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WORLD OCEAN DATABASE 2009

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PREFACE

The oceanographic databases described by this atlas series expands on the *World Ocean Database 2005* (WOD05) 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 ocean, 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).

The amount 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 such as the effect of increased carbon dioxide on coral reefs (Kleypas *et al.,* 1999). 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.

We have tried to structure the data sets in WOD09 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.

Kleypas, J. A., R. W. Buddemeier, D. Archer, J. P. Gattuso, C. Langdon, and B. N. Opdyke, 1999: Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. *Science*, 284, 118-120.

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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 Ocean Climate Laboratory (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 UNESCO 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, "data archaeology and rescue" projects have been supported with funding from the NOAA Environmental Science Data and Information Management (ESDIM) Program, NOAA Climate and Global Change Program, and the Climate Database Modernization 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 WOD09. The NATO sponsored 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 A. Grodsky, A. Pankov, and D. Smolyar of the OCL for their work in data digitization and their assistance in quality control of the data and metadata in WOD09, C. Forgy who performed invaluable work in quality control of data in this database, R. Gelfeld, and C. Sazama for their assistance in locating historical and recent data for inclusion in this database. We also thank NOAA colleagues T. Piccolo who reviewed and provided comments on Chapter 16 and E. Yarosh for his proofreading. J. 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. F. Mitchell and C. Paver helped with all the code lists and accessions, M. Hamilton supplied GTSPP data.

The OCL expresses thanks to those who provided comments and helped develop an improved *World Ocean Database 2009* (WOD09) product. Any errors in WOD09 are the responsibility of the Ocean Climate Laboratory.

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. Data are both historical and modern with the most recent data from 2008.

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)

This new release is known as *World Ocean Database 2009* (WOD09) and contains substantial amount of historical and recent data (through 2008) not previously available as part of the fully quality-controlled WOD series although all data received are now made available online within three months of entry into the database. As with our previous work, users can obtain the latest information on WOD09 (*e.g.* Errata sheet, Frequently Asked Questions and Updates) via the NODC Home Page, http://www.nodc.noaa.gov/ (click on *World Ocean Database 2009*). The purpose of this atlas is to describe the WOD09 database and show the historical distributions of profiles made using the various instrument types included in WOD09 as well as some specific variables that comprise WOD09. 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 WOD09.

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 at http://www.ngdc.noaa.gov/wdc/wdcmain.html.

1.1.2. Goals for World Ocean Database 2009 (WOD09)

Our goal in developing and distributing WOD09 is to make available to anyone, without restriction, the most complete set of historical ocean profile data and plankton measurements possible in electronic form along with ancillary metadata and quality control flags.

As with earlier versions of NODC/WDC databases, the data contained in WOD09 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).

Notably, WOD09 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 WOD09 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 risen 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 WOD09 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: Data from one or more casts at one geographic location.

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 WOD09, 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.*, 2006; Appendix for a list of country codes. Note that under an international effort to standardize codes, WOD has switched from IODE country codes to International Organization for Standardization (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), 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 corresponding 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, available online). 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 WOD09.

1.1.4. Datasets

The WOD09 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 WOD09 datasets are briefly described below and in more details in followings chapters. A list of datasets in WOD09 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.* (2009).

The WOD09 database includes oceanographic variables measured at “observed” depth levels as well as interpolated to a set of 33 “standard” depth levels. All climatic fields in the atlas are produced based on “standard” depth levels data.

Table 1.1. Instrument types in the WOD09

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 7.7% 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.)

iv.) *Plankton tow* – net tows or bottle casts from which plankton counts and/or biomass observations were taken (see Chapter 16.)

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). 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). For recording the information is sent back to the command unit 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. There are two manufacturers of XBTs, Sippican in the United States (was the first manufacturer), and TSK in Japan. A third manufacturer, Sparton, is no longer in business. XBTs have been deployed since 1966. 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). The recommended practice for exchanging and archiving XBT data (UNESCO, 1994) state these data should not be corrected or altered so as to provide a known base for a user to apply necessary depth correction. In 1996, both TSK and Sippican began distributing software which used the amended depth equation as the default. In the present 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. These distinctions are quite important for many areas of oceanographic research. 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 (see Chapter 4.)

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 include 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 WOD09 from the TAO, PIRATA, and most of the TRITON buoys are daily averages acquired from the TAO webpage http://www.pmel.noaa.gov/tao/index.shtml. The remainder of the TRITON buoys, the MARNET buoys and light-ships data were acquired from the Global Temperature and Salinity Profile Project (GTSPP, http://www.nodc.noaa.gov/GTSPP/gtspp-home.html) database (see Chapter 9.)

DRB Dataset – Drifting buoys

Drifting buoys are platforms which are advected by ocean currents, either at the surface, or at predetermined (usually shallow) depths. Drifting buoy data included in WOD09 were acquired from GTSPP database and from Arctic Buoy program archive. The GTSPP data are from the subset of oceanic drifting buoys which have multiple subsurface temperature measurement devices (thermistors) suspended from a chain. For more information on the ocean drifting buoys, see http://www.drifters.doe.gov/ or http://www.aoml.noaa.gov/phod/dac/dacdata.html (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 – Instrumented Autonomous Pinniped

Bathythermographs and CTDs attached to sea elephants. Temperature and salinity information is recorded during dives taken while feeding and transmitted to satellite upon surfacing (see Chapter 12.)

GLD Dataset - Gliders

The Glider (GLD) dataset is new in this *World Ocean Database* release. It contains data collected from reusable autonomous underwater vehicles (AUV) 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 saw-toothed trajectory through the water. The source of the GLD data is the Pacific Rim Military Exercises (RIMPAC) project courtesy of Marc Stewart of the University of Washington Applied Physics Laboratory (see Chapter 15.)

SUR Dataset – Surface-only data

Surface-only data are either data taken using some type of bucket, or data from thermosalinographs. These data are not the focus of WOD09. Only selected surface datasets which contained data from specific time periods and ocean areas which were not otherwise well covered by profile data are included in WOD09. 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 WOD09 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 WOD09.

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 WOD09 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, WOD09 contains approximately 1.8 million shallow casts so that the cost of the ship time to perform these measurements is approximately \$3.7 billion. In addition, WOD09 contains 0.3 million profiles deeper than 1000 m depth, so the cost in ship time to make these ”deep“ measurements is approximately \$3.1 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.

Table 1.2. Meteorological and Sea-state parameters stored in the WOD09

Variables	DATASETS					
	OSD	MBT	XBT	CTD	MRB	Total
Bottom depth (m)	1,451,069	617,108	444,565	352,007		2,864,749
Water color (Forel-Ule color scale)	231,968	12,411	429	1,087		245,895
Secchi disk visibility depth (m)	372,236	12,146	447	1,952		386,781
Wave direction (WMO 0877)	302,044	29,843	30,529	3,853		366,269
Wave height (WMO 1555)	164,546	114,145	47,257	9,768		335,716
Sea state (WMO 3700)	511,282	478,000	53,963	27,368		1,070,613
Wind force (Beafort Scale)	420,311	14,444	2,199	3,948		440,902
Wave period (WMO 3155 or NODC 0378)	104,604	34,385	37,765	9,439		186,193
Wind direction (WMO 0877)	954,473	653,395	151,590	51,571	348,776	2,159,805
Wind speed (in knots)	531,432	673,101	153,368	46,986	351,301	1,756,188
Barometric pressure (millibar)	658,706	337,933	26,181	46,764	2,546	1,072,130
Dry bulb temperature (°C)	891,584	622,633	135,336	50,644	375,780	2,075,977
Wet bulb temperature (°C)	230,377	495,859	49,841	35,062		811,139
Weather condition (WMO 4501 and WMO 4677)	628,704	514,729	41,754	35,194		1,220,381
Cloud type (WMO 0500)	322,837	25,453	14,321	20,197		382,808
Cloud cover (WMO 2700)	604,530	523,929	25,751	29,515		1,183,725
Horizontal visibility (WMO 4300)	50,952	185,428	857	22,666		259,903
Reference/Sea surface temperature (°C)	24,876	1,172,477	115,942	391	1,421	1,315,107
Absolute air humidity ($g\ m^{-3}$)	56,451	1,565		82		58,098
Sea surface salinity		2,556	11,652			14,208

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 WOD09 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 media

WOD09 is being distributed on-line (http://www.nodc.noaa.gov/OC5/indprod.html) and on DVD with all data compressed. Based on requests by users of our earlier products, the OCL developed a new ASCII format to make the most efficient use of space on storage media used to transfer data to users. To further minimize storage space requirements, the data have been compressed with the GZIP utility. For more information on data format see Johnson *et al.* (2009).

1.1.8. Application software interfaces

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 WOD09. In response to user requests, we have defined the WOD09 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.

1.2. COMPARISON OF WOD09 WITH PREVIOUS GLOBAL OCEAN PROFILE DATABASES

Table 1.3 show the amount of data available from different dataset types that were used in earlier global oceanographic analyses. During the past three years, the archives of historical oceanographic data have grown due to special data management and data observation projects that we discuss in section 3.1 of this atlas, as well as due to normal submission by scientists and operational ocean monitoring programs. With the distribution of WOD09 there are now approximately 7.9 million temperature profiles and 2.7 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 1.25 million temperature profiles since publication of *World Ocean Database 2005.*

Table 1.3. Comparison of the amount of data in WOD09 with previous ocean databases.

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

[1] Based on statistics from *Climatological Atlas of the World Ocean* (1982).
[2] Based on NODC Temperature Profile CD-ROM.
[3] WOD09 OSD dataset includes data from 121,763 low-resolution CTD casts and 1,489 low-resolution XCTD casts.
[4] WOD09 CTD dataset includes data from 5,985 high-resolution XCTD casts.
[5] WOD09 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 WOD09 – 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. DATA SOURCES

The oceanographic data that comprise WOD09 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, http://www.iode.org/.

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, http://www.ngdc.noaa.gov/wdc/ hosted by the National Geophysical Data Center located in Boulder, Colorado.

The MAST (Marine Science and Technology Programme) program of the European community promoted international oceanographic data exchange by emphasizing that MAST funded projects must contribute data to appropriate data centers.

It has become more common to release all data from a particular project on CD-ROM as a project data set. We have incorporated data from these CD-ROMs into the WOD09. Examples include: the British Ocean Flux Study (BOFS) and Ocean Margins Experiment (OMEX) datasets produced by the British Oceanographic Data Center and the North Sea Project Database sponsored by the MAST program of the European Community.

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, the Intergovernmental Oceanographic Commission of UNESCO initiated a project in 1993 known as 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, that 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 WOD09, approximately 3.7 million temperature profiles have been added to the historical archives of oceanographic data since 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

During 1995, World Data Center for Oceanography, Silver Spring, initiated a project entitled "*Global Ocean Database*" with support from the NOAA/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. A substantial effort is involved, but improvements to the archives greatly serve the user community.

The response to WDC requests for data has been excellent. We emphasize that some of, and in some cases the majority of, the data submitted by these institutions may have already existed in NODC/WDC databases. However, we have frequently found that 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 a "*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. IOC Global Temperature-Salinity Profile Program

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". [The GTSPP files include data from moored buoys (identified in WOD98 as "fixed platforms") such as the NOAA Tropical Atmosphere-Ocean (TAO) array of buoys (Hayes *et al.,* 1991; McPhaden, 1993, 1995) in the Pacific Ocean and from other buoy programs such as TRITON and PIRATA]. We incorporated XBT and TAO buoy profiles from this database into WOD09 for the period inclusive through February 2005.

Users wanting GTSPP data after this date can acquire the data over the Internet via the NODC website www.nodc.noaa.gov or by contacting the NODC User Services group (NODC.Services@noaa.gov).

Users wanting the complete TAO 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 the Pacific Marine Environmental Laboratory (http://www.pmel.noaa.gov/).

1.3.4. International Research Projects Data

Data from the WOCE DVD version 3.0 (CTD and OSD profiles) are included in WOD09. Some WOCE XBT profiles are also part of WOD09. Data from the Joint Global Ocean Flux Study (JGOFS) and the Global Ocean Ecosystem Dynamics (GLOBEC) are also included.

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 WOD09. The ICES website is www.ices.dk .

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 WOD09.

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 WOD09 has quality control flags associated with it. A description of these flags and general documentation describing software for reading and using the WOD09 database are found in Johnson *et al.* (2009). WOD09 now includes Quality Control Flags assigned by data submitters. Users can choose to accept or ignore these flags. It is clear that 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 the case. 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 are not representative of the large-scale permanent or semi-permanent features we attempt to reproduce with our analyses and will cause unrealistic features such as bullseyes 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 WOD09 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 33 standard levels.

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

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 OSD dataset.

Oxygen data in the CTD and PFL datasets received a slightly 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 therefore there are very few oxygen data in the PFL dataset.

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 WOA05, 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 pCO_2, DIC, Tritium, Helium, Δ^3Helium, Δ^{14}Carbon, Δ^{13}Carbon, Argon, Neon, CFC-11, CFC-12, CFC-113, and Δ^{18}Oxygen 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).

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*. (2009).

Plankton data have a different set of quality control detailed in Chapter 16 of this document as well as Johnson *et al*. (2009).

1.5. XBT DROP RATE ERROR

The XBT instrument does not measure pressure or depth directly. The depth of an XBT instrument as it falls through the water column is computed from the elapsed time from the moment the probe enters the water through use of a drop-rate equation. There are several models of the Sippican Expendable Bathythermograph instrument. The manufacturer's drop rate equation for the T4, T-6, and T-7 models are known to contain a systematic error. The systematic error in calculated depth can be as large as 25-30 m at depths of 750 m. To correct for this error a new drop rate equation has been computed (Hanawa *et al.,* 1995; UNESCO, 1994). By international agreement (UNESCO, 1994), XBT profile depths are supposed to be reported to and archived at data centers using the ”old“ drop-rate equation. This policy is to avoid possible confusion as to whether the profiles have been converted or not. NODC/WDC archives the XBT data as submitted. In fact, some data are submitted using the new drop-rate formula although none of these data are in WOD09. This fact can be demonstrated by using a code in the observed level profile metadata (Johnson *et al.,* 2006) (see Chapter 4).

The observed level XBT profiles are the same data as submitted by originators. However, in preparing standard level data for WOD09, the NODC/OCL corrected the depths of the originator's XBT profiles using the new drop-rate equation, before interpolating to standard levels.

1.6. STATISTICS OF INDIVIDUAL INSTRUMENT TYPES

We present a series of figures and tables which document the status of the archives of historical ocean profile through the presentation of summary statistics. More detailed information is presented in the individual chapters of this volume, each describing the historical distributions of an individual instrument or measurement type (*e.g.* CTD, MBT, XBT, OSD temperature and salinity, nutrients, chlorophyll, pH, alkalinity, pCO_2, and TCO_2 and plankton data).

Table A.1 (see Appendix) shows the number of stations or profiles in WOD09 submitted by individual countries for the OSD, CTD, MBT, and XBT datasets. This table is sorted by NODC country code. Table A.2 (see Appendix) shows the same information sorted alphabetically by country name.

1.7. 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.

1.8. 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 WOD09 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.

Note: for all charts of observations per depth, the count reflects the number of casts with at least one observation within the interval around each standard depth. The interval around each standard depth consists of 1/2 of the distance from the standard depth to the next shallower standard depth to 1/2 of the distance from the standard depth to the next deeper standard depth. The surface value reflects the 0 to 5 meter interval.

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

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2.1. INTRODUCTION

Data from Ocean Station Data (OSD) casts have historically referred to surface and sub-surface oceanographic measurements of temperature made from sea-going research ships using deep-sea reversing thermometers, measurements of dissolved and particulate constituents in seawater, and plankton at depths of interest in the water column. 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 term OSD to refer collectively to low vertical resolution, 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 2009* (WOD09**)**. Computer storage was still a scarce resource at the time 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 discrete oceanographic observations available to date totaling 2,544,196 casts covering the years 1772 to 2008 (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 locations (sometimes called hydrographic stations) along pre-selected cruise tracks. For each station, 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 bottles of different volumes. 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 the most commonly used types of water samplers to date for the serial collection of relatively small volumes of seawater. The stainless steel Gerard-Ewing bottle samplers are the most commonly used type of water sampler for the serial collection of relatively large volumes of seawater.

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 are salinity, dissolved oxygen, and major dissolved inorganic nutrients (Table 2.1). 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 [^{39}Ar], kripton-85 [^{85}Kr], and carbon-14 [^{14}C]). Present day analytical techniques for measuring ^{85}Kr in seawater, for example, require a sampling volume of about 1200 liters (Smethie and Mathiew, 1986; Smethie, 1994). The Gerard-Ewing samplers were first used during the Geochemical Ocean Sections Study (GEOSECS) program in the early 1970s (Bainbridge *et al.*, 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.

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 1.2-1.5 liters) at selected depths in the water column (Sverdrup *et al.,* 1942). The bottles with the ends open are sequentially attached to a metal wire in serial numbers at selected vertical intervals (typically about 12-24 bottles) and lowered to the desired depths in the water column. Then the bottles are closed in succession by the tripping action of a metal messenger that slides down the metal wire. Another messenger is typically arranged on the wire to be released by the inverting mechanism of each Nansen bottle, and slides down the cable until it reaches the next Nansen bottle below, and so on until the last and deepest bottle is closed. By fixing a sequence of bottles and messengers at intervals along the cable, a series of water samples at increasing depth are collected. When the bottles are brought back on deck, water samples are sequentially collected from each bottle and then analyzed at a later time for a variety of dissolved and particulate constituents. Because of their relatively small sampling volume, sampling is generally restricted to a small number of constituents present in seawater. The Nansen bottles often included two or more specially designed protected and un-protected 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.

Though the Nansen bottle was the sampling device of choice of oceanographic field research in the early 20th century, it had practical disadvantages: (1) its relatively small sampling volume limited the analysis to a small number of constituents (*e.g.,* salinity, dissolved oxygen, and inorganic nutrients); (2) its relatively poor metal seals had a tendency for sample water leakage resulting in degassing; and (3) its metal construction was thought to interfere with some seawater constituents (*e.g.,* inorganic and organic nutrients, gases such as oxygen, transition metals such as iron, *etc.*). Nansen bottles are no longer manufactured commercially. The Nansen bottles were generally replaced by the Niskin bottles beginning 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) at selected depths in the water column. Shale Niskin invented the Niskin bottle in 1966 based on the general idea of the Nansen bottle. Like the Nansen bottles, one or more Niskin bottles can be sequentially attached to a metal wire at selected vertical intervals and each bottle may often include two or more deep-sea glass mercury-filled reversing thermometers. In more recent years, Niskin bottles are frequently mounted around a circular rosette sampler metal frame with the capacity to hold as many as 36 bottles. The rosette frame is attached at the end of a wire with (or without) an electrical conductor. The bottles can then be closed at any depth or pressure by an electrical command from deck or from pre-set depth (pressure) values for research ships with or without an electrical conductor wires. When the closed Niskin bottles are brought back on deck, water samples can be collected from each bottle and then analyzed for different dissolved and particulate constituents. The rosette frame may include a CTD and other high-frequency sampling instruments (*e.g.*, fluorometers, polarographic oxygen sensors, transmissometers, *etc.*).

2.3. VARIABLES AND METADATA INCLUDED IN THE OSD DATASET

The OSD dataset includes a number of the most frequently measured *in situ* physical (temperature, salinity), chemical (dissolved gases, alkalinity, dissolved inorganic carbon, pH, inorganic nutrients, geochemical tracers), and biological (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 parameter (or stations in the case of plankton data), and sampled years of the parameters included in the OSD dataset. Each oceanographic station data record may contain simultaneous profiles of one or more of these parameters as a function of depth or pressure. The user can extract data from the OSD dataset both at observed depths and up to 33 nominal standard depth levels (Johnson *et al.,* 2009).

The observed level measurement values in the OSD dataset are the data submitted by the data originator converted to the WOD 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.,* 2009).

Physical parameters such as temperature, salinity, and pressure are conservative parameters which define the equation of state of seawater (*e.g.*, Millero and Poisson, 1981). By conservative parameters 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) 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 WOD09 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 test the calibration of salinity measurement instruments and 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; Culkin, 1986; Aoyama *et al.,* 2002; Kawano *et al.,* 2005; Saunders, 1986). 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, WOD09 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 parameters (Table 2.1).

Table 2.1. Parameters 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)	2,300,610 (1772-2008)
Salinity [S]	Dimensionless or unit less	2,059,855 (1874-2008)
Dissolved oxygen [O_2]	Milli-liter per liter (ml l^{-1})	747,349 (1898-2008)
Phosphate [HPO_4^{-2}]	Micro-mole per liter (µM)	454,933 (1922-2008)
Silicate [$Si(OH)_4$]	Micro-mole per liter (µM)	335,140 (1921-2008)
Nitrate [NO_3]	Micro-mole per liter (µM)	268,388 (1925-2008)(1)
pH	Dimensionless or unit less	196,843 (1910-2007)
Total Chlorophyll [Chl] unless specified	Micro-gram per liter (µg l^{-1})	154,046 (1933-2008)
Alkalinity [TALK]	Milli-equivalent per liter (meq l^{-1})	52,312 (1921-2008)
Partial pressure of carbon dioxide [pCO_2]	Micro-atmosphere (µatm)	3,372 (1967-2008)
Dissolved inorganic carbon [DIC]	Milli-mole per liter (mM)	13,146 (1958-2008)
Tritium [^3H]	Tritium Unit (TU)(2)	1,618 (1984-2003)
Helium [He]	Nano-mol per liter (nM)	2,116 (1984-2003)
Delta Helium-3 [Δ^3He]	Percent (%)	2,086 (1985-2003)
Delta Carbon-14 [$\Delta^{14}C$]	Per-mille (‰) deviation	956 (1990-2003)
Delta Carbon-13 [$\Delta^{13}C$]	Per-mille (‰) deviation	928 (1991-2003)
Argon [Ar]	Nano-mol per liter (nM)	75 (1993-1993)
Neon [Ne]	Nano-mol per liter (nM)	1,308 (1987-2002)
Chlorofluorocarbon-11 [CFC-11]	Pico-mole per liter (pM)	11,272 (1985-2008)
Chlorofluorocarbon-12 [CFC-12]	Pico-mole per liter (pM)	11,279 (1985-2008)
Chlorofluorocarbon-113 [CFC-113]	Pico-mole per liter (pM)	2,799 (1990-2006)
Delta Oxygen-18 [$\Delta^{18}O$]	Per-mille (‰) deviation	94 (1993-1996)
Pressure [P]	Decibar	140,432 (1890-2008)
Plankton taxonomy and Biomass	Various units (see Chapter 16)	218,695 (1905-2008)(3)

(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 Chapter 16).

Geochemical parameters such as dissolved oxygen (O_2), major dissolved inorganic nutrients (reactive phosphate [HPO_4^{-2}], nitrate and nitrite [NO_3+NO_2 or N+N], nitrate [NO_3], nitrite [NO_2], and silicate or silicic acid [$Si(OH)_4$], carbon species (alkalinity [TALK], dissolved inorganic carbon [DIC or TCO_2], partial pressure of carbon dioxide [pCO_2]) and pH are non-conservative parameters. 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 WOD09 includes NO_3+NO_2 and NO_3 data only. The concentrations of reactive NO_3+NO_2 and NO_2 are often estimated by independent photometric analyses where in one case NO_3 is measured indirectly by effectively reducing NO_3 to NO_2 while in the other only NO_2 is measured directly (Strickland and Parsons, 1972; Atlas *et al.,* 1971; Whitledge *et al.,* 1986; Gordon *et al.,* 1993). The concentration of NO_3 is then obtained by difference between the estimated concentrations of NO_3+NO_2 and NO_2 *(i.e.*, $NO_3 = NO_3+NO_2 - NO_2$). It is important to note that data reported as NO_3 in the *WOD09* should be used with caution because it is difficult to verify that the NO_3 data are NO_3+NO_2 or NO_3. When reported by the originator of the data, *WOD09* includes metadata information about whether the labeled nitrate measurement is reported as NO_3+NO_2 data. Historical DIC, TALK, pCO_2, and pH data in WOD09 seldom includes information about the methods, instruments, and scales used (Millero *et al.,* 1993a, 1993b; Ramette *et al.,* 1977; Clayton and Byrne, 1993; Robert-Baldo *et al.,* 1985; Bradshaw and Brewer, 1988; Byrne and Breland, 1989; Dickson, 1981; 1984; 1993; DOE, 1994).

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 paleo-temperatures (Broecker and Peng, 1982). The OSD dataset includes noble gases such as neon [Ne], argon [Ar], and helium [He]. 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 tracers (chlorofluorocarbons [CFC-11, CFC-12, and CFC-113], tritium [hydrogen-3 or ^3H], helium-3 [^3He], delta carbon-13 [$\Delta^{13}C$], delta carbon-14 [$\Delta^{14}C$], and delta oxygen-18 [$\Delta^{18}O$]) 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 bombfallout radionuclides (^{3}H) and natural isotopes (^{3}He) function as "clocks" recording the elapsed time since a parcel of water was last in contact with the oceanic surface layer [*e.g.*, Broecker and Peng, 1982; Broecker, 1991; 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 (also called CFCs or freons) 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 CFCs in the ocean are CFC-11 (R-11, freon-11, or trichlorofluoromethane [CCl_3F]), CFC-12 (R-12, freon-12, or dichlorodifluoromethane [CCl_2F_2]), and CFC-113 (1,1,2-Trichloro-1,2,2-trifluoroethane or trichlorotrifluoroethane [Cl_2FC-$CClF_2$]). 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 tracer data in the OSD dataset were collected as part of WOCE program in the 1990s. Additional sources of historical tracer data have been identified but were not included in time for the release of WOD09.

OSD chemical data received at 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 WOD09 common units, the data are converted from the originator's units to a common set of concentration units to facilitate the use of the WOD09 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·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 addition to the observed data (profiles as a function of depth of each sampled parameter), OSD casts include additional information (commonly referred to as "station header information") such as, but not limited to, ocean surface conditions (*e.g,.*, wave direction and height, sea state), meteorological observations (*e.g,*, cloud cover and type, visibility, wind speed and direction, barometric pressure, dry and wet bulb temperature), water color and transparency (*e.g,*, 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.* (2009) describes the WOD09 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 biochemical 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 inter-comparison of the long-term precision and accuracy of historical oceanographic chemical measurements. Not all data received at NODC contain complete metadata information. For example, approximately less than 20% of the OSD profiles contain parameter specific metadata information about the analytical methods and instruments used.

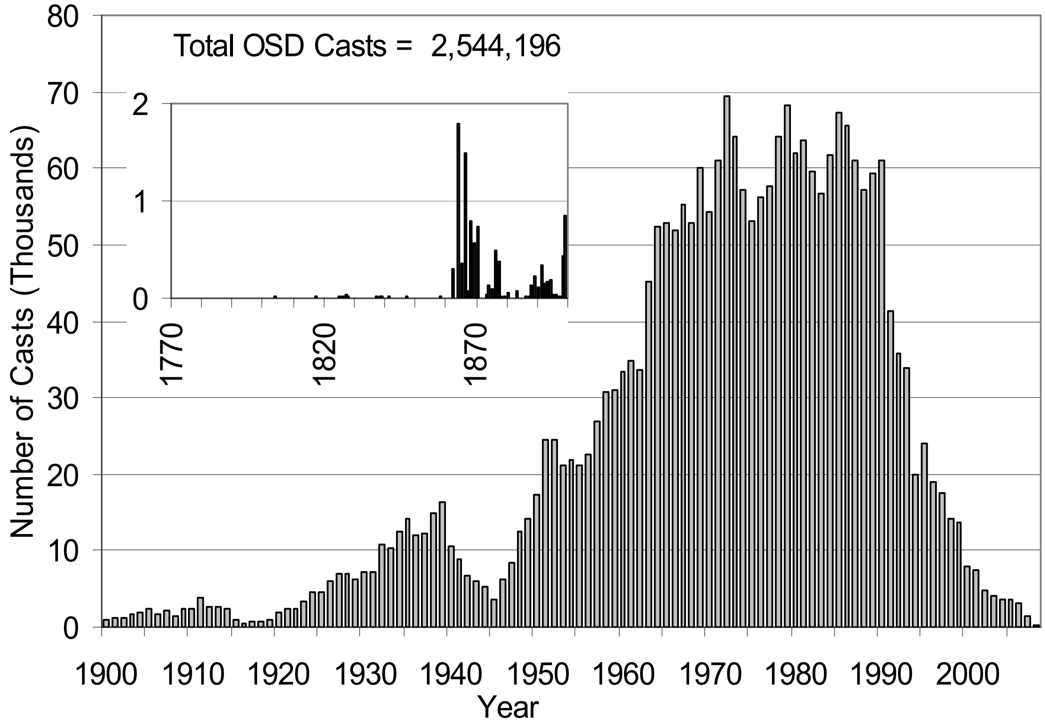

Figure 2.1. Time series of the number of OSD casts.

It is difficult to estimate the precision and accuracy 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, of DIC and TALK (DOE, 1994) or Dissolved Inorganic Carbon (Dennis A. Hansell per. Comm.). It is generally believed that adoption of CRM's will facilitate the inter-laboratory 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 parameters is worldwide and for some parameters spans 236 years (Tables 2.1 and 2.3). The number of OSD casts added to NODC databases has increased greatly since 1974 (Figure 2.4). However the coverage for each parameter is non-uniform 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 non-uniformity 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 parameters. Second, the sampling and analysis of biochemical parameters is quite more labor intensive when compared to temperature or conductivity measurements obtained by CTD instruments.

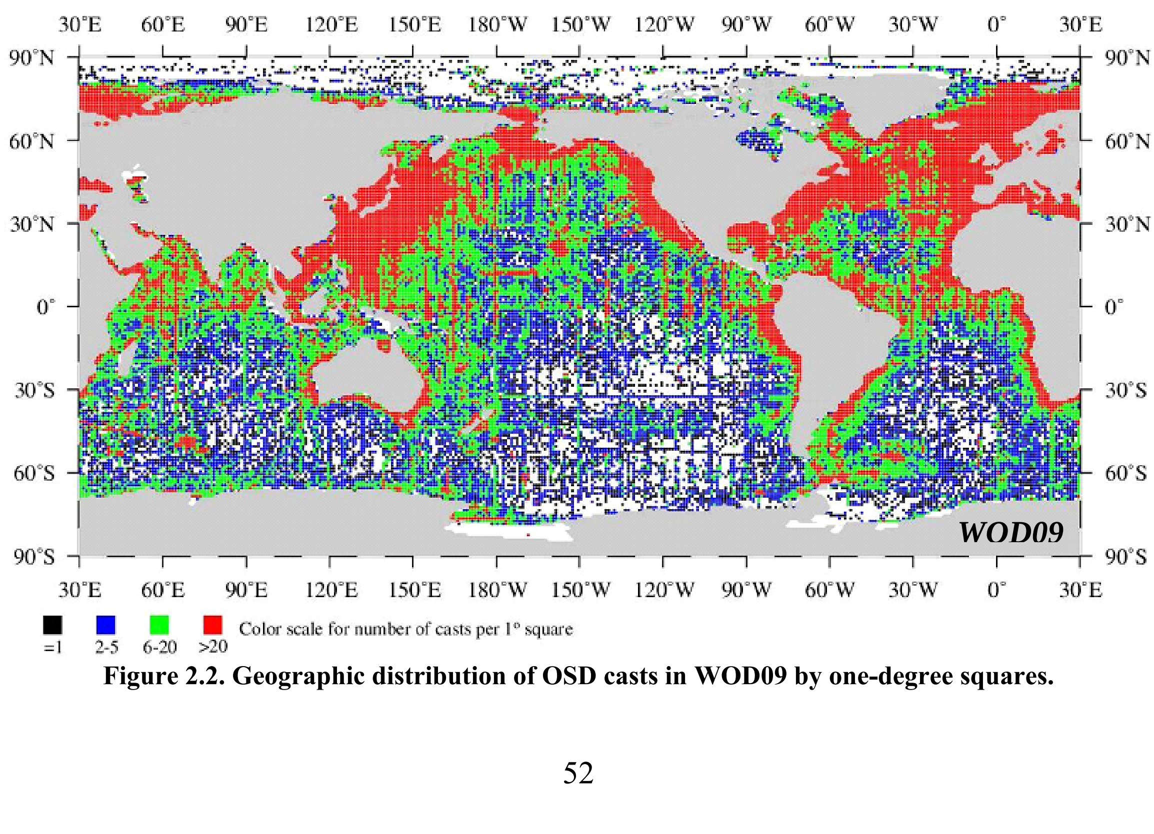

Figure 2.2. Geographic distribution of OSD casts in WOD09 by one-degree squares.

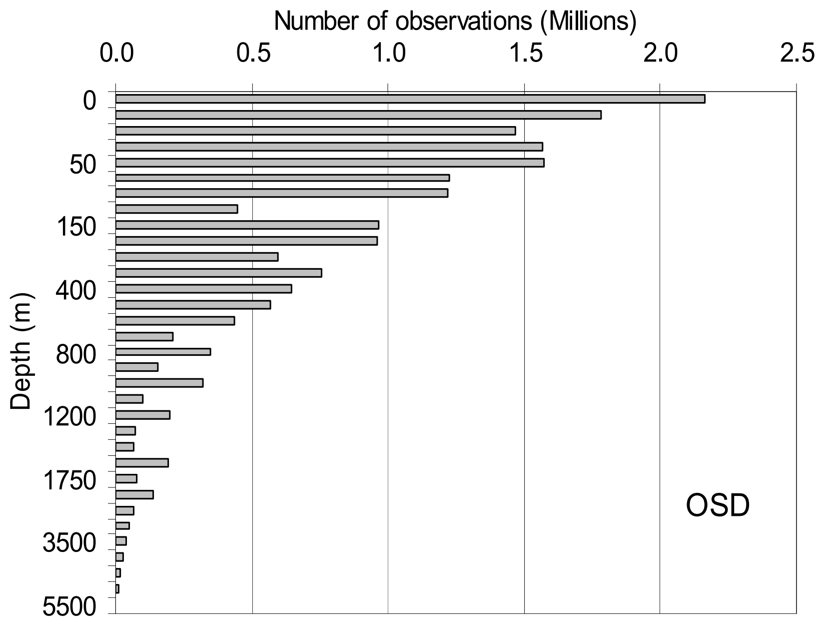

Figure 2.3. Distribution of Ocean Station Data (OSD) data at observed depth levels.

2.5. VARIABLES AND METADATA NOT INCLUDED IN THE OSD DATASET

The *World Ocean Database* includes data for other biochemical parameters not available as part of the WOD09 release. These parameters were not released as part of the WOD09 because a minimum of data quality control was not performed on these measurements. The parameters not present in the WOD09 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 WOD09 can retrieve the original data as sent to NODC. It is worth noting that in some cases, data received at NODC may include measured parameters which were not digitally stored in the *World Ocean Database* (*e.g.*, trace metals, organic compounds, *etc*.). Detailed information about these parameters is not maintained in the NODC OAS.

2.6. PROSPECTS FOR THE FUTURE

It is expected that relatively large amounts of historical chemical and biological data still exist in non-digital and digital form at data centers, research institutions, universities, and libraries worldwide. Biochemical 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). There are several types of chemical sensors available for autonomous and lagrangian platforms that can contribute to the *World Ocean Database*.

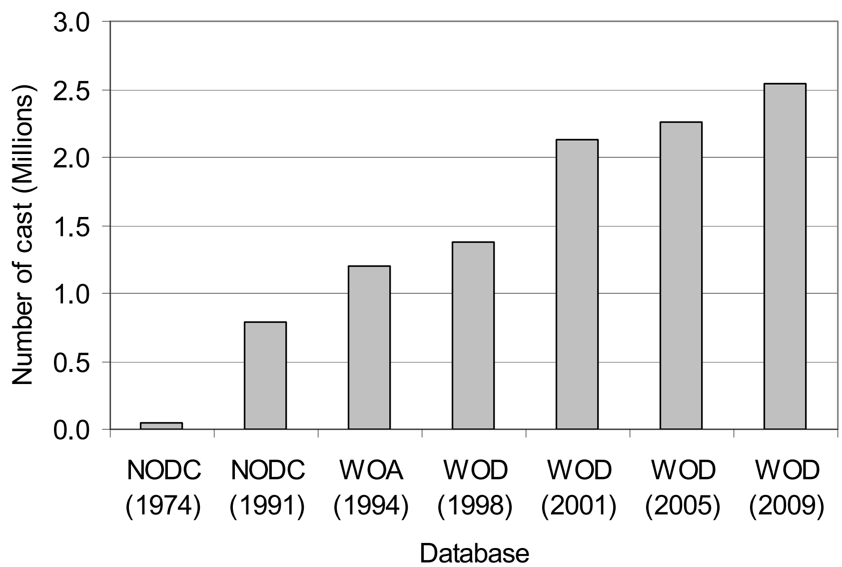

Figure 2.4. Number of OSD casts in NODC/WDC databases as a function of time.
The number of casts available at NODC prior to 1994 after Levitus (1982) and NODC Temperature-Profile CD-ROM (1991), the number of casts after 1994 is based on the World Ocean Atlas (WOA) and Database (WOD) series.

The *World Ocean Database* is a worldwide source of unrestricted access to historical oceanographic data information. Future releases of the *World Ocean Database* will be enhanced by the addition of more data and metadata and new parameters as well. It is hoped that users of the WOD09 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 to the NODC Ocean Climate Laboratory (http://www.nodc.noaa.gov/OCL/). Identification of new sources of chemical data to the WOD is beneficial for improving mechanisms for data and metadata 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, integrated, 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 the nature of oceanic variability in the instrumental record for present and future generations of observationalists, modelers, and public policy officials.

Table 2.2. The number of Ocean Station Data (OSD) casts as a function of year in WOD09 (total number of casts = 2,544,196).

YEAR	COUNT	YEAR	COUNT	YEAR	COUNT	YEAR	COUNT
1770	0	1831	0	1892	156	1953	21,075
1771	0	1832	0	1893	179	1954	21,972
1772	2	1833	0	1894	185	1955	21,199
1773	1	1834	0	1895	42	1956	22,679
1774	0	1835	0	1896	46	1957	26,894
1775	0	1836	8	1897	18	1958	30,821
1776	0	1837	17	1898	441	1959	31,085
1777	0	1838	11	1899	842	1960	33,461
1778	0	1839	15	1900	945	1961	34,807
1779	0	1840	9	1901	1,203	1962	33,571
1780	0	1841	21	1902	1,167	1963	45,164
1781	0	1842	8	1903	1,799	1964	52,397
1782	0	1843	0	1904	1,918	1965	52,802
1783	0	1844	0	1905	2,402	1966	51,811
1784	0	1845	0	1906	1,575	1967	55,324
1785	0	1846	3	1907	2,085	1968	52,987
1786	0	1847	28	1908	1,347	1969	60,510
1787	0	1848	0	1909	2,297	1970	54,214
1788	0	1849	1	1910	2,328	1971	60,967
1789	0	1850	3	1911	3,797	1972	69,338
1790	0	1851	1	1912	2,589	1973	64,101
1791	0	1852	0	1913	2,725	1974	57,303
1792	0	1853	0	1914	2,372	1975	53,753
1793	0	1854	0	1915	913	1976	56,274
1794	0	1855	4	1916	497	1977	57,843
1795	0	1856	0	1917	636	1978	64,117
1796	0	1857	6	1918	713	1979	68,393
1797	0	1858	23	1919	942	1980	61,916
1798	0	1859	5	1920	1,806	1981	63,717
1799	0	1860	0	1921	2,284	1982	60,056
1800	0	1861	0	1922	2,483	1983	56,775
1801	0	1862	299	1923	3,448	1984	61,988
1802	0	1863	0	1924	4,601	1985	67,561
1803	0	1864	1,798	1925	4,595	1986	65,609
1804	10	1865	352	1926	5,918	1987	60,998
1805	1	1866	1,494	1927	6,945	1988	57,155
1806	0	1867	78	1928	6,984	1989	59,396
1807	0	1868	791	1929	6,347	1990	61,196
1808	0	1869	557	1930	7,191	1991	41,469
1809	0	1870	727	1931	7,154	1992	35,822
1810	0	1871	0	1932	10,855	1993	33,913
1811	0	1872	0	1933	10,320	1994	20,138
1812	0	1873	30	1934	12,504	1995	24,383
1813	0	1874	132	1935	14,280	1996	19,104

1814	0	1875	90	1936	11,918	1997	17,816
1815	0	1876	500	1937	12,366	1998	14,372
1816	5	1877	383	1938	14,816	1999	13,587
1817	27	1878	25	1939	16,219	2000	7,901
1818	3	1879	17	1940	10,660	2001	7,369
1819	0	1880	49	1941	8,776	2002	4,758
1820	2	1881	2	1942	6,641	2003	4,010
1821	0	1882	8	1943	5,946	2004	3,629
1822	0	1883	79	1944	5,227	2005	3,593
1823	0	1884	1	1945	3,488	2006	3,213
1824	2	1885	0	1946	6,332	2007	1,560
1825	10	1886	17	1947	8,524	2008	203
1826	18	1887	28	1948	12,415		
1827	30	1888	128	1949	14,058		
1828	13	1889	221	1950	17,397		
1829	0	1890	122	1951	24,405		
1830	0	1891	342	1952	24,421		

Table 2.3. National contribution of OSD casts.

ISO[a] Country Codes	Country Name	OSD Casts	% of Total
SU	Union of Soviet Socialist Republics	558,266	21.94
JP	Japan	541,722	21.29
US	United States	374,130	14.71
GB	Great Britain	130,297	5.12
CA	Canada	119,815	4.71
99	Unknown / International	113,836	4.47
NO	Norway	94,922	3.73
DE	Germany	65,948	2.59
SE	Sweden	51,873	2.04
FI	Finland	46,379	1.82
FR	France	42,963	1.69
KR	Korea, Republic of	39,939	1.57
AU	Australia	35,748	1.41
DK	Denmark	32,497	1.28
ZA	South Africa	28,051	1.10
PE	Peru	26,979	1.06
NL	Netherlands	26,623	1.05
RU	Russia	19,611	0.77
IS	Iceland	18,781	0.74
PL	Poland	16,762	0.66
UA	Ukraine	15,755	0.62
DU	East Germany	15,209	0.60
IT	Italy	11,261	0.44
BR	Brazil	9,555	0.38
BE	Belgium	9,327	0.37
PT	Portugal	6,485	0.25
ES	Spain	6,226	0.24
CN	China, The Peoples Republic of	5,590	0.22
YU	Yugoslavia	5,410	0.21
CL	Chile	4,914	0.19
AR	Argentina	4,852	0.19
IN	India	4,478	0.18
ID	Indonesia	4,365	0.17
VE	Venezuela	3,590	0.14
EC	Ecuador	3,498	0.14
IL	Israel	3,463	0.14
TW	Taiwan	3,209	0.13
CI	Cote D'Ivoire (Ivory Coast)	3,148	0.12
RO	Romania	3,145	0.12
IE	Ireland	2,980	0.12
TR	Turkey	2,897	0.11
TH	Thailand	2,801	0.11

ISO[a] Country Codes	Country Name	OSD Casts	% of Total
GH	Ghana	2,670	0.10
MG	Malagasy Republic	2,523	0.10
MC	Monaco	2,088	0.08
SN	Senegal	1,975	0.08
NZ	New Zealand	1,917	0.08
GR	Greece	1,849	0.07
CD	Congo	1,836	0.07
MX	Mexico	1,457	0.06
NC	New Caledonia	1,344	0.05
CO	Colombia	1,338	0.05
MR	Mauritania	1,217	0.05
CU	Cuba	976	0.04
NG	Nigeria	968	0.04
LT	Lithuania	869	0.03
AO	Angola t	621	0.02
EG	Arab Republic of Egypt	544	0.02
AT	Austria	488	0.02
SG	Singapore	412	0.02
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	165	0.01
MY	Malaysia	154	0.01
PA	Panama	139	0.01
YE	Yemen	85	<0.01
MT	Malta	66	<0.01
	Total:	*2,544,196*	*100.00*

[a] ISO = International Organization for Standardization
http://www.iso.org/iso/country_codes.htm

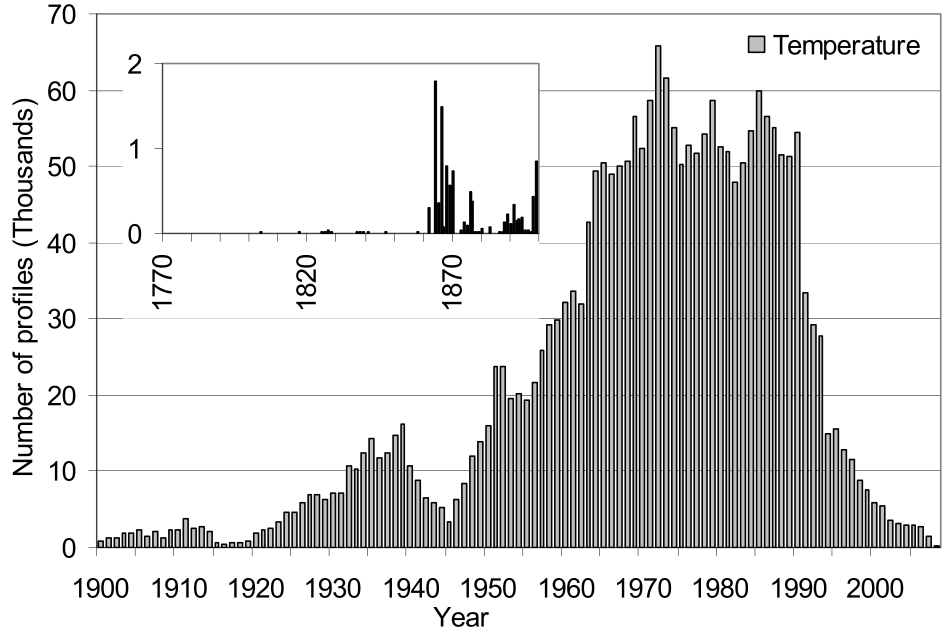

Figure 2.5. Time series of the number of temperature profiles in the OSD dataset.

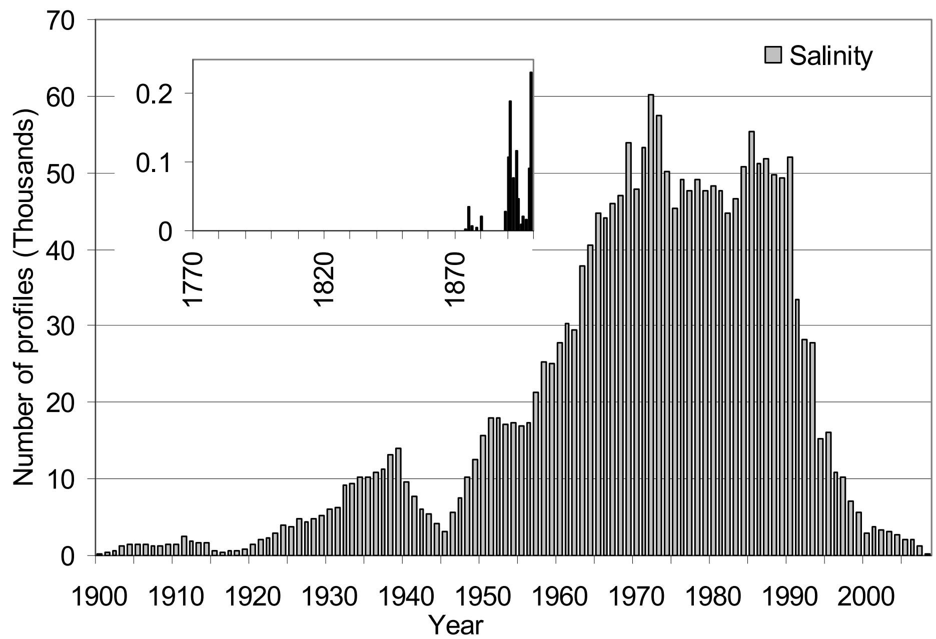

Figure 2.6. Time series of the number of salinity profiles in the OSD dataset.

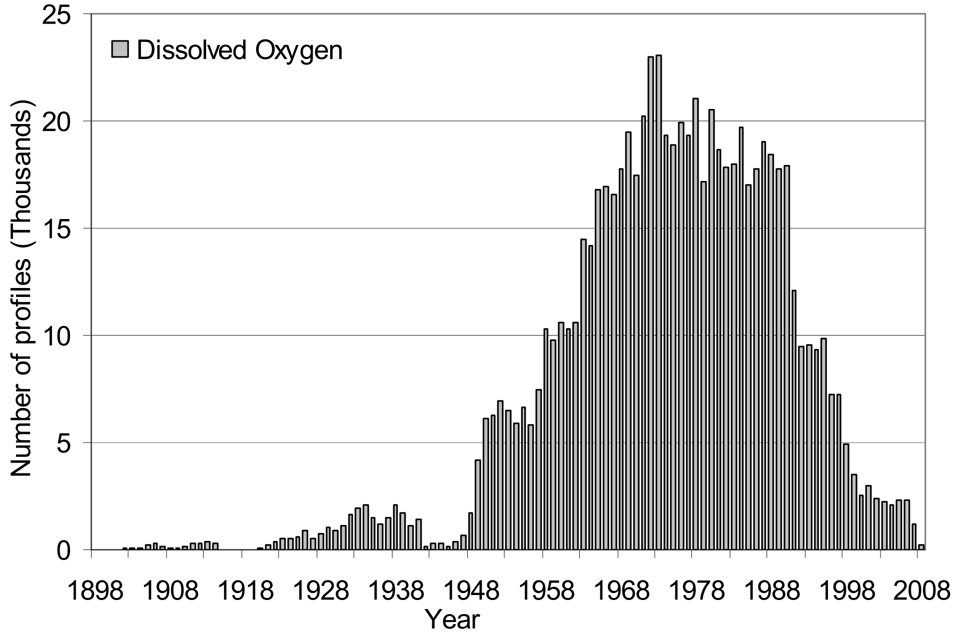

Figure 2.7. Time series of the number of dissolved oxygen profiles in the OSD dataset.

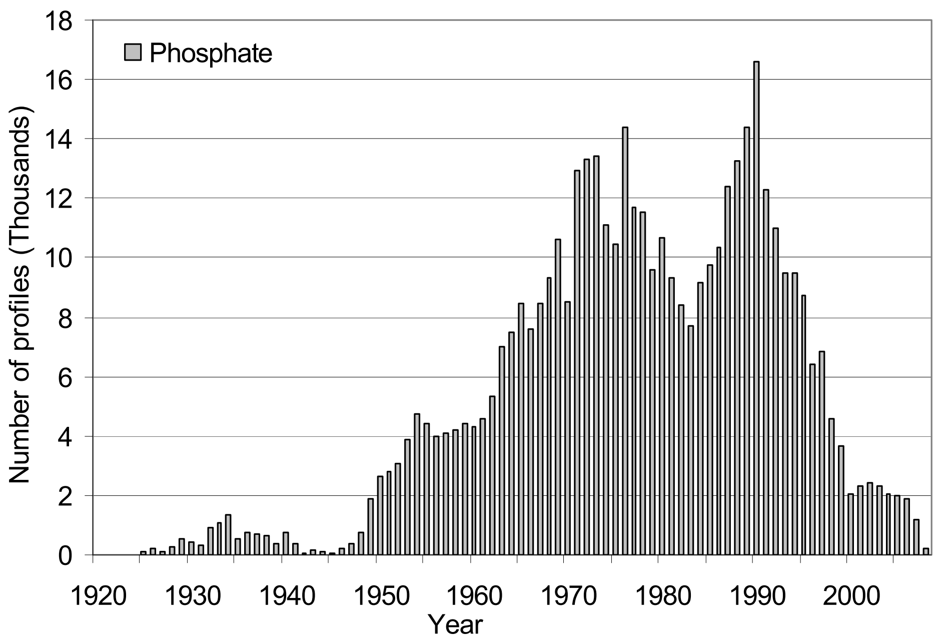

Figure 2.8. Time series of the number of Phosphate profiles in the OSD dataset.

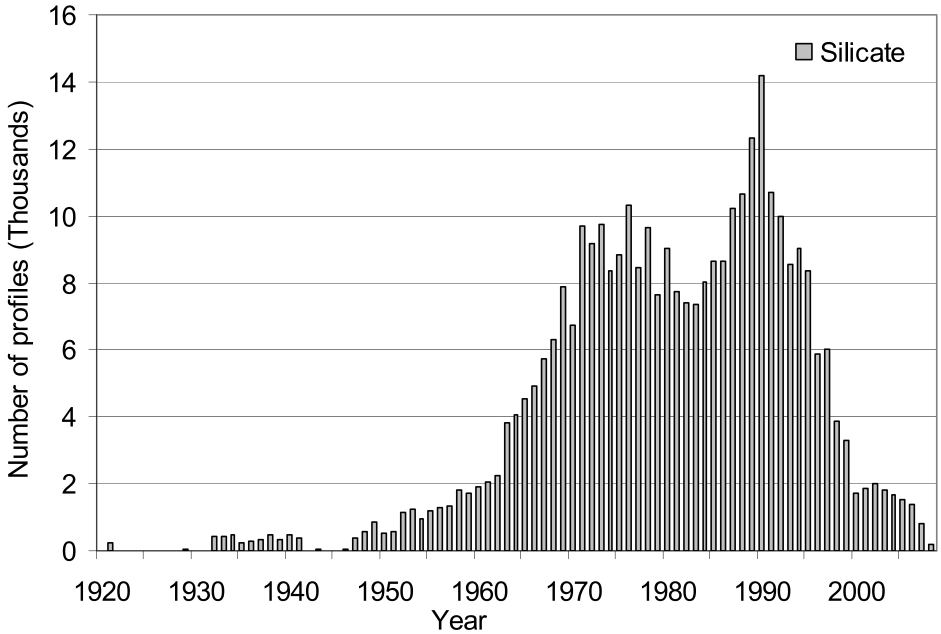

Figure 2.9. Time series of the number of silicate profiles in the OSD dataset.

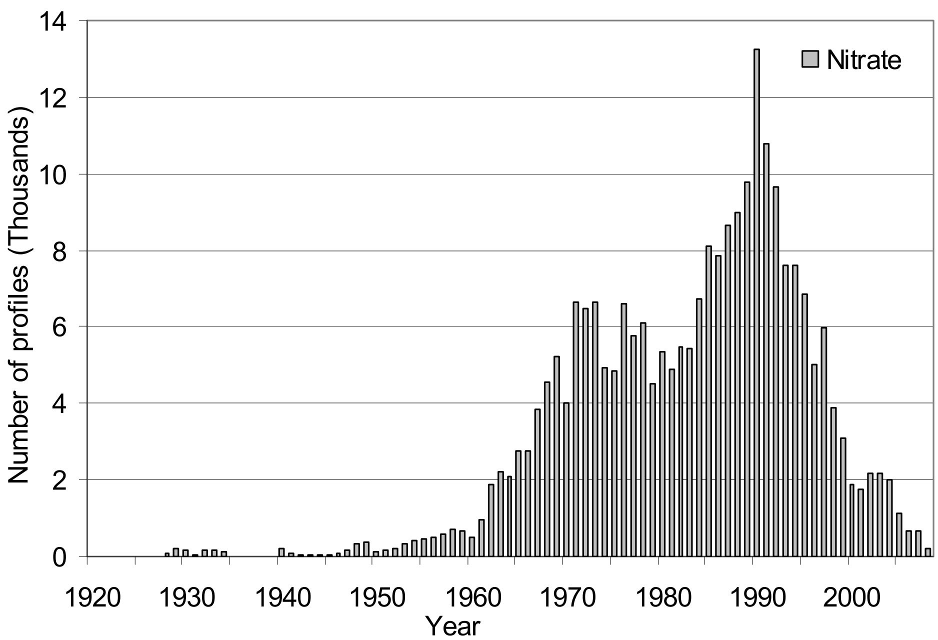

Figure 2.10. Time series of the number of Nitrate profiles in the OSD dataset. Profile count includes 21,055 profiles of Nitrate + Nitrite (N+N) minus 2,053 profiles that reported both N+N and Nitrate concentrations.

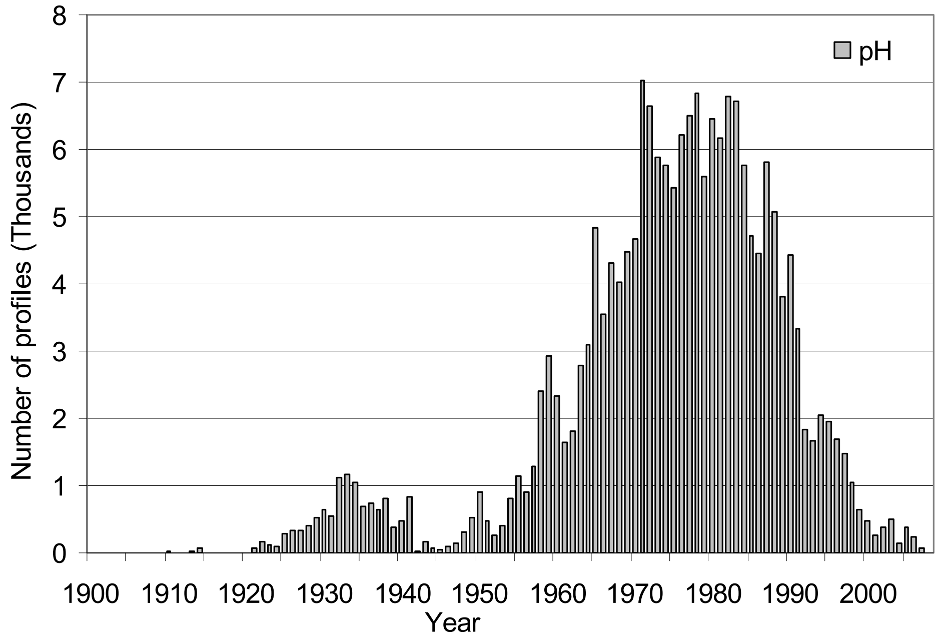

Figure 2.11. Time series of the number of pH profiles in the OSD dataset.

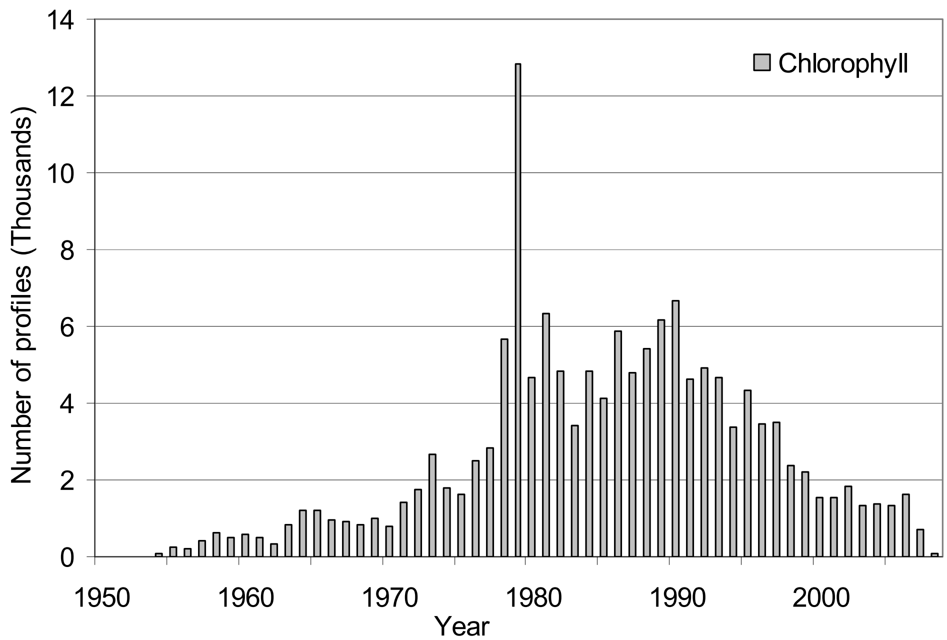

Figure 2.12. Time series of the number of Chlorophyll profiles in the OSD dataset.

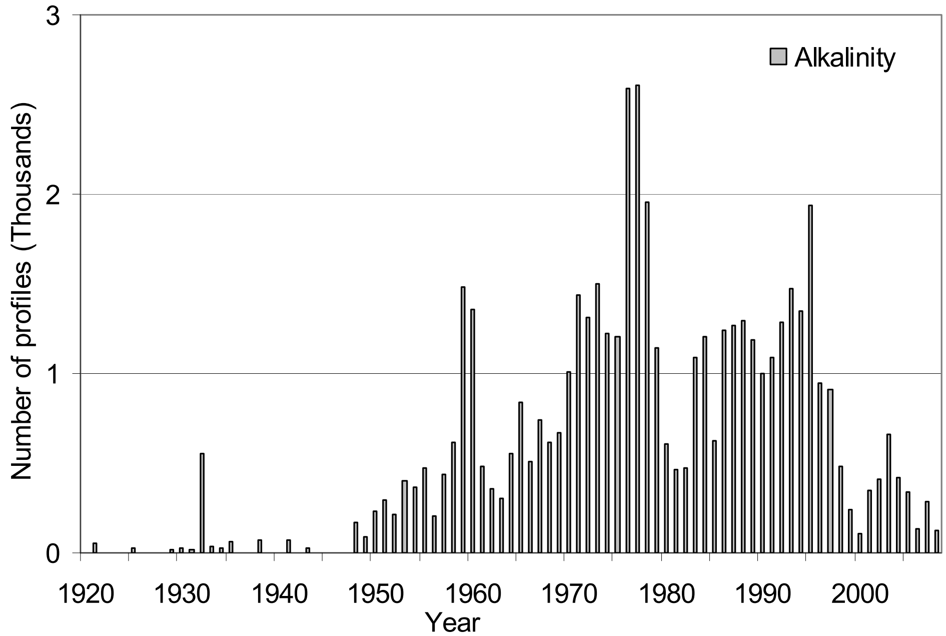

Figure 2.13. Time series of the number of alkalinity profiles in the OSD dataset.

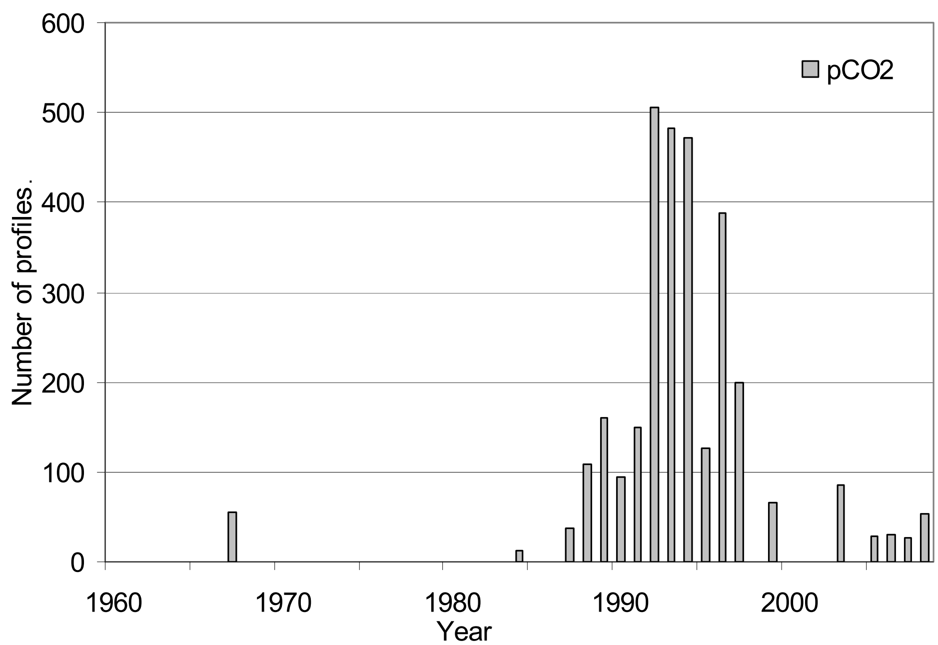

Figure 2.14. Time series of the number of partial pressure of carbon dioxide profiles in the OSD dataset.

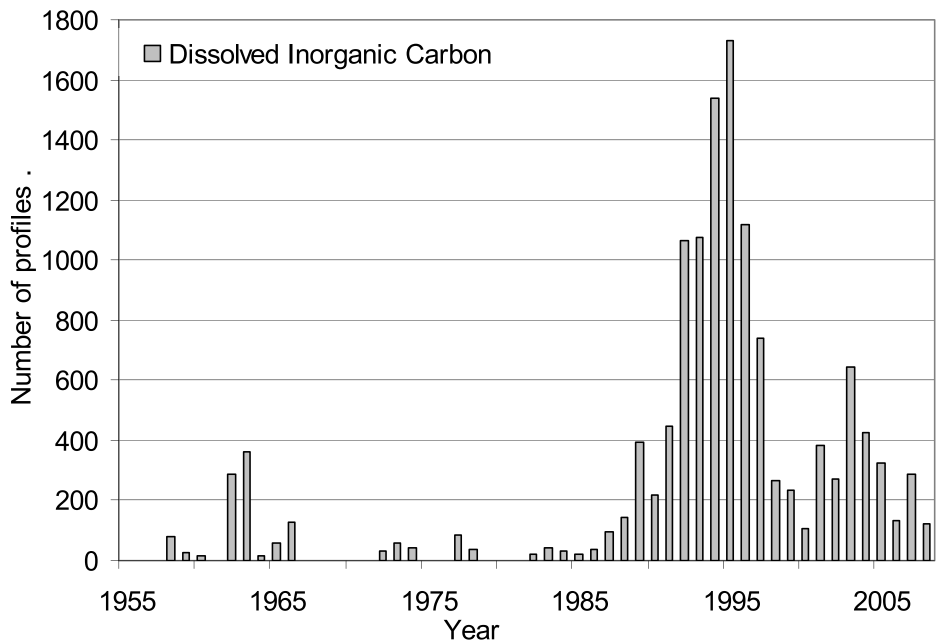

Figure 2.15. Time series of the number of dissolved inorganic carbon profiles in the OSD dataset.

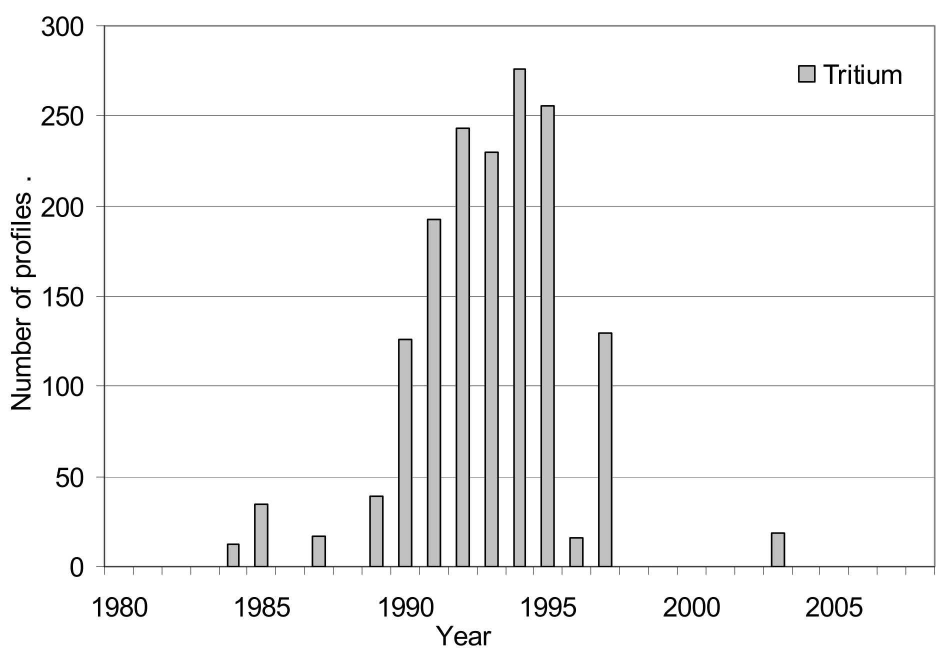

Figure 2.16. Time series of the number of tritium profiles in the OSD dataset.

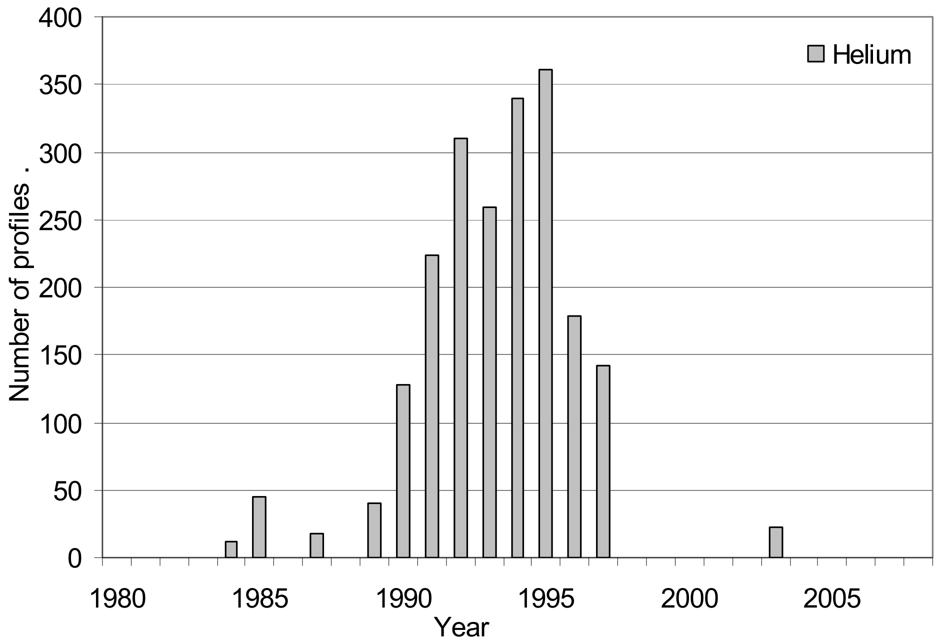

Figure 2.17. Time series of the number of helium profiles in the OSD dataset.

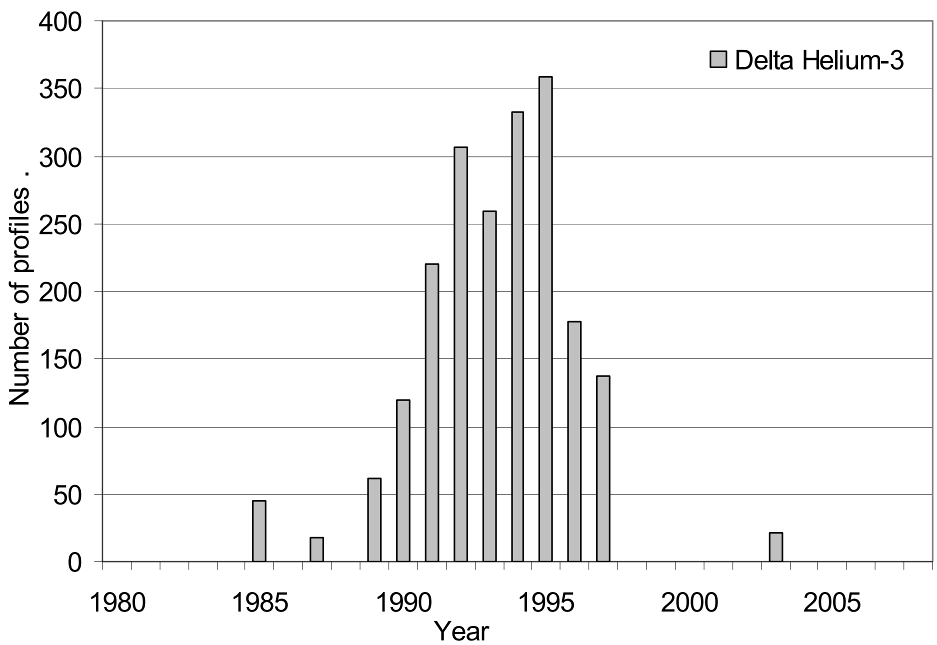

Figure 2.18. Time series of the number of delta-helium-3 profiles in the OSD dataset.

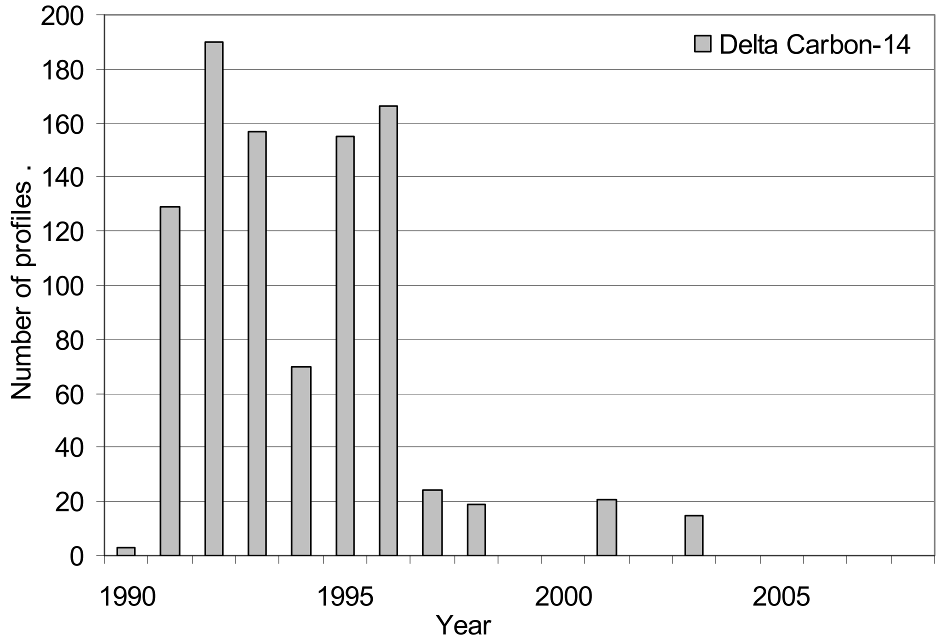

Figure 2.19. Time series of the number of delta-carbon-14 profiles in the OSD dataset.

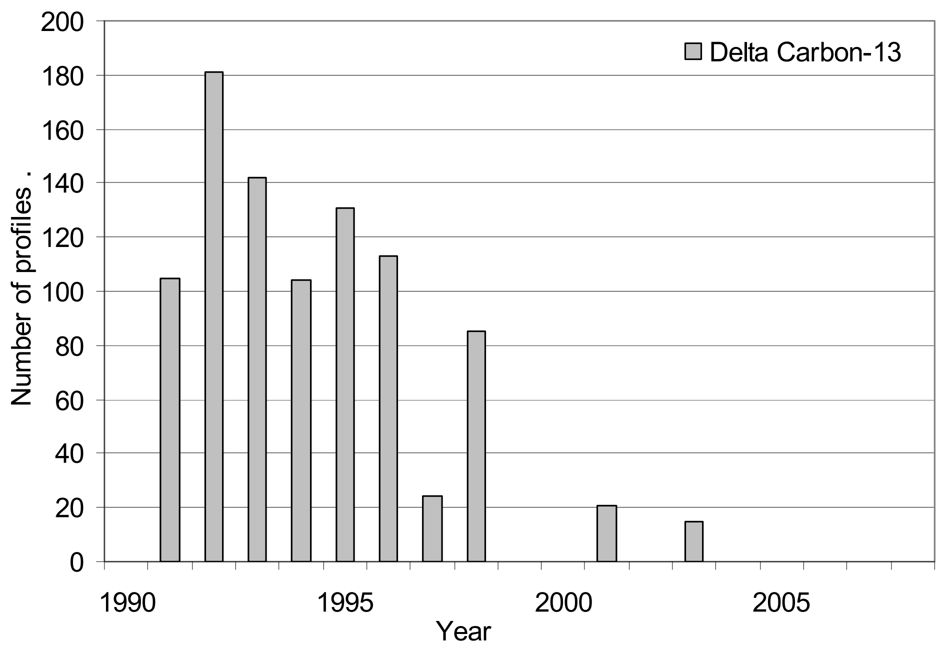

Figure 2.20. Time series of the number of delta-carbon-13 profiles in the OSD dataset.

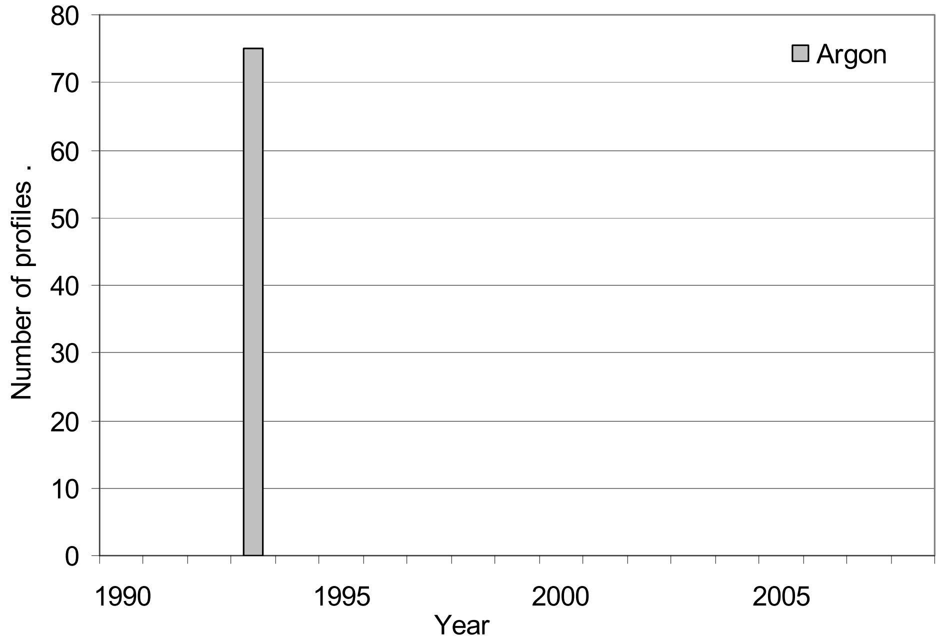

Figure 2.21. Time series of the number of argon profiles in the OSD dataset.

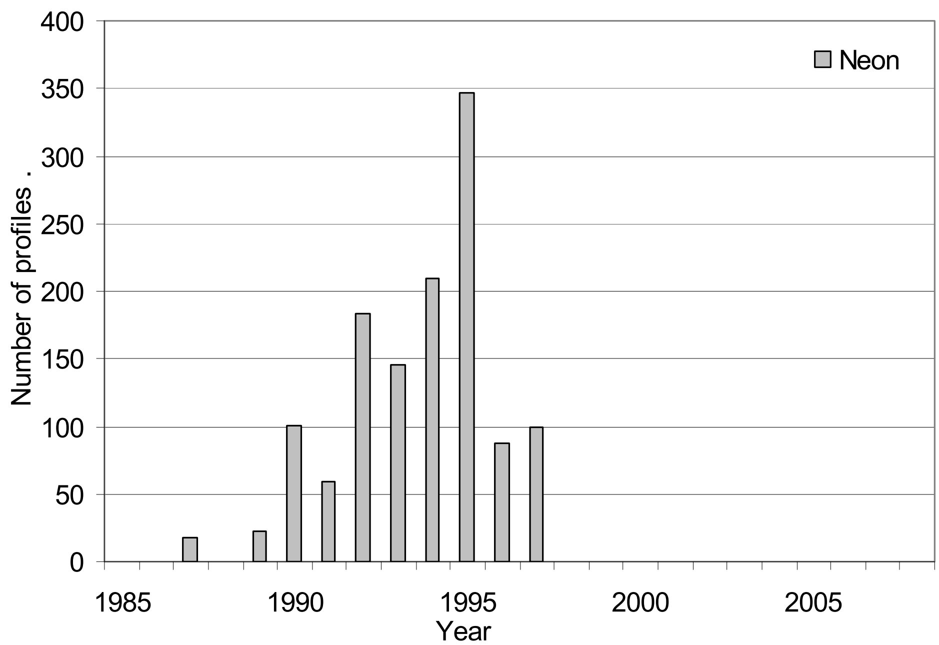

Figure 2.22. Time series of the number of neon profiles in the OSD dataset.

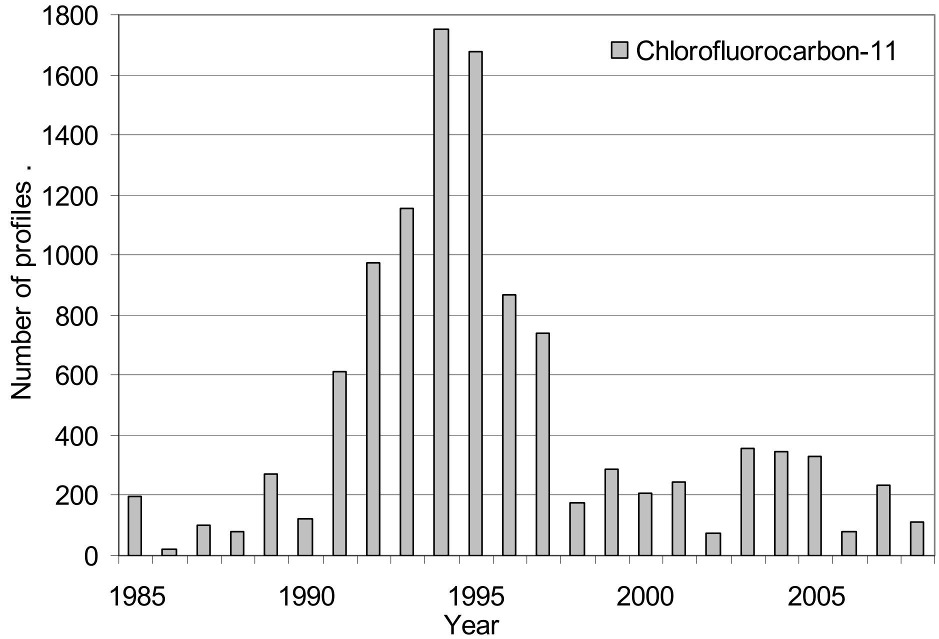

Figure 2.23. Time series of the number of chlorofluorocarbon 11 profiles in the OSD dataset.

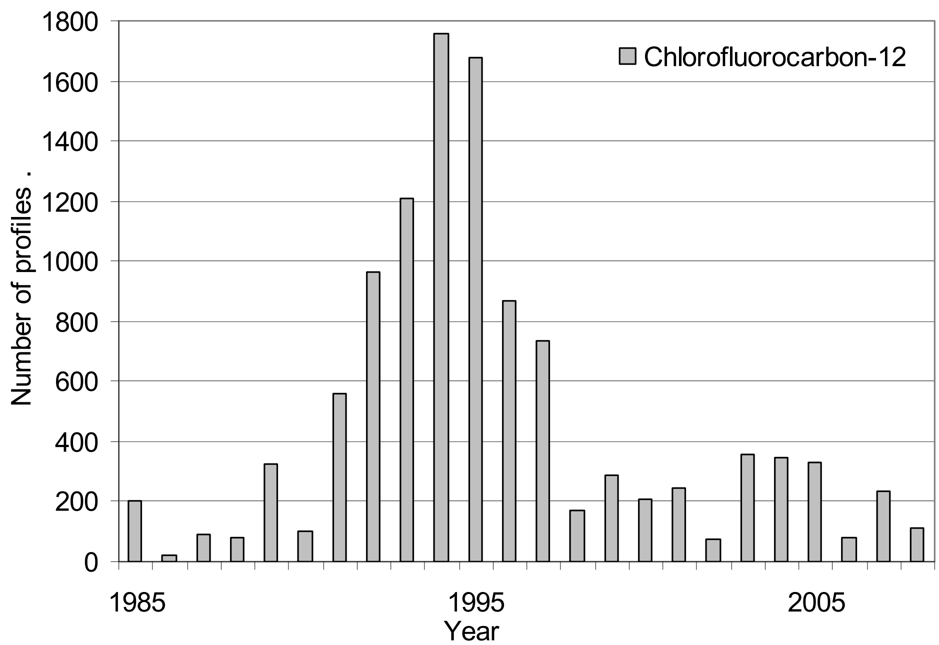

Figure 2.24. Time series of the number of chlorofluorocarbon 12 profiles in the OSD dataset.

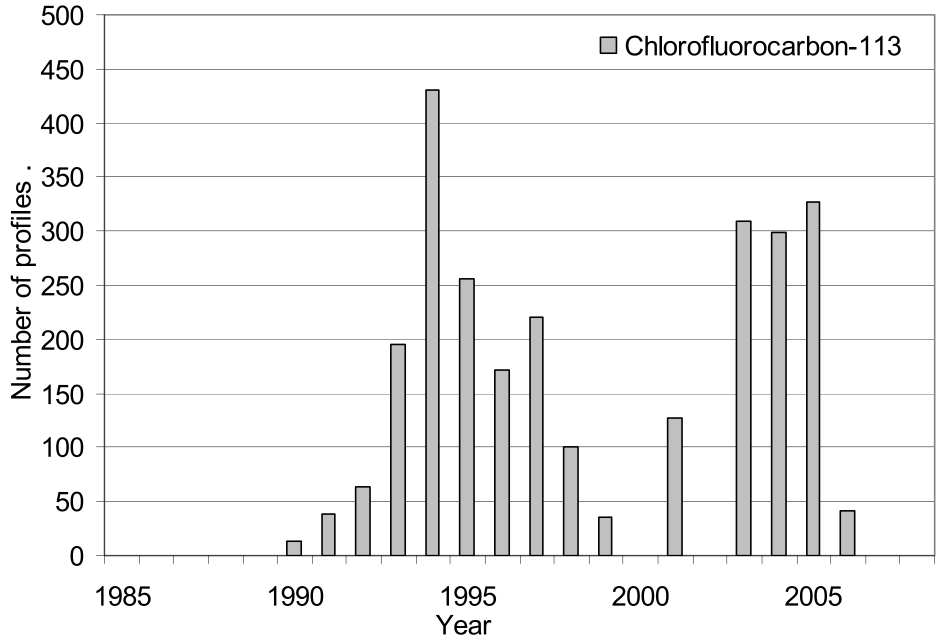

Figure 2.25. Time series of the number of chlorofluorocarbon 113 profiles in the OSD dataset.

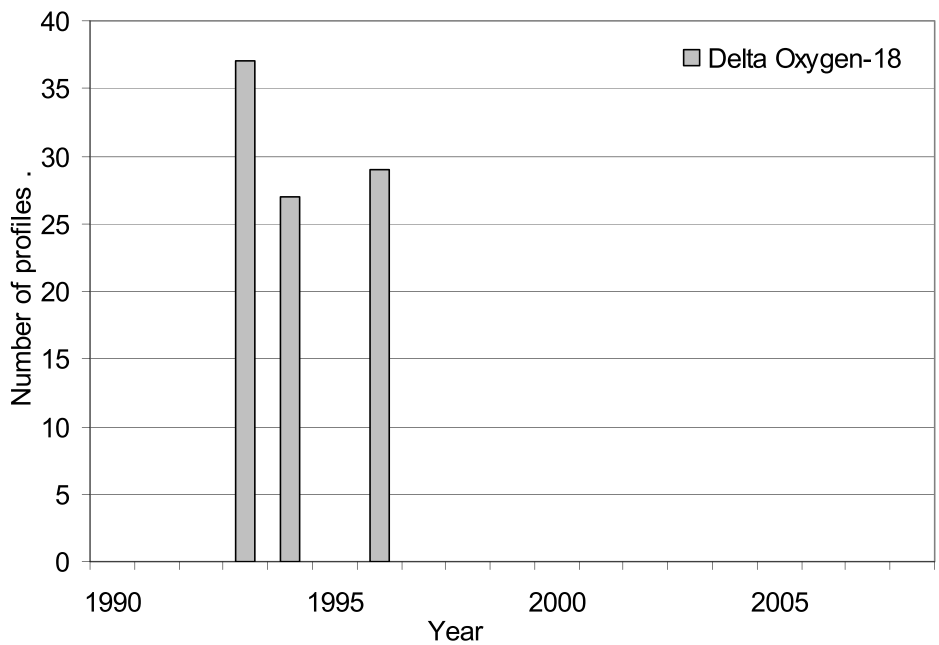

Figure 2.26. Time series of the number of delta-oxygen-18 profiles in the OSD dataset.

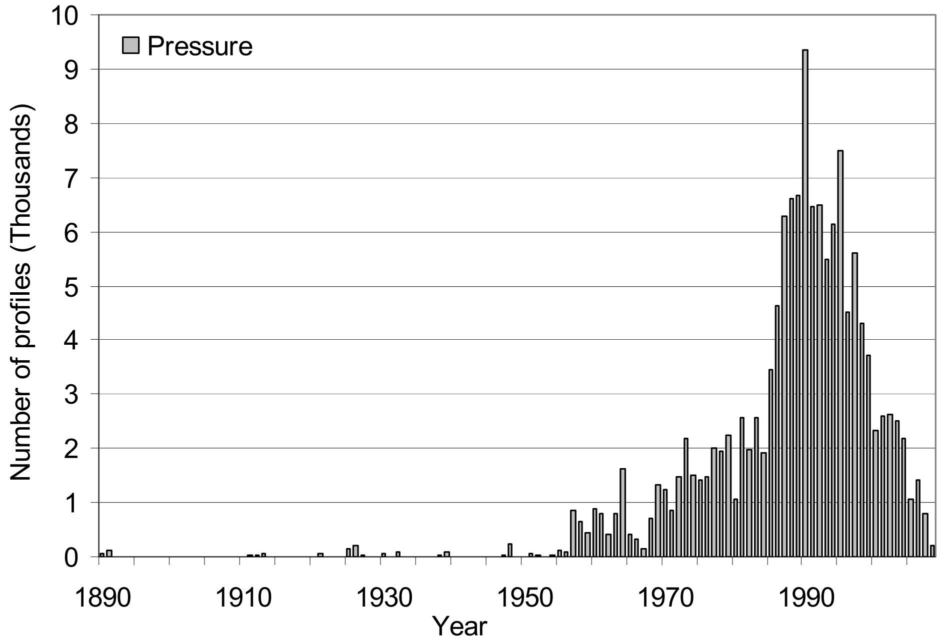

Figure 2.27. Time series of the number of profiles with pressure as a measured parameter in the OSD dataset.

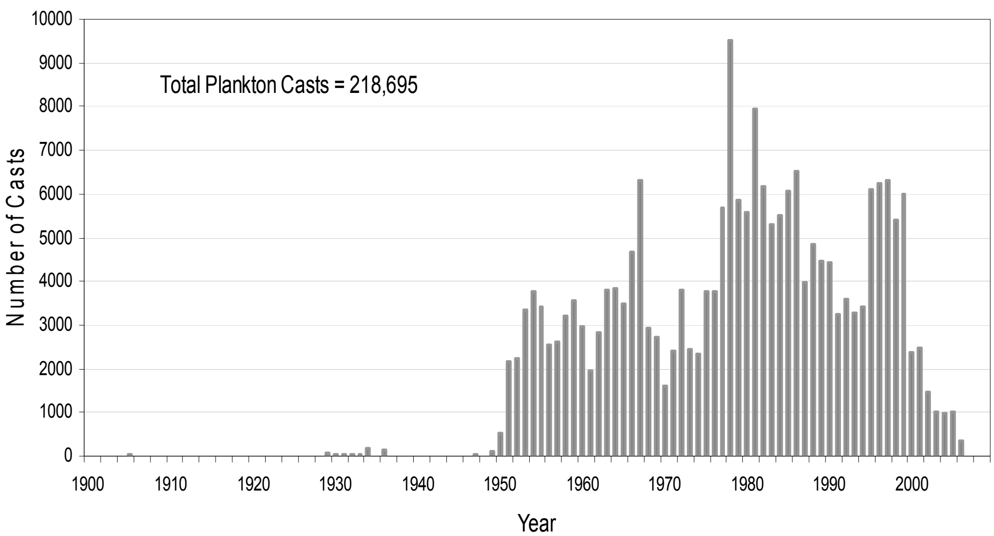

Figure 2.28. Time series of the number of plankton casts in the OSD dataset.

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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. CTDs measure pressure which is converted to depth.

Fundamental physical relationships between key water parameters and some constituents (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 speed of 1 $m \cdot s^{-1}$ and typical range of response time of temperature sensors can provide the vertical profiling at resolution 0.05 m to 0.3 m. In the past, electronic storage limitations allowed only selected levels of CTD record submitted to NODC/WDC to be stored in CTD database. Now CTD data that are submitted to at "sub-meter" vertical resolution are being archived at this resolution.

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) measurement from transmissometers discussed in Section 3.4.

CTD instrument 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 is submitted to NODC/WDC as 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 CTD dataset.

Table 3.1. List of all variables and profile counts in the WOD09 CTD dataset.

Variables	Profiles
Temperature	640,756
Salinity	628,119
Oxygen	85,767
Chlorophyll	36,707
Transmissivity	13,017
Pressure	430,635

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), 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 depends not only on the accuracy of CTD sensors. Other factors such as the difference in response time of temperature and conductivity sensors, varying speed 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).

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.

Table 3.2. The number of CTD casts in WOD09 as a function of year. The total number of casts = 641,845, including 5,985 HR XCTD casts

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1961	97	1973	5,225	1985	14,475	1997	26,871
1962	42	1974	7,573	1986	16,912	1998	25,048
1963	71	1975	7,635	1987	23,559	1999	25,391
1964	47	1976	8,770	1988	18,636	2000	22,239
1965	0	1977	9,058	1989	21,114	2001	21,703
1966	12	1978	17,575	1990	20,779	2002	18,991
1967	1,531	1979	10,793	1991	26,617	2003	14,914
1968	729	1980	9,897	1992	29,482	2004	12,487
1969	2,851	1981	12,691	1993	30,192	2005	15,851
1970	1,145	1982	10,595	1994	27,331	2006	14,842
1971	1,351	1983	12,269	1995	28,198	2007	14,490
1972	3,578	1984	13,186	1996	21,616	2008	12,297

There are a total of 641,845 CTD casts for the entire World Ocean. Table 3.3 gives the national contribution of CTD casts. The geographic distribution of CTD casts for World Ocean is shown on Figure 3.2. Distribution of the CTD observations on observed depth levels is shown on Figure 3.3. The CTD dataset contains data from 5,985 high-resolution (HR) XCTD casts (see chapter 5).

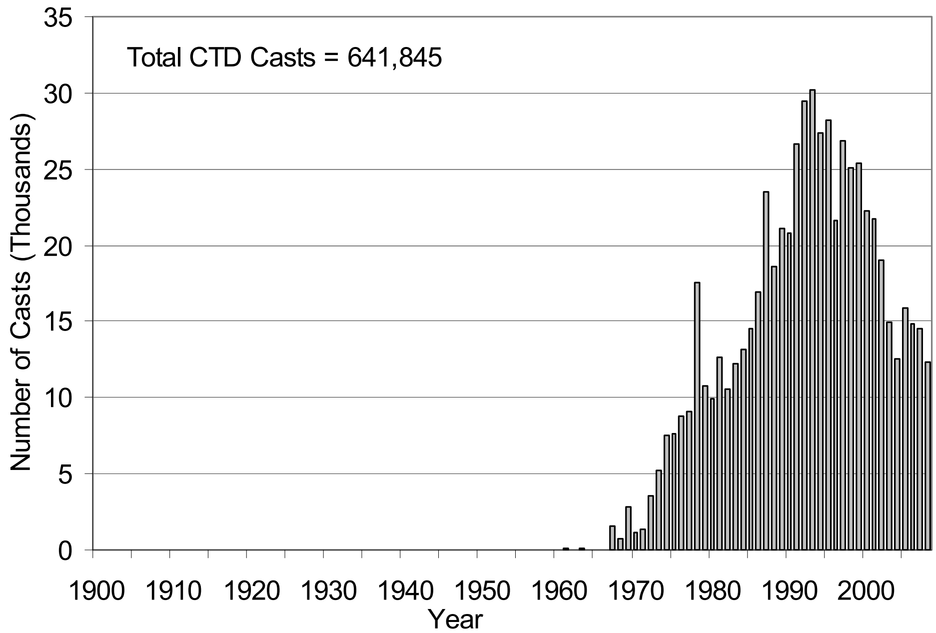

Figure 3.1. Temporal distribution of high-resolution CTD casts in WOD09 (including 5,985 HR XCTD casts).

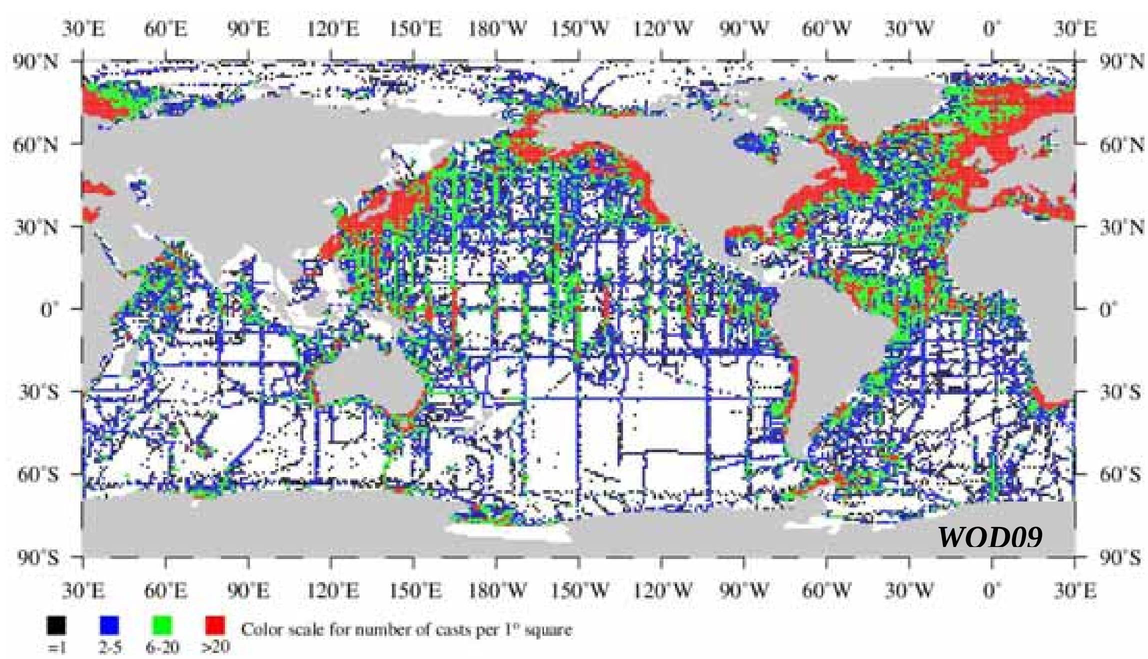

Figure 3.2. Geographic distribution of high-resolution CTD casts in WOD09 by one-degree squares (including 5,985 HR XCTD casts).

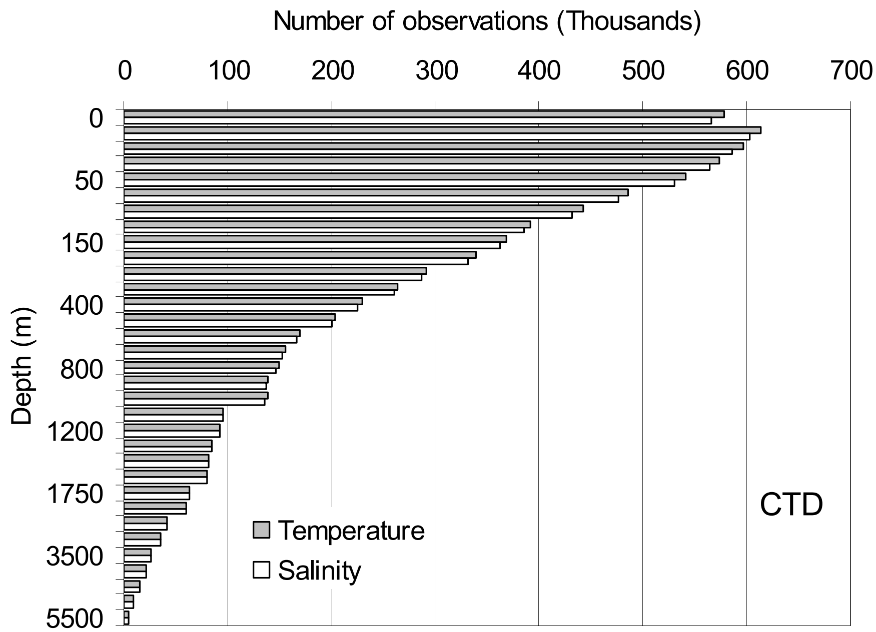

Figure 3.3. Distribution of high-resolution CTD data at observed depth levels in WOD09 (including 5,985 HR XCTD casts).

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Table 3.3. National contributions of high-resolution Conductivity / Temperature / Depth (CTD) casts.

ISO[a] Country Codes	Country Name	CTD Casts	% of Total
US	United States	172,396	26.86
CA	Canada	131,810	20.54
NO	Norway	66,274	10.33
DE	Germany	38,664	6.02
JP	Japan	37,197	5.80
FR	France	32,443	5.05
GB	Great Britain	28,006	4.36
TW	Taiwan	23,744	3.70
SU	Union of Soviet Socialist Republics	20,111	3.13
AU	Australia	13,678	2.13
IT	Italy	12,792	1.99
UA	Ukraine	9,443	1.47
99	Unknown / International	8,197	1.28
ZA	South Africa	6,357	0.99
ES	Spain	6,341	0.99
CL	Chile	6,067	0.95
DK	Denmark	3,370	0.53
CN	China	2,772	0.43
TR	Turkey	2,705	0.42
RU	Russia	2,569	0.40
NL	Netherlands	1,985	0.31
IS	Iceland	1,932	0.30
GR	Greece	1,837	0.29
PL	Poland	1,546	0.24
AR	Argentina	1,343	0.21
PT	Portugal	1,289	0.20
BR	Brazil	1,256	0.20
IL	Israel	914	0.14
DU	East Germany	824	0.13
IN	India	573	0.09
ZZ	Miscellaneous Organization	564	0.09
VE	Venezuela	389	0.06
KR	Korea; Republic Of	363	0.06
PA	Panama	290	0.05
FI	Finland	254	0.04
CY	Cyprus	235	0.04
EC	Ecuador	217	0.03
ID	Indonesia	213	0.03
BE	Belgium	212	0.03
SE	Sweden	113	0.02
NZ	New Zealand	102	0.02
BG	Bulgaria	90	0.01
PE	Peru	74	0.01
TN	Tunisia	73	0.01
EG	Egypt	69	0.01
MX	Mexico	59	0.01

ISO[a] Country Codes	Country Name	CTD Casts	% of Total
LB	Lebanon	42	0.01
RO	Romania	27	< 0.01
DZ	Algeria	13	< 0.01
IE	Ireland	10	< 0.01
HR	Croatia	1	< 0.01
	Total	*641,845*	*100.00*

[a] ISO = International Organization for Standardization
http://www.iso.org/iso/country_codes.htm

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 intensity 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 (http://www.wetlabs.com/iopdescript/attenintro.htm).

The majority of transmissometer data presented in WOD09 were collected using instruments operated at 660 nm (red) wavelength. Comprehensive set of optical data collected at various wavelengths can be found in The World-wide Ocean Optics Database (WOOD, http://wood.jhuapl.edu/wood/).

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 (e.*g.* 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 WOD09 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; 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 into the WOD09 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 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 WOD09 were collected during several international and U.S. national programs for the period of 1975-2007. 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 contributed beam attenuation data to WOD09. 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 in WOD09 for the World Ocean.

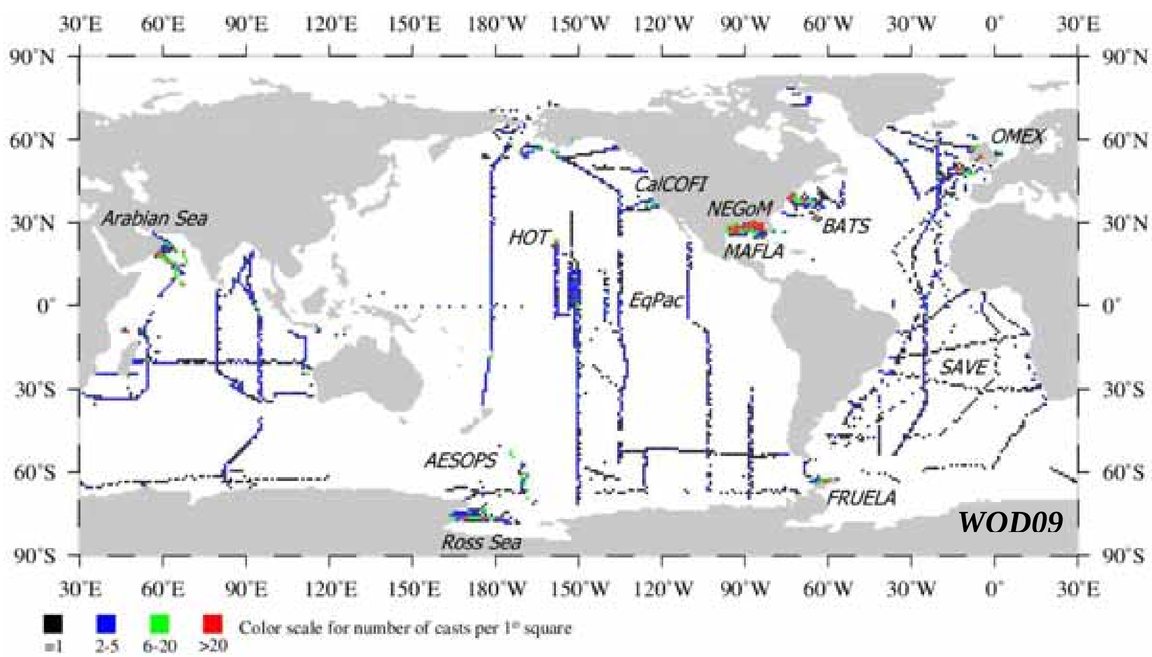

Figure 3.4.1. Geographic distribution of the BAC profiles in WOD09 by one-degree squares with major contributing projects marked.
Unmarked basin-wide lines represent WOCE and CLIVAR program data.

Table 3.4.1. Projects contributing to the WOD09 BAC data set.

NODC Project #	Project Name	# of Casts
225	World Ocean Circulation Experiment (WOCE)	2,307
65	Marine Ecosystems Analysis Project - New York Bight (MESA – NYB)	1,494
412	Mms/Northeast Gulf Of Mexico Phys Oceanographic Program (NEGOM)	894
305	Distribution/Abundance Of Marine Mammals In Northern Gulf Of Mexico (GULFCET II)	649
275	Bermuda Atlantic Time Series (BATS)	593
301	Hawaii Ocean Time-Series (HOT)	563
365	JGOFS/Arabian Sea Process Studies	464
361	Us JGOFS Antarctic Environments Southern Ocean Process Study (AESOPS)	462
70	The Mississippi, Alabama, Florida (MAFLA) Environmental Baseline Studies	387
453	The FRUELA (Name Of An 8th Century King Of Asturias) Project, Part Of The Spanish Contribution To The Study Of Biogeochemical Carbon Fluxes In The Southern Ocean	301
379	The ARABESQUE	287
78	International Decade Of Ocean Exploration / North Pacific Experiment (IDOE/NORPAX)	283
619	Atlantic Meridional Transect Program (AMT)	280
121	Southeast Area Monitoring And Assessment Program (SEAMAP)	230
373	Anatomy Of Gulf Stream Meanders (AGM)	222
372	Ocean Margin Exchange Project (OMEX)	220
216	South Atlantic Ventilation Experiment (SAVE)	202
406	Research On Ocean Atmosphere Variability & Ecosystem Response In Ross Sea	194
485	Climate Variability And Predictability (CLIVAR)	184
200	Joint Global Ocean Flux Study (JGOFS)	101
399	Plankton Reactivity In The Marine Environment (PRIME)	100
245	South East Florida And Caribbean Recruitment (SEFCar)	81
310	Equatorial Pacific Basin Study (EqPac)	80
527	U.S. Climate Variability And Predictability (US CLIVAR)	56
618	International Nusantara Stratification And Transport Program (INSTANT)	54
33	California Cooperative Oceanic and Fisheries Investigation (CalCOFI)	47
281	North Atlantic Bloom Experiment (NABE)	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	Lower Chesapeake Bay Monitoring	20
630	Meso-scale Vortices/Meanders In The Central Portion Of The Bransfield St. (BREDDIES)	7
122	Tropical Atlantic Study Of Transient Tracers In The Ocean	1
	Data with no project info	2,077
	Total:	*13,017*

Table 3.4.2 and Figure 3.4.2 present the temporal distribution of transmissometer profiles in WOD09 as a function of year. Figure 3.4.3 present distribution of the BAC observations on observed depth levels.

Table 3.4.2. The number of BAC profiles in WOD09 as a function of year. The total number of profiles = 13,017

YEAR	PROFILES	YEAR	PROFILES	YEAR	PROFILES	YEAR	PROFILES
1975	141	1984	24	1992	773	2000	201
1976	288	1985	23	1993	1,249	2001	21
1977	352	1986	45	1994	1,183	2002	0
1978	669	1987	451	1995	1,900	2003	123
1979	747	1988	405	1996	591	2004	24
1980	2	1989	414	1997	813	2005	169
1981	0	1990	250	1998	548	2006	333
1982	1	1991	388	1999	402	2007	224
1983	263						

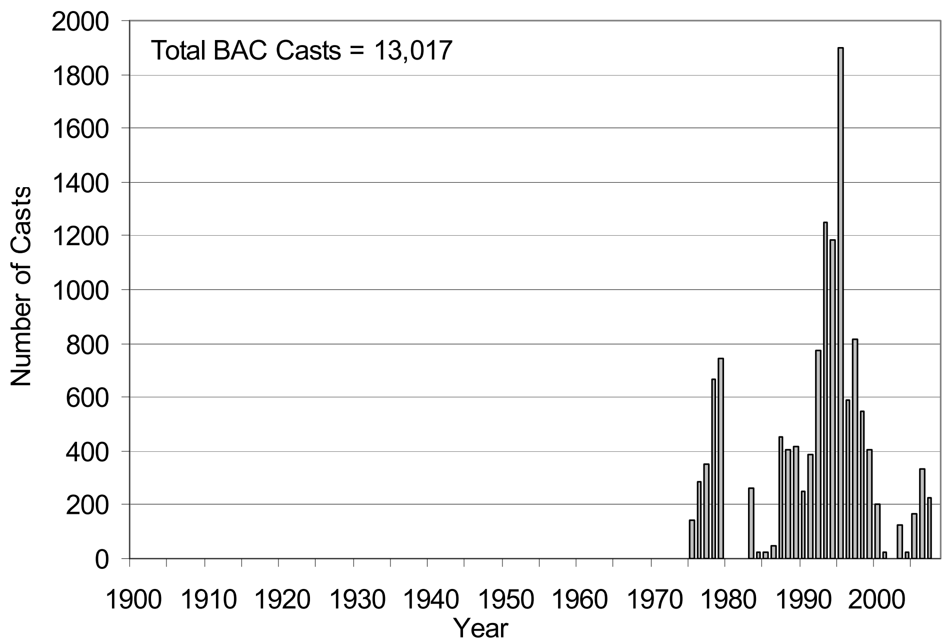

Figure 3.4.2. Temporal distribution of BAC profiles in WOD09.

3.4.3. Relevant Web Sites

Bermuda Atlantic Time Series (BATS): http://w3.bbsr.edu/cintoo/bats/bats.html.
Chelsea Technologies Group: http://www.chelsea.co.uk.
Global Transmissometer data base at Texas A&M University:
http://oceanography.tamu.edu/~pdgroup/DataDir/SMP-data.html.

Hawaiian Oceanographic Time Series (HOT):
http://hahana.soest.hawaii.edu/hot/hot_jgofs.html.
HOBILabs, Inc.: http://www.hobilabs.com.
Joint Global Ocean Flux Study (JGOFS): http://usjgofs.whoi.edu/.
Northeast Gulf of Mexico Program (NEGOM): http://seawater.tamu.edu/negom/.
The World-wide Ocean Optics Database (WOOD): http://wood.jhuapl.edu/wood/.
WetLabs, Inc.: http://www.wetlabs.com/.
World Ocean Circulation Experiment (WOCE): http://whpo.ucsd.edu/.

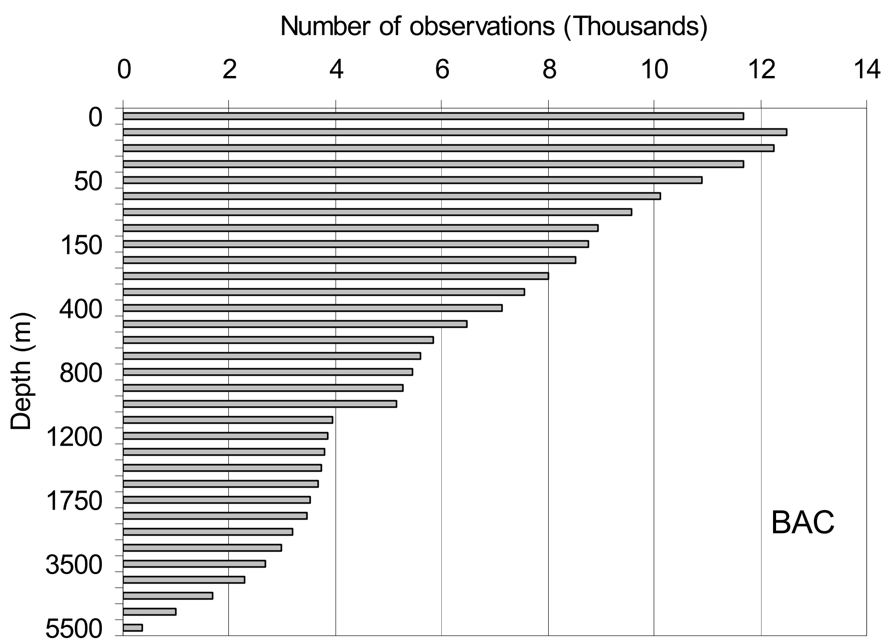

Figure 3.4.3. Distribution of BAC data at observed depth levels in WOD09.

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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 WOD09, 43.9% are known to have been obtained with probes manufactured by Lockheed Martin Sippican (formerly known as Sippican), 2.2% 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 most of the XBT profiles, or 53.7%. 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. The most popular model is the T-4, with about 23% of the XBT profiles in WOD09 known to be obtained with such a probe.

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

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

The XBT system does not directly measure depth. The depth of a temperature measurement measured 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 e*t 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 commmunication). 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).

4.4. CORRECTIONS TO XBT DEPTH-TIME EQUATION ERRORS

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 50%, or 1.06 million, of the total 2.10 million XBT temperature profiles in WOD09 have "unknown" model of XBT instrument. Of these, about 0.76 million are positively identified as coming from shipboard drops. The other 0.29 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 WOD09 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.* (2009) for more information on WOD09 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, a small number of pre-1996 data (2,945 drops) include depths that have been corrected by the originator before being submitted to NODC/WDC.

The XBT data in the WOD09 interpolated to standard levels uses the appropriate corrected depth when possible using the corrections of Levitus *et al*. (2009). Since about 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 WOD09 was 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 457,348 XBT drops during the relevant time period (1996-2008), there are 91,510 drops without depth-time equation information. Only 2% of XBT drops for years 2002-2008 lack information on the depth-time equation used, in contrast to about a third of XBT drops for years 1996-1999.

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 WOD09 ARE THE SAME DATA AS SUBMITTED BY THE ORIGINATORS. IF YOU ARE USING OBSERVED LEVEL XBT DATA FROM WOD09, PLEASE USE SECONDARY HEADER 54 TO SEE WHETHER A DEPTH CORRECTION IS NECESSARY.

THE STANDARD LEVEL XBT DATA IN WOD09 WERE PREPARED, WHEN NEEDED AND POSSIBLE, USING A CORRECTED DEPTH-TIME EQUATION AND THE XBT BIAS CORRECTION FOLLOWING LEVITUS *et al.* (2009).

XBT BIAS CORRECTIONS WERE RECALCULATED USING AN UPDATED DATA SET FOR WORLD OCEAN DATABASE 2009 AND WORLD OCEAN ATLAS 2009. NOTE THAT VALUES FOR YEAR 2007 WERE ALSO USED FOR 2008 DUE TO LACK OF XBT/CTD PAIRS IN 2008 FROM CURRENTLY AVAILABLE DATA (SEE APPENDIX 1).

IF YOU ARE USING STANDARD LEVEL XBT DATA FROM WOD09, 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.

4.6. XBT PROFILE DISTRIBUTIONS

Table 4.2 gives the yearly counts of XBT profiles for the World Ocean. Fig. 4.1 shows the time series of the yearly totals of Expendable Bathythermograph profiles for the World Ocean. There are a total of 2,104,490 XBT profiles for the entire World Ocean with 409,232 profiles (19.4%) measured in the southern hemisphere and 1,695,258 profiles (80.6%) measured in the northern hemisphere. Although 67 known countries contribute XBT data to WOD09, about 77% of the profiles are contributed by just 7 countries, as illustrated in Figure 4.4. Some country contributions merely reflect the flag of merchants ships in the Ship of Opportunity Program (SOOP), and they do not represent active national scientific programs, e.g. Liberia and Panama. 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 WOD09.
Total Number of Profiles = 2,104,490

YEAR	PROFILES	YEAR	PROFILES	YEAR	PROFILES	YEAR	PROFILES
1966	1,747	1977	54,420	1988	62,351	1999	55,625
1967	9,390	1978	53,374	1989	44,935	2000	39,838
1968	26,671	1979	56,293	1990	82,668	2001	29,194
1969	34,319	1980	55,228	1991	71,021	2002	26,105
1970	45,687	1981	54,917	1992	65,975	2003	26,267
1971	57,616	1982	56,026	1993	70,693	2004	31,104
1972	53,215	1983	58,937	1994	68,789	2005	27,834
1973	54,940	1984	56,089	1995	78,211	2006	24,755
1974	54,966	1985	68,648	1996	63,305	2007	20,501
1975	54,539	1986	75,116	1997	52,663	2008	10,311
1976	48,568	1987	71,793	1998	49,846		

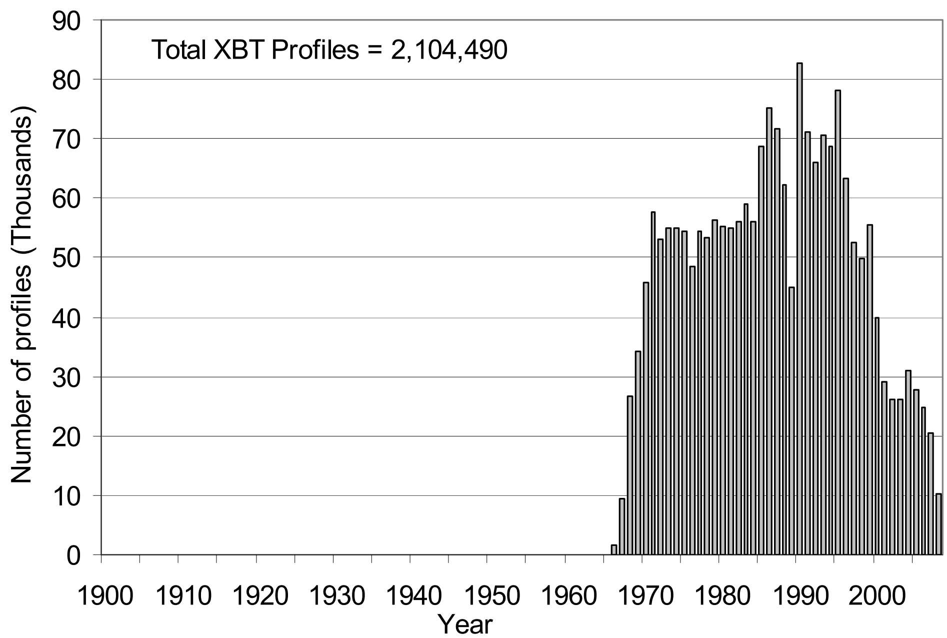

Figure 4.1. Temporal distribution of Expendable Bathythermograph (XBT) profiles in WOD09.

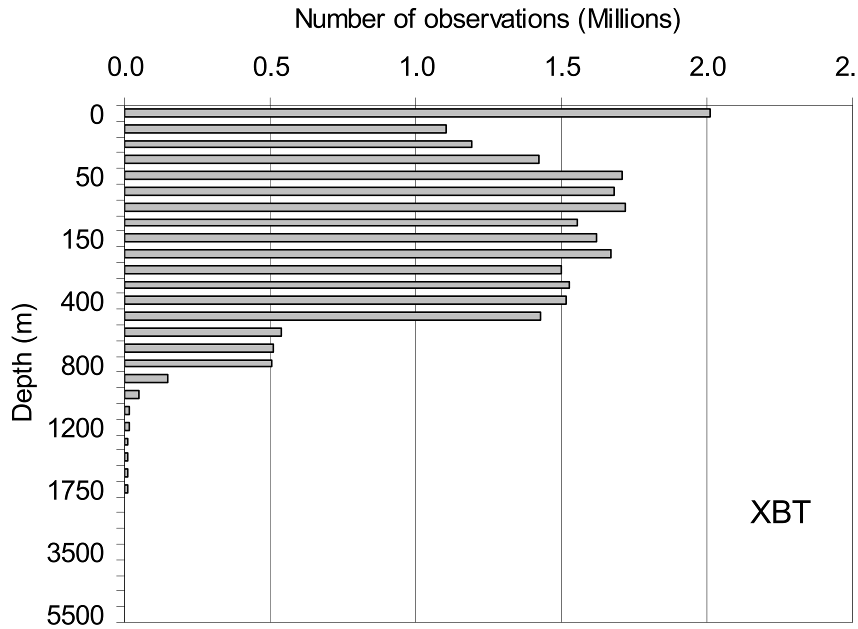

Figure 4.2. Distribution of Expendable Bathythermograph (XBT) data at observed depth levels in WOD09.

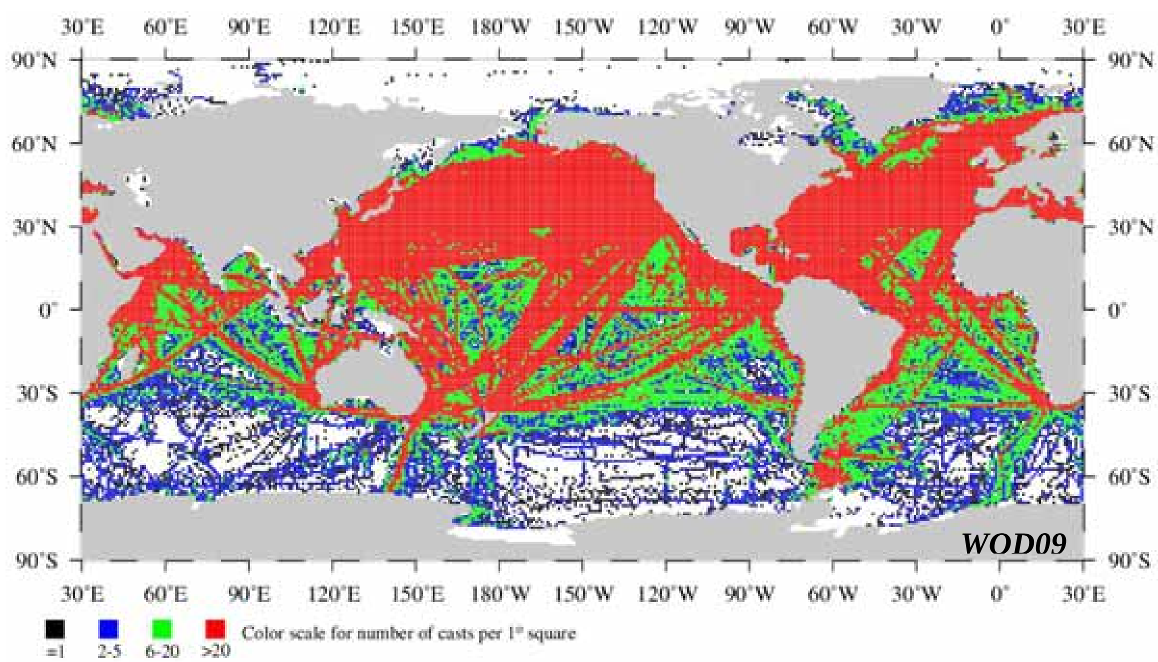

Figure 4.3. Geographic distribution of XBT profiles in WOD09 by one-degree squares.

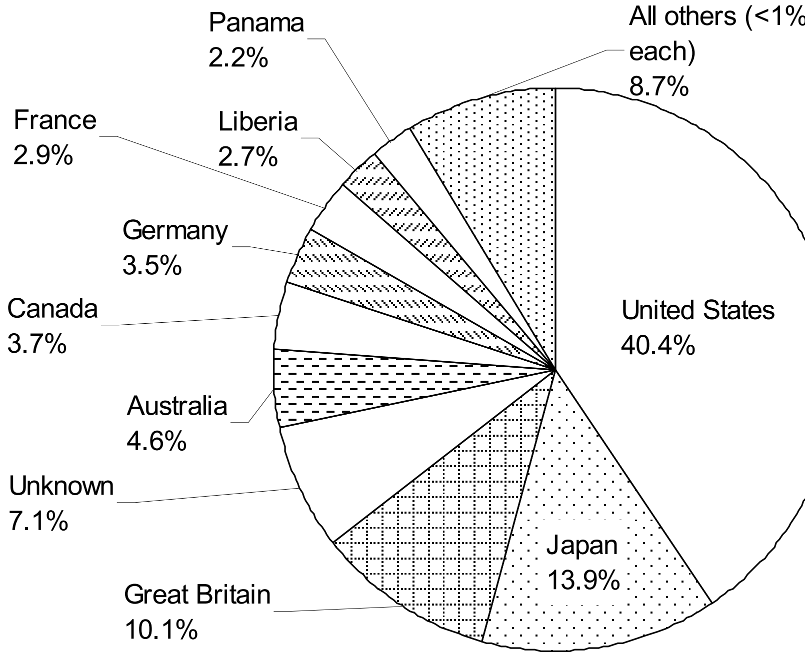

Figure 4.4. XBT data contribution by countries in WOD09.

Table 4.3. National contribution of XBT profiles in WOD09.

ISO[a] Country Code	Country Name	XBT Casts	% of Total
US	United States	851,184	40.45
JP	Japan	291,530	13.85
GB	Great Britain	213,130	10.13
99	Unknown	150,456	7.15
AU	Australia	96,677	4.59
CA	Canada	77,728	3.69
DE	Germany	73,242	3.48
FR	France	61,559	2.93
LR	Liberia	57,830	2.75
PA	Panama	47,215	2.24
SG	Singapore	19,005	0.90
NL	Netherlands	15,801	0.75
SU	Union of Soviet Socialist Republics	14,093	0.67
BS	Bahamas	12,511	0.59
DK	Denmark	11,420	0.54
AG	Antigua	11,169	0.53
ZA	South Africa	9,424	0.45
NO	Norway	7,908	0.38
NZ	New Zealand	6,298	0.30
VC	St. Vincent and Grenadines	5,993	0.28
CY	Cyprus	5,268	0.25
CN	China	5,166	0.25
IS	Iceland	4,574	0.22
SE	Sweden	4,552	0.22
BR	Brazil	4,437	0.21
BB	Barbados	4,381	0.21
HK	Hong Kong	4,309	0.20
ES	Spain	3,019	0.14
TO	Tonga	2,985	0.14
IT	Italy	2,605	0.12
WS	Western Samoa	2,475	0.12
CL	Chile	2,438	0.12
PH	Philippines	2,302	0.11
AR	Argentina	2,250	0.11
MX	Mexico	2,235	0.11
IN	India	1,895	0.09
KW	Kuwait	1,876	0.09
MT	Malta	1,452	0.07
GR	Greece	1,393	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
MH	Marshall Islands	949	0.05
FJ	Fuji	866	0.04
YU	Yugoslavia	797	0.04
PT	Portugal	732	0.03
PE	Peru	714	0.03
EC	Ecuador	492	0.02
MY	Malaysia	460	0.02
BE	Belgium	456	0.02
TR	Turkey	308	0.01
SA	Saudi Arabia	197	<0.01
ZZ	Miscellaneous Organization	195	<0.01
TH	Thailand	178	<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
FI	Finland	60	<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	12	<0.01
SC	Seychelles	11	<0.01
TT	Trinidad and Tobago	6	<0.01
RU	Russian Federation	1	<0.01
	Total:	*2,104,490*	*100.00*

[a] ISO = International Organization for Standardization
http://www.iso.org/iso/country_codes.htm

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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) profiler is an ocean profiling instrument that usually consists 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.ifremer.fr/ird/soopip/xctd_probes.html). XCTDs can be launched from ships, submarines, and airborne platforms.

The XCTD is a free-falling probe that is connected to the acquisition system through a thin insulated conductive wire transmitting the temperature and conductivity data back to the acquisition system in real time. Processed profile data can also be transmitted in real-time via satellite (*e.g.* INMARSAT). Depth is estimated using a fall-rate equation from the elapsed time between when the probe enters the water and the time each temperature-conductivity measurement is made. As a rule, a vendor supplied fall-rate equation is utilized. Profiles can be made as deep as 1500m with data points at every meter, or even more frequently. With a 4Hz sample rate and roughly 3.2 $m \cdot s^{-1}$ fall velocity, XCTD data are recorded every 0.8m (Johnson, 1995). Most recent probes, however, are able to sample every 40ms, which is approximately a 14 cm interval in depth (Mizuno and Watanabe, 1998).

The earliest XCTD data included in WOD09 were collected in 1993, and comprise 15 casts launched from the U.S. nuclear submarine *Pargo* on her first civilian oceanographic cruise in the Arctic Ocean (Morison *et al.,* 1998) within the framework of the Scientific Ice Expeditions Program (SCICEX). In total, 784 casts collected during SCICEX are included in WOD09.

Over the years, XCTD data were submitted to WOD09 in both high and low vertical resolution formats; therefore, these data are stored in two WOD09 datasets: high resolution data resides in the CTD dataset (5,985 XCTD casts), whereas low resolution data resides in the OSD dataset (1,489 XCTD casts).

5.2. XCTD PRECISION AND ACCURACY

The accuracy of XCTD data depends on the probe used and is usually ±0.02°C for temperature, ±0.03 $\mu S \cdot cm^{-1}$ for conductivity, and 2% for depth. System response time is 40 ms for conductivity and 100 ms 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 reported by Mizuno and Watanabe (1998).

Despite the fact that the XCTD instrument has been in use for some time now, some problems with data accuracy remain. An early comparison, performed by Hallock and Teague (1990), of XCTD data with CTD data concluded, "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 $\mu S \cdot cm^{-1}$ 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 XCTD profiles, both in temperature (Gille *et al*. 2009) and salinity (Yuan *et al*. 2004), required additional data treatment. Nevertheless, XCTDs can 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 a 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—the time between the moments of the probe entering the water and the end of transmission of the signal—by using a fall-rate equation. It must be noted that a straightforward use of some coefficients in a fall-rate equation may pose some problems. Johnson (1995) shows that the manufacturer-supplied fall-rate coefficients give a too slow 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 WOD09 while computing temperature and salinity values at standard depth levels. For that purpose elapsed time was recalculated from the depth values and then two different manufacturer-dependant depth equations were used for adjusted depth calculation.

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

$t = (s_1 \cdot d_x + s_2) - s_3,$

$$d_z = s_a \cdot t + s_b \cdot t^2,$$

where: $s_1 = 0.30731408$, $s_2 = 6.707 \cdot 10^{-9}$, $s_3 = -8.1899 \cdot 10^{-5}$;

$s_a = 3.227$, $s_b = -2.17 \cdot 10^{-4}$;

t – time since drop (seconds);

d_x – originally calculated depth (meters);

d_z – new calculated depth (meters).

For data collected by TSK instruments the 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:

$$t = (t_1 \cdot d_x + t_2) - t_3,$$

$$d_z = t_a \cdot t + t_b \cdot t^2,$$

where: $t_1 = 0.29585798$, $t_2 = 1.002 \cdot 10^{-9}$,

$t_3 = -3.1658 \cdot 10^{-5}$; $t_a = 3.426$,

$t_b = -4.70 \cdot 10^{-4}$;

t – time since drop (seconds);

d_x – originally calculated depth (meters);

d_z – 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 7,474 XCTD profiles for the entire World Ocean (5,985 in CTD and 1,489 in OSD) in WOD09.

Table 5.1. The number of XCTD casts in WOD09 as a function of year CTD/OSD[(1)]. Total Number of casts = 7,474.

YEAR	CAST	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1993	15	1997	131	2001	327/561	2005	818
1994	0	1998	166/118	2002	573	2006	998
1995	114	1999	309/214	2003	343	2007	463
1996	104	2000	439/596	2004	394	2008	791

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

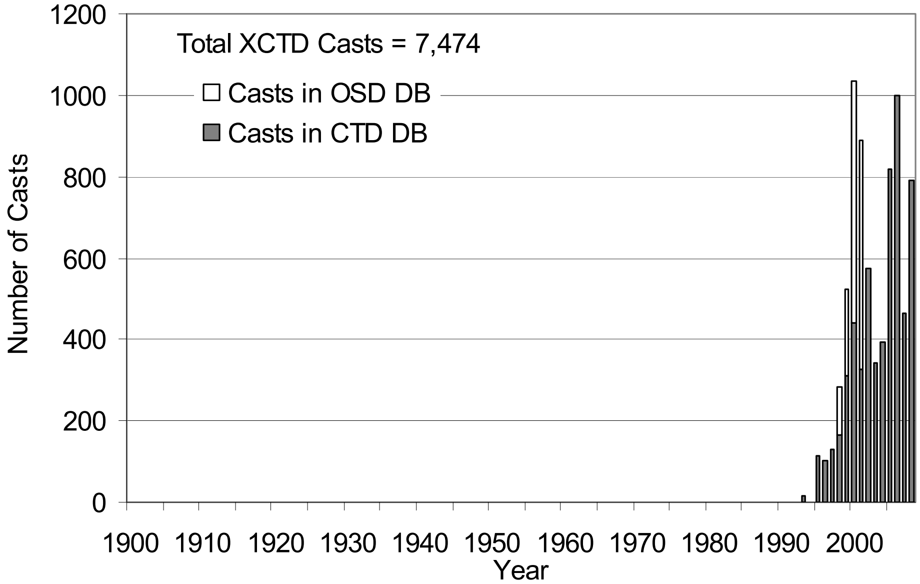

Figure 5.1. Temporal distribution of XCTD casts in WOD09.

Table 5.2 gives national contributions of XCTD data to WOD09. The geographic distribution of XCTD casts is shown on Figure 5.2.

Table 5.2. National contributions of XCTD casts in WOD09.

CTD/OSD[(1)]. Total Number of casts = 7,474.

ISO[a] Country Code	Country Name	XCTD Casts	% of Total
JP	Japan	4,222 / 446	62.46
US	United States	1,139 / 322	19.55
99	Unknown / International	24 / 721	9.97
PA	Panama	290 / 0	3.88
FR	France	239 / 0	3.20
CN	China	71 / 0	0.95
	Total: 7,474	*5,985 / 1,489*	*100.00*

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

[a] ISO = International Organization for Standardization
http://www.iso.org/iso/country_codes.htm

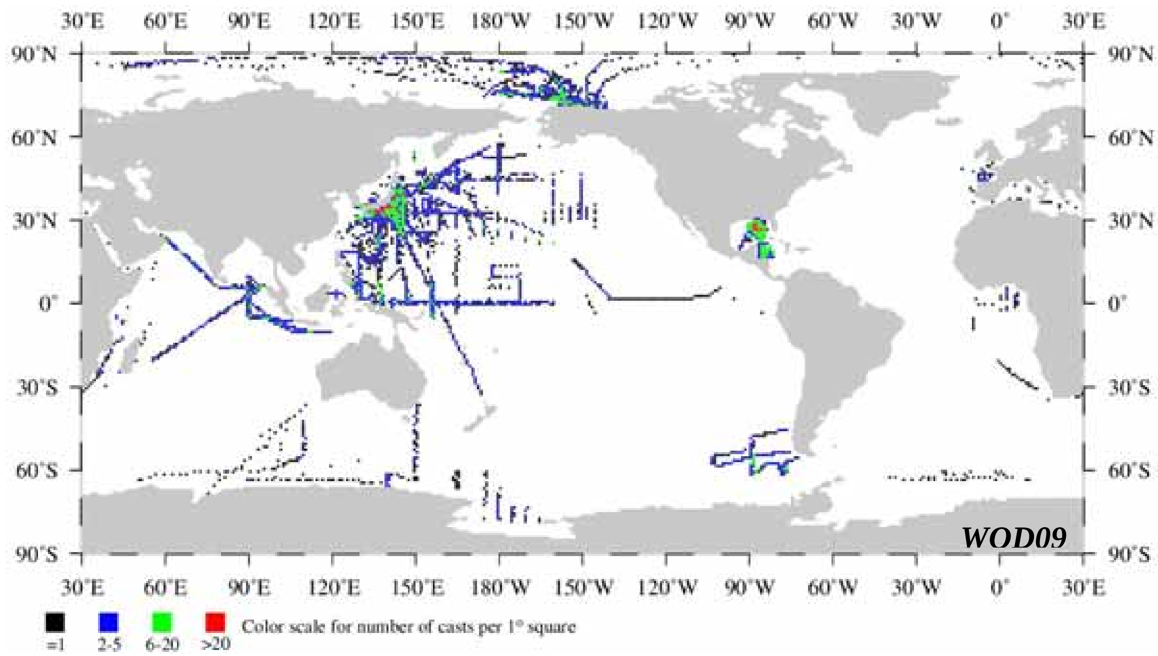

Figure 5.2. Geographic distribution of XCTD casts in WOD09 by one-degree squares.

While the majority of XCTD casts (4,588) have no information about the data-collecting organizations, a significant amount of XCTD data were collected and submitted by four institutions: Ocean Research Department of Japan Marine Science and Technology Center (JAMSTEC, 1,376 casts), Arctic Submarine Laboratory (ASL US, 784 Casts), Japan Oceanographic Data Center (JODC, 447 casts), and Japan Meteorological Agency (JMA, 260 casts).

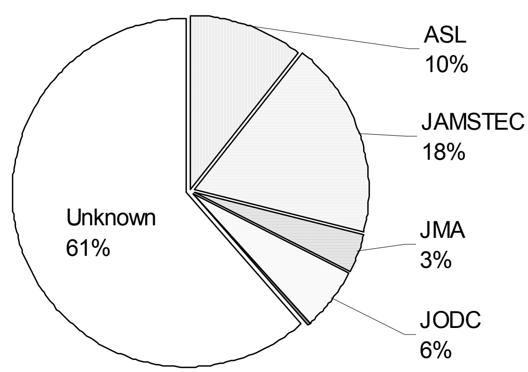

Figure 5.3. Contribution of XCTD casts from different institutions.

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

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

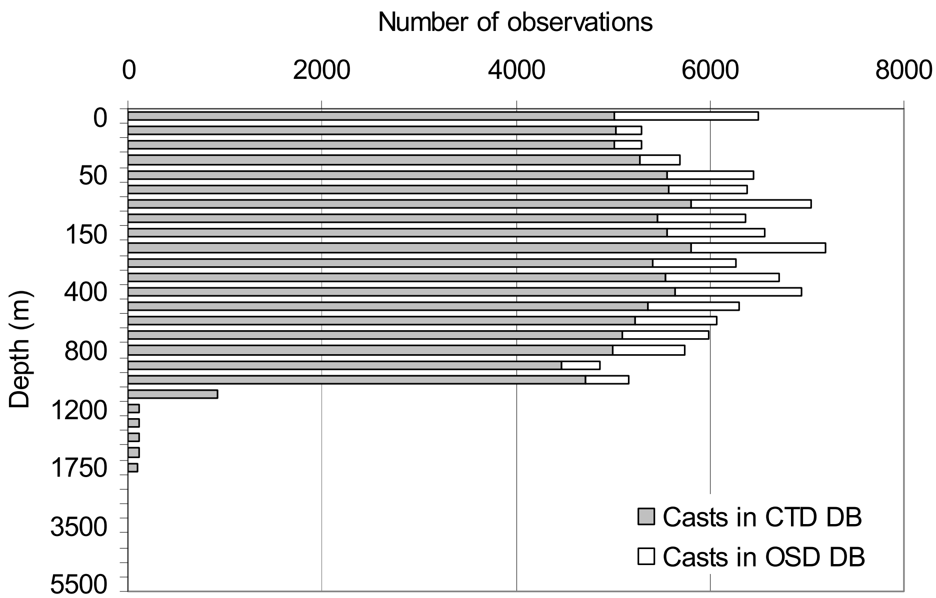

Figure 5.4. Distribution of XCTD data in WOD09 at observed depth levels.

5.5. RELEVANT WEB SITES

Arctic Submarine Laboratory (ASL): http://www.csp.navy.mil/asl/index.htm .

French Research Institute for Exploitation of the Sea (IFREMER): http://www.ifremer.fr/ird/soopip/xctd_probes.html

INMARSAT: http://www.inmarsat.com/

Japan Marine Science & Technology Center (JAMSTEC): http://www.jamstec.go.jp/jamstec-e/index-e.html.

Japan Meteorological Agency (JMA): http://www.jma.go.jp/jma/indexe.html.

Lockheed Martin Sippican, Inc.: www.sippican.com

Scientific Ice Expeditions Program (SCICEX): http://www.ldeo.columbia.edu/res/pi/SCICEX/.

Ship of Opportunity Programme (SOOP): http://www.ifremer.fr/ird/soopip/xctd_probes.html.

The Tsurumi Seiki Co., Ltd: http://www.tsk-jp.com/tska/index.html.

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, even 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 2005* (WOD09). The float's active movement is achieved by changes 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. Davis *et al*. (2001) calculate that they are equivalent in cost per profile (temperature only) to an XBT. But their value is much greater since they also measure salinity and are able to measure during any sea or weather condition (with the partial exception of ice cover). Profiling floats are adding measurements in geographic regions and seasons for which little, if any data were previously 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 geolocation. 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 geolocation 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 geolocated 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. From here it was a logical step to introduce oceanographic sensors onto the ALACE float to record temperature and salinity during the floats ascent to the surface. In 1991, the first temperature sensors were deployed on ALACE floats, making them Profiling ALACE floats (P-ALACE floats), and in 1994 both temperature and salinity sensors were deployed together (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. Since 1999, deployment has also taken place from C130 Aircraft by the U.S. Naval Oceanographic Office (NAVOCEANO). 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. The MARVOR float was created by the Institut Francais de REcherche de la MER (IFREMER) and Teklec (now Martec), a French engineering firm, within the framework of the WOCE program. MARVOR floats use the same geo-location principle as RAFOS floats, but they also cycle to the surface to send data to ARGOS satellites. 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). MARVOR floats have been deployed since 1994, PROVOR floats since 1997. Both Martec and Metocean (Canada) now produce PROVOR floats on the same design. MARVOR/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 WOD09.

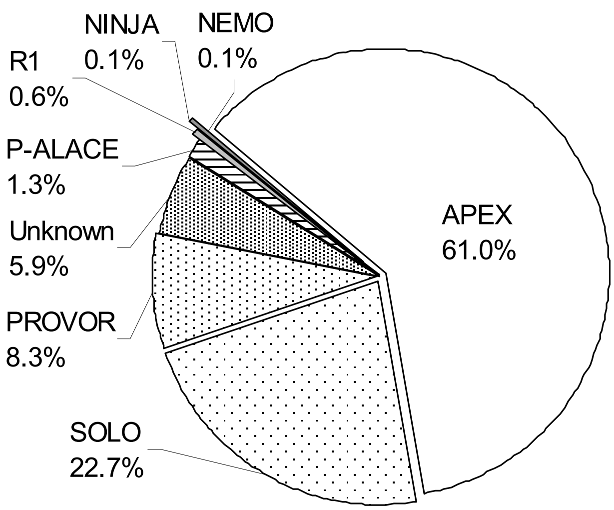

Figure 6.1. Casts from different types of profiling floats.

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 altimeter measuring sea surface heights and the Argo floats revealing the subsurface structure, evoking Jason and his ship the Argo from Greek mythology (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. Most float data is captured from the ARGOS 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 3,301 floats deployed as of September, 2009. 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.

The profiling float data in WOD09 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 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 (Total 168,988 casts as of Feb. 8, 2005). Float data in

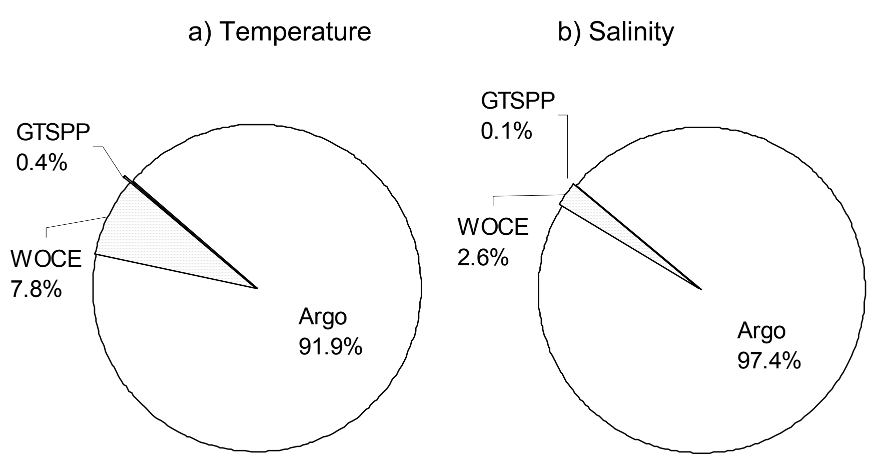

Figure 6.2. PFL data contributions from different sources.

World Ocean Database 2001 (WOD01) were all from GTSPP. These were replaced, when possible, by WOCE and Argo data, as these data have additional quality control.

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 $mS \cdot cm^{-1}$ ($milliSiemens \cdot centimeter^{-1}$). 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]; Bőhme and Send, 2005 [BS]; Durand and Reverdin 2005, Wong and Owens, 2009 [WO]). The Argo delayed-mode data are corrected for drift using either the WJO or BS algorithms, depending on the DAC which is making the correction. All DACs are in the process of transitioning to the WO method, which combines and improves on the WJO and BS methods. Delayed mode data are available in WOD09. If the pressure adjustment, temperature adjustment, or salinity adjustment variable is present in a cast (variable specific second 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 WOD09. 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, minutes of 10th meeting of International Argo Steering Team). This problem causes pressure sensor drift after deployment. Deployment of new floats was halted temporarily, until the pressure sensor design could be altered. Already deployed APEX floats are being monitored closely for sensor drift. The full extent of this problem is not yet apparent.

During a normal transmission to satellite, a float needs to stay at the surface up to 12 hours. This is where much of the biofouling occurs. Some floats have been equipped to communicate with two-way communicating satellites from Iridium. 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 cuts down on surface time. The problem is that Iridium is an expensive alternative.

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 by G. Johnson 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 WOD09.

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 WOD09**. 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
15821	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 WOD09 if they have not been removed beforehand. But there may be data with errors of this nature which escaped all quality control steps.

A data-stream error encountered while replacing the GTSPP version of the profiling floats with the U.S. GODAE (Argo) version was a mislabeling of the depth measurements as pressure measurements in the Argo version of the data. These errors came in that portion of the data which were gathered from the GTS, but for which no DAC in Argo is responsible. These data are included with Argo data even though they do not go through the same processing as other Argo data. The convention for data broadcast on the GTS is to use units of depth rather than pressure. Increasing the confusion, some DACs put pressure values out on the GTS instead of depth values. These problems have been solved. All DACs now put out data on the GTS with depth. All pressures for data not from DACs in Argo were recalculated from the depths both in WOD09, and the Argo data at the GDACs (T. Carval, personal communication). This involved about 25,000 profiles. There are still approximately 9,000 profiles for which the GTSPP depths match the Argo pressures. Since these data are from Argo DACS, it is assumed that pressure is the correct unit in these cases, so this is the unit used in WOD09.

6.7. ORIGINATORS FLAGS

The originators flags from the Argo program are kept intact in the WOD09 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, 2004).

Note that not all data marked with originators 3 or 4 are marked with WOD09 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 WOD09 standards, or that the failing test was not performed for WOD09. The user of WOD09 can choose to use the Argo flags, the WOD09 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 WOD09.

6.8. PFL DATA DISTRIBUTIONS

Figure 6.3 shows the geographic distribution of profiling floats for the period 1994-2005. This distribution shows that Argo has met one of its goals of full geographic coverage of non-ice covered ocean. The depth distribution, Figure 6.4 shows that many of the surface (0-5 meters) values do not exist or are missing. From 10 m depth the vertical distribution is steady until 400 meters where it begins to decrease down to 2000 meters. Table 6.2 shows that nearly 60% of the floats are of U.S. origin, followed by Canada at 12%. It also shows that many countries around the world are contributing profiling float data. The year distribution in Table 6.3 and Figure 6.5 shows the rapid increase of float distribution year by year.

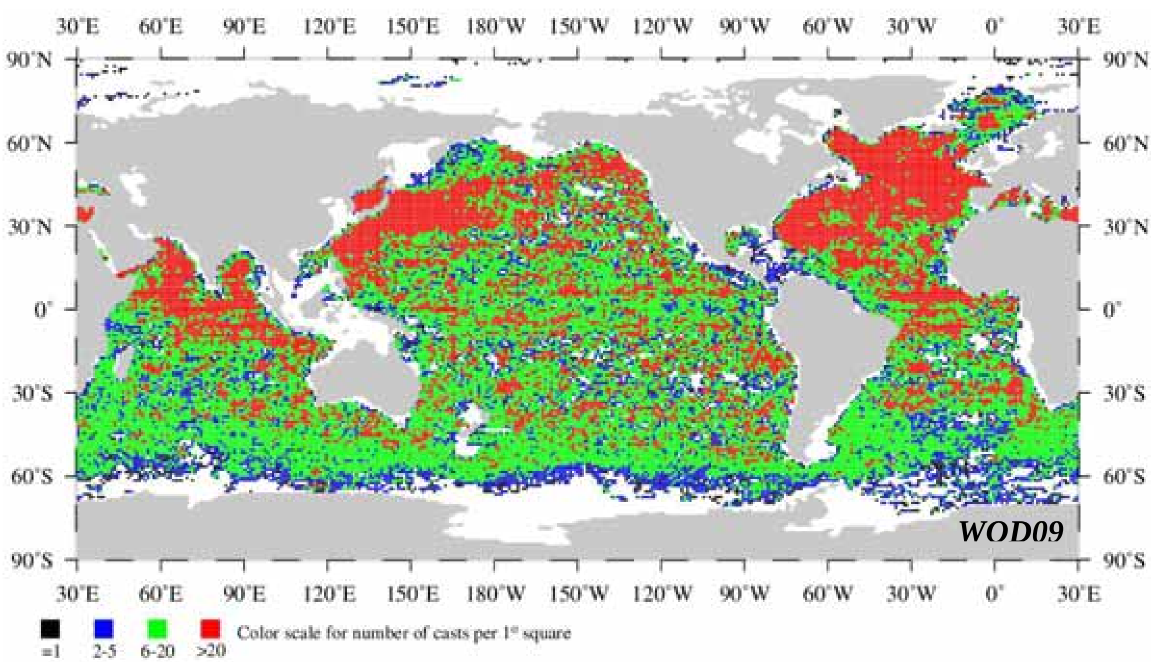

Figure 6.3. Geographic distribution of profiling floats (PFL) for the period 1994-2005 in WOD09 by one-degree squares.

Table 6.2. National contribution of PFL casts in WOD09.

ISO[a] Country Codes	Country Name	PFL Casts	% of Total
US	United States	306,252	56.51
JP	Japan	68,710	12.68
FR	France	27,787	5.13
CA	Canada	20,325	3.75
GB	Great Britain	19,226	3.55
AU	Australia	18,601	3.43
99	Unknown	18,028	3.33
IN	India	17,554	3.24
DE	Germany	16,992	3.14
KR	Korea, Republic of	10,740	1.98
EU	European Union	6,127	1.13
IT	Italy	2,927	0.54
NO	Norway	2,385	0.44
CL	Chile	1,558	0.29
DK	Denmark	1,465	0.27
ES	Spain	893	0.16
CN	China, The Peoples Republic of	853	0.16
NZ	New Zealand	565	0.10
NL	Netherlands	407	0.08
RU	Russia	306	0.06
IE	Ireland	164	0.03
MX	Mexico	101	0.02
	Total	*541,966*	*100.0*

[a] ISO = International Organization for Standardization
http://www.iso.org/iso/country_codes.htm

Table 6.3. The number of Profiling Float Data (PFL) casts as a function of year. The total number of casts = 541,966.

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1994	53	1998	11,591	2002	20,206	2006	92,100
1995	1,038	1999	14,283	2003	31,288	2007	106,021
1996	2,617	2000	13,911	2004	46,085	2008	113,205
1997	6,093	2001	14,674	2005	68,801		

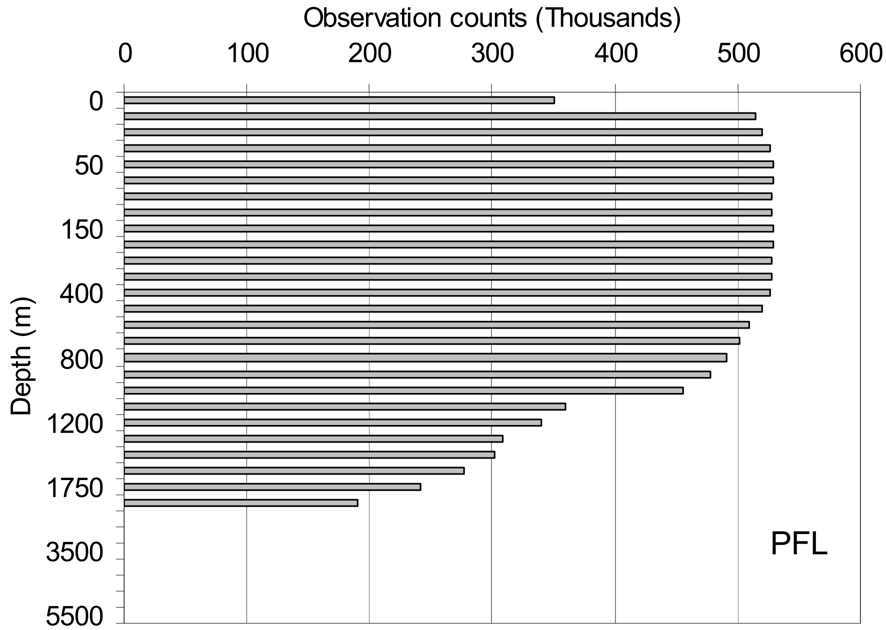

Figure 6.4. Distribution of Profiling Float Data (PFL) data at observed depth levels in WOD09.

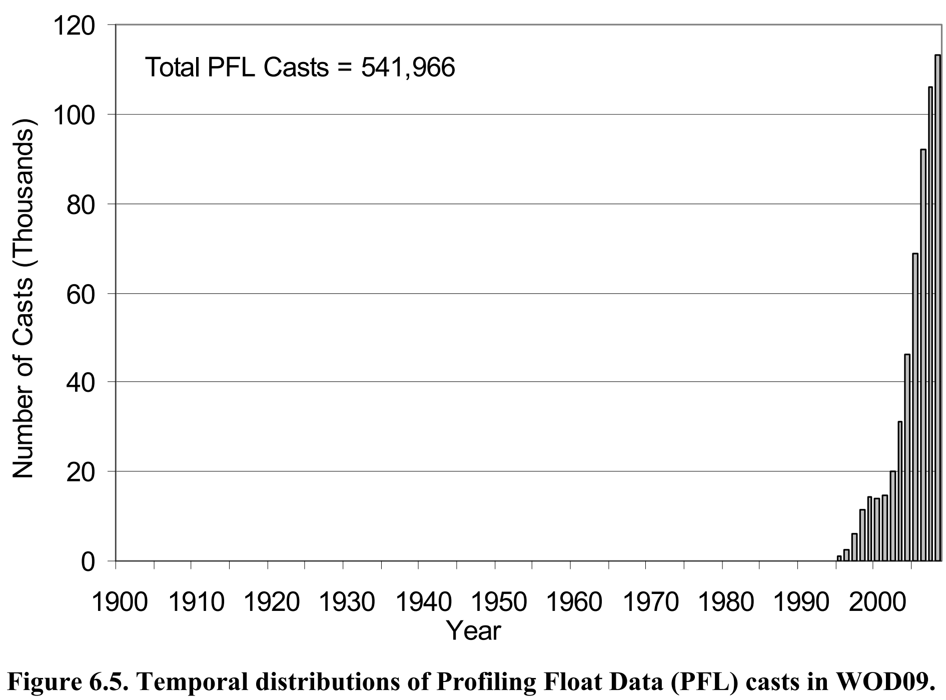

Figure 6.5. Temporal distributions of Profiling Float Data (PFL) casts in WOD09.

6.9. RELEVANT WEB SITES

Aanderaa Oxygen Sensor:
http://www.aanderaa.com/docs/B140_Oxygen_Optode_Temp_Sensor_3835.pdf.

Argo homepage: http://www.argo.ucsd.edu.

Argo Information Center homepage: http://argo.jcommops.org/.

FSI Excell CTD: http://www.falmouth.com/DataSheets/CTSensorDigital.pdf.

Seabird 41 CTD for ALACE floats: http://www.seabird.com/alace.htm.

Seabird 43 oxygen sensor: http://www.seabird.com/products/spec_sheets/43data.htm.

Seabird 9+ CTD:
http://www.seabird.com/pdf_documents/datasheets/911plusbrochureFeb05.pdf.

TSK CTD: http://tsk-jp.com/tska/PDF_Files/Seamate.pdf.

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[1]English version of Argo Information Center Newletter available on their website (see above).
[2] Document available on Argo Information Center website (see above).

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 1.5% of all the MBT profiles in our archives were collected between 1991 and 2000 (Table 7.1). While the U.S.A. is responsible for about half of all the MBT profiles, only Japan and Russia have significantly made MBT measurements and transferred them to oceanographic data centers in the last two decades. Indeed, these two countries account for 99.9% of the MBT profiles reported for the period mentioned above.

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 mean features by averaging over many measurements in space and/or time.

7.3. MBT SYSTEMATIC ERROR

Gouretski and Koltermann (2007) identified a systematic error between MBT temperature data and temperature data from approximately collocated (in space and time) reversing thermometers and CTDs. The source of this error has not been identified as of the publications of this atlas. The observed level MBT data are not corrected for this systematic error in the data represented by this atlas. However, the MBT data interpolated to standard depth levels is empirically corrected for this systematic error following Levitus *et al.* (2009).

MBT BIAS CORRECTIONS WERE RECALCULATED USING AN UPDATED DATA SET FOR WORLD OCEAN DATABASE 2009 AND WORLD OCEAN ATLAS 2009 (SEE APPENDIX 1).

We emphasize that this bias correction is not applied to the pre-1951 standard depth level MBT data nor the post-1992 standard depth level MBT data.

7.4. 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.

7.5. MBT PROFILE DISTRIBUTIONS

Table 7.1 gives the yearly counts of MBT profiles for the World Ocean. Figure 7.1 shows the time series of the yearly totals of Mechanical Bathythermograph profiles for the World Ocean. There are a total of 2,340,765 MBT profiles for the entire World Ocean with 260,763 profiles (11.1%) measured in the southern hemisphere and 2,080,002 profiles (88.9%) measured in the northern hemisphere. Table 7.3 gives national contributions of MBT profiles.

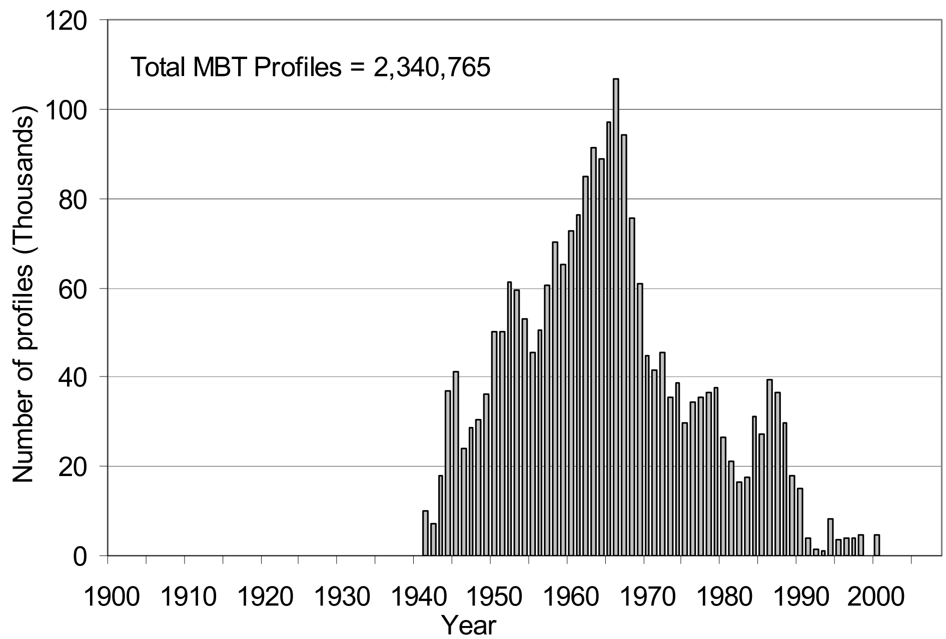

Figure 7.1. Temporal distribution of Mechanical Bathythermograph (MBT) profiles in WOD09.

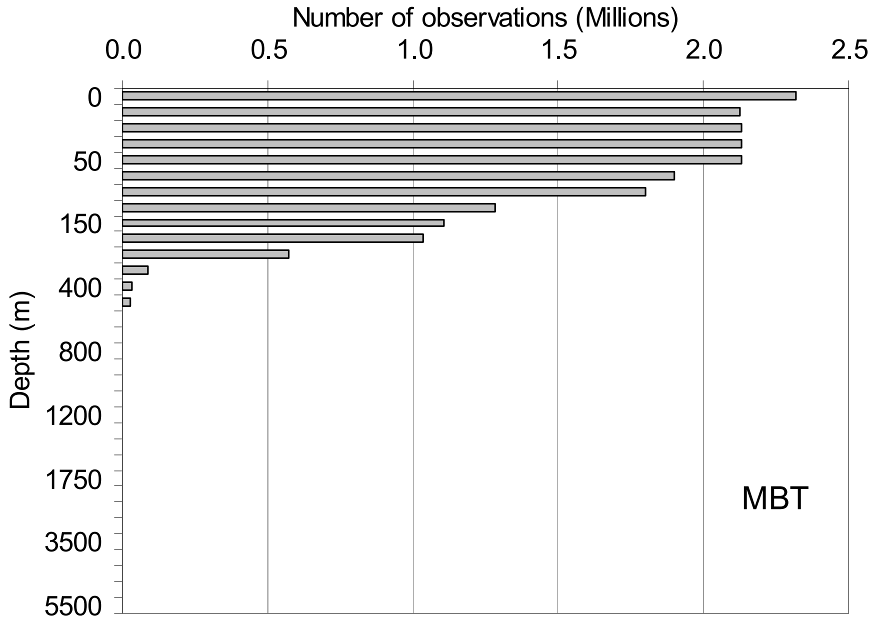

Figure 7.2. Distribution of Mechanical Bathythermograph (MBT) data at observed depth levels in WOD09.

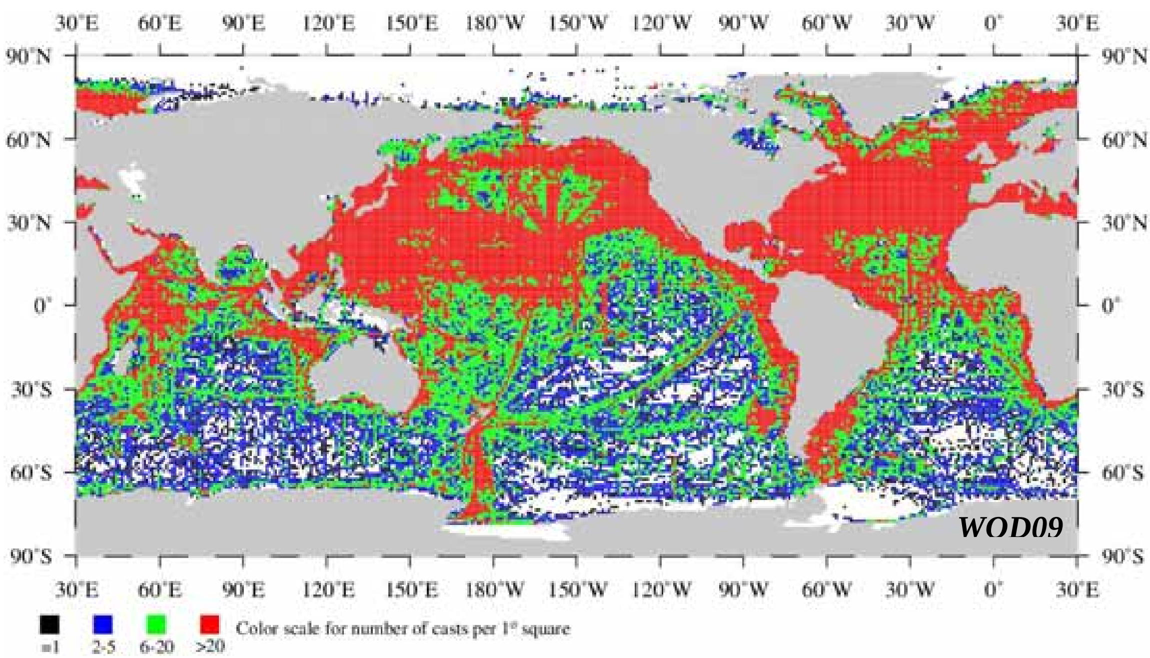

Figure 7.3. Geographic distribution of Mechanical Bathythermograph (MBT) profiles in WOD09 by one-degree squares.

Table 7.1. Number of all MBT profiles as a function of year in WOD09.
Total Number of Profiles = 2,340,765

YEAR	PROFILE	YEAR	PROFILE	YEAR	PROFILE	YEAR	PROFILE
1941	9,990	1956	50,530	1971	41,422	1986	39,505
1942	7,014	1957	60,486	1972	45,362	1987	36,530
1943	17,767	1958	70,106	1973	35,554	1988	29,684
1944	36,785	1959	65,241	1974	38,531	1989	18,024
1945	41,086	1960	72,656	1975	29,808	1990	14,921
1946	23,822	1961	76,384	1976	34,319	1991	3,829
1947	28,808	1962	84,905	1977	35,430	1992	1,554
1948	30,310	1963	91,327	1978	36,596	1993	1,169
1949	36,040	1964	89,006	1979	37,777	1994	8,417
1950	50,296	1965	97,198	1980	26,371	1995	3,453
1951	50,248	1966	106,874	1981	21,204	1996	3,905
1952	61,328	1967	94,331	1982	16,645	1997	3,859
1953	59,339	1968	75,460	1983	17,480	1998	4,552
1954	52,922	1969	60,909	1984	31,202	1999	0
1955	45,478	1970	44,912	1985	27,285	2000	4,819

Table 7.2. Comparison of observations taken with Mechanical Bathythermographs and reversing thermometers.
Reproduced from Leipper and Burt (1948).

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

*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 WOD09

ISO[a] Country Codes	Country Name	MBT Casts	% of Total
US	United States	1,169,369	49.96
SU	Union of Soviet Socialist Republics	449,359	19.20
JP	Japan	296,218	12.65
CA	Canada	184,844	7.90
GB	Great Britain	118,639	5.07
DE	Germany	25,005	1.07
AU	Australia	18,474	0.79
99	Unknown	16,393	0.70
FR	France	13,538	0.58
AR	Argentina	12,088	0.52
NL	Netherlands	8,088	0.35
IT	Italy	6,268	0.27
PE	Peru	5,212	0.22
CL	Chile	4,161	0.18
PT	Portugal	2,628	0.11
NZ	New Zealand	2,435	0.10
CD	Congo, The Democratic Republic	1,234	0.05
BE	Belgium	1,218	0.05
NO	Norway	913	0.04
EC	Ecuador	885	0.04
CO	Colombia	747	0.03
VE	Venezuela	673	0.03
IN	India	540	0.02
MG	Madagascar	405	0.02
GR	Greece	327	0.01
SN	Senegal	245	0.01
ES	Spain	195	<0.01
SL	Sierra Leone	187	<0.01
CI	Cote d'Ivoire	100	<0.01
MC	Monaco	97	<0.01
NG	Nigeria	89	<0.01
BR	Brazil	82	<0.01
TH	Thailand	77	<0.01
ZA	South Africa	20	<0.01
GH	Ghana	12	<0.01
	Total	*2,340,765*	*100.00*

[a] ISO = International Organization for Standardization
http://www.iso.org/iso/country_codes.htm

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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 archived in the underwater unit as it is lowered in the water column. Upon retrieval, the underwater unit is connected to a computer and data are retrieved and archived.

All DBT profiles are stored in the MBT dataset of WOD09.

8.2. DBT ACCURACY

The DBT has a temperature accuracy of ±0.05°C. However, Pankajakshan *et al.* (2003) reported 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 USA 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 80,325 DBT profiles for the entire World Ocean with 4,845 profiles (6.0%) measured in the southern hemisphere and 75,480 profiles (94.0%) measured in the northern hemisphere. Table 8.2 gives national contribution of DBT data.

Table 8.1. The number of Digital Bathythermograph (DBT) profiles as a function of year in WOD09. The total number of casts = 80,325.

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1977	27	1984	9,462	1991	4,662	1998	0
1978	234	1985	8,700	1992	2,285	1999	0
1979	1,920	1986	5,531	1993	2,507	2000	0
1980	5,280	1987	4,551	1994	108	2001	0
1981	5,918	1988	5,469	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 WOD09.

ISO[a] Country Codes	Country Name	DRB Casts	% of Total
JP	Japan	68,376	85.12
CA	Canada	11,102	13.82
KR	Korea, Republic of	847	1.06
	Total	*80,325*	*100.00*

[a] ISO = International Organization for Standardization
http://www.iso.org/iso/country_codes.htm

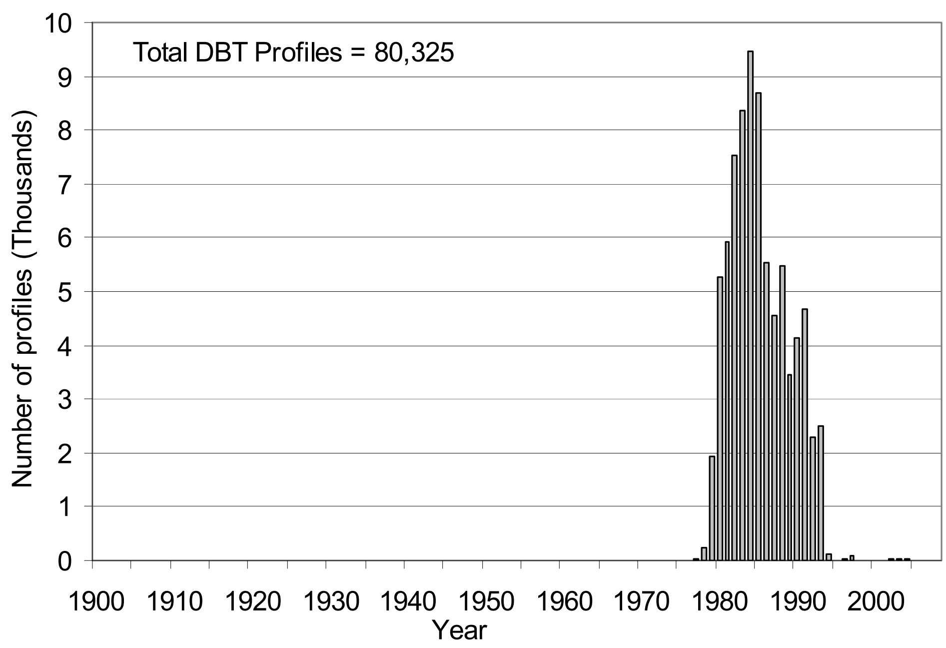

Figure 8.1. Temporal distribution of Digital Bathythermograph (DBT) profiles in WOD09.

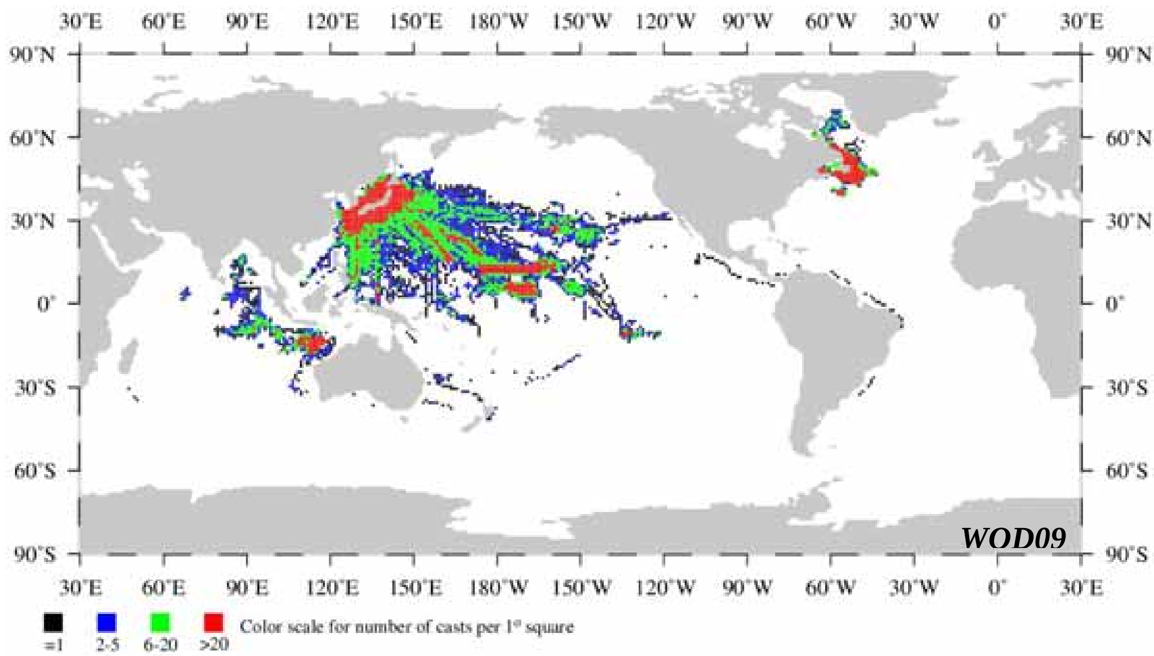

Figure 8.2. Geographic distribution of Digital Bathythermograph (DBT) profiles in WOD09 by one-degree squares.

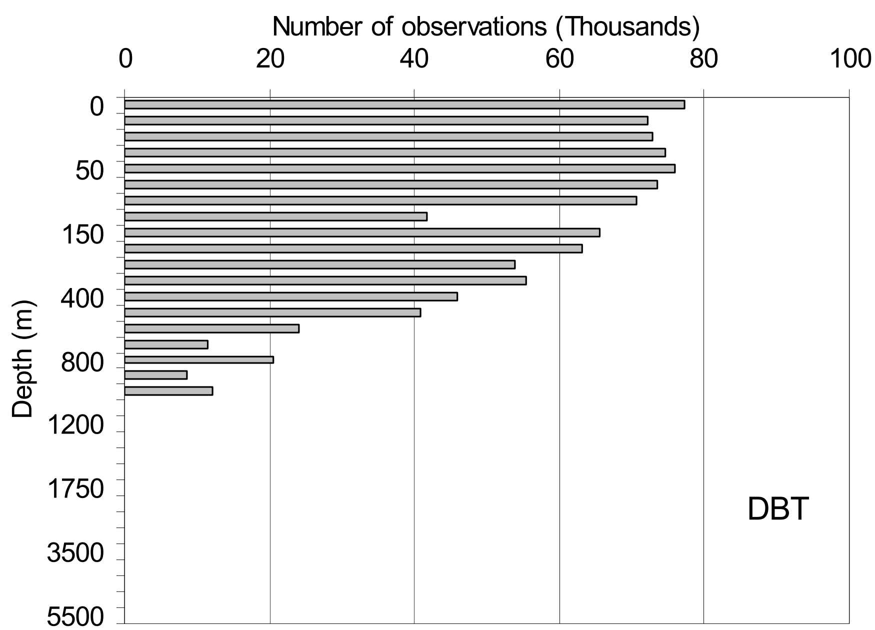

Figure 8.3. Distribution of Digital Bathythermograph (DBT) data at observed depth levels in WOD09.

8.4. REFERENCES AND BIBLIOGRAPHY

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CHAPTER 9: MOORED BUOY DATA (MRB)

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9.1. INTRODUCTION

The National Data Buoy Center web-site (http://seaboard.ndbc.noaa.gov/) notes that "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 following conclusions had been reported:

- 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 web site of the Data Buoy Cooperation Panel describes moored buoys as relatively large and expensive platforms. Data are usually collected by geostationary meteorological satellites such as GOES or METEOSAT. In case a moored buoy goes adrift, there may be a chance of potential loss of costly equipment and causing a possible hazard to navigation. Therefore, the ARGOS system is used for location determination for moored buoys. Additionally, some World Meteorological Organization (WMO) Member countries use the ARGOS system for transmitting meteorological observations from moored buoys (see http://www.dbcp.noaa.gov/dbcp/1hb.html#MB).

The WOD09 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, 2008. The majority of data came from ongoing programs: 380,388 casts collected from the TAO buoy array; 40,269 casts were acquired from the PIRATA program; 35,766 casts came from the TRITON program and 11,856 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). Additionally, 4,222 casts came from other unidentified sources (See Figure 9.1 for percentages and related internet links below for additional information).

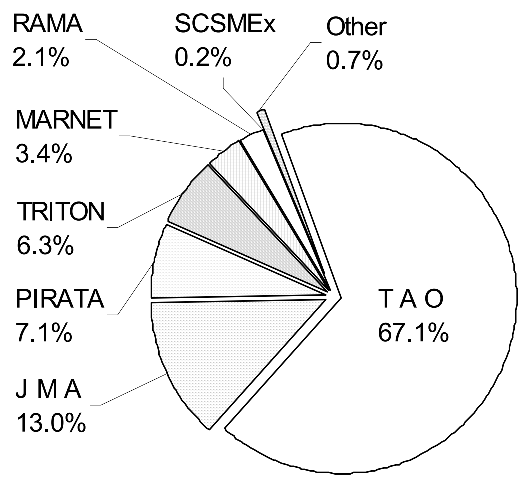

Figure 9.1. Distribution of the moored buoys data among the major research programs.

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. Since then it has steadily expanded to its present size of approximately 70 moorings. Moorings are typically separated by 2-3 degrees of latitude and 10-15 degrees of longitude. A TAO array provides surface wind, sea surface temperature (SST), upper ocean temperature, as well as upper-ocean 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 (http://www.pmel.noaa.gov/tao/index.shtml). 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 first ATLAS mooring was deployed in December 1984. The expansion of this array is the result of international collaboration between scientists from France, Japan, Korea and the USA. Collected data are transmitted to shore in real time using the ARGOS System (http://www.cls.fr/html/argos/welcome_en.html), processed by Collecte Localisation Satellites (CLS, http://www.cls.fr/) or Service ARGOS Inc.

(http://www.argosinc.com/), and placed on the Global Telecommunication System (GTS, http://www.wmo.ch/index-en.html). 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, http://www.wmo.ch/web/gcos/gcoshome.html), World Climate Research Programme (WCRP, http://www.wmo.ch/web/wcrp/wcrp-home.html), Climate Variability and Predictability Programme (CLIVAR, http://www.clivar.org/), and the World Weather Watch Programme (WWW, http://www.wmo.ch/web/www/www.html) (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 (http://www.pmel.noaa.gov/pirata/).

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 mooring and NIO (National Institute of Oceanography, India) began subsurface mooring deployment along the equator (McPhaden *et al.*, 2006). At the end of 2008, RAMA was 47% complete, with 22 of 46 mooring sites occupied with expectation that RAMA will be completed by the end of 2012. The proposed array will consist of 38 surface and 8 subsurface moorings. Mooring equipment, ship time, personnel, and/or logistic support have 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 PMEL, JAMSTEC and NIO websites (see links below).

The MARNET (Marine Environmental Monitoring Network in the North Sea and Baltic Sea) project has four of its 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. In the Baltic Sea two large discus buoys, stabilized mast, semi-submersible buoy and 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, http://www.bsh.de/). The data storage is a security back-up 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 are accommodated in deck containers; sea water pumping units (http://www.bsh.de/en/Marine_data/Observations/MARNET_monitoring_network/index.jsp).

Table 9.1. National contributions of MRB casts in WOD09.

ISO[a] Country Code	Country Name	MRB Casts	% of Total
US	USA	357,128	63.04
JP	Japan	137,181	24.21
BR	Brazil	21,670	3.82
DE	Germany	19,445	3.43
FR	France	18,616	3.29
99	International	11,599	2.05
TW	Taiwan	905	0.16
	Total	*566,544*	*100.00*

[a] ISO = International Organization for Standardization
http://www.iso.org/iso/country_codes.htm

There are five countries that have contributed the majority of the moored buoys data to WOD09—USA, Japan, Germany, Brazil, and France. Significant amount of data have no country information (mostly because of the multi-national nature of its acquisition and processing). Those data were obtained from the web-portals of the international research Programs (*i.e.* RAMA, *etc.*) Table 9.1 and Figure 9.2 provide detailed information on each country contribution.

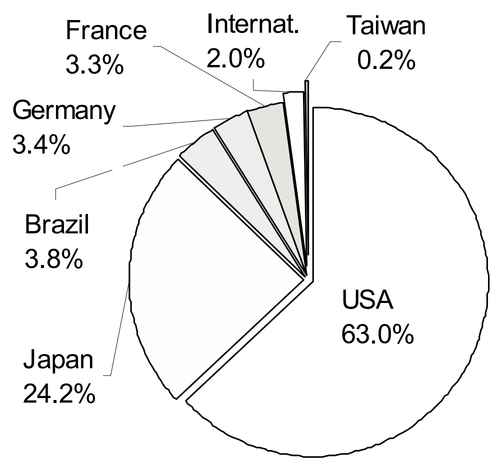

Figure 9.2. Distribution of the moored buoys data among the contributing countries.

9.2. MRB DATA PRECISION AND ACCURACY

The accuracy of MRB temperature and salinity data depends on the temperature and conductivity sensors. For TRITON buoys, for example, sensor range and accuracy are: conductivity 0-70/0.003 ms cm^{-1}; temperature -3 – 33/0.002°C; depth 0-1000 pounds per square inch absolute (psia) / 0.15% full scale (Kuroda, 2001; Ando *et al.*, 2005). Data acquired during TAO and PIRATA programs were collected from PROTEUS and ATLAS buoys using SeaBirds Electronics' SEACAT sensors having SST accuracy of 0.01°C for the PROTEUS moorings and 0.03°C for ATLAS moorings; subsurface temperature accuracy is 0.01°C for the PROTEUS moorings 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* (http://www.olympus.net/IAPSO/standardserv91_95.html). The three sea water 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.

9.3. MRB CAST DISTRIBUTIONS

Table 9.2 gives the yearly counts of MRB casts for the World Ocean: this is also graphically illustrated in Figure 9.3. Data flow was steadily increasing after the TOA buoys were deployed and reached its maxima in 1995-2000.

Table 9.2. The number of MRB casts in WOD09 as a function of year. Total number of casts = 566,544

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1980	299	1988	4,939	1996	31,361	2004	27,719
1981	543	1989	6,057	1997	33,024	2005	29,923
1982	535	1990	7,015	1998	37,341	2006	30,170
1983	1,008	1991	9,740	1999	40,194	2007	32,227
1984	1,098	1992	23,530	2000	37,735	2008	32,238
1985	1,586	1993	28,274	2001	28,717		
1986	2,963	1994	29,840	2002	27,548		
1987	3,695	1995	29,381	2003	27,844		

The geographic distribution of the MRB casts for 1980-2005 is shown in Figure 9.4. There are a total of 566,544 MRB casts for the entire World Ocean with ~467,300 casts (82%) measured in the tropical regions (15°N – 15°S). These data were contributed by the TAO, TRITON, PIRATA, and RAMA programs. The MARNET and JMA programs contributed ~43,450 casts (10%) north of 30°N. Approximately 8% of all casts

(~55,850, mostly collected by JMA) are within the 15-30°N band of latitudes.

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.

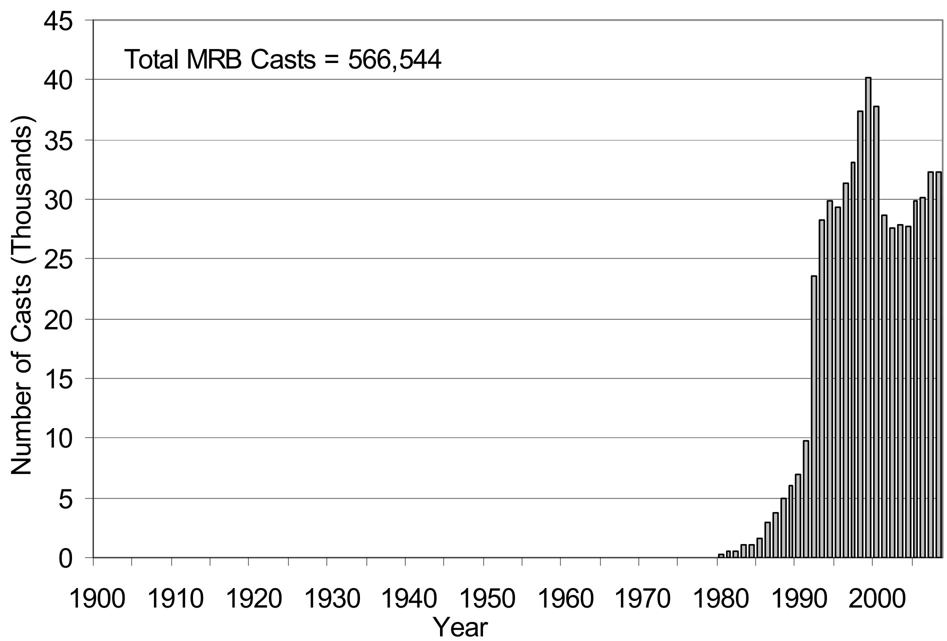

Figure 9.3. Temporal distribution of MRB casts in WOD09.

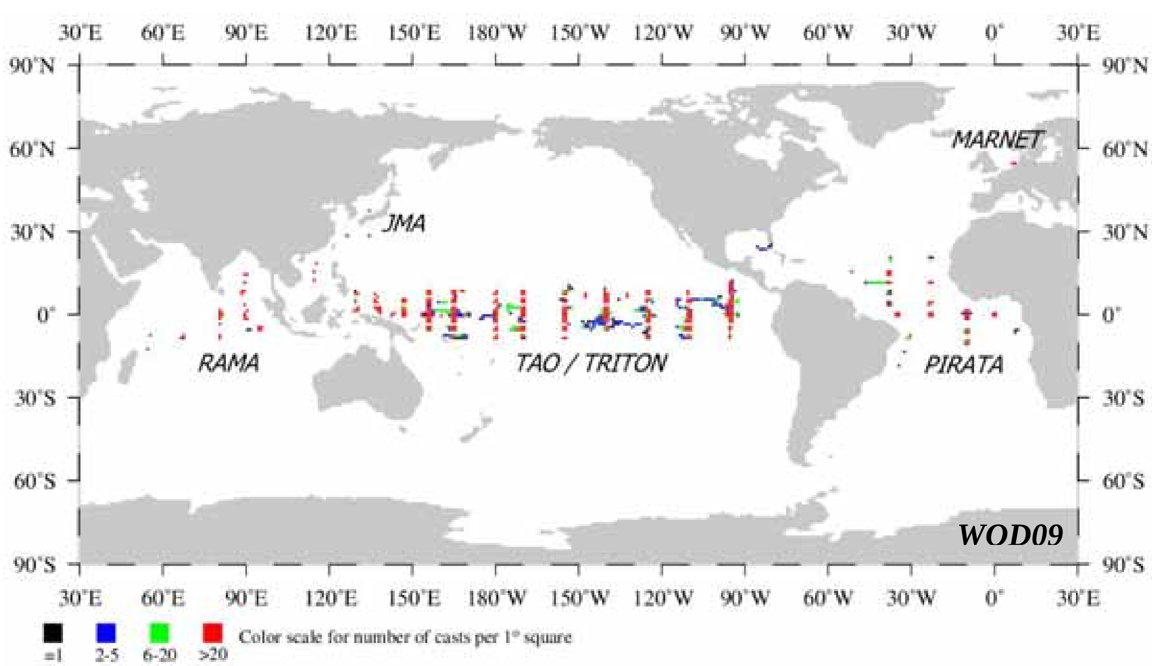

Figure 9.4. Geographic distribution of MRB casts collected by major research programs in WOD09 by one-degree squares.

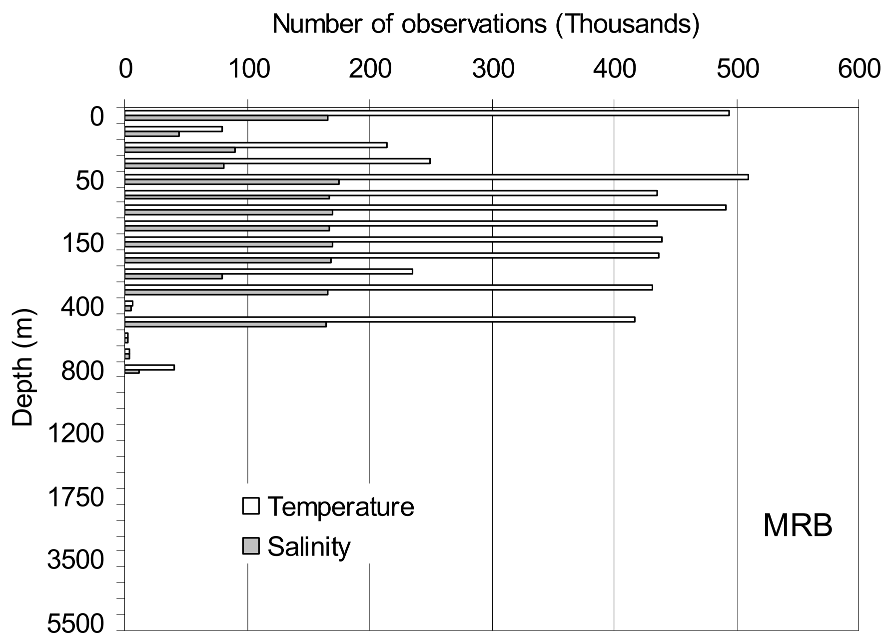

Figure 9.5. Distribution of MRB data at observed depth levels in WOD09.

9.4. RELEVANT WEB SITES

ARGOS Program: http://www.argos-system.org/html/applications/ocean_en.html .
Centre national de la recherche scientifique (CNRS): http://www.cnrs.fr/ .
Diretoria De Hidrografia E Navegação (DHN), Brazil:
http://www.mar.mil.br/dhn/dhn/index.html .
GOES Project: http://goes.gsfc.nasa.gov/).
L'Institut de recherché pour le développemen (IRD) http://www.ird.fr/ .
French Research Institute for Exploitation of the Sea (IFREMER):
http://www.ifremer.fr/ird/soopip/xctd_probes.html
Instituto Nacional de Pesquisas Espaciais (INPE), Brazil: http://www.inpe.br/ .
JAMSTEC TRITON Buoy project http://www.jamstec.go.jp/jamstec/OCEAN/TRITON/.
MARNET description available at
http://www.bsh.de/en/Marine_data/Observations/MARNET_monitoring_network/index.jsp .
METEOSAT: http://www.esa.int/SPECIALS/MSG/index.html.
National Data Buoy Center: http://seaboard.ndbc.noaa.gov/.
NOAA Magazine: http://www.magazine.noaa.gov/stories/mag22.htm.
PIRATA Program: http://www.pmel.noaa.gov/pirata/.
RAMA Program links:
http://www.noaanews.noaa.gov/stories2009/20090504_indianoceanbuoys.html ,
http://www.incois.gov.in/Incois/iogoos/home_indoos.jsp.
GTS: http://www.wmo.int/pages/prog/www/TEM/XGTS/gts.html,

PMEL: http://www.pmel.noaa.gov/tao/disdel/),
JAMSTEC: http://www.jamstec.go.jp/jamstec/TRITON/),
NIO: http://www.nio.org/data_info/deep-sea_mooring/oos-deep-sea-currentmeter-moorings.htm.

South China Sea Monsoon Experiment:
http://www.pmel.noaa.gov/tao/proj_over/scsmex/scsmex-display.html

TAO/TRITON collaboration: http://www.pmel.noaa.gov/tao/proj_over/triton.html.

Tropical Atmosphere Ocean Project: http://www.pmel.noaa.gov/tao/index.shtml.

WMO-IOC Data Buoy Cooperation Panel: http://www.dbcp.noaa.gov/dbcp/index.html.

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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 down 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 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. The direction and velocity of the sea ice floe was interpolated from changes in position from each buoy. Measurements were taken at twelve minute intervals. Subjected to the stresses and strains of the Arctic pack ice, these buoys varied greatly in their longevity, though the battery pack is supposed to last for approximately three years (Rigor, 2002; IABP, 2006; JAMSTEC, 2006).

The main 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 all the data from all drifting buoys via the Global Telecommunication System (GTS) as well as performs quality control on and archives the data. MEDS has been a Responsible National Oceanographic Data Center – RNODC, since January 1986 under the auspices of the Intergovernmental Oceanographic Commission (IOC). They acquire, processes, 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 and temperature and wind direction (MEDS, 2006). Currently, buoy data from GTSPP in the WOD09 database comes mostly from the United States 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) developing polar ocean profiler buoys. The joint development of the Ice Ocean Environmental Buoy (IOEB) with the Woods Hole Oceanographic Institution (WHOI) 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 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 it. Also, each buoy was expensive to assemble and required large scale camps and lots of equipment and materials to install on 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. The new buoy was named J-CAD (JAMSTEC Compact Arctic Drifter) and its mission was to conduct long-term observations in the Arctic Ocean multi-year ice zones, they are a participant of the 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 collects 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 their data in 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. This is so each sensor can be lowered through a 30 cm hole in the ice. A smaller hole means simpler equipment needed to drill it. It is equipped with three types of sensors: meteorological, oceanographic, and buoys status sensors. The J-CAD buoys consist of a floatation collar made of foam resin buoyancy material (Surlyn Ionomer resin manufactured by Du Pont Co.) enclosed by aluminum. The housing for instruments, also made from aluminum and foam resin, hold the data logger/controller engine (Tattletale model 8) with a 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 easily 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).

10.2. 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., 2006).

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., 2006).

10.3 DRB PROFILE DISTRIBUTIONS

There are data from 121,828 drifting buoy casts in WOD09, 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).

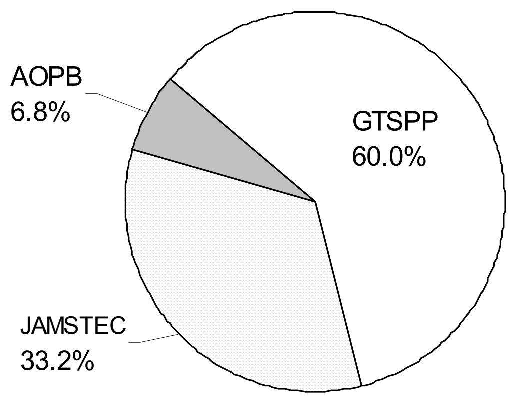

Figure 10.1. Distribution of the Drifter Buoys data in WOD09 among major research programs.

The geographic distribution of the DRB casts is illustrated on Figure 10.2. All 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 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 10.1. The number of DRB profiles in as a function of year in WOD09. The total number of profiles = 121,828.

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1985	217	1991	1,422	1997	0	2003	7,905
1986	482	1992	606	1998	3	2004	5,442
1987	447	1993	462	1999	4,770	2005	9,280
1988	1,387	1994	532	2000	12,611	2006	1,376
1989	1,510	1995	0	2001	62,952		
1990	1,175	1996	0	2002	9,249		

Table 10.2 gives national input to the DRB dataset by each contributing country.

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

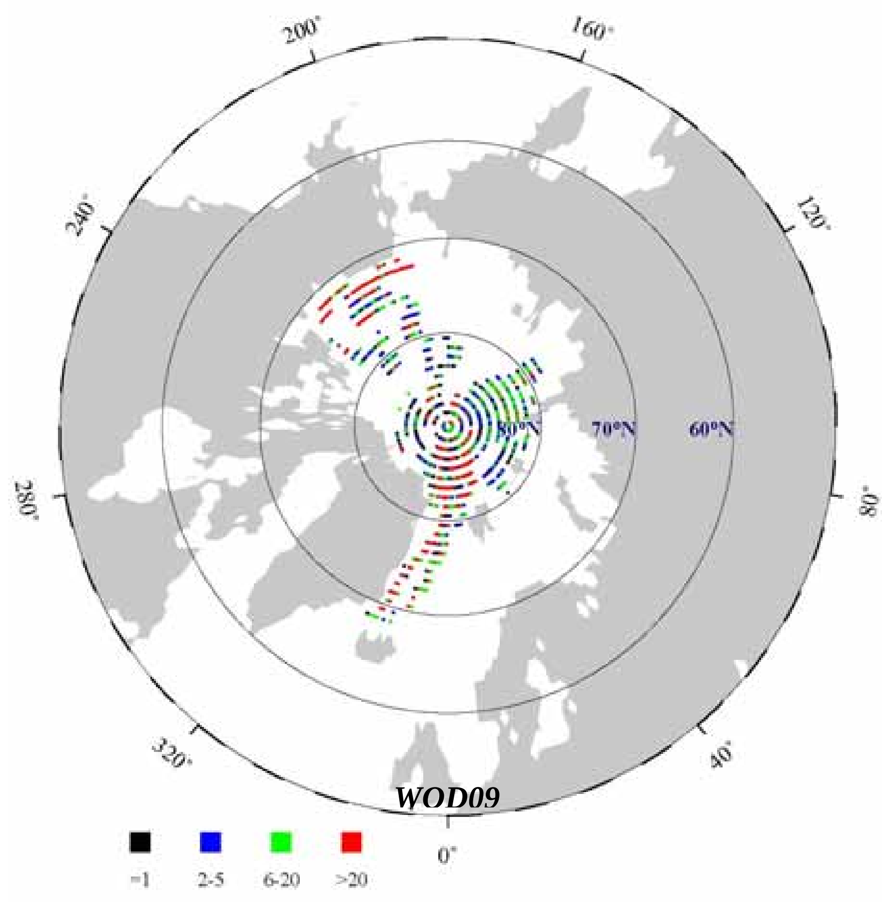

Figure 10.2. Geographic distribution of Drifting Buoy (DRB) Data in WOD09 by one-degree squares.

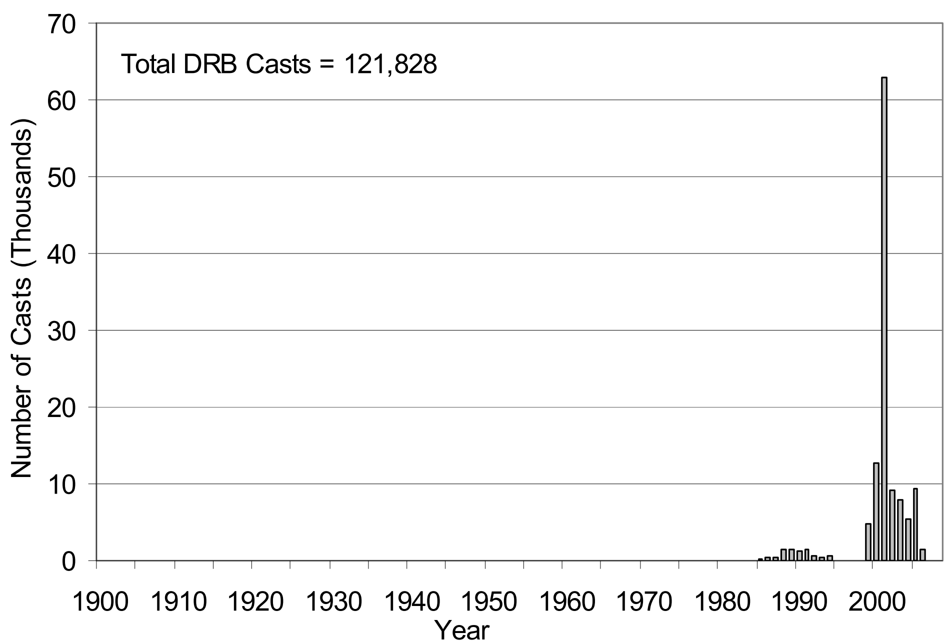

Figure 10.3. Time series of DRB casts as a function of year in WOD09.

Table 10.2. National contributions of DRB casts in WOD09.

ISO Country Code	Country Name	DRB Casts	% of Total
FR	France	58,100	47.69
JP	Japan	40,453	33.21
US	United States	22,735	18.66
99	Unknown	539	0.44
AU	Australia	1	<0.01
	Total	*121,828*	*100.00*

[a] ISO = International Organization for Standardization
http://www.iso.org/iso/country_codes.htm

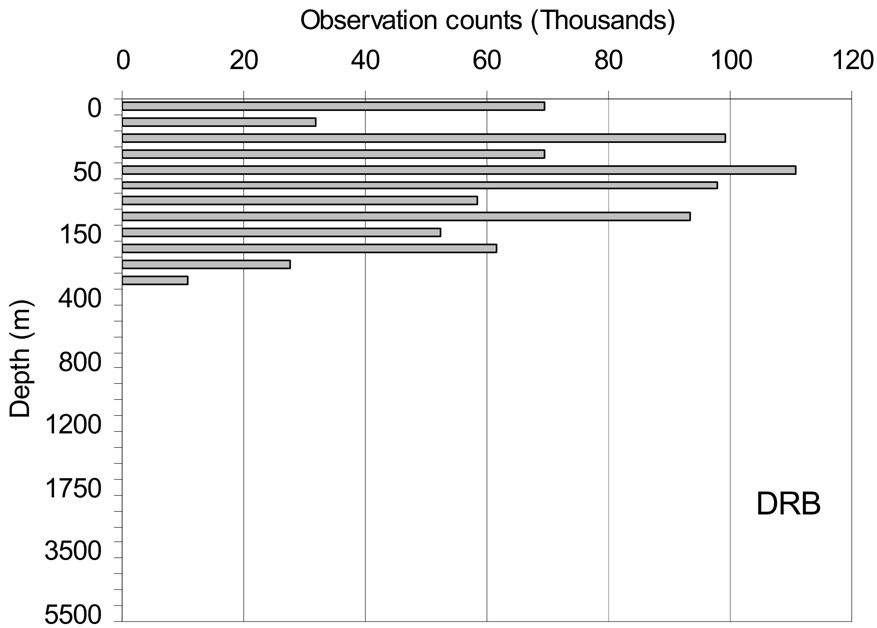

Figure 10.4. Distribution of DRB data at observed depth levels in WOD09.

10.4. RELEVANT WEB SITES

DBCP, 2006. Data Buoy Cooperation Panel, Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology, http://www.dbcp.noaa.gov/dbcp/index.html.

GTS, 2006. The Global Telecommunication System, World Meteorological Organization, http://www.wmo.ch/web/www/TEM/gts.html.

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

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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, http://www.jamstec.go.jp/arctic/J-CAD_e/jcadindex_e.htm.

MEDS, 2006. Marine Environmental Data Service (MEDS), Department of Fisheries and Oceans, Ontario, Canada, http://www.meds-sdmm.dfo-mpo.gc.ca/meds/Home_e.htm.

NDBC, 2006. National Data Buoy Center (NDBC), National Weather Service, National Oceanic and Atmospheric Administration, U.S. Dept. of Commerce, Mississippi, USA, http://www.ndbc.noaa.gov.

NPEO, 2006. The North Pole Environmental Observatory (NPEO) Project, Office of Polar Programs, National Science Foundation, Virginia, USA, http://psc.apl.washington.edu/northpole/index.html.

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Rigor, I. (2002), I*ABP drifting buoy, pressure, temperature, position, and interpolated ice velocity*. Compiled by the Polar Science Center, Applied Physics Laboratory, U. of Washington, Seattle, in association with NSIDC. Boulder, CO: National Snow and Ice Data Center. Digital media.

CHAPTER 11: UNDULATING OCEAN RECORDERS DATA (UOR)

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11.1. INTRODUCTION

As stated on The Sir Alister Hardy Foundation's web-site (http://192.171.163.165/history_cpr.htm): "The history of the Undulating Ocean Recorders (UOR) begins in 1925 when Sir Alister Hardy embarked on a two-year voyage to the Antarctic on the ship *Discovery* with the prototype of the Continuous Plankton Recorder (CPR Mark I). He designed this instrument specifically for the expedition. He recognized a need to sample over large space and time scales to evaluate changes in the abundance and distribution of plankton. In June 1932, the SS *Albatross* towed the first CPR and the continuous plankton survey was born. In 1959 the first transatlantic route was towed from Reykjavik to Newfoundland."

A need for fast CPR capable of sampling sea water at more than one depth was realized in the early 1970s and eventually led to developing the "Undulating Oceanographic Recorder" culminating in establishing the Plymouth Marine Laboratory (http://www.pml.ac.uk/). A machine called the Longhurst Hardy Plankton recorder aimed at sampling the plankton in vertical profiles was also developed to address those needs (http://192.171.163.165/parables/a12.htm).

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 under way. It can be used to carry instrumentation to sample plankton continuously and to measure chlorophyll, radiant energy, temperature, and salinity, all of which are recorded, with the measurement of depth (Aiken, 1981; Burt, 2000). This technique is often used for sampling large marine ecosystem or frontal zones because of its convenience and uninterrupted data coverage (Williams and Lindley, 1980; 1998; Pollard, 1986), its ability to sample a large area in a reasonable period of time (Brown *et al.*, 1996), and because the possibility to expand towards wider set of sensors, such as, for example, the light absorption sensors and attenuation meters (Barth and Bogucki, 2000).

The WOD09 UOR dataset consist 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 towing vehicle developed by Chelsea Technologies Group (http://www.chelsea.co.uk) from an original design by the Institute of Oceanographic Sciences (now the Southampton Oceanography Centre, UK). The towing vehicle is capable of undulating from the surface down to 500 meter depth with faired cable, or to 100 meter depth with un-faired, at tow speeds of 6.5-12 knots. It can follow a controlled and adjustable undulating path through the ocean. Sampled data from sensors mounted in the towed package are transmitted to the towing vessel for processing, display, and storage via a multi-core tow cable (http://www.chelsea.co.uk/Vehicles%20SeaSoar.htm).

Table11.1. Profiles count for major variables in the WOD09 UOR dataset.

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

WOD09 UOR data were collected in the framework of several major international programs in 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) were collected during recent Delaware Circulation and Dye Experiment (DECADE) organized by University of Delaware (U. of D.). This experiment was aimed to study the mixing and secondary circulation in the Delaware River plume. Data were acquired by means of Scanfish undulating towed vehicle equipped with Chelsea Ltd. MKIII AQUAtracka fluorometer fitted to 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). 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 at http://www.soest.hawaii.edu/COARE/index.html).

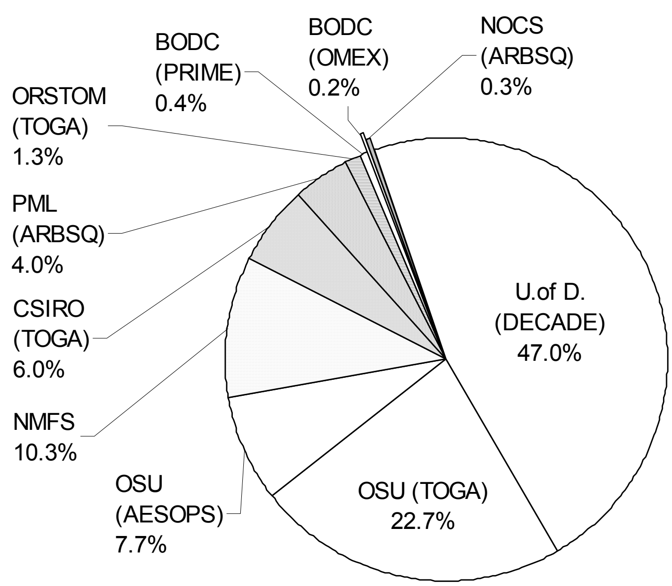

Figure 11.1. Distribution of the Undulating Ocean Recorder (UOR) data in WOD09 among the contributing institutions.

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

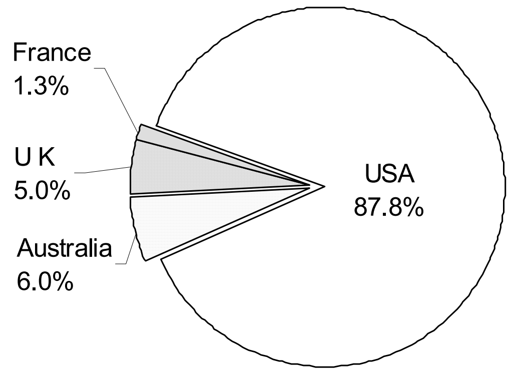

Figure 11.2. Distribution of the Undulating Ocean Recorders (OUR) data in WOD09 among the contributing countries.

The Oregon State University 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., 3,553 casts) and The National Oceanography Centre, Southampton (NOCS, U.K., 276 casts). The ARABESQUE project was aimed to study the upper ocean microbial biogeochemistry in the Arabian Sea. Its focus was on carbon and nitrogen cycling processes linked to climate change. The field programme was timed to coincide with the Southwest Monsoon and inter-monsoon period through to the onset of the Northeast Monsoon (http://www.bodc.ac.uk/products/bodc_products/arabesque/).

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 National Environment Research Counsil of UK (NERC) funded thematic project to study the role of plankton in oceanic biogeochemical fluxes. The PRIME data stored in WOD09 were collected in the northeast Atlantic in 1996 (http://www.bodc.ac.uk/products/bodc_products/prime/).

Additionally, BODC 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, focused on studying the processes taking place along the northwest European shelf break. (http://www.bodc.ac.uk/products/bodc_products/omex_1/).

11.2. UOR DATA PRECISION AND ACCURACY

The precision and accuracy of UOR data depends on the performance of the sensors and on post-processing of the data. A SeaSoar undulating vehicle is capable of carrying various instrumental packages. For the data stored in the WOD09 database, the Sea-Bird Electronics SBE9/11+ CTD instrument was the most common one. Presumably, UOR data submitted into WOD09 were corrected for effects of: a) variable flow rate (Huyer *et al.,* 1993), b) thermal mass (Lueck, 1990; Morrison *et al.,* 1993), and c) the offset of 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 11.3 illustrate this graphically.

Table 11.2. The number of all UOR casts as a function of year in WOD09. Total number of casts =88,190

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1992	11,913	1995	59	1998-99	0	2002	0
1993	14,500	1996	363	2000	9,054	2003	2,891
1994	3,988	1997	6,828	2001	0	2004	38,594

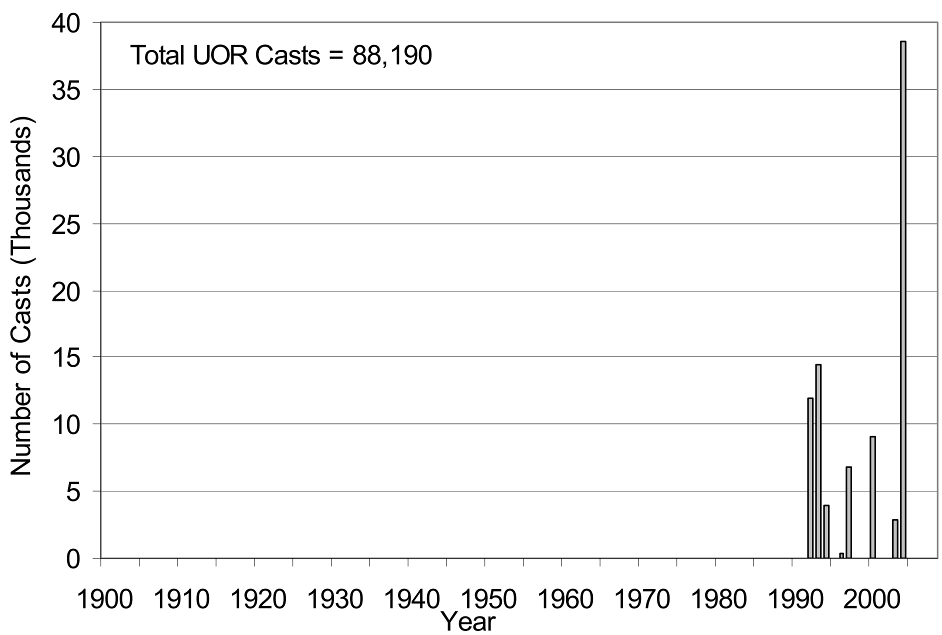

Figure 11.3. Temporal distribution of UOR casts in WOD09.

Table 11.3 gives national input to UOR dataset by each contributing country.

Table 11.3. National contributions of UOR casts in WOD09.

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
http://www.iso.org/iso/country_codes.htm

The geographic distribution of UOR casts and contributing projects is shown in Figure 11.4.

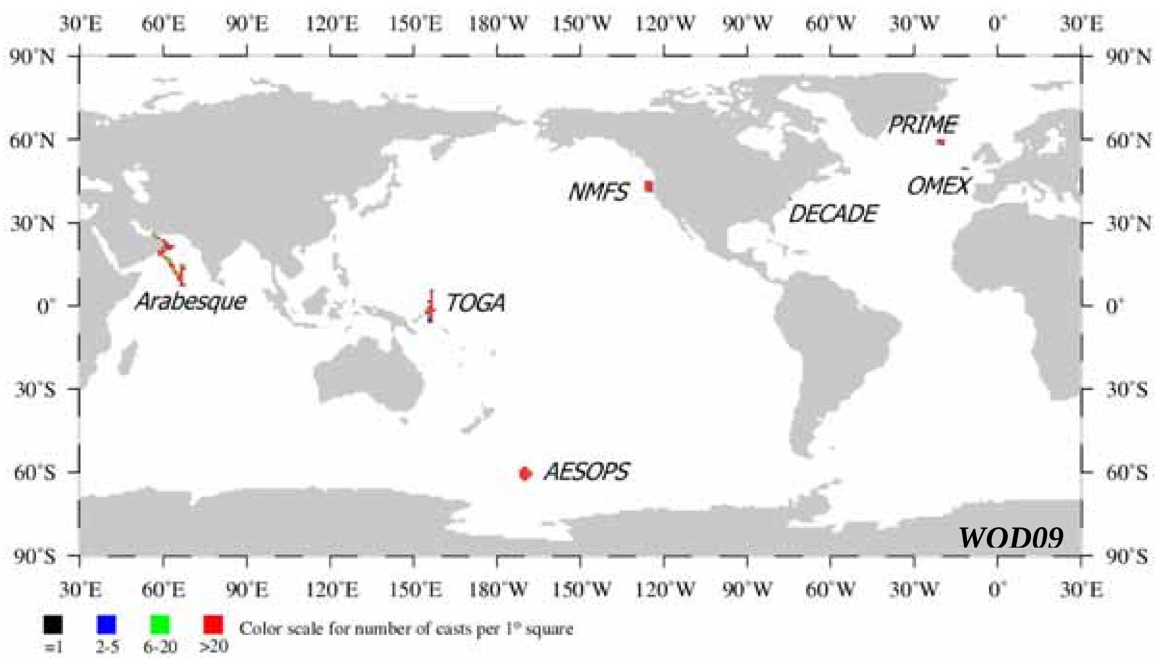

Figure 11.4. Geographic distribution of UOR casts and contributing projects in WOD09 by one-degree squares.

Figure 11.5 illustrates distribution of the UOR data as a function of depth at observed depth levels.

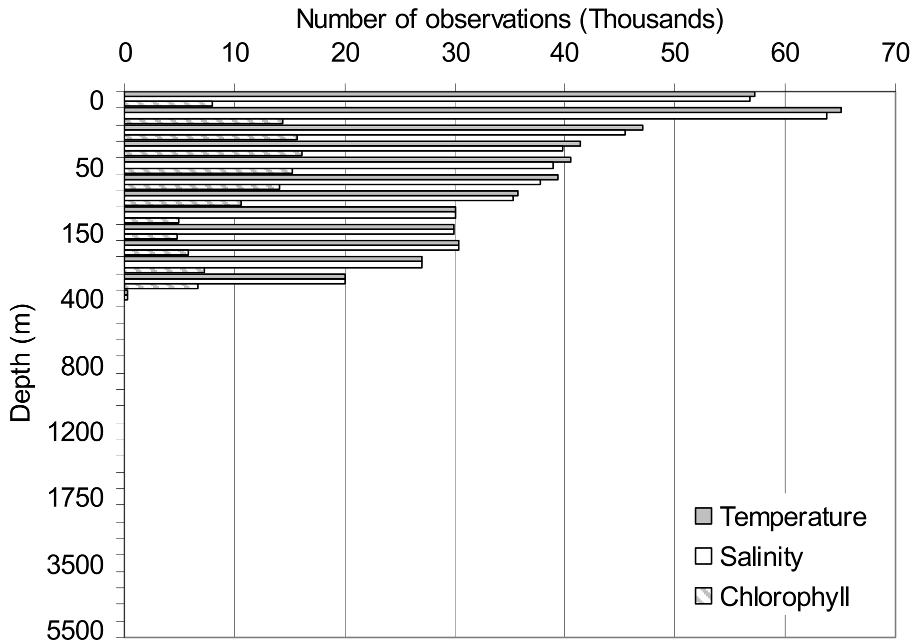

Figure 11.5. Distribution of UOR data at observed depth levels in WOD09.

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CHAPTER 12: INSTRUMENTED AUTONOMOUS PINNIPED 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. This pioneering work was followed up by various research groups that used other marine mammals, especially pinnipeds thanks to their size, to carry sensors and data loggers.

The Autonomous Pinniped Bathythermograph (APB) dataset presented in the WOD09 contains *in situ* temperature data from time-temperature-depth recorders (TTDR) manually attached to pinnipeds (*e.g*., elephant seals).

The instrumented pinnipeds data submitted to the NODC were collected by use of Northern elephant seals (*Mirounga angustirostris*) in the Northeast Pacific and Southern elephant seals (*Mirounga leonina*) in the Southern Ocean. The APB dataset in WOD09 is an update of the earlier version of the APB dataset in WOD05 by including Southern elephant seals data.

Data from 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). 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 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 CTD data.

12.2. INSTRUMENTATION

The APB data submitted to the NODC and presented in the WOD09 were collected by several research teams that used different sensors and data loggers. The instrumentation packages used by these research teams are basically 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 Northern Pacific elephant seals temperature and depth data were recorded by the Mk 3 TTDR data recording tags manufactured by Wildlife Computers, Seattle, Washington. The TTDRs were attached to the seal's fur on the dorsal midline above the shoulders using epoxy. Observations of the animal's surface behavior showed only the head was out of the water and the back remained underwater, therefore the temperature sensor was always submerged (Boehlert *et al.,* 2001). The TTDR data were recorded every 30 s and were retrieved with the instruments when the seals returned to the rookery months later. The instrument has a temperature resolution of 0.1ºC and an accuracy of 0.5ºC. All of the TTDRs had a manufacturer's stated minimum recording temperature of 4.8ºC (Boehlert *et al.,* 2001).

The pressure transducers on the TTDRs were calibrated prior to deployment using a pressure station. The Mk 3 TTDRs used had two transducer channels. In order to increase the accuracy on shallower dives TTDRs 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 Southern elephant seals were equipped with the Sea Mammal CTD, a specific configuration of Valeport's CTD. Temperature was measured by the Valeport fast response 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^{-1}, an accuracy of ±0.01mS·cm^{-1}, and a resolution of 0.002mS·cm^{-1}. Pressure was measured by the Keller PA-3L sensor, with a range of 2000 dbar, an accuracy of ±0.5% of full scale (±10m), and a resolution of 0.05 dbar.

12.4. GEOGRAPHICAL AND DEPTH DISTRIBUTION OF DATA

The WOD09 has a total of 89,583 APB vertical casts collected between 1997 and 2006. Figure 12.1 shows geographical distribution of 75,665 casts from Northern elephant seals in the Northeast Pacific and 13,918 casts from Southern elephant seals in the Southern Ocean, respectively. Figure 12.2 shows depth distribution of the entire data set.

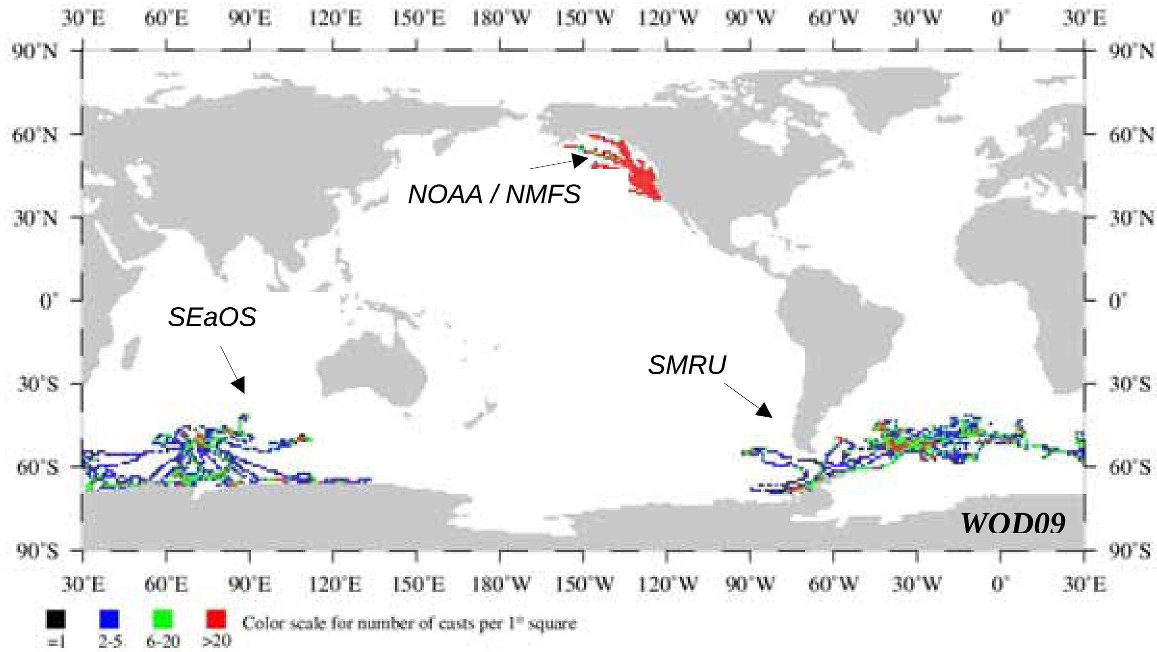

Figure 12.1. Geographical distribution of the APB data by one-degree squares.

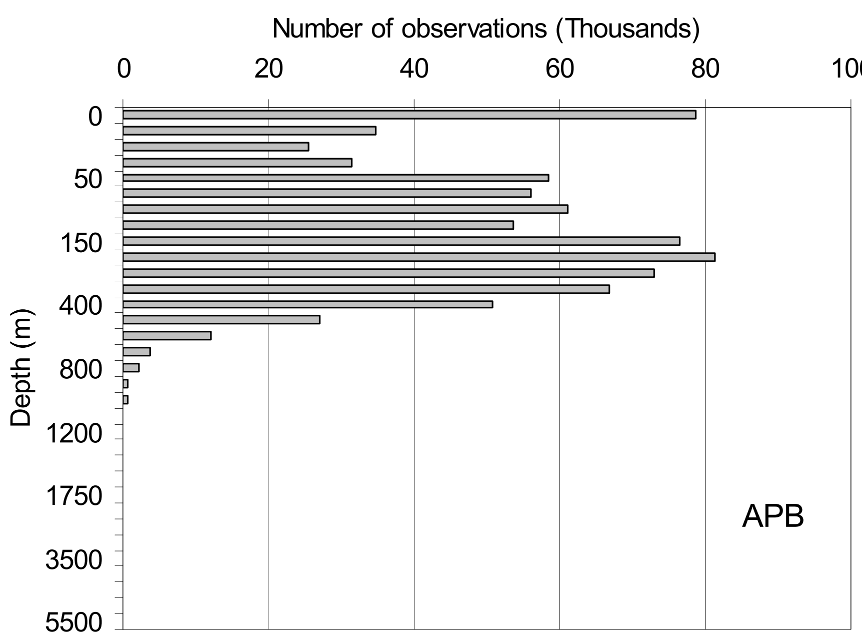

Figure 12.2. Distribution of Autonomous Pinniped Bathythermograph (APB) data at observed depth levels.

12.5. RELEVANT WEB SITES

NOAA/National Marine Fisheries Service, Southwest Fisheries Center, Pacific Fisheries Environmental Laboratory, Pacific Grove, California http://www.pfeg.noaa.gov/

Sea Mammal Research Unit: http://www.smru.st-andrews.ac.uk/pageset.aspx?psr=370

Ship of Opportunity Programme (SOOP) http://www.ifremer.fr/ird/soopip/index.html

Southern Elephant Seals as Oceanographic Samplers (SEaOS) http://biology.st-andrews.ac.uk/seaos/

Voluntary Observing Ships (VOS) http://www.ndbc.noaa.gov/vosinfo.shtml

Wildlife Computers, Seattle, WA http://www.wildlifecomputers.com

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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. WOD09 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 WOD09.

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 WOD09.
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

Table 13.2. National contributions of Micro Bathythermograph (Micro BT) profiles in WOD09.

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

[a] ISO = International Organization for Standardization
http://www.iso.org/iso/country_codes.htm

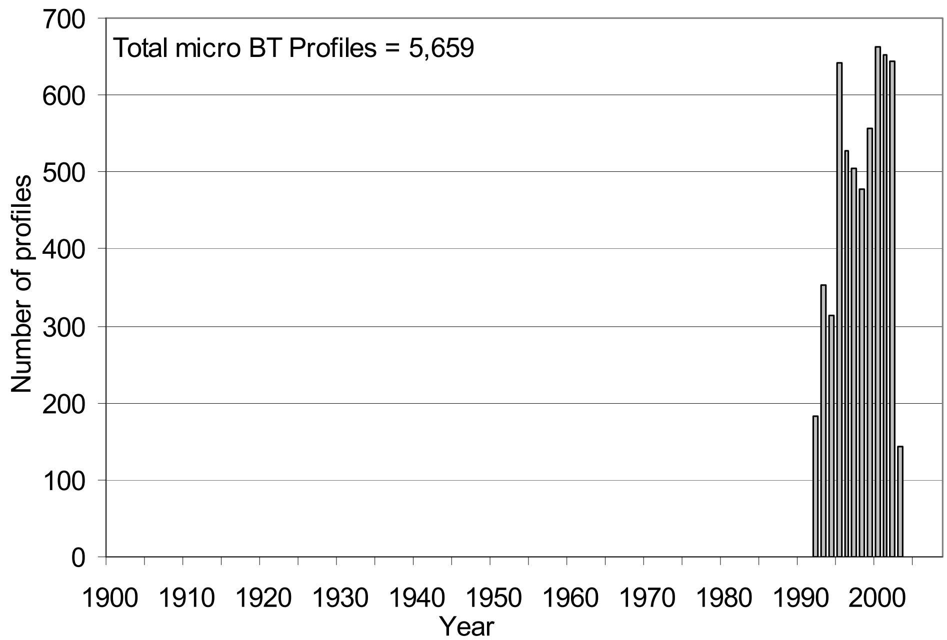

Figure 13.1. Temporal distribution of micro Bathythermograph data in WOD09.

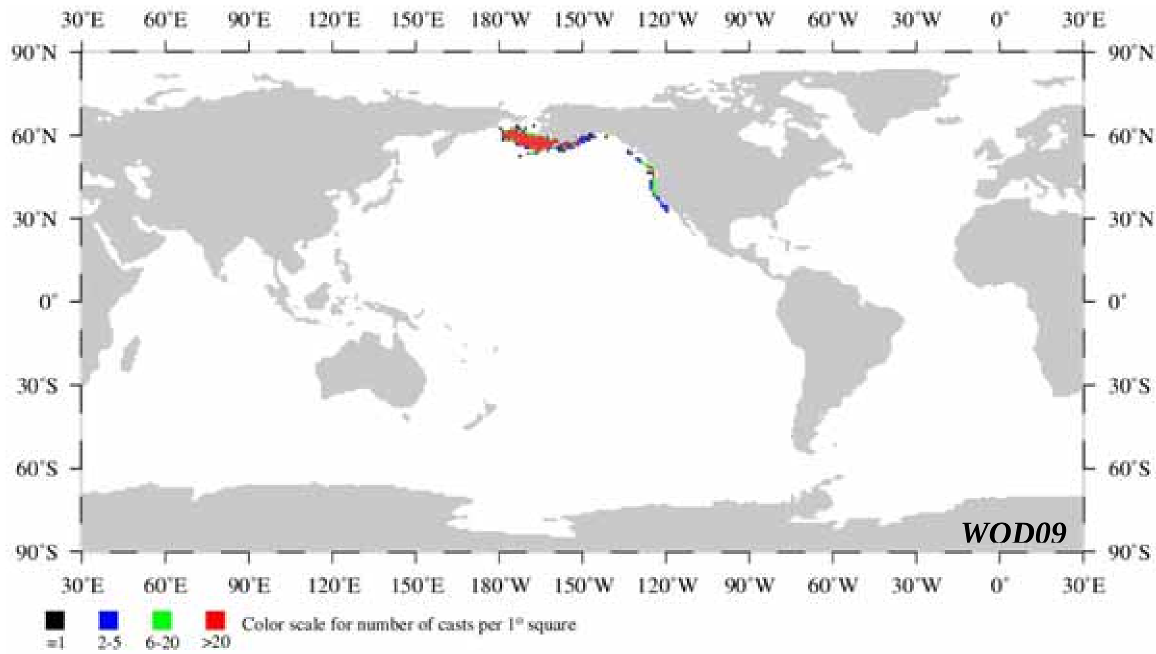

Figure 13.2. Geographic distribution of Micro Bathythermograph data in WOD09 by one-degree squares.

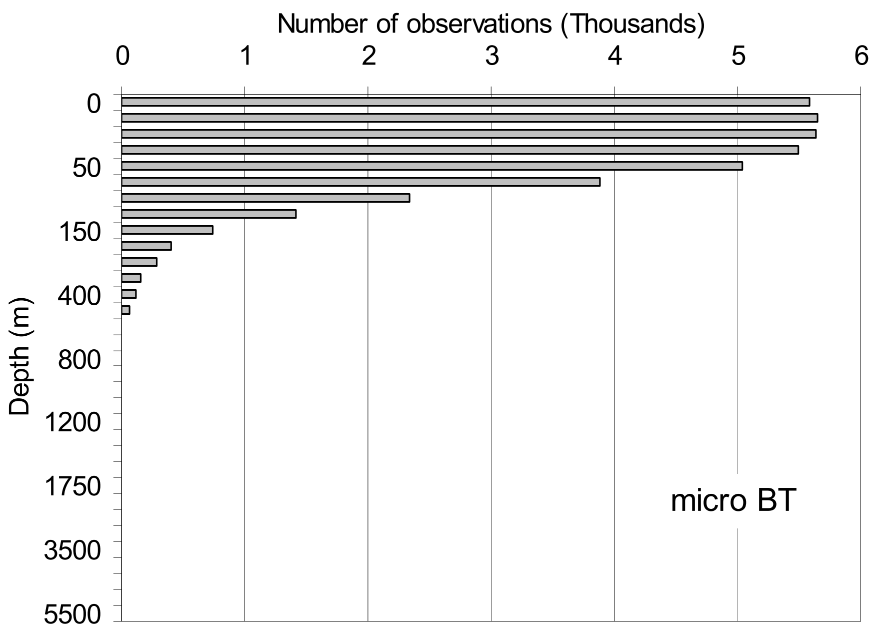

Figure 13.3. Distribution of micro Bathythermograph data at observed depth levels in WOD09.

CHAPTER 14: SURFACE-ONLY DATA (SUR)

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14.1. INTRODUCTION

The major focus of the WOD09 is sub-surface profile data. Therefore, surface data are included in WOD09 only if they were collected together with measurements of oceanographic variables of interest (Table 16.1), 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 WOD09 [*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 16.1). Table 16.2 lists the count of SUR observations as a function of year of collection since 1867.

14.2. DATA PRECISION

S 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.

Parameter [nominal abbreviation]	Reporting unit (nominal abbreviation)	Number of observations
Temperature [t]	Degree centigrade (°C)	502,358
Salinity [S]	Unit less	1,949,525
pH	Unit less	80
Total Chlorophyll [Chl] unless specified	Micro-gram per liter ($\mu g\ l^{-1}$)	44,256
Phaeophytin	Micro-gram per liter ($\mu g\ l^{-1}$)	118
Alkalinity [TALK]	Milli-equivalent per liter ($meq\ l^{-1}$)	77
Partial Pressure of Carbon Dioxide [pCO_2]	Micro-atmosphere (µatm)	36,217
Mole fraction of CO_2 in seawater [XCO_2sea]	Parts per million (ppm)	120,910
Air Temperature	Degree centigrade (°C)	49,648
CO_2warm[(1)]	Degree centigrade (°C)	59,680
Mole fraction of CO_2 in atmosphere [XCO_2atm]	Parts per million (ppm)	106,654
Barometric pressure	Milllibar (mb)	127,680
Latitude	Degrees of latitude	2,096,531
Longitude	Degrees of longitude	2,096,531
Julian Day	Day	2,096,531

[(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 WOD09 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 16.2). SUR data were collected routinely in the 19th century (Figure 16.1). But most of the SUR data were collected after the late 1990s (Figure 16.1). These SUR dataset consist of 207 cruises (Figure 16.2). Surface data collected before 1955 are often bucket samples, data acquired after 1957 are, most often, using 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 mainly were acquired by the TSG instruments mounted on ships-of-opportunity. Data collected over that period comprised more that 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 16.3 lists the input of data to the SUR dataset by country of origin. Figure 16.2 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 96% of the SUR data were acquired from three main sources: International Council for the Exploration of the Sea (ICES), Ship of Opportunity Programme (SOOP), and Institut Francais de Recherche Scientifique pour le developpement en Cooperation (ORSTOM). The remaining 3.8% came from the Scripps Institution of Oceanography (0.5%), National Institute for Environmental Studies (0.5%), Institute of Ocean Sciences, Sidney, Australia (0.4%), and several others.

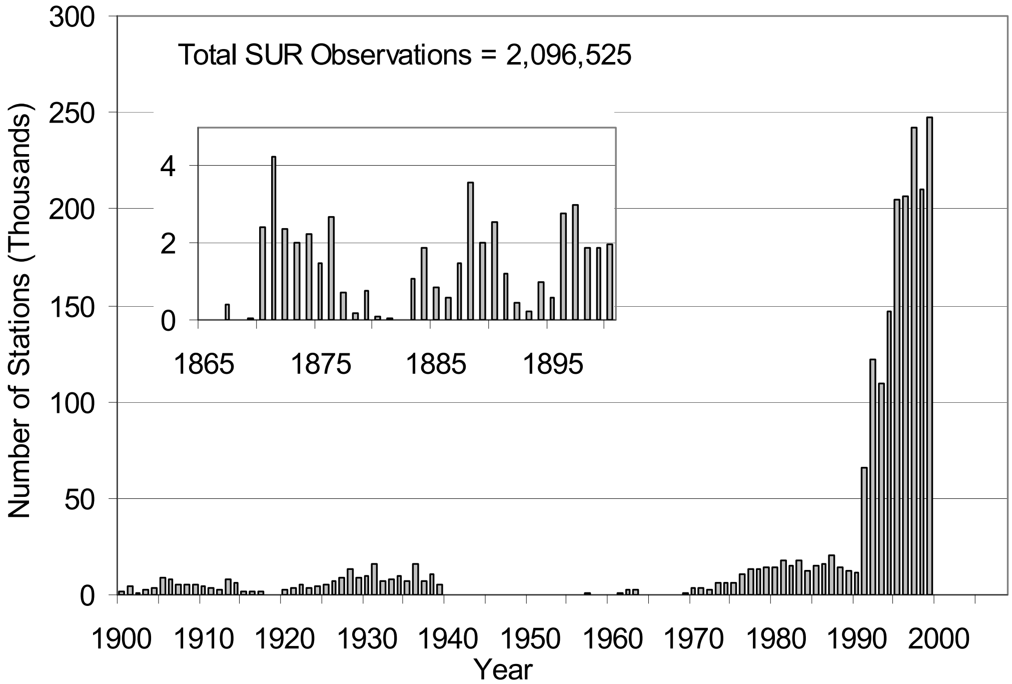

Figure 14.1. Temporal distribution of SUR observations in WOD09.

Table 14.2. Number or count of SUR observations as a function of year in WOD09.
Total number of observations (count) = 2,096,525

YEAR	COUNT	YEAR	COUNT	YEAR	COUNT	YEAR	COUNT
1867	398	1901	4,820	1935	7,355	1969	767
1868	0	1902	1,294	1936	16,058	1970	3,159
1869	44	1903	2,241	1937	7,488	1971	3,126
1870	2,421	1904	3,695	1938	10,858	1972	2,791
1871	4,261	1905	8,621	1939	5,745	1973	6,504
1872	2,366	1906	7,897	1940	48	1974	6,422
1873	2,029	1907	5,781	1941	0	1975	6,571
1874	2,240	1908	5,170	1942	0	1976	10,402
1875	1,480	1909	5,557	1943	0	1977	13,719
1876	2,691	1910	4,502	1944	0	1978	13,018
1877	725	1911	3,585	1945	0	1979	14,033
1878	187	1912	2,478	1946	0	1980	13,950
1879	780	1913	7,881	1947	0	1981	17,897
1880	68	1914	5,961	1948	0	1982	15,412
1881	41	1915	1,882	1949	0	1983	17,411
1882	15	1916	1,753	1950	0	1984	12,643
1883	1,075	1917	1,659	1951	0	1985	15,480
1884	1,884	1918	55	1952	26	1986	16,250
1885	861	1919	113	1953	22	1987	20,553
1886	601	1920	2,838	1954	0	1988	14,288
1887	1,475	1921	3,702	1955	0	1989	12,022
1888	3,589	1922	5,527	1956	0	1990	11,975
1889	2,013	1923	3,945	1957	839	1991	66,242
1890	2,523	1924	4,150	1958	0	1992	122,114
1891	1,197	1925	5,666	1959	0	1993	109,400
1892	468	1926	7,143	1960	0	1994	146,742
1893	214	1927	8,633	1961	555	1995	204,435
1894	1,003	1928	13,579	1962	2,961	1996	206,211
1895	570	1929	8,935	1963	2,972	1997	242,401
1896	2,777	1930	9,921	1964	0	1998	209,981
1897	3,005	1931	15,847	1965	0	1999	247,364
1898	1,885	1932	6,975	1966	0		
1899	1,885	1933	7,590	1967	0		
1900	1,975	1934	10,173	1968	0		

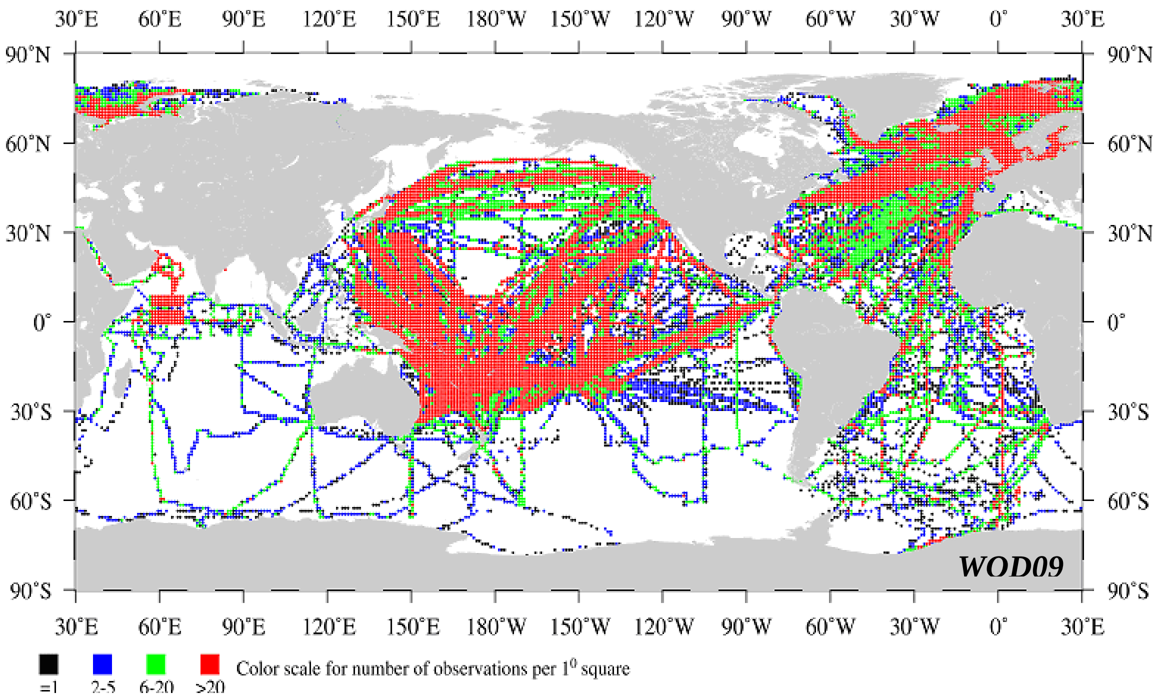

Figure 14.2. Geographic distribution of SUR observations in WOD09 by one-degree squares.

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Table 14.3. National contributions in the SUR dataset.

ISO[a] Country Codes	Country Name	Number of Cruises	Number of Observations	% of Total
FR	France	3,272	876,382	41.80
AU	Australia	85	681,879	32.52
99	Unknown	3,378	161,538	7.71
US	United States	63	100,492	4.79
DE	Germany	93	63,698	3.04
NO	Norway	245	59,714	2.85
JP	Japan	66	57,406	2.74
NC	New Caledonia	1,229	41,655	1.99
CA	Canada	34	18,682	0.89
GB	United Kingdom	345	16,514	0.79
DK	Denmark	178	8,274	0.39
PL	Poland	23	2,824	0.13
FL	Finland	18	2,593	0.12
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
EE	Estonia	3	84	< 0.01
IN	India	4	48	< 0.01
	Total	*9,150*	*2,096,525*	*100.00*

[a] ISO = International Organization for Standardization
http://www.iso.org/iso/country_codes.htm

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 several thousands 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 gradient. 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).

Table 15.1. Glider capabilities

Glider	Max depth, m	Max speed, $m \cdot s^{-1}$	Duration, days
Seaglider	1000	0.5	200
Slocum	2000	0.5	20
Spray	1500	0.5	330

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 2000 m (Table 15.1). Their battery lifetime ranges from a few weeks to several months. Gliders' speed is typically 0.5 $m \cdot s^{-1}$ (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.

15.2. GLIDER DESIGN AND OPERATION

There are several types of operational gliders developed thus far (Table 15.1): Seaglider (Eriksen *et al.*, 2001) built at the University of Washington, Slocum Gliders (Webb *et al.*, 2001) manufactured by Webb Research Corp, and Spray (Sherman *et al.*, 2001) built at Scripps Institution of Oceanography (Rudnick *et al.*, 2004). 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 and dive 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 75°). 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 0.5 $m \cdot s^{-1}$, 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 (Rudnick *et al.*, 2004).

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 at http://www.apl.washington.edu/projects/seaglider/summary.html.

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. GEOGRAPHICAL AND DEPTH DISTRIBUTION OF GLIDER DATA

Figure 15.1 shows the geographical distribution of 5,857 glider casts collected between 2004-2007. There are several major projects and Institutions collecting gliders data which are labeled on that figure: Pacific Rim Military Exercises (RIMPAC), Marine Environment and Security for the European Area Integrated Project (MERSEA), and Laboratorio di Simulazioni Numeriche del Clima e Degli Ecosistemi Marini (SINCEM). MERSEA project operates gliders in both Mediterranean Sea and in the North Atlantic (labeled on Fig. 15.1 as SPRAY004CIS and SPRAY004PAR).

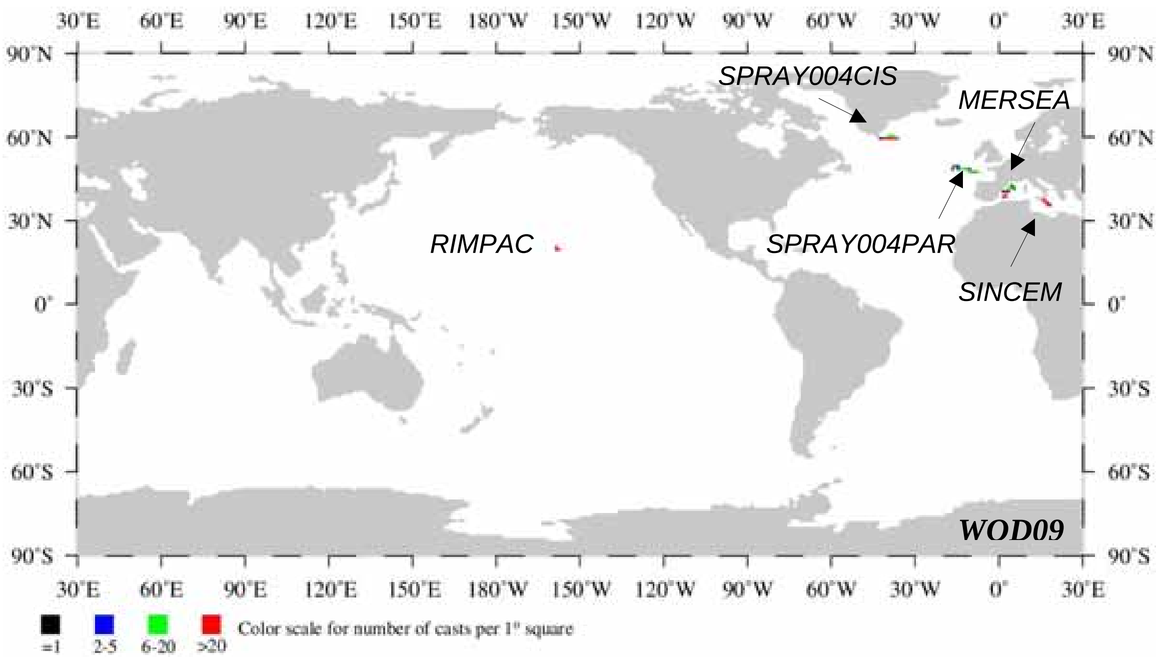

Figure 15.1. Geographical distribution of Glider observations in WOD09 by one-degree squares.

15.4. RELEVANT WEB SITES

Applied Physics Laboratory, University of Washington, Seaglider:
http://www.apl.washington.edu/projects/seaglider/summary.html

Autonomous Systems Laboratory, Woods Hole Oceanographic Institute:
http://asl.whoi.edu/news.html#

AUV Laboratory, Massachusetts Institute of Technology, Sea Grant College Program:
http://auvlab.mit.edu/MURI/1997_Rprtfinal.html

CTD Instrument: www.windows.ucar.edu/tour/link=/earth/Water/CTD.html&edu=high

Glider Information and Navigation Assistant (GINA):
https://seaglider.ocean.washington.edu/cgi-bin/all_missions.cgi?AT=1

Mediterranean Forecasting System:
http://www.ifm.uni-kiel.de/fb/fb1/po2/research/mfstep/product.html

Navy News (NewsStand): http://www.news.navy.mil/search/display.asp?story_id=21139

RIMPAC-04: http://www.defence.gov.au/rimpac04/

Rutgers University, Coastal Ocean Observation Lab, Institute of Marine and Coastal Sciences: http://marine.rutgers.edu/cool/projects/oceanrobots.htm

SBE 911 plus CTD:
http://www.seabird.com/pdf_documents/datasheets/911plusbrochureFeb05.pdf

SCRIPPS Institute of Oceanography, Spray: http://spray.ucsd.edu/

Webb Research Corporation: http://www.webbresearch.com/

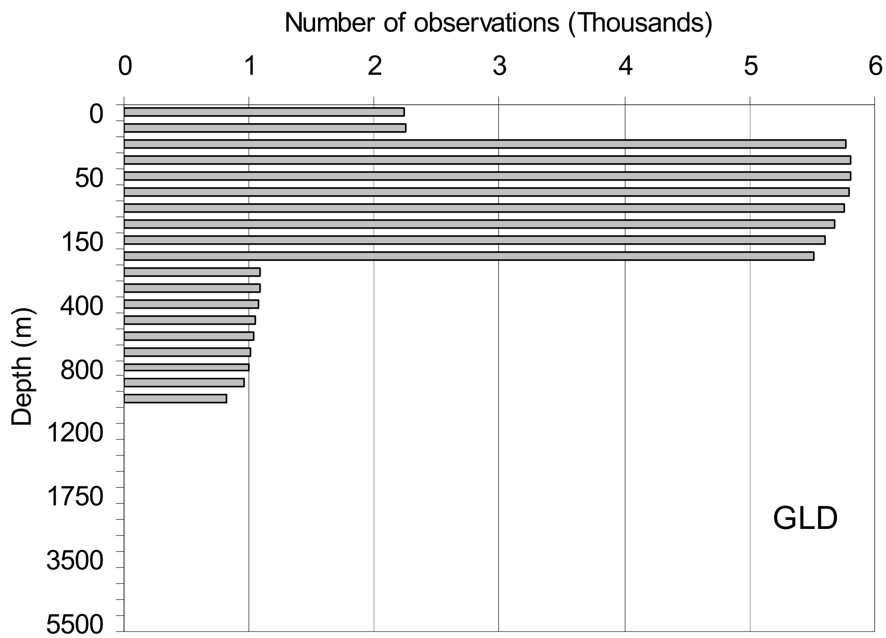

Figure 15.2. Distribution of Glider (GLD) data at observed depth levels.

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CHAPTER 16: PLANKTON DATA

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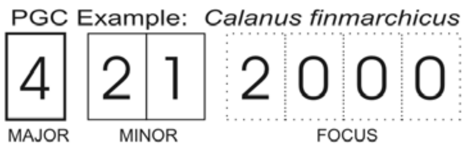
16.1. INTRODUCTION

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 2009* (WOD09) includes and extends the content of the previously released *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 WOD09 plankton data subset is a collection of measurements from serial bottle and plankton net-tow. The plankton measurements are represented in WOD09 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 WOD09 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. WOD09 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 and Schwartz 1998). The PGC is an ancillary code which places each taxon into broader groups (*e.g., phytoplankton, diatoms, zooplankton, copepods*) and allows the WOD09 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. WOD09 has replaced all BGC codes with their corresponding PGC codes.

The typical plankton cast, as represented in WOD09, stores taxon specific and/or biomass data in individual sets, called “Taxa-Record”. Figure 16.1 demonstrates an example of a plankton cast in WOD09.

```
Longitude  Latitude  Year  Month  Day   Time Cruise#   CC   Prof_#

-4.883     79.017    1991    6      9   ----   10438   DE   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    0        lower_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#	**772**
Project	**435**
Platform	**199**
Institution	**892**
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 WOD09 (using provided output software).

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 WOD09 documentation (Johnson *et al.,* 2009).

The alternative way to receive plankton data is a "csv" (comma-separated value) output file, which is available only through the WODselect – the online WOD09 database retrieval system (http://www.nodc.noaa.gov/OC5/SELECT/dbsearch/dbsearch.html).

```
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 WOD09 (*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 WOD09 documentation, Appendix 5.11, (Johnson *et al.,* 2009). 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. WOD09 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. WOD09 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 Ash-free Dry Mass	0.001	100	$mg \cdot m^{-3}$

WOD09 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 WOD09 have been contributed by 31 countries, 135 institutions and more than 40 projects. Significant amounts of data (98,500 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, 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 (~47,000 casts) was received from Coastal and Oceanic Plankton Ecology Production and Observation Database (COPEPOD)[1] as

[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 WOD09.

ISO[a] Country Code	Country Name	Plankton Casts	% of Total
US	United States	110,911	50.71
JP	Japan	41,372	18.92
PE	Peru	22,874	10.46
SU	Union of Soviet Socialist Republics	17,362	7.94
GB	Great Britain	15,680	7.17
ID	Indonesia	2,098	0.96
PT	Portugal	1,611	0.74
IN	India	970	0.44
DE	Germany	868	0.40
AU	Australia	763	0.35
FR	France	752	0.34
CA	Canada	656	0.30
PL	Poland	405	0.19
NO	Norway	403	0.18
EC	Ecuador	352	0.16
MX	Mexico	293	0.13
BR	Brazil	199	0.09
KR	Korea, Republic of	193	0.09
PH	Philippines	184	0.08
TW	Taiwan	141	0.06
ZA	South Africa	141	0.06
NC	New Caledonia	136	0.06
CO	Colombia	97	0.04
ES	Spain	71	0.03
BE	Belgium	38	0.02
NL	Netherlands	36	0.02
SG	Singapore	35	0.02
PK	Pakistan	22	0.01
AR	Argentina	11	0.01
SE	Sweden	11	0.01
TH	Thailand	10	<0.01
	Total	*218,695*	*100.00*

[a] ISO = International Organization for Standardization
http://www.iso.org/iso/country_codes.htm

a result of collaboration between NODC and National Marine Fisheries Service (NMFS).

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, 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. The 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	Plankton Casts	% of Total
33	*CalCOFI: California Cooperative Oceanic Fisheries Investigation	38,980	32.4
51	*MARMAP: Marine Resource Monitoring Assessment Prediction Program	19,646	16.4
121	*SEAMAP: Southeast Area Monitoring and Assessment Program	11,996	10.0
81	*OCSEAP: Outer continental shelf environmental assessment program	7,920	6.6
174	*FOCI: Fisheries-Oceanography Cooperative Investigations	6,663	5.5
3	*EASTROPAC (1967-1968)	5,544	4.6
526	GENERAL FISHERIES RESEARCH (YugNIRO)	5,438	4.5
243	KER: Kuroshio exploitation and utilization research (1977 - 1995)	4,234	3.5
93	BRINE DISPOSAL	4,198	3.5
25	IIOE: International Indian Ocean Expedition	2,045	1.7
240	USAP or USARP : United States Antarctic Research Project	1,770	1.5

NODC Project Code	Project Name	Plankton Casts	% of Total
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
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	0.6
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
82	PSERP: Mesa Puget Sound	396	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	0.3
310	JGOFS/EQPAC: Equatorial Pacific basin study	279	0.2
96	EPA: Buccaneer oil field	214	0.2
321	BOFS: Biogeochemical Ocean Flux Study	180	0.2
443	IMECOCAL: Investigaciones Mexicanas De La Corriente De California	174	0.1
34	MAZATLAN	119	0.1
255	CTZ: Coastal Transition Zone	100	< 0.1
245	SEFCAR: South Eastern Florida and Caribbean Recruitment	88	< 0.1
328	SIBEX: Second International Biomass Experiment - Fr	63	< 0.1
312	CEAREX: Coordinated Eastern Arctic Experiment	63	< 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	*120,195*	*100.0*

16.4. PLANKTON DATA DISTRIBUTIONS

The WOD09 plankton subset consists of 218,695 globally distributed casts (Figure 16.3). The temporal distribution of plankton sampling covers period from 1905 to 2006 year (Figure 16.4). Table 16.6 gives the yearly counts of plankton casts in the WOD09.

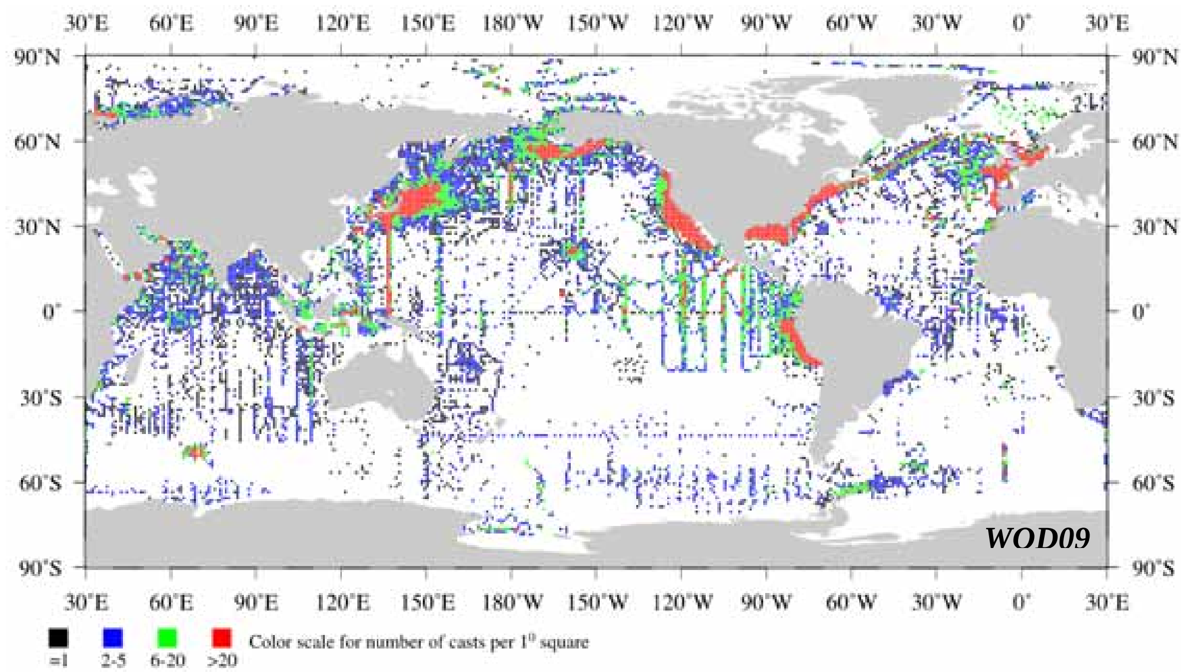


Figure 16.3. Geographic distribution of plankton (218,695 casts) in WOD09 by one-degree squares.

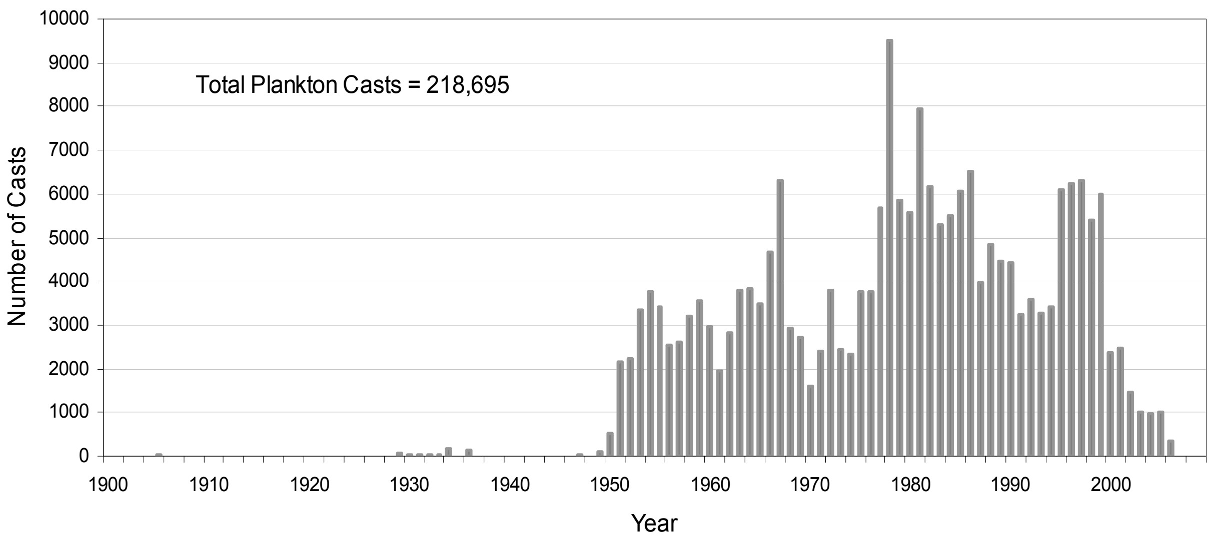


Figure 16.4. Temporal distributions of plankton casts in WOD09 as a function of year.

Table 16.6. Number of plankton casts in WOD09 as a function of year for the World Ocean
Total Number of Casts = 218,695

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1905	34	1947	24	1968	2932	1988	4842
1913	6	1949	98	1969	2716	1989	4449
1914	5	1950	514	1970	1605	1990	4432
1915	9	1951	2149	1971	2419	1991	3256
1921	17	1952	2247	1972	3801	1992	3590
1925	17	1953	3354	1973	2449	1993	3284
1927	16	1954	3758	1974	2318	1994	3428
1928	2	1955	3423	1975	3761	1995	6114
1929	71	1956	2548	1976	3752	1996	6223
1930	46	1957	2602	1977	5673	1997	6313
1931	36	1958	3222	1978	9500	1998	5393
1932	18	1959	3539	1979	5838	1999	6002
1933	19	1960	2962	1980	5581	2000	2369
1934	179	1961	1959	1981	7951	2001	2491
1936	123	1962	2814	1982	6152	2002	1461
1938	6	1963	3784	1983	5307	2003	1009
1939	10	1964	3816	1984	5507	2004	972
1940	2	1965	3473	1985	6053	2005	1025
1942	2	1966	4682	1986	6508	2006	342
1946	6	1967	6319	1987	3966		

16.5. PLANKTON CONTENT

The plankton measurements are represented in WOD09 as descriptive and numeric abundance, and biomass data. The majority (52 %) of plankton measurements are total biomass. Contributions of plankton casts by measurement type are shown in Figure 16.5.

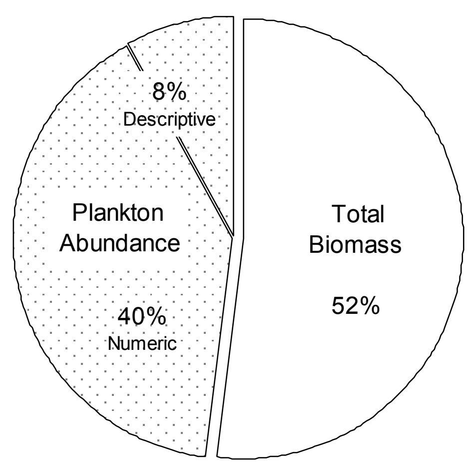


Figure 16.5 Contributions of Plankton casts by measurement type.

16.5.1. Abundance

The majority (84%) of plankton abundance measurements in WOD09 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 (16 %) of total abundance. The WOD09 plankton abundance content, listed by major plankton groups and sub-groups, is summarized in Table 16.7.

Table 16.7 WOD09 abundance measurements content.

PGC	Plankton Group	Numeric abundance (casts #)	Descriptive abundance (casts#)
1000000	**BACTERIA** (*all sub-groups*)	1986	26
1050000	Cyanobacteria	974	25
2000000	**PHYTOPLANKTON** (*all sub-groups*)	37461	21472
2040000	Granuloreticulosa (Foraminifera)	5506	96
2070000	Dinomastigota (Dinoflagellata)	14452	20406
2080000	Ciliophora (ciliates)	4632	6578
2100000	Haptomonada (Coccolithophorids)	5341	363
2110000	Cryptomonada (Chrytophyta)	1910	8
2120000	Discomitochondria	1333	242
2130000	Chrysomonada (Chrysophyta)	5181	4762
2160000	Diatoms (Bacillariophyta)	22487	19346
2270000	Actinopoda (amoeba)	3699	313
2280000	Chlorophyta (green algae)	1060	59
4000000	**ZOOPLANKTON** (*all sub-groups*)	44307	4299
4030000	Cnidaria (coelenterates)	15114	2184
4040000	Ctenophora (comb jellies)	3745	97
4050000	Platyhelminthes (flat worms)	2038	0
4090000	Nemertina (ribbon worms)	2326	1
4130000	Rotifera (rotifers)	2051	92
4180000	Entoprocta	2157	0
4190000	Arthropoda: Chelicerata	841	152
4200000	Arthropoda: Mandibulata ("insects")	4125	31
4210000	Arthropoda: Crustacea (*all sub-groups*)	38249	3943
4211000	*Crustacea*: Ostracoda	12378	179
4212000	*Crustacea*: Copepoda	34941	3692
4213000	*Crustacea*: Cirripedia (barnacles)	6789	489
4214000	*Crustacea*: Mysidacea	1045	8
4216000	*Crustacea*: Isopoda	3828	48
4217000	*Crustacea*: Amphipoda	14238	1369
4218000	*Crustacea*: Euphausiacea	16717	1649
4219000	*Crustacea*: Decapoda	14506	1025
4220000	Annelida (segmented worms)	13495	1771
4230000	Sipuncula	2075	2
4260000	Mollusca (*all sub-groups*)	18314	1118

PGC	Plankton Group	Numeric abundance (casts #)	Descriptive abundance (casts#)
4262500	*Mollusca*: Gastropoda (snails & slugs)	15973	364
4265000	*Mollusca*: Bivalvia (bivalve molluscs)	3189	115
4267500	*Mollusca*: Cephalopoda	4103	26
4300000	Brachiopoda (lamp shells)	2100	1
4310000	Phoronida	1230	0
4320000	Chaetognatha (arrow worms)	25695	2720
4330000	Hemichordata	2003	0
4340000	Echinodermata	5711	475
4350000	Urochordata (*all sub-groups*)	19066	2794
4352500	*Urochordata*: Ascidiacea (sea squirts)	869	0
4355000	*Urochordata*: Thaliacea (salps & doliolids)	6607	53
4357500	*Urochordata*: Larvacea / Appendicularia	17345	662
4360000	Cephalochordata / Leptocardia	2458	17
5000000	**ICHTHYOPLANKTON**	53179	177

The geographic distribution of numerical abundance casts of major plankton groups for WOD09 is shown in Figures 16.6 – 16.9.

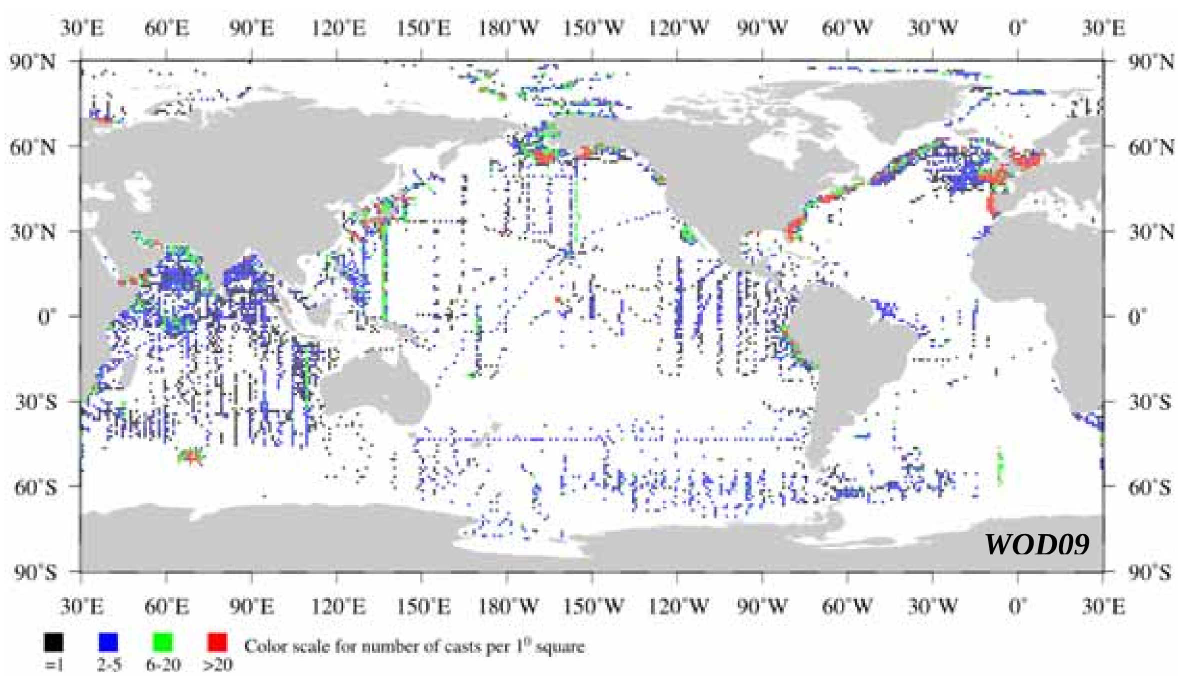


Figure 16.6. Geographic distribution of zooplankton numerical abundance (44,307 casts) in WOD09 by one-degree squares.

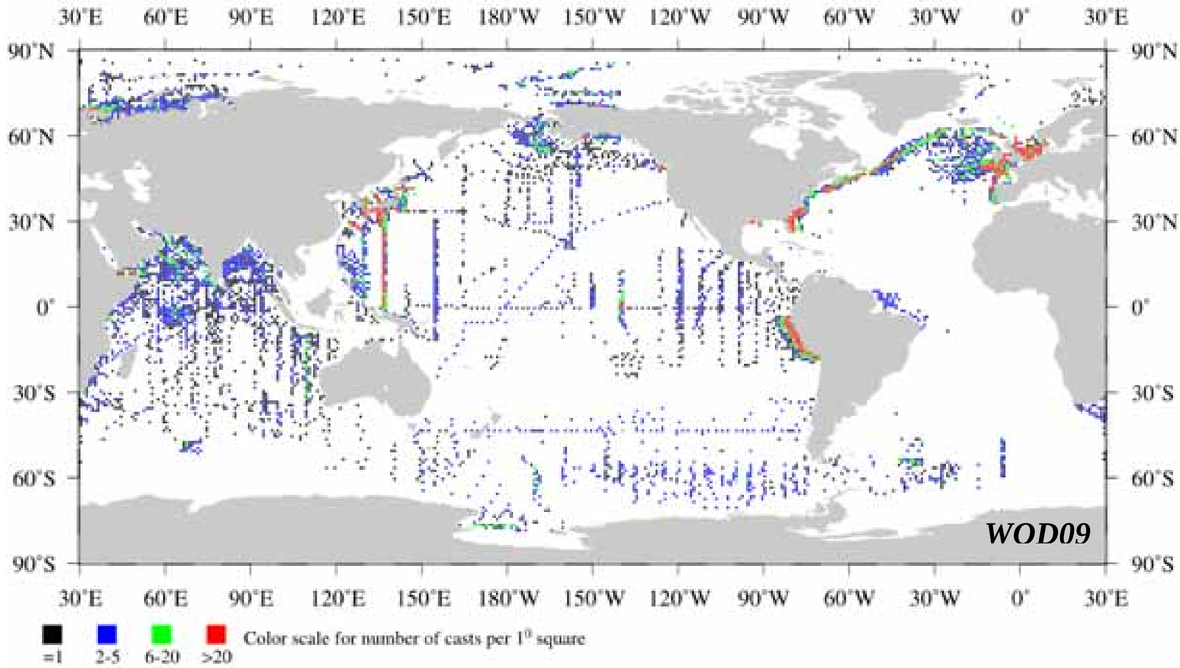


Figure 16.7. Geographic distribution of phytoplankton numerical abundance (37,461 casts) in WOD09 by one-degree squares.

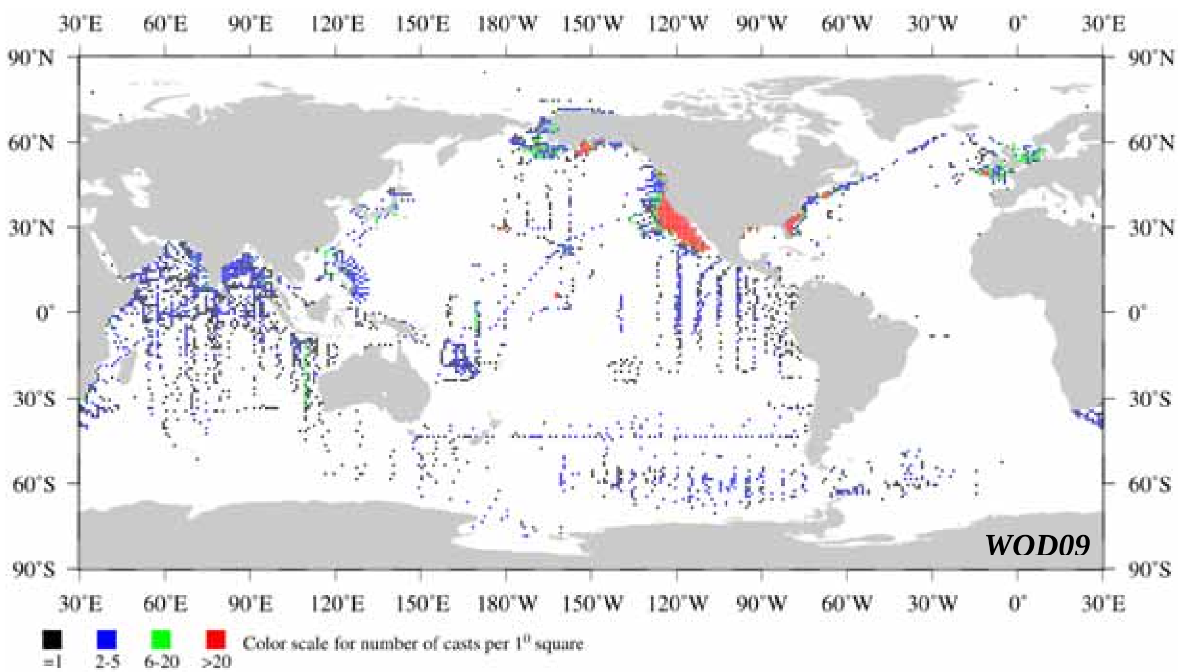


Figure 16.8. Geographic distribution of ichthyoplankton numerical abundance (53,179 casts) in WOD09 by one-degree squares.

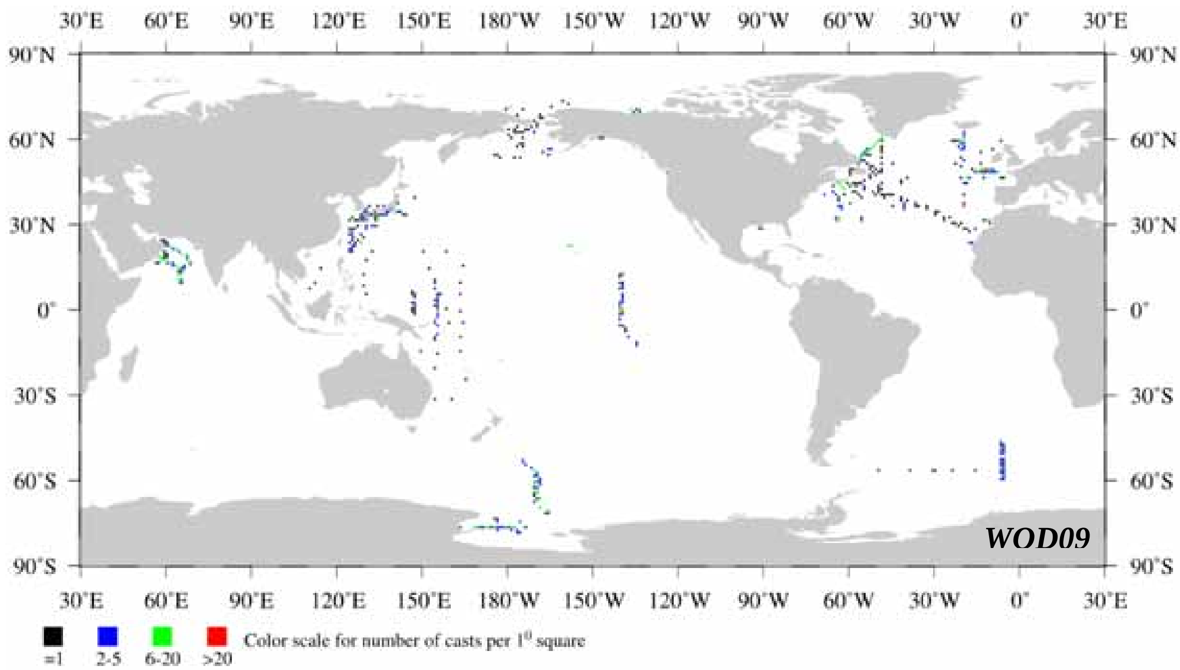


Figure 16.9. Geographic distribution of bacterioplankton numerical abundance (1,986 casts) in WOD09 by one-degree squares.

16.5.2. Total Biomass

The WOD09 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 using a settled volume, a displacement volume, a wet mass, a dry mass, or an ash-free dry mass. Although the sampling methods of total biomass data represented in the WOD09 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 60-70^{o}C.

Total Ash-free Dry Mass: a known weight of the dry sample ashed to a final weight at 450-500^{o}C.

Table 16.8. WOD09 biomass measurements content.

PGC Code	Taxonomic Description	Count of Casts	% of Total
-401	Total Displacement Volume	104,623	70.32
-402	Total Settled Volume	8,223	5.53
-403	Total Wet Mass	33,820	22.73
-404	Total Dry Mass	1,008	0.68
-405	Total Ash-free Dry Mass	274	0.18

The majority of WOD09 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 WOD09 documentation, Table. 6 (Johnson *et al.*, 2009).

The geographic distribution of biomass casts for WOD09 is shown in Figures 16.10. – 16.14.

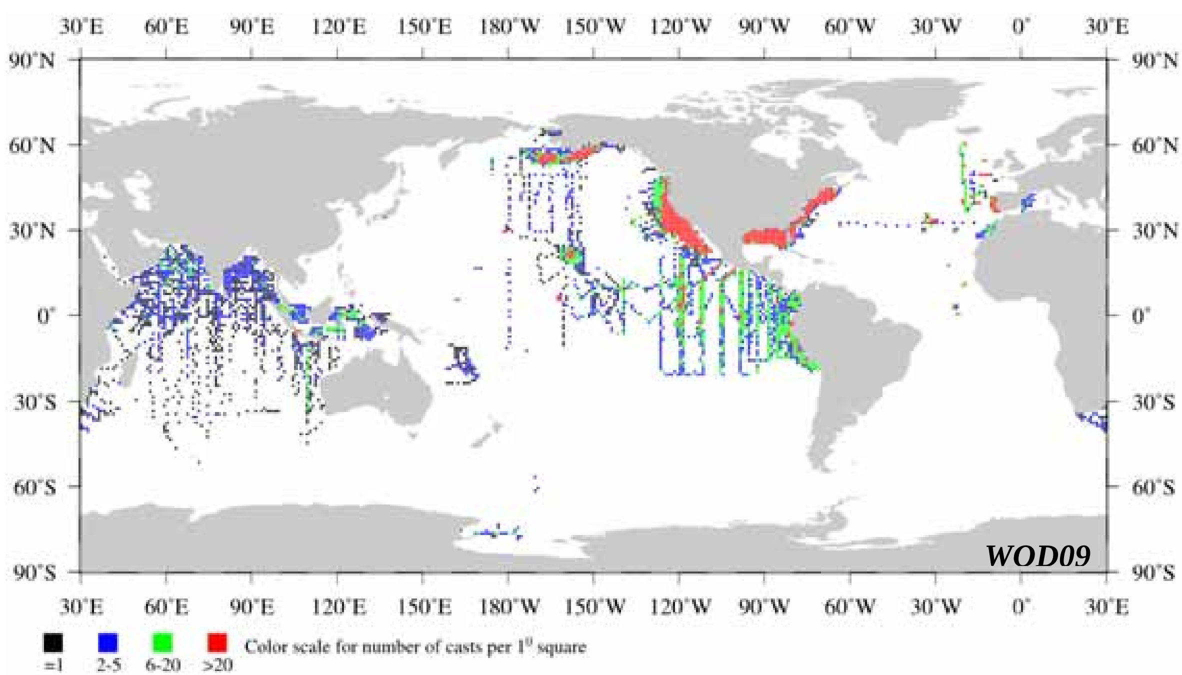


Figure 16.10. Geographic distribution of total displacement volume (104,623 casts) in WOD09 by one-degree squares.

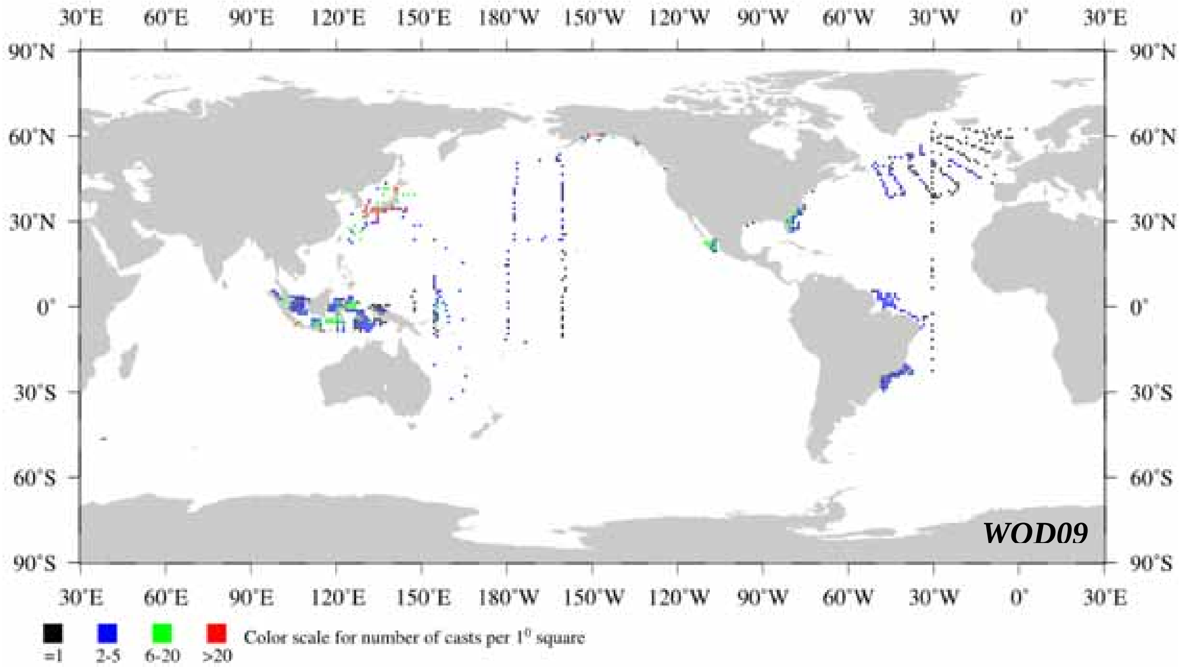


Figure 16.11. Geographic distribution of total settled volume (8,223 casts) in WOD09 by one-degree squares.

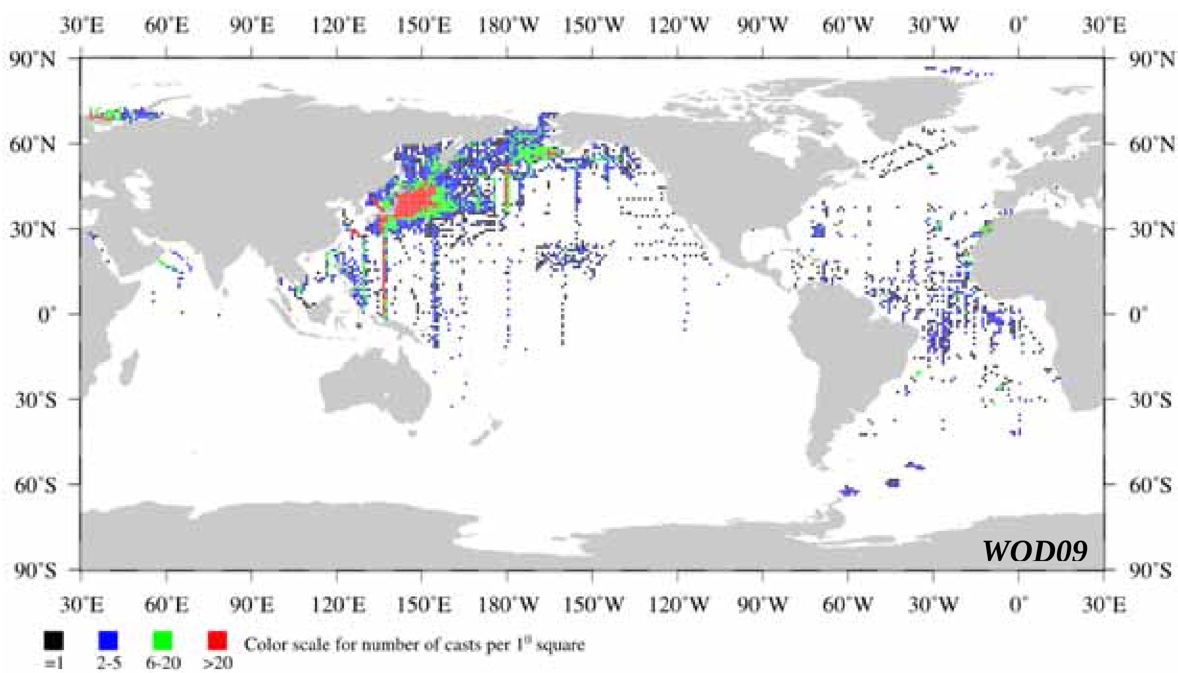


Figure 16.12. Geographic distribution of total wet mass (33,820 casts) in WOD09 by one-degree squares.

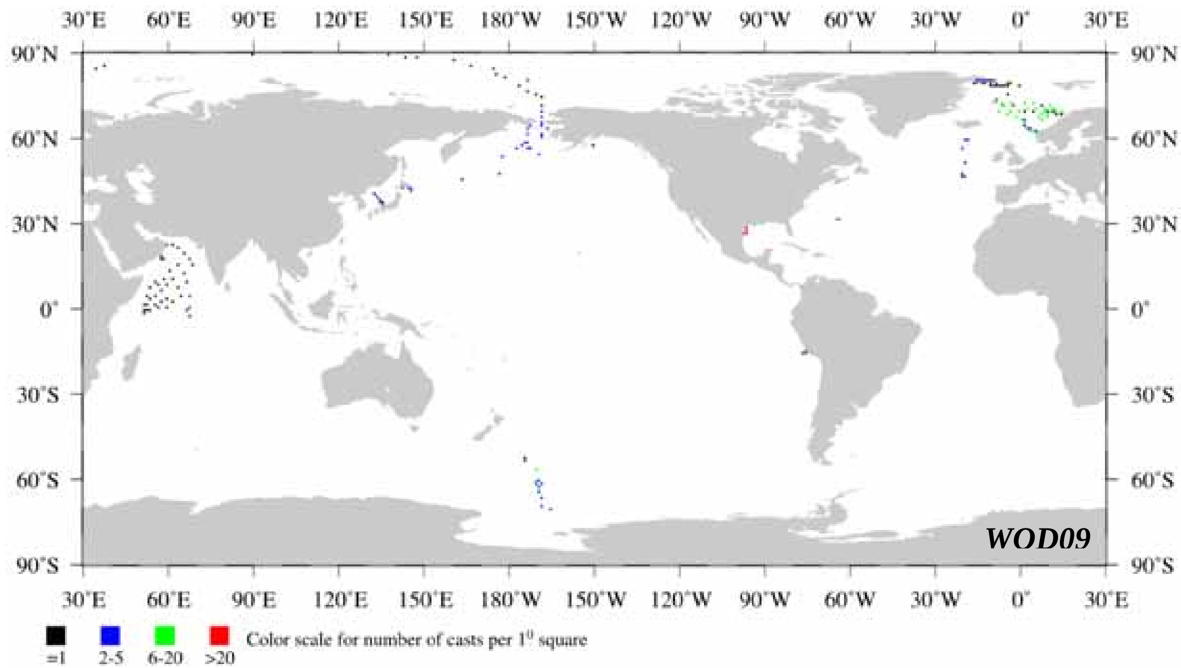


Figure 16.13. Geographic distribution of total dry mass (1,008 casts) in WOD09 by one-degree squares.

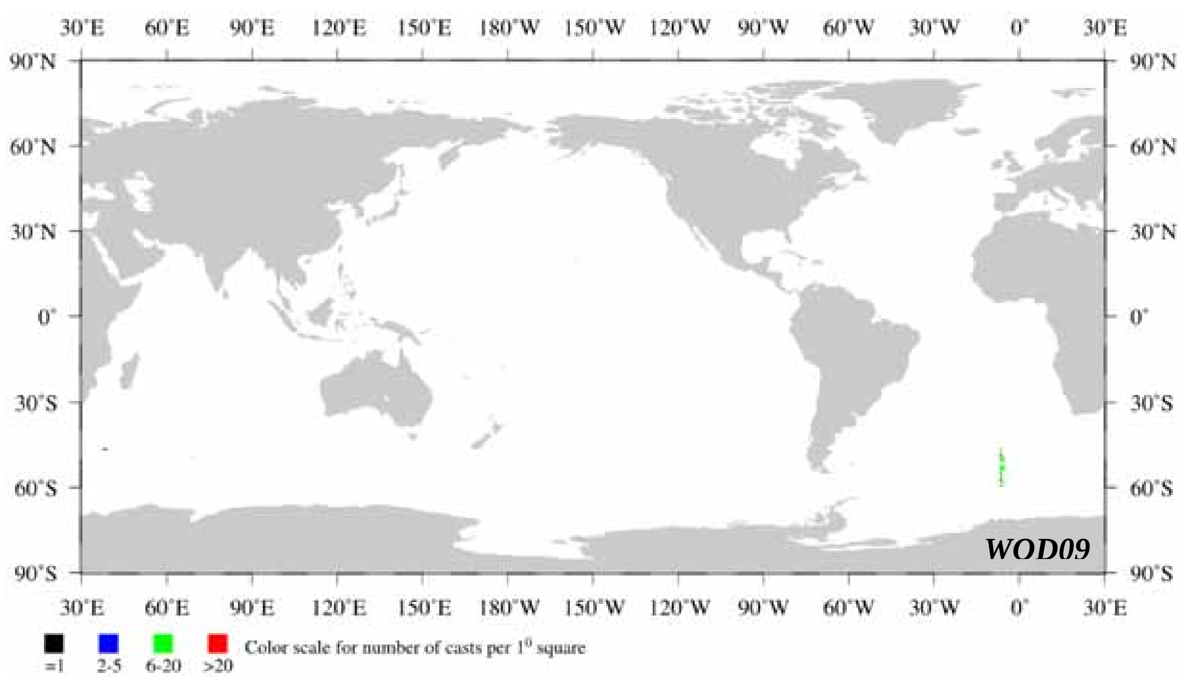


Figure 16.14. Geographic distribution of total ash-free dry mass (274 casts) in WOD09 by one-degree squares.

16.6. REFERENCES AND BIBLIOGRAPHY

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Appendix 1.

Table A1.1. Temperature bias corrections for XBT data

Year	Depth (m)															
	0	10	20	30	50	75	100	125	150	200	250	300	400	500	600	700
1966.5	0.117	0.200	0.228	0.200	-0.058	-0.055	-0.012	0.027	0.032	0.090	0.083	0.113	0.133	0.030	0.164	0.250
	944	*937*	*940*	*933*	*929*	*911*	*899*	*884*	*873*	*832*	*838*	*820*	*759*	*77*	*45*	*37*
1967.5	0.104	0.174	0.232	0.228	0.101	0.047	0.055	0.066	0.047	0.049	0.060	0.084	0.105	0.164	0.131	0.193
	1279	*1272*	*1276*	*1270*	*1262*	*1243*	*1224*	*1218*	*1196*	*1140*	*1165*	*1135*	*1067*	*270*	*149*	*116*
1968.5	0.086	0.134	0.172	0.202	0.149	0.081	0.068	0.056	0.054	0.089	0.084	0.090	0.106	0.167	0.185	0.178
	1521	*1506*	*1515*	*1509*	*1498*	*1458*	*1436*	*1420*	*1402*	*1339*	*1367*	*1338*	*1264*	*479*	*287*	*234*
1969.5	0.051	0.060	0.104	0.157	0.141	0.166	0.169	0.162	0.173	0.138	0.160	0.144	0.159	0.176	0.165	0.178
	1869	*1851*	*1858*	*1853*	*1837*	*1796*	*1766*	*1744*	*1727*	*1642*	*1677*	*1646*	*1530*	*726*	*440*	*379*
1970.5	0.117	0.134	0.167	0.228	0.236	0.217	0.200	0.199	0.167	0.169	0.165	0.156	0.169	0.191	0.177	0.185
	2060	*2030*	*2046*	*2041*	*2020*	*1981*	*1952*	*1918*	*1911*	*1814*	*1836*	*1814*	*1694*	*975*	*545*	*450*
1971.5	0.103	0.146	0.195	0.223	0.282	0.278	0.257	0.207	0.167	0.189	0.172	0.169	0.189	0.202	0.140	0.125
	2067	*2029*	*2043*	*2040*	*2015*	*1973*	*1958*	*1929*	*1928*	*1809*	*1866*	*1823*	*1678*	*1125*	*559*	*444*
1972.5	0.160	0.182	0.218	0.254	0.321	0.317	0.283	0.246	0.224	0.204	0.202	0.212	0.224	0.247	0.182	0.167
	2092	*2070*	*2096*	*2094*	*2065*	*2026*	*2005*	*1975*	*1970*	*1877*	*1909*	*1852*	*1723*	*1206*	*579*	*472*
1973.5	0.152	0.165	0.208	0.276	0.321	0.335	0.310	0.297	0.264	0.236	0.226	0.219	0.232	0.269	0.184	0.199
	2049	*2045*	*2048*	*2040*	*2020*	*1981*	*1962*	*1947*	*1941*	*1863*	*1881*	*1825*	*1725*	*1177*	*564*	*483*
1974.5	0.109	0.142	0.195	0.268	0.309	0.303	0.283	0.277	0.274	0.276	0.258	0.242	0.255	0.254	0.147	0.144
	2034	*2029*	*2037*	*2026*	*2002*	*1962*	*1938*	*1919*	*1905*	*1820*	*1839*	*1796*	*1690*	*1165*	*548*	*471*
1975.5	0.151	0.190	0.214	0.254	0.271	0.288	0.267	0.244	0.239	0.285	0.259	0.255	0.265	0.269	0.173	0.173
	1982	*1979*	*1985*	*1973*	*1954*	*1915*	*1897*	*1876*	*1856*	*1786*	*1796*	*1763*	*1662*	*1105*	*500*	*413*
1976.5	0.166	0.196	0.228	0.261	0.258	0.274	0.274	0.250	0.264	0.254	0.236	0.239	0.247	0.232	0.166	0.189
	1990	*1982*	*1992*	*1990*	*1967*	*1921*	*1900*	*1881*	*1865*	*1799*	*1810*	*1759*	*1680*	*1094*	*520*	*419*
1977.5	0.081	0.117	0.141	0.202	0.246	0.238	0.245	0.229	0.208	0.207	0.211	0.225	0.210	0.225	0.193	0.202
	2007	*1997*	*2008*	*1997*	*1977*	*1942*	*1909*	*1892*	*1870*	*1800*	*1821*	*1782*	*1702*	*1114*	*559*	*443*

Year	Depth (m)															
	0	**10**	**20**	**30**	**50**	**75**	**100**	**125**	**150**	**200**	**250**	**300**	**400**	**500**	**600**	**700**
1978.5	0.110	0.123	0.149	0.178	0.240	0.244	0.223	0.215	0.217	0.211	0.195	0.192	0.219	0.200	0.179	0.198
	1960	*1946*	*1957*	*1953*	*1930*	*1895*	*1884*	*1851*	*1834*	*1763*	*1777*	*1740*	*1654*	*1105*	*560*	*455*
1979.5	0.076	0.087	0.134	0.190	0.255	0.256	0.234	0.215	0.181	0.185	0.191	0.196	0.197	0.218	0.192	0.195
	1963	*1945*	*1963*	*1959*	*1941*	*1902*	*1882*	*1847*	*1824*	*1742*	*1751*	*1722*	*1641*	*1024*	*534*	*456*
1980.5	0.040	0.064	0.091	0.148	0.221	0.227	0.213	0.184	0.175	0.174	0.176	0.167	0.169	0.193	0.172	0.182
	1965	*1949*	*1964*	*1959*	*1945*	*1902*	*1884*	*1853*	*1825*	*1725*	*1750*	*1703*	*1620*	*955*	*504*	*420*
1981.5	0.111	0.117	0.133	0.178	0.235	0.227	0.205	0.175	0.153	0.161	0.169	0.175	0.188	0.192	0.172	0.195
	2002	*1990*	*1999*	*1988*	*1971*	*1928*	*1909*	*1881*	*1865*	*1776*	*1766*	*1732*	*1644*	*1020*	*579*	*489*
1982.5	0.114	0.125	0.175	0.209	0.259	0.263	0.214	0.169	0.164	0.172	0.167	0.175	0.148	0.178	0.133	0.102
	1970	*1955*	*1967*	*1956*	*1952*	*1913*	*1895*	*1862*	*1853*	*1766*	*1736*	*1688*	*1616*	*1033*	*532*	*465*
1983.5	0.098	0.098	0.143	0.189	0.227	0.204	0.191	0.138	0.139	0.143	0.132	0.139	0.126	0.165	0.122	0.081
	1962	*1949*	*1964*	*1952*	*1931*	*1899*	*1880*	*1862*	*1846*	*1785*	*1751*	*1711*	*1644*	*1142*	*638*	*565*
1984.5	0.096	0.086	0.130	0.164	0.180	0.170	0.142	0.103	0.103	0.098	0.096	0.095	0.091	0.118	0.060	0.044
	2038	*2047*	*2063*	*2049*	*2034*	*1995*	*1979*	*1967*	*1950*	*1893*	*1891*	*1852*	*1780*	*1268*	*753*	*678*
1985.5	0.139	0.122	0.156	0.190	0.208	0.172	0.109	0.087	0.086	0.072	0.078	0.061	0.069	0.097	0.074	0.039
	2163	*2179*	*2185*	*2171*	*2163*	*2109*	*2094*	*2084*	*2060*	*2015*	*2002*	*1952*	*1883*	*1379*	*864*	*791*
1986.5	0.152	0.153	0.196	0.217	0.222	0.165	0.121	0.100	0.075	0.055	0.056	0.042	0.045	0.089	0.050	0.029
	2193	*2215*	*2228*	*2223*	*2204*	*2164*	*2143*	*2123*	*2108*	*2049*	*2043*	*1993*	*1919*	*1405*	*884*	*819*
1987.5	0.130	0.126	0.151	0.174	0.211	0.122	0.089	0.066	0.057	0.028	0.039	0.044	0.040	0.083	0.019	0.020
	2158	*2174*	*2191*	*2190*	*2171*	*2134*	*2110*	*2091*	*2070*	*2024*	*2005*	*1965*	*1896*	*1420*	*956*	*886*
1988.5	0.114	0.107	0.130	0.147	0.179	0.113	0.084	0.046	0.039	0.019	0.013	0.024	0.031	0.057	-0.010	0.008
	2147	*2163*	*2180*	*2176*	*2157*	*2122*	*2095*	*2085*	*2059*	*2009*	*1982*	*1933*	*1855*	*1418*	*1062*	*1003*
1989.5	0.102	0.071	0.122	0.114	0.165	0.117	0.079	0.072	0.077	0.062	0.040	0.039	0.047	0.056	0.023	0.019
	2113	*2126*	*2144*	*2147*	*2135*	*2087*	*2067*	*2051*	*2039*	*1995*	*1960*	*1922*	*1848*	*1514*	*1219*	*1159*
1990.5	0.070	0.062	0.073	0.101	0.147	0.149	0.100	0.085	0.079	0.046	0.045	0.053	0.053	0.069	0.060	0.053
	2004	*2036*	*2061*	*2065*	*2049*	*2009*	*1998*	*1979*	*1966*	*1924*	*1882*	*1857*	*1806*	*1545*	*1363*	*1309*
1991.5	0.112	0.060	0.075	0.096	0.155	0.127	0.114	0.077	0.060	0.027	0.036	0.049	0.066	0.102	0.088	0.092
	2021	*2054*	*2075*	*2081*	*2065*	*2031*	*2019*	*1996*	*1980*	*1945*	*1924*	*1897*	*1868*	*1669*	*1533*	*1466*

Year	Depth (m)															
	0	**10**	**20**	**30**	**50**	**75**	**100**	**125**	**150**	**200**	**250**	**300**	**400**	**500**	**600**	**700**
1992.5	0.064	0.018	0.033	0.063	0.107	0.069	0.102	0.073	0.097	0.080	0.074	0.082	0.095	0.092	0.102	0.101
	2005	*2061*	*2095*	*2098*	*2073*	*2038*	*2037*	*2027*	*2010*	*1970*	*1956*	*1921*	*1887*	*1728*	*1611*	*1551*
1993.5	0.077	0.039	0.052	0.069	0.109	0.126	0.100	0.105	0.093	0.113	0.112	0.123	0.117	0.089	0.098	0.088
	1982	*2039*	*2064*	*2069*	*2051*	*2021*	*2018*	*2008*	*1995*	*1962*	*1940*	*1909*	*1880*	*1748*	*1646*	*1615*
1994.5	0.142	0.044	0.062	0.097	0.104	0.124	0.093	0.063	0.045	0.058	0.083	0.086	0.085	0.080	0.090	0.089
	1860	*1917*	*1948*	*1950*	*1938*	*1911*	*1900*	*1885*	*1870*	*1836*	*1807*	*1778*	*1746*	*1627*	*1538*	*1499*
1995.5	0.119	0.006	0.025	0.058	0.100	0.111	0.073	0.048	0.045	0.045	0.060	0.049	0.054	0.068	0.069	0.070
	1748	*1815*	*1845*	*1842*	*1832*	*1801*	*1786*	*1773*	*1765*	*1731*	*1696*	*1664*	*1634*	*1544*	*1468*	*1426*
1996.5	0.012	-0.029	0.006	0.070	0.073	0.072	0.052	0.029	0.063	0.083	0.064	0.055	0.046	0.037	0.045	0.040
	1444	*1498*	*1522*	*1515*	*1507*	*1487*	*1476*	*1434*	*1435*	*1407*	*1378*	*1353*	*1325*	*1238*	*1181*	*1154*
1997.5	0.078	0.054	0.072	0.086	0.113	0.089	0.063	0.050	0.021	0.058	0.074	0.074	0.048	0.039	0.050	0.046
	1287	*1303*	*1316*	*1314*	*1311*	*1281*	*1292*	*1245*	*1256*	*1242*	*1204*	*1174*	*1145*	*1074*	*1025*	*995*
1998.5	0.124	0.067	0.095	0.125	0.128	0.152	0.113	0.040	0.060	0.065	0.065	0.040	0.018	0.039	0.045	0.042
	1074	*1105*	*1114*	*1111*	*1113*	*1086*	*1093*	*1048*	*1057*	*1048*	*1032*	*992*	*971*	*907*	*859*	*832*
1999.5	0.157	0.091	0.118	0.125	0.138	0.112	0.129	0.110	0.100	0.063	0.063	0.054	0.037	0.036	0.034	0.028
	1039	*1083*	*1092*	*1091*	*1093*	*1065*	*1074*	*1024*	*1031*	*1019*	*1011*	*969*	*950*	*881*	*836*	*815*
2000.5	0.173	0.134	0.146	0.165	0.173	0.135	0.148	0.155	0.153	0.082	0.071	0.058	0.049	0.047	0.044	0.035
	947	*981*	*990*	*985*	*984*	*957*	*963*	*918*	*921*	*896*	*899*	*863*	*850*	*787*	*748*	*736*
2001.5	0.106	0.042	0.079	0.120	0.142	0.159	0.144	0.094	0.100	0.106	0.084	0.061	0.076	0.072	0.058	0.049
	896	*938*	*953*	*946*	*952*	*928*	*933*	*895*	*900*	*884*	*875*	*846*	*834*	*784*	*752*	*736*
2002.5	0.171	0.135	0.142	0.171	0.199	0.191	0.212	0.169	0.147	0.121	0.108	0.104	0.088	0.076	0.064	0.063
	832	*895*	*913*	*907*	*902*	*887*	*889*	*846*	*860*	*838*	*840*	*824*	*809*	*757*	*713*	*694*
2003.5	0.200	0.156	0.209	0.256	0.279	0.280	0.238	0.171	0.147	0.087	0.110	0.088	0.073	0.072	0.067	0.072
	842	*899*	*919*	*924*	*926*	*904*	*911*	*874*	*890*	*870*	*862*	*853*	*831*	*764*	*714*	*689*
2004.5	0.081	0.056	0.067	0.093	0.181	0.190	0.156	0.110	0.093	0.045	0.087	0.083	0.081	0.089	0.103	0.098
	762	*807*	*819*	*822*	*827*	*804*	*817*	*778*	*804*	*786*	*759*	*764*	*743*	*676*	*619*	*600*
2005.5	0.081	0.056	0.067	0.093	0.181	0.190	0.156	0.110	0.093	0.045	0.087	0.083	0.081	0.089	0.103	0.098
	762	*807*	*819*	*822*	*827*	*804*	*817*	*778*	*804*	*786*	*759*	*764*	*743*	*676*	*619*	*600*

Year	Depth (m)															
	0	**10**	**20**	**30**	**50**	**75**	**100**	**125**	**150**	**200**	**250**	**300**	**400**	**500**	**600**	**700**
2006.5	0.081	0.056	0.067	0.093	0.181	0.190	0.156	0.110	0.093	0.045	0.087	0.083	0.081	0.089	0.103	0.098
	762	*807*	*819*	*822*	*827*	*804*	*817*	*778*	*804*	*786*	*759*	*764*	*743*	*676*	*619*	*600*
2007.5	0.081	0.056	0.067	0.093	0.181	0.190	0.156	0.110	0.093	0.045	0.087	0.083	0.081	0.089	0.103	0.098
	762	*807*	*819*	*822*	*827*	*804*	*817*	*778*	*804*	*786*	*759*	*764*	*743*	*676*	*619*	*600*
2008.5	0.081	0.056	0.067	0.093	0.181	0.190	0.156	0.110	0.093	0.045	0.087	0.083	0.081	0.089	0.103	0.098
	762	*807*	*819*	*822*	*827*	*804*	*817*	*778*	*804*	*786*	*759*	*764*	*743*	*676*	*619*	*600*

Notes:
Each year represented by two lines:
First line shows Temperature bias corrections, which are subtracted from XBT temperature value interpolated to given standard depth for given year.
Second line shows *Number of pairs*, which is the number of 4x2 degree boxes with both XBT and CTD drops from which corrections were calculated.

Table A1.2. Temperature bias corrections for MBT data

Year	Depth										
	0	**10**	**20**	**30**	**50**	**75**	**100**	**125**	**150**	**200**	**250**
1951.5	0.076	0.129	0.147	0.124	0.156	0.152	0.065	0.074	0.060	0.037	0.114
	706	*668*	*676*	*671*	*675*	*630*	*578*	*466*	*411*	*351*	*331*
1952.5	0.115	0.143	0.149	0.165	0.155	0.153	0.099	0.048	0.068	0.042	0.113
	743	*700*	*715*	*702*	*714*	*666*	*597*	*493*	*446*	*389*	*359*
1953.5	0.155	0.203	0.237	0.230	0.195	0.174	0.135	0.093	0.106	0.038	0.099
	855	*837*	*846*	*833*	*835*	*789*	*707*	*587*	*541*	*436*	*481*
1954.5	0.165	0.236	0.286	0.294	0.275	0.207	0.172	0.117	0.105	0.076	0.079
	910	*883*	*913*	*898*	*884*	*840*	*757*	*672*	*574*	*429*	*520*
1955.5	0.171	0.269	0.327	0.303	0.307	0.214	0.247	0.178	0.136	0.136	0.106
	946	*896*	*947*	*927*	*928*	*863*	*798*	*702*	*583*	*435*	*532*
1956.5	0.183	0.255	0.303	0.299	0.258	0.196	0.235	0.191	0.176	0.164	0.146
	1184	*1117*	*1172*	*1162*	*1159*	*1093*	*1005*	*891*	*767*	*601*	*687*
1957.5	0.129	0.210	0.214	0.208	0.209	0.194	0.164	0.100	0.136	0.118	0.116
	1247	*1196*	*1252*	*1252*	*1246*	*1170*	*1092*	*960*	*856*	*682*	*730*
1958.5	0.119	0.192	0.202	0.208	0.205	0.135	0.112	0.070	0.098	0.049	0.058
	1382	*1317*	*1361*	*1362*	*1345*	*1281*	*1199*	*1080*	*966*	*789*	*774*
1959.5	0.138	0.196	0.204	0.193	0.203	0.105	0.073	0.034	0.008	-0.016	-0.043
	1466	*1434*	*1465*	*1457*	*1432*	*1355*	*1284*	*1186*	*1061*	*885*	*827*
1960.5	0.100	0.144	0.169	0.168	0.146	0.133	0.091	0.079	0.053	0.005	0.011
	1561	*1549*	*1582*	*1579*	*1538*	*1478*	*1422*	*1325*	*1235*	*1037*	*927*
1961.5	0.049	0.088	0.130	0.146	0.151	0.153	0.117	0.072	0.079	0.017	0.062
	1731	*1720*	*1750*	*1732*	*1691*	*1628*	*1590*	*1522*	*1441*	*1186*	*1063*
1962.5	0.040	0.097	0.124	0.158	0.203	0.169	0.150	0.103	0.109	0.070	0.048
	1916	*1905*	*1915*	*1899*	*1860*	*1797*	*1766*	*1705*	*1619*	*1355*	*1258*
1963.5	0.044	0.083	0.108	0.135	0.141	0.158	0.118	0.094	0.103	0.060	0.072
	2106	*2081*	*2107*	*2086*	*2049*	*1991*	*1949*	*1890*	*1808*	*1519*	*1419*
1964.5	0.067	0.108	0.146	0.167	0.182	0.180	0.132	0.110	0.113	0.092	0.077
	2182	*2149*	*2167*	*2145*	*2104*	*2042*	*1998*	*1939*	*1863*	*1623*	*1519*
1965.5	0.073	0.136	0.160	0.192	0.224	0.174	0.141	0.107	0.121	0.074	0.051
	2272	*2232*	*2257*	*2234*	*2198*	*2120*	*2080*	*2010*	*1936*	*1713*	*1524*

1966.5	0.069	0.120	0.139	0.147	0.171	0.162	0.173	0.156	0.176	0.134	0.110
	2238	*2196*	*2227*	*2205*	*2163*	*2105*	*2060*	*2008*	*1919*	*1728*	*1446*
1967.5	0.106	0.130	0.171	0.186	0.186	0.196	0.173	0.147	0.154	0.106	0.087
	2247	*2203*	*2229*	*2213*	*2162*	*2098*	*2056*	*2017*	*1912*	*1734*	*1361*
1968.5	0.125	0.133	0.138	0.140	0.189	0.158	0.133	0.114	0.096	0.062	0.007
	2211	*2160*	*2186*	*2180*	*2152*	*2080*	*2046*	*1992*	*1863*	*1719*	*1279*
1969.5	0.121	0.116	0.117	0.165	0.174	0.138	0.114	0.107	0.098	0.071	0.047
	2234	*2191*	*2210*	*2202*	*2178*	*2105*	*2072*	*2015*	*1884*	*1732*	*1225*
1970.5	0.121	0.124	0.121	0.145	0.172	0.171	0.176	0.158	0.103	0.076	0.071
	2229	*2180*	*2200*	*2193*	*2175*	*2091*	*2069*	*2004*	*1890*	*1746*	*1105*
1971.5	0.084	0.095	0.120	0.153	0.143	0.131	0.115	0.080	0.056	-0.010	-0.004
	2089	*2039*	*2054*	*2054*	*2044*	*1956*	*1942*	*1854*	*1764*	*1621*	*946*
1972.5	0.025	0.034	0.021	0.068	0.124	0.143	0.138	0.102	0.082	-0.015	-0.038
	1979	*1945*	*1967*	*1964*	*1946*	*1881*	*1866*	*1783*	*1730*	*1613*	*792*
1973.5	0.003	0.008	0.005	0.051	0.093	0.136	0.148	0.134	0.092	0.004	-0.007
	1894	*1864*	*1877*	*1864*	*1862*	*1792*	*1791*	*1738*	*1703*	*1597*	*701*
1974.5	0.002	0.022	0.030	0.059	0.096	0.174	0.162	0.129	0.095	0.005	-0.079
	1896	*1878*	*1892*	*1875*	*1866*	*1825*	*1805*	*1763*	*1735*	*1617*	*629*
1975.5	-0.008	0.025	0.027	0.070	0.136	0.154	0.135	0.098	0.082	-0.027	-0.083
	1861	*1851*	*1855*	*1851*	*1835*	*1799*	*1800*	*1756*	*1743*	*1640*	*581*
1976.5	0.042	0.056	0.082	0.117	0.124	0.143	0.164	0.126	0.101	0.013	-0.093
	1863	*1849*	*1860*	*1854*	*1836*	*1803*	*1793*	*1759*	*1754*	*1678*	*595*
1977.5	-0.003	0.024	0.041	0.084	0.166	0.146	0.135	0.116	0.094	0.027	-0.058
	1966	*1940*	*1943*	*1934*	*1925*	*1899*	*1887*	*1856*	*1847*	*1762*	*595*
1978.5	0.001	0.040	0.046	0.098	0.136	0.128	0.136	0.120	0.083	0.015	-0.085
	1927	*1898*	*1899*	*1890*	*1884*	*1849*	*1851*	*1820*	*1807*	*1720*	*547*
1979.5	-0.020	0.004	0.029	0.071	0.125	0.140	0.143	0.117	0.059	-0.030	-0.052
	1868	*1841*	*1842*	*1838*	*1833*	*1805*	*1798*	*1758*	*1747*	*1662*	*512*
1980.5	0.004	0.036	0.049	0.074	0.154	0.142	0.099	0.063	0.047	0.001	0.043
	1755	*1727*	*1749*	*1743*	*1734*	*1693*	*1696*	*1664*	*1639*	*1552*	*467*
1981.5	0.022	0.040	0.063	0.097	0.158	0.127	0.059	0.044	0.014	-0.043	0.043
	1714	*1687*	*1704*	*1703*	*1691*	*1650*	*1655*	*1635*	*1615*	*1538*	*441*
1982.5	0.030	0.036	0.074	0.090	0.117	0.081	0.091	0.030	0.001	-0.038	-0.080
	1721	*1694*	*1710*	*1709*	*1709*	*1669*	*1666*	*1646*	*1619*	*1529*	*566*

1983.5	0.024	0.025	0.047	0.078	0.091	0.072	0.060	0.036	0.027	-0.009	-0.075
	1688	*1672*	*1690*	*1683*	*1673*	*1644*	*1624*	*1617*	*1595*	*1524*	*675*
1984.5	-0.002	0.009	0.022	-0.001	0.040	0.031	0.035	0.009	0.002	-0.018	-0.105
	1692	*1688*	*1702*	*1705*	*1701*	*1679*	*1655*	*1625*	*1614*	*1540*	*741*
1985.5	0.004	0.025	0.023	0.027	0.002	0.024	-0.019	-0.011	-0.038	-0.061	-0.118
	1815	*1812*	*1823*	*1823*	*1822*	*1780*	*1766*	*1736*	*1722*	*1661*	*783*
1986.5	0.001	0.016	0.051	0.069	0.059	0.067	0.043	0.048	0.021	0.001	-0.092
	1776	*1777*	*1784*	*1786*	*1780*	*1754*	*1747*	*1699*	*1694*	*1634*	*782*
1987.5	-0.025	-0.022	-0.007	0.014	0.071	0.053	0.035	0.064	0.045	0.028	0.030
	1662	*1664*	*1681*	*1681*	*1682*	*1650*	*1643*	*1586*	*1584*	*1521*	*636*
1988.5	-0.096	-0.094	-0.074	-0.077	-0.021	-0.006	-0.018	-0.018	-0.034	-0.046	0.008
	1548	*1542*	*1553*	*1561*	*1554*	*1518*	*1516*	*1472*	*1455*	*1401*	*453*
1989.5	-0.043	-0.053	-0.063	-0.042	-0.008	0.000	-0.025	-0.041	-0.004	-0.041	-0.008
	1276	*1262*	*1274*	*1285*	*1287*	*1236*	*1239*	*1225*	*1219*	*1171*	*394*
1990.5	-0.020	-0.016	-0.065	-0.055	-0.043	-0.017	0.010	0.010	0.023	0.042	0.038
	1001	*1005*	*1014*	*1021*	*1018*	*992*	*986*	*973*	*959*	*924*	*341*
1991.5	-0.031	-0.021	-0.010	-0.010	-0.002	0.026	0.023	-0.002	-0.002	0.029	0.018
	755	*760*	*774*	*784*	*777*	*766*	*762*	*754*	*738*	*709*	*278*
1992.5	0.079	0.078	0.037	0.062	0.046	0.074	0.069	0.032	0.057	0.094	0.114
	570	*575*	*579*	*580*	*577*	*572*	*566*	*559*	*559*	*537*	*276*

Notes:
Each year represented by two lines:
First line shows Temperature bias corrections, which are subtracted from MBT temperature value interpolated to given standard depth for given year.
Second line shows *Number of pairs*, which is the number of 4x2 degree boxes with both MBT and CTD drops from which corrections were calculated.