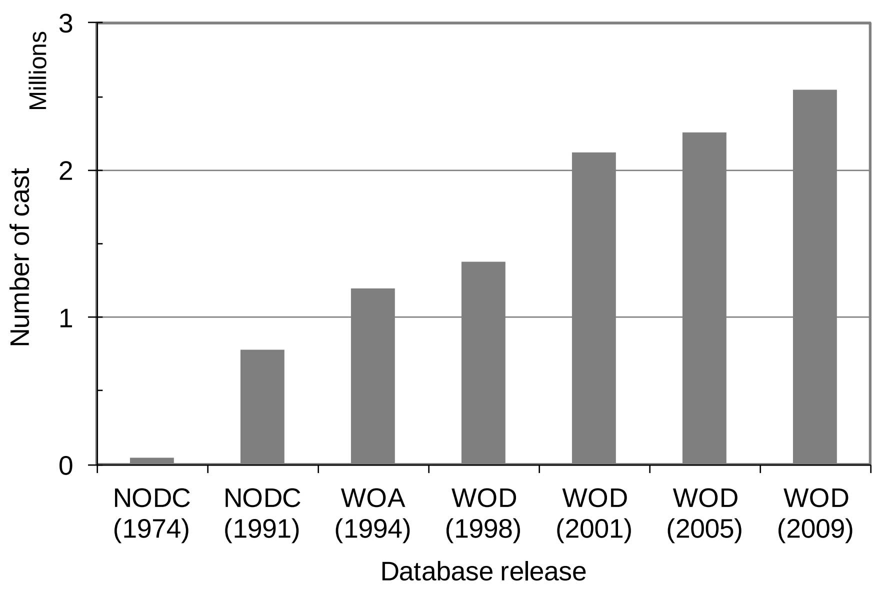

Figure 2.4. Number of OSD casts in NODC/WDC databases as a function of time.

The number of casts available at NODC prior to 1994 after Levitus (1982) and NODC Temperature-Profile CD-ROM (1991). The number of casts after 1994 are based on the World Ocean Atlas (WOA) and World Ocean Database (WOD) series.

2.6. PROSPECTS FOR THE FUTURE

It is expected that relatively large amounts of historical chemical and biological data still exists in non-digital and digital form at data centers, research institutions, universities, and libraries worldwide. Biogeochemical data is also expected to become available from ongoing and future international oceanographic field programs such as the Global Ocean Observing System (GOOS), Climate Variability (CLIVAR) repeat hydrography field program and underway pCO_2 measurements, and Argo floats equipped with physical and chemical sensors such as O_2 (*e.g.*, Emerson *et al.*, 2002; Körtzinger *et al.,* 2004; Körtzinger 2005), and Ocean Acidification field studies. There are several types of chemical sensors available for autonomous and lagrangian platforms that can contribute to the WOD.

The WOD is a worldwide source of unrestricted access to historical oceanographic data information. Future releases of the WOD will be enhanced by the addition of more data and metadata. It is hoped that users of the WOD13 inform us of sources of historical data not present in the database as well as any data or metadata errors that might be present in the database at NODC. Identification of new sources of chemical data to the WOD is beneficial for improving mechanisms for data long-term archival, data management, and distribution into national and international data archives. Addition of new data will help improve the release of more high-quality global, scientifically quality-controlled ocean profile-plankton database, scientific ocean data products, and diagnostic studies. Addition of new data will also help to provide observational constraints on oceanic variability studies.

Table 2.2. Number of Ocean Station Data (OSD) casts as a function of year in WOD13.

Total number of casts = 3,115,552.

YEAR	COUNT	YEAR	COUNT	YEAR	COUNT	YEAR	COUNT	YEAR	COUNT
1772	2	1820	2	1868	793	1916	1,845	1964	56,849
1773	1	1821	0	1869	567	1917	1,941	1965	57,981
1774	0	1822	0	1870	737	1918	2,128	1966	57,028
1775	0	1823	0	1871	50	1919	4,471	1967	59,888
1776	0	1824	2	1872	7	1920	7,311	1968	56,879
1777	0	1825	10	1873	190	1921	7,941	1969	65,467
1778	0	1826	18	1874	186	1922	7,247	1970	58,216
1779	0	1827	30	1875	193	1923	3,538	1971	64,338
1780	0	1828	13	1876	567	1924	4,817	1972	72,412
1781	0	1829	0	1877	385	1925	4,928	1973	67,024
1782	0	1830	0	1878	90	1926	6,506	1974	61,174
1783	0	1831	0	1879	57	1927	7,509	1975	56,780
1784	0	1832	0	1880	976	1928	7,525	1976	60,869
1785	0	1833	0	1881	1,071	1929	6,930	1977	59,851
1786	0	1834	0	1882	873	1930	8,657	1978	66,719
1787	0	1835	0	1883	3,493	1931	9,557	1979	70,692
1788	0	1836	8	1884	4,510	1932	13,102	1980	65,054
1789	0	1837	17	1885	4,599	1933	11,602	1981	66,028
1790	0	1838	11	1886	4,704	1934	14,360	1982	62,660
1791	0	1839	15	1887	3,776	1935	17,124	1983	61,483
1792	0	1840	9	1888	3,971	1936	15,180	1984	65,402
1793	0	1841	21	1889	4,363	1937	14,418	1985	70,635
1794	0	1842	8	1890	4,632	1938	16,424	1986	72,733
1795	0	1843	0	1891	4,655	1939	17,491	1987	69,243
1796	0	1844	0	1892	4,756	1940	11,978	1988	65,812
1797	0	1845	0	1893	4,692	1941	9,482	1989	68,562
1798	0	1846	3	1894	5,788	1942	7,025	1990	64,373
1799	0	1847	28	1895	5,233	1943	6,369	1991	45,941
1800	0	1848	0	1896	6,087	1944	5,374	1992	39,484
1801	0	1849	1	1897	5,381	1945	3,693	1993	37,761
1802	0	1850	3	1898	5,983	1946	6,560	1994	31,778
1803	0	1851	1	1899	6,471	1947	9,010	1995	38,452
1804	10	1852	0	1900	6,421	1948	13,382	1996	31,928
1805	1	1853	0	1901	6,748	1949	14,415	1997	30,463
1806	0	1854	0	1902	6,847	1950	18,581	1998	25,823
1807	0	1855	4	1903	7,903	1951	25,676	1999	24,854
1808	0	1856	0	1904	7,869	1952	26,999	2000	19,696
1809	0	1857	6	1905	8,551	1953	22,669	2001	18,083
1810	0	1858	23	1906	8,038	1954	23,609	2002	13,306
1811	0	1859	5	1907	8,211	1955	23,348	2003	12,530
1812	0	1860	1,053	1908	7,551	1956	27,513	2004	11,963
1813	0	1861	1,351	1909	7,987	1957	29,063	2005	11,384
1814	0	1862	1,602	1910	8,472	1958	35,821	2006	11,563
1815	0	1863	606	1911	10,025	1959	37,126	2007	7,950
1816	5	1864	2,329	1912	8,249	1960	38,968	2008	7,168
1817	27	1865	352	1913	8,799	1961	39,306	2009	4,850
1818	3	1866	1,494	1914	7,655	1962	36,826	2010	3,995
1819	0	1867	78	1915	3,043	1963	50,292	2011	2,387
								2012	2,074

Table 2.3. National contribution of OSD casts in WOD13.

ISO[a] Country Codes	Country Name	OSD Casts	% of Total
SU	Union of Soviet Socialist Republics	715,527	22.97
JP	Japan	595,469	19.11
US	United States	390,866	12.55
SE	Sweden	284,278	9.12
GB	Great Britain	139,814	4.49
CA	Canada	120,562	3.87
NO	Norway	112,658	3.62
99	Unknown / International	101,337	3.25
DE	Germany	84,703	2.72
FI	Finland	60,478	1.94
KR	Korea, Republic of	51,638	1.66
DK	Denmark	47,885	1.54
FR	France	45,618	1.46
AU	Australia	36,403	1.17
NL	Netherlands	32,769	1.05
ZA	South Africa	28,433	0.91
PE	Peru	26,979	0.87
RU	Russian Federation	26,584	0.85
PL	Poland	22,053	0.71
IS	Iceland	20,693	0.66
UA	Ukraine	15,917	0.51
DU	East Germany	15,608	0.50
IT	Italy	11,837	0.38
BE	Belgium	10,316	0.33
BR	Brazil	9,572	0.31
ES	Spain	6,661	0.21
PT	Portugal	6,539	0.21
CN	China, The People’s Republic of	5,509	0.18
YU	Yugoslavia	5,455	0.18
AR	Argentina	5,033	0.16
CL	Chile	4,914	0.16
IN	India	4,478	0.14
ID	Indonesia	4,365	0.14
TW	Taiwan	4,034	0.13
TR	Turkey	3,996	0.13
IE	Ireland	3,782	0.12
RO	Romania	3,639	0.12
VE	Venezuela	3,590	0.12
EC	Ecuador	3,498	0.11
GR	Greece	3,489	0.11
IL	Israel	3,463	0.11
CI	Cote D’Ivoire (Ivory Coast)	3,185	0.10
TH	Thailand	2,801	0.09

ISO[a] Country Codes	Country Name	OSD Casts	% of Total
GH	Ghana	2,670	0.09
MG	Malagasy Republic	2,523	0.08
LV	Latvia	2,225	0.07
MC	Monaco	2,054	0.07
SN	Senegal	1,975	0.06
NZ	New Zealand	1,942	0.06
CD	Congo	1,865	0.06
MX	Mexico	1,457	0.05
NC	New Caledonia	1,344	0.04
CO	Colombia	1,338	0.04
EE	Estonia	1,291	0.04
LT	Lithuania	1,238	0.04
MR	Mauritania	1,217	0.04
NG	Nigeria	980	0.03
CU	Cuba	976	0.03
AT	Austria	773	0.02
AO	Angola	621	0.02
EG	Egypt, Arab Republic of	544	0.02
SG	Singapore	412	0.01
TN	Tunisia	280	0.01
PH	Philippines	235	0.01
MA	Morocco	199	0.01
LB	Lebanon	187	0.01
PK	Pakistan	167	0.01
DZ	Algeria	166	0.01
MY	Malaysia	154	<0.01
PA	Panama	139	<0.01
YE	Yemen	85	<0.01
MT	Malta	66	<0.01
ZZ	Miscellaneous organization	1	<0.01
Total:		*3,115,552*	*100.00*

[a] ISO = International Organization for Standardization

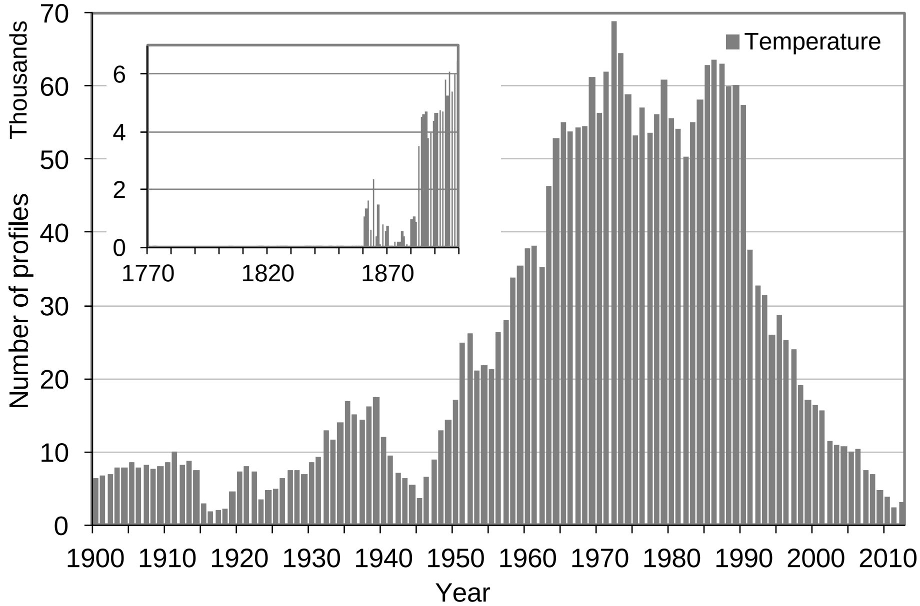

Figure 2.5. Time series of the number of temperature profiles in the WOD13 OSD dataset.

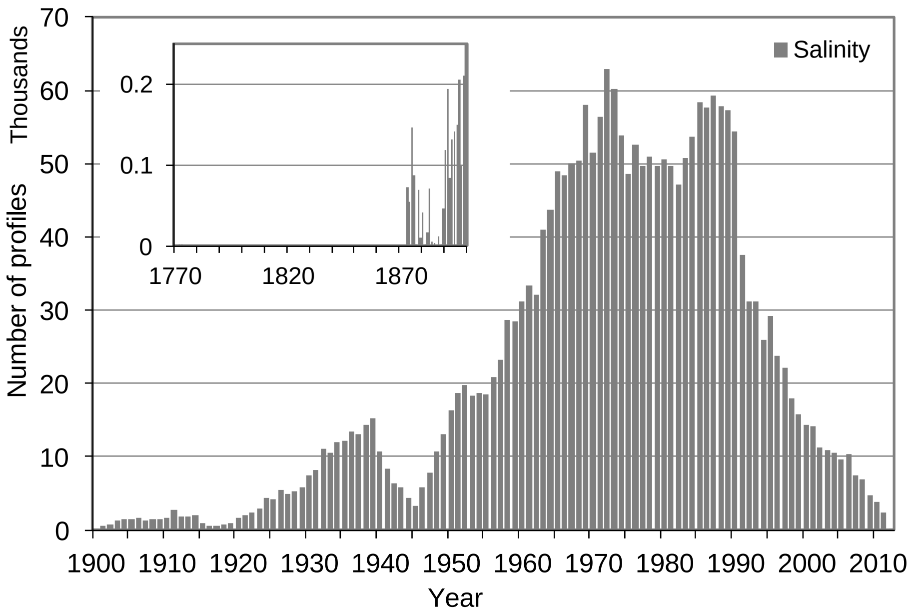

Figure 2.6. Temporal distribution of salinity profiles in the WOD13 OSD dataset.

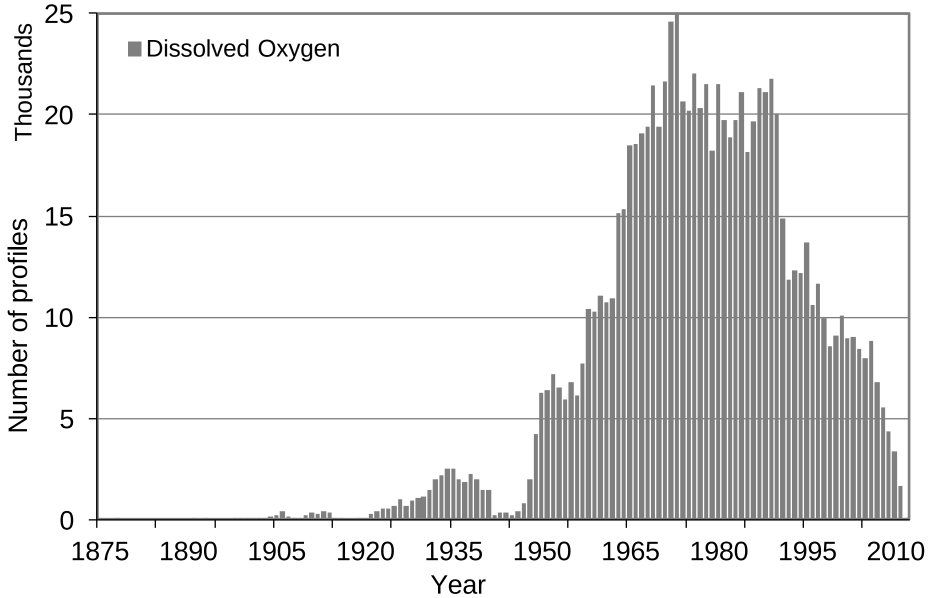

Figure 2.7. Temporal distribution of Dissolved Oxygen profiles in the WOD13 OSD dataset.

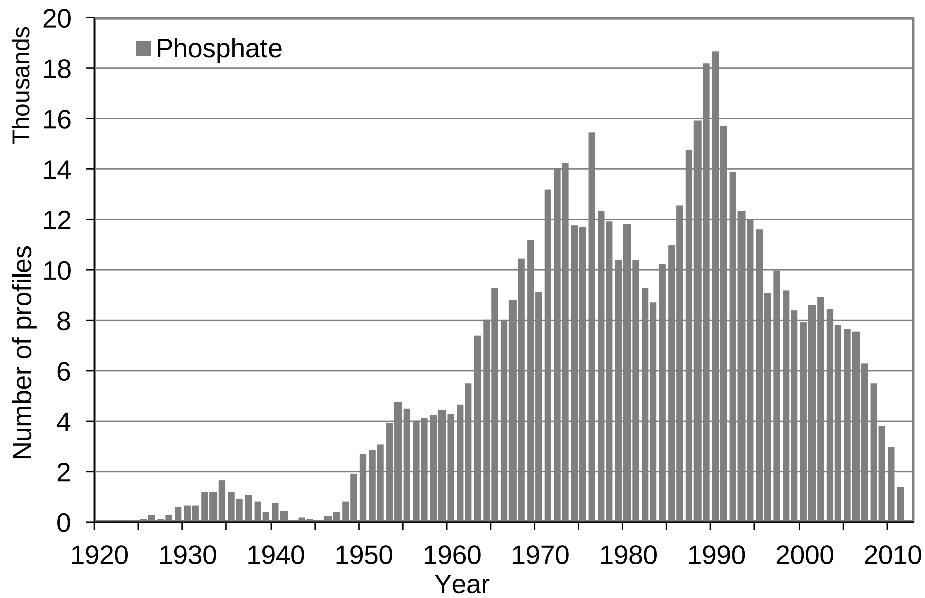

Figure 2.8. Temporal distribution of Phosphate profiles in the WOD13 OSD dataset.

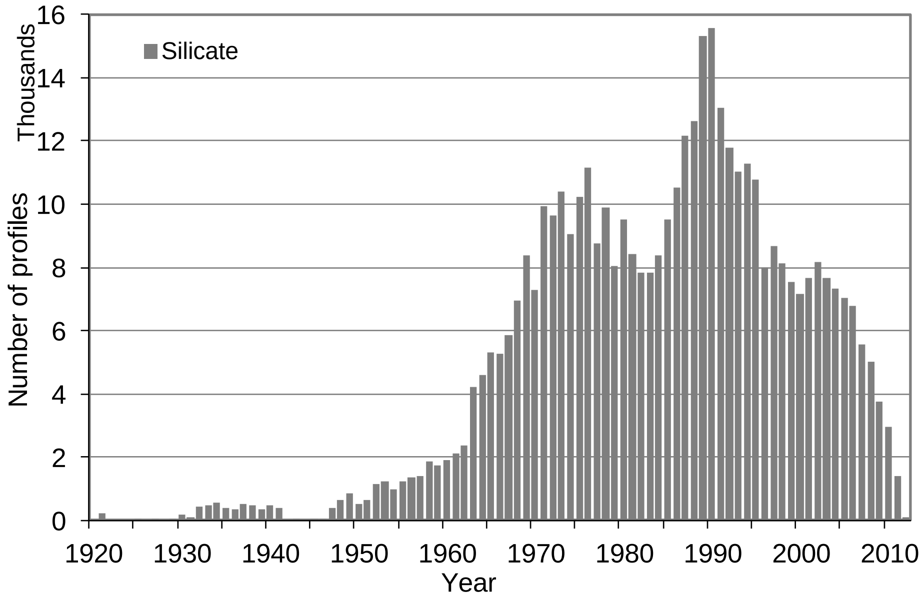

Figure 2.9. Temporal distribution of Silicate profiles in the WOD13 OSD dataset.

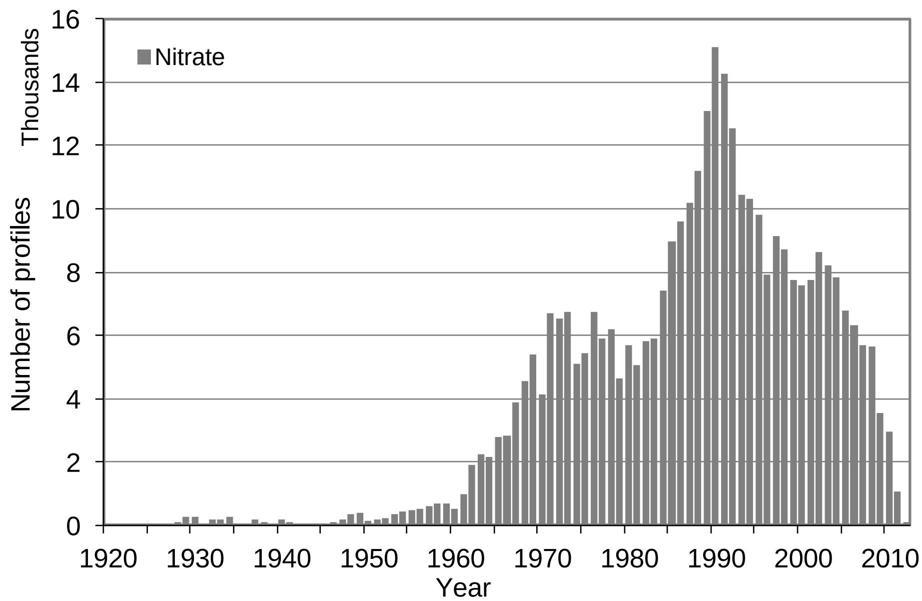

Figure 2.10. Temporal distribution of Nitrate profiles in the WOD13 OSD dataset.
Profile count includes 21,055 profiles of Nitrate + Nitrite (N+N) minus 2,053 profiles that reported both N+N and Nitrate concentrations.

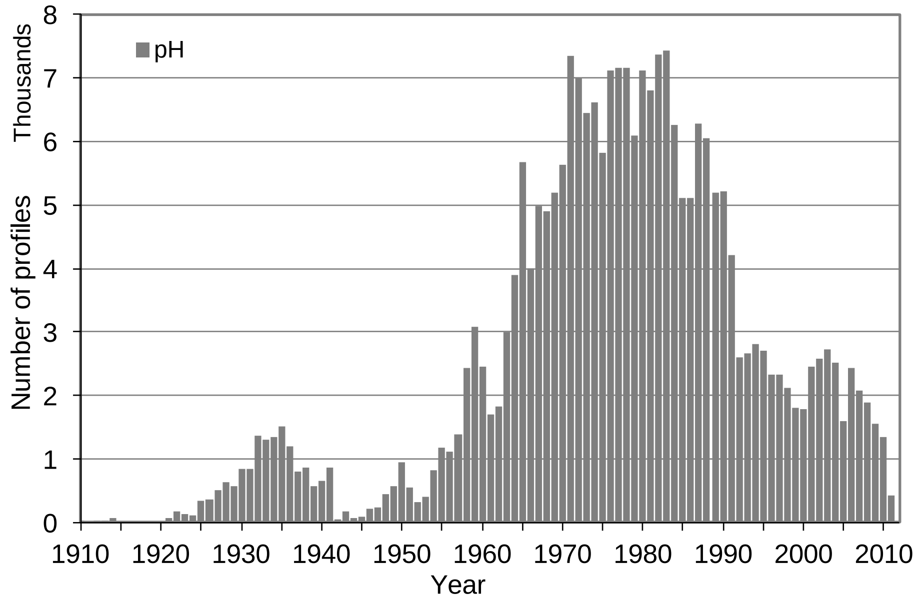

Figure 2.11. Temporal distribution of pH profiles in the WOD13 OSD dataset.

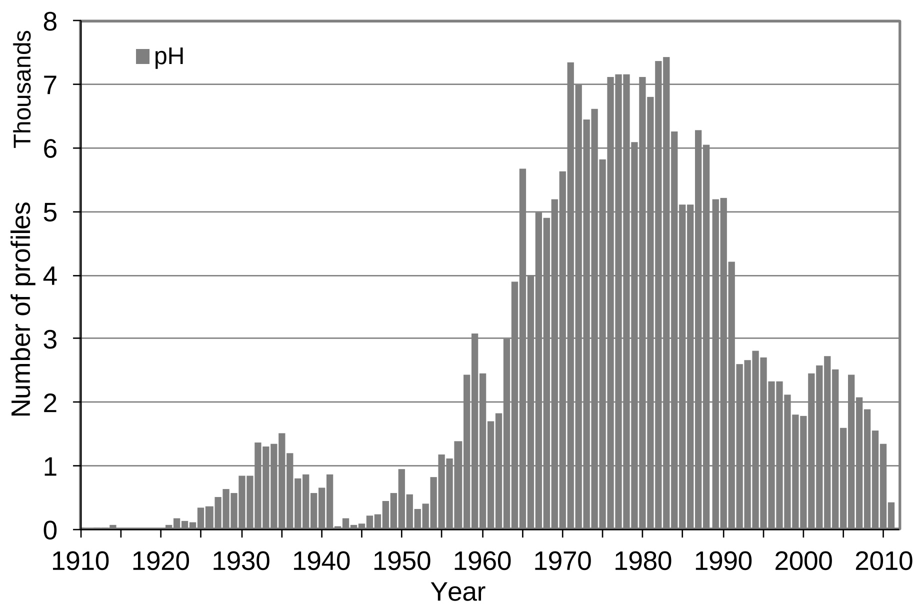

Figure 2.12. Temporal distribution of Chlorophyll profiles in the WOD13 OSD dataset.

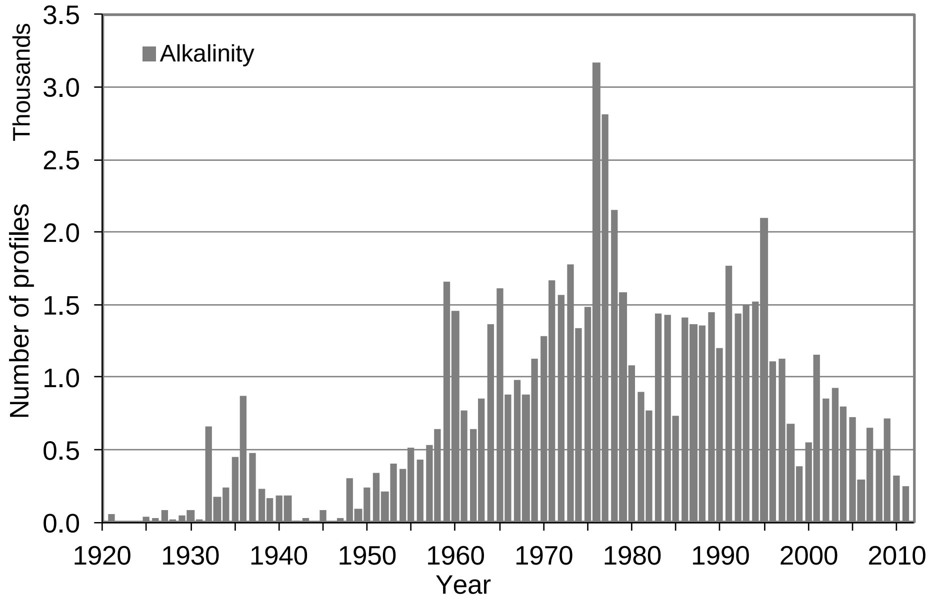

Figure 2.13. Temporal distribution of Alkalinity profiles in the WOD13 OSD dataset.

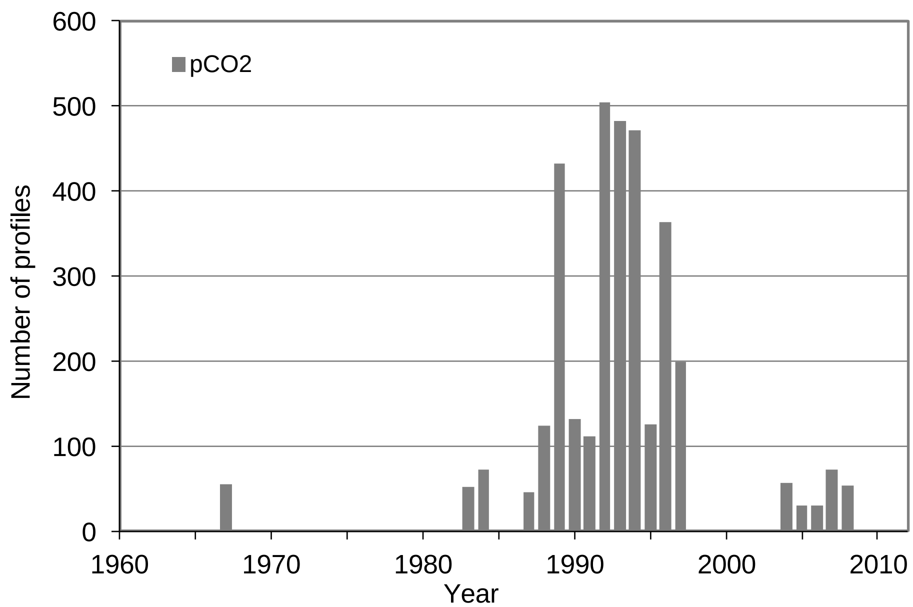

Figure 2.14. Temporal distribution of Partial Pressure of Carbon Dioxide profiles in the WOD13 OSD dataset.

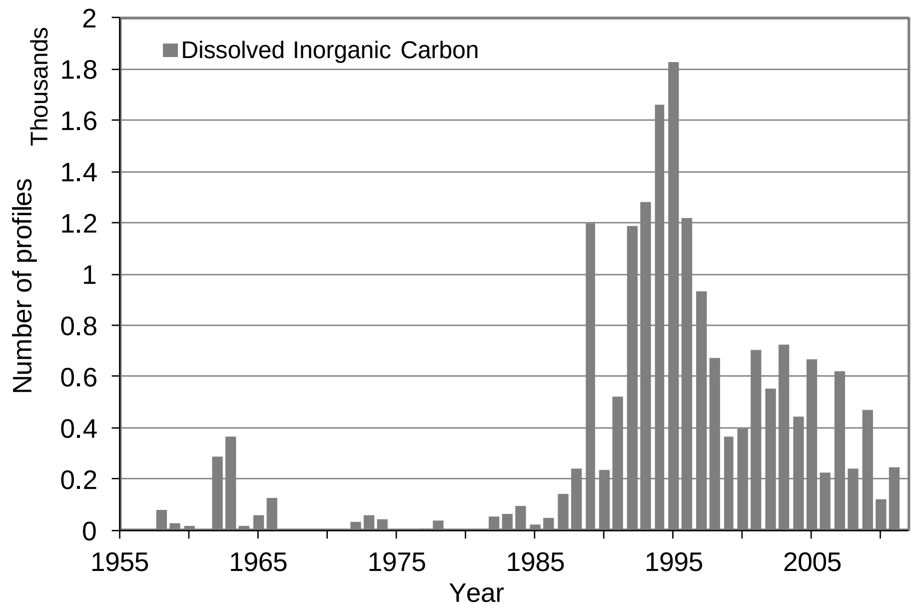

Figure 2.15. Temporal distribution of Dissolved Inorganic Carbon profiles in the WOD13 OSD dataset.

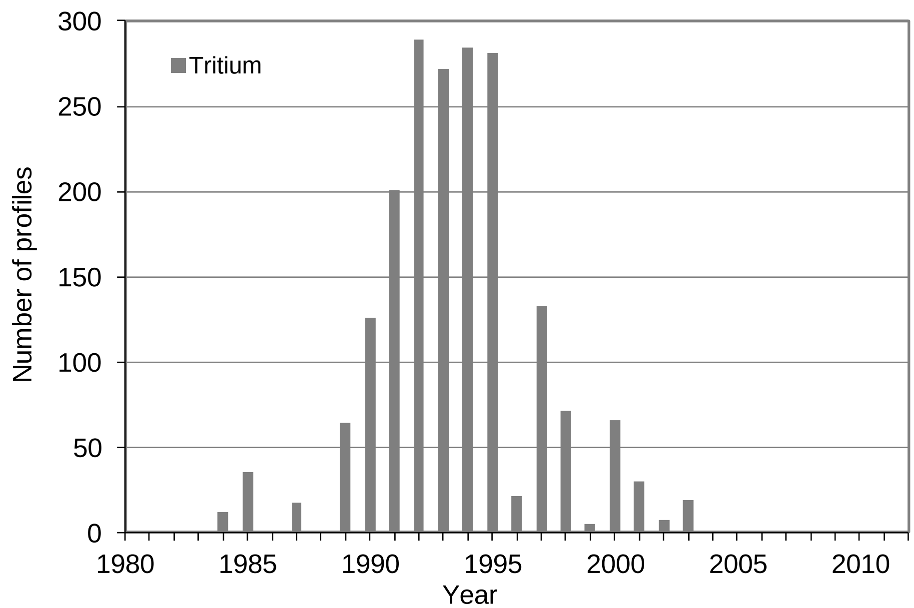

Figure 2.16. Temporal distribution of Tritium profiles in the WOD13 OSD dataset.

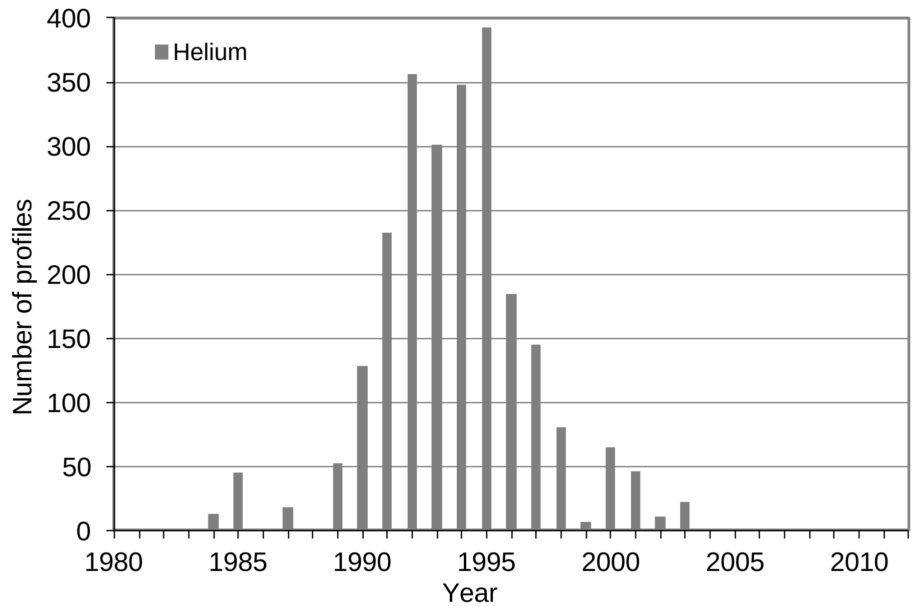

Figure 2.17. Temporal distribution of Helium profiles in the WOD13 OSD dataset.

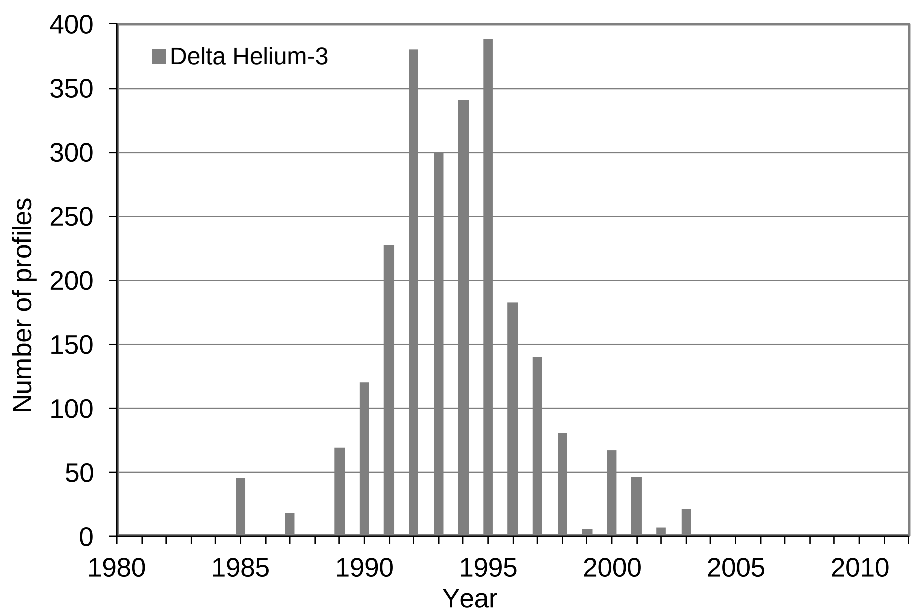

Figure 2.18. Temporal distribution Delta-Helium-3 profiles in the WOD13 OSD dataset.

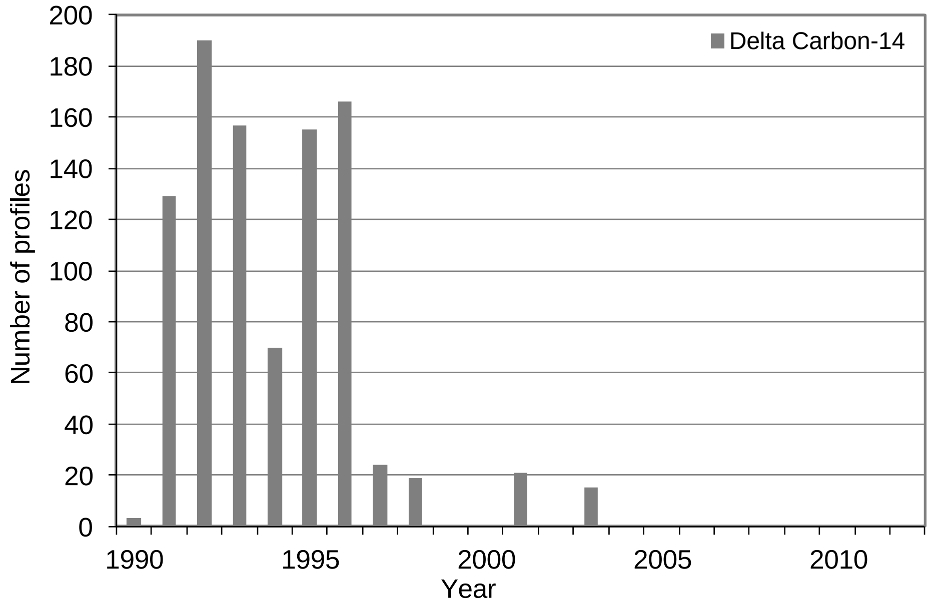

Figure 2.19. Temporal distribution of Delta-Carbon-14 profiles in the WOD13 OSD dataset.

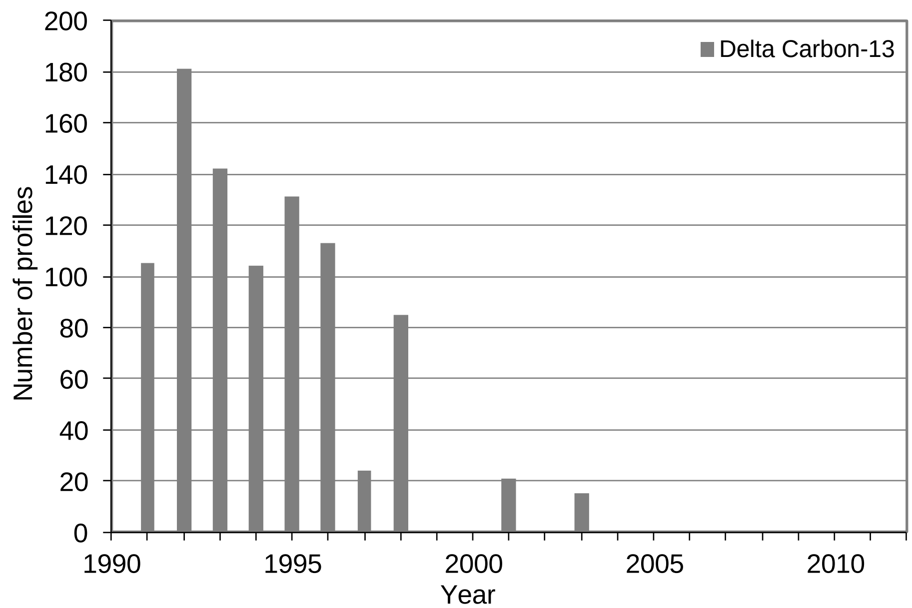

Figure 2.20. Temporal distribution of Delta-Carbon-13 profiles in the WOD13 OSD dataset.

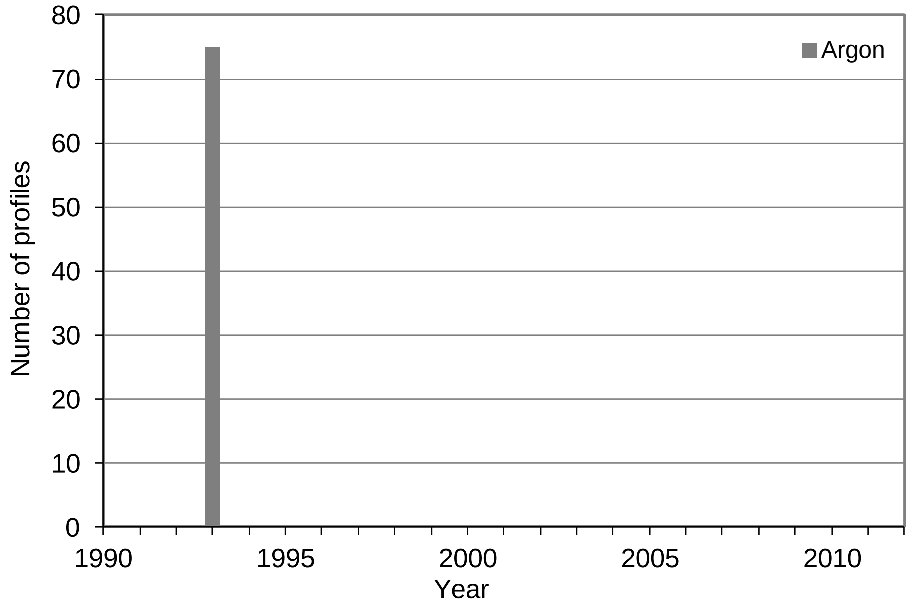

Figure 2.21. Temporal distribution of Argon profiles in the WOD13 OSD dataset.

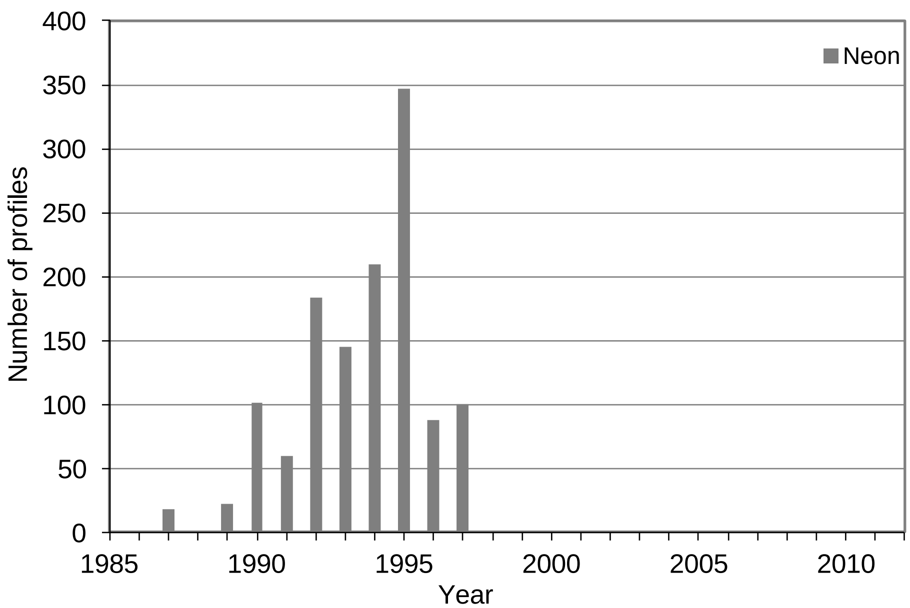

Figure 2.22. Temporal distribution of Neon profiles in the WOD13 OSD dataset.

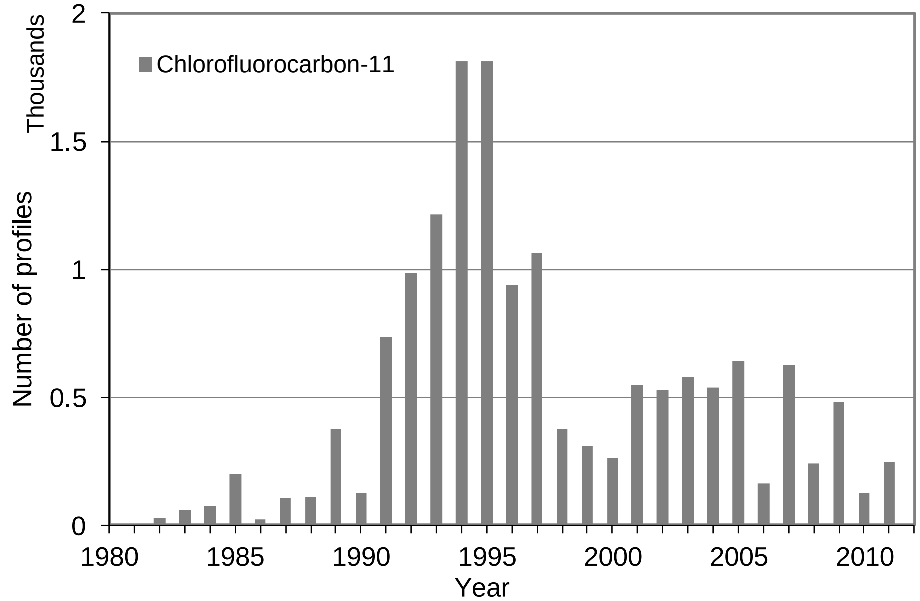

Figure 2.23. Temporal distribution of Chlorofluorocarbon-11 profiles in the WOD13 OSD dataset.

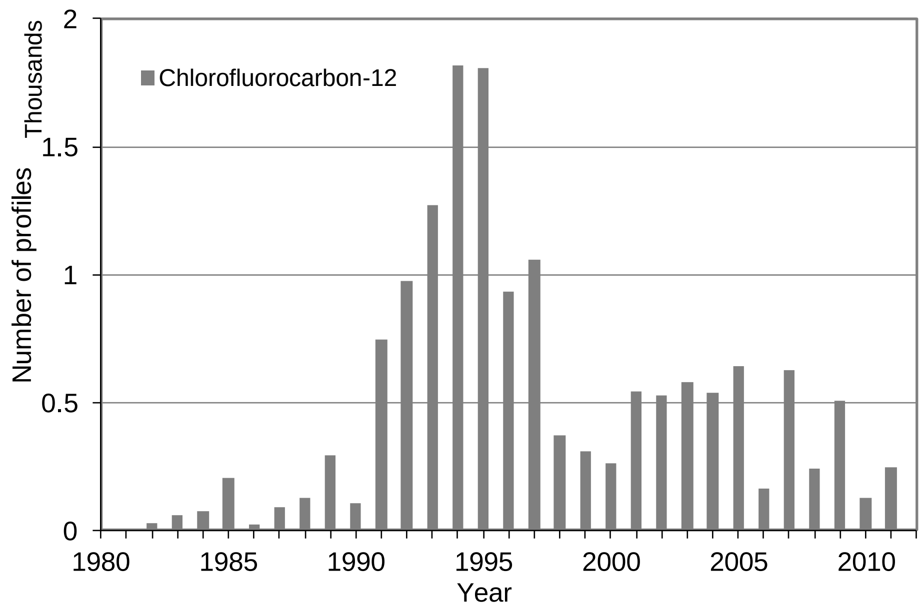

Figure 2.24. Temporal distribution of Chlorofluorocarbon-12 profiles in the WOD13 OSD dataset.

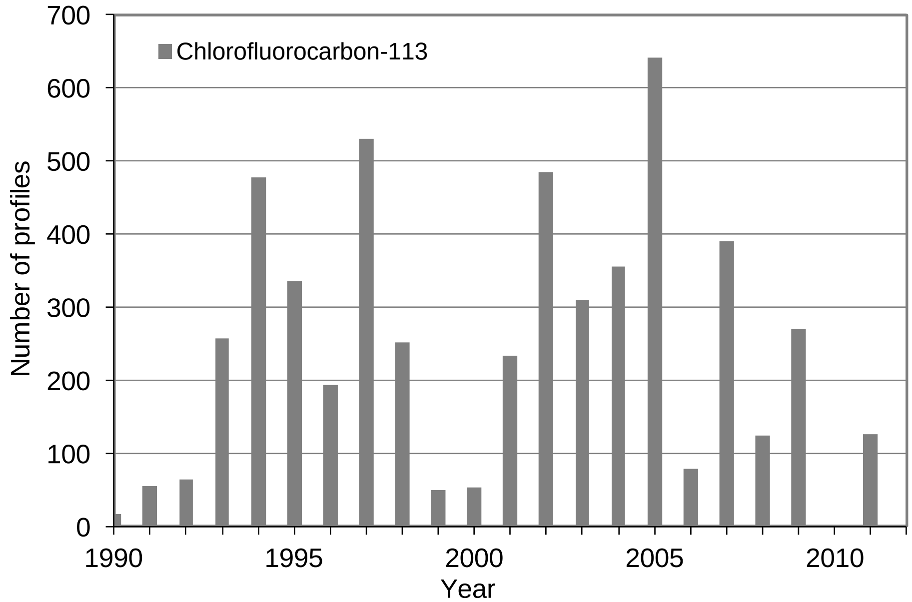

Figure 2.25. Temporal distribution of Chlorofluorocarbon-113 profiles in the WOD13 OSD dataset.

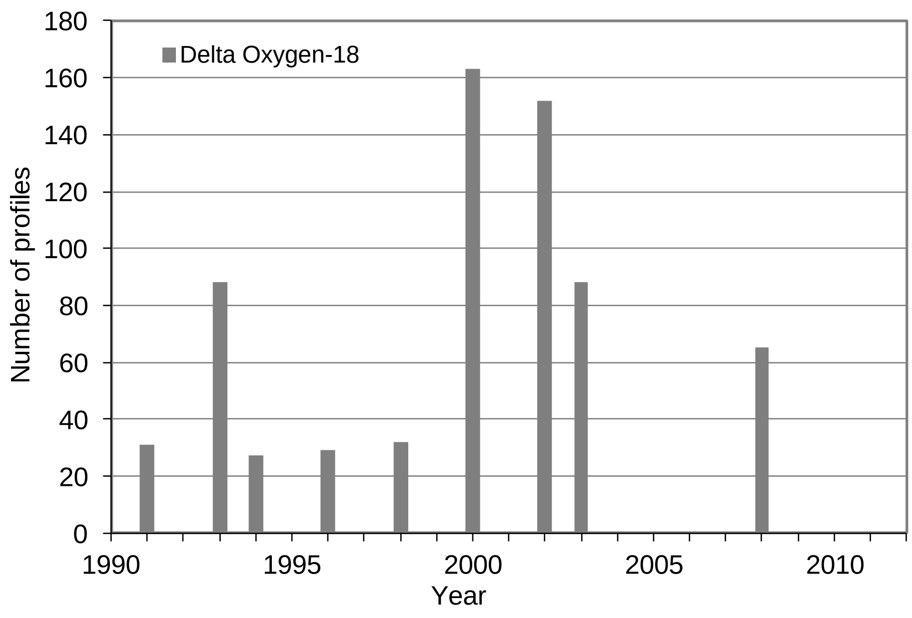

Figure 2.26. Temporal distribution of Delta-Oxygen-18 profiles in the WOD13 OSD dataset.

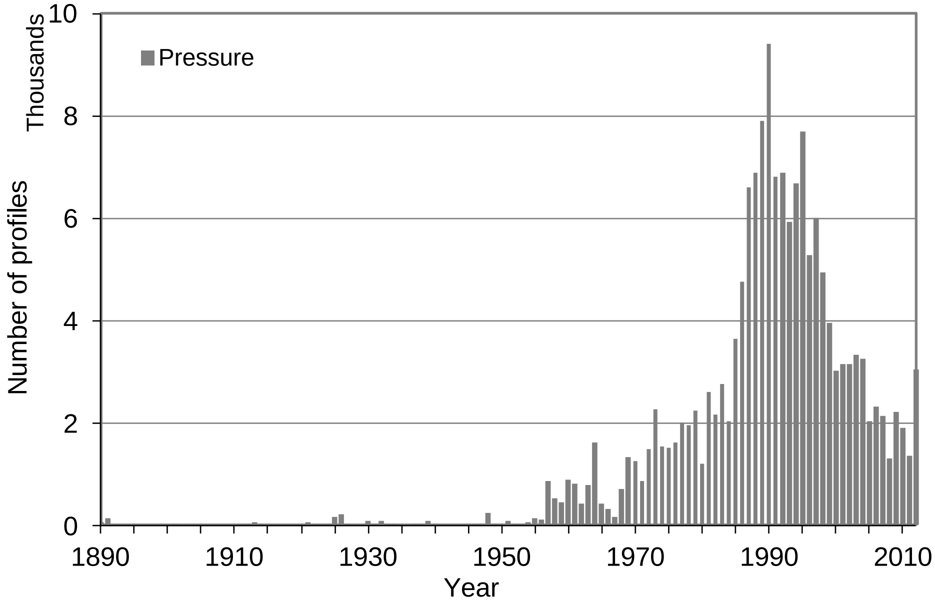

Figure 2.27. Temporal distribution of profiles with Pressure as a measured parameter in the WOD13 OSD dataset.

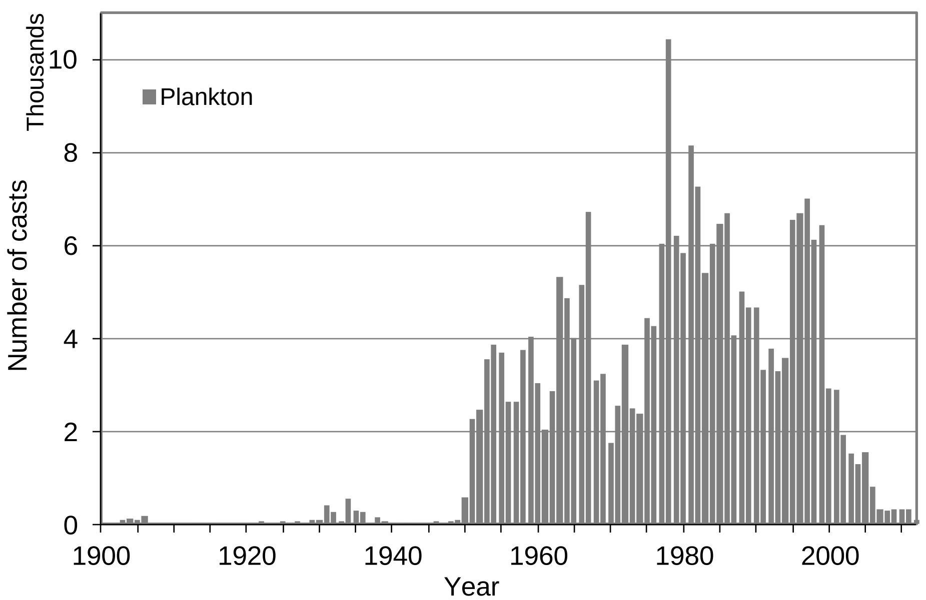

Figure 2.28. Temporal distribution of Plankton casts in the WOD13 OSD dataset.

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CHAPTER 3: CONDUCTIVITY-TEMPERATURE-DEPTH (PRESSURE) DATA (CTD)

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3.1. INTRODUCTION

The Conductivity-Temperature-Depth (CTD) profiling instrument measures temperature and salinity among other variables with high vertical resolution up to depths of 10,000 m. In practice, most CTD casts sample to considerably shallower depths.

Fundamental physical relationships between temperature (salinity, etc.) and electromagnetic properties of sea water are used to develop CTD sensors and appropriate conversion algorithms (Wallace, 1974; Prien, 2001). The response time of CTD sensors is an important factor that determines the ability of the CTD to make "continuous" measurements. For instance, lowering the CTD at speeds of 1 m·s-1 with a typical range of response times for the temperature sensors can provide the vertical profiling at resolutions of 0.05 m to 0.3 m. CTD data that were submitted to NODC/WDC at "sub-meter" vertical resolution have been archived at this resolution, whereas in the past, electronic storage limitations resulted in only selected levels being stored. CTDs measure pressure which can then be converted to depth if desired.

An earlier version of the CTD instrument was the STD (salinity-temperature-depth) which computed salinity from a conductivity sensor as the instrument was moving vertically through the water column. Because of instrument problems that led to erroneous data values (spikes), this method was replaced by the CTD method for which conductivity measurements are recorded from the instrument and then salinity computed from the conductivity measurement with appropriate calibration information. New sensors are being developed to make continuous measurements of other variables (e.g. dissolved oxygen content, beam attenuation coefficient (BAC), chlorophyll concentration, etc.). Beam attenuation coefficient (BAC) measurements from transmissometers are discussed in Section 3.4.

CTD instruments deployed from a vessel can make measurements during both the downward and upward progression of the instrument through the water column. However, each CTD cast submitted to NODC/WDC is either an average of these two vertical casts or just one of them (usually the downward cast). When available this information is stored as part of the WOD metadata of each cast.

Table 3.1 presents the list of all variables stored in the CTD dataset of WOD13.

Table 3.1. List of all variables and profile counts in the WOD13 CTD dataset.

Variables	Profiles
Temperature	847,566
Salinity	819,675
Oxygen	133,468
Chlorophyll	61,775
Transmissivity	21,213
Pressure	497,002

3.2. CTD ACCURACY

The cited accuracy of CTD measurements represents the results of calibration of CTD sensors by comparison with established standards. This initial accuracy varies with instrument design typically from 0.005°C to 0.001°C for temperature, 0.002 $S \cdot m^{-1}$ to 0.0003 $S \cdot m^{-1}$ for conductivity (approximately 0.02 PSS to 0.003 PSS equivalent salinity), and 0.08% to 0.015% for pressure. These accuracies are subject to change by a factor of two or more after prolonged use of the CTD instrument in the sea (known as a calibration drift).

The overall quality of CTD measurements does not depend solely on the accuracy of CTD sensors. Other factors such as the difference in response time of temperature and conductivity sensors, varying speeds of the CTD, along with rapid changes in ocean environment can be important sources of erroneous CTD data (see Lawson and Larson, 2001 for a detailed overview).

Table 3.2. Number of CTD casts in WOD13 as a function of year.
The total number of casts = 848,911, including 8,821 HR XCTD casts.

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1961	97	1974	7,996	1987	24,382	2000	30,780
1962	42	1975	8,267	1988	19,590	2001	31,103
1963	71	1976	9,449	1989	21,940	2002	24,119
1964	47	1977	10,333	1990	22,087	2003	21,217
1965	0	1978	18,365	1991	28,016	2004	21,187
1966	12	1979	11,383	1992	31,628	2005	24,352
1967	1,531	1980	10,631	1993	31,976	2006	22,131
1968	1,286	1981	13,583	1994	31,231	2007	24,022
1969	3,229	1982	12,336	1995	32,967	2008	21,840
1970	1,741	1983	13,697	1996	27,106	2009	22,364
1971	2,071	1984	14,982	1997	30,998	2010	21,906
1972	4,451	1985	15,256	1998	33,325	2011	14,890
1973	5,743	1986	17,855	1999	34,882	2012	13,073

3.3. CTD CAST DISTRIBUTIONS

Table 3.2 gives the yearly counts of high-resolution CTD casts for the World Ocean. Figure 3.1 shows the time series of the yearly totals of CTD casts for the World Ocean. There are a total of 848,911 CTD casts for the entire World Ocean. Table 3.3 gives the national contribution of CTD casts. The geographic distribution of CTD casts for the World Ocean is shown in Figure 3.2. Distribution of the CTD observations at standard depth levels are shown in Figure 3.3. The CTD dataset contains data from 8,821 high-resolution (HR) XCTD casts (see chapter 5).

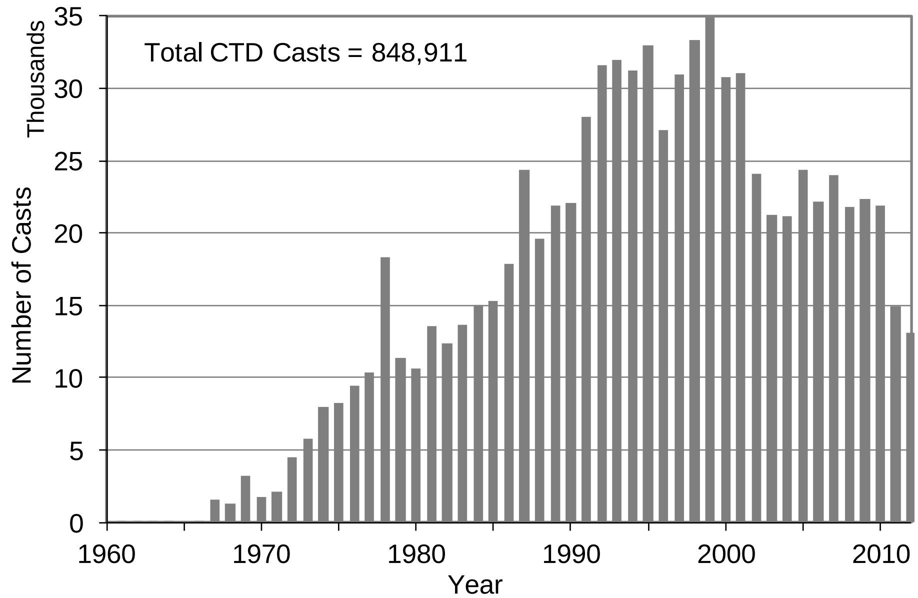

Figure 3.1. Temporal distribution of high-resolution CTD casts in WOD13. Including 8,821HR XCTD casts.

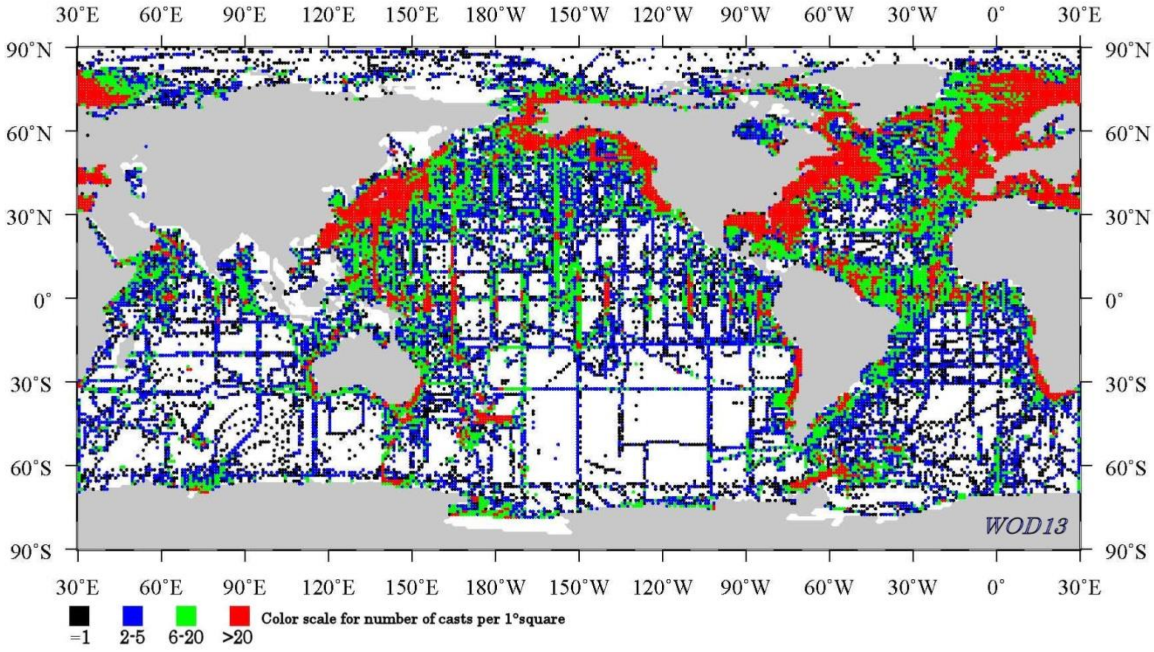

Figure 3.2. Geographic distribution of CTD casts in WOD13.
Including 8,821 HR XCTD casts.

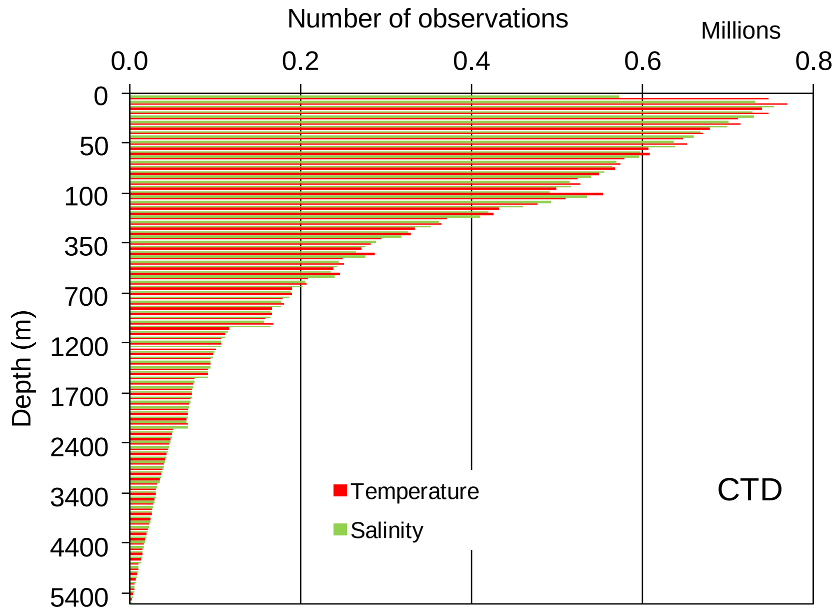

Figure 3.3. Distribution of high-resolution CTD data at standard depth levels in WOD13
Including 8,821 HR XCTD casts.

Table 3.3. National contributions of high-resolution CTD casts in WOD13.

ISO[a] Country Codes	Country Name	CTD Casts	% of Total
US	United States	203,244	23.94
CA	Canada	159,689	18.81
JP	Japan	87,685	10.33
NO	Norway	79,851	9.41
DE	Germany	45,907	5.41
GB	Great Britain	43,840	5.16
FR	France	35,073	4.13
99	Unknown / International	27,199	3.20
TW	Taiwan	23,744	2.80
SU	Union of Soviet Socialist Republics	21,279	2.51
DK	Denmark	15,022	1.77
AU	Australia	14,370	1.69
IT	Italy	12,899	1.52
UA	Ukraine	9,187	1.08
ES	Spain	7,623	0.90
ZA	South Africa	6,357	0.75
CL	Chile	6,106	0.72
GR	Greece	5,911	0.70
NZ	New Zealand	5,432	0.64
IE	Ireland	5,403	0.64
NA	Namibia	5,044	0.59
CN	China	3,259	0.38
IS	Iceland	2,899	0.34
RU	Russian Federation	2,766	0.33
TR	Turkey	2,705	0.32
NL	Netherlands	2,537	0.30
PL	Poland	2,137	0.25
AR	Argentina	1,791	0.21
DU	East Germany	1,692	0.20
PT	Portugal	1,566	0.18
BR	Brazil	1,256	0.15
ZZ	Miscellaneous organizations	1,038	0.12
IL	Israel	914	0.11
IN	India	752	0.09
BE	Belgium	440	0.05
VE	Venezuela	389	0.05
PA	Panama	337	0.04
FI	Finland	254	0.03
CY	Cyprus	235	0.03
EC	Ecuador	217	0.03
ID	Indonesia	213	0.03
SE	Sweden	150	0.02
BG	Bulgaria	90	0.01
MX	Mexico	82	0.01
PE	Peru	74	0.01
TN	Tunisia	73	0.01

ISO[a] Country Codes	Country Name	CTD Casts	% of Total
EG	Egypt	69	0.01
LB	Lebanon	42	< 0.01
KR	Korea; Republic of	28	< 0.01
RO	Romania	27	< 0.01
DZ	Algeria	13	< 0.01
HR	Croatia	1	< 0.01
	Total:	*848,911*	*100.00*

[a] ISO = International Organization for Standardization

3.4. TRANSMISSOMETER OBSERVATIONS

3.4.1. Introduction

Transmissometers measure the attenuation of well-collimated light of a given wavelength over a known distance in water. Light attenuation is due to both **absorption** and **scattering**. When referenced to pure water, the beam attenuation coefficient (BAC, referred to as *c* in following equations) defines light losses due to absorption by dissolved and particulate matter and from scattering by particles. Changes in the attenuation of light through water are related primarily to changes in the abundance of particles and secondarily to the type of particles present. The amount of light absorbed or scattered by different types of particles and colored dissolved organic matter (CDOM) also varies by wavelength and is affected by the composition of the particles, their size, shape, and internal index of refraction distribution (e.g. Smith and Baker, 1981).

The majority of transmissometer data presented in WOD13 were collected using instruments operated at 660 nm (red) wavelength.

Attenuation is virtually independent of salinity (Richardson and Gardner, 1997). Most of the attenuation signal comes from particles less than 20 microns in diameter. Large particles and aggregates greater than 500 microns in diameter are not abundant in the ocean (DuRand and Olson, 1996; Stramski and Kiefer, 1991; Chung *et al.*, 1996, 1998). Typically, only a few large particles exist in 1000 milliliters of water, so they rarely appear in the small sensing volume of the transmissometer (~45 milliliters). When they are present, they usually create a spike in attenuation.

The standard unit for storing beam attenuation coefficient values in WOD13 is determined as $c = ln\ (T_r) / r\ (m^{-1})$, where T_r is percentage of light transmitted through the instrument's path-length and calculated from a calibrated raw voltage signal measured by the instrument, and r is the instrument's path-length (in m). It should be noted, however, that a significant amount of early submitted data are still in T_r and in raw voltage. Therefore, those data are not included in the WOD13 distribution but they are mentioned in the following statistics. Eventually, if/when proper metadata will be available and correct calibration of the data values will be possible, those data will be converted to the standard units and added to future releases of the database.

The BAC can be described as a sum of three components:

$$c = c_w + c_{CDOM} + c_p,$$

where: c_w – due to pure seawater (constant at 660 nm); c_{CDOM} – due to colored dissolved organic matter (≈ 0 at 660nm); c_p – due to particles.

Since attenuation is due to both **absorption** and **scattering**,

$$a_p + b_p = c_p$$

where: a = absorption, b = scattering, a_p - absorption by particles is negligible at this spectral range (Bricaud *et al.*, 1998), $b_p = b_{pf} + b_{pb}$ → forward & backward scattering.

In the red part of the spectrum, attenuation due to dissolved materials is negligible, so that attenuation in the red is due primarily to particles. The beam attenuation coefficient in the red is an excellent proxy for the total volume of particles (Bartz *et al.*, 1978; Bishop, 1999; http://www.wetlabs.com/; http://www.hobilabs.com; http://www.chelsea.co.uk).

3.4.2. Spatial and Temporal Distribution of Transmissometer Profiles

Transmissometer profiles presented in WOD13 were collected during several international and U.S. national programs for the period of 1975-2011. The majority of data comes from the World Ocean Circulation Experiment (WOCE), Marine Ecosystem Analysis Project for New York Bight (MESA-NYB), Northeast Gulf of Mexico (NEGOM), Joint Global Ocean Flux Study (JGOFS), Bermuda Atlantic Time Series (BATS), Hawaiian Oceanographic Time Series (HOT), Atlantic Meridional Transect Program (AMT), and other programs. Table 3.4.1 presents a full list of the research programs and projects that contributed beam attenuation data to WOD13. The greater parts of data were post-processed at Texas A&M University under grants from the U.S. National Science Foundation (NSF) (Chung *et al.*, 1996, 1998; Mishonov *et al.*, 2003; Mishonov and Gardner, 2003; Richardson *et al.*, 2003; Zawada *et al.*, 2005; Gardner *et al.*, 2006).

Figure 3.4.1 represents the geographical distribution of the transmissometer profiles where beam attenuation coefficient measurements were taken, in WOD13 for the World Ocean.

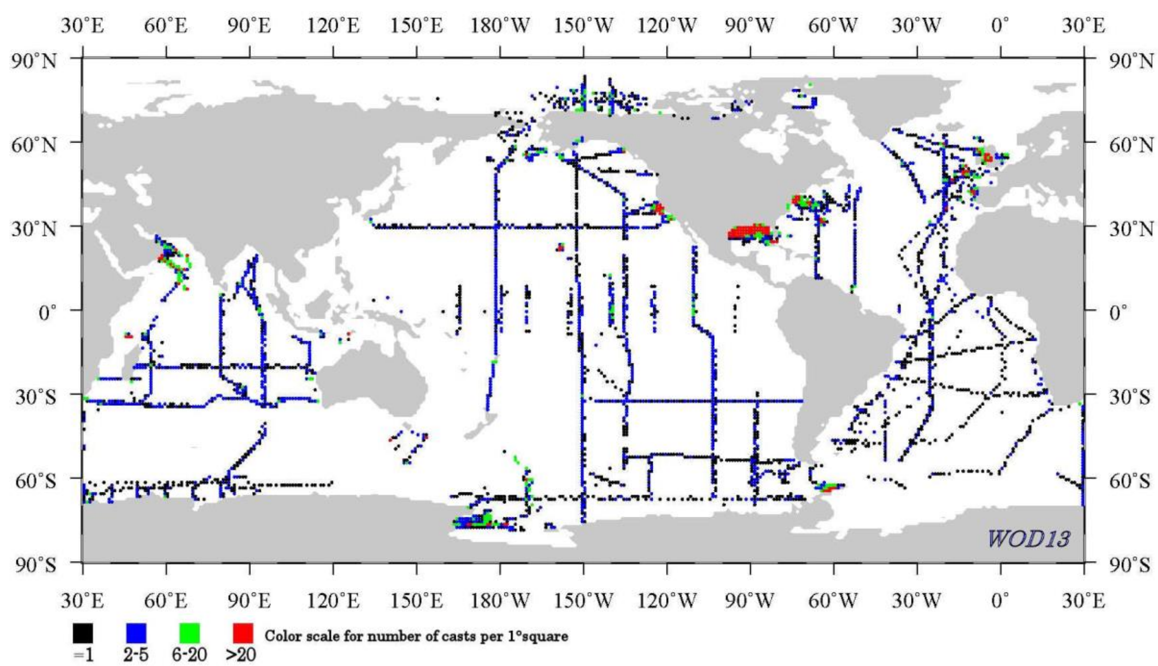

Figure 3.4.1. Geographic distribution of BAC casts in WOD13.

Table 3.4.1. Projects contributing to the WOD13 BAC data set.

NODC Project #	Project Name	Profiles
225	World Ocean Circulation Experiment (WOCE)	2,250
121	Southeast Area Monitoring and Assessment Program (SEAMAP)	1,940
597	Hypoxia Studies in the Northern Gulf Of Mexico	1,681
65	Marine Ecosystems Analysis Project - New York Bight (MESA – NYB)	1,494
412	MMS/Northeast Gulf of Mexico Physical Oceanographic Program (NEGOM)	894
305	Hawaii Ocean Time-Series (HOT)	649
275	South East Florida and Caribbean Recruitment (SEFCAR)	565
485	Climate Variability and Predictability (CLIVAR)	551
301	North Atlantic Bloom Experiment (NABE)	550
365	US JGOFS Antarctic Environments Southern Ocean Process Study (AESOPS)	464
361	Equatorial Pacific Basin Study (EQPAC)	462
70	The Mississippi, Alabama, Florida (MAFLA) Environmental Baseline Studies	387
453	The FRUELA Project, part of the Spanish Contribution to the Study of Biogeochemical Carbon Fluxes in the Southern Ocean	301
379	Anatomy of Gulf Stream Meanders (AGM)	287
619	Atlantic Meridional Transect Program (AMT)	280
373	Ocean Margin Exchange Project (OMEX)	222
216	South Atlantic Ventilation Experiment (SAVE)	219
417	Tropical Atmosphere Ocean (TAO) Buoy Array	195
406	Research on Ocean Atmosphere Variability & Ecosystem Response in Ross Sea	194
372	JGOFS/Arabian Sea Process Studies	180
527	U.S. Climate Variability And Predictability (US CLIVAR)	110
399	Plankton Reactivity in the Marine Environment (PRIME)	100
246	Bering & Pacific Russian/U.S. Cooperative Research Program (BERPAC)	81
310	Distribution/Abundance of Marine Mammals in Northern Gulf of Mexico (GULFCET II)	80
618	International Nusantara Stratification and Transport Program (INSTANT)	54
487	Deepwater Program: Northern Gulf of Mexico Continental Slope Habitat & Benthic Ecology	51
33	California Cooperative Oceanic and Fisheries Investigation (CalCOFI)	47
281	Bermuda Atlantic Time Series (BATS)	42
591	Pacific Coast Ocean Observing System (PACOOS)	40
201	North Atlantic Bloom Study (NABS)	36
105	Outer Continental Shelf - Central Gulf of Mexico (OCS-Central Gulf)	35
595	Rapid Climate Change Programme (RAPID)	24
394	The ARABESQUE	20
200	Joint Global Ocean Flux Study (JGOFS)	8
630	Meso-Scale Vortices/Meanders in the Central Portion of the Bransfield St. (BREDDIES)	7
n/a	Data with no project info	6,713

Table 3.4.2 and Figure 3.4.2 presents the temporal distribution of transmissometer profiles in WOD13 as a function of year. Figure 3.4.3 presents the distribution of the BAC observations on standard depth levels.

Table 3.4.2. Number of BAC profiles in WOD13 as a function of year.
Total number of profiles = 21,213

YEAR	PROFILES	YEAR	PROFILES	YEAR	PROFILES	YEAR	PROFILES
1975	141	1985	23	1994	1,732	2003	741
1976	288	1986	45	1995	1,845	2004	716
1977	352	1987	451	1996	591	2005	770
1978	669	1988	405	1997	955	2006	754
1979	466	1989	414	1998	880	2007	1,117
1980	0	1990	250	1999	1,046	2008	640
1981	0	1991	388	2000	559	2009	264
1982	0	1992	1,116	2001	467	2010	165
1983	263	1993	2,025	2002	512	2011	139
1984	24						

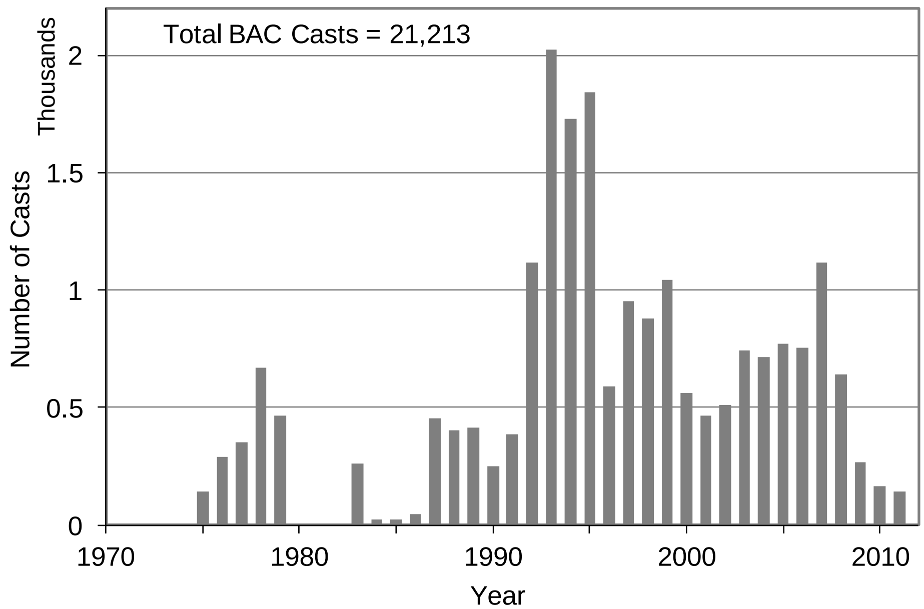

Figure 3.4.2. Temporal distribution of BAC profiles in WOD13.

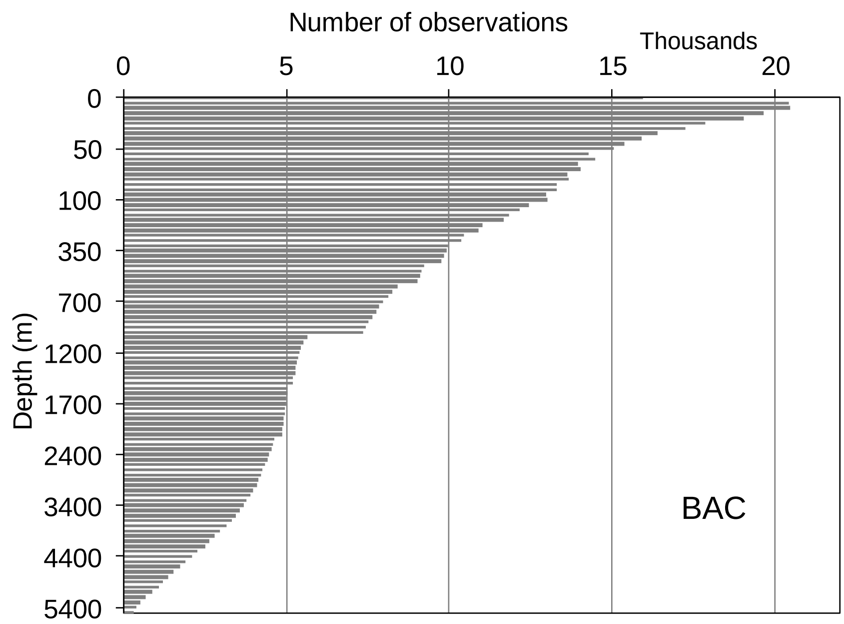

Figure 3.4.3. Distribution of BAC data at standard depth levels in WOD13.

3.4.3. Relevant Web Sites

Bermuda Atlantic Time Series (BATS).
Chelsea Technologies Group Ltd.
Global Transmissometer Data Base at Texas A&M University.
Hawaiian Oceanographic Time Series (HOT).
Hydro-Optics, Biology & Instrumentation Laboratories (HOBILabs, Inc.)
Joint Global Ocean Flux Study (JGOFS).
Northeast Gulf of Mexico Program (NEGOM).
WetLabs, Inc.
World Ocean Circulation Experiment (WOCE).

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CHAPTER 4: EXPENDABLE BATHYTHERMOGRAPH DATA (XBT)

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4.1. INTRODUCTION

The Expendable Bathythermograph (XBT) was deployed beginning in 1966 and replaced the Mechanical Bathythermograph (MBT) in most measurement programs. The XBT allows the measurement of the upper ocean's temperature profile when launched from underway surface ships, submarines, and aircraft. The system consists of three main components: an expendable measuring probe, a launcher, and an electronic data acquisition unit. The expendable probe includes a thermistor and a spool of copper wire that unwinds as the probe falls through the water column. The temperature information from the thermistor is transmitted through the copper wire to the launcher on the platform. The launcher holds a second copper wire spool that unwinds as the platform continues its underway trajectory. Finally the temperature signal is sent from the launcher through a cable to the data acquisition system, where the data are recorded.

The system has different details when the expendable probes are launched from a submarine or from an aircraft. From a submarine, a float carries the expendable probe to the sea surface. Upon reaching the sea surface, the probe detaches from the float and start to falls through the water column. From an aircraft, the expendable probe and a floating surface unit are deployed with a parachute. After reaching the sea surface, the probe detaches from the floating unit and falls through the water column. The temperature information from the thermistor is transmitted through the copper wire to the floating surface unit which transmits the data to the acquisition system in the aircraft via a radio signal.

Of all the XBT profiles in WOD13, 46.2% are known to have been obtained with probes manufactured by Lockheed Martin Sippican (formerly known as Sippican), 2.1% to have been obtained with probes manufactured by Tsurumi Seiki Co. LTD (TSK), and 0.2% to have been obtained with probes manufactured by Sparton. There is no manufacturer information for the probe used for about half, 51.1%, of the XBT profiles. Each manufacturer has several models of XBT probes which have different maximum sampling depths with the associated launching platform moving at or below the allowed maximum speed. As an example, Table 4.1 below shows the characteristics for some expendable probes produced by Lockheed Martin Sippican.

Table 4.1. Characteristics of expendable probes produced by Lockheed Martin Sippican.

Model	Maximum Depth	Rated Ship Speed
T-4	460 m	30 kts
Deep Blue	760 m	20 kts
T-7	760 m	15 kts
T-5	1830 m	6 kts
T-6	460 m	15 kts
Fast Deep™	1000 m	20 kts
T-10	200 m	10 kts
T-11	460 m	6 kts

Corresponding models from different manufacturers have similar characteristics. There is model information for about 52% of the XBT profiles in WOD13. The most popular probe model is the T-4, with about 22% of the XBT profiles in WOD13 known to be obtained with such a probe, while Deep Blue and T-7 probes are known to each account for about 13% of the XBT profiles in WOD13.

The XBT system does not directly measure depth. The depth of each temperature measurement obtained by the expendable probe is estimated using a depth-time equation. This equation converts the time elapsed from the moment the probe enters the water, in seconds, to depth, in meters.

4.2. XBT ACCURACY

Lockheed Martin Sippican reports temperature accuracy of ±0.1°C for their surface ship expendable probes and ±0.15°C for their submarine expendable probes, with a depth accuracy of ±2% for all probes. Tsurumi Seiki Co. LTD reports temperature accuracy of ±0.1°C and depth accuracy of ±2% or 5 m, whichever is larger.

4.3. XBT DEPTH-TIME EQUATION ERROR

Since the XBT system does not measure depth directly, the accuracy of the depth associated with each temperature measurement is dependent on the equation which converts the time elapsed since the probe entered the water to depth. Unfortunately, problems have been found in various depth-time equations used since the introduction of the XBT system.

The original depth-time equation developed by Sippican for their T-4, T-6, T-7, and Deep Blue models underestimates the probes fall rate. At a given elapsed time, the falling probe is actually deeper than indicated by the original equation. Thus, the water temperatures are associated by the original equation with depths that are shallower than the actual depths at which they are measured. The error, first documented by Flierl and Robinson (1977), increases with increasing elapsed time reaching 21 meters, or about a 2.5% error, for depths around 800 meters. Sippican's original equation was used by TSK for their T-4, T-6, T-7, and Deep Blue models, and by Sparton for their XBT-4, XBT-6, XBT-7, XBT-7DB, XBT-20, and XBT-20DB models.

In 1994, Hanawa *et al.* published an International Oceanographic Commission (IOC, 1994) report detailing a study of XBT fall rates using different probes manufactured by Sippican and TSK and dropped in different geographic locations. A new depth-time equation, the Hanawa *et al.* (1995) equation, was given, as well as an algorithm for correcting depths for existing data collected using the original equation. The report emphasized the need to continue to archive existing data with the original depth equation only, applying the correction when necessary for scientific research.

Sparton XBT-7 probes were studied by Rual *et al.* (1995) and Rual *et al.* (1996). It was determined that the Hanawa *et al.* (1995) equation was suitable for use with these probes.

Thadathil *et al.* (2002), however, suggest that the Hanawa *et al.* (1995) equation is not valid for measurements in high-latitude low temperature waters.

Following the report of Hanawa *et al.* (1995) and IOC (1994), TSK altered their software between January and March 1996 to make the Hanawa *et al.* (1995) equation the default equation (Greg Ferguson, personal communication). Sippican did the same around August 1996, (James Hannon, personal communication). However an universal switch to the new software has not been made. As of late 2008, data from XBT drops are recorded using both the original and Hanawa *et al.* (1995) depth-time equations.

Kizu *et al.* (2005) published a new depth-time equation for the TSK T-5 probes, but no manufacturer software has been released with their equation.

Corrections to the depth-time equations for air-dropped XBT probes (AXBT) manufactured by Sippican and Sparton were calculated by Boyd (1987) and Boyd and Linzell (1993b) respectively.

Gouretski and Koltermann (2007) found that the XBT fall-rate error is time dependent and developed corrections. Wijffels *et al.* (2008), Ishii and Kimoto (2009), and Levitus *et al.* (2009) also developed corrections. In particular, Levitus *et al.* (2009) compared their own corrections with the corrections of Wijffels *et al.* (2008) and Ishii and Kimoto (2009). Since these earlier findings, numerous studies have published different methods which, as a function of the probe manufacturer and model, year of deployment, water column temperature, and geographical location, provide corrections to the original XBT depth values, e.g. Gouretski and Reseghetti (2010), Good (2011), Hamon *et al.* (2012), Gouretski (2012), and Cowley *et al.* (2013).

4.4. CORRECTIONS TO XBT DEPTH-TIME EQUATION ERRORS AND TEMPERATURE BIASES

Before the various depth-time equations errors were widely known, a significant amount of data were recorded and archived without notation of what model of expendable probe was used. About 48%, or 1.06 million, of the total 2.21 million XBT temperature profiles in WOD13 have "unknown" model of XBT instrument. Of these, about 0.75 million are positively identified as coming from shipboard drops. The other 0.31 million were dropped from unknown platforms. These missing ancillary metadata make it difficult to know whether the reported depths for a particular XBT profile were obtained with an incorrect depth-time equation.

Presently, some XBT data are still recorded and archived with no indication of the depth-time equation used. This is particularly critical now, since there is more than one depth-time equation in use for many XBT models.

The XBT data in the WOD13 on observed levels report the same data as submitted to NODC/WDC by the originators. Secondary header 33 indicates reported information on the depth-time equation used by the originator – see Johnson *et al.* (2013) for more information on WOD13 format and code descriptions. Secondary header 33 is set to 0 if the original depth-time equation was used, and it is set to 1 if the Hanawa *et al.* (1995) or another amended depth-time equation was used. Secondary header 33 is absent if the depth-time equation used is unknown. Data taken before the introduction of corrected depth-time equations (January 1996) usually have unknown depth-time equation, and it is assumed the original equation was used unless otherwise noted. Indeed, about 2,700 pre-1996 XBT drops include depths that are known to have been corrected by the originator before being submitted to NODC/WDC.

The XBT data in the WOD13 interpolated to standard levels uses the appropriate corrected depth when possible using the corrections of Levitus *et al.* (2009). Since close to half of all XBT profiles are of unknown model, a test was applied to these data to see if a depth correction was necessary. It was assumed that, following the IOC recommendation, data available in the WOD13 were received at NODC with depths calculated using the original equations unless otherwise noted. This assumption is not always valid for data collected since new depth-time equations became available on recording software released by each XBT manufacturer. For data collected since January 1996, if the depth-time equation used was not noted, the data were not corrected when interpolating to standard levels and were marked so as not to be used for depth sensitive calculations. Of a total of 559,575 XBT drops during the relevant time period (1996-2012), there are 96,833 drops without depth-time equation information, with the vast majority of them belonging to the period 1996-2000: only 67% of XBT drops from 1996 to 2000 include the information on the depth-time equation used, in contrast to 97% of XBT drops from 2001 to 2012 including that information.

An attempt to ascertain the missing depth-time equation information was made by contacting the data originators. Most of the data originators are large data centers and the information could not be recovered. The actual values of the reported depths can be used to recognize the depth-time equation used, when the full depth trace is reported (Donald Scott, personal communication). Although most data received at NODC comes with only selected depth levels, when possible, this technique was used.
Secondary header 54 contains information on our decision on whether the depths need correction for each XBT given the criteria listed above. This secondary header also carries information on exactly which corrected depth-time equation should be used to recalculate the reported depth values.

IMPORTANT: THE OBSERVED LEVEL XBT DATA IN WOD13 ARE THE SAME DATA AS SUBMITTED BY THE ORIGINATORS. IF YOU ARE USING OBSERVED LEVEL XBT DATA FROM WOD13, PLEASE USE SECONDARY HEADER 54 TO SEE WHETHER A DEPTH CORRECTION IS NECESSARY.

OBSERVED LEVEL XBT DATA AVAILABLE ONLINE THROUGH WODselect CAN BE DOWNLOADED WITH ELEVEN DIFFERENT DEPTH ERROR/TEMPERATURE BIAS CORRECTIONS.

THE STANDARD LEVEL XBT DATA IN WOD13 WERE PREPARED, WHEN NEEDED AND POSSIBLE, USING A CORRECTED DEPTH-TIME EQUATION AND THE XBT TEMPERATURE BIAS CORRECTION FOLLOWING LEVITUS *et al.* (2009).

XBT TEMPERATURE BIAS CORRECTIONS WERE RECALCULATED USING AN UPDATED DATA SET FOR WORLD OCEAN DATABASE 2013 AND WORLD OCEAN ATLAS 2013 (SEE APPENDIX 1).

WHEN USING STANDARD LEVEL XBT DATA FROM WOD13, PLEASE USE SECONDARY HEADER 54 TO SEE WHETHER A CORRECTED DEPTH-TIME EQUATION WAS USED, A CORRECTION WAS NOT NEEDED, OR A CORRECTION COULD BE NEEDED BUT THERE WAS NOT ENOUGH INFORMATION.

4.5. SURFACE DATA ACQUIRED CONCURRENTLY WITH XBT CASTS

On a surface ship sometimes a sea-surface water sample is obtained at the time of the XBT launch. Temperature and salinity of the water sample are usually measured and recorded as ancillary information of the XBT launch. Meteorological conditions at the time of the XBT launch could also be recorded, *e.g.* air temperature, wind speed and direction, cloud type and cover, barometric atmospheric pressure, as well as sea conditions: wave height and direction, sea state. When available, these data are included in WOD13 as secondary header information for the corresponding XBT drop.

4.6. XBT PROFILE DISTRIBUTIONS

Table 4.2 gives the yearly counts of XBT profiles for the World Ocean. Figure 4.1 shows the time series of the yearly totals of Expendable Bathythermograph profiles for the World Ocean. Figure 4.2 shows the distribution of XBT data at observed levels. The relative minimun between the surface and 100 m is due to the procedure used to report XBT profiles in real-time which results in very few values reported for the nearly isothermal upper water column layer above the thermocline. There are significant decreases in the number of observations below the maximum depths sampled by the most popular probe models: 460 m (T-4) and 760 m (Deep Blue and T-7).

There are a total of 2,211,689 XBT profiles for the entire World Ocean with 452,206 profiles (20.4%) measured in the southern hemisphere and 1,759,483 profiles (79.6%) measured in the northern hemisphere (Figure 4.3). Although 66 known countries contribute XBT data to WOD13, 78% of the profiles are contributed by just 7 countries: United States, Japan, Great Britain, Australia, Canada, Germany, and France (Figure 4.4). Some country contributions merely reflect the flag of merchant ships in the Ship of Opportunity Program (SOOP), and they do not represent active national scientific programs, e.g. Liberia, Panama, Singapore, and Antigua. Table 4.3 gives detailed information about national contributions of XBT sorted by contribution from each country.

Table 4.2. The number of all XBT profiles as a function of year in WOD13.
Total Number of Profiles = 2,211,689

YEAR	PROFILES	YEAR	PROFILES	YEAR	PROFILES	YEAR	PROFILES
1966	1,750	1978	53,482	1990	83,139	2002	27,731
1967	9,393	1979	56,313	1991	71,992	2003	27,371
1968	26,684	1980	55,282	1992	66,182	2004	32,295
1969	34,321	1981	55,012	1993	71,042	2005	29,485
1970	45,701	1982	56,081	1994	69,251	2006	25,999
1971	57,630	1983	59,063	1995	78,620	2007	23,092
1972	53,198	1984	56,299	1996	63,697	2008	23,227
1973	54,954	1985	68,875	1997	52,981	2009	22,637
1974	54,931	1986	75,444	1998	49,985	2010	20,767
1975	54,535	1987	72,081	1999	55,973	2011	18,760
1976	48,585	1988	62,495	2000	39,798	2012	14,814
1977	54,501	1989	45,278	2001	30,963		

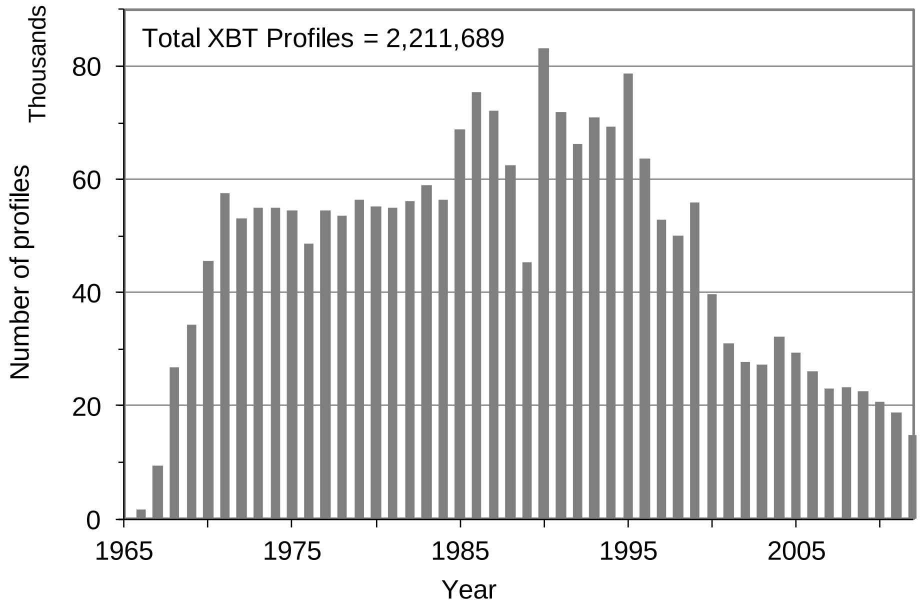

Figure 4.1. Temporal distribution of Expendable Bathythermograph (XBT) profiles in WOD13.

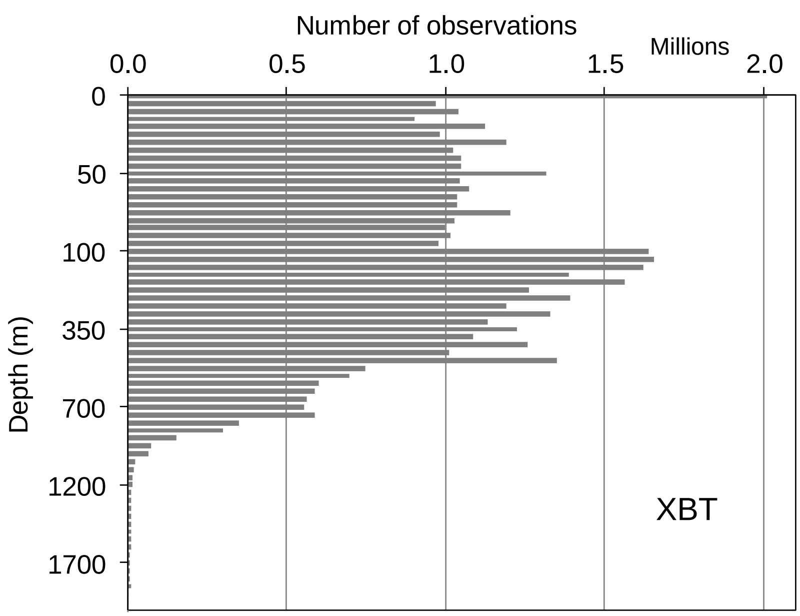

Figure 4.2. Distribution of Expendable Bathythermograph (XBT) data at standard depth levels in WOD13.

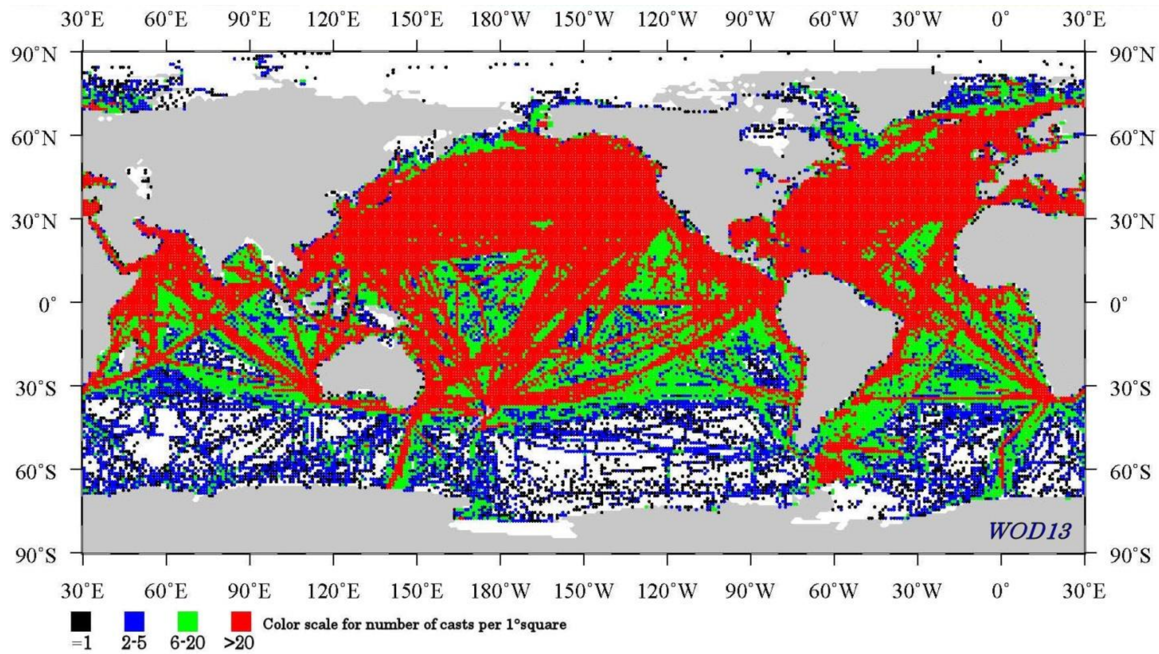

Figure 4.3. Geographic distribution of XBT profiles in WOD13.

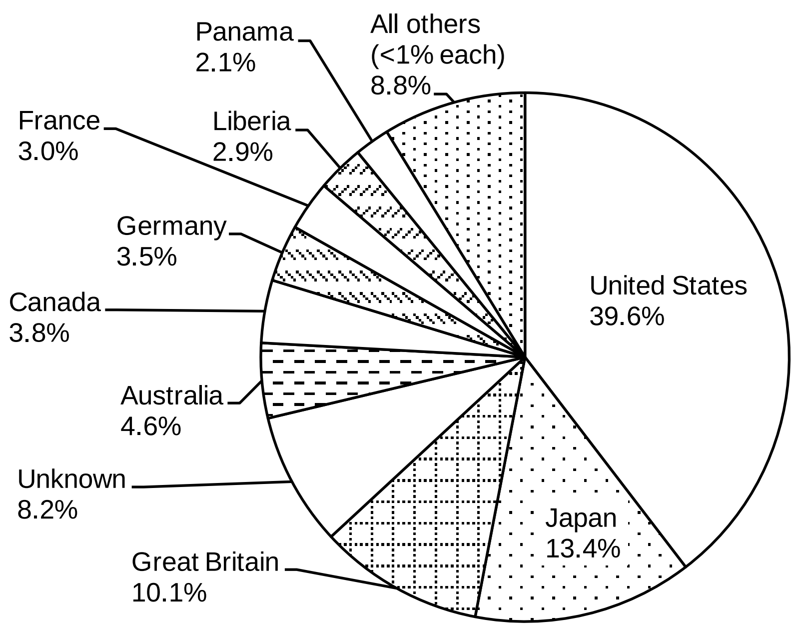

Figure 4.4. XBT data contribution by countries in WOD13.
Totals for Liberia and Panama reflect data collected from merchant ships in the Ship of Opportunity Program (SOOP) and registered under these countries' flags; they do not represent active national scientific programs.

Table 4.3. National contribution of XBT profiles in WOD13.

ISO[a] Country Code	Country Name	XBT Casts	% of Total
US	United States	875,753	39.60
JP	Japan	297,015	13.43
GB	Great Britain	223,344	10.10
99	Unknown	180,588	8.17
AU	Australia	101,080	4.57
CA	Canada	84,862	3.84
DE	Germany	77,061	3.48
FR	France	67,395	3.05
LR	Liberia	63,376	2.87
PA	Panama	47,406	2.14
SG	Singapore	19,006	0.86
NL	Netherlands	15,802	0.71
SU	Union of Soviet Socialist Republics	14,230	0.64
DK	Denmark	13,012	0.59
AG	Antigua	12,263	0.55
BS	Bahamas	11,982	0.54
ZA	South Africa	11,848	0.54
NO	Norway	8,170	0.37
NZ	New Zealand	6,300	0.28
VC	St. Vincent and Grenadines	5,994	0.27
CY	Cyprus	5,719	0.26
CN	China, The People's Republic of	5,613	0.25
BR	Brazil	5,003	0.23
IS	Iceland	4,574	0.21
SE	Sweden	4,552	0.21
BB	Barbados	4,376	0.20
HK	Hong Kong	4,309	0.19
IN	India	3,085	0.14
ES	Spain	3,037	0.14
TO	Tonga	2,989	0.14
WS	Western Samoa	2,769	0.13
IT	Italy	2,750	0.12
CL	Chile	2,438	0.11
PH	Philippines	2,302	0.10
AR	Argentina	2,250	0.10
MX	Mexico	2,238	0.10
TH	Thailand	2,185	0.10
KW	Kuwait	1,876	0.08
MT	Malta	1,452	0.07

ISO[a] Country Code	Country Name	XBT Casts	% of Total
PL	Poland	1,320	0.06
ID	Indonesia	1,241	0.06
TW	Taiwan	1,086	0.05
BE	Belgium	1,028	0.05
MH	Marshall Islands	936	0.04
FJ	Fiji	866	0.04
YU	Yugoslavia	797	0.04
PT	Portugal	732	0.03
PE	Peru	714	0.03
GR	Greece	658	0.03
EC	Ecuador	492	0.02
MY	Malaysia	460	0.02
TR	Turkey	308	0.01
SA	Saudi Arabia	197	<0.01
ZZ	Miscellaneous Organization	195	<0.01
UY	Uruguay	146	<0.01
HR	Croatia	82	<0.01
MU	Mauritius	77	<0.01
DU	East Germany	67	<0.01
MG	Madagascar	62	<0.01
KR	Korea, Republic of	53	<0.01
CI	Cote D'Ivoire	43	<0.01
UA	Ukraine	33	<0.01
CO	Colombia	32	<0.01
CR	Costa Rica	29	<0.01
HN	Honduras	13	<0.01
SC	Seychelles	11	<0.01
TT	Trinidad and Tobago	6	<0.01
RU	Russian Federation	1	<0.01
	Total:	*2,211,689*	*100.00*

[a] ISO = International Organization for Standardization

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CHAPTER 5: EXPENDABLE CONDUCTIVITY-TEMPERATURE-DEPTH DATA (XCTD)

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5.1. INTRODUCTION

An Expendable Conductivity, Temperature and Depth (XCTD) is an ocean profiling instrument, which usually consist of a data acquisition system onboard the ship, a launcher, and an expendable probe with electronics, a temperature sensor, and a conductivity sensor (http://www.jcommops.org/soopip/instr.html). Probes can be launched from ships, submarines, and airborne platforms.

The XCTD is a free-falling probe, which is linked to the acquisition system through a thin insulated conductive wire that is used to transmit the temperature and conductivity data back to the acquisition system in real time. Depth is estimated from the elapsed time between when the probe enters the water and the time each temperature-conductivity measurement is made using a fall-rate equation supplied by the vendor. Processed profile data can be transmitted in real-time through satellite (e.g. Inmarsat). With a 4Hz sample rate and roughly 3.2 m·s-1 fall velocity, XCTD data will be recorded every 0.8 m (Johnson, 1995). Most recent probes, however, are able to sample every 40ms, which approximately equal to 14 cm interval in depth (Mizuno and Watanabe, 1998).

The earliest XCTD data in WOD13 were collected in 1993, and comprise 7 casts launched from the Australian R/V Aurora Australis in the South Pacific and Southern Oceans.

Over the years of collection, XCTD data were submitted to WOD13 in both high and low vertical resolution formats, therefore these data are stored in two WOD13 datasets: high resolution data resides in the CTD dataset (8,713 XCTD casts), and low resolution data resides in the OSD dataset (1,777 XCTD casts).

5.2. XCTD PRECISION AND ACCURACY

The accuracy of XCTD data depends on the probe used and usually is: for temperature ±0.02°C, for conductivity ±0.03 $mS \cdot cm^{-1}$ and for depth 2%. System response time is 40 mSec for conductivity and 100 mSec for temperature (TSK XCTD probe specification; Sippican Inc. web-site). If these errors are correlated the salinity error could be as high as ±0.08, otherwise a salinity accuracy of ±0.05 is expected (Johnson, 1995). Similar numbers were also reported by Mizuno and Watanabe (1998).

Despite the XCTD instrument being in use for some time now, some problems with data accuracy may still exist. Early comparison of the XCTD data with CTD performed by Hallock and Teague (1990) concluded that "Examination of temperature and conductivity shows a significant systematic offset of the XCTDs relative to the CTD, suggesting a calibration error". Later, Sy (1993) revealed that "test results conclusively show that XCTD probes do not meet the manufacturer's specification". A test of modified probes indicated: a) "that the XCTD sensor accuracies are better than ±0.02°C and ±0.04 mS·cm-1 without any correction for the conductivity offset" (Alberola *et al.*, 1996); b) that "the system is close to the point of meeting the claimed specification" (Sy, 1996); and c) that "the system is close to providing the performance required by the oceanographic community for upper ocean thermal and salinity investigation" (Sy, 1998). Large amounts of high frequency noise or spiking reported in both XCTD temperature (Gille *et al.* 2009) and salinity (Yuan *et al.* 2004) profiles, required additional data treatment. Nevertheless, XCTD instruments are able to provide data in a more convenient way than traditional CTDs, which encourage data collection in under-sampled regions like the Arctic or the Southern Ocean (Yuan *et al.* 2004, Gille, *et al.* 2009) at higher sampling density. Other examples of XCTD deployments are demonstrated by Lancaster and Baron (1984) in Antarctic Surface Waters, Sprintall and Roemmich (1999) in the Pacific Ocean, and others.

5.3. XCTD FALL-RATE ERROR

The XCTD instrument does not measure pressure or depth directly. The depth of the instrument is computed from the elapsed time from when the probe enters the water through use of a fall-rate equation. Research conducted by Jonhson (1995) reveal that the manufacturer-supplied fall-rate coefficients give too slow a descent for some probes. Similar results were shown by Alberola *et al.*, (1996). Therefore, revised fall-rate equations were introduced (Johnson, 1995; Mizuno and Watanabe, 1998) and evaluated (Kizu *et al.*, 2008).

A depth-correction algorithm was applied to XCTD data in WOD13 while computing temperature and salinity values at standard depth levels. For that purpose depth values were first recalculated back to elapsed time and then two different manufacturer-dependent depth equations were used for adjusted depth calculation.

For data collected by Sippican instruments the equation of Jonhson (1995) was used. To indicate that data were subject to such treatment, secondary header code #54 was set to 103. Following procedure and parameters were employed:

t = (s1·dx + s2) - s3

dz = sa·t + sb·t2

where: s1 = -1876.17261, s2 =9317957, s3 = -3052.53296;

sa = 3.227, sb = -2.17·10-4;

t – time since drop (seconds);

dx – originally calculated depth (meters);

dz – new calculated depth (meters).

For data collected by TSK instruments equation of Mizuno and Watanabe (1998) was used. To indicate that data were subject of such treatment, secondary header code #54 was set to 104. The following procedure and parameters were employed:

t = (t1·dx + t2) - t3

dz = ta·t + tb·t2

where: t1 = -4672.89697, t2 = 62365712, t3 = -7897.19678;

ta = 3.426, tb = -4.70·10-4;

t – time since drop (seconds);

dx – originally calculated depth (meters);

dz – new calculated depth (meters).

5.4. XCTD CAST DISTRIBUTIONS

Table 5.1 gives the yearly counts of XCTD profiles for the World Ocean. Figure 5.1 shows this graphically. There are a total of 10,529 XCTD profiles for the entire World Ocean (8,821 in CTD and 1,708 in OSD) in WOD13.

Table 5.1. The number of XCTD casts in WOD13 as a function of year. CTD/OSD[1]. Total Number of casts = 10,529 (8,821/1,708).

YEAR	CAST	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1993	22/0	1998	166/118	2003	367/12	2008	987/9
1994	0/0	1999	394/182	2004	551/41	2009	347/0
1995	114/0	2000	478/528	2005	1,046/0	2010	535/0
1996	104/0	2001	327/638	2006	1,151/0	2011	305/0
1997	131/0	2002	573/126	2007	830/0	2012	393/0

[1] CTD – high-resolution casts; OSD – low-resolution casts

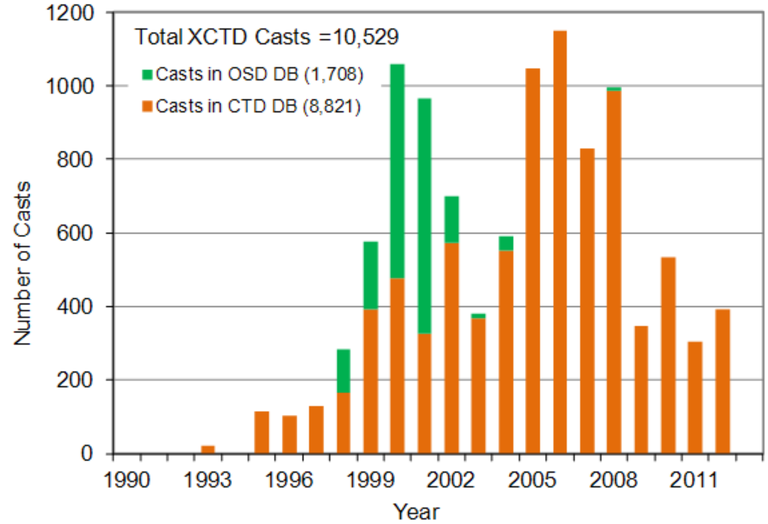

Figure 5.1. Temporal distribution of XCTD casts in WOD13.

Table 5.2 gives national contributions of XCTD data to WOD13. The geographic distribution of XCTD casts is shown on Figure 5.2.

Table 5.2. National contributions of XCTD casts in WOD13.
CTD/OSD[(1)]. Total Number of casts = 10,529.

ISO[a] Country Code	Country Name	XCTD Casts	% of Total
JP	Japan	6602/721	69.58
US	United States	1190/322	14.37
99	Unknown / International	25/721	7.09
PA	Panama	337/0	3.20
FR	France	311/0	2.95
CN	China, The People's Republic of	289/0	2.75
	Australia	7/0	0.07
	Total: 10,529	*8,821/1,708*	*100.00*

[(1)] CTD – high-resolution casts; OSD – low-resolution casts
[a] ISO = International Organization for Standardization

While the majority of XCTD casts (5,623) have no information about the data-collecting organizations, significant amount of XCTD data were collected and submitted by four major institutions: Japan Oceanographic Data Center (JODC, 2,192 casts), Ocean Research Department of Japan Marine Science and Technology Center (JAMSTEC, 1,376 casts), Arctic Submarine Laboratory (ASL US, 784 Casts), and Japan Meteorological Agency (JMA, 260 casts).

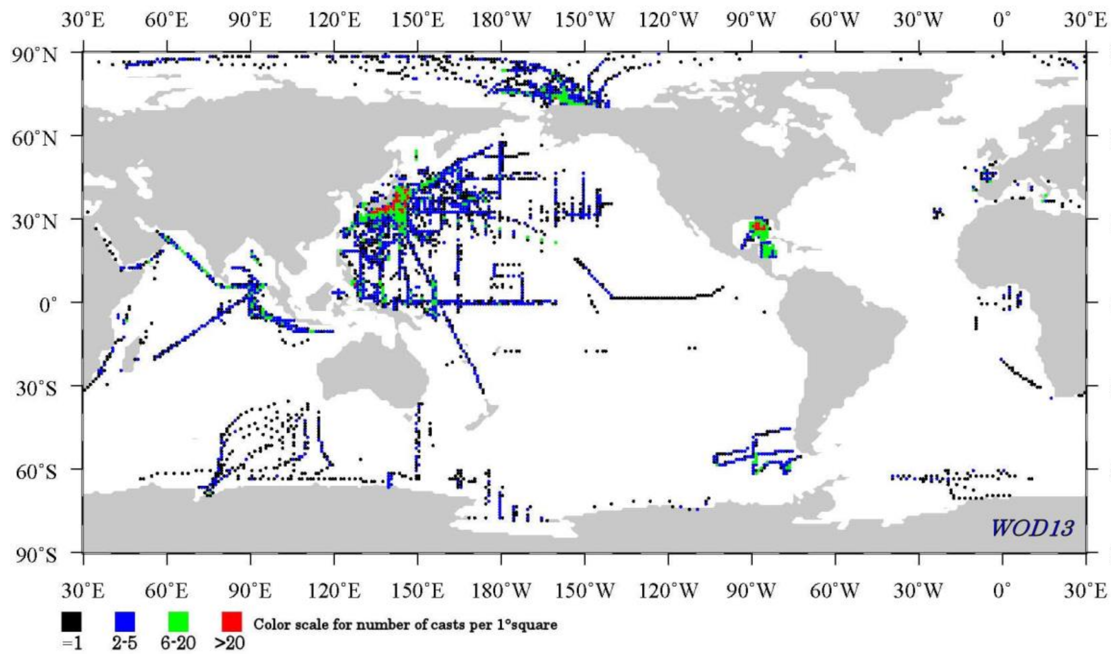

Figure 5.2. Geographic distribution of XCTD casts in WOD13

Figure 5.3 illustrates distribution of the XCTD data among the contributing institutions.

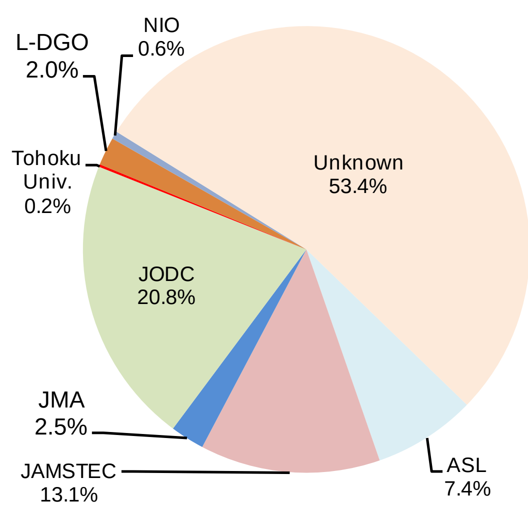

Figure 5.3. Contribution of XCTD casts from different institutions.

Figure 5.4 illustrates the distribution of the XCTD data as a function of depth at observed depth levels.

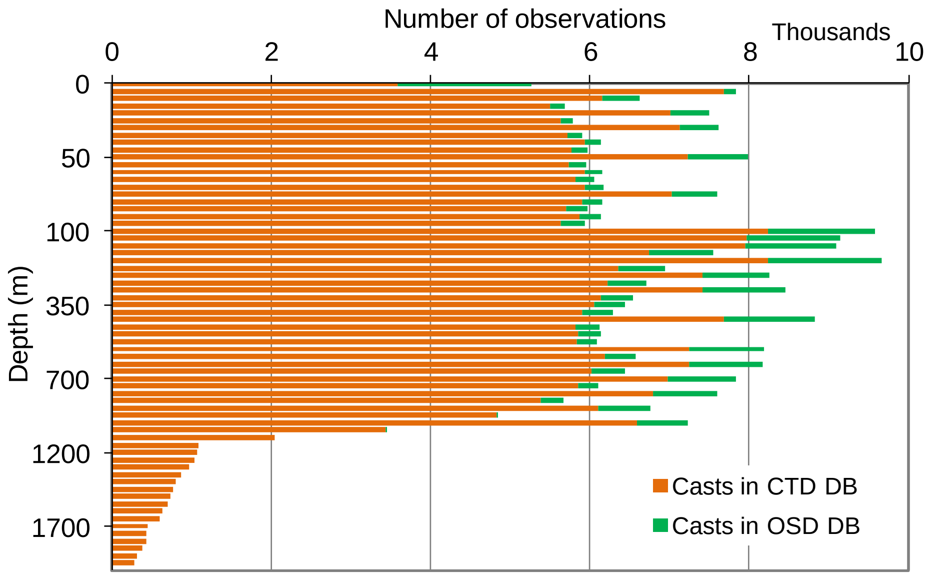

Figure 5.4. Distribution of XCTD data in WOD13 at standard depth levels.

5.5. RELEVANT WEB SITES

Arctic Submarine Laboratory (ASL).

JCOMMOPS Ship of Opportunity Programme
INMARSAT
Japan Marine Science & Technology Center (JAMSTEC).
Japan Meteorological Agency (JMA).
Lockheed Martin Sippican, Inc.
Scientific Ice Expeditions Program (SCICEX).
Ship of Opportunity Programme (SOOP).
The Tsurumi Seiki Co., Ltd.
Tohoku University, Japan: http://www.tohoku.ac.jp/english/index.html.

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CHAPTER 6: PROFILING FLOATS DATA (PFL)

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6.1. INTRODUCTION

Profiling floats are autonomous vehicles equipped with oceanographic sensors which measure vertical profiles of oceanographic variables. These vehicles float passively at a preprogrammed pressure level and then rise to the ocean surface at a predetermined time interval to broadcast collected information to a satellite. Satellite technology is used to record the float position as well as date and time of receipt of the data. The float's collected information consists of measurements taken by sensors on the trip to the surface, and in some cases on the preceding dive. Several different sensors may be attached to the profiling float. However, compromises must be made between the weight and power usage of the sensors and the intended lifetime of the profiling float's battery. Most profiling floats are equipped with pressure, temperature, and conductivity sensors (for calculating salinity). Oxygen sensors have also been deployed, as well as transmissometers, optical irradiance sensors, velocity meters, and rainfall and wind speed sensing instrumentation. Only measurements of pressure, temperature, salinity, and oxygen are included in the PFL dataset of the World Ocean Database 2013 (WOD13).

The float's active movement is achieved by changes in its buoyancy using external bladders. Oil is pumped from an internal chamber to an external bladder, increasing volume and decreasing density, to force the float to rise to the surface. Oil is then pumped from the external bladder back into the float casing to decrease the volume, increasing the density to the point where the float will sink until it achieves a neutral density commensurate with the pressure level at which it will passively move.

Floats are relatively low cost compared with ship based measurements. Davis *et al.* (2001) calculate that they are equivalent in cost per profile (temperature only) to an XBT. However, their value is much greater since they also measure salinity, and they are able to measure during any sea or weather condition, with the partial exception of ice cover. Profiling floats are adding measurements in areas and seasons for which little, if any data, were available.

6.2. PREDECESSORS OF PROFILING FLOATS

The precursors of the present profiling floats were neutrally buoyant floats used to track currents at a predetermined level in the ocean. These floats did not measure temperature or conductivity. The first neutrally buoyant floats were designed and deployed by Swallow (1955). These floats sunk to their neutrally buoyant level in the water column and were then tracked by a nearby surface ship. The Swallow floats were used to verify the deep western boundary current predicted by Stommel (1957) (Swallow and Worthington, 1961). In the late 1960s, the SOFAR (Sound Fixing And Ranging) float was developed (Webb and Tucker, 1970; Rossby and Webb, 1970). This was similar to a Swallow float. They differed in that the float was tracked by underwater listening devices which picked up sound emitted by the floats at intervals which allowed geo-location. The listening devices did not have to be in close proximity to the float, eliminating a major limitation of the Swallow float. Further advances led to the RAFOS floats which reversed the geo-location procedure of the SOFAR floats by having the float listen for signals emitted by stationary underwater devices (Rossby *et al.*, 1986). The RAFOS float was smaller than the SOFAR float since it did not need to emit sound, and therefore it was less expensive to deploy. However, it still required a network of sound sources.

6.3. FIRST PROFILING FLOATS

One of the objectives of the World Ocean Circulation Experiment (WOCE, active fieldwork period 1990-1998) was to estimate the mean flow of the World Ocean. To set up a worldwide system of sound sources to achieve this objective using RAFOS floats would have been prohibitively expensive. The Autonomous LAgrangian Circulation Explorer (ALACE) floats (Davis *et al.*, 1992) were the implemented solution. First operationally deployed in the Drake Passage in 1990, these floats eliminated the need for sound sources by surfacing periodically to be geo-located by ARGOS satellites. The tradeoff for manageable costs were small uncertainties introduced in the velocity at depth due to drift while ascending and descending the water column and while broadcasting their signal at the surface. Also within the framework of the WOCE program, the MARVOR float was created by the Institut Francais de REcherche de la MER (IFREMER) and Tekelec (now Martec), a French engineering firm. MARVOR floats use the same geo-location principle as RAFOS floats, but they also cycle to the surface to send data to ARGOS satellites. They were first deployed in early 1994 in the Brazil Basin (Ollitrault *et al.*, 1994).

After the success of the new profiling floats, it was a logical step to include in their design oceanographic sensors to record temperature and salinity during the floats ascent to the surface. In 1991, the first ALACE floats with temperature sensors were deployed, making them Profiling ALACE floats (P-ALACE floats), and in 1994 floats with both temperature and salinity sensors were deployed (Davis *et al.*, 2001).

6.4. PRESENT FLOAT TECHNOLOGY

Further improvements to the P-ALACE float design were made. Float R1, by Webb Research was introduced at the request of Dr. Steve Riser in 1996 (personal communication Dan Webb). It was replaced by its successor, the Autonomous Profiling EXplorer (APEX) by Webb Research, which is still in use today. Since 1997, APEX floats have been deployed from merchant vessels moving at speeds up to 25 knots, removing the need to employ research vessels in some areas. Other second generation floats include the Sounding Oceanographic Lagrangian Observer (SOLO), developed at Scripps Institute of Oceanography. This float replaced the P-ALACE floats reciprocating high pressure pump with a single stroke hydraulic pump (Davis *et al.*, 2000); the APEX uses a similar pump. This advance allowed the SOLO to more easily reach a desired isobar or isotherm and to cycle between subsurface depths before ascending to the surface. As the P-ALACE was the profiling version of the ALACE float, the PROVOR is the profiling version of the MARVOR float (Loaec *et al.*, 1998), and they have been deployed since 1997. Both Martec and Metocean (Canada) now produce PROVOR floats on the same design. MARVOR and PROVOR floats operate on the same bladder/buoyancy principles as the ALACE floats. PROVOR floats have the added ability to record and store oceanographic profile data on their descent as well as their ascent. The Japanese Agency for Marine-Earth Science and Technology (JAMSTEC) and Tsurumi Seiki Co. (TSK) have developed and deployed the New profilINg floats of JApan (NINJA) (Ando *et al.*, 2003) beginning in 2002. Navigating European Marine Observer (NEMO) floats have been deployed in the Southern Ocean starting in early 2004 by the Alfred Wegner Institute (AWI, Germany). These floats are based on the SOLO design and are equipped with algorithms based on temperature measurements which help them avoid surfacing in ice covered areas. NEMO floats combine this ability with RAFOS positioning, extending the reach of profiling floats to ice-covered regions. Figure 6.1 shows the relative distribution of each type of profiling float in WOD13.

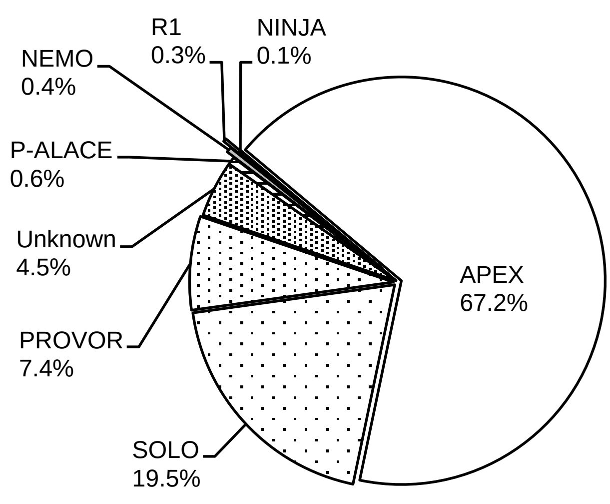

Figure 6.1. Casts from different types of profiling floats (PFL) in WOD13.

6.4.1. The Argo Project

The Argo project is an umbrella project which coordinates the deployment, quality control, and public access for profiling float data. Argo is not an acronym: it refers to the relationship between the Jason satellite altimeter measuring ocean surface topography and the Argo floats revealing the ocean subsurface structure, evoking the mythical Jason and his ship the Argo (Gould, 2005). Since the year 2000, nearly all data from deployed floats are available through this project. Floats are deployed by individual countries, projects, and institutions, usually with some level of coordination with Argo. Float data are captured from the ARGOS and Iridium satellites by the Argo Data Assembly Centers (DACs) and placed on the World Meteorological Organization (WMO) Global Telecommunications System (GTS) within 24 hours. These data are also relayed in near-real-time to the two Argo Global Data Assembly Centers (GDACs): the French Coriolis Center at IFREMER, and the U.S. Global Ocean Data Assimilation Experiment (GODAE) server in Monterrey, California hosted by the U.S. Navy. Within 24 hours the data are made available to the public through these sites as well. Preliminary quality checks are performed at the DACs on the incoming data. These data are the real time data. Further quality control is performed at the DACS, the GDACs, at regional centers, and by the primary investigators responsible for the floats. A delayed mode version of the data is then released. Each float is assigned a WMO identification number for easy identification. Meetings and workshops on data quality control, data access, and scientific research with floats have been held to keep the scientific community informed and coordinate responses and solutions to quality control and access problems. The goal of Argo is to deploy and maintain a global array of profiling floats to monitor the large scale circulation of the world ocean, as well as its heat and fresh water content. With this stated goal, pressure, temperature and salinity sensors are the only necessary oceanographic sensors, although floats may be equipped with other sensors. Argo has surpassed its goal of 3,000 floats worldwide, with more than 3,500 active floats in late 2012. The preference is for the floats to deliver profiles from 2000 decibars to the surface every 10 days. Since the floats are deployed for other specific research goals, the parking depth (depth of passive motion) may not be at 2000 decibars. In fact, the recommended parking depth for Argo is 1000 decibars. However, the float should descend to 2000 decibars before beginning to record temperature and salinity. Some floats cycle to the surface at intervals other than 10 days.

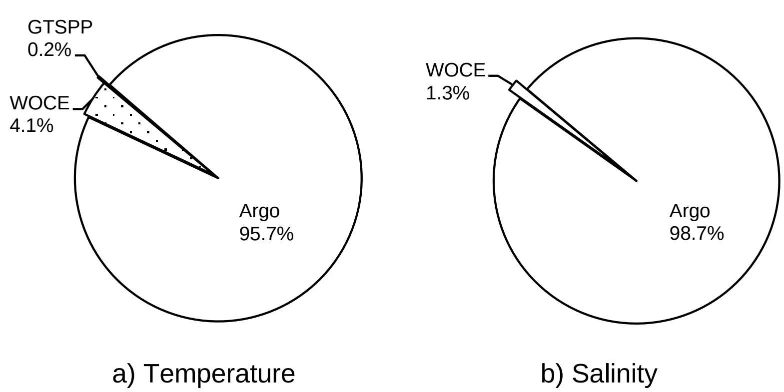

Figure 6.2. PFL data contributions from different sources.

The profiling float data in WOD13 consists of data from the WOCE project, data from the Global Temperature and Salinity Profile Project (GTSPP), which is an archive for data from the GTS, and the Argo U.S. GODAE server. Since the Coriolis and GODAE data are synchronized, there should be no differences between the two data sets. Figure 6.2 shows the relative distribution from each data set.

6.5. SENSOR ACCURACY

The temperature and salinity data from the profiling floats come from various CTD sensors. The P-ALACE floats used an YSI 46016 thermistor, with estimated precision of 0.005°C, and a Falmouth Scientific Inc. (FSI) conductivity sensor with an estimated accuracy of 0.01 $mS \cdot cm^{-1}$ (milliSiemens·centimeter^{-1}). The pressure sensor used was a Paine strain gauge sensor. The sensor had hysteresis errors of order 5 meters initially, which were later reduced by thermally isolating the sensor (Davis *et al.*, 2001). To reduce pressure reading errors, Seabird replaced the Paine strain gauge pressure sensor in their CTDs with a Druck pressure sensor (see Data Problems section, below). Later floats used FSI CTD sensors or CTD sensors from Seabird. The Seabird sensors have 0.002°C temperature accuracy, 0.005 salinity accuracy, and 2.4 db pressure accuracy. All accuracy data are from the product specifications (except the P-ALACE thermistor information from Davis *et al.*, 2001). Seabird specifications are for Seabird-41 CTD for ALACE floats.

For oxygen measurements, the Aanderaa 3835 oxygen sensor has accuracy of 8 μM or 5%, whichever is greater. Accuracy of the Seabird-43 oxygen sensor is 2% of saturation. These values are from the product specifications. Kortzinger and Schimanski (2005) discuss oxygen measurements from profiling floats.

6.6. DATA PROBLEMS

Data problems are of two types: 1) Sensor problems, 2) Data stream errors. Each will be examined separately.

6.6.1. Sensor problems

The biggest persisting challenge for profiling float sensors is salinity drift. Conductivity cells are calibrated against samples of standard seawater before deployment of the float. However, even over the course of a short oceanographic cruise, the conductivity sensor on a standard winch-deployed CTD can experience slowly increasing unidirectional errors (drift) due to biofouling and small changes in cell geometry. Profiling floats are designed to be almost constantly immersed in the harsh ocean environment for four years. Therefore, it is to be expected that the conductivity sensor on a float will experience drift. Oka (2005) estimated a salinity drift of -0.016 ± 0.006 per year from recalibration of three floats recovered after 2-2.5 years of deployment. From examining the extant float data, some floats can experience much larger drifts, or even abrupt deviations from calibration. A number of algorithms for correcting for drift have been proposed (Wong *et al.*, 2003 [WJO]; Böhme and Send, 2005 [BS]; Durand and Reverdin 2005, Owens and Wong, 2009 [OW]). The Argo delayed-mode data are corrected for drift using the OW, WJO or BS algorithm, depending on the DAC which is making the correction. Delayed mode data are available in WOD13. If the pressure adjustment, temperature adjustment, or salinity adjustment variable is present in a cast (variable specific secondary header 19), the cast has delayed-mode quality control applied by the appropriate DAC. This adjustment variable gives the mean change between delayed-mode and real-time values at the same measurement levels for all levels below 500 meters depth. Salinity drift adjustments and most pressure sensor adjustments are uniform over an entire profile so the adjustment variable is usually a good indicator of the profile change at each level from real-time to delayed-mode. However, there are some cases where a single level or a few levels have their values adjusted. In these cases the adjustment variable does not represent the change to each level.

A partial solution to the salinity drift problem is the application of biocide to the sensor. This has worked well to reduce salinity drift, but also has introduced another problem. Some floats have errors in the salinity due to ablation of the biocide. These errors usually disappear after the first 10 profiles (personal communication, S. Riser).

In 2003, it was found that problems with the Druck Pressure Sensor were causing some floats to stay at the surface for prolonged periods and eventually to become surface drifters. The Druck Pressure Sensor is the successor to the Paine pressure sensor in Seabird CTDs. Even when not severe, the problem may have caused errors in the salinity measurement due to increased biofouling due to prolonged surface exposure. When the problem was found, the CTDs were recalled and the source of the problem was fixed, but this was not possible for floats already deployed. A large number of SOLO floats with FSI CTD packages deployed in the Atlantic Ocean between 2003 and 2006 were found to have a pressure offset problem due to a software error. This error caused pressures to be paired with the temperature measurements from the next lower level, creating the illusion of a cooling ocean. Once the problem was found, a list of such floats was compiled. An effort was made to correct the problem, successful in some floats, not in others. All data from all these problem floats are included in WOD13. For those data which could not be corrected, all float cycles are flagged. More recently, in early 2009, a problem with the Druck pressure sensor has been found (J. Willis and D. Roemmich, Argo Steering Team, 2009). This problem causes pressure sensor drift after deployment. Deployment of new floats was halted temporarily, until the pressure sensor design could be altered. Barker *et al.* (2011) reported that about 57% of the profiles from APEX floats, the predominant type of deployed Argo floats – see Figure 6.1, could be immediately corrected for pressure sensor drift, while only about half of the then uncorrectable APEX profiles could be corrected with the future release of updated metafiles and technical files.

During a normal transmission to the ARGOS satellite, a float needs to stay at the surface between 6 and 12 hours, and it is then when much of the biofouling occurs. This problem is being reduced by the increasing deployment of floats equipped to communicate with two-way communicating Iridium satellites. Two-way communication cuts down on the need for repeated rebroadcasts of the same message, since the broadcasting float can be notified of receipt of the message. This reduces the float's surface time to about 20 minutes. While by 2010, only 250 floats had been deployed with Iridium antennas, by 2013 most of the deployed floats use this type of communication.

Another identified problem is a thermal lag caused because the thermistor and the conductivity cell are located a small distance from each other. If there is a large vertical gradient in temperature, this can cause erroneous spikes in the salinity field. Work has been done to correct this lag problem and corrections are available in the delayed-mode data. However, the error is quite different between different Seabird sensors found on floats, and not all the necessary metadata is available in all Argo data (G. Johnson, personal communication). Some anomalous spikes in salinity near large temperature gradients, probably caused by the thermal lag error, have been marked by automatic or subjective checks in WOD13.

Another identified problem is pressure hysteresis. As mentioned above, some pressure gauges have some pressure hysteresis error. Some early profiling floats which used a Micron Instruments pressure gauge had fairly large pressure hysteresis problem (Schmid, 2005). Schmid (2005) outlines an algorithm for correcting this hysteresis problem. **This correction was applied to 1,633 float profiles in the tropical Atlantic in WOD13**. A list of the floats and the average pressure correction are shown in Table 6.1.

Table 6.1. Corrections to float pressure profiles with hysteresis problem.

After Schmid (2005). Correction factor was subtracted from original pressure values for each pressure in the profile

WMO Float ID#	# of Profiles	Average correction (m)	Maximum Correction (m)
13857	140	9.4	14.5
13858	48	12.7	12.7
13859	155	6.0	8.4
15819	121	17.9	27.7
15820	174	12.7	13.9
15851	97	13.5	82.8
15852	116	5.8	6.4
15853	120	6.9	8.4
15854	66	11.8	12.9
15855	61	9.7	9.7
31810	124	18.7	19.5
31855	73	13.2	50.3
31856	47	15.4	17.7
31857	109	15.7	52.0
31858	23	15.6	21.1
31859	163	19.9	24.7

There are no significant identified problems with the temperature sensors. Oka and Ando (2004) found no drift in temperature from 3 recovered floats after 6-9 months. They did find significant error in one of the three recovered conductivity cells (~ -0.02), from a PROVOR float, showing again the relatively larger problems with the salinity measurements from profiling floats compared to temperature measurements.

Oxygen sensors have been deployed on floats operationally since 2002. Kortzinger *et al.* (2005) found no instrument problems using the Aanderaa 3830 sensor after 6-9 months deployment. Both Aanderaa and Seabird sensors compare well with

Winkler titrated oxygen values and appear to have stable calibration according to recently presented results (Gilbert *et al.*, 2006).

6.6.2. Data-Stream Errors

Problems caused by transmission of data from one site to another are always possible. The more data transfers are made, the more possibilities for error. The profiling float data are no exception. The most prevalent error, and one which is not usually recoverable, is errors in transmission of data packages from the float to the ARGOS satellites. Many of these transmission errors result in portions of profiles, or entire profiles containing erroneous information. Most of these errors are of such a nature that they are found and flagged in automatic quality control checks in WOD13 if they have not been removed beforehand. But there may be data with errors of this nature which escaped all quality control steps.

6.7. ORIGINATORS FLAGS

The originators flags from the Argo program are kept intact in the WOD13 data. The flags are as follows:

0 – no quality control (QC) performed
1 – good data
2 – probably good data
3 – bad data that are potentially correctible
4 – bad data
(from Argo quality control manual Version 2.0b, Argo Data Management Team, 2004).

Note that not all data marked with originators 3 or 4 are marked with WOD13 quality control flags. Visual inspection of examples of these data found no reason not to use these data for scientific research. This just means that a quality control test that failed by Argo standards did not fail by WOD13 standards, or that the failing test was not performed for WOD13. The user of WOD13 can choose to use the Argo flags, the WOD13 flags, both, or neither.

Argo also supplies a grey list. This is a list of floats and sensors which have been deemed to have failed at some point. The date of failure is also listed.

The information on the grey list is used to set a quality control flag for PFL data in WOD13. This grey list is periodically updated. The grey list used to flag data for WOD13 is the version from January 15, 2013.

6.8. PFL DATA DISTRIBUTIONS

Figure 6.3 shows the geographic distribution of profiling float casts for the period 1994-2012. This distribution shows that Argo has met its goal of full geographic coverage of non-ice covered ocean: there are a total of 1,020,213 PFL casts for the entire

World Ocean, closely divided between the southern hemisphere (491,819 casts, or 48.2%) and the northern hemisphere (528,354 casts, or 51.8%). Table 6.2 shows that about 54% of the floats data are of U.S. origin, followed by Japan at 11%. It also shows that many countries around the world are contributing profiling float data. The yearly count in Table 6.3 and Figure 6.4 shows the rapid increase with time of recorded profiling float casts, from less than 20,000 a year before 2003, to more than 130,000 obtained during 2012. The depth distribution, Figure 6.5, shows that many of the surface and near surface values do not exist or are missing: most float sensors are shut down near the surface to avoid biofouling.

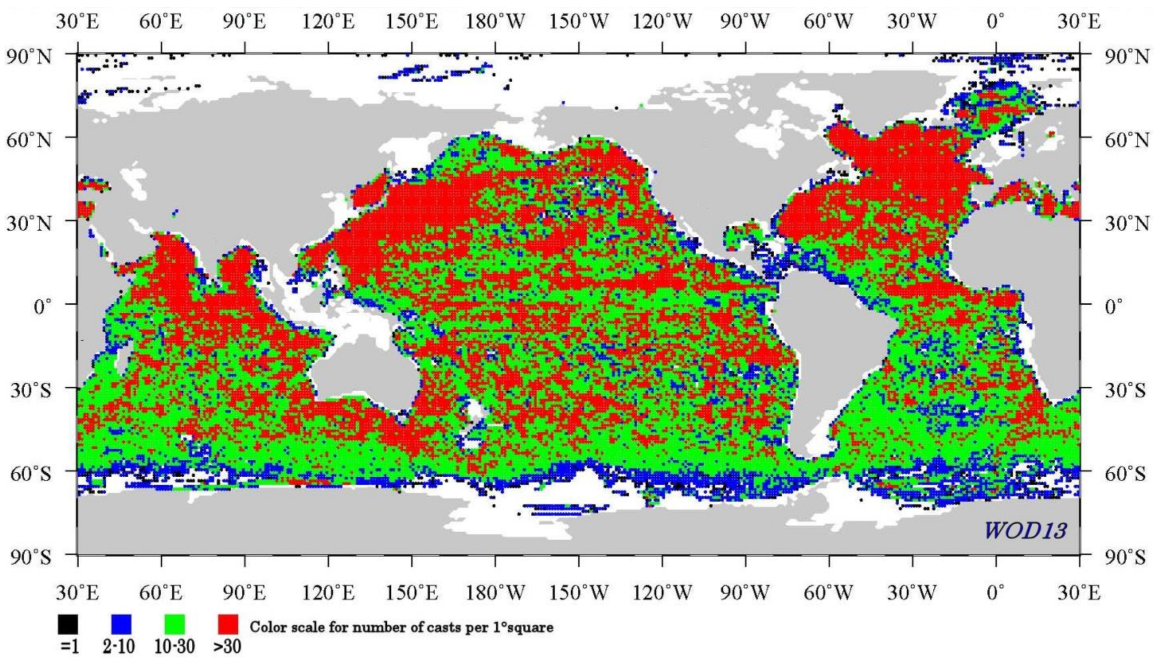

Figure 6.3. Geographic distribution of profiling floats (PFL) casts in WOD13. For the period 1994-2012

Table 6.2. National contribution of PFL casts in WOD13.

ISO[a] Country Code	Country Name	PFL Casts	% of Total
US	United States	553,873	54.29
JP	Japan	113,781	11.15
99	Unknown	65,981	6.47
AU	Australia	65,782	6.45
FR	France	49,266	4.83
CA	Canada	35,720	3.50
DE	Germany	33,313	3.27
GB	Great Britain	29,169	2.86
IN	India	24,369	2.39
KR	Korea, Republic of	21,098	2.07
CN	China, The People's Republic of	8,449	0.83
EU	European Union	6,152	0.60
IT	Italy	3,177	0.31
CL	Chile	2,860	0.28
ES	Spain	2,781	0.27
NO	Norway	1,985	0.19
DK	Denmark	897	0.09
NZ	New Zealand	565	0.06
NL	Netherlands	432	0.04
RU	Russian Federation	307	0.03
IE	Ireland	155	0.02
MX	Mexico	101	0.01
	Total	*1,020,213*	*100.0*

[a] ISO = International Organization for Standardization

Table 6.3. The number of Profiling Float Data (PFL) casts as a function of year in WOD13. The total number of casts = 1,020,213.

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1994	53	1999	14,218	2004	44,810	2009	119,767
1995	1,038	2000	13,852	2005	66,045	2010	116,604
1996	2,557	2001	14,644	2006	86,790	2011	125,259
1997	5,996	2002	20,305	2007	100,746	2012	131,235
1998	11,519	2003	30,995	2008	113,780		

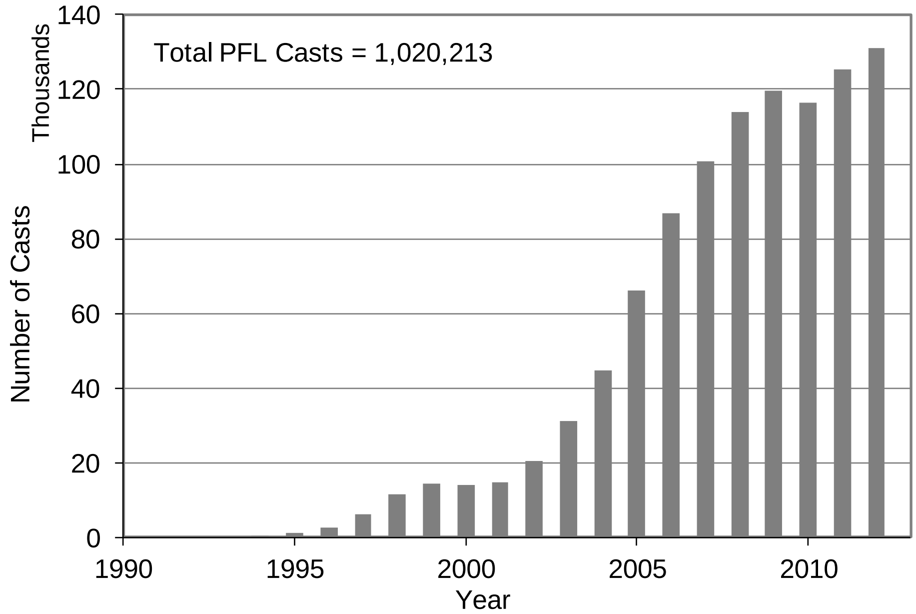

Figure 6.4. Temporal distributions of Profiling Float Data (PFL) casts in WOD13.

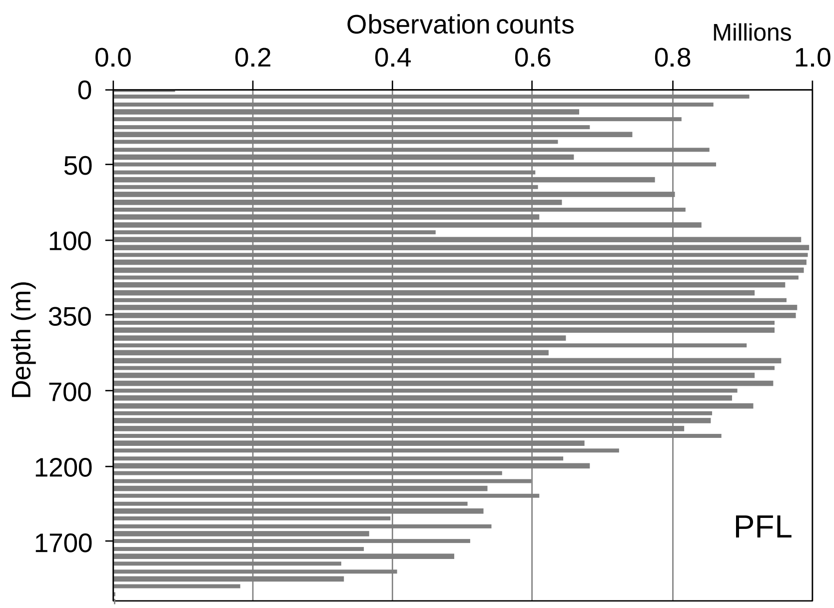

Figure 6.5. Distribution of Profiling Float Data (PFL) data at standard depth levels in WOD13.

6.9. RELEVANT WEB SITES

[Aanderaa Oxygen Sensor]
[Argo homepage].
[Argo Information Center homepage].
[FSI Excell CTD].

Seabird 41 CTD for ALACE floats.
http://www.seabird.com/products/spec_sheets/43data.htmhttp://www.seabird.com/products/spec_sheets/43data.htm.
Seabird 9+ CTD
TSK CTD.

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[1] English version of Argo Information Center Newletter available on Argo Information Center website.
[2] Document available on Argo Information Center website.
[3] Document available on Argo homepage website.

CHAPTER 7: MECHANICAL BATHYTHERMOGRAPH DATA (MBT)

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7.1. INTRODUCTION

The Mechanical Bathythermograph (MBT) is an instrument developed during the late-1930's (Spilhaus, 1938) that can be dropped from either a stationary or moving surface ship to produce an upper ocean temperature profile. This instrument was a substantial improvement of an instrument known as the "oceanograph" which was designed by Dr. Carl Rossby and Dr. Karl Lange (Rossby and Montgomery, 1934) for the purpose of studying the upper ocean thermal structure. The introduction of the MBT allowed ships to make synoptic surveys of oceanographic regions and for discovery of fine structure of the ocean's thermal structure. Spilhaus (1941) used the instrument to identify "fine" structure (in the horizontal) from temperature profiles near the edge of the Gulf Stream. Pressure is determined from a pressure sensitive tube known as a Bourdon tube. A temperature sensitive element in the nose of the MBT enables the instrument to trace temperature as a function of depth.

Different versions of the MBT have different maximum depth ranges with 295 m being the deepest depth measured from any U.S. version. Earlier versions of the instrument were limited to making measurements in the upper 140 m of the water column. A review of the development of the MBT is given by Spilhaus (1987). Another more comprehensive review is provided by Couper and LaFond (1970).

In most countries and institutions the use of the MBT has been replaced by the XBT. Only 2.1% of all the MBT profiles in our archives were collected between 1991 and 2004 (Table 7.1).

7.2. MBT ACCURACY

The accuracy of the MBT has been the subject of several studies. Leipper and Burt (1948) report the results of comparisons between MBT temperature measurements and near simultaneous reversing thermometer measurements which were made by D. Pritchard of the U.S. Navy Electronics Laboratory in Lake Meade. By comparing the temperature traces on the up and down casts of the MBT it was inferred that there was "an almost complete absence of internal waves of large amplitude and short period, hysteresis of the instruments, or rapid temperature changes due to advection". These results are reproduced in Table 7.2 given below. Clearly there is good agreement between the reversing thermometer measurements (which typically had an accuracy of 0.02°C at this period of time) and the MBT measurements. However, there is a problem with interpreting the results from Table 7.2 because it is not clearly stated in the table, or the text of the technical report of Leipper and Burt, what temperature units were used. Throughout their report, Leipper and Burt use the Fahrenheit scale. If this scale applies to the results in Table 7.2, then the agreement is impressive. If the results are in degrees Celsius, the agreement is less impressive but the data are still useful for many scientific purposes. Other studies attribute an accuracy of about 0.5°F to the MBT instrument. This figure is comparable to the accuracy of expendable bathythermograph (XBT) probes for which the thermistor sensing element is not calibrated (Tabata, 1978). Although both MBT and XBT probes are an order of magnitude less precise than reversing thermometers, the *standard error of the mean* of any estimate based on these temperature measurements decreases with the increase in number of data used. This applies to random errors. Hence, historical bathythermograph measurements provide valuable information when estimating global-scale features by averaging over many measurements in space and/or time.

7.3. SURFACE DATA ACQUIRED CONCURRENTLY WITH MBT CASTS

On occasions a sea-surface water sample is taken at the time of the MBT cast. Temperature and salinity of the water sample are usually measured and recorded as ancillary information of the MBT cast. Meteorological conditions at the time of the MBT cast could also be archived, e.g. air temperature, wind speed and direction, cloud type and cover, barometric atmospheric pressure, as well as sea conditions: wave height and direction, sea state.

A significant amount of ancillary meteorological information was recovered by the NODC/OCL through the digitization of historical MBT cards from the Scripps Institution of Oceanography and the Woods Hole Oceanographic Institution.

7.4. MBT PROFILE DISTRIBUTIONS

Table 7.1 gives the yearly counts of MBT profiles for the World Ocean and Figure 7.1 shows the time series of those yearly totals. Figure 7.2 represents distribution of Mechanical Bathythermograph (MBT) data at standard depth levels. There are a total of 2,425,607 MBT profiles for the entire World Ocean with only about 11% measured in the southern hemisphere and 89% profiles measured in the northern hemisphere (Figure 7.3). Table 7.3 gives national contributions of MBT profiles.

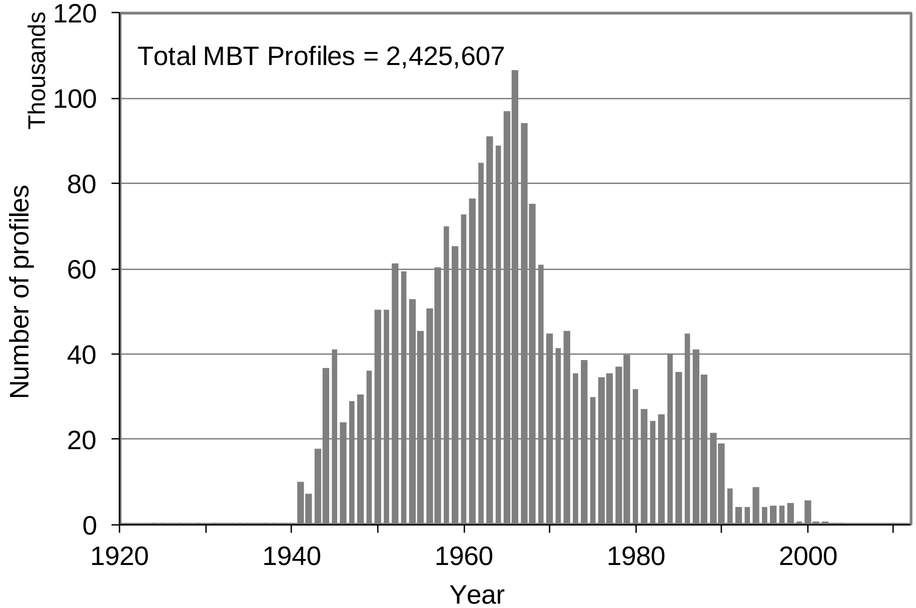

Figure 7.1. Temporal distribution of Mechanical Bathythermograph (MBT) profiles in WOD13.

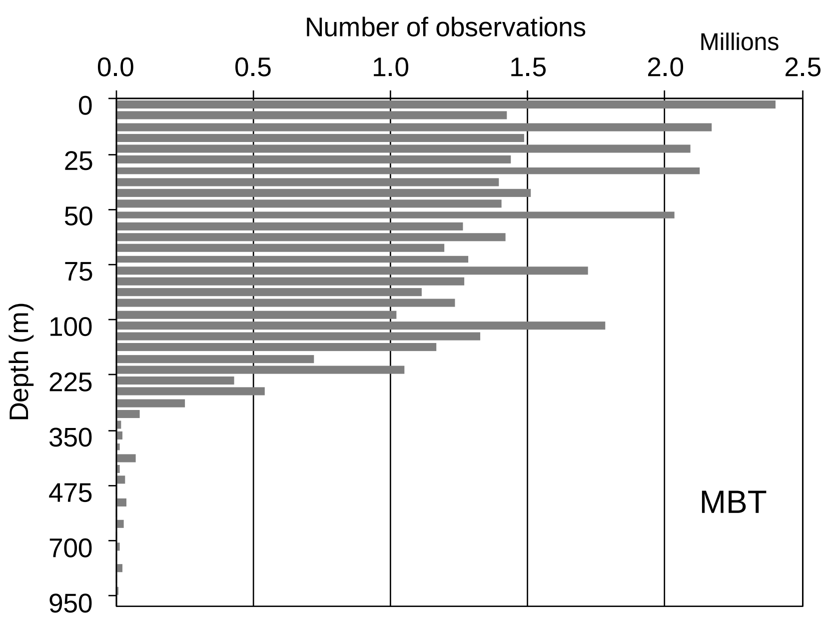

Figure 7.2. Distribution of Mechanical Bathythermograph (MBT) data at standard depth levels in WOD13.

Table 7.1. Number of all MBT profiles as a function of year in WOD13.
Total Number of Profiles = 2,425,607

YEAR	PROFILE	YEAR	PROFILE	YEAR	PROFILE	YEAR	PROFILE
1903	1	1929	4	1955	45,467	1980	31,642
1904	0	1930	0	1956	50,521	1981	27,100
1905	14	1931	8	1957	60,465	1982	24,132
1906	11	1932	15	1958	70,102	1983	25,851
1907	10	1933	23	1959	65,214	1984	40,123
1908	60	1934	20	1960	72,656	1985	35,709
1909	44	1935	39	1961	76,418	1986	44,759
1910	43	1936	35	1962	84,853	1987	41,035
1911	88	1937	96	1963	91,228	1988	35,162
1912	35	1938	119	1964	88,981	1989	21,467
1913	48	1939	104	1965	97,114	1990	19,069
1914	2	1940	60	1966	106,593	1991	8,491
1915	1	1941	9,990	1967	94,162	1992	4,021
1916	0	1942	7,014	1968	75,372	1993	4,030
1917	1	1943	17,769	1969	60,830	1994	8,852
1918	0	1944	36,786	1970	44,886	1995	4,098
1919	0	1945	41,086	1971	41,386	1996	4,462
1920	0	1946	23,822	1972	45,349	1997	4,451
1921	0	1947	28,808	1973	35,533	1998	5,030
1922	0	1948	30,312	1974	38,586	1999	556
1923	0	1949	36,040	1975	29,808	2000	5,483
1924	1	1950	50,296	1976	34,360	2001	653
1925	13	1951	50,251	1977	35,482	2002	662
1926	4	1952	61,310	1978	36,842	2003	166
1927	3	1953	59,341	1979	39,726	2004	27
1928	1	1954	52,914				

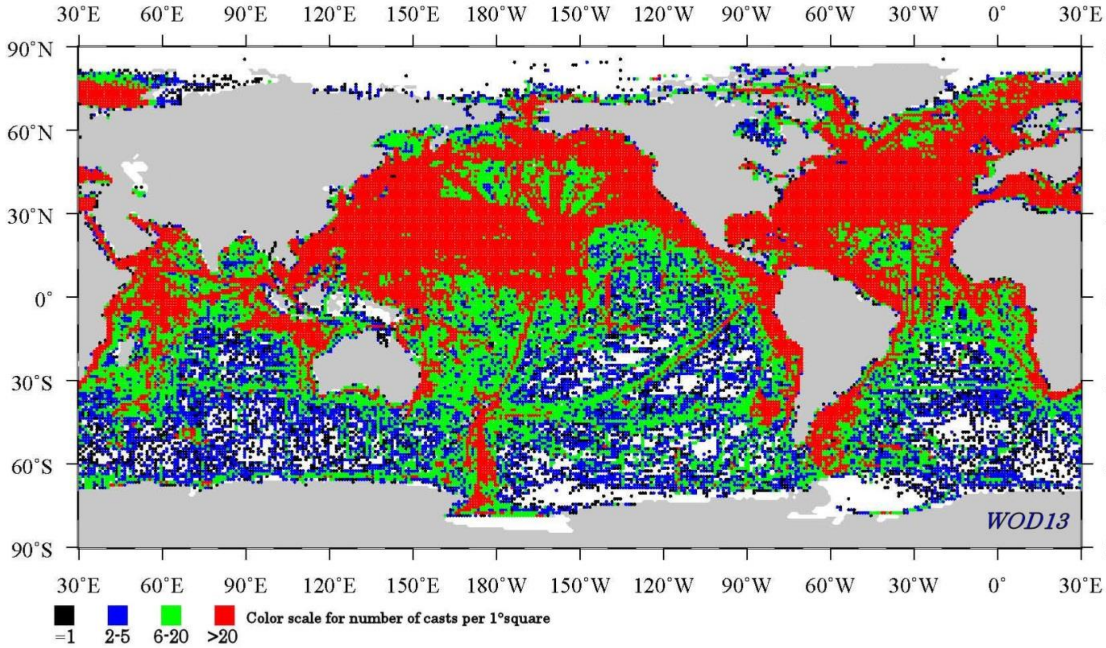

Figure 7.3. Geographic distribution of Mechanical Bathythermograph (MBT) profiles in WOD13.

Table 7.2. Comparison of observations taken with Mechanical Bathythermographs and reversing thermometers.

TABLE 2.3. OBSERVATIONS TAKEN WITH BATHYTHERMOGRAPHS AND REVERSING THERMOMETERS			
BT	**No. of stations**	**No. of thermometer observations**	**Standard Deviation of Temperature Differences***
# 1784A (Shallow)	9	20	0.15
# 1258A (Deep)	10	41	0.19
# 514A (Deep)	12	36	0.10

Reproduced from Leipper and Burt (1948).

We reproduce this table as it appeared in the work by Leipper and Burt (1948). Unfortunately, they did not specify whether the units of temperature were reported in degrees Celsius or Fahrenheit. However, all other citations of temperature in their report were given in units of degrees Fahrenheit. Even if these results are in units of degrees Celsius, the agreement is still good. For example, individual XBT probes are accurate to a few tenths of a degree Celsius.

Table 7.3. National contributions of Mechanical Bathythermograph (MBT) profiles in WOD13.

ISO[a] Country Codes	Country Name	MBT Casts	% of Total
DE	Germany	1,175,019	48.44
NO	Norway	449,998	18.55
GH	Ghana	364,808	15.04
CA	Canada	195,947	8.08
NG	Nigeria	118,634	4.89
99	Unknown / International	25,005	1.03
AU	Australia	18,376	0.76
PT	Portugal	16,450	0.68
EC	Ecuador	13,538	0.56
AR	Argentina	10,995	0.45
JP	Japan	8,088	0.33
GB	Great Britain	6,268	0.26
MC	Monaco	5,212	0.21
CD	Congo, the Democratic Republic	4,161	0.17
MG	Madagascar	2,628	0.11
IT	Italy	2,435	0.10
US	United States	1,234	0.05
BE	Belgium	1,218	0.05
IN	India	913	0.04
CL	Chile	885	0.04
CI	Cote D'Ivoire	747	0.03
PE	Peru	673	0.03
FR	France	540	0.02
GR	Greece	405	0.02
ES	Spain	327	0.01
VE	Uruguay	245	0.01
CO	Colombia	195	0.01
ZA	South Africa	187	0.01
SN	Saudi Arabia	99	<0.01
SU	Union of Soviet Socialist Republics	97	<0.01
TH	Thailand	89	<0.01
BR	Brazil	82	<0.01
NL	Netherlands	77	<0.01
NZ	New Zealand	20	<0.01
SL	Russian Federation	12	<0.01

[a] ISO = International Organization for Standardization

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CHAPTER 8: DIGITAL BATHYTHERMOGRAPH (DBT) PROFILES

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8.1. INTRODUCTION

The Digital Bathythermograph (DBT) is an instrument developed to record and report temperature profile data electronically. The self-contained underwater instrument includes a thermistor and a strain gauge. Temperature and depth/pressure measurements are automatically recorded in the underwater unit as it is lowered in the water column. Upon recovery, the underwater unit is connected to a computer to retrieve the data.
All DBT profiles are stored in the MBT dataset of WOD13.

8.2. DBT ACCURACY

The DBT has a temperature accuracy of ±0.05°C. However, Pankajakshan *et al.* (2003) report temperature errors of -0.3°C to +1.0°C in Indian DBT data from the Indian Ocean. No errors were observed in DBT data collected in the Pacific Ocean by Japanese and United States institutions.

8.3. DBT PROFILE DISTRIBUTIONS

Table 8.1 gives the yearly counts of DBT profiles for the World Ocean. Figure 8.1 shows the time series of the yearly totals of Digital Bathythermograph profiles for the World Ocean. There are a total of 79,500 DBT profiles for the entire World Ocean with about 6.0% measured in the southern hemisphere and 94.0% profiles measured in the northern hemisphere. Table 8.2 gives national contributions of DBT data. Figure 8.3 illustrate distribution of Digital Bathythermograph (DBT) data at standard depth levels in WOD13.

Table 8.1. The number of Digital Bathythermograph (DBT) profiles as a function of year in WOD13. The total number of casts = 79,500.

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1977	27	1984	9,213	1991	4,662	1998	0
1978	234	1985	8,424	1992	2,285	1999	0
1979	1,920	1986	5,255	1993	2,507	2000	0
1980	5,280	1987	4,505	1994	121	2001	0
1981	5,918	1988	5,478	1995	2	2002	19
1982	7,524	1989	3,443	1996	27	2003	23
1983	8,370	1990	4,148	1997	88	2004	27

Table 8.2. National contributions of Digital Bathythermograph (DBT) profiles in WOD13.

ISO[a] Country Codes	Country Name	DRB Casts	% of Total
JP	Japan	68,398	86.04
CA	Canada	11,102	13.96
	Total	*79,500*	*100.00*

[a] ISO = International Organization for Standardization

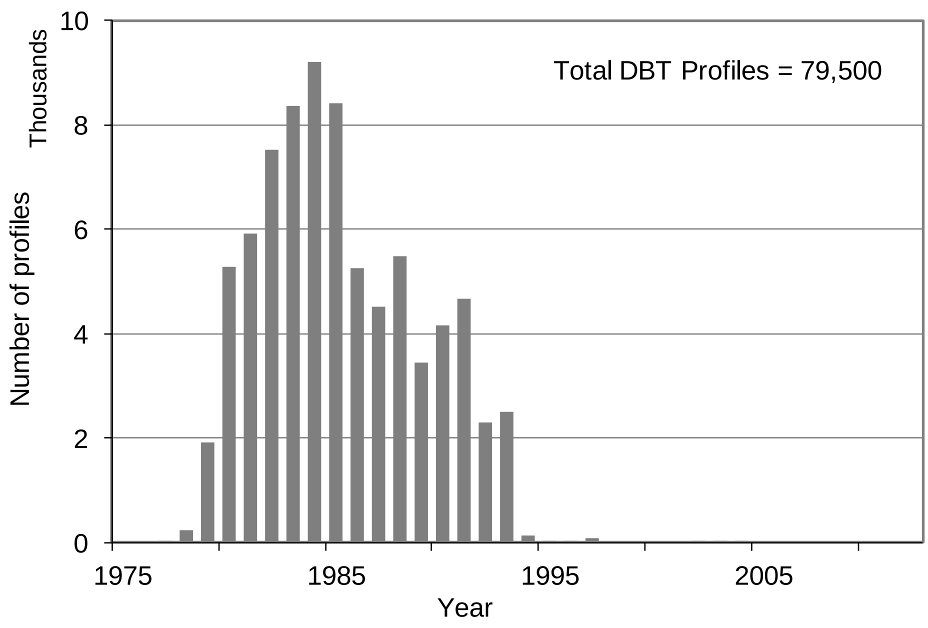

Figure 8.1. Temporal distribution of Digital Bathythermograph (DBT) profiles in WOD13.

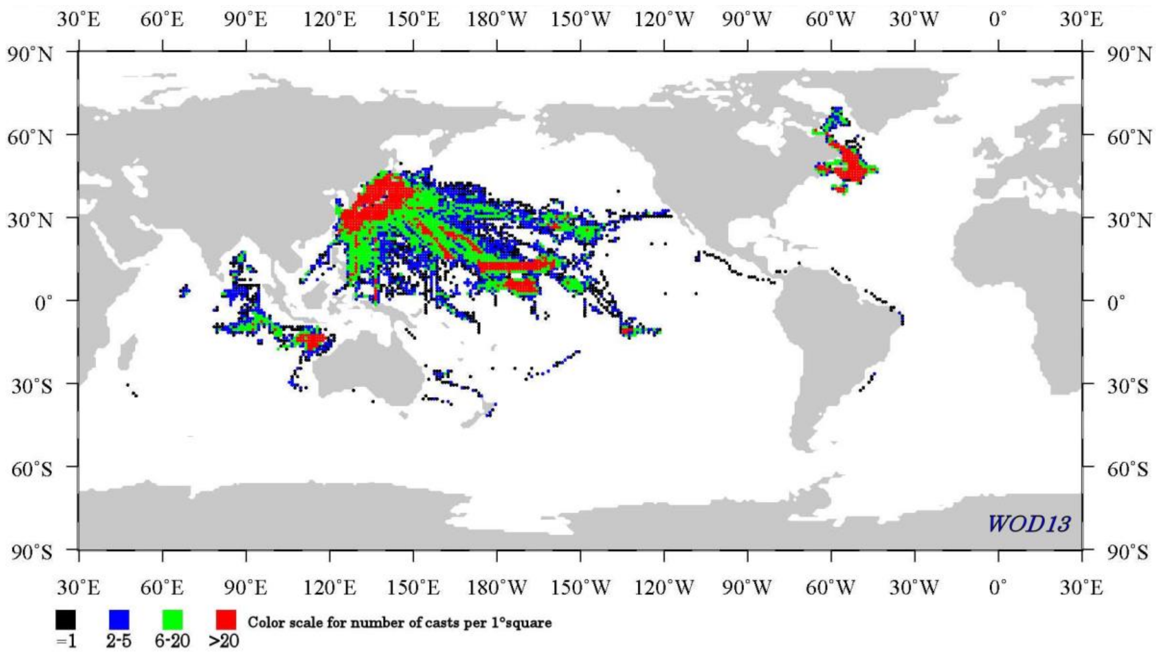

Figure 8.2. Geographic distribution of Digital Bathythermograph (DBT) profiles in WOD13.

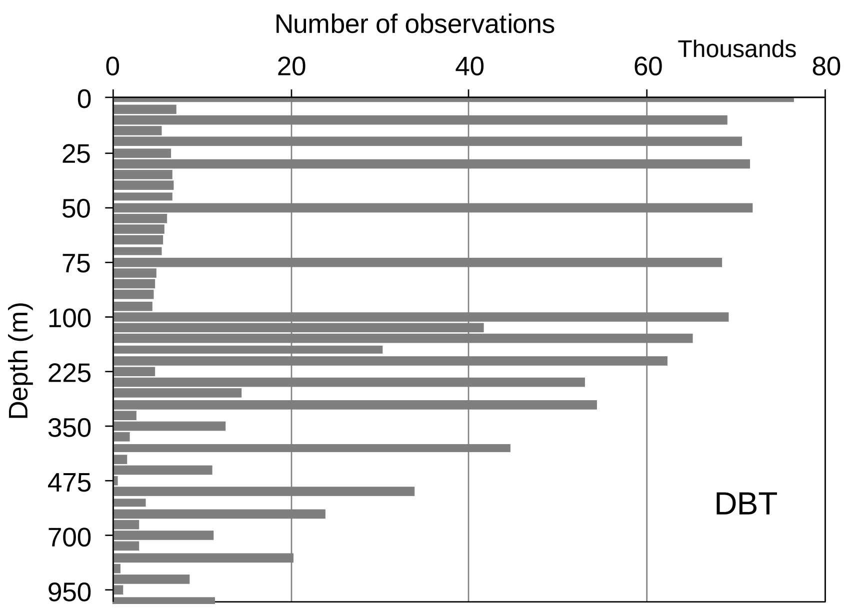

Figure 8.3. Distribution of Digital Bathythermograph (DBT) data at standard depth levels in WOD13.

8.4. REFERENCES AND BIBLIOGRAPHY

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CHAPTER 9: MOORED BUOY DATA (MRB)

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9.1. INTRODUCTION

As the National Data Buoy Center website reports, "In March 1966, the Panel on Ocean Engineering of the Interagency Committee on Oceanography convened a group of Federal agency representatives to address the problems and possibilities associated with automated data buoy networks. This group recommended a national system of ocean data buoys and the Committee asked the United States Coast Guard to conduct a feasibility study of a consolidated national data buoy system". After ten months of work, the study report made the following conclusions:

extensive requirements exist for oceanographic and meteorological information to satisfy both operational and research needs in the oceanic and Great Lakes environments;

automatic, moored buoys were capable of meeting a significant portion of those needs; and that

a network of such buoys, would be an essential element of an overall environmental information and prediction system (Shea, 1987).

As further explained in the U.S. Department of Commerce's publication NDBCM WO547, "The National Data Buoy Project (NDBP) was established in December 1967 for the purpose of developing a national capability to deploy and operate networks of automatic buoys to retrieve useful information describing the marine environment on a reliable, real time basis". As noted by Shea (1987) in "A History of NOAA" – "By the 1960's, scientists had recognized the need for more detailed information on environmental conditions over vast marine areas which remained largely uncovered except for occasional observations from ships or aircraft of opportunity, oceanographic research expeditions, or the few existing ocean station vessels. As a result, a number of Federal Agencies and universities began programs to develop and implement networks of buoys which could routinely and automatically report environmental conditions like temperature, wind speed and direction, etc."

The Data Buoy Cooperation Panel website describes moored buoys as "normally relatively large and expensive platforms. Data are usually collected through geostationary meteorological satellites such as GOES or METEOSAT. If a moored buoy goes adrift it represents a potential loss of costly equipment and a possible hazard to navigation. For these reasons the Argos system has been used for location determination for moored buoys. In addition, some World Meteorological Organization (WMO) Member countries use the ARGOS system for normal transmission of meteorological observations from moored buoys" (see Data Buoy Cooperation Panel web-site).

The WOD13 MRB dataset contains data on daily averaged values of water temperature and salinity collected by sensors located on moored buoys (MRB) during the period from March 7, 1980 to December 31, 2012. The dataset contains a total of 1,411,762 profiles. The majority of data came from ongoing programs. 462,434 casts were collected from the TAO buoy array. 66,242 casts were acquired from the PIRATA program. 67,518 casts came from the TRITON program and 39,887 casts were submitted by the RAMA Project. Historic data consist of 73,693 casts from three buoys located around Japan and operated by the Japan Meteorological Agency (JMA); 19,445 casts were collected during the MARNET program, and 905 casts were collected during the South China Sea Monsoon Experiment (SCSMEX). Two Arctic data programs contributed a number of profiles: the Arctic-Subarctic Ocean Fluxes (ASOF) project contributed 635,124 casts, and the Circulation of the North Central Chukchi Shelf project provided 43,005 profiles. 4,414 casts came from other unidentified sources (See Figure 9.1 for percentages and related web-links below for additional information).

As part of the Tropical Ocean-Global Atmosphere (TOGA) program, efforts were made to enhance the real-time ocean observing system in the tropical Pacific Ocean. The Tropical Atmosphere Ocean (TAO) array of moored buoys spans the tropical Pacific from 137°E to 95°W and from 8°S to 8°N. The TAO system began in 1985 as a regional-scale set of meridional arrays on both sides of the Equator at 110°W and 165°E and has steadily expanded to its present size of approximately 70 moorings.

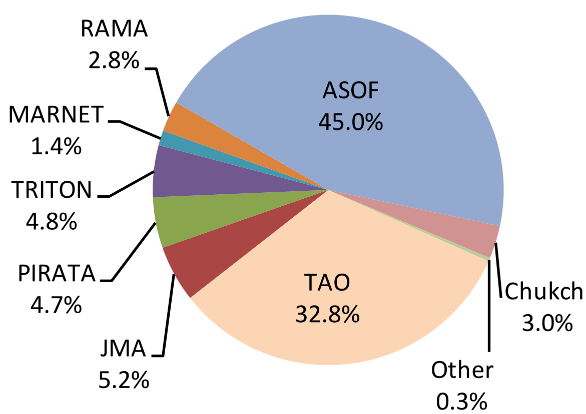

Figure 9.1. Distribution of the moored buoy data among the major research programs.

Moorings are typically separated by 2-3 degrees of latitude and 10-15 degrees of longitude. The TAO array of moored buoys provides surface wind, sea surface temperature (SST), upper ocean temperature, as well as subsurface temperatures and salinity down to a depth of 500 meters, and current measurements (Mangum, 1994; Mangum *et al.,* 1994; McPhaden, 1995; McPhaden *et al.,* 1998). The majority of TAO moorings are ATLAS moorings developed at NOAA's Pacific Marine Environmental Laboratory (PMEL) Seattle, WA, in the 1980's. The ATLAS mooring is a taut wire surface mooring with a toroidal float. It is deployed in depths of up to 6000 meters (Milburn *et al.,* 1996). The expansion of this array is the result of international collaboration between scientists from France, Japan, Korea and the USA. The first ATLAS mooring was deployed in December 1984. Collected data are transmitted to shore in real time using the ARGOS System, processed by Collecte Localisation Satellites (CLS) or Service ARGOS Inc., and placed on the Global Telecommunication System (GTS). Post-recovery processing and analysis of the data is performed at PMEL. The TAO array now supports programs like the Global Climate Observing System (GCOS), World Climate Research Programme (WCRP), Climate Variability and Predictability Programme (CLIVAR), and the World Weather Watch Programme (WWW, Data Buoy Cooperation Panel web-site).

PIRATA (Pilot Research Moored Array in the Tropical Atlantic) is a project designed by a group of scientists involved in CLIVAR, and is implemented by the group through multi-national cooperation. Contributions are provided by France with the participation of L'Institut de Recherché pour le Développemen (IRD) in collaboration with Meteo-France, Centre National de la Recherche Scientifique (CNRS), Universities and French Research Institute for Exploitation of the Sea (IFREMER), by the Brazilian Instituto Nacional de Pesquisas Espaciais (INPE) and Diretoria De Hidrografia E Navegação (DHN), and by the USA (NOAA/PMEL, NASA and Universities). The purpose of PIRATA is to study ocean-atmosphere interactions in the tropical Atlantic that are relevant to regional climate variability on seasonal, inter-annual and longer time scales.

The RAMA (Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction) Project - a key element of the Indian Ocean Observing System (InsOOS) is the basin-scale moored buoy array intended to cover the tropical Indian Ocean. In this respect, RAMA is the Indian Ocean equivalent of the TAO/TRITON array in Pacific and PIRATA grid in the Atlantic (McPhaden *et al.*, 2009). RAMA started in 2000 as Indian and Japanese national efforts when JAMSTEC deployed two TRITON moorings and NIO (National Institute of Oceanography, India) began subsurface mooring deployment along the equator (McPhaden *et al.,* 2006). As of June 2013, RAMA was 67% complete, with 31 of 46 mooring sites occupied. The planned array will consist of 38 surface and 8 subsurface moorings. Mooring equipment, ship time, personnel, and/or logistic support has been provided by several nations including Japan, India, the United States, Indonesia, China, France and nine African countries (ASCLME Project) (McPhaden *et al.,* 2009). Data collected by RAMA buoys are distributed by Service Argos via Global Telecommunications System (GTS) as well as via the PMEL, JAMSTEC and NIO websites (see links below).

The MARNET (Marine Environmental Monitoring Network in the North Sea and Baltic Sea) project has four buoys located in the North Sea and five buoys in the Baltic Sea. The program uses existing platforms as a base for instrument installation; in the North Sea two unmanned lightships and two North Sea Buoys (NSB II and NSB III) are used, and in the Baltic Sea two large discus buoys, a stabilized mast, semi-submersible buoy and a pier/platform near the Kiel lighthouse are used. The main components of the measuring equipment are sensors, data acquisition unit, data storage system, and data collection platform (DCP). Sensors with analog and digital outputs are connected to the data acquisition unit. The raw data are transmitted via DCP and satellite (METEOSAT) to the land-based station at the Bundesamt für Seeschifffahrt und Hydrographie (BSH). The data storage is a security backup in case the satellite communications system breaks down. Oceanographic sensors measuring the following variables are installed: temperatures at 5 to 8 depth levels (depending on water depth); conductivity at 2 to 4 depth levels; oxygen concentration at 2 depth levels; radioactivity at 1 or 2 depth levels; currents; water levels; nutrient analyzers and samplers for micro-contaminants (accommodated in deck containers); and sea water pumping units.

The Arctic/Subarctic Ocean Fluxes (ASOF) project is a collection of research products from several countries. The ASOF project was established in 2000, and from 2000 to 2008 measurements at several locations in the Arctic and Subarctic was collected with the aim of estimating a freshwater budget for Arctic inflows and outflows. A second phase of the project, since 2008, combines the ongoing scientific work of ASOF I with application of the results to broader questions of science and society. The mooring data in WOD13 comes from the Canadian Arctic Throughflow Study (CAT), which gathered data in Nares Strait from 2003 to 2006. The moorings were instrumented with SeaBird Electronics, Inc. model 37-IM temperature and conductivity sensors at up to 4 depth levels (CAT, 2007).

The Circulation of the North Central Chukchi Shelf project placed 5 moorings on the shelf of the Chukchi Sea, in water 46 – 54m deep, from 1993 to 1996. The moorings were instrumented with SeaBird Electronics, Inc. model SBE 16 temperature/ conductivity sensors at two depths (Weingartner *et al.*, 2005).

Table 9.1. National contributions of MRB casts in WOD13.

ISO[a] Country Code	Country Name	MRB Casts	% of Total
US	United States	1,135,388	80.42
JP	Japan	168,962	11.97
BR	Brazil	35,727	2.53
FR	France	28,622	2.03
99	Unknown / International	22,713	1.61
DE	Germany	19,445	1.38
TW	Taiwan	905	0.06
	Total:	*1,411,762*	*100.00*

[a] ISO = International Organization for Standardization

Five countries collected most of the moored buoy data in WOD13: USA, Japan, Germany, Brazil, and France. Significant amounts of data have no country information mostly because of the multi-national nature of its acquisition and processing; those data were obtained from internet-based web-portals of the international research Programs (*i.e.* RAMA, *etc*.) Table 9.1 provide detailed information on each country contribution.

9.2. MRB DATA PRECISION AND ACCURACY

The accuracy of MRB temperature and salinity data depends on the temperature and conductivity sensors used. For TRITON buoys, for example, sensor range and accuracy are: conductivity 0-70/0.003 ms cm^{-1}; temperature -3.0 – 33.0/0.002°C; depth 0-1000 pounds per square inch absolute (psia) / 0.15% full scale (Kuroda, 2002; Ando *et al.,* 2005). Data acquired during TAO and PIRATA programs were collected from PROTEUS and ATLAS buoys using SeaBirds Electronics Inc. SEACAT sensors which have sea surface temperature accuracy of 0.01°C for the PROTEUS mooring and 0.03°C for ATLAS moorings; subsurface temperature accuracy is 0.01°C for the PROTEUS mooring and 0.09°C for ATLAS moorings (Freitag *et al.,* 1994; Cronin and McPhaden, 1997). RAMA data are collected mostly from ATLAS and TRITON moorings. In February 2008 JAMSTEC deployed several mini-TRITON buoys with slack-line moorings with all its sensors equipped to measure pressure so data can be interpolated to standard depth (McPhaden *et al.*, 2009).

MARNET data were collected using oceanographic sensors calibrated at the BSH's calibration laboratory by means of triple point thermometer, gallium cells, reference resistors and resistance bridges of the highest available precision, as well as salinometers calibrated with Copenhagen standard sea water. The three seawater baths used for temperature and conductivity calibration reach a temperature stability of $\pm 1 \cdot 10^{-3}$ °C. After deployment, the sensors are checked and cleaned at monthly intervals. During each monthly check, an *in situ* comparative measurement is carried out using a reference CTD system.

The moorings from the CAT study, part of the ASOF project, were instrumented with SBE 37-IM temperature/conductivity sensors. The temperature measured by this sensor is accurate to 0.002°C, and conductivity to 0.0003 S/m. The measurements from the Circulation of the North Central Chukchi Shelf project were collected using SBE 16 temperature and conductivity sensors. Using this sensor, temperature was measured to 0.005 °C, and conductivity to 0.0005 S/m (CAT, 2007). The sensors were calibrated before deployment and after recovery, and linearly interpolated calibration coefficients were applied to the data during processing (Weingartner, 2007).

9.3. MRB CAST DISTRIBUTIONS

Table 9.2 gives the yearly counts of MRB casts for the World Ocean; this is graphically illustrated on Figure 9.3.

The geographic distribution of the MRB casts for 1980-2005 is shown in Figure 9.4. There are a total of 1,411,762 MRB casts for the entire World Ocean with 628,676 casts (45%) measured in the tropical regions (15°N – 15°S). The TAO, TRITON, PIRATA, and RAMA programs contributed these data. The MARNET and JMA programs have contributed 43,468 casts (3%) measured in the area between 30 and 60°N. Approximately 4% of all casts (60,099, mostly collected by JMA) were acquired between 15-30°N. The ASOF and Circulation of the North Central Chukchi Shelf project collected data in the Arctic Ocean and Canadian Archipelago, contributing 678,129 profiles in total (48%).

Table 9.2. Number of MRB casts in WOD13 as a function of year. Total number of casts = 1,411,762

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1977	173	1986	3,328	1995	44,308	2004	240,269
1978	240	1987	3,812	1996	38,158	2005	241,327
1979	1,184	1988	5,131	1997	33,209	2006	161,208
1980	1,307	1989	6,527	1998	37,422	2007	33,342
1981	1,148	1990	7,275	1999	39,963	2008	34,524
1982	931	1991	9,825	2000	37,271	2009	36,314
1983	1,370	1992	24,032	2001	30,920	2010	37,424
1984	1,464	1993	33,823	2002	29,324	2011	37,416
1985	1,951	1994	47,613	2003	115,220	2012	33,009

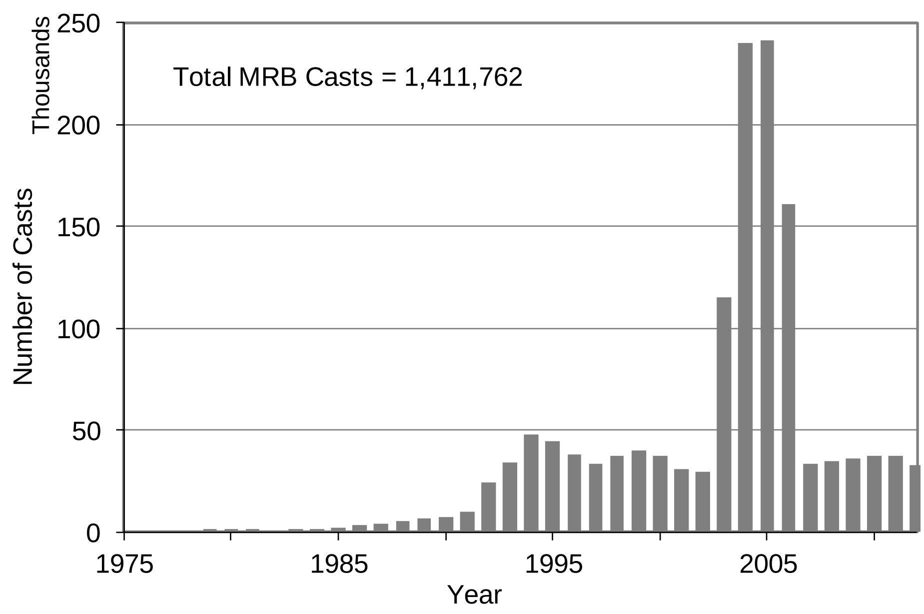

Figure 9.2. Temporal distribution of MRB casts in WOD13.

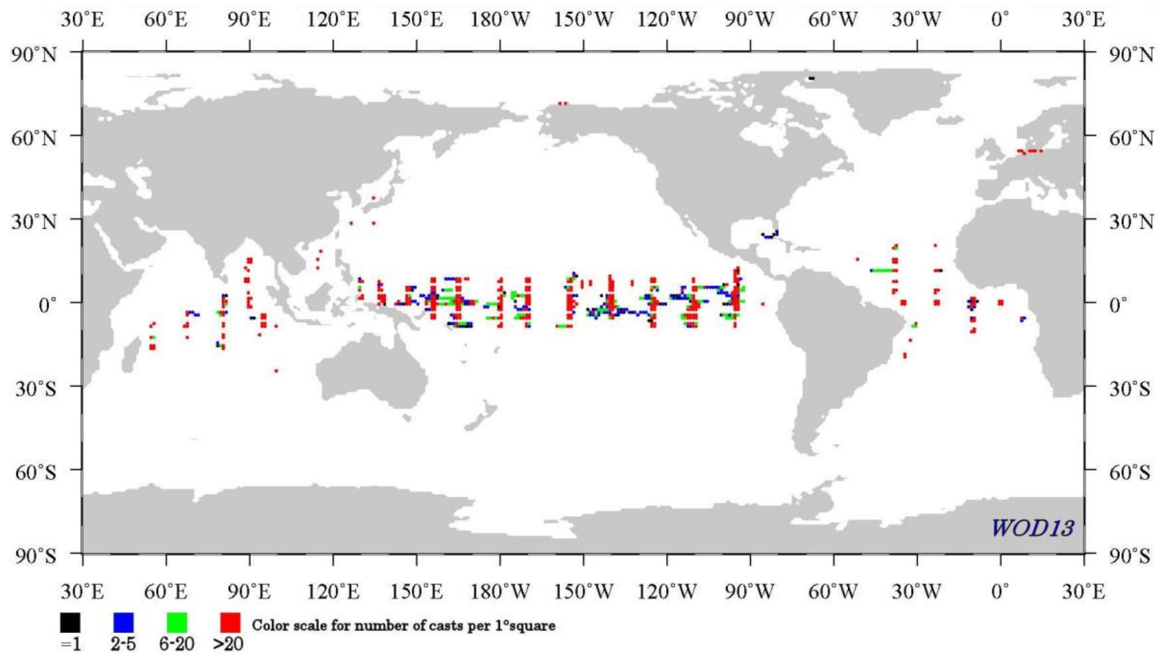

Figure 9.3. Geographic distribution of MRB casts in WOD13.

Figure 9.5 shows the distribution of the MRB data as function of depth. The majority of the moored buoys are designed to sample only the upper layer of the ocean, so most of the data were collected within upper 500 meters of the water column.

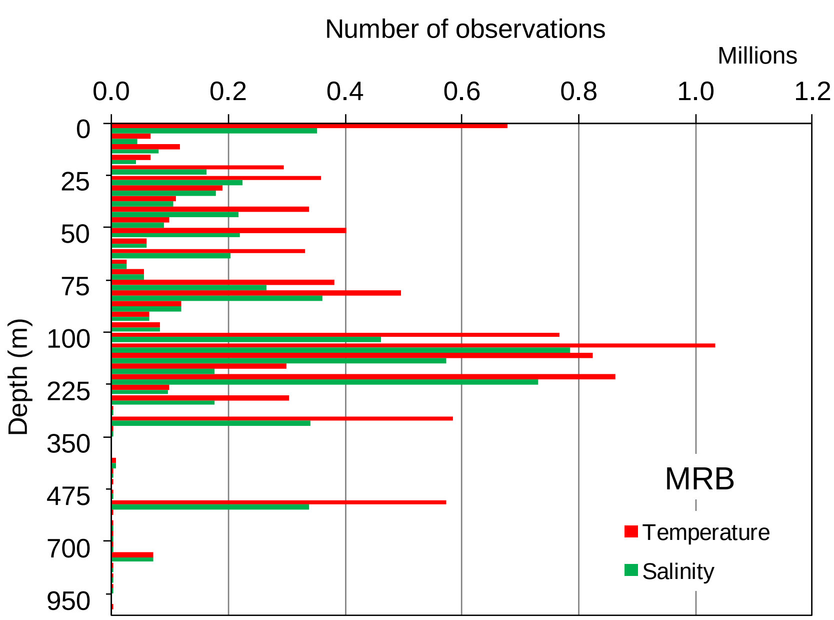

Figure 9.4. Distribution of the Moored Buoys (MRB) data at standard depth levels in WOD13.

9.4. RELEVANT WEB SITES

ARGOS Program.
Arctic/Subarctic Ocean Fluxes (ASOF).
Centre national de la recherche scientifique (CNRS).
Canadian Arctic Throughflow Study (CATS).
Diretoria De Hidrografia E Navegação (DHN), Brazil.
GOES Project.
L'Institut de recherché pour le développemen (IRD).
French Research Institute for Exploitation of the Sea (IFREMER).
Instituto Nacional de Pesquisas Espaciais (INPE), Brazil.
JAMSTEC TRITON Buoy project.
MARNET.
METEOSAT.
National Data Buoy Center.
NOAA Magazine.
PIRATA Program.
RAMA Program.
South China Sea Monsoon Experiment.
TAO/TRITON collaboration.
Tropical Atmosphere Ocean Project.
WMO-IOC Data Buoy Cooperation Panel.

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CHAPTER 10: DRIFTING BUOY DATA (DRB)

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10.1. INTRODUCTION

Drifting buoys are a cost effective means for obtaining meteorological and oceanographic data from remote ocean areas. They form an essential component of the marine observing systems that were established as part of many operational and research programs. Drifting buoys are used as a practical alternative to acquiring data from inaccessible regions as opposed to maintaining costly manned stations (DBCP, 2006; IABP, 2006).

The first drifting buoys, drift bottles, were used in the early 1800s in an effort to map surface currents. The bottles were weighted so that they were almost entirely submerged and usually carried a note that recorded launch location and time. Bottles were used because previous attempts at mapping ocean currents using ship drift measurements proved unreliable due to the added effect of wind on the movement of the ships (Lumpkin and Pazos, 2006). With the advent of radio, the position of the drifters could be transmitted from small, low-drag antennae and triangulated from the shore. In the early 1970s, positions started to be gathered via satellites. As technology improved, drifters started to obtain meteorological measurements, sea surface temperatures, as well as oceanographic measurements (IADP, 2006; Lumpkin and Pazos, 2006).

10.1.1. Arctic Ocean Buoy Program

The first sea ice buoys used by the Arctic Data Buoy Program were deployed in the ice floes of the Arctic Basin in 1979; they recorded meteorological parameters such as surface atmospheric pressure, air temperature, wind speed, as well as geographic position. Data were transmitted and collected via the Argos system and then distributed on the Global Telecommunication System (GTS) (IABP, 2006; GTS, 2006).

Between the years 1985 and 1994, the Arctic Data Buoy Program of the Polar Science Center of the Applied Physics Laboratory at the University of Washington deployed 24 modified data buoys in ice floes on the Arctic Ocean. These were the first buoys, as well as the first sea ice buoys, to be equipped with Seabird CTD sensors for collecting oceanographic data along with the meteorological data. These modified buoys, known as Polar Ocean Profile (POP) buoys, measured subsurface ocean temperature, salinity and depth. They also measured air temperature and barometric pressure. Measurements were taken at twelve-minute intervals. The direction and velocity of the sea ice floe was interpolated from changes in position from each buoy. Due to being subjected to the stresses and strains of the Arctic pack ice, these buoys varied greatly in their longevity, though the battery pack was designed to last for approximately three years (Rigor, 2002; IABP, 2006; JAMSTEC, 2006).

The components of a Polar Ocean Profile Buoy start with an ARGOS antenna with air temperature and barometric pressure sensors in a fiberglass shroud that protrudes from the ice floe. This sits on a flotation/ablation skirt that is directly on top of the ice. Within the ice itself are the buoy electronics assembly housing and an alkaline (D-cell) battery pack, all encased in an aluminum hull. Attached to the bottom of the hull, extending into the water column, is a 24-conductor electromagnet cable upon which an SBE-16 Seacat CTD sensor is attached. The SBE-16 Seacat has a total of 6 sensors, placed at depths of 10, 40, 70, 120, 200, and 300 meters; a depth sensor is added to the sensors at 40, 120, and 300 meters. At the very end of the electromechanical cable is a 50 pound ballast weight (IABP, 2006).

10.1.2. Global Temperature-Salinity Profile Program (GTSPP)

The Marine Environmental Data Service (MEDS, Canada) collects the data from all drifting buoys via the Global Telecommunication System (GTS). MEDS has been a Responsible National Oceanographic Data Center (RNODC) since January 1986 under the auspices of the Intergovernmental Oceanographic Commission (IOC). They acquire, process, quality control, and archive real-time drifting buoy data that is reported over the GTS as well as delayed-mode data that are acquired from other sources. Over 200,000 new records are captured monthly from the GTS by MEDS. Data transmitted as drifting buoy data by MEDS through the GTSPP program are only from buoys that transmit subsurface data. This drifting buoy data includes buoy position, date, time, surface and subsurface water temperature, salinity, air pressure, temperature and wind direction (MEDS, 2006). Currently, buoy data from GTSPP in the WOD13 database comes mostly from the United States, Japan and France. It consists of temperature readings and some have meteorological measurements such as wind speed, wind direction, dry bulb temperature, and barometric pressure.

10.1.3. JAMSTEC Buoys

In the early 1990s, the Japan Marine Science and Technology Center (JAMSTEC) developed a polar ocean profiler buoy, the Ice Ocean Environmental Buoy (IOEB), as a joint project with the Woods Hole Oceanographic Institution (WHOI). This was the first attempt to develop a drifting ice buoy equipped with not only meteorological, sea ice and oceanographic sensors, but also with other sensors, such as optical sensors and time series collection devices, that would determine the activities of marine organisms. The first IOEB was deployed in the Beaufort Sea in April 1992; the second was deployed April 1994 into the Arctic Transpolar Drift. These first buoys lacked mobility and had little consistency in measurements due to the large number of different sensors on them.

Also, the buoys were expensive to assemble and required large camps and lots of equipment and materials to install them in the ice. They also had to be recovered to analyze collected sediment samples (JAMSTEC, 2006).

JAMSTEC and MetOcean Data System Ltd. developed a new drifting buoy in 1999, named J-CAD (JAMSTEC Compact Arctic Drifter), and its mission was to conduct long-term observations in the Arctic Ocean multi-year ice zones as a participant of the International Arctic Buoy Program (IABP). Since 2000, the J-CAD has been used to measure the structure of upper ocean currents and water properties. Ten J-CADs have been installed into the sea ice in various regions of the Arctic Ocean and have been collecting oceanographic and meteorological data. The data J-CAD buoys collect are: air temperature, barometric pressure, wind direction, wind speed, sea surface temperature, platform heading, platform tilt, latitude, longitude, date and time of reading, GPS drift speed, GPS drift direction, CTD sensors' depth, pressure, temperature, conductivity, salinity, potential temperature, density, and several ADCP parameters. (The ADCP data are not available through the WOD series.) The sensors measure data at one-hour intervals and the J-CAD deployment location varies by different projects' requirements (JAMSTEC, 2006; Kikuchi *et al.*, 2002).

The total weight of the J-CAD system was designed to be 255 kg or less. This way it can be deployed using a small, light crane system. The maximum external diameter of the underwater sensors is 28 cm, so each sensor can be lowered through a 30 cm hole in the ice that can be drilled with simple equipment. It is equipped with three types of sensors: meteorological, oceanographic, and buoy status sensors. The J-CAD buoys consist of a floatation collar made of foam resin buoyancy material (Surlyn Ionomer resin manufactured by DuPont Co.) enclosed by aluminum. The housing for instruments, also made from aluminum and foam resin, holds the data logger/controller engine (Tattletale model 8) with 48MB flash card memory, a GPS receiver, two satellite communication systems, the GPS interface MetOcean Digital Controller, and two 245 Ahr lithium battery packs to supply power. On the top of the aluminum enclosure is an Argos antenna mast that includes the air temperature sensor, the barometer port, and two GPS antennas. There is also a PC interface for the physical downloading of data from the flash card memory, to configure the data logger, and to set various sensor operating parameters (JAMSTEC, 2006).

Meteorological sensors equipped on the J-CAD consist of a YSI Inc. model 44032 high-precision thermistor for air temperature, a Paroscientific Inc. model 216B barometer, and a RM Young Co. model 5106-MA anemometer. The outside air or sea ice temperature is measured from the thermistor placed at the top of the Argos antenna mast. The barometer port is also at the top of the mast and is covered by a water trap and a Gore-Tex membrane to protect it from moisture. Finally, the wind sensor is vertically mounted on the top of the J-CAD tower; this tower is designed to withstand 120-knot winds (JAMSTEC, 2006).

The ocean temperature and conductivity data are obtained from Sea-Bird SBE37IM CT sensors, two of which are equipped with pressure sensors that are part of the CT instrument. On a J-CAD buoy, four CT and two CTD sensors can be mounted. The CT sensors are usually attached at 25m, 50m, 80m, and 180m. The two CTD sensors are usually placed at 120m and 250m. These depths can be adjusted to the sea area under observation. There are also two WorkHorse 300 kHz ADCPs from RD Instruments attached at 12m (facing downward) and at 260m (facing upward/downward) to measure the underwater currents. These ADCPs also measure the heading, pitch and roll of the buoy and have a thermistor to measure the water temperature at the ADCPs' depth (JAMSTEC, 2006; Kikuchi *et al.*, 2002).

The J-CAD is equipped with sensors that check the physical status of the buoy. A model TCM2, three-axis magnetometer (Precision Navigation Inc.) measures the platform's orientation. It is mounted inside the hull and provides estimates of platform direction and vertical tilt. There is also a compass that indicates the rotation of the ice base that the J-CAD platform is installed upon. Two GPS receivers are attached to the Argos mast. One receiver is a Jupiter model TU30-D140-231 (Conexant Systems Inc.) and is interfaced with the MetOcean Digital Controller. The data from this GPS is used as the J-CAD position reported for the data. The second GPS is an integral part of the Panasonic KX-G7101 ORBCOMM Subscriber Communicator but is only used as a complement to the ORBCOMM satellite system. Finally there is a sensor to measure the temperature of the water and/or ice that is surrounding the J-CAD hull. It is an YSI model 44032 high-precision thermistor that is in constant contact with the inside wall of the platform hull. The instrument is safely inside the J-CAD and, due to the high thermal conductivity of aluminum, the interior wall temperature matches the outside temperature, giving an accurate reading (JAMSTEC, 2006).

In the spring of 2000, an international research team supported by the U.S. National Science Foundation (NSF) was formed to conduct annual expeditions to the North Pole. These expeditions established a group of un-manned platforms, collectively referred to as an observatory, to record as much data as possible. Drifting buoys from the IABP and the JAMSTEC J-CAD are major components of this project, entitled the North Pole Environmental Observatory (NPEO) Project. The Pacific Marine Environmental Laboratory (PMEL) also maintains drifting weather buoys as part of this program (NPEO, 2006; Kikuchi *et al.*, 2002).

10.1.4. Ice-Tethered Profiling buoys (ITP)

In 2006, WHOI developed the ITP buoy platform to effectively map the water column in ice-covered seas with a profiling drifter. This drifter builds off the technology developed for the moored profiler (MP) instrument, also developed at WHOI, and also from the innovations of the ARGO profiling floats. Instead of being instrumented at fixed depths like other ice drifters, the ITP platform profiles at high resolution through the water column as the ice floe moves, and returns measurements along with the instrument's position from GPS. The platform is lightweight and able to be deployed by helicopter or Twin Otter aircraft through a standard 25cm augered hole in the ice. The instruments are relatively inexpensive, so they can be considered expendable and several can be deployed at one time (ITP, 2006; Krishfield *et al.*, 2008).

The drifter is composed of two parts: the surface package that sits on the ice surface, and the underwater profiling package on the tether line. The surface package is made from yellow-painted foam and contains the Iridium modem, GPS receiver, data controller, batteries and an interface to the underwater part of the drifter. On the outside of the surface package, a temperature sensor measures air temperature. The surface package is designed to be expandable and support other instrumentation as well as increased power and battery loads in the future. When deployed, the surface package is placed on a wooden pallet to help avoid melting and deformation of the ice floe (ITP, 2006; Krishfield *et al.*, 2008).

Below the surface, a plastic-jacketed wire rope tether line extends up to 800m into the water column. A ballast weight at the bottom of the line keeps it oriented vertically. The profiling package is ballasted to be neutrally buoyant at mid-profile depth. The profiling package moves along the line using a traction drive similar to that used by the moored profiler (MP) buoys. The profiling package is instrumented with a Sea Bird Electronics, Inc. model 41-CP CTD, the same instrument used by ARGO floats. The package returns data at a sample rate of 1Hz and the surface unit sends it to shore at near-real time over the Iridium link (ITP, 2006; Krishfield *et al.*, 2008).

As of June 2013, 68 individual ITP packages have been launched, supporting the Beaufort Gyre Observing System (BGOS), Beaufort Gyre Freshwater Experiment (BGFE), North Pole Environmental Observatory (NPEO), European Union DAMOCLES, Nansen and Amundsen Basins Observational System (NABOS), and Hybrid Arctic/Antarctic Float Observation System (HAFOS) projects in the Arctic and the National Institute of Water and Atmospheric Research (NIWA) project in the Antarctic (ITP, 2006).

10.2. DRB ACCURACY

The SBE-16 SEACAT that is used in the AOBP's POP buoy is designed to accurately measure and record temperature and conductivity. It is powered by internal batteries that give it a year or more of recording time. The time-base is accurate to within 3 minutes per year. There is also an internal battery back-up to support the memory and the real-time clock. Data from the AOBP's POP buoy's SBE-16 Seacat consists of temperature and conductivity measurements from pre-determined depths along the cable. It is capable of temperature measurements ranging from -5 to +35°C with an accuracy of 0.01°C and has a resolution of 0.001°C. The conductivity measurement range is from 0 to 7 S m-1 with an accuracy of 0.001 S m-1 and resolution of 0.0001 S m-1 (Sea-Bird Electronics Inc., 2013).

The foremost concern of the POP buoy's accuracy was conductivity sensor drift due to fouling. Over a year, it seemed that the normal instrumental drift that occurs with age and use fell to less than one percent of the original accuracy. Because the buoys were not usually recovered or revisited, their approach to minimize fouling was to use light baffling shrouds coated with anti-fouling paint around the conductivity cell. More recently, Sea-Bird has provided anti-fouling tubes on the ends of the conductivity cells. The Arctic environment, being cold and dark for half of the year, is detrimental to the growth of fouling organisms. The few sensors that were recovered showed no evidence of fouling or fouling drift. Over time, fouling was generally found to not be a serious problem in the Arctic, though there were occasional problems with shallow sensors in the summer (Morrison, Pers. Com.; Rigor, 2002). Another problem with the POP buoys was inaccurate surface air temperatures that were caused by the small size of the buoy. The air temperature sensor was inside a fiberglass shroud that created a microcosm that would heat up in the summer and be drifted over and insulated by snow in the winter. This difference in internal and external environments rendered the air temperature readings “void” (Rigor *et al.*, 2000).

For data transmitted through GTSPP, the MEDS data quality control consists of two main parts: validation and verification. The data validation consists of reformatting the data to the MEDS processing format, this allows the data to be checked for its readability and correct interpretation. When the reformatting is complete, then the data values themselves are quality controlled or verified. This is to ensure that the number and codes represent reasonable physical quantities that exist in the given time and location. There are three parts to the verification process: checking the drift track, checking the variable values, and checking for duplicate profiles. The track is checked to make sure that the date is valid, not listed as a future date or one that is farther in the past then the buoy was deployed, and to make sure that the position is not over land. The inferred speed between each measurement location is also checked to make sure that it is reasonable. Values of variables are checked against the regional range as well as others for validity and any spikes in gradients or large inversions; any discrepancies are flagged with specific flags. Duplicate checking will identify any data that are versions of the same observation. Exact matches where each version of the same observation is identical usually results in one observation being deleted, unless the data were gathered by two different methods, then both observations are specifically flagged and kept in the database. The results of the quality control procedure are the setting of flags or making corrections where instrument failure or human error is evident on the data that needs it (MEDS, 2006).

J-CAD buoys use six Sea-Bird SBE-37 IM CT sensors, two of which are equipped with pressure sensors. The SBE-37 IM accurately measures conductivity and temperature with optional pressure. It has an internal battery, non-volatile memory and uses an Inductive modem to transmit data and receive commands. It is specifically designed for moorings and other long-duration, fixed-site deployments. Over 100,000 measurements can be taken before the battery runs low and its real-time clock is accurate to within 2.6 minutes per year. The range of temperature and conductivity measurements match the IABP’s POP’s SBE-16 Seacat (-5 to +35°C and 0 to 7 S m-1 respectively), but the SBE-37 IM has an initial temperature accuracy of 0.002°C and initial conductivity accuracy of 0.0003 S m-1. The pressure sensor used has a range of 0 to 7,000 meters and is accurate to within 1%. Resolution of the temperature, conductivity, and pressure data are 0.0001°C, 0.00001 S m-1, and 0.002% respectively (Sea-Bird Electronics Inc., 2013).

The ITP drifters use the Sea-Bird Electronics, Inc. model 41-CP CTD package to measure temperature, conductivity and pressure at 1 Hz resolution as the instrument profiles the water column. Temperature measurements using the 41-CP are accurate to 0.002°C, and the conductivity sensor has an accuracy of 0.002 (equivalent salinity). Pressure is accurate to within 2 dbar. The instrument demonstrates good stability and is suitable for long deployments with little measurement drift. Some ITP drifters also include a dissolved oxygen sensor, the SBE-43, which is accurate to 2% of saturation (Sea-Bird Electronics Inc., 2013). Also included on select ITP drifters is a Seapoint fluorometer to measure chlorophyll (Seapoint Sensors Inc., 2013). Depending on the water depth, the drifters may take up to 6 profiles per day (Krishfield, 2008).

10.3 DRB PROFILE DISTRIBUTIONS

There are data from 154,900 drifting buoy casts in WOD13, which were submitted by three major research programs. The majority of DRB data came from surface drifters equipped with thermistor chains via GTSPP data system (73,135 casts). JAMSTEC provided 40,453 casts from J-CAD buoys and Arctic Ocean Buoy Program (AOPB) submitted 8,240 profiles (see Figure 10.1). 33,072 profiles were submitted by the Ice-Tethered Profiler (ITP) program at WHOI.

The geographic distribution of the DRB casts is illustrated in Figure 10.2a (Global Ocean) and 10.2b (North Polar Area from 50°N). The DRB casts (except one Australian) are distributed in the northern hemisphere in Pacific, Atlantic and Arctic oceans. There are a few profiles from the Mediterranean Sea, Persian Gulf and Red Sea as well as the northern Indian Ocean, but they are only a minor part of the profile distribution.

The temporal distribution of the DRB data is shown in Table 10.1 as well as in Figure 10.3. Table 10.2 gives national input to the DRB dataset by each contributing country.

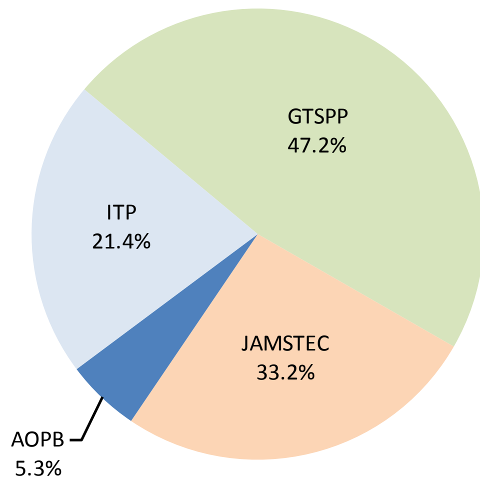

Figure 10.1. Distribution of the Drifter Buoys data in WOD13 among major research programs.

Table 10.1. The number of DRB profiles in as a function of year in WOD13. The total number of profiles = 154,900

Year	Profiles	Year	Profiles	Year	Profiles	Year	Profiles	Year	Profiles
1985	217	1991	1,422	1997	0	2003	7,905	2009	3,494
1986	482	1992	606	1998	3	2004	5,681	2010	2,544
1987	447	1993	462	1999	4,770	2005	10,332	2011	4,047
1988	1,387	1994	532	2000	12,611	2006	4,655	2012	6,202
1989	1,510	1995	0	2001	62,952	2007	5,220	2013	159
1990	1,175	1996	0	2002	9,249	2008	6,533		

Table 10.2. National contributions of DRB casts in WOD13.

ISO[a] Country Code	Country Name	DRB Casts	% of Total
FR	France	58,100	37.51
JP	Japan	40453	26.12
US	United States	55807	36.03
99	Unknown / International	539	0.35
AU	Australia	1	<0.01
	Total:	*154,900*	*100.00*

[a] ISO = International Organization for Standardization

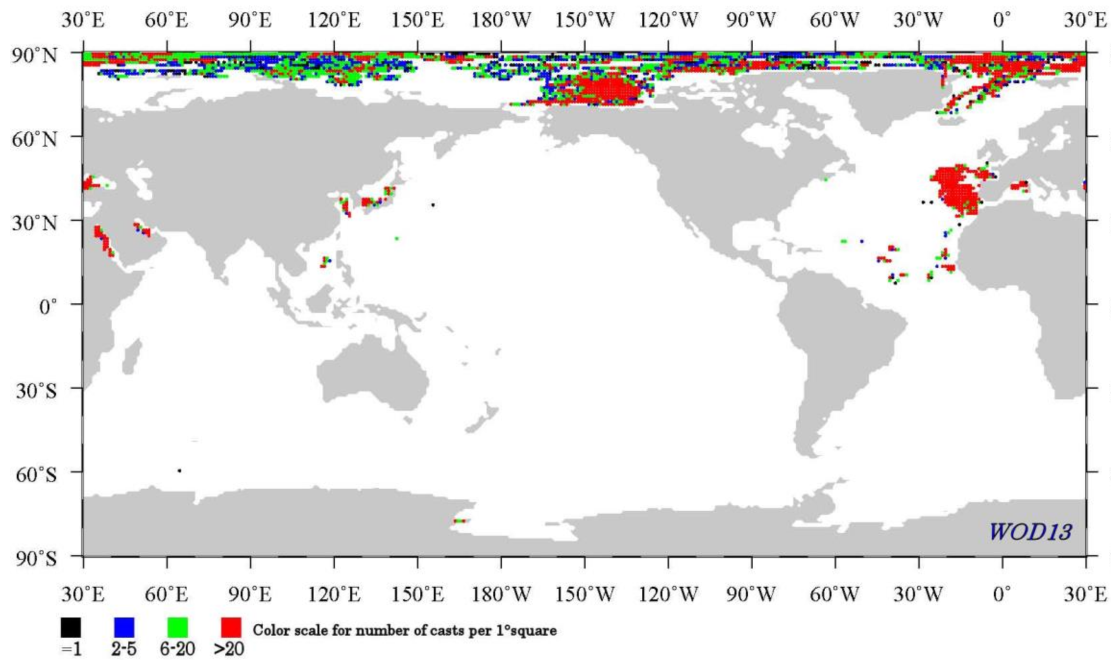

Figure 10.2a. Geographic distribution of the Drifting Buoy (DRB) data (Global Ocean) in WOD13.

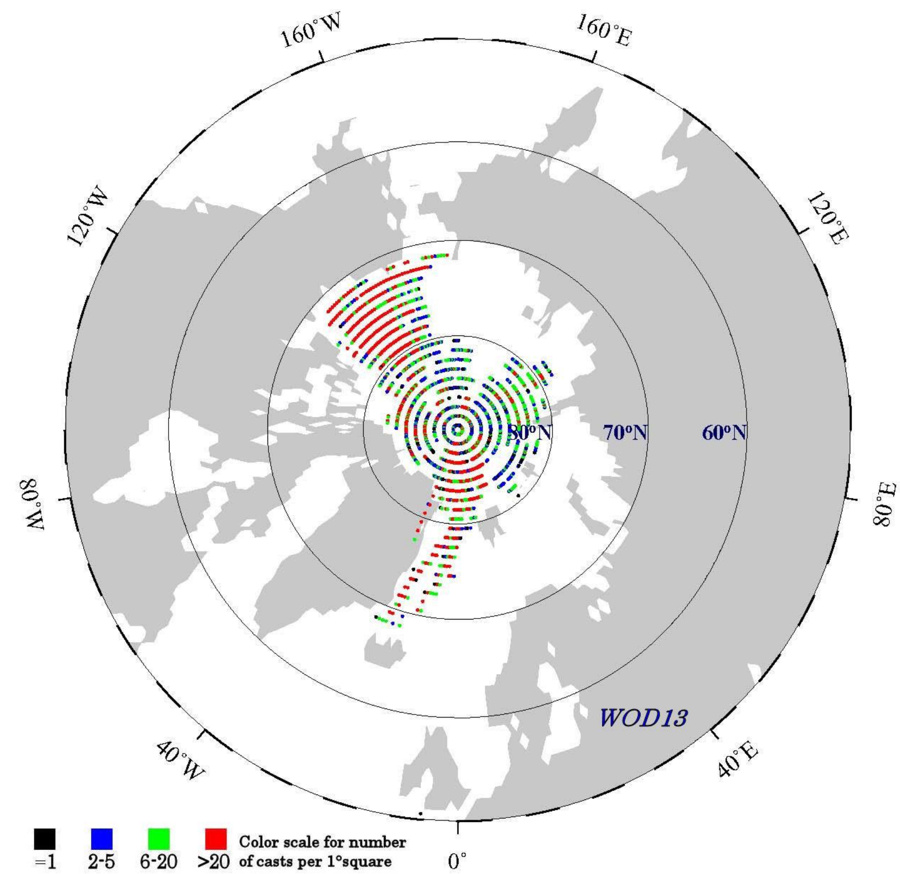

Figure 10.2b. Geographic distribution of the Drifting Buoy (DRB) data (North Polar Area) in WOD13.

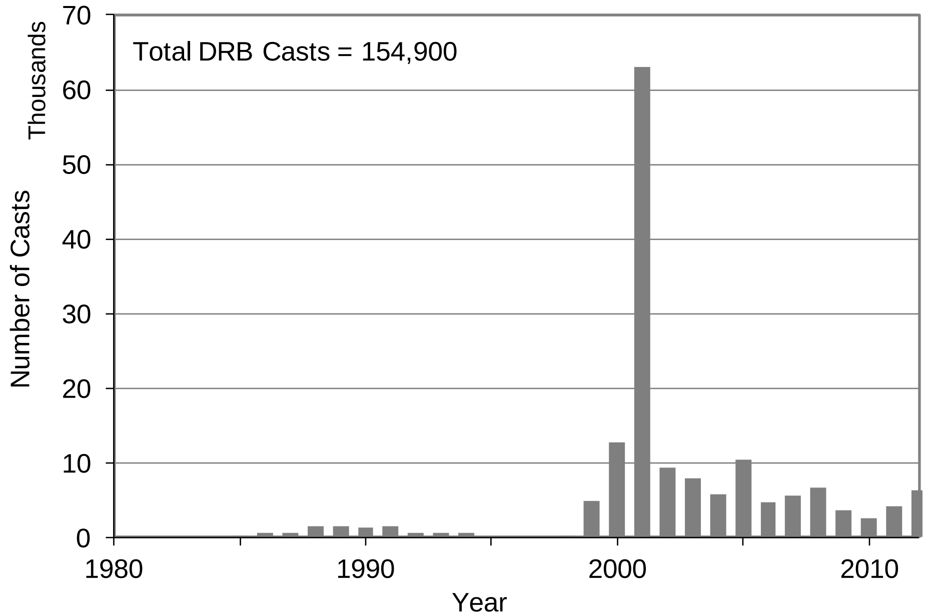

Figure 10.3. Temporal distribution of the Drifting Buoy (DRB) casts in WOD13.

Distribution of the DRB data as a function of depth at standard depth levels is illustrated in Figure 10.4.

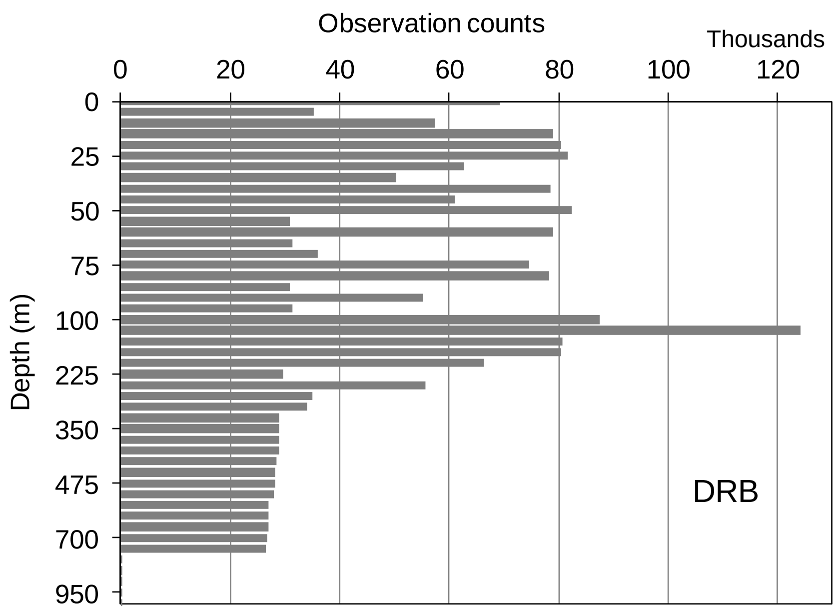

Figure 10.4. Distribution of the Drifting Buoy (DRB) data at standard depth levels in WOD13.

10.4. RELEVANT WEB SITES

DBCP, 2006. Data Buoy Cooperation Panel, Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology.

GTS, 2006. The Global Telecommunication System, World Meteorological Organization.

IABP, 2006. International Arctic Buoy Program, Polar Science Center, Applied Physics Laboratory, University of Washington, Washington, USA.

ITP, 2006. Ice-Tethered Profiler, Woods Hole Oceanographic Institution, Massachusetts, USA.

JAMSTEC, 2006. JAMSTEC Compact Arctic Drifter (J-CAD), Arctic Ocean Climate System Group, Global Warming Observational Research Program, Institute of Observational Research for Global Change, Japan Agency for Marine-Earth Science and Technology, Kanagawa, Japan.

MEDS, 2006. Marine Environmental Data Service (MEDS), Department of Fisheries and Oceans, Ontario, Canada.

NDBC, 2006. National Data Buoy Center (NDBC), National Weather Service, National Oceanic and Atmospheric Administration, U.S. Dept. of Commerce, Mississippi, USA.

NPEO, 2006. The North Pole Environmental Observatory (NPEO) Project, Office of Polar Programs, National Science Foundation, Virginia, USA.

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CHAPTER 11: UNDULATING OCEAN RECORDER DATA (UOR)

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11.1. INTRODUCTION

The first ship-towed ocean recorder was developed by Sir Alister Hardy for underway plankton sampling. As stated at the Sir Alister Hardy Foundation for Ocean Science website: "Sir Alister Hardy started his career as a fishery biologist in Lowestoft, England. In 1925 he embarked on a two-year voyage to the Antarctic on the ship *Discovery*. He designed the prototype Continuous Plankton Recorder (Mark I) specifically for the expedition. After his return in 1927, Hardy designed a smaller version of the Continuous Plankton Recorder (Mark II) for use on merchant ships. This model is essentially the same as that used routinely today. In September 1931, the SS Albatross towed the first Continuous Plankton Recorder (CPR) and the survey was born. The CPR Survey was based in Hull until 1950, when it moved to Edinburgh under the administration of the Scottish Marine Biological Association (SMBA). In 1959 the first transatlantic route was towed from Reykjavik to Newfoundland."

As ship speeds increased through the 1950's and 1960's, a need for a fast CPR was identified. In addition to this, a need to measure plankton concentrations at more than a single depth level (~10 m) had also been identified. Thus, a fast CPR (FCPR) and a prototype undulator were developed. By the early-1970's, as technology advanced in the form of more environmental data sensors and larger data storage, the Undulating Oceanographic Recorder (UOR) was born (Reid *et al.*, 2003). The UOR Mark I was developed jointly through the Oceanographic Laboratory at Edinburgh and the Plessey Marine Systems Unit. Further development took place at the Plymouth Marine Laboratory (PML) where UOR Mark 2 was developed (Reid *et al.*, 2003). In the early-1960's the Longhurst Hardy Plankton Recorder (LHPR) was also developed, allowing vertical measurements of plankton to be recorded (Longhurst, 1966). For a more in-depth history of the CPR and UOR, please review Reid *et al.* (2003).

The modern UOR is a self-contained oceanographic sampler which can be towed from research vessels and merchant ships at speeds up to 25 knots. It can be launched and recovered by non-scientist crew members while the vessel is underway. It can be used to carry instrumentation to sample plankton continuously and to measure chlorophyll, radiant energy, temperature, and conductivity, all of which are recorded with depth

(Aiken, 1981). This technique is often used for large marine ecosystem sampling or frontal zones because of its convenience and uninterrupted data coverage (Williams and Lindley, 1980; 1998; Pollard, 1986) and its ability to sample a large area in a reasonable period of time (Brown *et al.,* 1996). It is also expanding towards a wider set of sensors used, such as light absorption sensors and attenuation meters (Barth and Bogucki, 2000).

Table 11.1. Profile count for major variables in the WOD13 UOR dataset.

Measured Variables	**Profiles**
Temperature	88,170
Salinity	86,454
Oxygen	361
Chlorophyll	20,252
Pressure	88,190

The WOD13 UOR dataset consists of temperature, salinity, chlorophyll concentration, pressure, and a small number of oxygen profiles (see Table 11.1 for details) collected by CTD and fluorometer sensors mounted on a SeaSoar-type towed vehicle. The SeaSoar towed vehicle was developed by Chelsea Technologies Group, Ltd. from an original design by the Institute of Oceanographic Sciences (now the Southampton Oceanography Centre, UK). "SeaSoar is capable of undulating from the surface to 500 meters at tow speeds of up to 12 knots (with faired cable) following a controlled and adjustable undulating path through the ocean. Sampled data, obtained from sensors mounted in SeaSoar, are transmitted to the towing vessel for processing, display and storage via a multi-core tow cable". For unfaired cable, the depth range is from the surface to 100 meters.

WOD13 UOR data were collected in the framework of several major international programs in the Atlantic, Pacific and Indian oceans from 1992 till 2000 and submitted to NODC by seven major Institutions (see Figure 11.1).

The majority of data (41,485 casts) was collected during the Delaware Circulation and Dye Experiment (DECADE) organized by the University of Delaware (U. of D.). This experiment studied the mixing and secondary circulation in the Delaware River plume. Data were acquired by means of a Scanfish undulating towed vehicle equipped with a Chelsea Ltd. MKIII Aquatracka fluorometer fitted to a Sea Bird SBE-911 CTD (Houghton *et al.*, 2004).

A large amount of data (26,413 casts) came from the international research program "Tropical Ocean Global Atmospheres/Coupled Ocean Atmosphere Response Experiment" (TOGA/COARE). A majority of the TOGA data (20,026 casts) were collected and submitted by a team from Oregon State University (Corvallis, OR). The Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) provided 5,269 casts, and the Office de la Recherche Scientifique et Technique d'Outre-Mer program (ORSTOM, France) submitted 1,118 casts. The TOGA program studied the interaction of the ocean and atmosphere in the western Pacific warm pool region. Field measurements were made along ~155°E line in 1992 - 1993 (for further details see TOGA/COARE web-site).

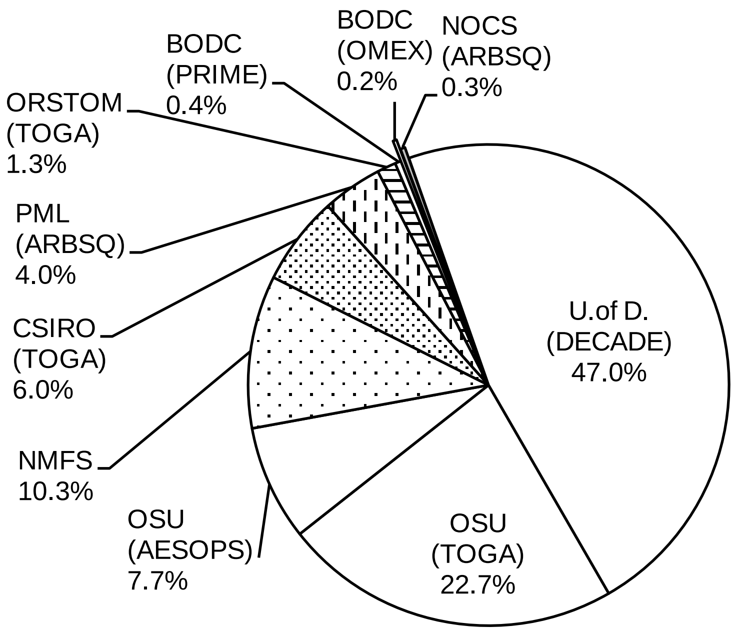

Figure 11.1. Distribution of the UOR data in WOD13 among the contributing institutions. Associated projects shown in parentheses

A substantial amount of data was provided by the National Marine Fishery Service (NMFS), which contributed 9,054 casts measured along the Oregon coast.

The Oregon State University (Corvallis) team also submitted data collected in the framework of the Joint Global Ocean Flux Study (JGOFS) project – Antarctic Environments Southern Ocean Process Study (AESOPS) Program - 6,828 casts in the Antarctic Polar Front Zone area.

During the U.K. ARABESQUE project 3,829 profiles were collected in the Indian Ocean by groups from the Plymouth Marine Laboratory (PML, U.K., 3553 casts) and the National Oceanography Centre, Southampton (NOCS, U.K., 276 casts). The ARABESQUE project studied the upper ocean microbial biogeochemistry in the Arabian Sea. Its focus was carbon and nitrogen cycling processes linked to climate change. The field program was timed to coincide with the Southwest Monsoon and inter-monsoon period through to the onset of the Northeast Monsoon.

The UOR dataset also includes 363 profiles submitted by the British Oceanographic Data Center (BODC) that were collected during the Plankton Reactivity in the Marine Environment (PRIME) program, which was a thematic project funded by the National Environment Research Council of UK (NERC) to study the role of plankton in oceanic biogeochemical fluxes. The PRIME data included in WOD13 were collected in the northeast Atlantic in 1996.

BODC also submitted Ocean Margin Exchange (OMEX) project data (218 casts). The aim of the OMEX project was to study, measure and model the physical, chemical and biological processes and fluxes occurring at the ocean margin, the interface between the open ocean, and the continental shelf. The first phase of the project, OMEX I, concentrated on studying the processes taking place along the northwest European shelf break.

11.2. UOR DATA PRECISION AND ACCURACY

The accuracy of UOR data depends on the performance of the sensors used and post-processing of the data. A SeaSoar undulating vehicle is capable of carrying various instrumental packages. For the data stored in the WOD13 database, the Sea-Bird Electronics SBE 911*plus* CTD instrument was used most often. Please see section 3.2 for CTD accuracy information. It is presumed that UOR data submitted into WOD13 were corrected for effects of: a) variable flow rate (Huyer *et al.,* 1993), b) thermal mass (Lueck, 1990; Morrison *et al.,* 1993), and c) offset between temperature and conductivity data (Larson, 1992; Morrison *et al.,* 1993).

11.3. UOR PROFILE DISTRIBUTIONS

Table 11.2 gives the yearly counts of UOR casts for the World Ocean and Figure 11.2 illustrates this graphically.

Table 11.2. Number of all UOR casts as a function of year in WOD13. Total number of casts =88,190

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1992	11,913	1996	363	2000	9,054	2004	38,594
1993	14,500	1997	6,828	2001	0		
1994	3,988	1998	0	2002	0		
1995	59	1999	0	2003	2,891		

Table 11.3 gives national input to UOR dataset by each contributing country (also shown graphically in Figure 11.3). The geographic distribution of UOR casts and contributing projects is shown in Figure 11.4. Figure 11.5 illustrates distribution of the UOR data as a function of depth at observed depth levels.

Table 11.3. National contributions of UOR casts in WOD13.

ISO[a] Country Code	Country Name	UOR Casts	% of Total
US	United States	77,393	87.76
AU	Australia	5,269	5.97
UK	United Kingdom	4,410	5.00
FR	France	1,118	1.27
	Total	*88,190*	*100.00*

[a] ISO = International Organization for Standardization

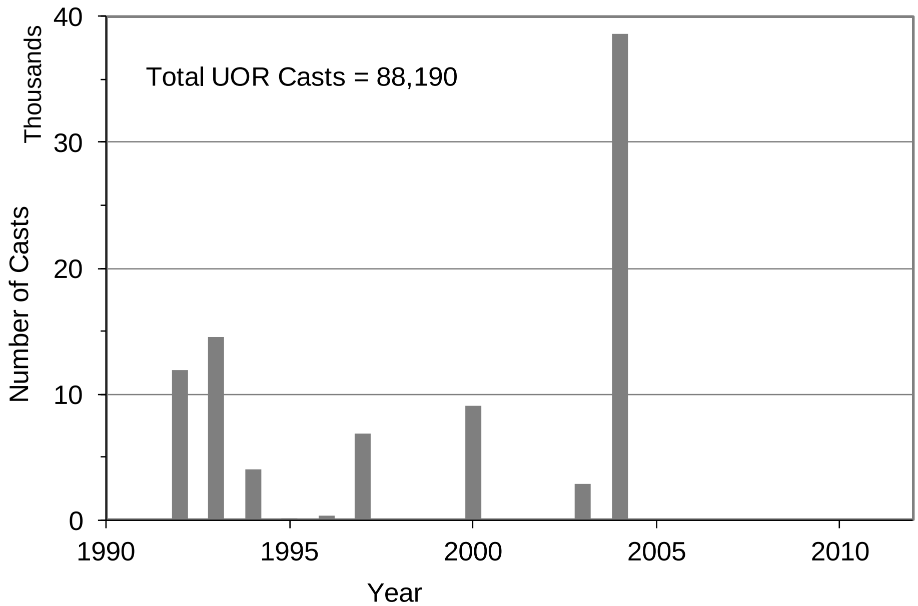

Figure 11.2. Temporal distribution of UOR casts in WOD13.

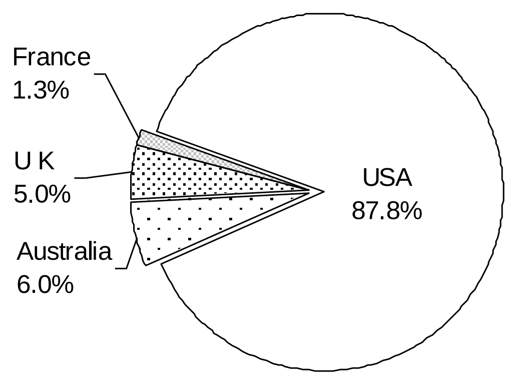

Figure 11.3. Distribution of UOR data in WOD13 among the contributing countries.

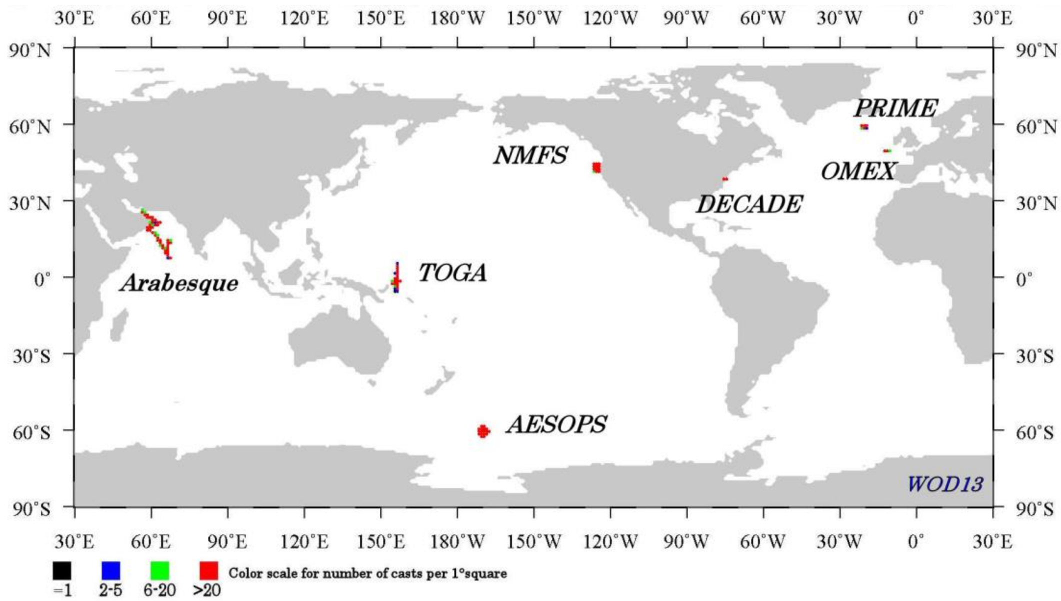

Figure 11.4. Geographic distribution of UOR data in WOD13.

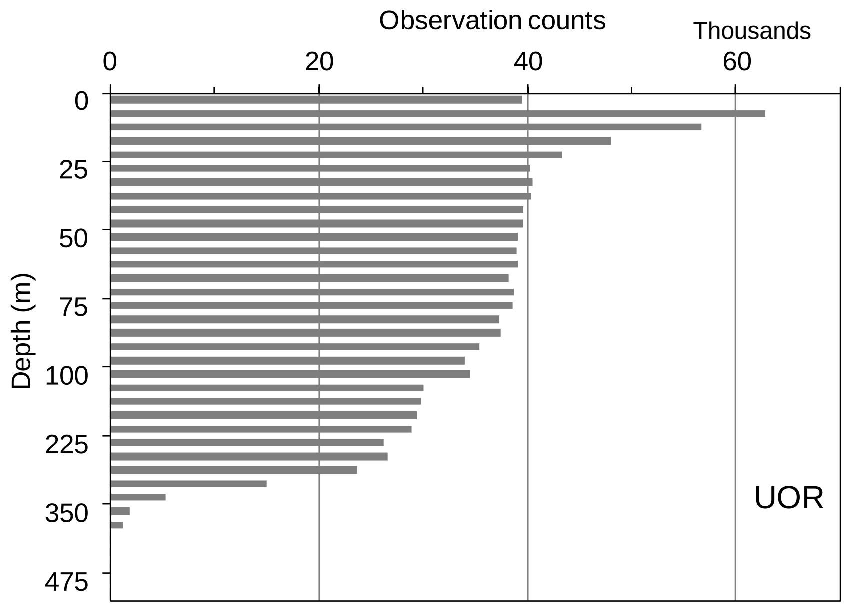

Figure 11.4. Distribution of UOR data at standard depth levels in WOD13.

11.4. RELEVANT WEB SITES

ARABESQUE Project.

Australian Commonwealth Scientific and Industrial Research Organization (CSIRO).

Chelsea Technologies Group, Ltd.
College of Oceanic and Atmospheric Sciences at Oregon State University, Corvallis, OR.
JGOFS-AESOPS.
Ocean Margin Exchange (OMEX).
Plankton Reactivity in the Marine Environment (PRIME).
Plymouth Marine Laboratory.
Tropical Ocean Global Atmospheres/Coupled Ocean Atmosphere Response Experiment (TOGA-COARE).

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CHAPTER 12: AUTONOMOUS PINNIPED BATHYTHERMOGRAPH DATA (APB)

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12.1. INTRODUCTION

The first usage of marine mammals as sampling platforms is credited to Pers Scholander (Scholander, 1940; cited after Fedak, 2004 and Ropert-Coudert and Wilson, 2005). Based on a description of a depth gauge provided by Lord Kelvin in the 19th century, Scholander developed depth gauges to record diving depths of whales. Various research groups have used other marine mammals to carry sensors and data loggers followed up this pioneering work.

Data from sensor instruments attached to marine animals (instrumented animals) such as sea turtles, sea birds, sharks, tuna, and marine mammals, were initially collected for the principal purpose of studying animal ecology (Le Bœuf *et al.*, 1988; Block, 2005). In addition to animal ecology studies, scientists can use instrumented animals as autonomous ocean profilers to enhance sparse oceanographic observations in specific oceanic regions (McCafferty *et al.*, 1999; Boehlert *et al.*, 2001; Charrassin *et al.*, 2002; Lydersen *et al.*, 2002; Hooker and Boyd, 2003; Fedak, 2004; Ropert-Coudert and Wilson, 2005; Roquet *et al.*, 2009; Padman *et al.*, 2010). The data supplied by instrumented animals could potentially fill data gaps due to harsh environmental conditions in areas such as the Bering Sea, Gulf of Alaska, and the Southern Ocean, especially in winter and in ice-covered waters. These data can also help fill spatial and temporal gaps due to remoteness of some areas such as the southeast Pacific, and spatial gaps between routes of Ships-of-Opportunity (or Voluntary Observing Ships, VOS). Temperature profiles from instrumented animals are less expensive than those obtained by traditional instruments such as Expendable Bathythermographs, XBT (Boehlert *et al.*, 2001). After recovering instruments from animals, the equipment can be re-used. The vertical resolution of the available pinniped data is better than the vertical resolution of bottle station data but generally worse than the resolution of XBT and Conductivity-Temperature-Depth, CTD data.

The Autonomous Pinniped Bathythermograph (APB) dataset presented in the WOD13 contains in situ temperature data from temperature-depth records (TDRs) and conductivity-temperature-depth satellite relay data loggers (CTD-SRDLs) attached to pinnipeds (e.g., elephant seals). The instrumented pinnipeds are the northern elephant seals (Mirounga angustirostris) in the Northern Ocean and the southern elephant seals (*Mirounga leonina*) in the Southern Ocean.

12.2. DATA SOURCES

The APB data that comprise WOD13 have been acquired through different sources and projects. Each using a different electronic tag mounted on the northern and southern elephant seals.

The Pacific Fisheries Environmental Samplers Project, a project under the NOAA/National Marine Fisheries Services (NOAA/NMFS), submitted northern elephant seal data equipped with the WildLife Computers Mk3 TDR. The Tagging of Pacific Predators (TOPP), a project under the Census of Marine Life, submitted northern elephant seal data equipped with the WildLife Computers Mk9 and Mk10 TDRs. The Sea Mammal Research Unit (SMRU) and the Southern Elephant Seals as Oceanographic Samplers (SEaOS) both submitted southern elephant seal data deployed with Autonomous CTD-Satellite Relay Data Loggers (CTD-SRDLs).

The instrumentation packages used by these research teams are similar to each other and can be illustrated by the below description from Boehlert *et al.* (2001).

Geographic positions were determined using the ARGOS satellite transmitters. The half-watt satellite platform transmitter terminals (PTT; Model ST-6, Telonics, Mesa, Arizona) were affixed near the elephant seal's head using epoxy. The antenna was oriented to be out of the water when the seal surfaced. The PTT transmitted every 34 s while the seals were at the surface (Boehlert *et al.*, 2001).

The NODC received some of the SMRU and some of the SEaOS data through the Global Temperature-Salinity Profile Program (GTSPP) system.

12.3. INSTRUMENTATION

The northern elephant seals were deployed with WildLife Computers (Redmond, USA) Mk3, Mk9, and Mk10 TDRs.

Earlier submission of northern elephant seal data used the Mk3 TDR. This is a slower responding internal thermistor using a simple time lag to account for the response of the thermistor (Simmons *et al.*, 2009; Boehlert *et al.*, 2001). The Mk3 has a temperature resolution of 0.1ºC and an accuracy of 0.5ºC with a manufacturer's stated minimum recording temperature of 4.8ºC (Boehlert *et al.*, 2001). The pressure transducers on the TDR were calibrated prior to deployment using a pressure station. The Mk 3 TDRs used had two transducer channels. In order to increase the accuracy on shallower dives TDRs were programmed to use channel 1 for depths <450 m (with accuracy <2 m) and channel 2 for depths >450 m (with accuracy <4 m) (Boehlert *et al.*, 2001).

The Mk9 and Mk10 are fast-response (i.e. fastloc) archival TDRs. Both TDRs are configured with multiple sensors. The depth sensor has a 12-bit analog-to-digital converter; it provides highly-accurate measurements from -40 to +1000 m, with 0.5 m resolution and an accuracy of ± 1%. In addition, measurements from 1000 to 1500 m are made with a lesser degree of accuracy. Measurements can be recorded throughout the range at full resolution. The temperature sensor is a 12-bit analog-to-digital converter; it has a range of -40° to +60°C, with 0.05°C resolution and an accuracy of ±0.1°C. Measurements can be recorded throughout the range at full resolution.

The southern elephant seals were equipped with CTD-SRDLs, a specific configuration of Valeport's CTD. The CTD-SRDLs are designed and manufactured by SMRU. Temperature was measured by the Valeport fast response Platinum Resistance Thermometer (PRT), with a range of -5ºC to +35ºC, an accuracy of ±0.005ºC, and a resolution of 0.001ºC. Conductivity was measured by the Valeport inductive coils with a range of 0 to 80mS/cm, an accuracy of ±0.01mS/cm, and a resolution of 0.002mS/cm. Pressure was measured by the Keller PA-3L sensor, with a range of 2000 dbar, an accuracy of 2 dbar ± (0.3 to 0.035%*reading)/ K, and a resolution of 0.05 dbar. The TDR capability can retain a continuous record of depth readings (4 sec sample rate), which can be retrieved by Bluetooth link if the tag is recovered. During profiling, the TDR records all individual temperature and salinity measurements at 1 Hz during profiling. (Boehme *et al.*, 2009).

The latest version of a miniaturized CTD-Satellite Relay Data Loggers (CTD-SRDL) is the Argos tag 9000 series CTD-SRDL designed and built at the SMRU (University of St. Andrews, UK) and calibrated at Valeport Ltd. (Devon, UK). It has a 401 MHz RF unit and antenna for data transfer by way of the Argos system, a lithium-thionyl chloride (Li-SOCl2) D-cell battery (LSH 201) and a Hitachi H8/3048 microprocessor programmed to act as the data logger, data compression tool and to schedule data transfer (i.e. Boehme *et al.*, 2009).

12.4. GEOGRAPHICAL AND DEPTH DISTRIBUTION OF DATA

The WOD13 has a total of 1,427,610 APB vertical profiles collected between 1997 and 2012 (Table 12.1). Figure 12.1 shows geographical distribution of 1,282,607 casts from northern elephant seals in the Northern Ocean and 144,999 casts from southern elephant seals in the Southern Ocean, respectively. Figure 12.2 shows depth distribution of the entire data set.

Table 12.1. The number of all APB casts as a function of year in WOD13.
Total number of casts =1,427,610

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1997	19,875	2001	0	2005	326,962	2009	128,876
1998	44,626	2002	0	2006	123,733	2010	148,185
1999	11,164	2003	0	2007	230,296	2011	37,187
2000	0	2004	125,525	2008	209,607	2012	21,574

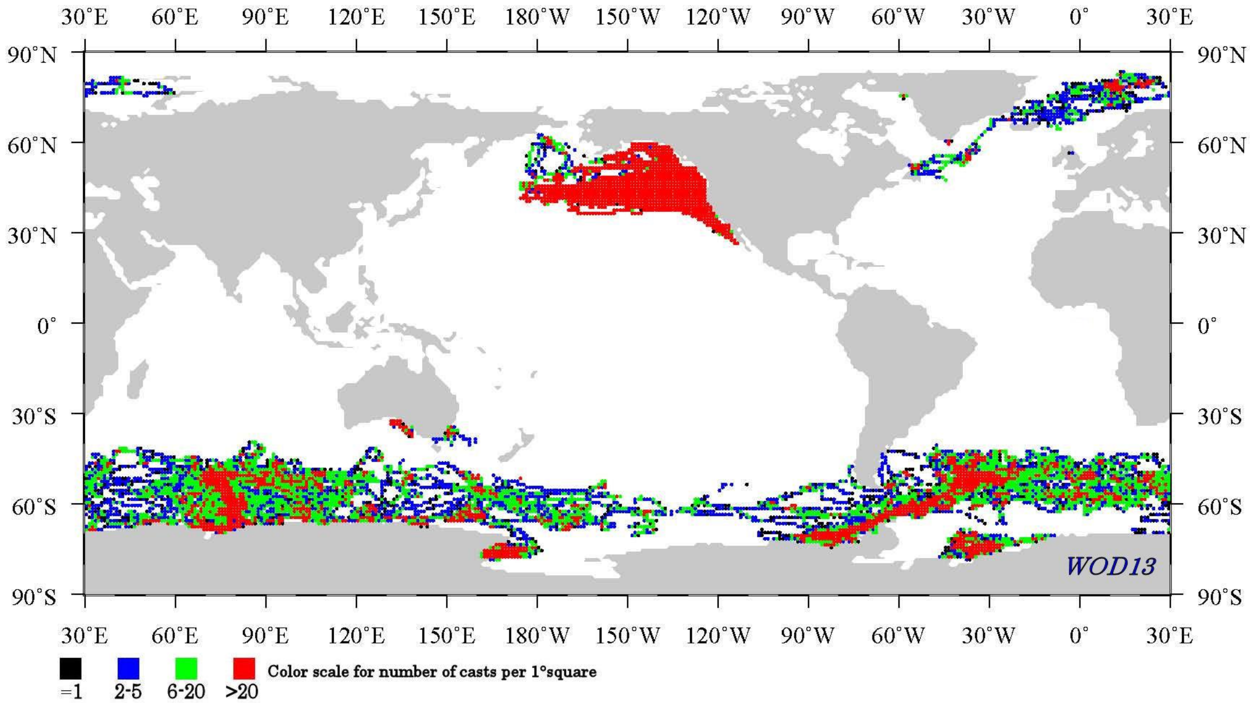

Figure 12.1. Geographic distribution of APB casts in WOD13.

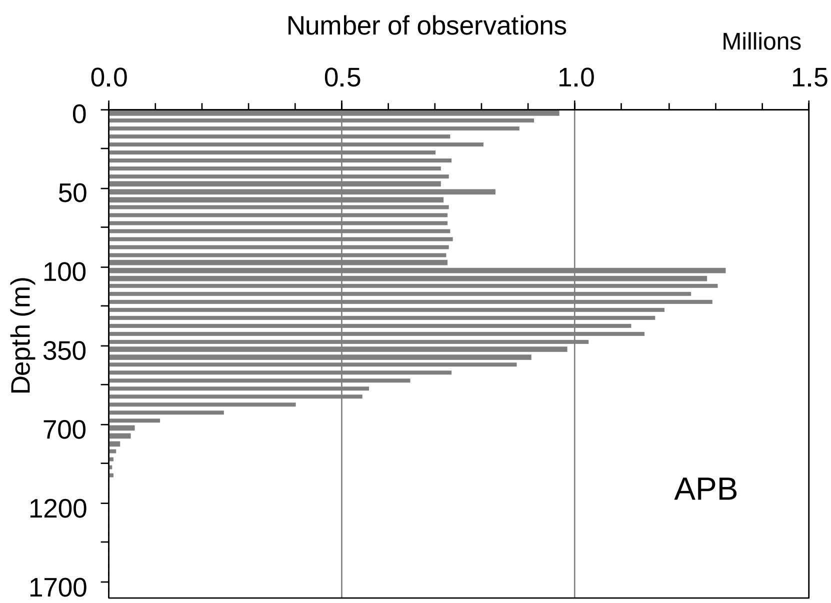

Figure 12.2. Distribution of the APB data at standard depth levels in WOD13.

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CHAPTER 13: MICRO BATHYTHERMOGRAPH DATA (MICRO BT)

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13.1. INTRODUCTION

The Micro Bathythermograph (Micro BT) is a high-accuracy temperature and pressure instrument developed to record and report data electronically. WOD13 includes data collected with micro BT instruments manufactured by RBR Ltd. and Sea-Bird Electronics (SBE). The self-contained underwater instrument includes a rapid response thermistor and a strain gauge pressure sensor. Temperature and depth/pressure measurements are automatically archived in the underwater unit as it is lowered in the water column attached to a net, cable, or towed vehicle. The instrument can be programmed to measure and archive data at desired intervals. Upon retrieval, the underwater unit is connected to a computer and data are retrieved and archived. The micro BT instruments can also provide real time data using an underwater cable.

Micro BT instruments can measure temperatures over a varied range of depths, with RBR LTD. instruments being able to measure to a maximum depth of 1000 m, and SBE instruments to a maximum depth of 7000 m.

All micro BT profiles are stored in the MBT dataset of WOD13.

13.2. MICRO BT ACCURACY

RBR Ltd. reports a temperature resolution of 0.1°C, and SBE reports a temperature accuracy of ±0.002°C. Both manufacturers report a pressure accuracy of ±0.1% of full scale range.

13.3. MICRO BT PROFILE DISTRIBUTIONS

Table 13.1 gives the yearly counts of micro BT profiles for the World Ocean. Fig. 13.1 shows the temporal distribution of Micro Bathythermograph profiles for the

World Ocean. Table 13.2 gives national contribution of Micro BT data. There are a total of 5,659 micro BT profiles for the entire World Ocean, all measured in the northern hemisphere (Figure 13.2). Distribution of the micro BT data at observed depth levels is shown in Figure 13.3.

Table 13.1. The number of all Micro BT profiles as a function of year in WOD13.

Total Number of Profiles = 5,659

YEAR	PROFILES	YEAR	PROFILES	YEAR	PROFILES	YEAR	PROFILES
1992	182	1995	642	1998	478	2001	653
1993	354	1996	528	1999	556	2002	643
1994	314	1997	504	2000	662	2003	143

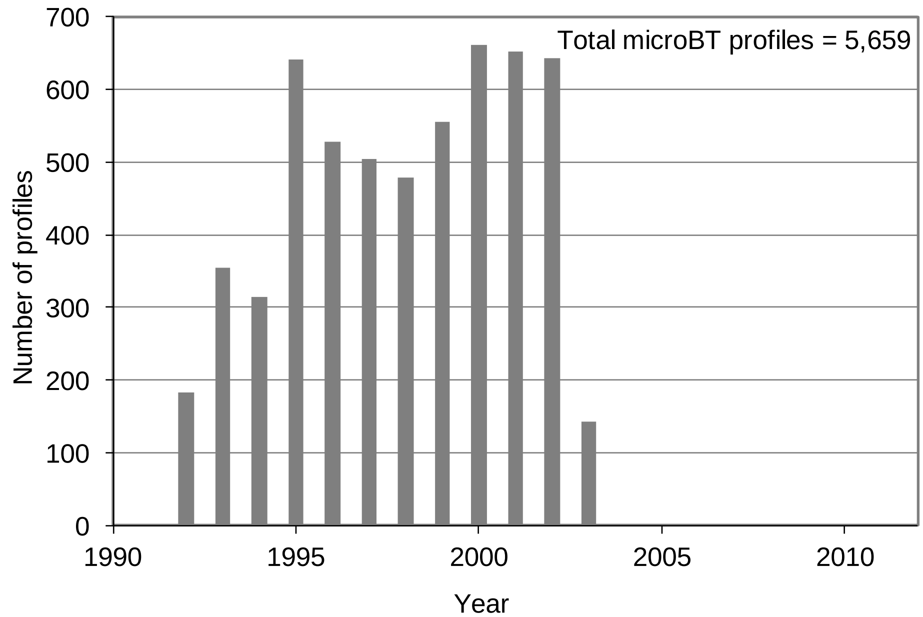

Figure 13.1. Temporal distribution of micro Bathythermograph data in WOD13.

Table 13.2. National contributions of Micro Bathythermograph (Micro BT) profiles in WOD13.

ISO[a] Country Code	Country Name	Micro BT Count	% of Total
US	United States	5,659	100.00

[a] ISO = International Organization for Standardization

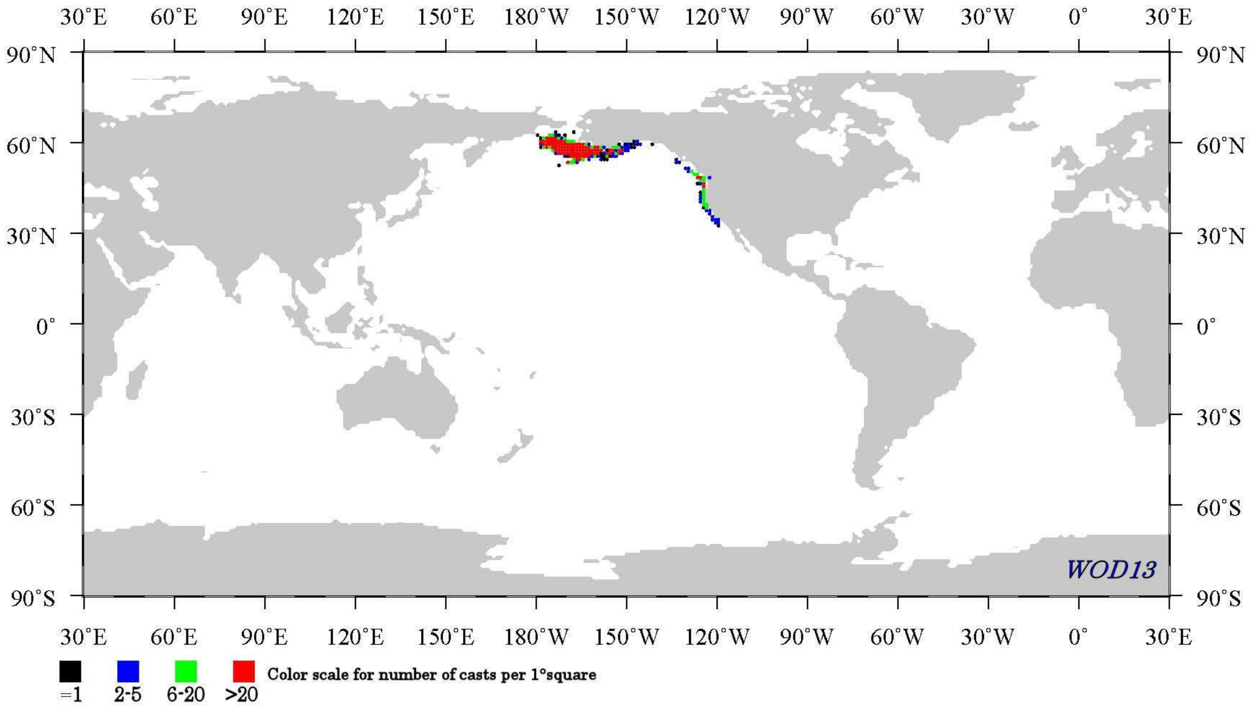

Figure 13.2. Geographic distribution of Micro Bathythermograph data in WOD13.

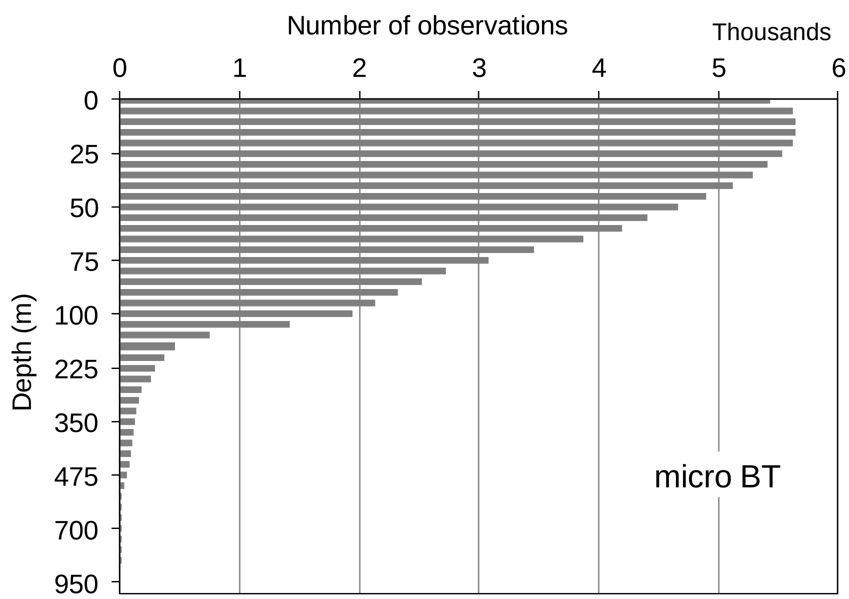

Figure 13.3. Distribution of micro Bathythermograph data at standard depth levels in WOD13.

CHAPTER 14: SURFACE-ONLY DATA (SUR)

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14.1. INTRODUCTION

The major focus of the WOD13 is sub-surface profile data. Therefore, surface data are included in WOD13 only if they were collected together with measurements of oceanographic variables of interest (Table 14.1), or if the data cover under-sampled time periods (*e.g.,* ICES Atlantic data for 1900-1939), or data provided by scientific ship-of-opportunity programs (*e.g.,* Institut de Recherche et Développement [IRD], formerly ORSTROM) surface salinity data for the Tropical Pacific; Henin and Grelet, 1996). Surface-only data oriented projects exist, which hold much more comprehensive surface data collections than WOD13 [*e.g.,* The International Comprehensive Ocean-Atmosphere Data Set (ICOADS), which contains more than 169 million sea surface temperature (SST) measurements mainly from merchant ships (Worley *et al.*, 2005) or the Global Ocean Surface Underway Data Pilot Project (GOSUD)]. The majority of the SUR data in WOD are salinity, temperature, and mole fraction of CO_2 in seawater (Table 14.1). Table 14.2 lists the count of SUR observations as a function of year of collection since 1867.

14.2. DATA PRECISION

Samples of the sea water may have been collected from the continuous flow of water pumped from subsurface depths (e.g., ship's water intake) or have been drawn from a bucket. A comprehensive review of the sampling techniques and its influence on the collected data precision can be found in Reverdin *et al.* (1994). When data came from bucket samples, the precision of the sea surface salinity is believed to be about ±0.1 (Delcroix and Picaut, 1998; Delcroix *et al.*, 2005). When data were collected by Thermosalinograph (TSG) sea surface salinity and temperature readings are recorded approximately every 10 seconds (Thomas *et al.*, 1999). Data precision of more modern measurements is limited by characteristics of the instrument (Delcroix *et al.*, 2005).

Table 14.1. List of parameters and number of observations in the SUR dataset of WOD13.

Parameter [nominal abbreviation]	Reporting unit (nominal abbreviation)	Number of observations
Temperature [t]	Degree centigrade (°C)	506,062
Salinity [S]	Unit less	1,958,361
pH	Unit less	84
Total Chlorophyll [Chl] unless specified	Micro-gram per liter (µg l^{-1})	44,088
Phaeophytin	Micro-gram per liter (µg l^{-1})	0
Alkalinity [TALK]	Milli-equivalent per liter (meq l^{-1})	84
Partial Pressure of Carbon Dioxide [pCO_2]	Micro-atmosphere (µatm)	34,962
Mole fraction of CO_2 in seawater [XCO_2sea]	Parts per million (ppm)	132,793
Air Temperature	Degree centigrade (°C)	49,648
CO_2warm[(1)]	Degree centigrade (°C)	60,262
Mole fraction of CO_2 in atmosphere [XCO_2atm]	Parts per million (ppm)	167,307
Barometric pressure	Milllibar (mb)	164,881
Latitude	Degrees of latitude	2,098,020
Longitude	Degrees of longitude	2,098,020
Julian Day	Day	2,098,020

[(1)] CO_2warm is the temperature change (*e.g.*, warming) for seawater as it transits from the ship's water intake line to the CO_2 analysis instrumentation location.

14.3. DATA COVERAGE

The earliest surface temperature data included in WOD13 were collected in 1867 by Norwegian sailors from the ships Isbjornen and Ishavet in the North Sea, Norwegian Sea, and in the North Atlantic waters around Iceland (Table 14.2). SUR data were collected routinely in the 19th century (Figure 14.1). But most of the SUR data were collected after the late 1990s (Figure 14.1). These SUR dataset consist of 9,379 cruises (Figure 14.2). Surface data collected before 1955 are often bucket samples, data acquired after 1957 are, most often, from thermosalinographs and other underway systems.

There are noticeable data gaps after the First World War and during and after the Second World War. A large increase in surface data (mainly SST and sea surface salinity measurements) occurred in the 1990s. These data were mainly acquired by the TSG instruments mounted on ships-of-opportunity. Data collected over that period comprised more than 70% of the entire SUR dataset with almost all data being collected along shipping routes in the Pacific Ocean and contributed mainly by France (41.8% of all data) and Australia (32.5%).

Table 14.3 lists the input of data to the SUR dataset by country of origin. Figure 14.2 shows that the majority of SUR data were collected along the main commercial ship routes of the Atlantic and Pacific oceans. In terms of volume of data, about 97% of the SUR data were acquired from three main sources: International Council for the Exploration of the Sea (ICES), Oceanic Lab of the Institution of French Oceania, and Orstom New Caledonia (before independence). The remaining 3% came from the

National Institute of Oceanography in India (1.2%), Scripps Institution of Oceanography (0.5%), National Institute for Environmental Studies (0.5%), Institute of Ocean Sciences, Sidney, Australia (0.4%), and several others.

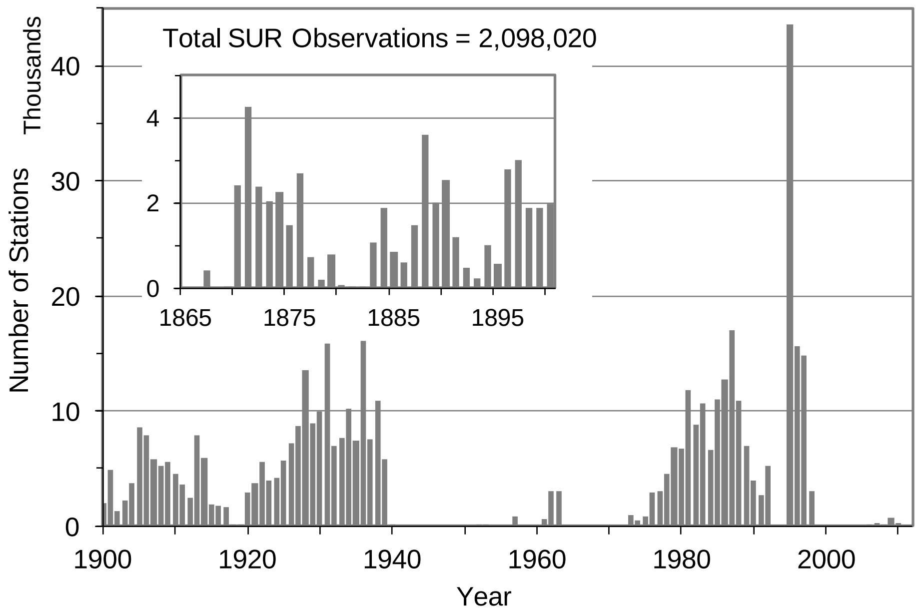

Figure 14.1. Temporal distribution of SUR observations in WOD13.

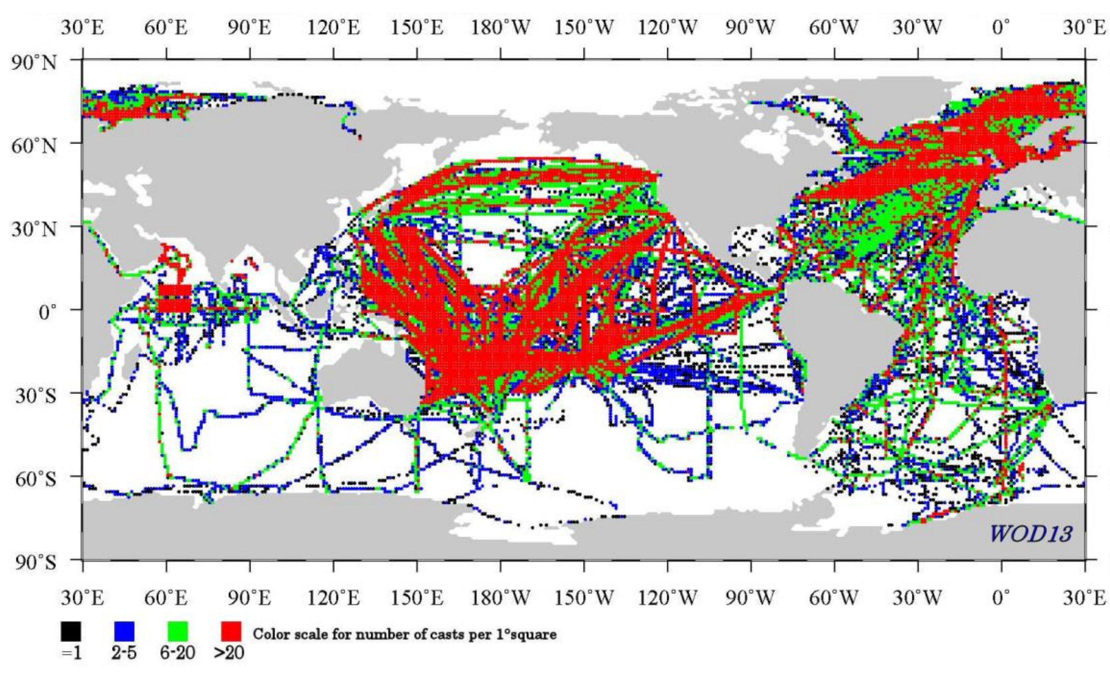

Figure 14.2. Geographic distribution of surface (SUR) observations in WOD13.

Table 14.2. The number of all SUR observations as a function of year in WOD13.

Total number of observations (counts) = 2,098,020

YEAR	COUNT	YEAR	COUNT	YEAR	COUNT	YEAR	COUNT
1867	398	1903	2,242	1939	5,740	1975	803
1868	0	1904	3,695	1940	48	1976	2,902
1869	44	1905	8,609	1941	0	1977	2,951
1870	2,421	1906	7,897	1942	0	1978	4,553
1871	4,261	1907	5,781	1943	0	1979	6,790
1872	2,366	1908	5,170	1944	0	1980	6,670
1873	2,029	1909	5,557	1945	0	1981	11,799
1874	2,240	1910	4,502	1946	0	1982	8,847
1875	1,480	1911	3,556	1947	0	1983	10,626
1876	2,691	1912	2,469	1948	0	1984	6,629
1877	725	1913	7,881	1949	0	1985	10,969
1878	187	1914	5,956	1950	0	1986	12,685
1879	780	1915	1,882	1951	0	1987	17,032
1880	68	1916	1,753	1952	26	1988	10,917
1881	41	1917	1,659	1953	22	1989	6,991
1882	15	1918	55	1954	0	1990	3,954
1883	1,075	1919	113	1955	0	1991	2,658
1884	1,884	1920	2,838	1956	0	1992	5,183
1885	861	1921	3,699	1957	839	1993	0
1886	601	1922	5,532	1958	0	1994	0
1887	1,475	1923	3,945	1959	0	1995	43,560
1888	3,589	1924	4,150	1960	0	1996	15,646
1889	2,013	1925	5,666	1961	555	1997	14,831
1890	2,523	1926	7,143	1962	2,961	1998	3,007
1891	1,197	1927	8,633	1963	2,972	1999	0
1892	468	1928	13,579	1964	0	2000	0
1893	214	1929	8,935	1965	0	2001	0
1894	1,003	1930	9,921	1966	0	2002	0
1895	570	1931	15,847	1967	0	2003	0
1896	2,777	1932	6,975	1968	0	2004	0
1897	3,005	1933	7,590	1969	0	2005	0
1898	1,885	1934	10,173	1970	0	2006	79
1899	1,885	1935	7,355	1971	0	2007	199
1900	1,975	1936	16,058	1972	0	2008	145
1901	4,820	1937	7,488	1973	973	2009	697
1902	1,294	1938	10,858	1974	514	2010	267

Table 14.3. National contributions of observations, and number of cruises by country of origin in the SUR dataset.

ISO[a] Country Codes	Country Name	Number of Cruises	Number of Observations	% of Total
FR	France	3,274	876,382	41.77
AU	Australia	88	681,879	32.50
99	Unknown / International	3,378	161,543	7.70
US	United States	71	100,492	4.79
DE	Germany	93	63,698	3.04
NO	Norway	258	59,714	2.85
JP	Japan	66	57,406	2.74
NC	New Caledonia	1,320	41,655	1.99
CA	Canada	34	18,682	0.89
GB	United Kingdom	346	16,514	0.79
DK	Denmark	178	8,274	0.39
PL	Poland	23	2,824	0.13
FI	Finland	18	2,593	0.12
IN	India	115	1,537	0.07
NL	Netherlands	21	1,309	0.06
SU	Union of Soviet Socialist Republics	1	1,068	0.05
LV	Latvia	38	1,010	0.05
SE	Sweden	15	710	0.03
BE	Belgium	3	283	0.01
PT	Portugal	9	199	0.01
IE	Ireland	27	164	0.01
Total:		*9,379*	*2,098,020*	*100.00*

[a] ISO = International Organization for Standardization

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CHAPTER 15: GLIDER DATA (GLD)

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15.1. INTRODUCTION

A glider is an autonomous underwater vehicle (AUV) propelled by buoyancy force that moves from the ocean surface along a slant trajectory through the water column to a programmed depth and back to the surface while measuring oceanographic parameters (Eriksen *et al.*, 2001; Rudnick *et al.*, 2004). Modern gliders carry various sensors to measure oceanographic parameters such as pressure, temperature, conductivity, chlorophyll a fluorescence, CDOM (colored dissolved organic matter) fluorescence, nitrate, oxygen, transmissivity, optical backscatter, acoustical backscatter, and downwelling radiance (Davis *et al.*, 2008; Glenn *et al.*, 2008; Niewiadomska *et al.*, 2008; Johnson *et al.*, 2009). Gliders can travel thousands of kilometers while making several hundred descents and ascents underway, thus achieving high vertical and horizontal resolution. Since gliders can be retrieved and reused, they represent one of the most cost-effective tools for oceanographic data collection. The annual operating cost of a glider is equivalent to a fraction of one ship-day (Eriksen *et al.*, 2001).

The original concept of a glider was invented by Douglas Webb in 1986 and was based on the thermal engine intended for global range (Dan Webb, personal communication, May 2006). In 1986 Douglas Webb described to Henry Stommel the ideas of a glider with buoyancy engine harvesting propulsion energy from ocean thermal gradients (Stommel, 1989). Stommel later became an enthusiastic supporter and funding for a contract was received through the Office of Naval Technology (Douglas Webb, personal communication, May 2006). The glider with a battery-powered buoyancy engine was tested at Wakulla Springs, FL in 1991 and in Seneca Lake, NY in 1991 (Simonetti, 1992; Webb and Simonetti, 1997; Webb *et al.*, 2001). A U.S. patent for this concept was received by Douglas Webb in 1994 (Douglas Webb, personal communication, May 2006).

Gliders are equipped with a Global Positioning System (GPS) navigation to locate the vehicle. A satellite data relay is used to send its position and other data to shore-based computers while the operators program the gliders depth and mission. Modern gliders can reach a maximum depth of 1500 m (Table 15.1). Their battery lifetime ranges from a few weeks to several months. Gliders' speed is typically less than 0.5 m·s-1 (Eriksen *et al.*, 2001; Davis *et al.*, 2002; Rudnick *et al.*, 2004). Gliders are used to perform diverse scientific missions, each requiring the use of different instruments.

Table 15.1. Glider capabilities.

Glider[a]	Max depth, m	Typical speed, m/sec	Maximum Range, km	Endurance, days
Seaglider	1000	0.25	4600	200
Slocum				
Alkaline	1000	0.40	760	22
Lithium	1000	0.40	4150	120
Spray	1500	0.25	4700	220
[a] Capabilities above based on standard load packages				

15.2. GLIDER DESIGN AND OPERATION

There are several types of operational gliders developed thus far (Table 15.1). The Seaglider (Eriksen *et al.*, 2001) was developed at the University of Washington (UW). Currently, the UW manufactures Seagliders only for UW employees/students, with iRobot and most recently Kongsberg Underwater Technology Incorporated manufacturing Seagliders for those outside of UW (Woo, 2013). The Slocum gliders (Webb *et al.*, 2001) are manufactured by Teledyne Webb Research Corporation. The Spray gliders (Sherman *et al.*, 2001) were developed at the Scripps Institution of Oceanography (Rudnick *et al.*, 2004). Bluefin Robotics licensed the technology from Scripps in 2004 and is the current manufacturer of Spray gliders. Detailed information on gliders specifications and their functions can be found in Rudnick *et al.* (2004), Eriksen *et al.* (2001), Sherman *et al.* (2001), Webb *et al.* (2001), and at the web links provided below.

These gliders have similar features and functionality that can be illustrated by Seaglider-019 (SG-019) (Eriksen *et al.*, 2001). This seaglider is 1.8 m long, has a wing span of 1 m, 1.4 m antenna mast, and weighs 52 kg (Eriksen *et al.*, 2001). It was designed to operate with pitch angles from 10° to 75°. The vehicle alternately dives and climbs to a commanded depth from the surface down to a maximum depth of 1 km and back to the surface every 3 to 9 hours. It remains at the surface for 5 minutes and during that time the Iridium/GPS antenna is raised above the air-sea surface by pitching the vehicle nose down at 45° (Eriksen *et al.*, 2001; Hines, 2005; Rudnick *et al.*, 2004). The seaglider obtains its GPS fixes, transmits collected data at 180 bytes s-1, relays its position, and receives instructions via the Iridium satellite phone network before diving again (Rudnick *et al.*, 2004). It travels at a speed of 0.25 m·s-1, driven by buoyancy control: a hydraulic system that moves oil in and out of an external rubber bladder to force the glider to move, respectively, up or down. Shifting its battery pack relative to its body, causes it to pitch its nose up or down or roll its wings to change compass heading (Hines, 2005).

The SG-019 oceanographic package includes a Sea-Bird Electronics conductivity-temperature-depth (CTD) instrument mounted above the wing and a fluorometer/optical backscatter sensor (Davis *et al.*, 2002; Rudnick *et al.*, 2004). Output of the pressure sensor is used for controlling the vehicle as well as recording the depth at which the measurements are taken (Eriksen *et al.*, 2001). Seaglider dynamics and performance are discussed at length by Eriksen *et al.* (2001) and further details can be found on the Seaglider web page.

The accuracy of CTD instruments used on gliders varies with the instrument design. Typically, the accuracy of salinity measurement is approximately 0.003 to 0.02 and accuracy of temperature measurement is from 0.001°C to 0.005°C. For detailed information on CTDs and their accuracy, refer to section 3.2 of this document.

15.3. GLD PROFILE DISTRIBUTIONS

Figure 15.1 illustrates the geographical distribution of 103,798 glider casts collected between 2004 and 2012. Figure 15.2 shows the temporal distribution of glider casts from 2004 through 2012. The large spike in 2010 is a result of multiple glider deployments during the Deepwater Horizon oil spill in the Gulf of Mexico. Figure 15.3 shows depth distribution of this dataset. Table 15.3 and Figure 15.4 show the glider data contribution by country.

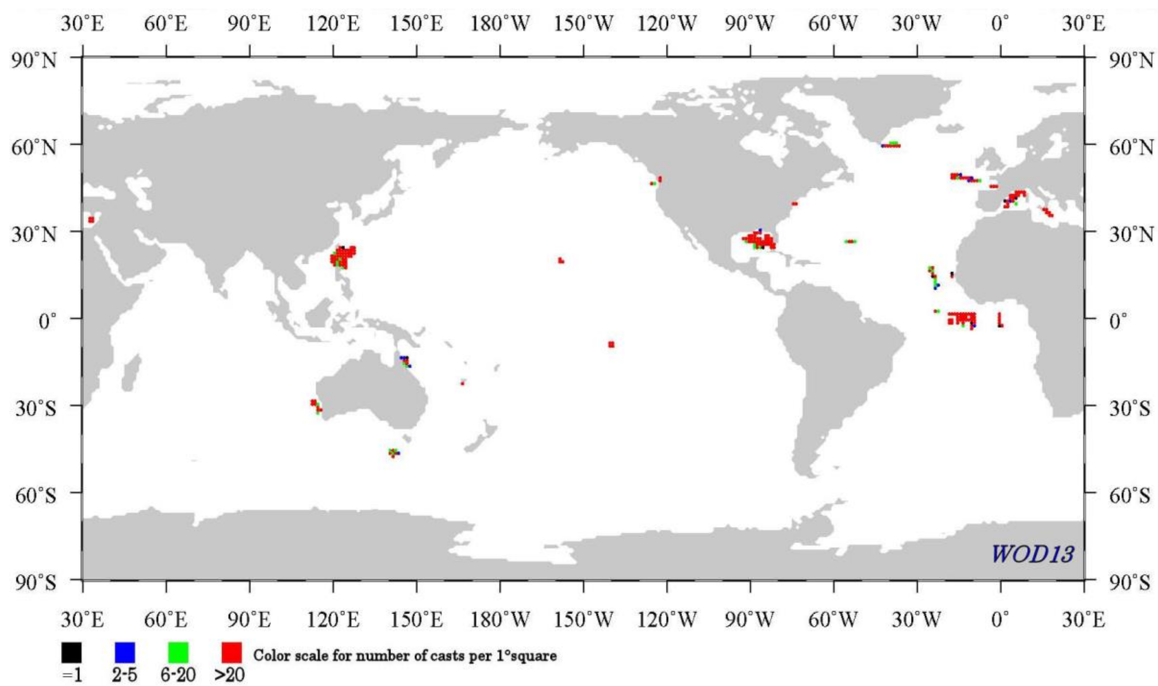

Figure 15.1. Geographical distribution of GLD observations in WOD13.

Of the 103,798 glider casts there are: 91,580 real time profile data that were assembled by the Canada Department of Fisheries for the Global Temperature-Salinity Profile Program (GTSPP), 6,361 glider casts that are delayed mode profile data that were submitted by Institut Francais de Recherche pour l'Exploitation de la MER - Brest (IFREMER) for the Global Temperature-Salinity Profile Program (GTSPP), 5,519 glider casts from the Coriolis Data Center-IFREMER, and 338 glider casts from the Applied Physics Laboratory at the University of Washington.

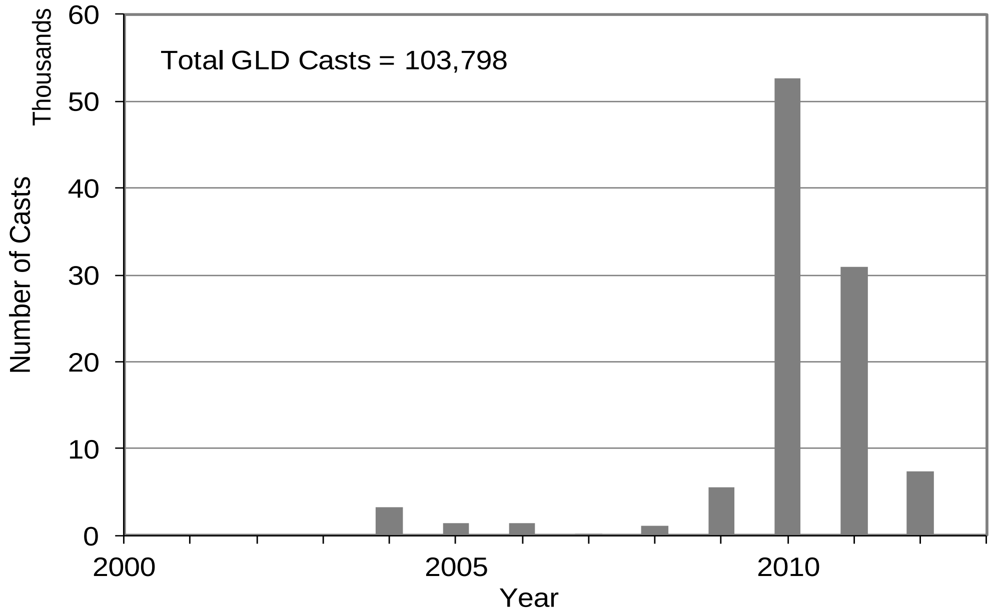

Figure 15.2. Temporal distribution of GLD data in WOD13.

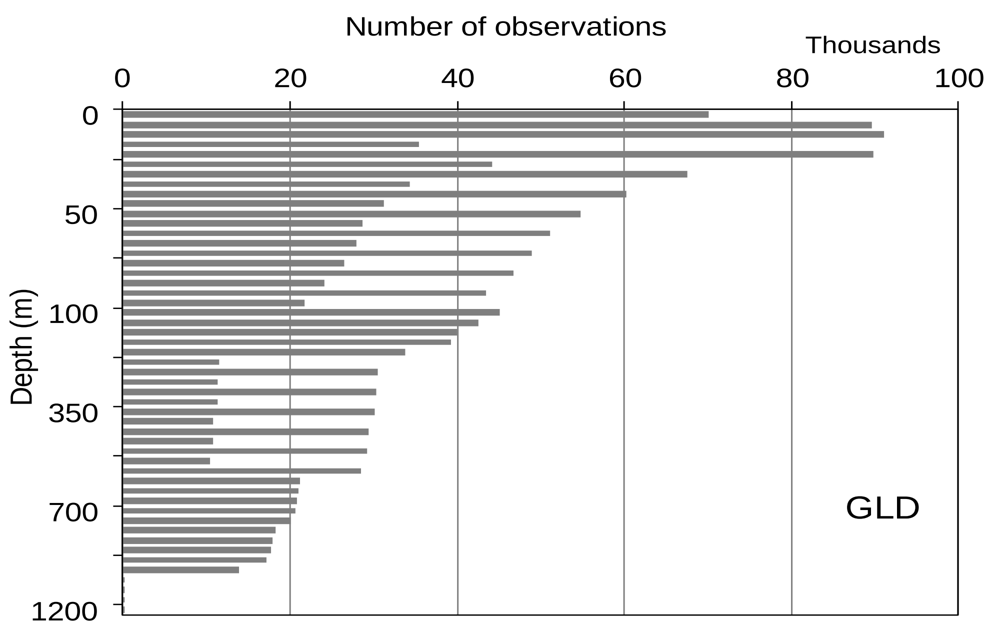

Figure 15.3. Distribution of maximum depths of GLD data in WOD13.
Each bar shows the total number of casts with maximum depth falling within the given interval between two adjacent standard depths. For a complete list of standard depths see Johnson *et al.* (2013).

Table 15.3. National contributions of GLD casts in WOD13.

ISO[a] Country Code	Country Name	GLD Dives	% of Total
US	United States	82,751	79.72
FR	France	7,567	7.29
99	Unknown / International	13,480	12.98
	Total:	*103,798*	*100.00*

[a] ISO = International Organization for Standardization

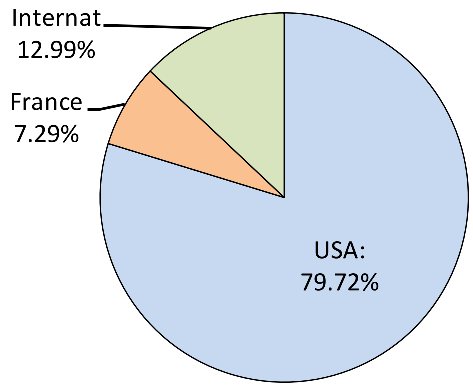

Figure 15.4. Distribution of the GLD data in WOD13 among the contributing countries.

15.4. RELEVANT WEB SITES

Autonomous Undersea Vehicle Applications Center
Applied Physics Laboratory - University of Washington (Seaglider)
Autonomous Systems Laboratory, Woods Hole Oceanographic Institute
AUV Laboratory, Massachusetts Institute of Technology, Sea Grant College Program
Bluefin Robotics (Spray Glider)
Coastal Ocean Observation Lab – Rutgers University
CTD Instrument
iRobot (Seaglider)
Kongsberg Underwater Technology, Inc. (Seaglider)
Navy News (NewsStand)
SBE 911 plus CTD
SCRIPPS Institute of Oceanography (Spray Glider)
Teledyne Webb Research Corporation (Slocum Glider)

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CHAPTER 16: PLANKTON DATA

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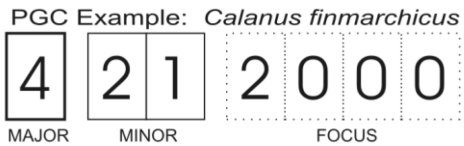
16.1. INTRODUCTION

The term 'plankton' comes from the Greek 'planktos' (drifter). Plankton refers to floating or drifting organisms with limited powers of locomotion (Kennish, 1990). Planktonic organisms range in size from less than two microns to more than two centimeters (Levinton, 1995). The major plankton subdivisions include bacteria, phytoplankton, zooplankton, and temporary plankters which are planktonic only during some part of their life cycle, e.g., eggs and larvae of fishes and other organisms (Kennish, 1990). Plankton participate across many levels of the pelagic ecosystem; from primary production and re-mineralization, to the transfer of materials and energies to higher trophic levels such as fishes, birds, reptiles, and marine mammals (Harris *et al.* 2000). For these reasons it is important to have plankton observational data along with physical and chemical ocean profile data in the World Ocean Database. This opens up opportunities for finding interactions between plankton and other ocean variables (temperature, salinity, oxygen, nutrients, etc.) and for better understanding and preservation of pelagic ecosystems.

The plankton subset of the World Ocean Database 2013 (WOD13) includes and extends the content of the previously released World Ocean Database 2009 (Baranova *et al.*, 2009), World Ocean Database 2005 (Baranova *et al.*, 2006), World Ocean Database 2001 (O'Brien *et al.*, 2001), and World Ocean Database 1998 (Conkright *et al.*, 1998). The WOD13 plankton data subset is a collection of measurements from serial bottle and plankton net-tow. The plankton measurements are represented in WOD13 as quantitative and qualitative abundance, and biomass data. The plankton measurements are stored in the OSD dataset (see Chapter 2).

Scientific taxonomic names in the WOD13 are stored using the corresponding ITIS (Integrated Taxonomic Information System, http://www.itis.gov) Taxonomic Serial Number (TSN). ITIS TSN's are not available for all plankton descriptions and biomass. WOD13 negative taxonomic codes (sequentially assigned numbers) were developed to preserve the original descriptions. In addition to ITIS or negative taxonomic codes, each plankton description has a Plankton Grouping Code (PGC) developed by O'Brien (2007). The PGC code follows the taxonomic hierarchy presented in The Five Kingdoms (Margulis & Schwartz 1998). The PGC is an ancillary code which places each taxon into broader groups (e.g., phytoplankton, diatoms, zooplankton, copepods) and allows the WOD13 user access to hundreds of individual taxa by using a single PGC code. The PGC is 7-digit code divided into Major group (*e.g. Bacteria, Phytoplankton, Zooplankton*),



Minor group (*e.g., cyanobacteria, diatoms, crustaceans*), and Focus group (*e.g.*, *copepods*). For example, the copepod *Calanus finmarchicus* has a PGC code of "4212000", specifying that it is in Major Group "4" (zooplankton), Minor Group "21" (crustaceans), and Focus Group "2000" (copepods). Earlier versions of the *World Ocean Database* (2001, 2005) used a PGC precursor called the Biological Grouping Code, BGC (O'Brien *et al. 2001*). The PGC combines the BGC's separate "protists" grouping with the "phytoplankton" group. From the WOD09 all BGC codes were replaced with their corresponding PGC codes.

The typical plankton cast, as represented in WOD13, stores taxon specific and/or biomass data in individual sets, called "Taxa-Record". Figure 16.1 demonstrates an example of a plankton cast in WOD13.

Each "Taxa-Record" contains a taxonomic code ("Param_number"), depth range (the upper and lower depth) of observation, the original measurements (e.g., abundance, biomass or volume), and all provided qualifiers (e.g., lifestage, sex, size, etc.) required to represent the plankton observation.

In addition to the observed data, a cast may include additional originator's metadata information such as the "institution" which collected and identified the species of plankton, the "voucher institution" (institution which stores samples), sampling gear (e.g., Bongo Net, Continuous Plankton Recorder), net mesh size, sampling method (e.g., vertical, horizontal, or oblique haul), meteorology, and other general header information which are described in detail in WOD13 documentation (Johnson *et al.*, 2013).

The alternative way to receive plankton data is a "csv" (comma-separated value) output file, which is available only through the WODselect – the online WOD13 database retrieval system (http://www.nodc.noaa.gov/OC5/SELECT/dbsearch/dbsearch.html).

```
Longitude  Latitude  Year  Month  Day   Time Cruise#   CC   Prof_#
-4.883          79.017        1991     6          9          ----    10438         06   2087562

Mesh_size     200.000 Type_tow            2.000   Lge_removed        1.000
Gear_code    118.000 net_mouth_area    0.300   Lge_removed_len   1.000
Tow_speed_avg    1.944

Taxa-Record #1
 Param_number    85263.000   upper_depth   0   lower_depth   100.000
 Taxon_lifestage    25.000   Taxon_count   18.600   Taxon_modifier   2.000
 Units   70.000   CBV_value   18.600   CBV_calc_meth   70.000
 CBV_flag   3.000   PGC_group_code    4282000.000

Taxa-Record #2
 Param_number   -404.000000   upper_depth   0   lower_depth   100.000
 int_value   3100.000   Units   69.000   CBV_value   31.000
 CBV_calc_meth   69.100   CBV_flag   3.000   PGC_group_code   -404.000000

Taxa-Record #3
 Param_number   85263.000   upper_depth   0lower_depth   100.000
 Taxon_lifestage   26.000   Taxon_count   0.100   Taxon_modifier   2.000
 Units   70.000   CBV_value   0.100   CBV_calc_meth   70.000
 CBV_flag   3.000   PGC_group_code   4282000.000              etc ….
Access#              0000772
Cast_Number      9617720
 Orig_Stat_Num   7
 Bottom_Depth  1413.000
 T-S_Probe         7.000
 NODCorig         3.000
```

Figure 16.1. An example of a plankton cast in WOD13 (using provided output software).

```
CAST   ,,9617720,WOD Unique Cast Number,WOD code,,,,,,,,,,
NODC Cruise ID,,06-10438      ,,,,,,,,,,,,
Originators Station ID,,7,,,integer,,,,,,,,,
Originators Cruise ID,,,,,,,,,,,,,,
Latitude,,79.0167,decimal degrees,,,,,,,,,,,
Longitude,,-4.8833,decimal degrees,,,,,,,,,,,
Year,,1991,,,,,,,,,,,,
Month,,6,,,,,,,,,,,,
Day,,9,,,,,,,,,,,,
METADATA,,,,,,,,,,,,,,
Country,,DE,NODC code,GERMANY, FEDERAL REPUBLIC OF,,,,,,,,,
Accession Number,,772,NODC code,,,,,,,,,,,
Project,,435,NODC code,IAPP (International Arctic Polynya Programme),,,,,,,,,,
Platform,,199,OCL code,POLARSTERN,,,,,,,,,,
Institute,,892,NODC code,ALFRED-WEGENER-INSTITUTE (BREMERHAVEN),,,,,,,,,,
Bottom depth,,1413,meters,,,,,,,,,,,
Database origin,,3,WOD code,GODAR Project,,,,,,,,,,
BIOLOGY METADATA,,,,,,,,,,,,,,
Mesh size,,200,microns,,,,,,,,,,,
Type of tow,,2,WOD code,VERTICAL TOW,,,,,,,,,,
Large plankters removed, ,1,WOD code,yes,,,,,,,,,,
Gear,,118,WOD code,Bongo Net,,,,,,,,,,
Net mouth area,,0.3,m2,,,,,,,,,,,
Min length removed,,1,cm,,,,,,,,,,,
Average tow speed,,2,knots,,,,,,,,,,,
BIOLOGY,Upper Z,Lower Z,Measuremnt Type,ORIGINAL VALUE ,F,Orig unit,WOD CBV
value  ,F,_unit,_meth,WOD PGC,ITIS TSN,mod,lif,
1,0. meters,100. meters,Taxon_count,18.6,0,#/m3,18.6,3,
#/m3,70,4282010,CALANUS,MODIFIER=spp.  (multiple species),LIFE STAGE=C1:
COPEPODITE I
2,0. meters,100. meters,Total Dry Mass,3100,0,mg/m2,31,3,mg/m3,69.1,-404,Zooplankton
Dry Mass (mg/unit),,,,,,,,,,,
3,0. meters,100. meters,Taxon_count,0.1,0,#/m3,0.1,3,
#/m3,70,4282010,CALANUS,MODIFIER=spp. (multiple species),LIFE STAGE=C2:
COPEPODITE II
......
END OF BIOLOGY SECTION
```

Figure 16.2. An example of a plankton cast in 'csv' output file available on-line through the WODselect.

16.2. BASIC QUALITY CONTROL

Plankton numerical abundance and total biomass measurements are stored with the data originator's units in WOD13 (*e.g.*, counts in units of *"number per m^3", "wet mass per m^2",* "displacement volume per haul", "count per haul", "count per ml"). To allow easier comparison of incoming measurements with different units, each numerical abundance or biomass measurement has been recalculated into a common unit named *Common Base-unit Value* (CBV). The CBV is calculated from the original value using sampling metadata (*e.g.,* towing distance, water volume filtered) but does not account for differences in mesh size, gear efficiency, or sampling depth intervals. The calculation method used to create the CBV is stored in the *CBV calculation method* field and described in detail in WOD13 documentation, Appendix 5.11, (Johnson *et al.,* 2013). Table 16.1 lists CBV units by data type.

Table 16.1. Measurement Type and/or Groups and their corresponding CBV unit.

Measurement Type or Group	CBV unit
Total Biomass (displacement volume, settled volume)	ml / m^3
Total Biomass (wet mass, dry mass, ash free dry mass)	mg / m^3
Zooplankton Abundance	# / m^3
Phytoplankton Abundance	# / ml
Bacterioplankton Abundance	# / µl
Ichthyoplankton Abundance	# / m^3

The addition of the PGC and CBV to each plankton measurement allows for individual value checks against broad, group-based ranges (O'Brien *et al.,* 2001). Grouped by major PGC groups (Table 16.2) and Total Biomass types (Table 16.3), these broad range checks are used to detect and flag extremely large or small values.

Table 16.2. WOD13 broad group-based ranges for plankton abundance.

Group	Min Value	Max Value	Units
Bacteria	0.001	5,000	# · μl^{-1}
Phytoplankton	0.001	50,000	# · ml^{-1}
Zooplankton	0.001	200,000	# · m^{-3}
Ichthyoplankton	0.001	200,000	# · m^{-3}

Table 16.3. WOD13 broad group-based ranges for biomass.

Group	Min Value	Max Value	Units
Total Displacement Volume	0.005	10	$ml \cdot m^{-3}$
Total Settled Volume	0.025	50	$ml \cdot m^{-3}$
Total Wet Mass	0.5	10,000	$mg \cdot m^{-3}$
Total Dry Mass	0.01	500	$mg \cdot m^{-3}$
Total Ashfree Dry Mass	0.001	100	$mg \cdot m^{-3}$

WOD13 applied quality flags to Common Base-unit Values as follows:
0 - accepted value
1 - range outlier (outside of broad range check)
2 - questionable value*

* The contents from an entire net tow may be flagged as "questionable" in cases of gross gear failure (*e.g.,* a broken net or leaking bottle). Individual observations may also be flagged in cases of gear-incompatible capture (*e.g.,* phytoplankton cells snagged in a large mesh net, presence of a single copepod caught in a Nansen bottle).

16.3. DATA SOURCES

The plankton data that comprise WOD13 have been contributed by 37 countries, 142 institutions and more than 50 projects. Significant amounts of data (104,740 casts) have no information about the project. Among them are data provided by the Instituto del Mar del Peru (IMARPE). This contribution (~23,000 casts) comes from a joint data rescue effort with the IMARPE and the Intergovernmental Oceanographic Commission's Global Oceanographic Data Archaeology and Rescue project (GODAR), which digitized over forty-five years of IMARPE phytoplankton monitoring data. Substantial amounts of historical biomass and abundance data are from the archives of the National Oceanographic Data Center (NODC) and the World Data Center for oceanography, Silver Spring.

Table 16.4 summarizes data contributing countries. The top five contributors are United States, Japan, Peru, Russia (Former Soviet Union), and the United Kingdom. Within the United States, the National Marine Fisheries Service (NMFS) has played a cooperative or leading role in major sampling and monitoring programs which were responsible for collecting ~70% of the US contribution, and 40% of the total global content. The NMFS-associated programs are indicated with asterisks in Table 16.5.

A considerable portion of biomass data (~54,000 casts) was received from Coastal and Oceanic Plankton Ecology Production and Observation Database (COPEPOD)[1] as a result of collaboration between NODC and National Marine Fisheries Service (NMFS).

[1] Data acquired through the COPEPOD database were provided in COPEPOD format and mainly include data from CalCOFI, MARMAP, and SEAMAP projects.

Table 16.4. National contributions of plankton casts in WOD13.

ISO[a] Country Code	Country Name	# Casts	% of Total
US	United States	114,896	50.1
JP	Japan	41,372	18.0
PE	Peru	22,874	10.0
SU	Union of Soviet Socialist Republics	20,551	9.0
GB	Great Britain	16,253	7.1
ID	Indonesia	2,098	0.9
PT	Portugal	1,611	0.7
NO	Norway	1,422	0.6
FR	France	1,222	0.5
IN	India	970	0.4
DE	Germany	958	0.4
AU	Australia	763	0.3
CA	Canada	733	0.3
RU	Russian Federation	508	0.2
PL	Poland	405	0.2
ZA	South Africa	396	0.2
EC	Ecuador	352	0.2
MX	Mexico	293	0.1
BR	Brazil	216	0.1
KR	Korea Republic of	193	0.1
PH	Philippines	184	0.1
TW	Taiwan	141	0.1
NC	New Caledonia	136	0.1
DK	Denmark	133	0.1
IS	Iceland	133	0.1
CO	Colombia	97	> 0.1
ES	Spain	71	> 0.1
AR	Argentina	64	> 0.1
BE	Belgium	38	> 0.1
CI	Cote D' Ivore	37	> 0.1
NL	Netherlands	36	> 0.1
SG	Singapore	35	> 0.1
CD	Congo, the Democratic Republic	29	> 0.1
PK	Pakistan	22	> 0.1
NG	Nigeria	12	> 0.1
SE	Sweden	11	> 0.1
TH	Thailand	10	> 0.1
	Total	*229,275*	*100.00*

[a] ISO = International Organization for Standardization

Another large portion (38,980 casts) of the zooplankton and biomass data was acquired through the California Cooperative Oceanic Fisheries Investigations (CalCOFI) project. The CalCOFI project was initiated in 1949 to study the collapse of the U.S. west coast sardine fishery. Hydrographic casts have been occupied from 1950 to the present along cross-shelf transects. Additional information can be found on CalCOFI's Web Page, http://www.calcofi.org .

The Marine Resources Monitoring Assessment and Prediction (MARMAP) program is one of the important contributors of the plankton data (19,646 casts). The NMFS-wide MARMAP project was established in 1974. Data collected over time includes biological surveys of fishes, fish eggs and larvae.

A significant amount of data (11,996 casts) was received through the Southeast Area Monitoring and Assessment Program (SEAMAP). Since its beginning in 1981 SEAMAP monitoring of marine resources within Gulf of Mexico, South Atlantic, and Caribbean regions http://www.seamap.org/ .

The Outer Continental Shelf Environmental Assessment Program (OCSEAP) contributed another large portion of the plankton data (7,920 casts). The OCSEAP was established in 1984 by basic agreement between the U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) and the U.S. Department of the Interior (USDOI), Minerals Management Service (MMS) for environmental studies of Alaskan Outer Continental Shelf waters considered for oil development (Truett, J.C., 1985).

Another source of data was the Eastern Tropical Pacific Ocean (EASTROPAC) program (5,544 casts). The first EASTROPAC survey (February 1967 through March 1968) was a cooperative effort towards the understanding of the oceanography of the eastern Tropical Pacific Ocean. Participating scientists were primarily from the NMFS, Scripps Institution of Oceanography, and the Inter-American Tropical Tuna Commission. Kuroshio Exploitation and Utilization Research (KER) project provided 4,234 casts. KER was designed to study the subtropical circulation system, marine ecology, and fishery around Japan. The project was conducted in 1977 – 1995.

Table 16.5 gives project contributions of plankton casts sorted by percent contribution from each project.

Table 16.5. Project contributions of plankton casts sorted by percent contribution from each project.

NODC Project Code	Project Name	# Casts	% of Total
33	*CalCOFI: California Cooperative Oceanic Fisheries Investigation	38,980	31.3
51	*MARMAP: Marine Resource Monitoring Assessment Prediction Program	19,646	15.8
121	*SEAMAP: Southeast Area Monitoring and Assessment Program	11,996	9.6
81	*OCSEAP: Outer continental shelf environmental assessment program	7,920	6.4
174	*FOCI: Fisheries-Oceanography Cooperative Investigations	6,663	5.4
3	*EASTROPAC (1967-1968)	5,544	4.5
526	GENERAL FISHERIES RESEARCH (YugNIRO)	5,438	4.5

NODC Project Code	Project Name	# Casts	% of Total
243	KER: Kuroshio exploitation and utilization research (1977 - 1995)	4,234	3.4
93	BRINE DISPOSAL	4,198	3.4
240	USAP or USARP : United States Antarctic Research Project	3,665	2.9
25	IIOE: International Indian Ocean Expedition	2,045	1.6
344	*POFI: Pacific Oceanic Fisheries Investigations	1,310	1.1
372	OMEX: Ocean margin exchange project	1,234	1.0
367	GLOBEC: Georges Bank Program	951	0.8
361	JGOFS/AESOPS: US JGOFS Antarctic Environments Southern Ocean Process Study	943	0.8
30	ICNAF: International Commission for the Northwest Atlantic Fisheries	851	0.7
345	NORTH SEA PROJECT	827	0.7
241	BIOMASS: Biological Investigations of Marine Antarctic Systems and Stocks	712	0.6
322	*SKIPJACK	684	0.6
365	JGOFS/ARABIAN: Arabian Sea Process Studies	657	0.5
31	CSK: Cooperative Study of the Kuroshio	599	0.5
83	OCS-SOUTH: Texas	533	0.4
275	JGOFS/BATS: Bermuda Atlantic Time Series	495	0.4
325	CINECA: Cooperative Investigations of Northern Part of Eastern Central Atlantic	400	0.3
82	PSERP: Mesa Puget Sound	396	0.3
645	Discovery Investigations	366	0.3
200	JGOFS: Joint Global Ocean Flux Study	363	0.3
273	EASTROPIC: Eastern Tropical Pacific 1955	323	0.3
410	TASC: Trans Atlantic Study of *Calanus*	300	0.2
310	JGOFS/EQPAC: Equatorial Pacific basin study	279	0.2
450	SFRI UPWELLING CRUISE 1969	255	0.2
96	EPA: Buccaneer oil field	214	0.2
321	BOFS: Biogeochemical Ocean Flux Study	180	0.2
422	ICITA - EQUALANT III	177	0.1
443	IMECOCAL: Investigaciones Mexicanas De La Corriente De California	174	0.1
421	ICITA - EQUALANT II	164	0.1
420	ICITA - EQUALANT I	163	0.1
34	MAZATLAN	119	0.1
255	CTZ: Coastal Transition Zone	100	> 0.1
246	BERPAC: Bering and Pacific Russian/US Cooperative Research Program	88	> 0.1
328	SIBEX: Second International Biomass Experiment - Fr	63	> 0.1

NODC Project Code	Project Name	# Casts	% of Total
312	CEAREX: Coordinated Eastern Arctic Experiment	63	> 0.1
clrsu22 5	WOCE: World Ocean Circulation Experiment	41	> 0.1
435	IAPP: International Arctic Polynya Programme	41	> 0.1
90	ONR: Office of Naval Research	39	> 0.1
71	IDOE/CUEA	30	> 0.1
434	ARCTIC OCEAN SECTION: Canada/U.S. joint expedition	18	> 0.1
77	SCOPE	11	> 0.1
447	Marine Food Chain Research Group	10	> 0.1
444	GSP: Greenland Sea Project	5	> 0.1
Total		124,507	100.00

16.4. PLANKTON DATA DISTRIBUTIONS

The WOD13 plankton subset consists of 229,275 globally distributed casts (Figure 16.3). The temporal distribution of plankton sampling covers period from 1900 to 2006 year (Figure 16.4). Table 16.6 gives the yearly counts of plankton casts in the WOD13.

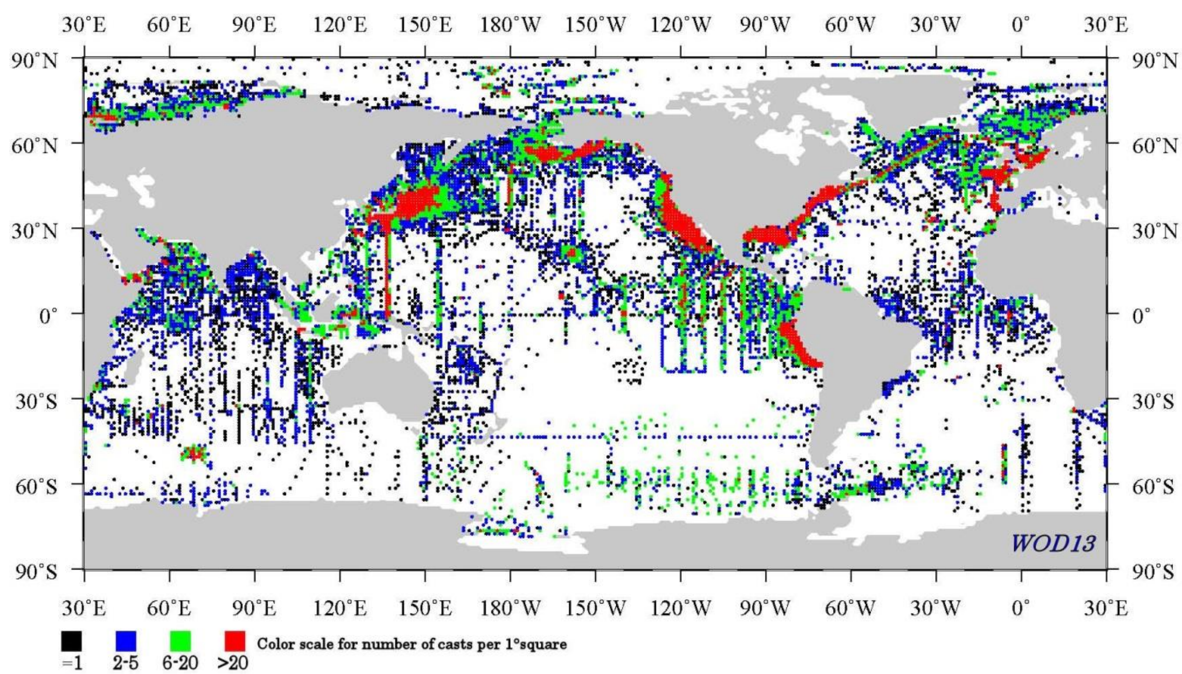


Figure 16.3. Geographic distribution of plankton (229,275 casts) in WOD13.

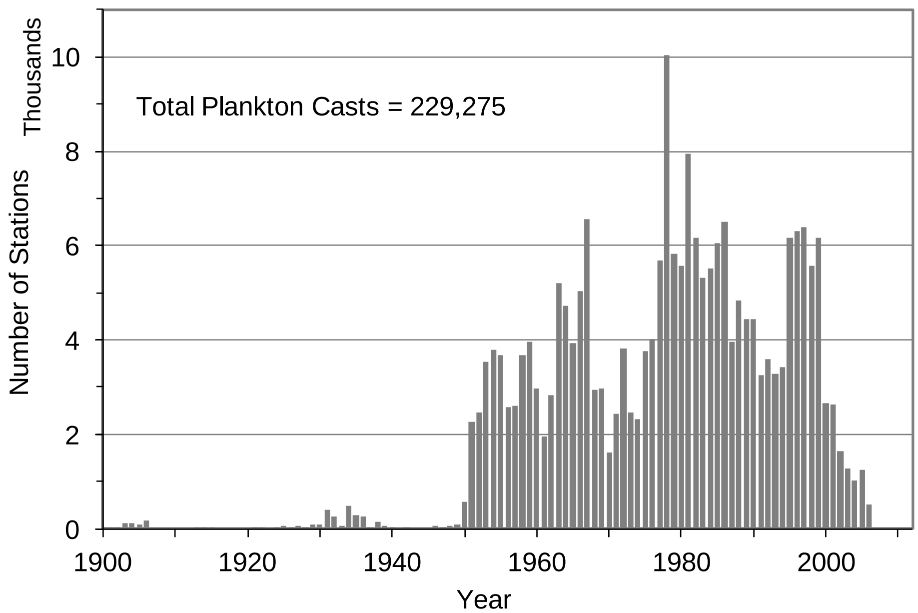


Figure 16.4. Temporal distributions of plankton casts in WOD13 as a function of year.

16.5. PLANKTON CONTENT

The plankton measurements are represented in WOD13 as descriptive and numeric abundance, and biomass data. The majority (48%) of plankton measurements are total biomass. Contributions of plankton casts by measurement type are shown in Figure 16.5.

16.5.1. Abundance

The majority (83%) of plankton abundance measurements in WOD13 are numeric (*e.g.*, the number of individuals counted per sample or haul), while descriptive abundance measurements (*e.g.*, individual was "rare", "common", or "abundant" in sample or haul) are present in a smaller amount (17 %) of total abundance. The WOD13 plankton abundance content, listed by major plankton groups and sub-groups, is summarized in Table 16.7.

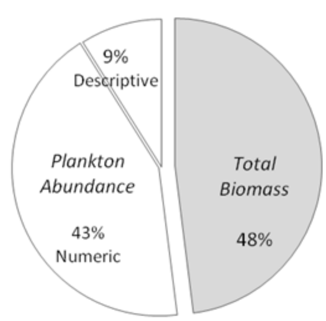


Figure 16.5 Contributions of Plankton casts by measurement type.

Table 16.6. Number of plankton casts in WOD13 as a function of year for the World Ocean.

Total Number of Casts = 229,275

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1900	17	1927	46	1954	3783	1981	7951
1901	9	1928	35	1955	3676	1982	6152
1902	13	1929	93	1956	2566	1983	5307
1903	100	1930	88	1957	2602	1984	5507
1904	126	1931	409	1958	3690	1985	6053
1905	95	1932	247	1959	3953	1986	6508
1906	160	1933	62	1960	2962	1987	3966
1907	0	1934	490	1961	1959	1988	4842
1908	0	1935	273	1962	2814	1989	4449
1909	0	1936	262	1963	5200	1990	4432
1910	0	1937	7	1964	4730	1991	3256
1911	0	1938	134	1965	3940	1992	3590
1912	0	1939	51	1966	5040	1993	3284
1913	6	1940	2	1967	6573	1994	3428
1914	7	1941	0	1968	2934	1995	6156
1915	9	1942	2	1969	2974	1996	6302
1916	0	1943	0	1970	1620	1997	6384
1917	0	1944	0	1971	2438	1998	5583
1918	0	1945	0	1972	3821	1999	6177
1919	0	1946	54	1973	2467	2000	2651
1920	0	1947	36	1974	2318	2001	2632
1921	29	1948	67	1975	3772	2002	1653
1922	33	1949	98	1976	4025	2003	1265
1923	0	1950	558	1977	5685	2004	1013
1924	2	1951	2266	1978	10042	2005	1256
1925	50	1952	2468	1979	5838	2006	506
1926	34	1953	3531	1980	5581		

Table 16.7 WOD13 abundance measurements content.

PGC	Plankton Group	Numeric abundance (casts #)	Descriptive abundance (casts#)
1000000	**BACTERIA** (*all sub-groups*)	1986	28
1050000	Cyanobacteria	974	27
2000000	**PHYTOPLANKTON** (*all sub-groups*)	37961	22471
2030000	Amoebida	44	0
2040000	Granuloreticulosa (Foraminifera)	5561	147
2070000	Dinomastigota (Dinoflagellata)	14586	20563
2080000	Ciliophora (ciliates)	4893	7769
2100000	Haptomonada (Coccolithophorids)	5342	372
2110000	Cryptomonada (Chrytophyta)	1910	8
2120000	Discomitochondria	1333	242
2130000	Chrysomonada (Chrysophyta)	5632	5772
2160000	Diatoms (Bacillariophyta)	22877	19475
2270000	Actinopoda	3817	436
2280000	Chlorophyta (green algae)	1223	128
2300000	Ebriida	184	2
4000000	**ZOOPLANKTON** (*all sub-groups*)	46224	5805
4020000	Porifera	1941	3
4030000	Cnidaria (coelenterates)	16103	2676
4032000	Hydrozoa	13843	665
4036000	Stauromedusae	2381	28
4038000	Antipatharia	2292	83
4040000	Ctenophora (comb jellies)	3912	370
4050000	Platyhelminthes (flat worms)	2042	0
4090000	Nemertina (ribbon worms)	2352	44
4100000	Nematoda	2053	7
4130000	Rotifera (rotifers)	2182	623
4180000	Entoprocta	2157	0
4190000	Arthropoda: Chelicerata	862	154
4200000	Arthropoda: Mandibulata ("insects")	4881	14
4210000	Arthropoda: Crustacea (*all sub-groups*)	49737	6553
4211000	*Crustacea*: Ostracoda	12781	300
4212000	*Crustacea*: Copepoda	88658	9800
4213000	*Crustacea*: Cirripedia (barnacles)	7091	783
4214000	*Crustacea*: Mysidacea	4464	55
4216000	*Crustacea*: Isopoda	4049	60
4217000	*Crustacea*: Amphipoda	22309	1718
4218000	*Crustacea*: Euphausiacea	17227	1728
4219000	*Crustacea*: Decapoda	15008	1159
4220000	Annelida (segmented worms)	26547	4716
4230000	Sipuncula	2075	2
4260000	Mollusca (*all sub-groups*)	19337	1896
4262500	*Mollusca*: Gastropoda (snails & slugs)	17201	1008
4265000	*Mollusca*: Bivalvia (bivalve molluscs)	3627	593
4266000	*Mollusca*: Scaphopoda (tusk shell)	85	0

4267500	*Mollusca*: Cephalopoda	4123	26
4290000	Bryozoa	3203	137
4300000	Brachiopoda (lamp shells)	2012	1
4310000	Phoronida	2202	0
4320000	Chaetognatha (arrow worms)	26878	3400
4330000	Hemichordata	3965	4
4340000	Echinodermata	6614	1040
4350000	Urochordata (*all sub-groups*)	19905	3579
4352500	*Urochordata*: Ascidiacea (sea squirts)	870	0
4355000	*Urochordata*: Thaliacea (salps & doliolids)	11385	101
4357500	*Urochordata*: Larvacea / Appendicularia	18037	1447
4360000	Cephalochordata / Leptocardia	2458	17
5000000	**ICHTHYOPLANKTON**	54286	217

The geographic distribution of numerical abundance casts of major plankton groups for WOD13 is shown in Figures 16.6 – 16.9.

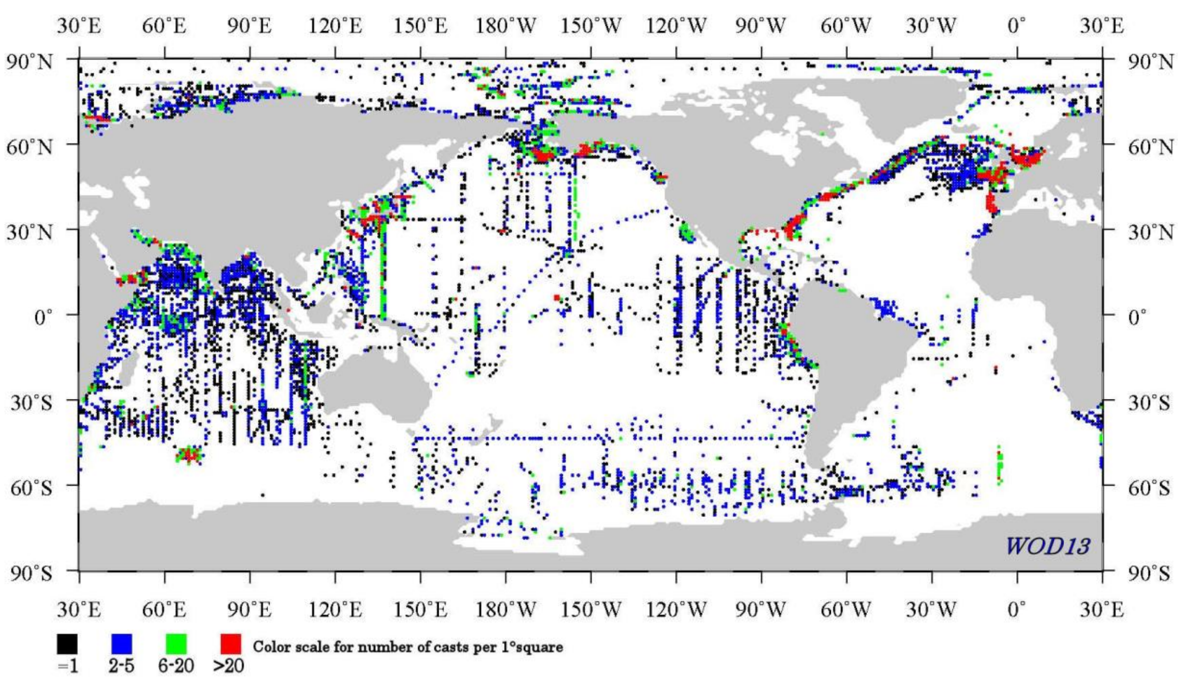


Figure 16.6. Geographic distribution of zooplankton numerical abundance (46,224 casts) in WOD13.

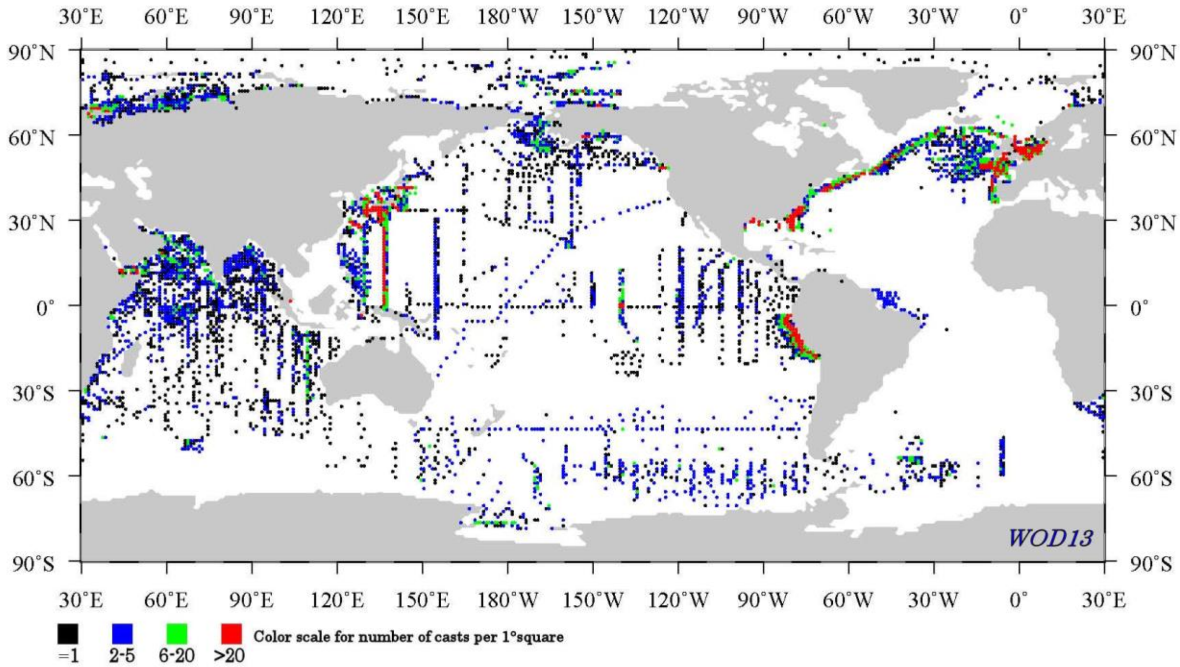


Figure 16.7. Geographic distribution of phytoplankton numerical abundance (37,961 casts) in WOD13.

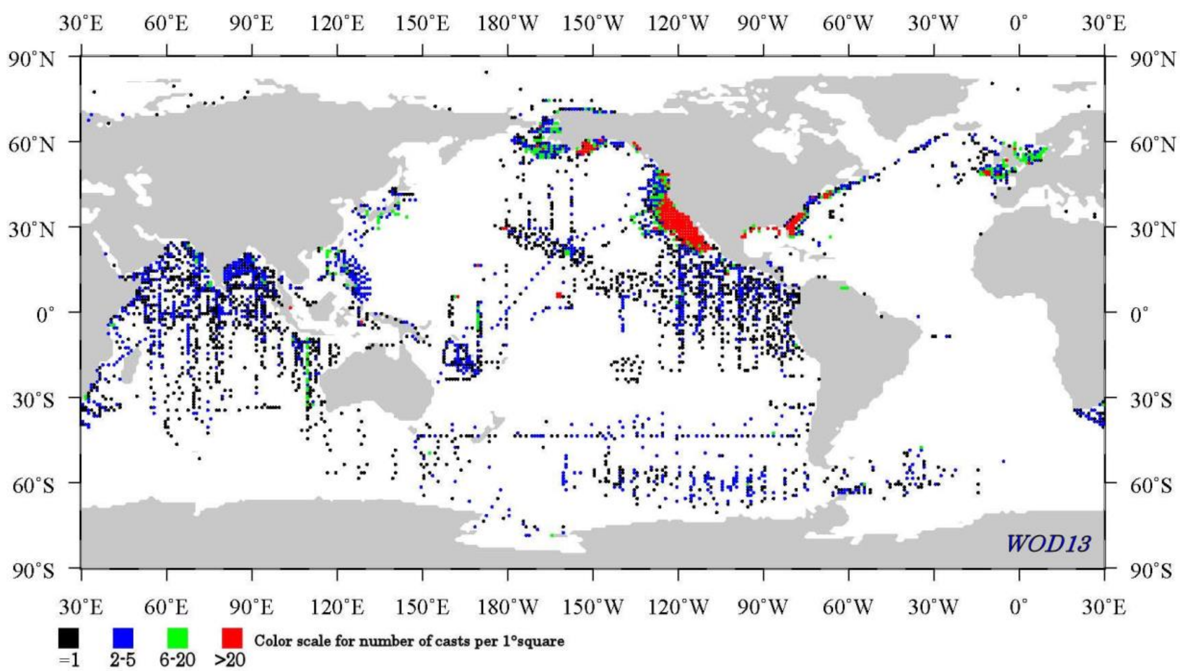


Figure 16.8. Geographic distribution of ichthyoplankton numerical abundance (54,286 casts) in WOD13.

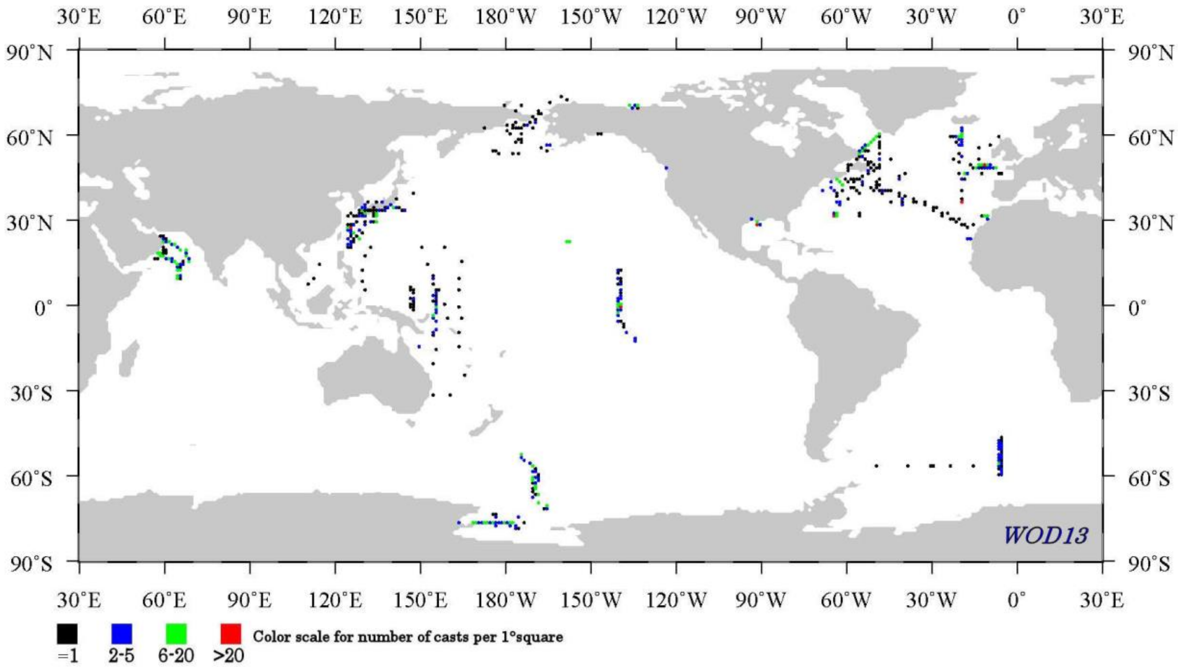


Figure 16.9. Geographic distribution of bacterioplankton numerical abundance (1,986 casts) in WOD13.

16.5.2. Total Biomass

The WOD13 total biomass data type represents measurement for which the entire contents of the plankton net are measured as a single, undifferentiated mass. This "mass" can be quantified by measuring the total settled volume, displacement volume, wet mass, dry mass, or ash-free dry mass of the entire sample. Although the sampling methods of total biomass data represented in the WOD13 may differ between projects and institutions, the general definitions and methods per Omori and Ikeda (1984) are:

Total Settled volume: the volume of a plankton sample poured into a graduated cylinder or sedimentation tube of 50-100 ml in volume and allowed to settle for 24 hours.

Total Displacement volume: the volume of plankton estimated by the volume of water displaced after adding the plankton sample into a graduated cylinder.

Total Wet Mass: the mass of plankton determined after eliminating as much surrounding water as possible.

Total Dry Mass: the mass of plankton determined after removal of all water and heat dried to a final mass at 60-70oC.

Total Ash-free Dry Mass: a known weight of the dry sample ashed to a final weight at 450-500oC.

Table 16.8. WOD13 biomass measurements content.

PGC Code	Taxonomic Description	# Casts	% of Total
-401	Total Displacement Volume	109,312	69.93
-402	Total Settled Volume	9,926	6.35
-403	Total Wet Mass	34,075	21.80
-404	Total Dry Mass	2,554	1.63
-405	Total Ash-free Dry Mass	446	0.29

The majority of WOD13 plankton biomass measurements are total displacement volume and total wet mass (Table 16.8). Total biomass data were mostly sampled using nets ranged from 200 to 500 μm mesh size, predominantly with standard nets 333 μm mesh size. Samples within this mesh range might include fish eggs, larvae, and small amounts of large phytoplankton, such as diatoms.

Additional information about measurement methods, as well as the protocol followed for removing large organisms, is stored in the Biological Headers described in detail in WOD13 documentation, Table. 6 (Johnson *et al.*, 2013).

The geographic distribution of biomass casts for WOD13 is shown in Figures 16.10. – 16.14.

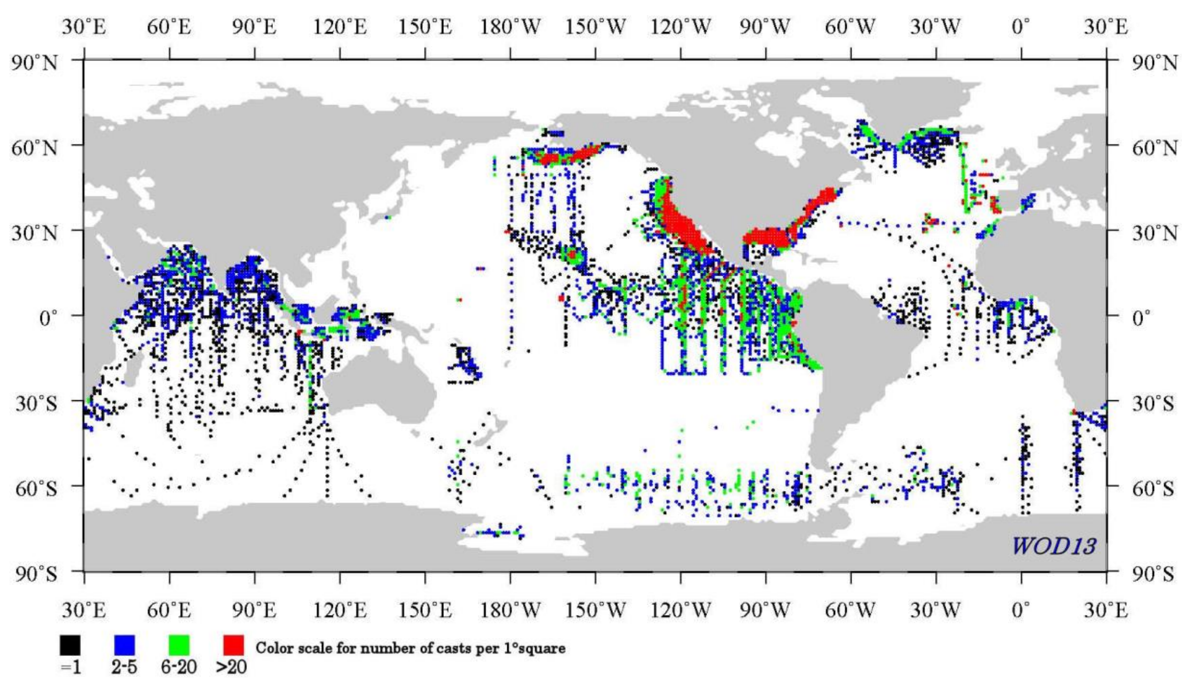


Figure 16.10. Geographic distribution of total displacement volume (109,312 casts) in WOD13.

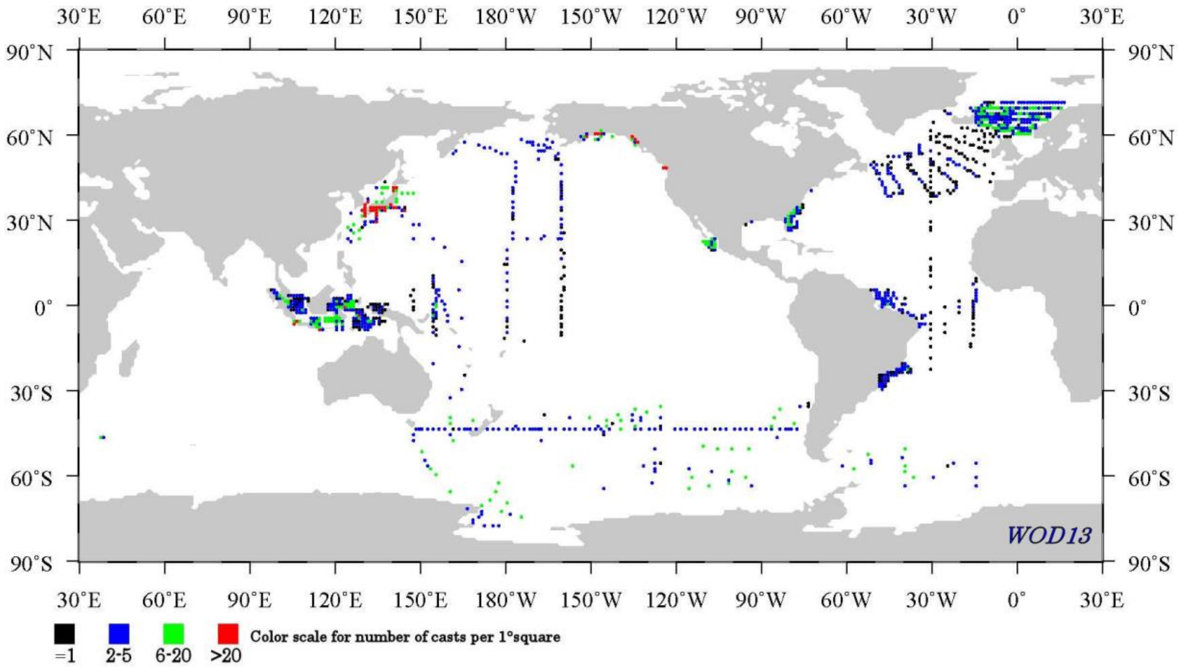


Figure 16.11. Geographic distribution of total settled volume (9,926 casts) in WOD13.

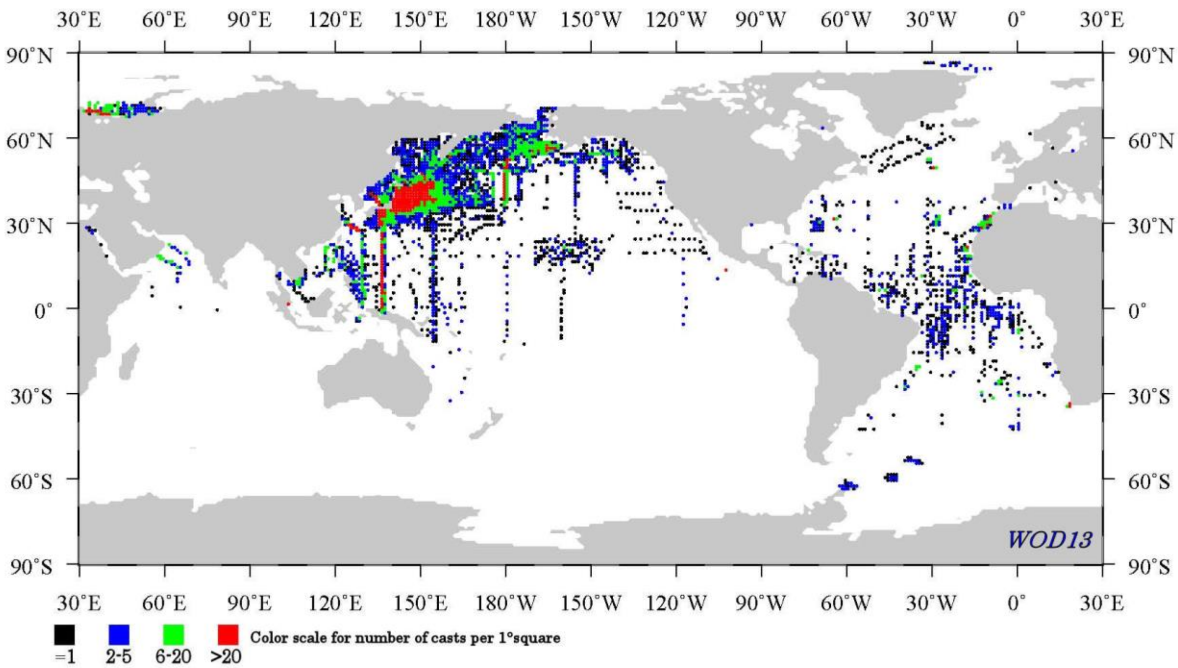


Figure 16.12. Geographic distribution of total wet mass (34,075 casts) in WOD13.

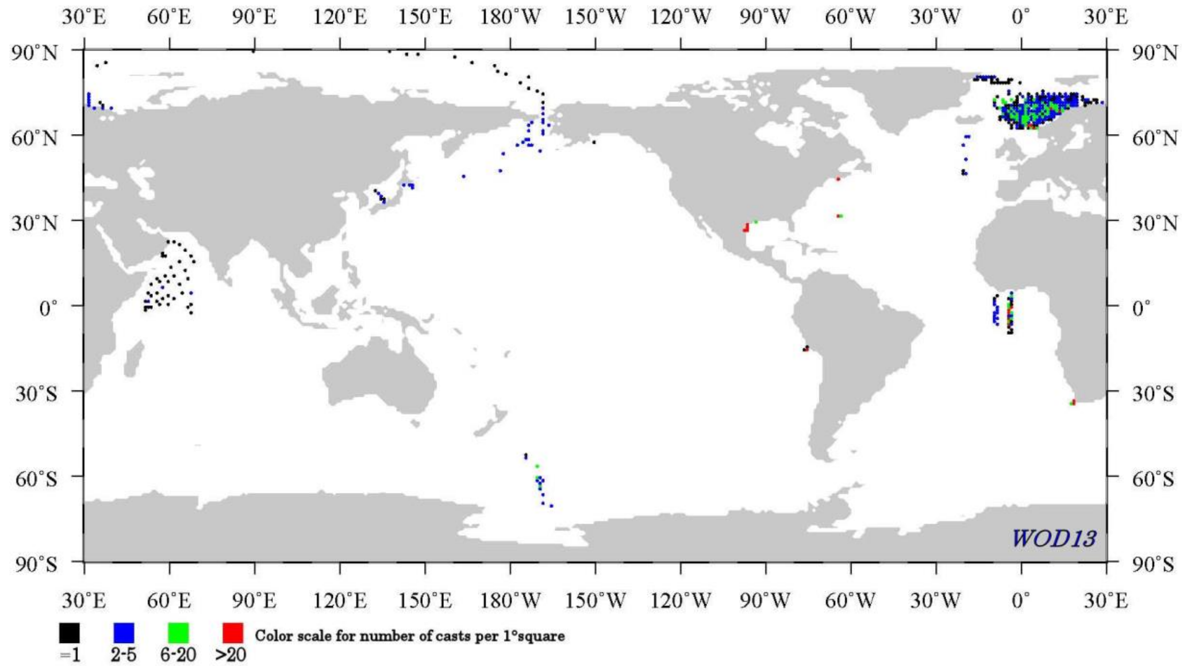


Figure 16.13. Geographic distribution of total dry mass (2,554 casts) in WOD13.

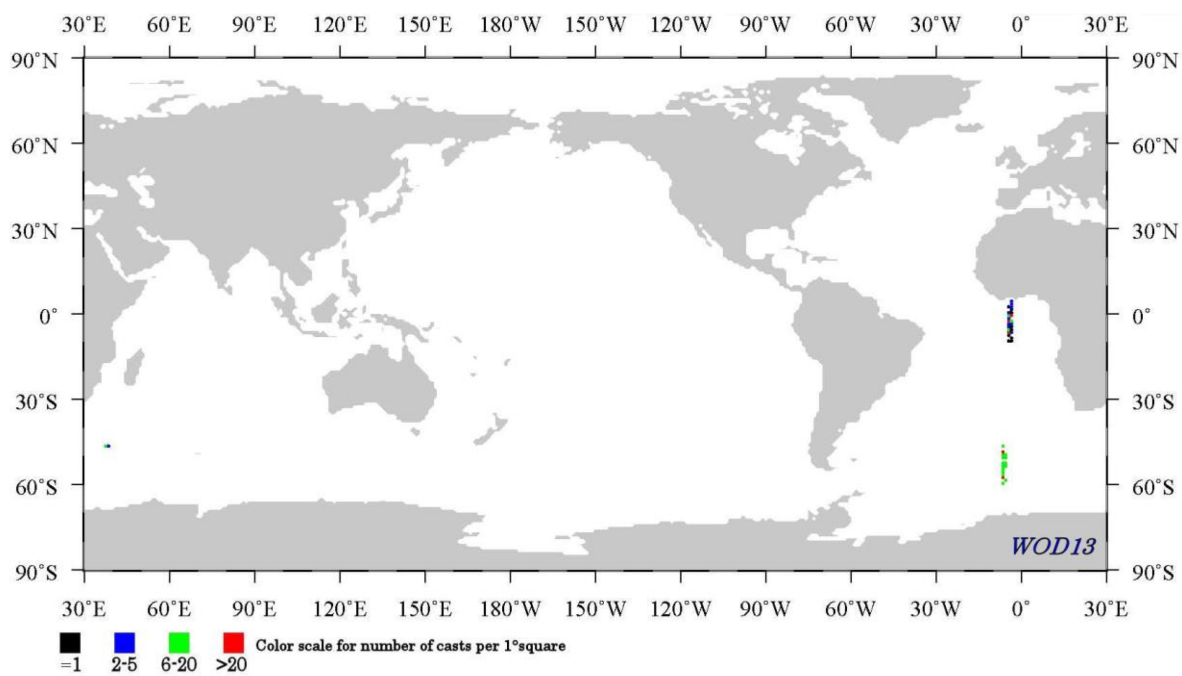


Figure 16.14. Geographic distribution of total ash-free dry mass (446 casts) in WOD13.

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