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WORLD OCEAN DATABASE 2018
Pre-release

Tim P. Boyer, Olga K. Baranova, Carla Coleman,
Hernan E. Garcia, Alexandra Grodsky, Ricardo A. Locarnini,
Alexey V. Mishonov, Christopher R. Paver, James R. Reagan,
Dan Seidov, Igor V. Smolyar, Katharine W. Weathers, Melissa M. Zweng

Technical Editor: Alexey V. Mishonov

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Ocean Climate Laboratory

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National Centers for Environmental Information
User Services Team
NOAA/NESDIS
National Centers for Environmental Information
SSMC3, 4th floor
1315 East-West Highway
Silver Spring, MD 20910-3282

Telephone: (301) 713-3277
E-mail: NCEI.Services@noaa.gov
WEB: http://www.nodc.noaa.gov/

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PREFACE

The oceanographic databases described by this atlas series expands on the *World Ocean Database 2013* (WOD13) product and its predecessors. We have expanded by including substantial amounts of both recent and historical data not previously available. Earlier National Oceanographic Data Center (NODC)/World Data System (WDS) oceanographic databases, and products derived from these databases, have proven to be of great utility to the international oceanographic, climate research, and operational environmental forecasting communities. In particular, the objectively analyzed fields of temperature and salinity derived from these databases have been used in a variety of ways. These include use as boundary and/or initial conditions in numerical ocean circulation models, verification of numerical simulations of the ocean, as a form of "sea truth" for satellite measurements such as altimetric observations of sea surface height among others. Increasingly, nutrient fields are being used to initialize and/or verify biogeochemical models of the world ocean. In addition, NODC/WDS products are critical for support of international assessment programs such as the Intergovernmental Program on Climate Change (IPCC) of the United Nations.

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

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

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

Sydney Levitus
National Oceanographic Data Center/World Data Center for Oceanography- Silver Spring
Silver Spring, MD
September, 2018

ACKNOWLEDGMENTS

This work was made possible by a grant from the NOAA Climate and Global Change Program which enabled the establishment of a research group, the OCL, at the NODC (now NCEI). 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.

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.

The OCL expresses thanks to those who provided comments and helped develop an improved *World Ocean Database 2018* (WOD18) product. Any errors in WOD18 are the responsibility of the Ocean Climate Laboratory.

A special acknowledgement to Syd Levitus who initiated the World Ocean Database project and guided the OCL from its inception until 2013. We would also like to acknowledge Margarita Gregg, who retired as head of NCEI in 2018. In addition to her guidance as director of NCEI, Margarita oversaw the production of the WOD from the 1998 through 2005 versions. We would not have compiled these earlier versions, nor the present without Margarita's tireless oversight. Daphne Johnson, instrumental in incorporating many of the Russian historical data sets and writing and editing the documentation and tutorials for both the WOD and the World Ocean Atlas series, retired after the release of WOD13. Her work has greatly informed the completion of WOD18. Finally we offer a fond remembrance of Carla Forgy who died earlier this year. Carla was a dedicated digitizer of data and her work will live on in the WOD. We miss most Carla's cheerful and calm presence on our team.

CHAPTER 1: INTRODUCTION

Tim P. Boyer, Olga K. Baranova, Carla Coleman, Hernan E. Garcia, Alexandra Grodsky, Ricardo A. Locarnini, Alexey V. Mishonov, Todd D. O'Brien, Christopher R. Paver, James R. Reagan, Dan Seidov, Igor V. Smolyar, Katharine W. Weathers, Melissa. M. Zweng

Ocean Climate Laboratory
National Centers for Environmental Information
Silver Spring, MD

ABSTRACT

The World Ocean Database (WOD) is 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, Freon, Helium, Δ^{3}Helium, Neon, and plankton.

1.1. INTRODUCTION

1.1.1 Purpose

The World Ocean Database (WOD) was first conceived as a way to provide reproducibility for the World Ocean Atlas (WOA) series. The WOA series is a continuation of the Climatological Atlas of the World Ocean (Levitus, 1982) a set of global one-degree gridded climatological mean fields of oceanographic variables at standard depth levels in the ocean to be used, among other things, as initial and boundary conditions for coupled climate models. In order to produce comprehensive mean fields of oceanographic variables, aggregation of subsurface oceanographic measurements from many different sources, collected for many different reasons, using different instrumentation, different methods, different levels of calibration, quality monitoring, recording, formatting, metadata, units, and media delivery, were aggregated, converted to a uniform form, and quality controlled. The observation's original values and depths are preserved in the WOD along with quality flags assigned both by the data originator and in the WOD quality procedures. Values interpolated from observed depths to standard levels are also included in the WOD, as these standard level interpolated values are the direct input into the WOA fields. Quality flags on standard level interpolated values are also included. These latter flags include subjective flags from the inspection and iterative calculation of the WOA gridded fields. Designated WOD quality flags on original observations denote whether the observation was used to interpolate to standard levels. Designated WOD quality flags on standard levels denote whether an interpolated value was used to calculate WOA gridded fields. Thus WOD can be used to reproduce WOA. WOD has many further uses beyond reproducing climatological mean fields. For this reason, WOD is (since 2007) updated on a quarterly basis in a preliminary state. The fully quality controlled WOD is released in conjunction with each release of the WOA.

1.1.2 Contributors

The WOD is simply the final step in gathering oceanographic profile data together for public dissemination. The inventors, oceanographers, and engineers who conceived, designed, and tested the oceanographic instrumentation and measurement techniques are responsible for the plethora and variety of oceanographic data. The primary investigators, marine technicians, ship's crew, and volunteers who made and continue to make many of the oceanographic measurements, often under harsh conditions, are responsible for the quality and quantity of the oceanographic data. The institutions which maintain the platforms and the projects which plan, fund, and execute the field campaigns and operational ocean monitoring are responsible for the spatial and temporal coverage of the oceanographic profile data. Finally, the data managers are responsible for the preservation and reusability of the data. This is a vast network, maintained and updated over time which should receive the credit for the aggregated WOD. We have attempted to ensure that this credit is visible in the data itself. Every cast contains (when supplied) information on the instrumentation, platform, project, institution, and data management entity. The accession number, a number assigned to each data set received and archived at NCEI, is also found with each cast. More information about who submitted the data to NCEI and the original data themselves can be located using this accession number. The archive at NCEI and those who populate and maintain it also deserve credit for the continual availability of historical oceanographic data. Finally, international organizations such as the Intergovernmental Oceanographic Commission's (IOC) International Oceanographic Data and Information Exchange (IODE) and the World Data System (WDS) for Oceanography should be credited for creating and facilitating a global culture of data exchange and preservation. The use of Data Object Identifiers (DOIs) and more specifically cascading DOIs shows great promise in a more succinctly and more easily accessible way to document credit for the different aspects of each oceanographic cast – from marine techs, to primary investigators to institutions, projects, quality assurance, data managers, etc. In the future we intend to include a DOI (when possible) with each cast for a particular data set (right now represented by the accession number). This DOI will point to a set of related DOIs which document the different contributors and their role in the making of the given measurements.

1.1.3 Size and shape

WOD incorporates 20,547 different data sets received and archived at NCEI. The data represent the results of 216,845 oceanographic cruises on 8,215 different platforms from 798 institutes around the world and 553 separate projects. The number of platforms is lower than might be expected, as some platform identifiers are generic (e.g. profiling float, moored buoy, drifting buoy) since the platform list is mainly used to identify ships. There are 3.56 billion individual profile measurements (depth/pressure vs. measured variable) in the WOD. Of these 1.95 billion are temperature, 1.13 billion salinity, 260 million oxygen, and 4.5 million plankton measurements. There are an additional 22 million meteorological/sea state observations. These measurements make up the 15.7 million oceanographic casts in the WOD.

1.1.4 Data Organization

Data in the WOD 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 lowered or raised vertically in the water column. For surface-only data, the profile consists of measurements taken along a horizontal path. For moored buoys and drifting buoys, the instrument does not move vertically in the water column, so a profile is a discrete set of concurrent measurements from the instruments placed at different depths on a wire attached to the buoy.

Cast: A set of one or more profiles taken concurrently or nearly concurrently. Meteorological and other ocean data, *e.g.* Secchi disk depth 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 WOD is assigned a unique cast number. If the cast is subsequently replaced by higher quality data, the unique cast number is inherited. If any alteration is made to a cast, this information is noted in comments to the quarterly database update, referenced by the unique cast number. For surface-only data in dataset SUR, a cast is defined as a collection of concurrent surface measurements at discrete latitudes and longitudes over an entire cruise (see definition of cruise below). Latitude, longitude and Julian year-day values are included with each set of measured oceanographic variables.

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

Cruise: A set of stations is grouped together if they fit the “cruise” definition. A cruise is defined as a specific deployment of a single platform for the purposes of a coherent oceanographic investigation. For an oceanographic research vessel, this deployment is usually well-defined with a unique set of scientific investigators collecting data for a specific project or set of projects. In some cases different legs of a deployment with the same equipment and investigators are assigned different cruise numbers, as per the investigators designation. In the case when merchant ships-of-opportunity (SOO) are used for data collection, a cruise is usually defined as the time at sea between major port calls. Profiling floats, instrumented pinnipeds, moored buoys, and drifting buoys are assigned the same cruise number for the life of the platform (life of the sensor package for pinnipeds). For, gliders, each specific deployment is designated a cruise. 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 the WOD, 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. The International Standards Organization (ISO) country codes are used (see https://www.iso.org/publication/PUB500001.html). For data for which no information on country is present, a country code of 99 is used. For data for which there is no way to identify a specific cruise, a cruise number of zero (0) is used.

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

Accession Number: A group of stations received and archived at the NCEI. Each collection submitted to NCEI is given a unique "accession number". Using this number, a user can get an exact copy of the original data sent to NCEI as well as information about the data itself (*i.e.* metadata) through the NCEI Geoportal (https://www.nodc.noaa.gov/archivesearch/catalog/search/search.page). 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 cast number will remain unchanged. If a profile for a variable not previously stored with a cast becomes available, the profile will be added to the existing cast, and a variable-specific accession number will be added to the station to record the source of the new profile.

WOD 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 WOD.

1.1.5. WOD Datasets

The WOD 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 WOD datasets are briefly described below and in more details in following chapters. A list of datasets in WOD 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 Garcia *et al.* (2018).

The WOD includes oceanographic variables measured at "observed" depth levels as well as interpolated to a set of 137 "standard" depth levels. All climatic fields in the World Ocean Atlas (WOA) are produced based on "standard" depth levels data. Note that the 40 standard depth levels used in previous versions of WOD (before 2013) are all among the 137 standard depth levels used in WOD18, to provide continuity.

Table 1.1. Instrument types in the WOD18

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, Digital BT (DBT), micro-BT (μBT)
XBT	Expendable (XBT) data
SUR	Surface only data (bucket, thermosalinograph)
APB	Autonomous Pinniped Bathythermograph - Time-Temperature-Depth recorders and CTDs attached to elephant seals
MRB	Moored buoy data mainly from the Equatorial buoy arrays -TAO
PFL	Profiling float data, mainly from the Argo program
DRB	Drifting buoy data from surface drifting buoys with thermistor chains and from ice-tethered profilers
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 calculate salinity. CTDs are usually mounted on a metal frame (a rosette) and lowered through the water column suspended from a cable. The frame is often used to hang bottles for collecting water samples. Low-resolution here refers to a limited number of temperature and/or salinity measurements made along the vertical profile. Usually, but not always, these measurements are recorded at the depths at which bottles are tripped to collect water samples. This dataset also include data from the older Salinity-Temperature-Depth (STD) instruments - the precursor to the CTD. About 5.6% of all data in the OSD dataset are listed as containing temperature and/or salinity data measured by CTD/STD (see Chapter 3.)

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

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

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

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

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

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

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

XBT Dataset – low and high-resolution Expendable Bathythermographs

Expendable Bathythermograph (XBT) probes are torpedo-shaped devices attached to a spool of copper wire. The instrument is launched over the side of a moving ship, from an airplane, or from a submarine. Temperature is estimated by measurements of the resistance in a semi-conductor (called a thermistor). 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 (original developer), and TSK in

Japan. A third manufacturer, Sparton, is no longer in business. XBTs have been deployed since 1966. XBTs were the major ocean observing system for temperature from 1967 to 2001 (advent of the Argo program). Many researchers (e.g. 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. More recently, there has been a great deal of research into time (year) dependent fall-rate and temperature biases, spurred by a paper by Gourestki and Koltermann (2007) which showed that there was a year to year difference in the XBT bias. For more information on these studies and more on how the XBT bias is handled in the WOD, please see Chapter 4 and the NCEI XBT bias webpage (https://www.nodc.noaa.gov/OC5/XBT_BIAS/xbt_bias.html). .

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. Argo profiling float data are obtained from the Coriolis Global Data Assembly Center (http://www.coriolis.eu.org/Observing-the-Ocean/ARGO) with smaller non-Argo contributions from the World Ocean Circulation Experiment (WOCE) and the Global Temperature and Salinity Profile Program (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. Initially, MBTs recorded temperature as a function of depth by scratching a line on a smoked glass plate with a stylus, later recording was on paper. 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), the PIRATA buoy array (in the tropical Atlantic), the RAMA buoy array (in the tropical Indian Ocean), MARNET buoys and light-ships (in the North Sea and the Baltic Sea). The data in the WOD from the TAO, PIRATA, RAMA and most of the TRITON buoys are daily averages acquired from the Pacific Marine Environmental Laboratory (PMEL). The remainder of the TRITON buoys, the MARNET buoys and light-ships data were acquired GTSPP (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 WOD13 were acquired from GTSPP database, from the Japanese Arctic Buoy program archive, and from the Woods Hole Ice-Tethered Profiler Program (Toole *et al*, 2011). The GTSPP data are from the subset of oceanic drifting buoys, which have multiple subsurface temperature measurement devices (thermistors) suspended from a chain, the others are ice drifters with profilers attached (see Chapter 10.)

UOR Dataset – Undulating Oceanographic Recorders (Towed CTDs)

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

APB Dataset – Autonomous Pinniped Bathythermographs

The earliest data in this WOD dataset consist of bathythermographs attached to sea elephants. Later, CTDs were used. Temperature and salinity information are recorded during dives taken while feeding and transmitted to satellite upon surfacing (see Chapter 12.)

GLD Dataset - Gliders

GLD 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 sawtoothed trajectory through the water (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 the WOD. 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 WOD. Note that a "cast" here refers to an entire cruise of surface-only measurements (see Chapter 14.)

Meteorological and Sea state measurements data

Ship-based research cruises, and some operational oceanographic cruises, recorded atmospheric measurements (air temperature, barometric pressure, wind speed and direction, humidity, visibility, weather conditions, cloud cover and type) and sea state measurements (sea sate condition, wave height and period, transparency). Additionally, many of the Equatorial moored buoys record air temperature, wind speed and direction. These measurements augment and inform the subsurface oceanographic profile data. Counts of each meteorological/sea state variable are shown in Table 1.2. In addition to auxiliary information for understanding ocean profile data, these measurements are important in their own right. In addition to retention in the WOD, all atmospheric and sea state measurements are available through the International Comprehensive Atmospheric and Oceanographic Data Set (ICOADS; Freeman *et al.*, 2016).

1.1.6. 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 WOD Ocean Station Data (OSD) dataset.

The computation we describe was first performed in 1982 by Mr. Rene Cuzon du Rest, of the former 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 ten "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, the WOD OSD dataset contains approximately 2.4 million shallow casts (deepest depth between 2 and 1000 m depth) so that the cost of the ship time to perform these measurements is approximately $4.8 billion. In addition, the WOD contains 0.4 million profiles deeper than 1000 m depth, so the cost in ship time to make these deep measurements is approximately $4.2 billion. Thus, the total replacement cost of the OSD dataset is about $9 billion, a figure based only on ship-time operating costs, not salaries for scientists, technicians, or any other costs. More recent platforms and instruments, such as XBTs dropped from volunteer merchant ships or autonomous platforms such as Argo floats, have much lower costs than OSD and in some cases are publicly available in near-real time. Still, the long term preservation and maintenance of these data also has a significant economic value for the future study of historic oceanographic conditions.

Table 1.2. Meteorological and Sea-state parameters stored in the WOD18

Variables	OSD	MBT	XBT	CTD	MRB	Total
Bottom depth (m)	1,781,917	615,848	495,878	565,701		*3,259,620*
Water color (Forel-Ule color scale)	282,347	12,438	476	11,234		*304,997*
Secchi disk visibility depth (m)	446,556	12,175	452	16,407		*474,283*
Wave direction (WMO 0877)	361,390	30,033	30,569	7,905		*427,948*
Wave height (WMO 1555)	228,895	114,357	51,098	27,321		*417,826*
Sea state (WMO 3700)	571,052	478,526	53,968	33,663		*1,132,023*
Wind force (Beafort Scale)	604,603	14,444	3,270	5,174		*626,268*
Wave period (WMO 3155 or NODC 0378)	133,999	34,771	41,296	17,602		*224,010*
Wind direction (WMO 0877)	1,245,186	653,765	157,616	88,118	608,817	*2,621,216*
Wind speed (in knots)	610,146	673,468	158,822	69,163	614560	*1,993,197*
Barometric pressure (millibar)	764,618	338,252	30,048	82,290		*1,198,814*
Dry bulb temperature (°C)	1,152,078	622,991	140,862	73,185	651,101	*2,501,025*
Wet bulb temperature (°C)	232,747	495,846	52,403	43,691		*816,944*
Weather condition (WMO 4501 and WMO 4677)	655,928	514,988	46,451	44,278		*1,255,876*
Cloud type (WMO 0500)	363,823	25,589	14,341	25,403		*427,466*
Cloud cover (WMO 2700)	707,477	524,094	29,038	46,571		*1,301,904*
Horizontal visibility (WMO 4300)	103,671	185,591	877	24,336		*312,492*
Reference/Sea surface temperature (°C)	23,889	1,171,336	117,389	570		*1,312,132*
Absolute air humidity (g m^{-3})	95,718	1,768		677		*97,995*
Sea surface salinity		2,615	12,380			*14,214*

1.1.7. 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/NCEI 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 the WOD has been to expand this data fusion activity by increasing the number of variables as part of standardized databases – even if the variables do not have corresponding WOA fields.

1.1.8. Distribution media

WOD is being distributed through the NCEI archive (https://catalog.data.gov/dataset/ncei-standard-product-world-ocean-database-wod). For consistency with earlier releases, the WOD is also available in a native ASCII format which makes the most efficient use of space on storage media used to transfer data to users (see https://www.nodc.noaa.gov/OC5/WOD/pr_wod.html, yearly and geographically sorted). To further minimize storage space requirements for the ASCII format, the data have been compressed with the **gzip** utility. The archived version of the WOD is in netCDF format, which follows the Climate-Forecast ragged-array convention (http://cfconventions.org/). Due to the importance of keeping all oceanographic variables, metadata, meteorological data, and sea state information for a cast together, the CF convention of having all variables in a file use the same array dimension is not followed. For more information on data format see Garcia *et al.* (2018).

1.1.9. Application software interfaces

Understanding that not all users are comfortable with CF netCDF files, nor with WOD native ASCII, we have available a suite of programs (in C and FORTRAN) which demonstrate how to convert the ASCII data files to forms, such as comma-separated value (csv) which can be used in standard software packages. A program for converting and displaying data from the netCDF files is also available (https://www.nodc.noaa.gov/OC5/WOD/wod_programs.html). Python routines for reading the WOD native ASCII format have been provided by the International Quality Controlled Database (IQuOD) project (https://github.com/IQuOD/wodpy).

1.1.10 Units

The units for oxygen, nutrients and tracers have been changed for WOD18. Rather than *per liter* ($ml \cdot l^{-1}$ for oxygen, $\mu mol \cdot l^{-1}$ for phosphate, total phosphorus, silicate, nitrite, nitrate, $nanomoles \cdot l^{-1}$ for helium, argon, and neon, $picomoles \cdot l^{-1}$ for CFC-11, CFC-12, and CFC-113) WOD now uses *per kilogram* ($\mu mol \cdot kg^{-1}$ for oxygen, phosphate, total phosphorus, silcate, nitrite, nitrate, $nanomoles \cdot kg^{-1}$ for helium, argon, and neon, $picomoles \cdot kg^{-1}$ for CFC-11, CFC-12, CFC-12). While titrated measurements of molecules in sea water are performed on water volumes, it is common practice for oceanographers to use mass based values as these are directly comparable regardless of a volume of waters dependence on temperature and salinity.

Even so, the conversion to *per kg* from *per liter* was executed using a constant density (1025 $kg \cdot m^{-3}$) to ensure a simple reconversion to original units.

1.2. COMPARISON OF WOD18 WITH PREVIOUS GLOBAL OCEAN PROFILE DATABASES

Table 1.3 shows the amount of data available from different dataset types that were used in earlier global oceanographic analyses. During the past 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 the WOD there are now approximately 15.7 million temperature profiles and 8.5 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 almost 3 million oceanographic profiles since publication of *World Ocean Database 2013.*

1.3. DATA SOURCES

The oceanographic data that comprise the WOD have been acquired through many sources and projects as well as from individual scientists. In addition, many international organizations such as the IODE and WDS have facilitated data exchanges, which have provided many data to the WOD.

1.3.1 IODE

IODE (https://www.iode.org/) activities of the 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). The WOD became an IODE project in 2001 and has received logistical and planning support since that time. IODE has also been instrumental in facilitating international data flow to the WOD and in promoting and enhancing the use of WOD internationally.

1.3.2 The World Data System

The WDS 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 the WDS for Oceanography, collocated with NCEI, since its inception. There are two other oceanographic centers in the WDS, World Data Center (WDC) for Oceanography, Obninsk, Russia (formerly WDC-B for Oceanography) and WDC for Oceanography, Tianjin, China. Additional information about the WDS can be found on the WDS web pages (https://www.icsu-wds.org/).

Table 1.3. Comparison of the number of oceanographic casts in WOD18 compared to previous WOD versions

Dataset	NCEI (1974)[1]	NCEI (1991)[2]	WOA94	WOD98	WOD01	WOD05	WOD09	WOD13	WOD18
OSD[3]	425,000	783,912	1,194,407	1,373,440	2,121,042	2,258,437	2,541,298	3,115,552	3,220,635
CTD[4]	na	66,450	89,000	189,555	311,943	443,953	641,845	848,911	1,029,231
MBT[5]	775,000	980,377	1,922,170	2,077,200	2,376,206	2,421,940	2,426,749	2,425,607	2,430,807
XBT	290,000	704,424	1,281,942	1,537,203	1,743,590	1,930,413	2,104,490	2,211,689	2,303,354
MRB	na	na	na	107,715	297,936	445,371	566,544	1,411,762	1,585,135
DRB	na	na	na	na	50,549	108,564	121,828	251,712	227,871
PFL	na	na	na	na	22,637	168,988	547,985	1,020,216	1,867,873
UOR	na	na	na	na	37,645	46,699	88,190	88,190	127,544
APB	na	na	na	na	75,665	75,665	88,583	1,713,132	1,804,605
GLD	na	na	na	na	na	338	5,857	103,798	1,148,669
Total casts	**1,490,000**	**2,535,163**	**4,487,519**	**5,285,113**	**7,037,213**	**7,900,368**	**9,155,099**	**13,190,569**	**15,861,868**
Plankton	na	na	na	83,650	142,900	150,250	218,695	242,727	245,059
SUR[6]	na		na	na	4,743	9,178	9,178	9,289	9,289

[1] Based on statistics from *Climatological Atlas of the World Ocean* (1982).
[2] Based on NCEI Temperature Profile CD-ROM.
[3] WOD18 OSD dataset includes data from 178,442 low-resolution CTD and 1,708 low-resolution XCTD casts.
[4] WOD18 CTD dataset includes data from 10,953 high-resolution XCTD casts.
[5] WOD18 MBT dataset includes data from: 2,339,471 MBT, 80,200 DBT and 11,136 Micro-BT casts.
[6] Surface data are represented differently from cast (profile) data in the database – all observations in a single cruise have been combined into one "cast" with zero depth, value(s) of variable(s) measured, latitude, longitude, and Julian year-day to identify data and position of individual observations.

1.3.1. IOC Global Oceanographic Data Archaeology and Rescue Project

NCEI and several other oceanographic data centers initiated "data archaeology and rescue" projects around 1991. Based on the success of these projects, the IOC 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. Levitus *et al.* (1994) described results from the first phase of this project. With the publication and distribution of the WOD, 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 NCEI/WDS "Global Ocean Database Project" in 1996.

1.3.2. Near-real time data sources

GTSPP (Searle, 1992; IOC, 1998) is a project sponsored by the IOC/IODE and the Joint Committee for Oceanography and Marine Meteorology (JCOMM) to develop databases of temperature-salinity profiles reported in "real-time". WOD incorporates XBT, XCTD, CTD, glider, and pinniped data from GTSPP with the expectation that delayed-mode (received some time after 48 hours with full resolution, calibration, and quality assurance) data will be received and incorporated later. Often delayed mode data are never received, leaving the near real time version the sole record in the WOD for many casts.

Users wanting GTSPP data directly can acquire the data via the NCEI GTSPP website (https://www.nodc.noaa.gov/GTSPP/).

Tropical moored buoy data from the TAO/TRITON array (McPhaden *et al.*, 1998) and the PIRATA and RAMA arrays were obtained from PMEL. Users wanting the complete TAO/TRITON/PIRATA/RAMA buoy database comprised of data that have had the benefit of additional PMEL processing and quality control, can find the data at https://www.pmel.noaa.gov/tao/drupal/disdel/.

Profiling floats from the Argo program were obtained through the Coriolis Global Data Assembly Center. Users wanting the most up to date Argo data and quality control should obtain their data via Coriolis web site (http://www.coriolis.eu.org/Observing-the-Ocean/ARGO) or the U. S. GODAE mirror site (http://www.usgodae.org/argo/argo.html).

1.3.3. International Research Projects Data

Data from WOCE, the Climate Variability (CLIVAR) program (WCRP, 1995), and GO-SHIP are maintained at the CLIVAR and Carbon Hydrographic Data Office (http://cchdo.ucsd.edu/) and updated to the WOD on a quarterly basis.

1.3.4. ICES Contribution

The International Council for Exploration of the Sea (ICES; http://www.ices.dk) has collected data from participating countries since its inception in 1902. ICES has been an important provider of data to the WOD and continues to make available their latest updates on a quarterly basis.

1.3.5. 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(NCEI)/WDC databases. Recent U.S. Navy data have been acquired from the U.S. Navy MOODS database. In addition, the Australian Navy reports profile data in real-time including data from their Exclusive Economic Zone (EEZ).

1.3.6. 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, CA) 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 IOC (see https://www.wmo.int/pages/prog/amp/mmop/JCOMM/OPA/SOT/soop.html; IOC, 1989) and are the main provider of XBT data to the WOD through the GTSPP.).

1.4. QUALITY CONTROL FLAGS

Each individual data value and each profile in WOD18 has quality control flags associated with it. A description of these flags and general documentation describing software for reading and using the WOD18 database are found in Garcia *et al.* (2018). WOD also includes Quality Control Flags assigned by data submitters. 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 WOD flags represent data values used or not used in the calculation of the WOA climatological mean fields.

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 possible 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.

1.4.1. Levels of Quality Control

Different oceanographic variables in the WOD datasets have various levels of quality control performed on them. Those oceanographic variables in datasets used for calculating climatological means have the highest level of quality control. This includes all preliminary and automatic quality control checks and subjective checks performed in evaluating the quality of the resultant climatological fields. The automatic checks include minimum/maximum range assessment for 31 ocean areas at 102 standard levels.

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

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

Chlorophyll, pH, and alkalinity values in the OSD dataset 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 WOA18, so no standard deviation checks were performed. All other checks were done as for oxygen in the CTD, PFL, DRB, UOR and GLD 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 in the OSD dataset. 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 and PFL datasets were subject to this lowest level of quality control as well. A. Mishonov set the minimum and maximum values.

For more information about the quality control procedures, see Garcia *et al.* (2018).

Plankton data have a different set of quality control detailed in Chapter 16 of this document as well as Garcia *et al.* (2018).

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

Substantial amounts of historical ocean data continue to be transferred to NCEI/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 (e.g. Helber *et al.*, 2012 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 IODE GODAR and World Ocean Database projects 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 because of international cooperation, the scientific community will be able to make more and more realistic estimates of variability and to place confidence intervals of the more frequently sampled variables such as temperature.

1.6. LAYOUT OF THE REST OF THIS DOCUMENT

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

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

Hernan E. Garcia, James Reagan, Olga K. Baranova, Tim P. Boyer, Ricardo A. Locarnini, Alexey V. Mishonov, Dan Seidov, Igor V. Smolyar, Melissa M. Zweng

Ocean Climate Laboratory
NOAA National Centers for Environmental Information
Silver Spring, Maryland, USA

2.1. INTRODUCTION

Data from Ocean Station Data (OSD) casts have historically referred to surface and sub-surface oceanographic physical, chemical, and biological measurements at depths of interest in the water column (*i.e*., profiles) made from sea-going research ships using a variety of water samplers. OSD data are frequently referred to as “bottle data” and the entire OSD collection may be alternatively referred to as the “Bottle Dataset”. Here we adopt the general term OSD to refer collectively to low vertical resolution spacing between profile samples, serial (discrete) water column measurements (bottles, buckets), plankton (bottles, net-tows), relatively low vertical (depth or pressure) resolution Expendable Conductivity-Temperature-Depth (XCTD), and relatively low vertical resolution Conductivity-Temperature-Depth (CTD) data in the *World Ocean Database 2018* (WOD18**)**. High vertical resolution Conductivity-Temperature-Depth data are in the CTD dataset. Salinity-temperature-depth (STDs) and CTDs were introduced around the mid-1960s. Many oceanographic 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, low-resolution CTD and STD measurements are recorded at the depths at which water samples have been collected and usually some data at additional depths.

The OSD dataset includes 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 without restriction to date totaling 3,220,635 casts covering the years 1772 to 2017 (Figure 2.1). The description that follows is a general description 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 stations (sometimes-called hydrographic stations) at geographic locations along generally pre-selected cruise tracks. For each station, discreet water samples from the ocean surface to some selected depth of the water column were obtained by means of a variety of specially designed sampling water bottles of different volumes depending on the target measurements. Some of the very early historical oceanographic measurements of the water column were collected by means of wood or metal buckets.

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

The majority of the most commonly analyzed constituents dissolved in seawater in the OSD dataset were obtained from a relatively small sample volume of seawater. The most commonly analyzed constituents in seawater have been salinity, dissolved oxygen, and the major dissolved inorganic nutrients: nitrate, silicate, and phosphate (Table 2.1). Many additional chemical constituents such as trace metals and transient tracers have been measured with the emergence of more precise and clean chemical measurements and sampling techniques. For example, large volumes of seawater are needed for the analysis of chemical constituents in trace concentrations present in seawater such as isotopes (*e.g.*, argon-39, kripton-85, and carbon-14). Present day analytical techniques for measuring kripton-85 in seawater, for example, require a sampling volume of about 1200 liters (Smethie and Mathiew, 1986; Key, 1994; Smethie, 1994). The Gerard-Ewing samplers were first used during the Geochemical Ocean Sections Study (GEOSECS) program in the early 1970s (Bainbridge, 1980; Craig, 1972;

1974; Craig and Turekian, 1980) and subsequently used during several research cruises such as the Transient Tracers in the Ocean (TTO, Williams, 1986), South Atlantic Ventilation Experiment (SAVE, Smethie and Jacobs, 1992), World Ocean Circulation Experiment (WOCE), and CLIVAR programs. Below we describe briefly the main features of the Nansen and Niskin bottles.

2.3. VARIABLES AND METADATA INCLUDED IN THE OSD DATASET

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

The observed level measurement values in the OSD dataset are the data submitted by the data originator converted to the WOD data format as a function of depth or pressure. All data in OSD are in WOD nominal units (Table 2.1). The profiles at standard levels in the OSD dataset are the measurements submitted by the data originator vertically interpolated to selected depth levels. The profiles include quality flags for observed and standard depth level data (Garcia *et al.,* 2018).

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

Temperature measurements have been obtained by means of manual (*i.e.*, visual readings of temperature from reversing thermometers) and automated (*i.e.*, digital recordings of temperature from STDs and CTDs) sensor instruments. Temperature measurements have been obtained following several International Temperature Scales (ITS) definitions dating back to the early 1900s (*i.e.*, ITS-1927; ITS-1948, ITS-1968) to the ITS-1990 (Preston-Thomas, 1990). Temperature data in WOD18 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 an electrical conductivity ratio (UNESCO, 1981; Lewis and Perkins, 1981; Culkin and Ridout, 1998). Under the PSS-1978 definition, salinity values are unitless or dimensionless (Millero, 1993). Seawater standards provide a means to facilitate the inter-comparison of ocean salinity measurements against samples of known electrical conductivity ratio (UNESCO, 1981; Mantyla, 1980; 1987; 1994; Culkin and Smed, 1979; Aoyama *et al.,* 2002; Kawano *et al.,* 2005). More recently, the concept of absolute salinity anomaly has been introduced to compute absolute salinity values in terms of salinity values using the PSS-78 definition (McDougall *et al.*, 2009). In all cases, WOD18 salinity data are not corrected for "standard sea water" changes (Mantyla, 1994) or converted to any salinity scale other than the scale the measurements were reported in.

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

Geochemical variables such as dissolved oxygen (O_2), dissolved inorganic nutrients (reactive phosphate, nitrate, and silicate or silicic acid), carbon species (alkalinity, dissolved inorganic carbon, partial pressure of carbon dioxide) and pH are non-conservative variables. Their concentrations or values 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 WOD18 includes nitrate plus nitrite (N+N) and nitrate data only. The concentrations of N+N and nitrite are often estimated by photometric analyses where in one case nitrate is measured indirectly by effectively reducing nitrate to nitrite while in the other only nitrite is measured (*e.g.,* Strickland and Parsons, 1972; Atlas *et al.,* 1971; Whitledge *et al.,* 1986; Gordon *et al.,* 1993). The concentration of nitrate is then obtained by the difference between the estimated concentrations of N+N and nitrite. It is important to note that data reported as nitrate in the WOD18 should be used with caution because it is difficult to verify in some cases whether the nitrate data are N+N or nitrate. Except for low oxygen zones, the nominal nitrite concentrations in the open ocean are generally very low. When reported by the originator of the data, WOD18 includes metadata information about whether the labeled nitrate measurement is reported as N+N data. Historical dissolved inorganic carbon (DIC), alkalinity (ALK), partial pressure of CO_2 (pCO_2), and pH data in WOD18 have not always included information about the methods, instruments, and scales used (Millero *et al.,* 1993a, 1993b; Ramette *et al.,* 1977; Robert-Baldo *et al.,* 1985; Bradshaw and Brewer, 1988; Byrne and Breland, 1989; Dickson, 1981; 1984; 1993; DOE, 1994). When reported, modern geochemical data include additional metadata including the use of certified reference materials (CRM) and scales.

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 helped minimize 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. Most modern O_2 chemical titration measurements use Carpenter's whole bottle titration method and an amperometric or photometric end-detection with an estimated uncertainty of about 1 µmol kg^{-1}.

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

Parameter [nominal abbreviation]	Reporting unit (nominal abbreviation)	Number of profiles (sampled years)
Temperature	Degree centigrade (°C)	2,845,911 (1772-2017)
Salinity	Dimensionless or unit less	2,408,713 (1873-2017)
Dissolved oxygen	Micro-mole per kilogram ($\mu mol \cdot kg^{-1}$)	913,215 (1878-2017)
Phosphate	Micro-mole per kilogram ($\mu mol \cdot kg^{-1}$)	597,499 (1922-2017)
Silicate	Micro-mole per kilogram ($\mu mol \cdot kg^{-1}$)	461,801 (1921-2017)
Nitrate	Micro-mole per kilogram ($\mu mol \cdot kg^{-1}$)	372,557 (1925-2017)(1)
pH	Dimensionless or unit less	265,898 (1910-2017)
Chlorophyll(4)	Micro-gram per liter ($\mu g \cdot l^{-1}$)	220,059 (1933-2017)
Alkalinity(4)	Milli-equivalent per liter ($meq \cdot l^{-1}$)	71,932 (1921-2017)
Partial pressure of carbon dioxide	Micro-atmosphere (µatm)	3,086 (1967-2014)
Dissolved inorganic carbon(4)	Milli-mole per liter ($mmol \cdot l^{-1}$)	21,588 (1958-2017)
Tritium	Tritium Unit (TU)(2)	1,876 (1984-2015)
Helium	Nano-mol per kilogram ($nmol \cdot kg^{-1}$)	1,979 (1984-2013)
Delta Helium-3	Percent (%)	1,113 (1985-2013)
Delta Carbon-14	Per-mille (‰) deviation	1,726 (1987-2014)
Delta Carbon-13	Per-mille (‰) deviation	1,800 (1991-2014)
Argon	Nano-mol per kilogram ($nmol \cdot kg^{-1}$)	73 (1993-1993)
Neon	Nano-mol per kilogram ($nmol \cdot kg^{-1}$)	1,381 (1987-2013)
Chlorofluorocarbon-11	Pico-mole per kilogram ($pmol \cdot kg^{-1}$)	16,530 (1982-2017)
Chlorofluorocarbon-12	Pico-mole per kilogram ($pmol \cdot kg^{-1}$)	16,617 (1982-2017)
Chlorofluorocarbon-113	Pico-mole per kilogram ($pmol \cdot kg^{-1}$)	6,706 (1990-2016)
Delta Oxygen-18	Per-mille (‰) deviation	1,186 (1991-2010)
Pressure	Deci-bar	207,107 (1890-2017)
Plankton taxonomy and Biomass	Various units	245,059 (1900-2015)(3)

Table 2.1a Notes:

(1) Profile count includes 21,055 profiles of Nitrate + Nitrite (N+N) minus 2,053 profiles that reported both N+N and Nitrate concentrations.

(2) One tritium unit (TU) equals 1 tritium atom in 10^{18} hydrogen atoms.

(3) Plankton count refers to the number of stations casts (see Plankton Chapter).

(4) Reporting units will change in the final version of WOD18 from a per-volume to a per-mass basis.

Table 2.1b. Reporting unit changes in WOD18 from World Ocean Database 2013 (WOD13) in the Oceanographic Station Data (OSD) dataset.

Variable	Reporting unit in WOD13	Reporting unit WOD18 units
Dissolved Oxygen	Milli-liter per liter ($ml \cdot l^{-1}$)	Micro-mole per kilogram ($\mu mol \cdot kg^{-1}$)
Phosphate	Micro-mole per liter ($\mu mol \cdot l^{-1}$)	Micro-mole per kilogram ($\mu mol \cdot kg^{-1}$)
Silicate	Micro-mole per liter ($\mu mol \cdot l^{-1}$)	Micro-mole per kilogram ($\mu mol \cdot kg^{-1}$)
Nitrate	Micro-mole per liter ($\mu mol \cdot l^{-1}$)	Micro-mole per kilogram ($\mu mol \cdot kg^{-1}$)
Helium	Nano-mol per liter ($nmol \cdot l^{-1}$)	Nano-mol per kilogram ($nmol \cdot kg^{-1}$)
Argon	Nano-mol per liter ($nmol \cdot l^{-1}$)	Nano-mol per kilogram ($nmol \cdot kg^{-1}$)
Neon	Nano-mol per liter ($nmol \cdot l^{-1}$)	Nano-mol per kilogram ($nmol \cdot kg^{-1}$)
CFC-11	Pico-mol per liter ($nmol \cdot l^{-1}$)	Pico-mol per kilogram ($pmol \cdot kg^{-1}$)
CFC-12	Pico-mol per liter ($nmol \cdot l^{-1}$)	Pico-mol per kilogram ($pmol \cdot kg^{-1}$)
CFC-113	Pico-mol per liter ($nmol \cdot l^{-1}$)	Pico-mol per kilogram ($pmol \cdot kg^{-1}$)

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 vertical 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 obtained by chemical analysis of discrete water samples. In recent years, the quality of sensor-based O_2 data have improved dramatically. 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 so that users can make informed decisions about how to use such data.

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

OSD chemical data received at the National Center for Environmental Information (NCEI) are reported by originators of the data in a variety of concentration units that may differ from the WOD standard units (Table 2.1) and the international system of units in oceanography (UNESCO, 1985). When originator's units differ from a set of adopted WOD common units, the data are converted from the originator's units to a common set of concentration units to facilitate the use of the WOD data. For example, originator's chemical concentration units reported in per-volume units were converted to per-mass units assuming a constant density of seawater equal to 1025 $kg \cdot m^{-3}$ (*e.g.*, an arbitrary choice) , the standard element atomic weights of 1989 (CRC, 1993), and a molar volume of O_2 of 22.3916 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). The WOD18 O_2 concentrations in per-mass units are temperature and pressure independent.

In addition to the observed data (profiles as a function of depth of each sampled variable), OSD casts include additional information (commonly referred to as "station header information") such as ocean surface conditions (*i.e.*, wave direction and height, sea state), meteorological observations (*i.e.*, cloud cover and type, visibility, wind speed and direction, barometric pressure, dry and wet bulb temperature), water color and transparency (*i.e.*, Secchi disk depth), and originator's information about the data collected (instrumentation, methods, units, quality flags, stations and cruise labels, institutions, platforms, principal investigators, *etc.*). Garcia *et al.* (2018) describes the WOD18 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 any originator's 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 facilitate identifying 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 (now part of NOAA's National Centers for Environmental Information, NCEI). The biogeochemical data in the OSD dataset have been measured using a variety of manual and automated analytical methods. It is beyond the scope of this work to describe the evolution and intercomparison of the uncertainty, precision, and accuracy of historical oceanographic chemical measurements. Not all data received at NCEI contained complete metadata information.

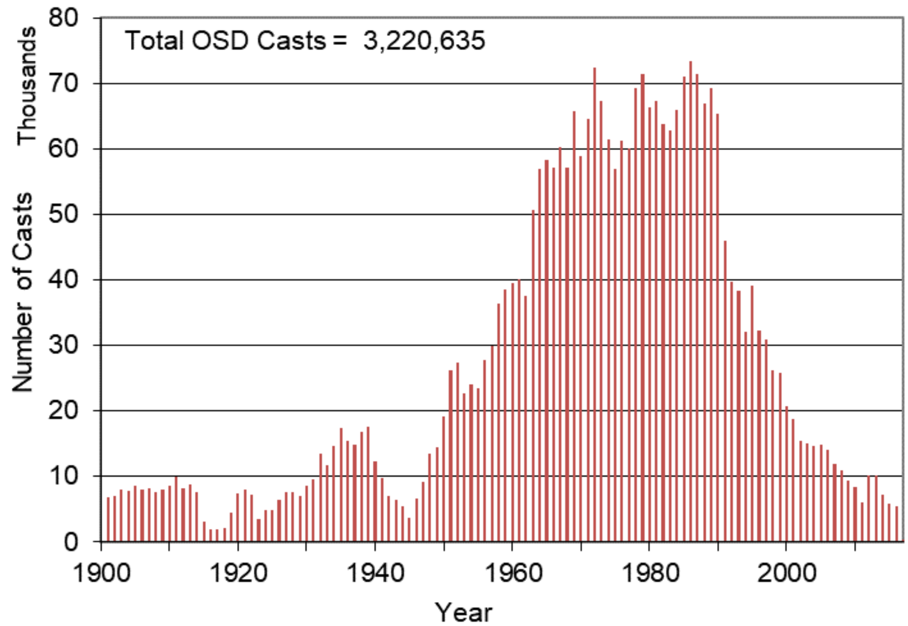

Figure 2.1. Time series of the number of Ocean Station Data (OSD) casts in WOD18

It is difficult to estimate the uncertainty 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 provide relatively consistent high-quality measurements. In the past few years certified reference materials (CRMs) of known chemical concentrations have been used for the analysis, for example, Dissolved Inorganic Carbon and Alkalinity (DOE, 1994) or Dissolved Inorganic Carbon (Dennis A. Hansell per. Comm.). The adoption of CRMs facilitates the interlaboratory comparison of measurements collected by different ocean observing systems. Farringtion (2000) provides a summary of advances in chemical oceanography for the 1950-2000 period.

2.4. OSD DATA COVERAGE

The sampling coverage of the OSD variables is worldwide and for some variables spans several decades (Tables 2.1 and 2.3). The number of OSD casts added to WOD has increased greatly since 1974 (Figure 2.4, however, the coverage for each variable is not uniform in space or time (Table 2.2, Figures 2.5-2.28). The largest numbers of oceanographic profiles present in the OSD dataset are 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 have a specific research goal that may require sampling of a limited number of variables. Second, the sampling and analysis of biochemical variables is more labor intensive when compared to temperature or conductivity measurements obtained by CTD instruments.

2.5. PARAMETERS AND METADATA NOT INCLUDED IN THE OSD DATASET

The WOD includes data for other biochemical variables not available as part of the WOD18 release. These variables were not released as part of the WOD18 because a minimum of data quality control was not performed on these measurements. The variables not present in the WOD18 include dissolved and particulate organic carbon, nitrite, total phosphorus, ammonia, various chlorophyll pigments, and primary production. In addition, NCEI maintains a database of originator's data files and documentation as part of the Ocean Archive System (OAS). Users of the WOD18 can retrieve the original data as sent to NCEI. It is worth noting that in some cases, data received at NCEI may include measured variables, which were not digitally stored in the WOD (*e.g.*, trace metals, organic compounds, *etc*.). Information about these variables is maintained in the OAS and available via the NCEI Geoportal.

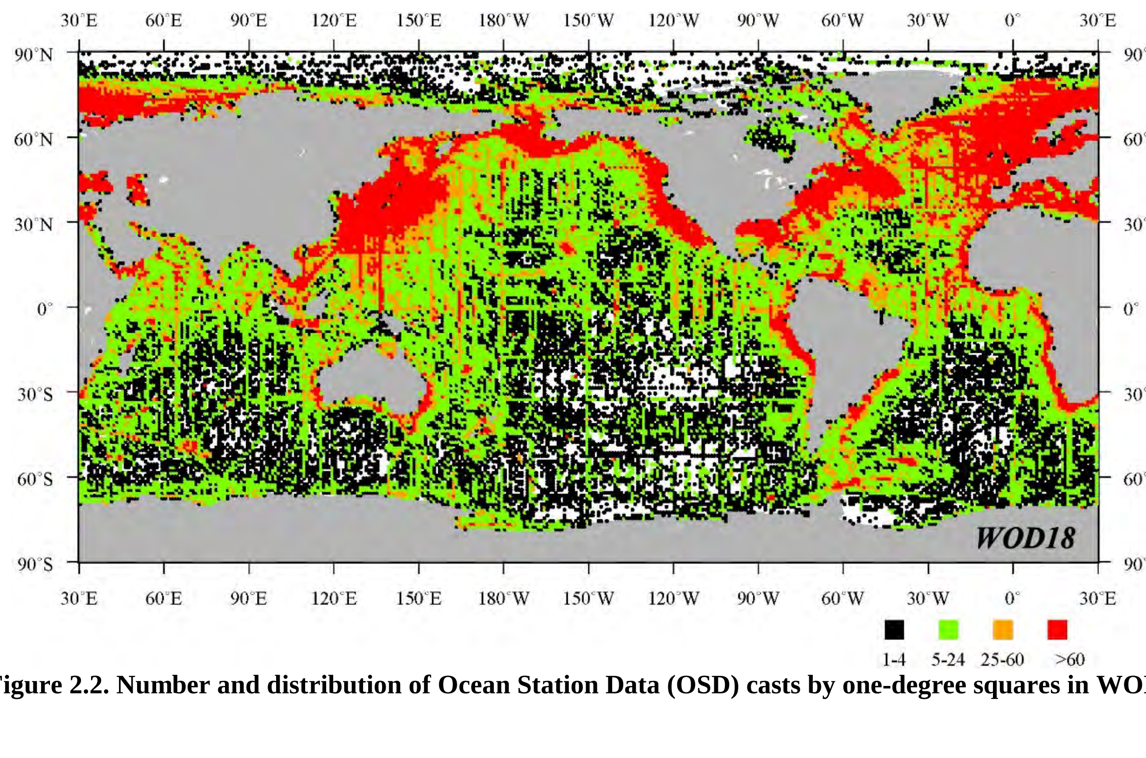

Figure 2.2. Number and distribution of Ocean Station Data (OSD) casts by one-degree squares in WOD18

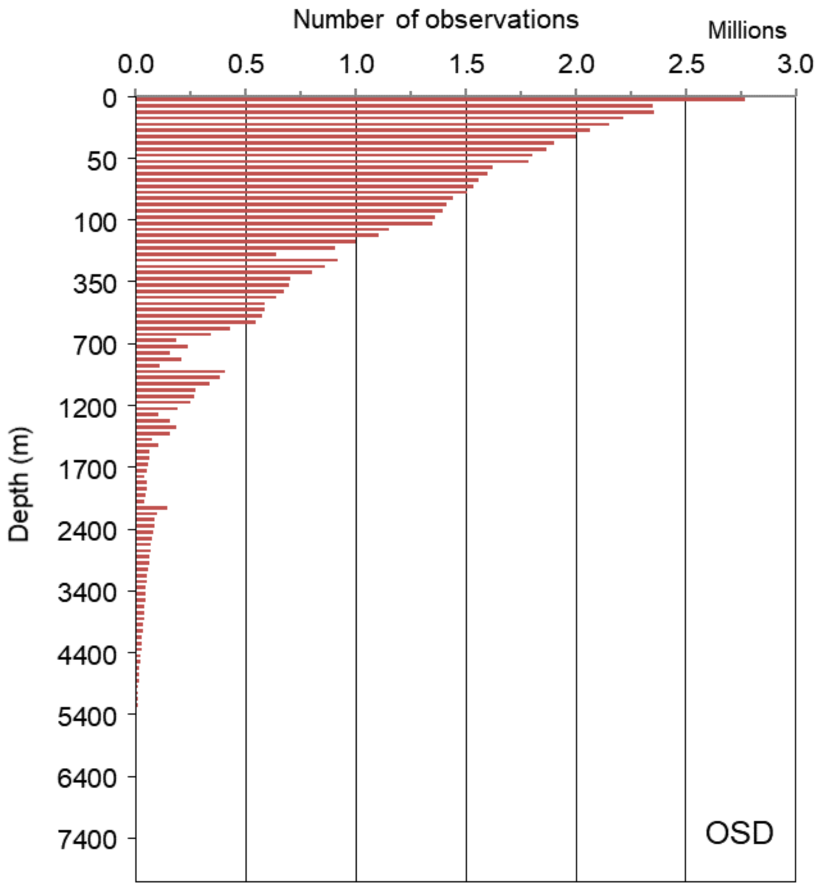

Figure 2.3 Number of Ocean Station Data (OSD) Temperature observations as a function of standard depth levels in WOD18.

2.6. PROSPECTS FOR THE FUTURE

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

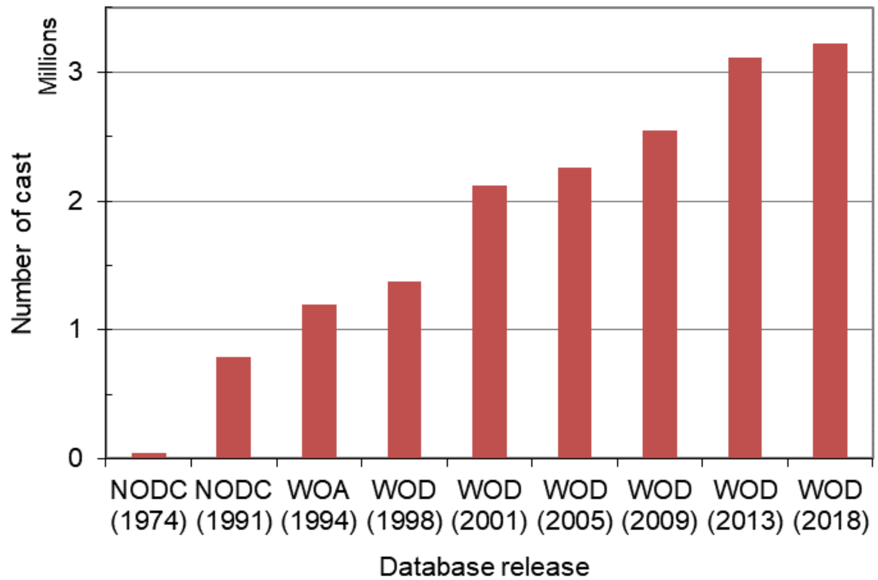

Figure 2.4. Number of OSD casts in NCEI (previously NODC)/WDS databases as a function of time The number of casts available at NODC prior to 1994 after Levitus (1982) and NODC Temperature-Profile CD-ROM (1991). The number of casts after 1994 based on the World Ocean Atlas (WOA) and World Ocean Database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

The WOD is a worldwide source of unrestricted access to historical oceanographic data information. Future releases of the WOD will be enhanced by the addition of more data and metadata. It is hoped that users of the WOD18 inform us of sources of historical data not present in the database as well as any data or metadata errors that might be present in the database at NCEI. Identification of new sources of chemical oceanographic data to the WOD is beneficial for improving mechanisms for long-term data archival, data management, and data distribution into national and international data archives. Addition of new data will help improve the release of an improved high-quality global, scientifically quality-controlled ocean profile-plankton database, ocean data products, and diagnostic studies. Addition of new data will also help to provide observational constraints on oceanic variability studies.

Table 2.2. The number of Ocean Station Data (OSD) casts as a function of year in WOD18
(Total number of casts = 3,222,035).

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1773	1	1835	0	1897	5,381	1958	36,429
1774	0	1836	8	1898	6,369	1959	38,474
1775	0	1837	17	1899	6,471	1960	39,579
1776	0	1838	11	1900	6,463	1961	40,023
1777	0	1839	15	1901	6,748	1962	37,539
1778	0	1840	9	1902	7,020	1963	50,694
1779	0	1841	21	1903	7,903	1964	56,941
1780	0	1842	8	1904	7,869	1965	58,235
1781	0	1843	0	1905	8,551	1966	57,189
1782	0	1844	0	1906	8,038	1967	60,209
1783	0	1845	0	1907	8,211	1968	57,094
1784	0	1846	3	1908	7,551	1969	65,663
1785	0	1847	28	1909	7,987	1970	58,817

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1786	0	1848	0	1910	8,472	1971	64,612
1787	0	1849	1	1911	10,025	1972	72,319
1788	0	1850	3	1912	8,249	1973	67,301
1789	0	1851	1	1913	8,799	1974	61,437
1790	0	1852	0	1914	7,655	1975	56,968
1791	0	1853	0	1915	3,043	1976	61,238
1792	0	1854	0	1916	1,845	1977	60,087
1793	0	1855	4	1917	1,941	1978	69,199
1794	0	1856	0	1918	2,128	1979	71,511
1795	0	1857	6	1919	4,471	1980	66,332
1796	0	1858	23	1920	7,311	1981	67,398
1797	0	1859	5	1921	7,941	1982	63,718
1798	0	1860	1,053	1922	7,247	1983	62,771
1799	0	1861	1,351	1923	3,538	1984	65,958
1800	84	1862	1,602	1924	4,817	1985	70,973
1801	0	1863	606	1925	4,928	1986	73,393
1802	0	1864	2,329	1926	6,506	1987	71,390
1803	0	1865	352	1927	7,509	1988	66,885
1804	10	1866	1,494	1928	7,525	1989	69,245
1805	1	1867	78	1929	6,930	1990	65,387
1806	0	1868	793	1930	8,667	1991	45,872
1807	0	1869	567	1931	9,557	1992	39,678
1808	0	1870	737	1932	13,460	1993	38,372
1809	0	1871	50	1933	11,786	1994	32,031
1810	0	1872	7	1934	14,686	1995	39,127
1811	0	1873	226	1935	17,458	1996	32,185
1812	0	1874	193	1936	15,518	1997	30,860
1813	0	1875	196	1937	14,765	1998	26,263
1814	0	1876	573	1938	16,774	1999	25,798
1815	0	1877	385	1939	17,523	2000	20,683
1816	5	1878	90	1940	12,378	2001	18,756
1817	27	1879	57	1941	9,756	2002	15,414
1818	3	1880	976	1942	7,025	2003	15,069
1819	0	1881	1,071	1943	6,388	2004	14,711
1820	2	1882	873	1944	5,389	2005	14,761
1821	0	1883	3,493	1945	3,693	2006	14,149
1822	0	1884	4,510	1946	6,595	2007	11,943
1823	0	1885	4,599	1947	9,131	2008	10,945
1824	2	1886	4,704	1948	13,392	2009	9,325
1825	10	1887	3,776	1949	14,425	2010	8,465
1826	18	1888	3,971	1950	19,159	2011	6,103
1827	30	1889	4,363	1951	26,130	2012	10,230
1828	13	1890	4,632	1952	27,393	2013	10,201
1829	0	1891	4,655	1953	22,697	2014	7,268
1830	0	1892	4,756	1954	23,982	2015	5,740
1831	0	1893	4,692	1955	23,486	2016	5,492
1832	0	1894	5,788	1956	27,828	2017	429
1833	0	1895	5,233				

Table 2.3. National contribution of OSD casts in WOD18

ISO1 Country Codes	Country Name	OSD Casts	% of Total
SU	Union of Soviet Socialist Republics	745,592	23.15%
JP	Japan	597,236	18.54%
US	United States	412,386	12.80%
SE	Sweden	289,252	8.98%
GB	Great Britain	143,594	4.46%
CA	Canada	124,314	3.86%
NO	Norway	114,086	3.54%
99	Unknown / International	99,786	3.10%
DE	Germany	93,042	2.89%
FI	Finland	63,720	1.98%
DK	Denmark	55,071	1.71%
KR	Korea, Republic of	51,638	1.60%
FR	France	49,996	1.55%
AU	Australia	39,567	1.23%
NL	Netherlands	34,567	1.07%
ZA	South Africa	28,979	0.90%
PE	Peru	26,979	0.84%
RU	Russia	26,751	0.83%
PL	Poland	25,309	0.79%
IS	Iceland	20,710	0.64%
UA	Ukraine	15,917	0.49%
DU	East Germany	15,608	0.48%
IT	Italy	12,074	0.37%
BE	Belgium	10,776	0.33%
BR	Brazil	9,572	0.30%
ES	Spain	7,279	0.23%
IE	Ireland	6,650	0.21%
PT	Portugal	6,539	0.20%
CN	China, The Peoples Republic of	5,509	0.17%
YU	Yugoslavia	5,455	0.17%
AR	Argentina	5,046	0.16%
CL	Chile	4,914	0.15%
IN	India	4,488	0.14%
ID	Indonesia	4,397	0.14%
TW	Taiwan	4,062	0.13%
EE	Estonia	4,048	0.13%
TR	Turkey	3,996	0.12%
RO	Romania	3,639	0.11%
VE	Venezuela	3,590	0.11%
EC	Ecuador	3,498	0.11%
GR	Greece	3,489	0.11%
IL	Israel	3,463	0.11%

ISO1 Country Codes	Country Name	OSD Casts	% of Total
CI	Cote D'Ivoire (Ivory Coast)	3,185	0.10%
TH	Thailand	2,801	0.09%
GH	Ghana	2,670	0.08%
MG	Malagasy Republic	2,523	0.08%
LV	Latvia	2,266	0.07%
MC	Monaco	2,054	0.06%
SN	Senegal	1,975	0.06%
NZ	New Zealand	1,942	0.06%
CD	Congo	1,865	0.06%
MX	Mexico	1,457	0.05%
LT	Mauritania	1,429	0.04%
NC	New Caledonia	1,344	0.04%
CO	Colombia	1,338	0.04%
MR	Mauritania	1,217	0.04%
NG	Nigeria	980	0.03%
CU	Cuba	976	0.03%
AT	Austria	773	0.02%
AO	Angola t	621	0.02%
EG	Arab Republic of Egypt	544	0.02%
SG	Singapore	412	0.01%
TN	Tunisia	280	0.01%
PH	Philippines	235	0.01%
MA	Morocco	199	0.01%
LB	Lebanon	187	0.01%
PK	Pakistan	167	0.01%
DZ	Algeria	166	0.01%
MY	Malaysia	154	0.00%
PA	Panama	139	0.00%
YE	Yemen	85	0.00%
MT	Malta	66	0.00%
ZZ	Miscellaneous organization	1	0.00%
		3,220,635	100.00%

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

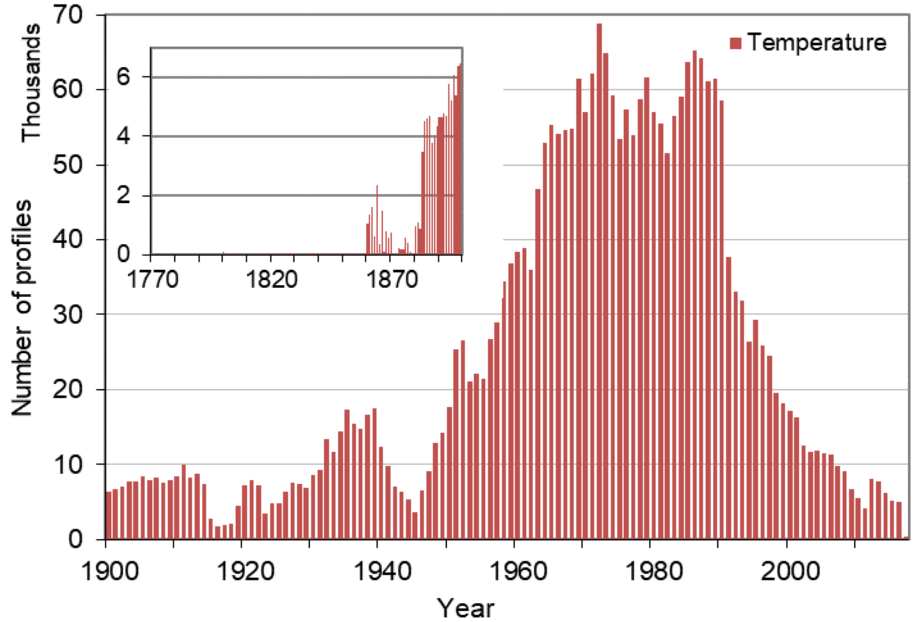

Figure 2.5. Time series of the number of temperature profiles in the WOD18 OSD dataset

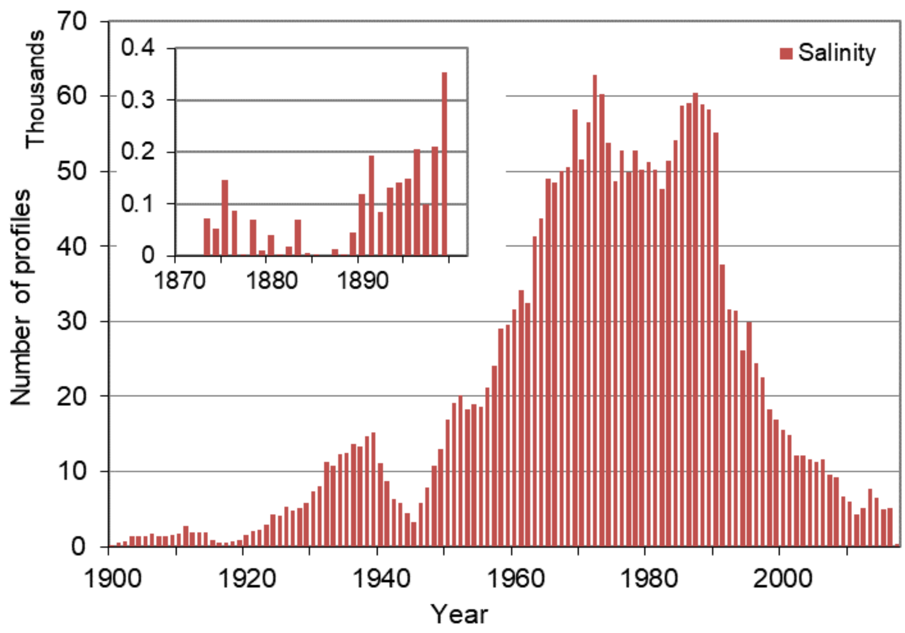

Figure 2.6. Time series of the number of salinity profiles in the WOD18 OSD dataset

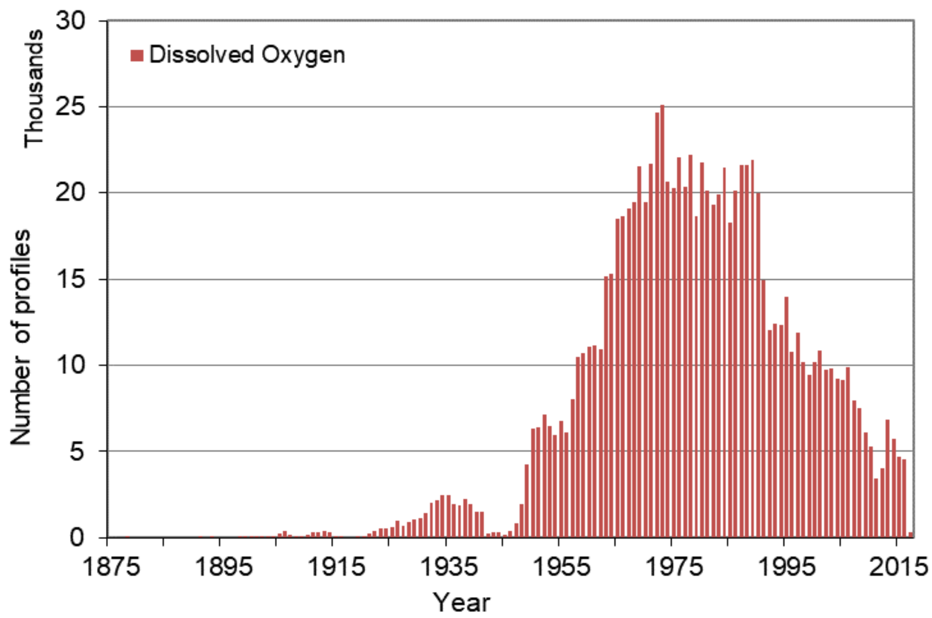

Figure 2.7. Time series of the number of dissolved oxygen profiles in the WOD18 OSD dataset

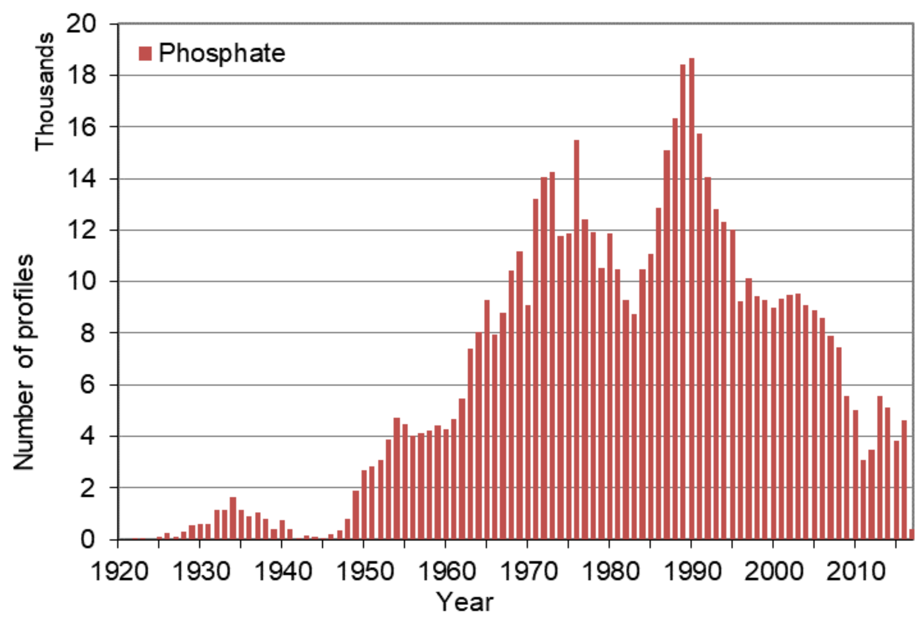

Figure 2.8. Time series of the number of Phosphate profiles in the WOD18 OSD dataset

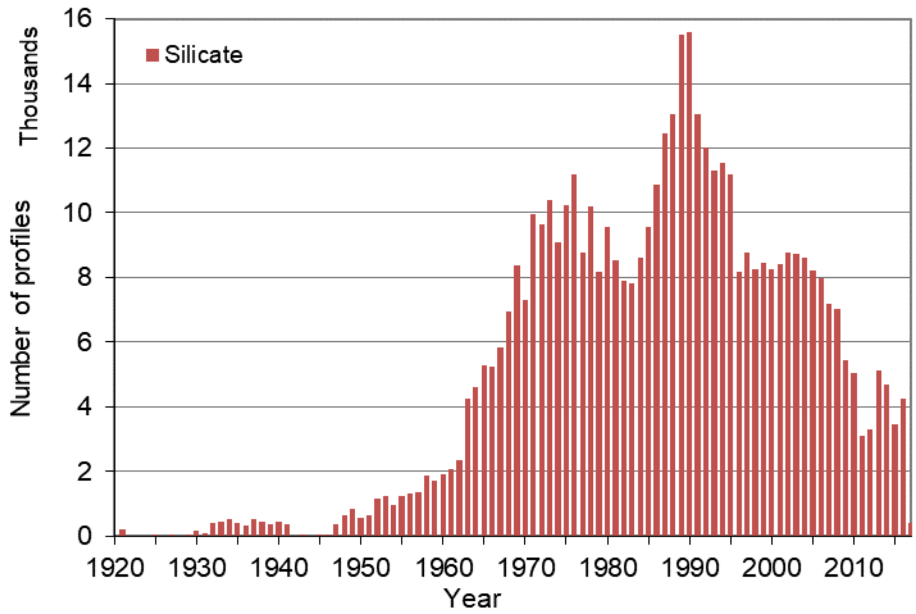

Figure 2.9. Time series of the number of silicate profiles in the WOD18 OSD dataset

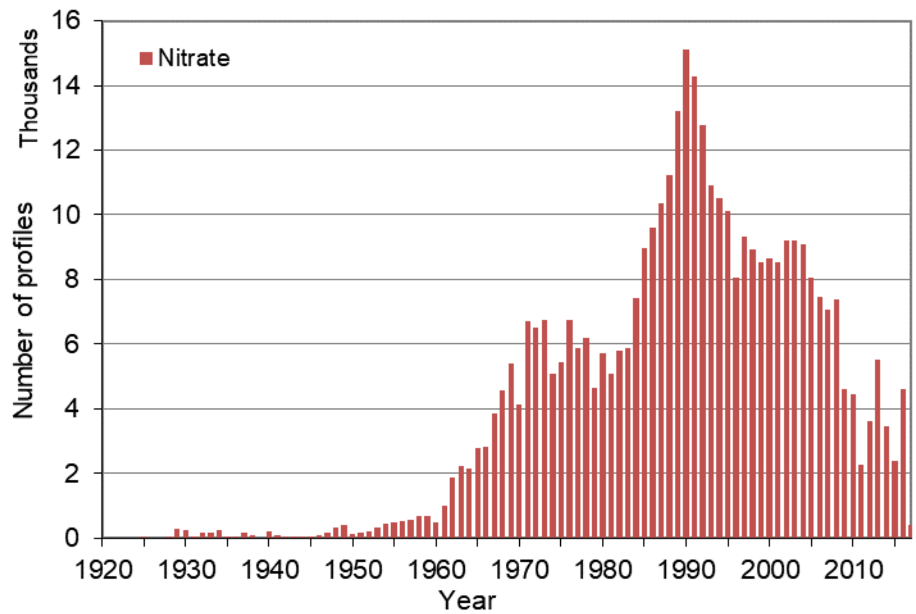

Figure 2.10. Time series of the number of Nitrate profiles in the WOD18 OSD dataset

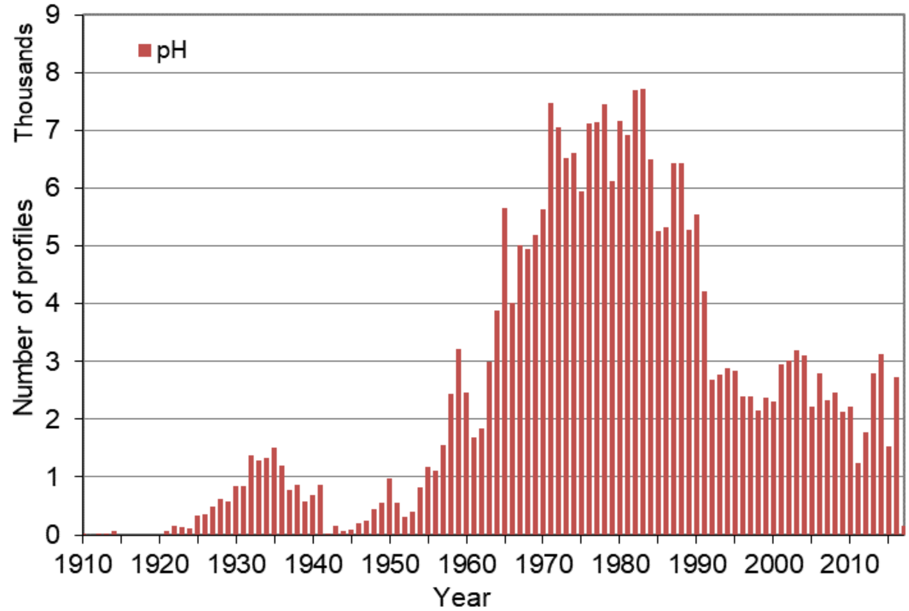

Figure 2.11. Time series of the number of pH profiles in the WOD18 OSD dataset

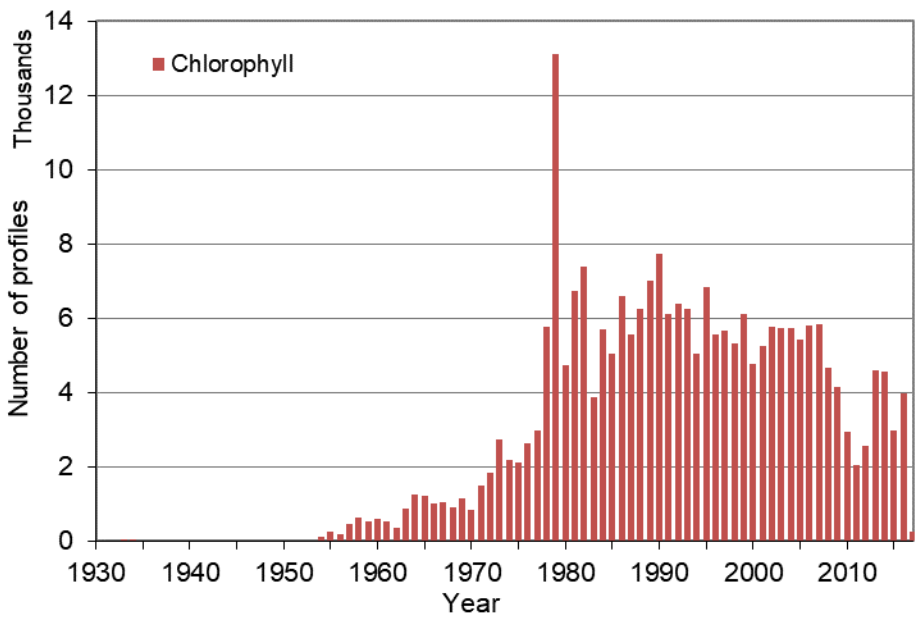

Figure 2.12. Time series of the number of Chlorophyll profiles in the WOD18 OSD dataset

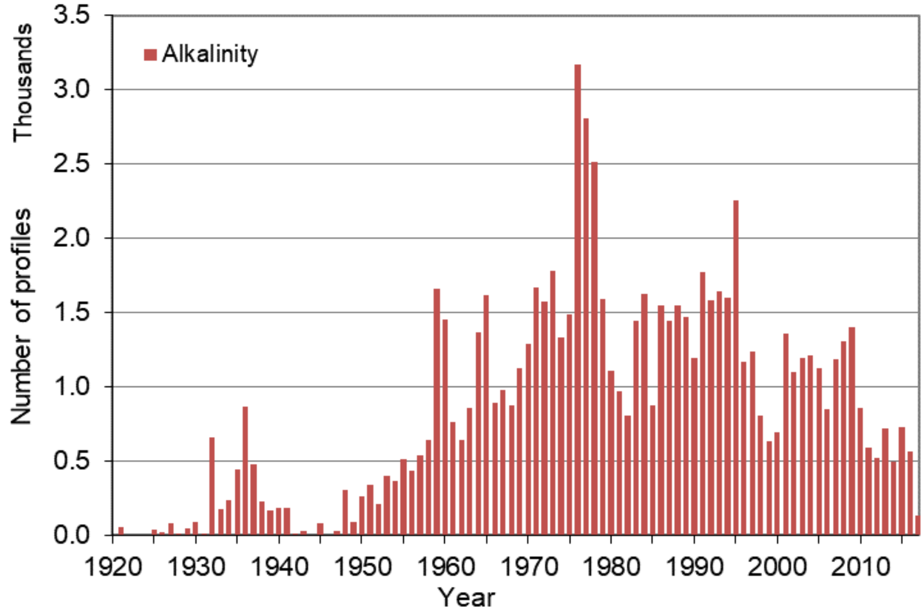

Figure 2.13. Time series of the number of alkalinity profiles in the WOD18 OSD dataset

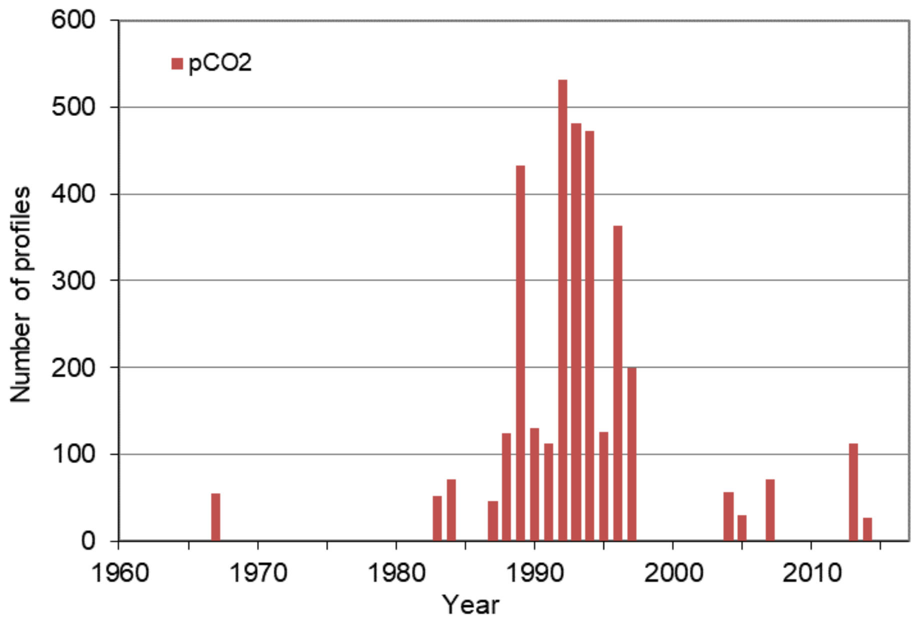

Figure 2.14. Time series of the number of partial pressure of carbon dioxide profiles in the WOD18 OSD dataset

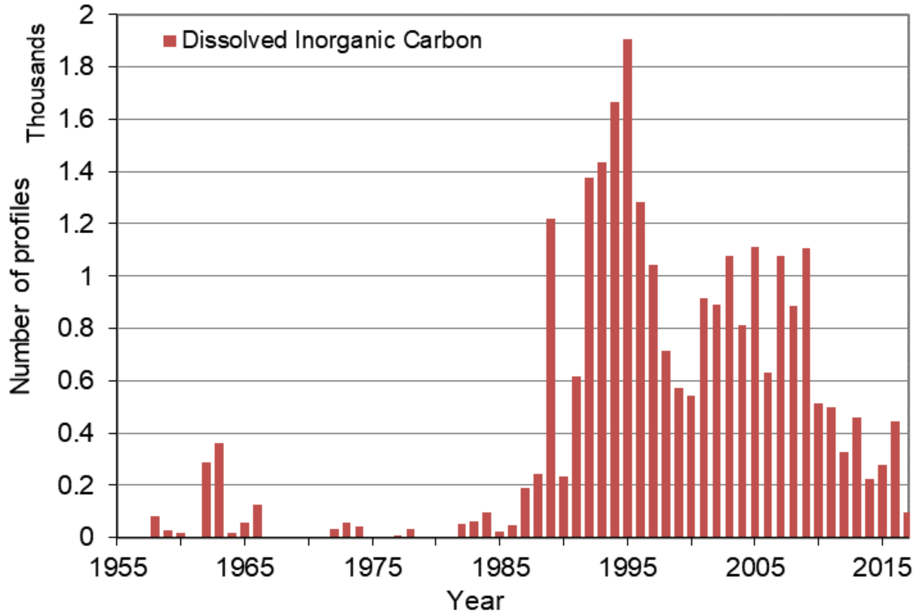

Figure 2.15. Time series of the number of dissolved inorganic carbon profiles in the WOD18 OSD dataset

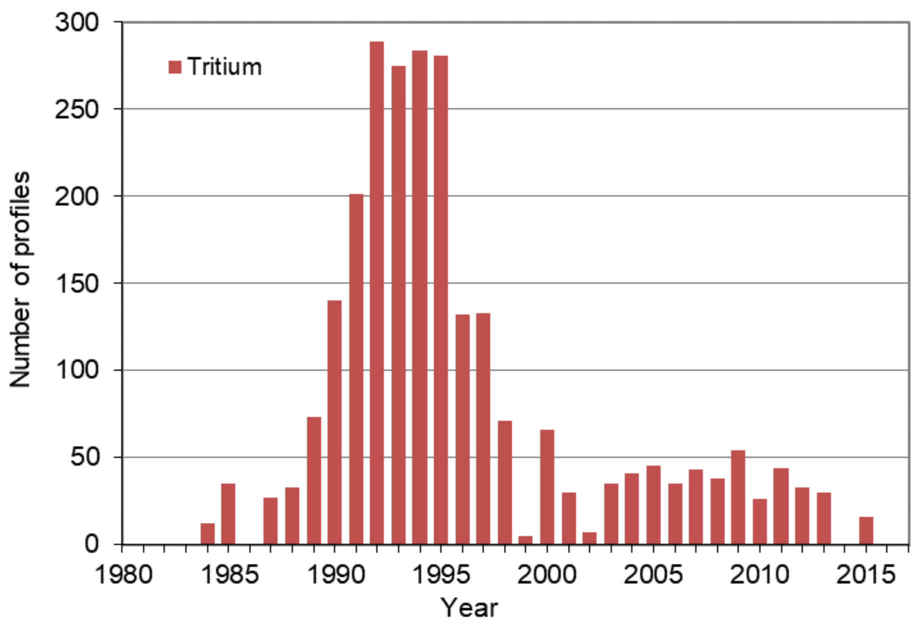

Figure 2.16. Time series of the number of tritium profiles in the WOD18 OSD dataset

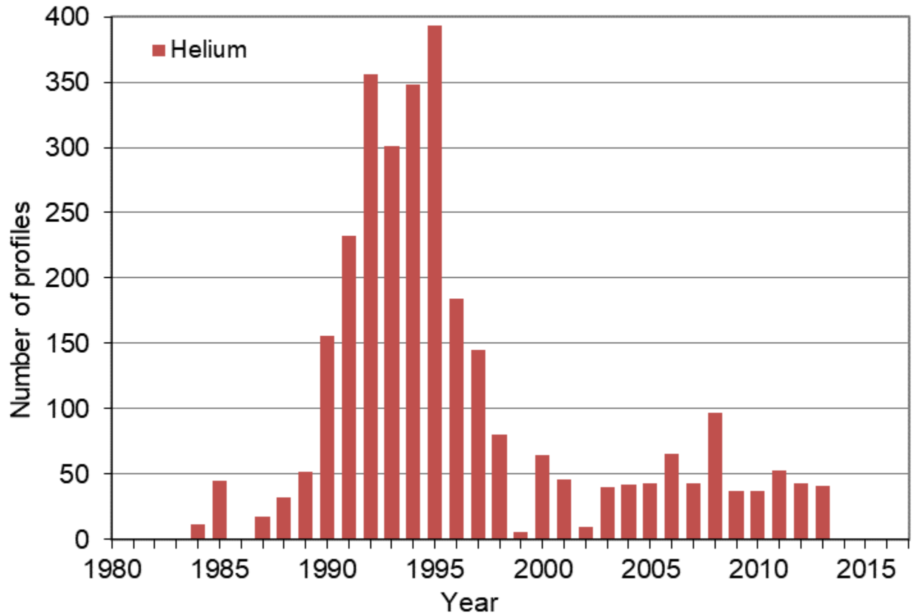

Figure 2.17. Time series of the number of helium profiles in the WOD18 OSD dataset

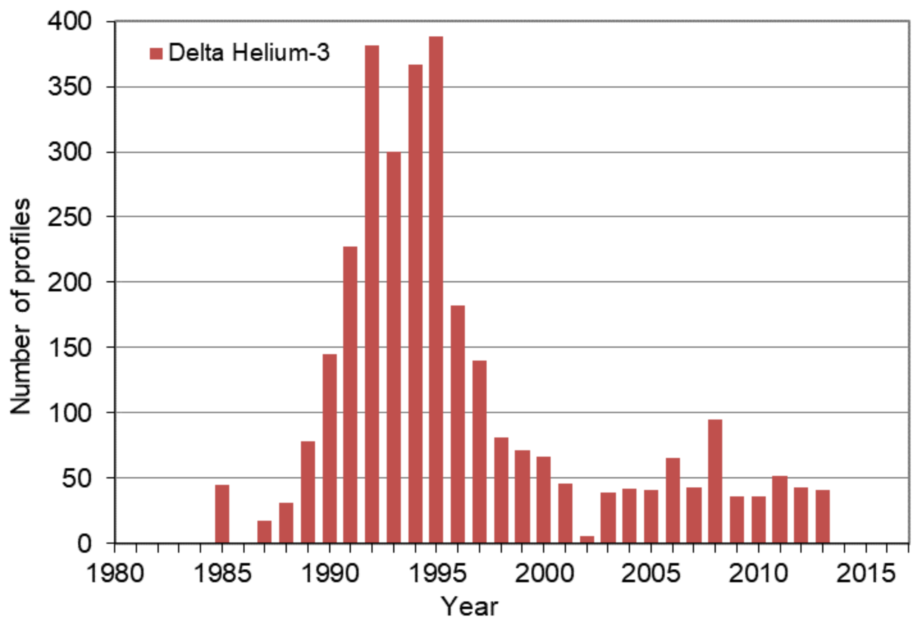

Figure 2.18. Time series of the number of delta-helium-3 profiles in the WOD18 OSD dataset

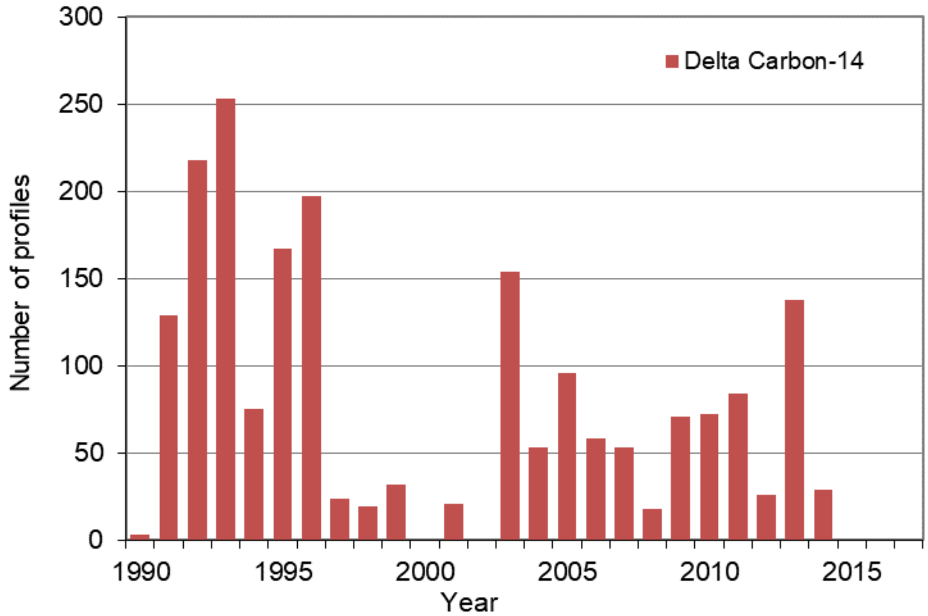

Figure 2.19. Time series of the number of delta-carbon-14 profiles in the WOD18 OSD dataset

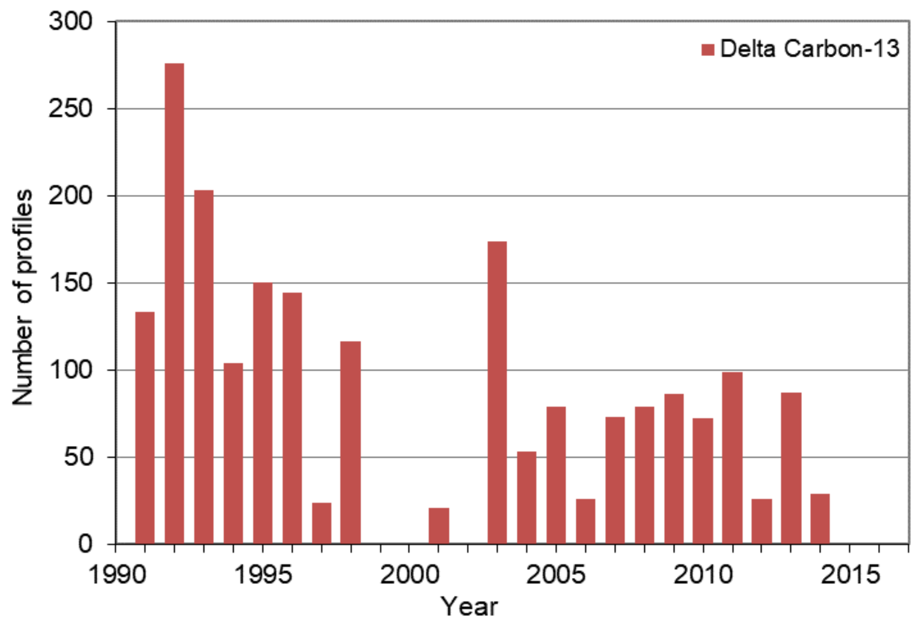

Figure 2.20. Time series of the number of delta-carbon-13 profiles in the WOD18 OSD dataset

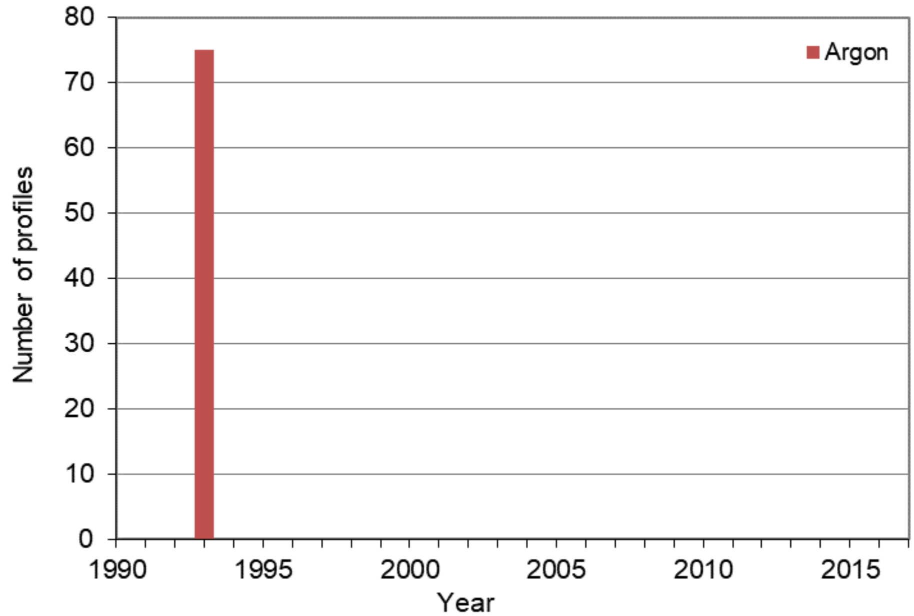

Figure 2.21. Time series of the number of argon profiles in the WOD18 OSD dataset

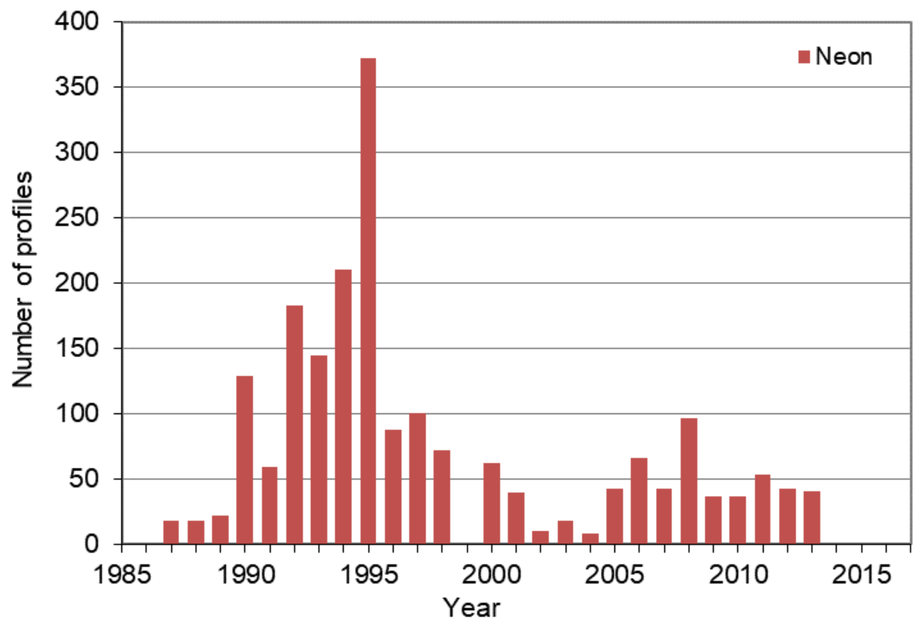

Figure 2.22. Time series of the number of neon profiles in the WOD18 OSD dataset

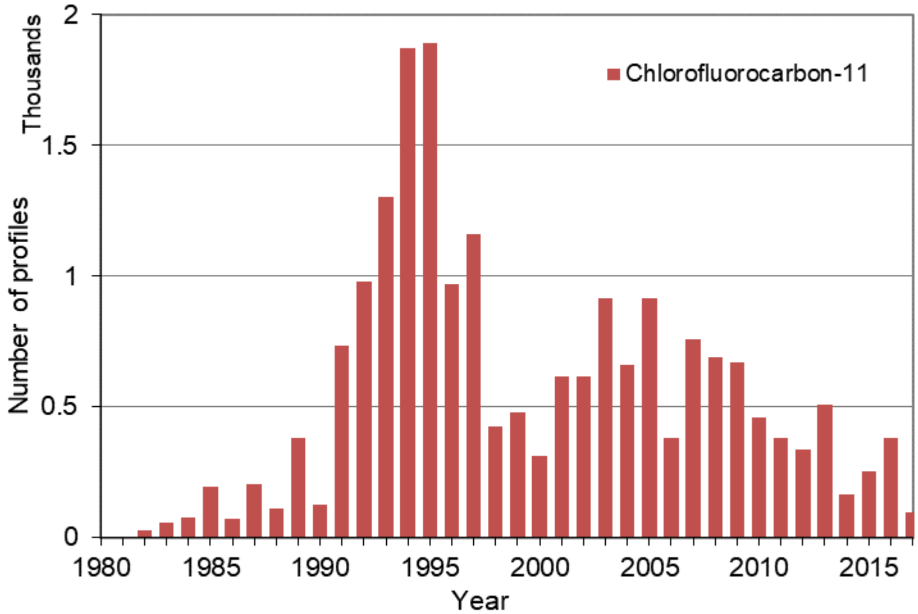

Figure 2.23. Time series of the number of chlorofluorocarbon-11 profiles in the WOD18 OSD dataset

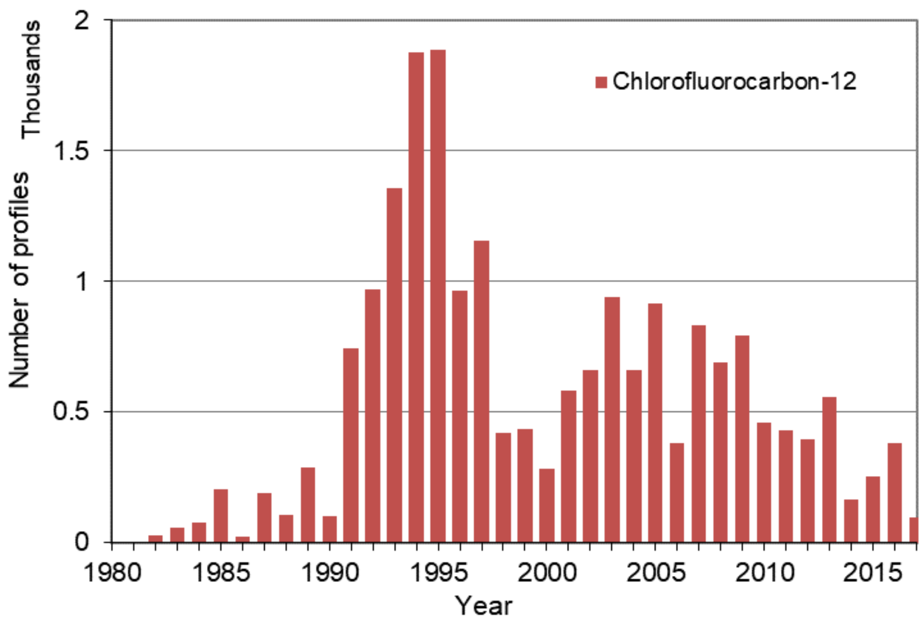

Figure 2.24. Time series of the number of chlorofluorocarbon-12 profiles in the WOD18 OSD dataset

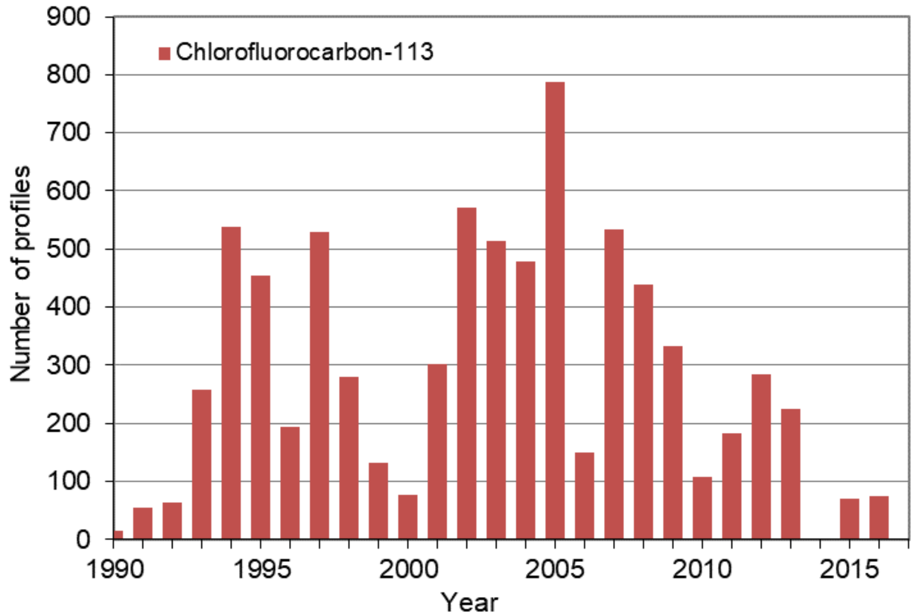

Figure 2.25. Time series of the number of chlorofluorocarbon-113 profiles in the WOD18 OSD dataset

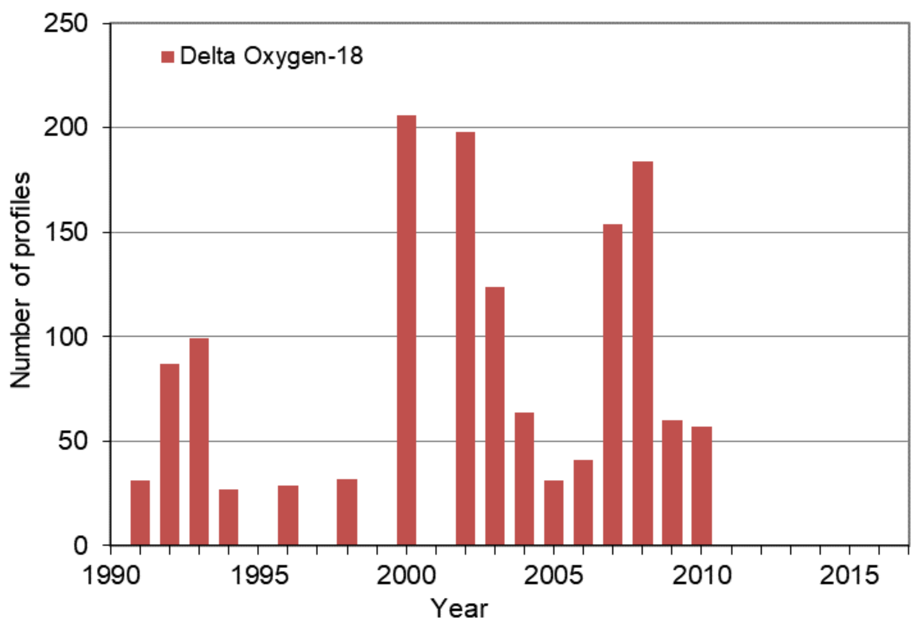

Figure 2.26. Time series of the number of delta-oxygen-18 profiles in the WOD18 OSD dataset

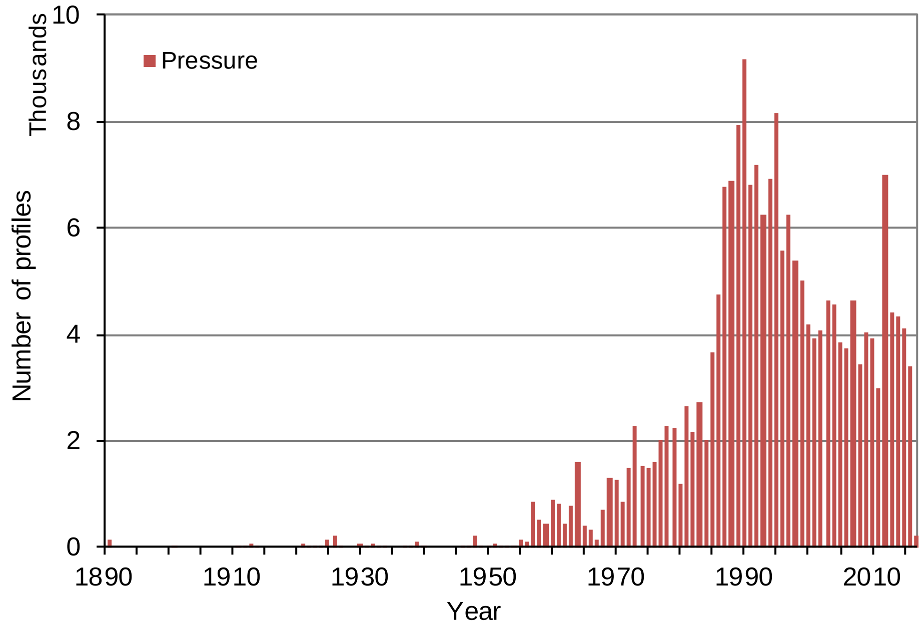

Figure 2.27. Time series of the number of profiles with pressure as a measured parameter in the WOD18 OSD dataset

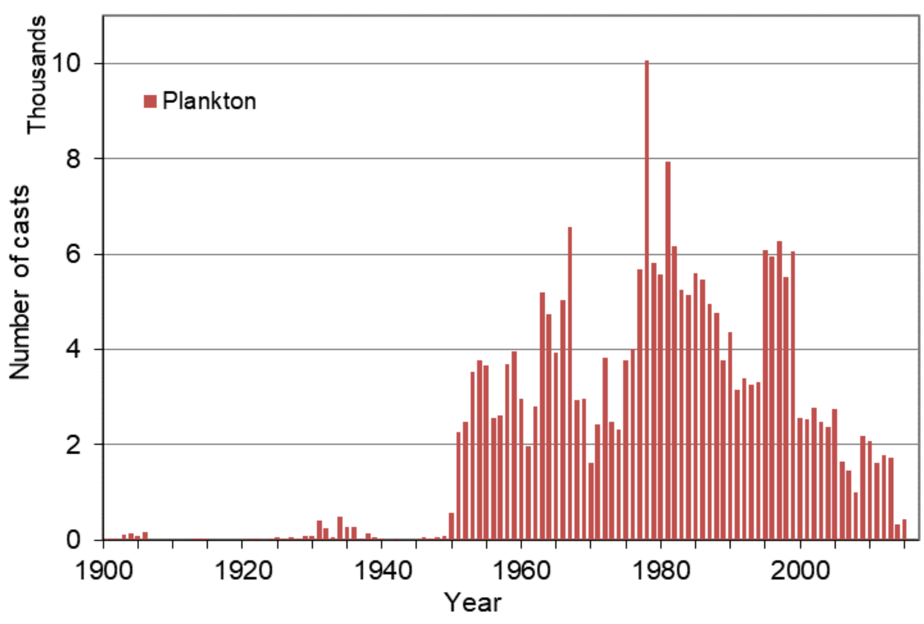

Figure 2.28. Time series of the number of plankton casts in the WOD18 OSD dataset

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

Christopher R. Paver, Alexey V. Mishonov, Tim P. Boyer, Olga K. Baranova, Hernán E. García, Ricardo A. Locarnini, James R. Reagan, Dan Seidov, Igor V. Smolyar, Melissa M. Zweng

Ocean Climate Laboratory
National Center for Environmental Information
Silver Spring, MD

3.1. INTRODUCTION

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

Fundamental physical relationships between temperature (salinity, *etc.*) and electromagnetic properties of sea water are used to develop CTD sensors and appropriate conversion algorithms (Wallace, 1974; Prien, 2001). The sampling rate of CTD sensors – up to 24 Hz for the SBE 911plus (Sea-Bird Scientific; SBE 911plus CTD) - is an important factor that determines the ability of the CTD to make "continuous" measurements. For instance, lowering a CTD at speeds of 1 $m \cdot s^{-1}$ with a typical range of response times for the temperature sensors can provide vertical profiling at resolutions of 0.05 m to 0.3 m.

CTD data submitted to NCEI for archive and inclusion into WOD are stored in their original vertical resolution. In instances where there are more than 6,000 depth-variable measurements in a single profile, those values are generally binned to a lower resolution in WOD. In the past, electronic storage limitations resulted in only selected levels being archived. While processing the original data for inclusion into WOD, pressure values take preference over reported depth values for reporting the depth-measurement values. The pressure values are converted to depths using Saunders and Fofonoff's equation (1976).

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.

Newer sensors have been developed to make continuous measurements of other variables such as dissolved oxygen content, beam attenuation coefficient (BAC; Section 3.4), and chlorophyll concentration. All sensor and derived variables collected via the CTD are stored in the NCEI archive, however, only select variables are maintained in WOD. These variables are identified in table 3.1.

Table 3.1. List of all variables and profile counts in the WOD18 CTD dataset.

Variables	Profiles
Pressure	617,993
Temperature	1,027,934
Conductivity	69,864
Salinity	998,041
Oxygen	187,617
Chlorophyll	84,897
Transmissivity	32,704

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 0.001°C to 0.005°C for temperature, 0.0003 $S{\cdot}m^{-1}$ to 0.002 $S{\cdot}m^{-1}$ for conductivity (approximately 0.003 to 0.02 equivalent salinity), and 0.015% to 0.08% for pressure. These accuracies are subject to change after prolonged use of the CTD (known as a calibration drift).

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

3.3. CTD CAST DISTRIBUTIONS

There are a total of 1,029,231 CTD casts for the entire World Ocean. The earliest reported CTD casts available in WOD are from 1961, however increased reporting didn't occur until 1967 during the International Cooperative Effort Toward Understanding of the Oceanography of the Eastern Tropical Pacific (EASTROPAC; Vilchis and Ballance, 2005), thereafter the number of reported casts increased annually (Table 3.2, Figure 3.1). Then in 1978, a jump in reported casts occurred as a result of sampling contributed by the Institute for Marine Research at Kiel University mainly aboard the *R/V Meteor.* Almost a decade later in 1987, reported casts increased to over 20,000 in part to relatively greater contributions from Canada, Great Britain, the Soviet Union, and the United States. Peak reported CTD observations occurred in 1999 at over 35,000 casts. From about 2002 to 2016, total reported yearly casts were averaging around 25,000. The three nations contributing the most CTD casts are the United States, Canada, and Japan, reporting almost 52% of the total in WOD (Table 3.2). The Atlantic Ocean is the most reportedly sampled basin in WOD, with roughly 62% of the total (Figure 3.2). The coastal regions of the northern hemisphere are the most densely sampled areas, mainly around the continent of Europe, the western North Atlantic boundary with North America, and the western North Pacific boundary around central Asia. The least sampled areas for CTD continue to be the Arctic Ocean and the Southern Ocean, more so for the open waters of the South Pacific. Distribution of the high-resolution CTD observations for temperature and salinity at standard depth levels are shown in Figure 3.3.

Table 3.2. The number of high-resolution CTD casts in WOD18 as a function of year.

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1961	97	1976	9,448	1990	23,345	2004	23,137
1962	42	1977	10,334	1991	28,560	2005	24,755
1963	71	1978	18,448	1992	31,939	2006	23,454
1964	47	1979	11,597	1993	33,509	2007	29,256
1965	0	1980	10,858	1994	33,094	2008	28,812
1966	12	1981	13,988	1995	34,543	2009	25,512
1967	1,531	1982	12,446	1996	28,739	2010	26,227
1968	1,286	1983	13,858	1997	32,146	2011	23,331
1969	3,229	1984	15,438	1998	34,560	2012	24,571
1970	1,740	1985	15,878	1999	35,263	2013	27,817
1971	2,074	1986	17,856	2000	30,874	2014	26,840
1972	4,451	1987	25,910	2001	31,642	2015	23,195
1973	5,743	1988	20,134	2002	25,072	2016	21,945
1974	7,996	1989	23,625	2003	22,760	2017	15,642
1975	8,257						

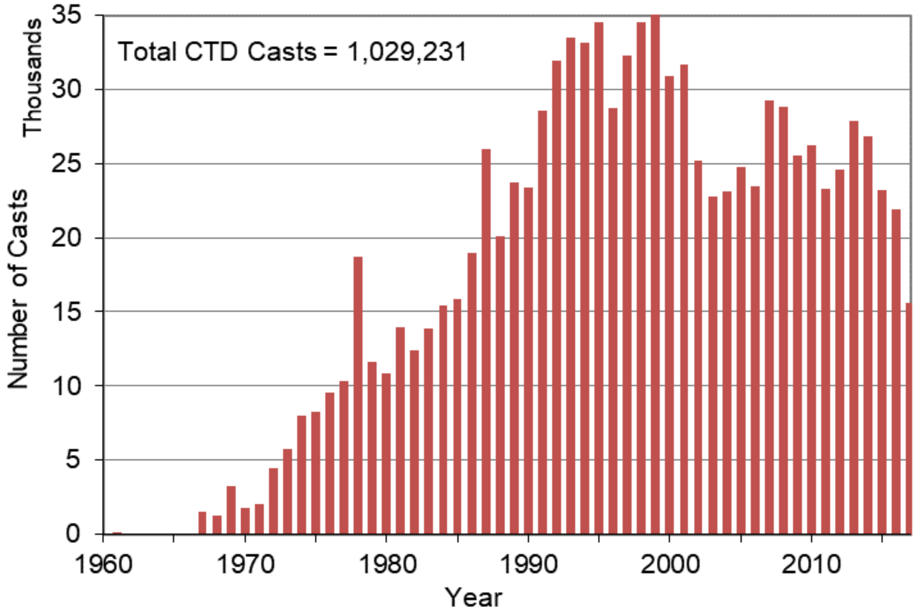

Figure 3.1. Temporal distribution of high-resolution CTD casts in WOD18.

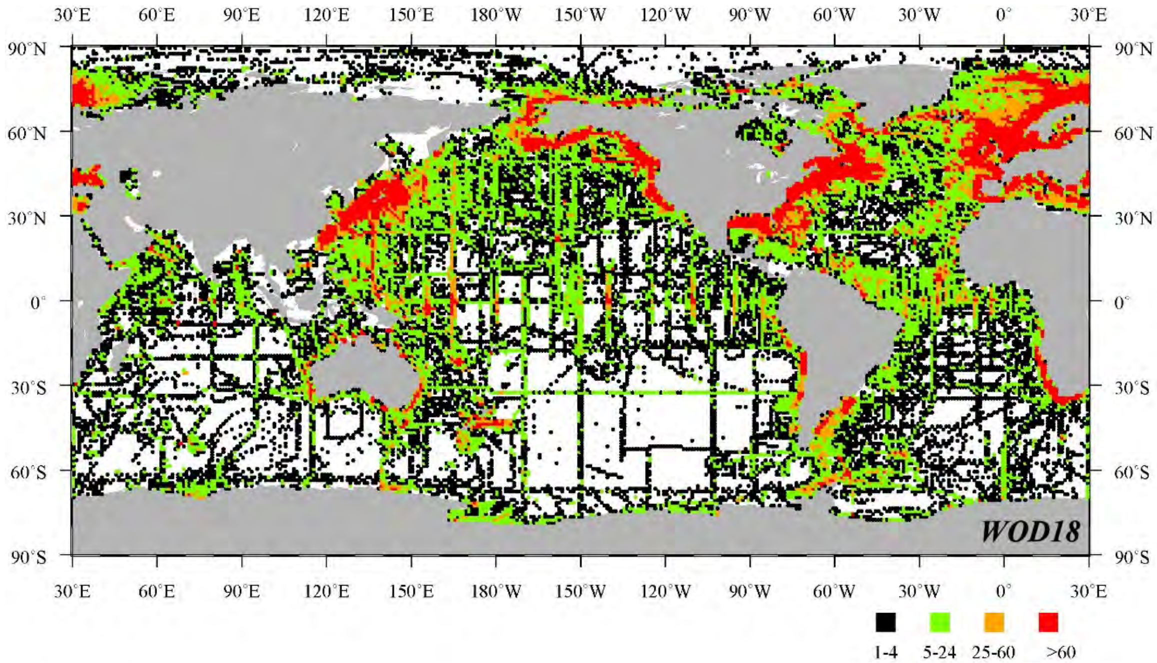

Figure 3.2. Geographic distribution of high-resolution CTD casts in WOD18.

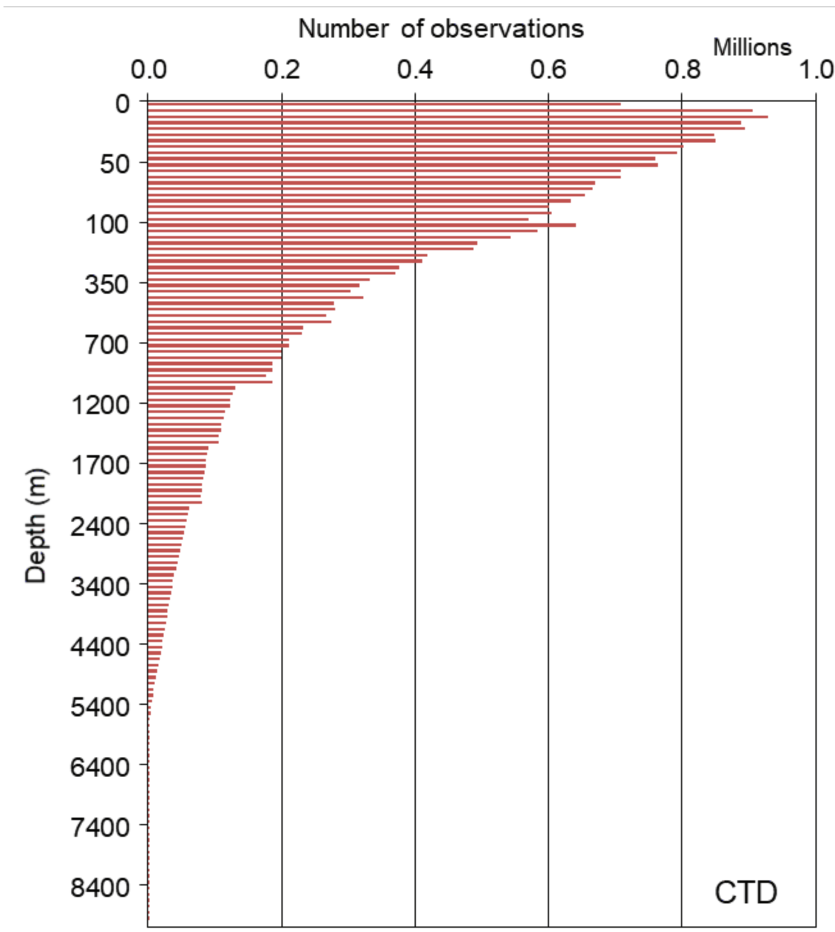

Figure 3.3. Distribution of high-resolution CTD casts at standard depth levels in WOD18.

Table 3.3. National contributions of high-resolution CTD casts in WOD18.

ISO[1] 3166-1 Country Codes	Country Name	CTD Casts	% of Total
US	United States	233,545	22.69
CA	Canada	177,900	17.28
JP	Japan	122,101	11.86
NO	Norway	97,801	9.50
DE	Germany	56,452	5.48
GB	Great Britain	47,840	4.65
FR	France	44,194	4.29
SU	Soviet Union	29,790	2.89
99**	Unknown	28,572	2.78
TW	Taiwan	23,744	2.31
AU	Australia	23,678	2.30
DK	Denmark	20,520	1.99
IT	Italy	12,918	1.26
ZA	South Africa	12,110	1.18
UA	Ukraine	9,187	0.89
IE	Ireland	8,849	0.86
ES	Spain	8,307	0.81
AR	Argentina	7,895	0.77
NZ	New Zealand	7,248	0.70
CL	Chile	6,106	0.59
GR	Greece	5,912	0.57
NA	Namibia	5,044	0.49
IS	Iceland	4,989	0.48
NL	Netherlands	4,589	0.45
PL	Poland	3,862	0.38
FI	Finland	3,570	0.35
RU	Russian Federation	3,286	0.32
CN	China	2,970	0.29
PT	Portugal	2,843	0.28
TR	Turkey	2,705	0.26
EE	Estonia	2,374	0.23
DU	East Germany	1,692	0.16
BR	Brazil	1,256	0.12
ZZ[2]	Miscellaneous organization	1,170	0.11
IL	Israel	914	0.09
IN	India	692	0.07
SE	Sweden	464	0.05
BE	Belgium	440	0.04
VE	Venezuela	389	0.04
CY	Cyprus	235	0.02
EC	Ecuador	217	0.02
ID	Indonesia	213	0.02
LT	Lithuania	149	0.01
BG	Bulgaria	90	0.01
MX	Mexico	82	0.01
PE	Peru	74	0.01
TN	Tunisia	73	0.01
EG	Egypt	69	0.01
LB	Lebanon	42	<0.01
KR	Korea; Republic of	28	<0.01

ISO[1] 3166-1 Country Codes	Country Name	CTD Casts	% of Total
RO	Romania	27	<0.01
DZ	Algeria	13	<0.01
HR	Croatia	1	<0.01

[1] ISO = International Organization for Standardization.
[2] Codes '99' and 'ZZ' are not official ISO 3166-1 codes. These are supplemental codes for WOD.

3.4. TRANSMISSOMETER OBSERVATIONS

3.4.1. Introduction

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

The majority of transmissometer data presented in WOD18 were collected using instruments operated at 660 nm (red) wavelength.

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

The standard unit for storing beam attenuation coefficient values in WOD18 is determined as $c = ln\ (T_r) / r\ (m^{-1})$, where T_r is percentage of light transmitted through the instrument's path-length and calculated from a calibrated raw voltage signal measured by the instrument, and r is the instrument's path-length (in m). It should be noted, however, that a significant amount of early submitted data are stored in T_r (percent) and even in raw voltage (volts). Therefore, those data are not included in the WOD18 distribution but they are mentioned in the following statistics. Eventually, if/when proper metadata will be available and correct calibration of the data values will be possible, those data will be converted to the standard units and added to future releases of the database.

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

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

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

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

$$a_p + b_p = c_p$$

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

In the red part of the spectrum, attenuation due to dissolved materials is negligible, so that attenuation in the red is due primarily to particles. The beam attenuation coefficient in the red is an excellent proxy for the total volume of particles (Bartz *et al.,* 1978; Bishop, 1999; http://www.wetlabs.com/; http://www.hobilabs.com; http://www.chelsea.co.uk) and often used for regional and global assessments of the benthic nepheloid layers (Gardner et. al, 2018a, 2018c) and particulate matter distribution/concentration (Gardner *et al.*, 2018b).

3.4.2. Spatial and Temporal Distribution of Transmissometer Profiles

Transmissometer profiles presented in WOD18 were collected during several international and U.S. national programs for the period of 1975-2017. The majority of data comes from the World Ocean Circulation Experiment (WOCE), Marine Ecosystem Analysis Project for New York Bight (MESA-NYB), Northeast Gulf of Mexico (NEGOM), Joint Global Ocean Flux Study (JGOFS), Bermuda Atlantic Time Series (BATS), Hawaiian Oceanographic Time Series (HOT), Atlantic Meridional Transect Program (AMT), and other programs. Table 3.4.1 presents a full list of the research programs and projects that contributed beam attenuation data to WOD18. In table 3.4.2 the major contributing countries are listed. 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 global geographical distribution of the WOD18 transmissometer profiles where beam attenuation coefficient measurements were taken.

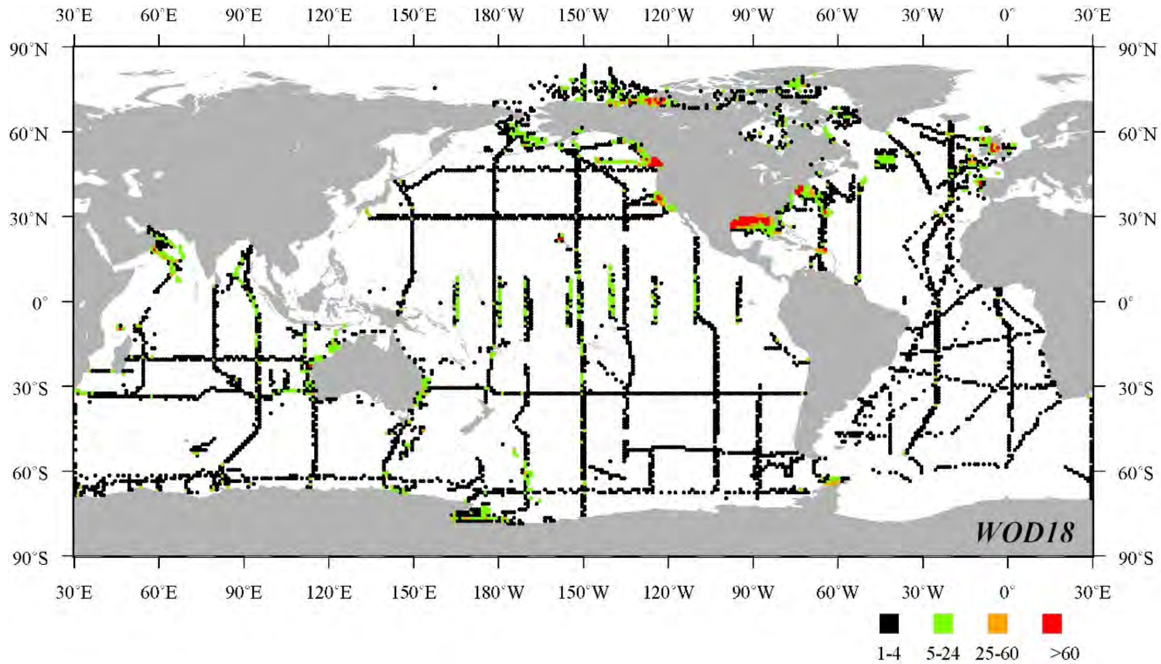

Figure 3.4.1. Geographic distribution of the BAC profiles in WOD18

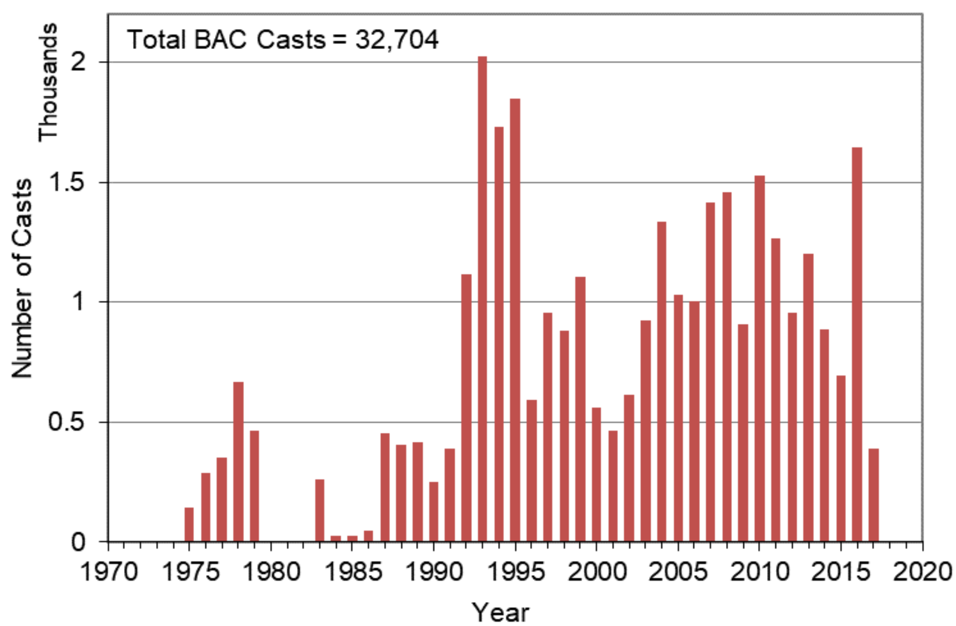

Figure 3.4.2. Temporal distribution of BAC profiles in WOD18

Table 3.4.1. Projects contributing to the WOD18 BAC data set

NODC Project #	Project Name	Profiles
225	World Ocean Circulation Experiment (WOCE)	2,333
121	Southeast Area Monitoring and Assessment Program (SEAMAP)	1,940
597	Hypoxia Studies in the Northern Gulf Of Mexico	1,681
65	Marine Ecosystems Analysis Project - New York Bight (MESA – NYB)	1,494
412	MMS/Northeast Gulf of Mexico Physical Oceanographic Program (NEGOM)	894
417	Tropical Atmosphere Ocean (TAO) Buoy Array	781
305	Distribution/Abundance of Marine Mammals in Northern Gulf of Mexico (GULFCET II)	649
275	JGOFS - Bermuda Atlantic Time-series (BATS)	565
301	JGOFS - Hawaii Ocean Time-series (HOT)	550
485	Climate Variability and Predictability (CLIVAR)	470
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 Project, part of the Spanish Contribution to the Study of Biogeochemical Carbon Fluxes in the Southern Ocean	301
379	JGOFS - ARABESQUE	287
619	Atlantic Meridional Transect Program (AMT)	280
373	Anatomy of Gulf Stream Meanders (AGM)	222
216	South Atlantic Ventilation Experiment (SAVE)	219
406	Research on Ocean Atmosphere Variability & Ecosystem Response in Ross Sea	194
372	Ocean Margin Exchange Project (OMEX)	180
399	Plankton Reactivity in the Marine Environment (PRIME)	100
527	U.S. Climate Variability And Predictability (US CLIVAR)	88
246	Bering & Pacific Russian/U.S. Cooperative Research Program (BERPAC)	81
310	JGOFS - Equatorial Pacific Basin Study (EQPAC)	80
618	International Nusantara Stratification and Transport Program (INSTANT)	54
487	Deepwater Program: Northern Gulf of Mexico Continental Slope Habitat & Benthic Ecology	51
33	California Cooperative Oceanic and Fisheries Investigation (CalCOFI)	47
281	JGOFS - North Atlantic Bloom Experiment (NABE)	42
591	Pacific Coast Ocean Observing System (PACOOS)	40
201	JGOFS - 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
200	Joint Global Ocean Flux Study (JGOFS)	8
630	Meso-Scale Vortices/Meanders in the Central Portion of the Bransfield St. (BREDDIES)	7
n/a	Data with no project info	17,640

Table 3.4.2. Countries contributing to the WOD18 BAC data set

ISO[1] 3166-1 Country Codes	Country	BAC Profiles	% of Total
US	USA	22,135	67.7%
CA	Canada	5,118	15.7%
GB	Great Britain	2,391	7.3%
AU	Australia	1,553	4.7%
JP	Japan	509	1.6%
ES	Spain	308	0.9%
DE	Germany	196	0.6%
SU	USSR	164	0.5%
NL	Netherlands	99	0.3%
IT	Italy	76	0.2%
NZ	New Zealand	60	0.2%
ID	Indonesia	54	0.2%
FR	France	25	0.1%
BE	Belgium	16	0.0%
	Total	32,704	*100.0%*

[1] ISO = International Organization for Standardization.

Table 3.4.3 and Figure 3.4.2 presents the temporal distribution of transmissometer profiles in WOD18 as a function of year. Figure 3.4.3 presents the distribution of the BAC observations on standard depth levels.

Table 3.4.3. The number of BAC profiles in WOD18 as a function of year
The total number of profiles = 32,704

YEAR	PROFILES	YEAR	PROFILES	YEAR	PROFILES	YEAR	PROFILES
1975	141	1986	45	1997	955	2008	1,458
1976	288	1987	451	1998	880	2009	906
1977	352	1988	405	1999	1,106	2010	1,527
1978	669	1989	414	2000	559	2011	1,266
1979	466	1990	250	2001	466	2012	953
1980	0	1991	388	2002	615	2013	1,201
1981	0	1992	1,116	2003	923	2014	884
1982	0	1993	2,025	2004	1,336	2015	695
1983	263	1994	1,732	2005	1,029	2016	1,645
1984	24	1995	1,845	2006	1,005	2017	391
1985	23	1996	591	2007	1,416		

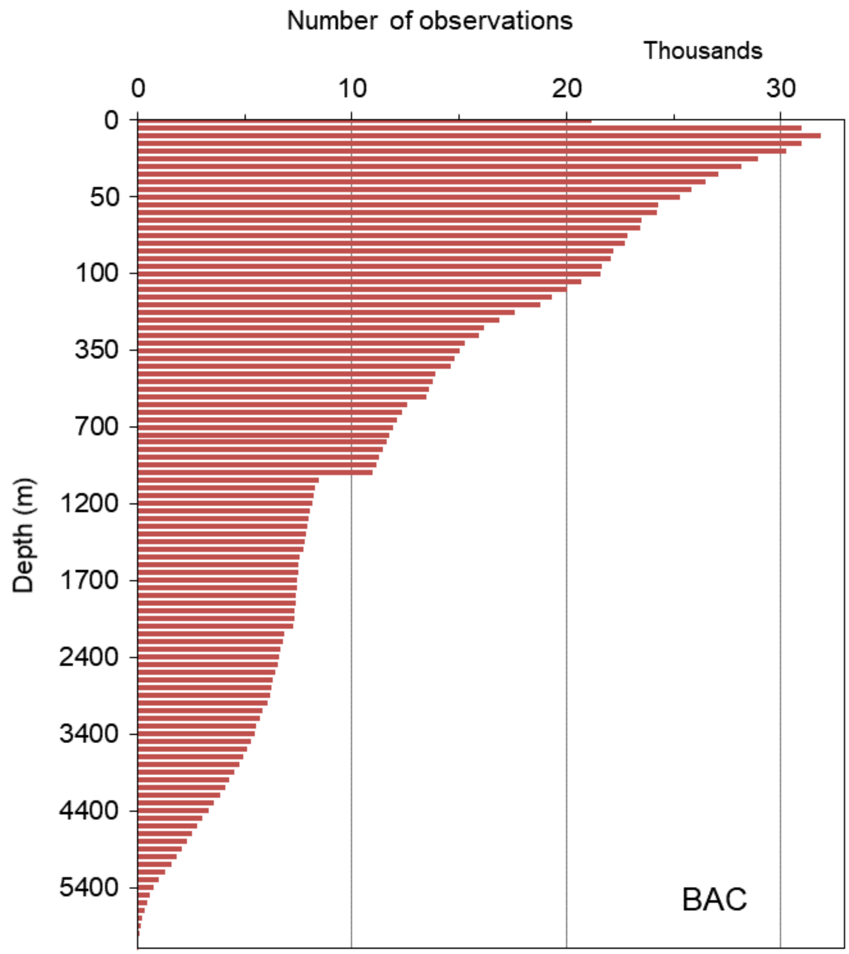

Figure 3.4.3. Distribution of BAC data at standard depth levels in WOD18

3.4.3. Instruments used for data collection

Beam attenuation data in WOD18 over the years of data collection were acquired by different instruments listed in table 3.4.4 below. It should be noted that large amount of data were submitted without proper information about instruments used for measurements and lacking metadata on data calibration. Therefore using those data for comparison and joint analyses could present a challenge.

Table 3.4.4. The number of BAC profiles in WOD18 collected by different instruments

WOD instrument code	Instrument name	Profiles	%
468	SeaTech (0.25m/660nm)	7,049	21.6
474	C-Star (0.25m/660nm)	7,077	21.7
469	Unknown Transmissometer	2,733	8.4
781	C-Star (0.10m/660nm)	1,004	3.1
784	SeaTech (0.05m/660nm)	664	2.0
4001	SeaTech (1.00/660nm)	39	0.1
472	Chelsea Alpha tracka Mk II (0.25m/660nm)	24	0.1
	No instrument info	14,114	43.2
	Total	*32,704*	*100.0*

3.4.4. Relevant Web Sites

Bermuda Atlantic Time Series (BATS): http://bats.bios.edu/.
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/.
WetLabs, Inc.: http://www.wetlabs.com/.
World Ocean Circulation Experiment (WOCE): http://whpo.ucsd.edu/.

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CHAPTER 4: EXPENDABLE BATHYTHERMOGRAPH DATA (XBT)

Ricardo A. Locarnini, Tim P. Boyer, Olga K. Baranova, Hernán E. García, Alexey V. Mishonov, Christopher R. Paver, James R. Reagan, Igor V. Smolyar, Melissa M. Zweng

Ocean Climate Laboratory
National Centers for Environmental Information / NOAA
Silver Spring, MD

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. While current acquisition systems store the data in digital form, initially the data were recorded in paper strip charts.

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 *World Ocean Database 2018* (WOD18), 48.3% 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 0.3% to have been obtained with probes manufactured by Sparton. There is no manufacturer information for the probe used for just less than half, 49.2%, of the XBT profiles. Each manufacturer has several models of XBT probes which have different maximum sampling depths with the associated launching platform moving at or below the allowed maximum speed. As an example, Table 4.1 below shows the characteristics for some expendable probes produced by Lockheed Martin Sippican.

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

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

Corresponding models from different manufacturers have similar characteristics. There is model information for about 53.9% of the XBT profiles in WOD18. The most popular probe model is the T-4, with 21% of the XBT profiles in WOD18 known to be obtained with such a probe, while Deep Blue and T-7 probes are known to account for 16.5% and 12.1%, respectively, of the XBT profiles in WOD18.

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

4.2. XBT ACCURACY

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

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.

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

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

Following the report of Hanawa *et al.* (1995) and IOC (1994), TSK altered their software between January and March 1996 to make the Hanawa *et al.* (1995) equation the default equation (Greg Ferguson, personal communication). Sippican did the same around August 1996, (James Hannon, personal communication). However, a 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). New time-dependent temperature bias adjustments, as well as depth-time equation corrections, are actively studied and calculated as new analysis and more temperature data from XBT, MBT, and CTD instruments become available (Gouretski and Reseghetti, 2010; Good, 2011; Hamon *et al.*, 2012; Gourestki, 2012; Cowley *et al.*, 2013; Cheng *et al.*, 2014). In a summary of instrumental biases and errors, Cheng *et al.* (2016) report that XBT data need four different related corrections: depth correction, time-dependent temperature bias, temperature-dependent depth and temperature corrections, and surface offset.

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 46%, or 1.06 million, of the total 2.3 million XBT temperature profiles in WOD18 have "unknown" model of XBT instrument. Of these, about 0.76 million are positively identified as coming from shipboard drops. The other 0.3 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 WOD18 on observed levels report the same data as submitted to NCEI/WDC by the originators. Secondary header 33 indicates reported information on the depth-time equation used by the originator – see Garcia *et al.* (2018) for more information on WOD18 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, only 3,348 pre-1996 XBT drops include depths that are known to have been corrected by the originator before being submitted to NCEI/WDC.

The XBT data in the WOD18 interpolated to standard levels uses the appropriate corrected depth when possible using the corrections of Levitus *et al.* (2009). Since close to half of all XBT profiles are of unknown model, a test was applied to these data to see if a depth correction was necessary. It was assumed that, following the IOC recommendation, data available in the WOD18 were received at NCEI 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 652,502 XBT drops during the relevant time period (1996-2017), there are 98,662 drops without depth-time equation information, with the vast majority of them belonging to the period 1996-2000: only 67% of XBT drops from 1996 to 2000 include the information on the depth-time equation used, in contrast to 97% of XBT drops from 2001 to 2017 including that information.

An attempt to ascertain the missing depth-time equation information was made by contacting the data originators. Most of the data originators are large data centers and the information could not be recovered. The actual values of the reported depths can be used to recognize the depth-time equation used, when the full depth trace is reported (Donald Scott, personal communication). Although most data received at NCEI 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 WOD18 ARE THE SAME DATA AS SUBMITTED BY THE ORIGINATORS. IF YOU ARE USING OBSERVED LEVEL XBT DATA FROM WOD18, PLEASE USE SECONDARY HEADER 54 TO SEE WHETHER A DEPTH CORRECTION IS NECESSARY.

THE STANDARD LEVEL XBT DATA IN WOD18 WERE PREPARED, WHEN NEEDED AND POSSIBLE, USING A CORRECTED DEPTH-TIME EQUATION AND THE XBT BIAS ADJUSTMENT FOLLOWING LEVITUS *ET AL.* (2009).

XBT BIAS ADJUSTMENTS WERE RECALCULATED USING AN UPDATED DATA SET FOR WORLD OCEAN DATABASE 2013 AND WORLD OCEAN ATLAS 2013. YEARS 2008 TO 2012 HAVE THEIR OWN TEMPERATURE BIAS ADJUSTMENTS IN THE UPDATED LEVITUS SCHEME. VALUES FOR YEAR 2012 WERE USED FOR 2013 TO 2017.

IF YOU ARE USING STANDARD LEVEL XBT DATA FROM WOD18, 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.

THE OBSERVED LEVEL XBT DATA IN WOD18 ARE ALSO OFFERED ONLINE THROUGH *WODSelect* AND, IN ADDITION TO THE LEVITUS SCHEME ADJUSTMENT, CAN BE PREPARED WITH MORE THAN TEN DIFFERENT TIME-DEPENDENT TEMPERATURE ADJUSTMENTS OR DEPTH CORRECTIONS. PLEASE USE SECONDARY HEADER 54 TO IDENTIFY THE CORRECTION USED TO PREPARE THE DOWNLOADED DATA.

4.5. SURFACE DATA ACQUIRED CONCURRENTLY WITH XBT CASTS

On a surface ship sometimes, a sea-surface water sample is obtained at the time of the XBT launch. Temperature and salinity of the water sample are usually measured and recorded as ancillary information of the XBT launch. Meteorological conditions at the time of the XBT launch could also be recorded, *e.g.* air temperature, wind speed and direction, cloud type and cover, barometric atmospheric pressure, as well as sea conditions: wave height and direction, sea state. When available, these data are included in WOD18 as secondary header information for the corresponding XBT drop.

4.6. XBT PROFILE DISTRIBUTIONS

There are a total of 2,303,354 XBT profiles for the entire World Ocean with 493,387 profiles (21.4%) measured in the southern hemisphere and 1,809,967 profiles (78.6%) measured in the northern hemisphere (Figure 4.1). Table 4.2 gives the yearly counts of XBT profiles for the World Ocean. Figure 4.2 shows the time series of the yearly totals of Expendable Bathythermograph profiles for the World Ocean. After its introduction, XBT yearly totals increase dramatically to about, or above, 50,000 for most years from 1970 to 1999, with peaks in the mid-1980's and early to mid-1990's. The decrease in yearly totals in recent years is partially due to the delay between the time of the observations and their reporting by the originators to the NCEI/WDC.

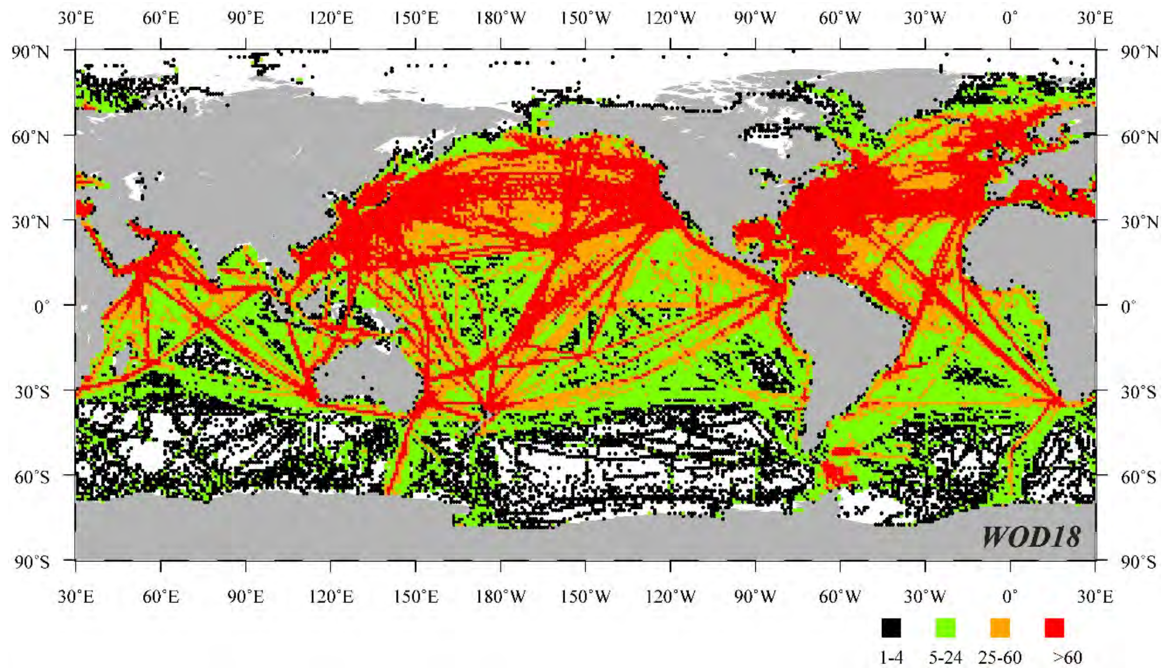

Figure 4.1. Geographic distribution of XBT profiles in WOD18: number of profiles by one-degree squares.

Figure 4.3 shows the distribution of XBT data at observed levels. The relative minimum in observations between the Surface and 50 m is due to the old custom of not reporting all levels in the isothermal layer between the surface and the top of the thermocline. There are significant decreases in the number of observations below the maximum depths sampled by the most popular probe models: 460 m (T-4) and 760 m (Deep Blue and T-7).

Although 66 known countries contribute XBT data to WOD18, 79% of the profiles are contributed by just 7 countries: United States, Japan, Great Britain, Australia, Canada, Germany, and France (Figure 4.4). Some country contributions merely reflect the flag of merchant ships in the Ship of Opportunity Program (SOOP), and they do not represent active national scientific programs, e.g. Liberia, Panama, Singapore, and Antigua. Table 4.3 gives detailed information about national contributions of XBT sorted by contribution from each country.

Table 4.2. The number of all XBT profiles as a function of year in WOD18.
Total Number of Profiles = 2,303,354

YEAR	PROFILES	YEAR	PROFILES	YEAR	PROFILES	YEAR	PROFILES
1966	1,750	1979	56,122	1992	66,172	2005	29,607
1967	9,390	1980	55,322	1993	71,031	2006	26,254
1968	26,684	1981	55,034	1994	69,200	2007	23,191
1969	34,321	1982	56,002	1995	78,703	2008	23,735
1970	45,701	1983	58,917	1996	63,730	2009	23,173
1971	57,628	1984	56,235	1997	53,105	2010	21,170
1972	53,173	1985	68,825	1998	50,054	2011	19,670
1973	54,949	1986	75,291	1999	56,035	2012	17,909
1974	54,888	1987	72,058	2000	39,912	2013	18,184
1975	54,430	1988	62,474	2001	31,029	2014	19,165
1976	48,480	1989	45,255	2002	27,778	2015	16,885
1977	54,408	1990	82,969	2003	27,404	2016	17,428
1978	53,387	1991	72,053	2004	32,387	2017	14,697

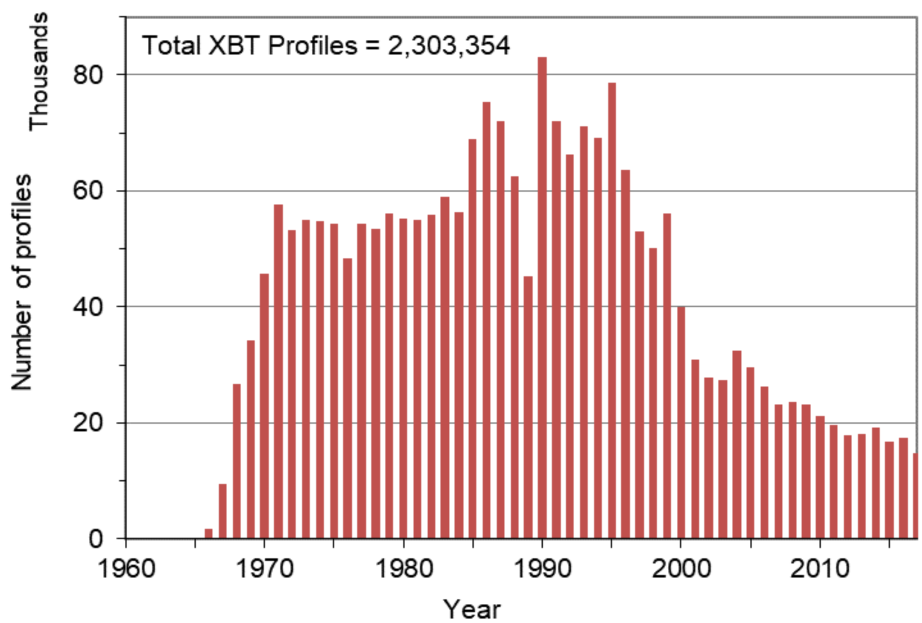

Figure 4.2. Temporal distribution of Expendable Bathythermograph (XBT) profiles in WOD18.

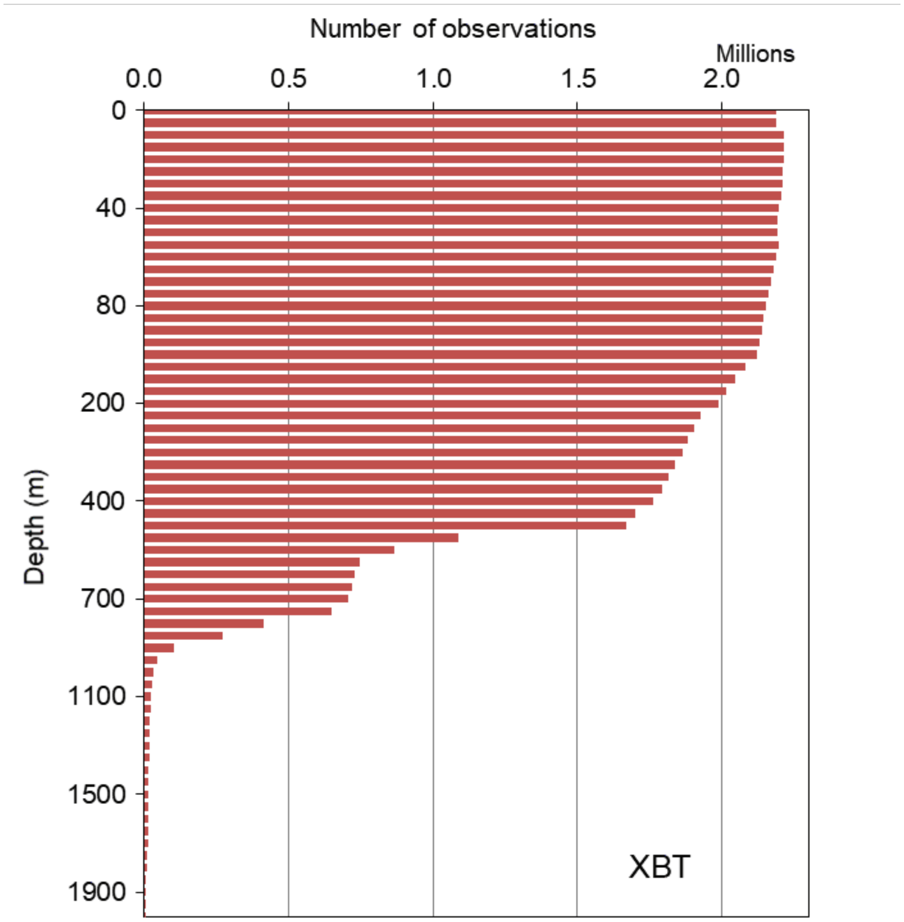

Figure 4.3. Distribution of Expendable Bathythermograph (XBT) data at standard depth levels in WOD18.

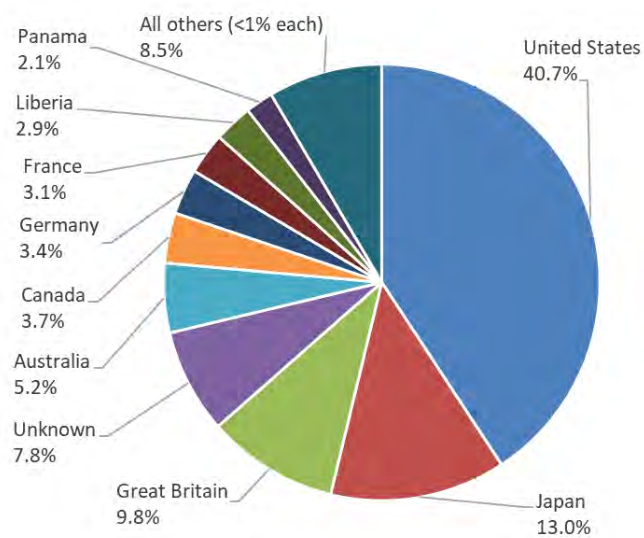

Figure 4.4. XBT data contribution by countries in WOD18. Totals for Panama and Liberia include data obtained from merchant ships in the Ship of Opportunity Program (SOOP).

Table 4.3. National contribution of XBT profiles in WOD18.

ISO[1] Country Code	Country Name	XBT Casts	% of Total
US	United States	938,490	40.74
JP	Japan	300,055	13.03
GB	Great Britain	224,601	9.75
99	Unknown	178,675	7.76
AU	Australia	118,655	5.15
CA	Canada	85,788	3.72
DE	Germany	77,701	3.37
FR	France	70,827	3.08
LR	Liberia	66,060	2.87
PA	Panama	47,405	2.06
SG	Singapore	19,006	0.83
NL	Netherlands	15,802	0.69
SU	Union of Soviet Socialist Republics	14,226	0.62
DK	Denmark	13,169	0.57
AG	Antigua	12,136	0.53
ZA	South Africa	12,119	0.53
BS	Bahamas	11,978	0.52
NO	Norway	8,448	0.37
NZ	New Zealand	6,300	0.27
VC	St. Vincent and Grenadines	5,994	0.26
CY	Cyprus	5,719	0.25
CN	China, The People's Republic of	5,613	0.24
BR	Brazil	5,285	0.23
IS	Iceland	4,574	0.20
SE	Sweden	4,551	0.20
BB	Barbados	4,376	0.19
HK	Hong Kong	4,308	0.19
IT	Italy	3,227	0.14
IN	India	3,085	0.13
ES	Spain	3,001	0.13
TO	Tonga	2,989	0.13
WS	Western Samoa	2,769	0.12
AR	Argentina	2,535	0.11
CL	Chile	2,438	0.11
PH	Philippines	2,302	0.10
MX	Mexico	2,238	0.10
TH	Thailand	1,901	0.08
KW	Kuwait	1,876	0.08
MT	Malta	1,452	0.06

ISO[1] Country Code	Country Name	XBT Casts	% of Total
PL	Poland	1,320	0.06
ID	Indonesia	1,241	0.05
TW	Taiwan	1,082	0.05
BE	Belgium	1,028	0.04
MH	Marshall Islands	936	0.04
FJ	Fiji	866	0.04
YU	Yugoslavia	797	0.03
PT	Portugal	732	0.03
PE	Peru	714	0.03
GR	Greece	658	0.03
EC	Ecuador	492	0.02
MY	Malaysia	460	0.02
TR	Turkey	307	0.01
SA	Saudi Arabia	197	<0.01
ZZ	Miscellaneous Organization	195	<0.01
UY	Uruguay	146	<0.01
HR	Croatia	82	<0.01
MU	Mauritius	77	<0.01
DU	East Germany	67	<0.01
MG	Madagascar	62	<0.01
KR	Korea, Republic of	53	<0.01
CI	Cote D'Ivoire	43	<0.01
UA	Ukraine	33	<0.01
CO	Colombia	32	<0.01
CR	Costa Rica	29	<0.01
HN	Honduras	13	<0.01
SC	Seychelles	11	<0.01
TT	Trinidad and Tobago	6	<0.01
RU	Russian Federation	1	<0.01
	Total:	*2,303,354*	*100.00*

[1] 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)

Christopher R. Paver, Ricardo A. Locarnini, Tim P. Boyer, Hernán E. García, Alexey V. Mishonov, Dan Seidov, Olga K. Baranova, Melissa M. Zweng

Ocean Climate Laboratory
National Center for Environmental Information
Silver Spring, MD

5.1. INTRODUCTION

An Expendable Conductivity, Temperature and Depth (XCTD) is an ocean profiling instrument, which usually consist of a data acquisition system and launcher onboard the vessel, and a digital XCTD consisting of a thermistor and conductivity sensor. Probes can be launched from ships, submarines, and airborne platforms. Prior to 1999, Tsurumi Seiki Company, Ltd. (TSK) and Sippican Inc. (now Lockheed Martin Corp.; LHM) manufactured XCTDs. In 1999, TSK became the sole manufacturer of XCTDs with LHM becoming a distributor (LHM, XCTD profiling system website; Gille *et al.*, 2009).

The XCTD is a free-falling probe, which is linked to the acquisition system through a thin insulated conductive wire that is used to transmit the temperature and conductivity data back to the acquisition system in real time. Depth is estimated from the elapsed time between when the probe enters the water and the time each temperature-conductivity measurement is made using a fall-rate equation supplied by the vendor. Older probes, with a 4 Hz sample rate and roughly 3.2 $m \cdot s^{-1}$ fall velocity, can record data every 0.8 m (Johnson, 1995). More recent probes, however, are able to sample at 25 Hz, every ~420 ms, which approximately equal to 17 cm interval in depth (TSK).

Over the years of collection, XCTD data were submitted in both high and low vertical resolution formats, therefore these data are stored in two WOD18 datasets: high resolution data resides in the CTD dataset (10,953 XCTD casts), and low resolution data resides in the OSD dataset (1,708 XCTD casts). The earliest XCTD data in WOD18 are 22 casts collected in the Coral Sea in December of 1991.

5.2. XCTD PRECISION AND ACCURACY

The precision and accuracy of XCTD data depends on the make and model. Current specifications from TSK identify similar accuracy and precision for temperature and conductivity. Temperature accuracy and precision are ±0.02 °C and 0.01 °C, respectively. Conductivity accuracy and precision are ±0.03 $mS \cdot cm^{-1}$ and ±0.017 $mS \cdot cm^{-1}$, respectively. Depth accuracy is 4.6 m or 2% of depth, whichever is greater. System response time is 40 ms for conductivity and 100 ms for temperature (TSK). 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). Mizuno and Watanabe (1998) also reported similar numbers.

Despite the XCTD instrument being in use for some time now, some problems with data accuracy may still exist. Early comparison of the XCTD data with CTD performed by Hallock and Teague (1990) concluded that "Examination of temperature and conductivity shows a significant systematic offset of the XCTDs relative to the CTD, suggesting a calibration error". Later, Sy (1993) revealed that "test results conclusively show that XCTD probes do not meet the manufacturer's specification". A test of modified probes indicated: a) "that the XCTD sensor accuracies are better than ±0.02°C and ±0.04 $mS \cdot cm^{-1}$ 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 both XCTD temperature (Gille *et al.* 2009) and salinity (Yuan *et al.* 2004) profiles, required additional data treatment. Nevertheless, XCTD instruments are able to provide data in a more convenient way than traditional CTDs, which encourage data collection in under-sampled regions like the Arctic or the Southern Ocean (Yuan *et al.* 2004, Gille, *et al.* 2009) at higher sampling density. Lancaster and Baron (1984) in Antarctic Surface Waters, and Sprintall and Roemmich (1999) in the Pacific Ocean demonstrate other examples of XCTD deployments.

5.3. XCTD FALL-RATE ERROR

The XCTD instrument does not measure pressure or depth directly. The depth of the instrument is computed from the elapsed time from when the probe enters the water through use of a fall-rate equation. Research conducted by Johnson (1995) reveal that the manufacturer-supplied fall-rate coefficients give too slow a descent for some probes. Alberola *et al.*, (1996), showed similar results. Therefore, revised fall-rate equations were introduced (Johnson, 1995; Mizuno and Watanabe, 1998; Koso *et al.*, 2005) and evaluated (Kizu *et al.,* 2008). Uchida *et al.* (2011) developed a data processing method to obtain high-quality XCTD data.

A depth-correction algorithm was applied to XCTD data in WOD09 while computing temperature and salinity values at standard depth levels. For that purpose, depth values were first recalculated back to elapsed time and then two different manufacturer-dependent depth equations were used for adjusted depth calculation. Manufacturer-provided fall rate coefficients for the different XCTD make and models can be found on the Global Temperature and Salinity Profile Programme's (GTSPP) website for the World Meteorological Organization (WMO) 1770 code table.

For data collected by Sippican instruments (Table 5.1) the equation of Johnson (1995) was used. To indicate that data were subject to such treatment, secondary header code #54 was set to 103. Following procedure and parameters were employed:

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

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

where: s_1 = -1876.17261, s_2 =9317957, s_3 = -3052.53296;

s_a = 3.227, s_b = -2.17·10^{-4};

t – time since drop (seconds);

d_x – originally calculated depth (meters);

d_z – new calculated depth (meters).

For data collected by TSK instruments, (Table 5.1) 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 = -4672.89697, t_2 = 62365712, t_3 = -7897.19678;

t_a = 3.426, t_b = -4.70·10^{-4};

t – time since drop (seconds);

d_x – originally calculated depth (meters);

d_z – new calculated depth (meters).

Table 5.1. XCTD make/model and total profile count in WOD18.

Sippican XCTD Model	Total casts CTD/OSD	TSK XCTD Model	Total casts CTD/OSD	TSK XCTD Model	Total casts CTD/OSD
Standard	98 / 1	Undocumented (possibly XCTD-1)	8,796 / 843	XCTD-2	325 / 0
Deep	53 / 0	Aircraft (AXCTD)	0 / 1	XCTD-2F	430 / 0
Aircraft (AXCTD)	0 / 862	XCTD-1	221 / 0	XCTD-3	44 / 0
Subsurface (SSXCTD)	0 / 1				

5.4. XCTD CAST DISTRIBUTIONS

Table 5.2 gives the yearly counts of XCTD profiles for the World Ocean. Figure 5.1 shows this graphically. There is a total of 12,661 XCTD profiles for the entire World Ocean (10,953 in CTD and 1,708 in OSD) in WOD18.

Table 5.2. The number of XCTD casts in WOD18 as a function of year
Total Number of casts = 12,661 (10,953/1,708).

YEAR	CAST CTD/OSD[1]	YEAR	CASTS CTD/OSD[1]	YEAR	CASTS CTD/OSD[1]	YEAR	CASTS CTD/OSD[1]
1991	22 / 0	1998	166 / 118	2005	1,046 / 0	2012	393 / 0
1992	0 / 0	1999	405 / 182	2006	1,151 / 0	2013	595 / 0
1993	28 / 0	2000	478 / 582	2007	830 / 0	2014	250 / 0
1994	0 / 0	2001	327 / 638	2008	997 / 9	2015	436 / 0
1995	139 / 0	2002	573 / 126	2009	352 / 0	2016	484 / 0
1996	104 / 0	2003	479 / 12	2010	535 / 0	2017	175 / 0
1997	131 / 0	2004	551 / 41	2011	305 / 0		

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

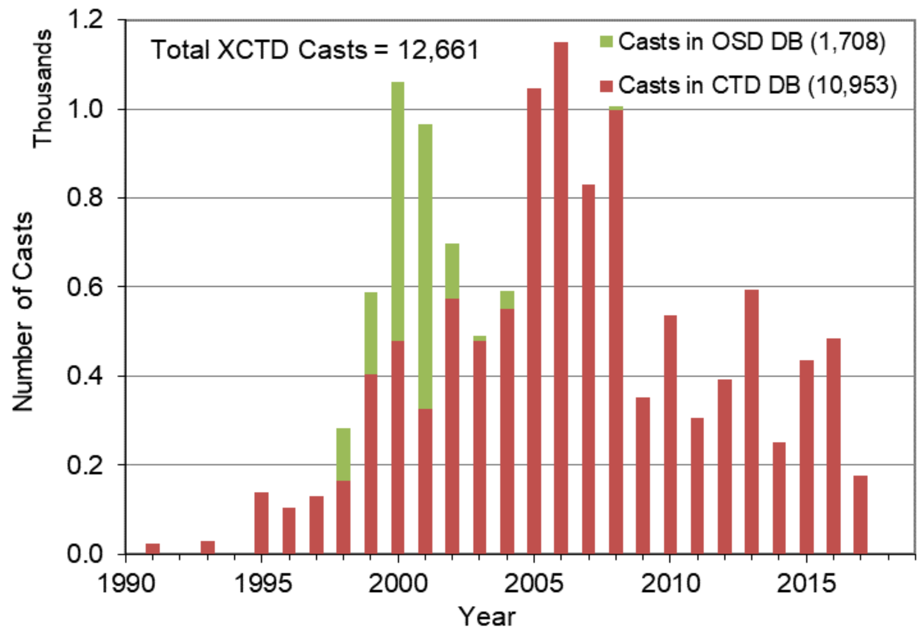

Figure 5.1. Temporal distribution of Expendable Conductivity, Temperature and Depth (XCTD) casts in WOD18.

Table 5.3 gives national contributions of XCTD data to WOD18. The geographic distribution of XCTD casts is shown on Figure 5.2.

Table 5.3. National contributions of XCTD casts in WOD18.

ISO[1] 3166-1 Country Code	Country Name	XCTD Casts CTD/OSD[2]	% of Total
JP	Japan	8,481 / 665	*72.2%*
US	United States	1,319 / 322	*13.0%*
FR	France	366 / 0	*2.9%*
PA	Panama	337 / 0	*2.7%*
CN	China, The People's Republic of	289 / 0	*2.3%*
AU	Australia	71 / 0	*<1.0%*
IN	India	60 / 0	*<1.0%*
IT	Italy	1 / 0	*<1.0%*
99[3]	Unknown	29 / 721	*7.1%*
	Total: 12,661	10,953 / 1,708	*100.0%*

[1] ISO = International Organization for Standardization
[2] CTD = high-resolution casts; OSD = low-resolution casts
[3] Code '99' is not from ISO 3166-1. It is a supplementary code used in WOD.

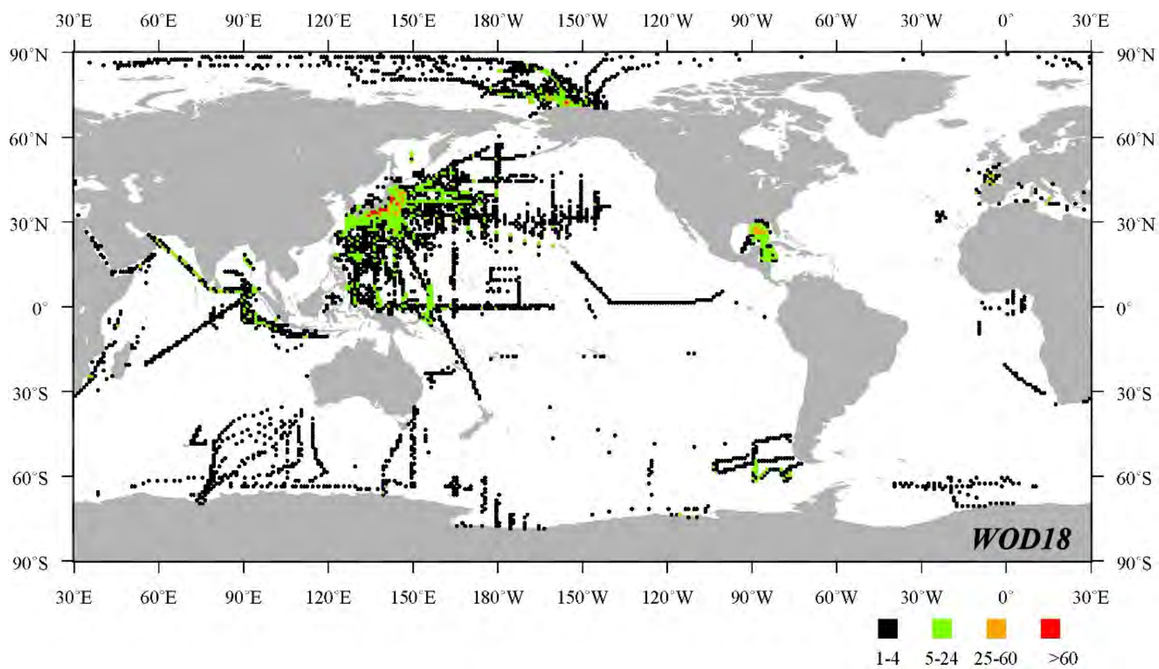

Figure 5.2. Geographic distribution of Expendable Conductivity, Temperature and Depth (XCTD) casts in WOD18.

While the majority of XCTD casts (7,628) have no information about the data-collecting organizations, significant amount of XCTD data were collected and submitted by four major institutions. Among them: Japan Oceanographic Data Center (JODC, 2,195 casts), Ocean Research Department of Japan Marine Science and Technology Center (JAMSTEC, 1,376 casts), Arctic Submarine Laboratory (ASL US, 897 Casts), and Japan Meteorological Agency (JMA, 260 casts).

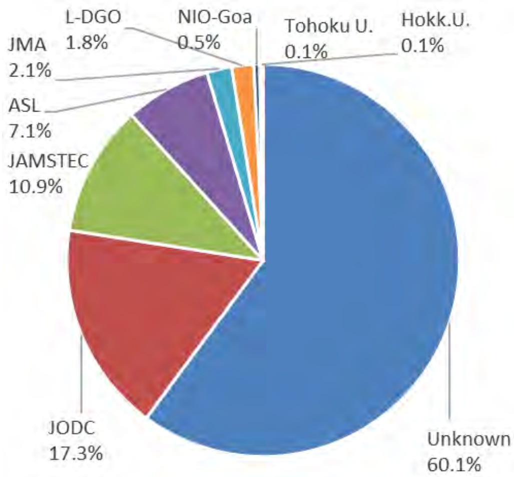

Figure 5.3. Contribution of XCTD casts from different institutions.

Figure 5.3 illustrates distribution of the XCTD data among the contributing institutions. It should be noted that, unfortunately, the majority of XCTD data stored in WOD are lacking the information about contributing institutions.

Figure 5.4 illustrates the distribution of the hi- and low-res XCTD data in CDT (red bars) and OSD (green bars) databases as a function of depth at standard depth levels

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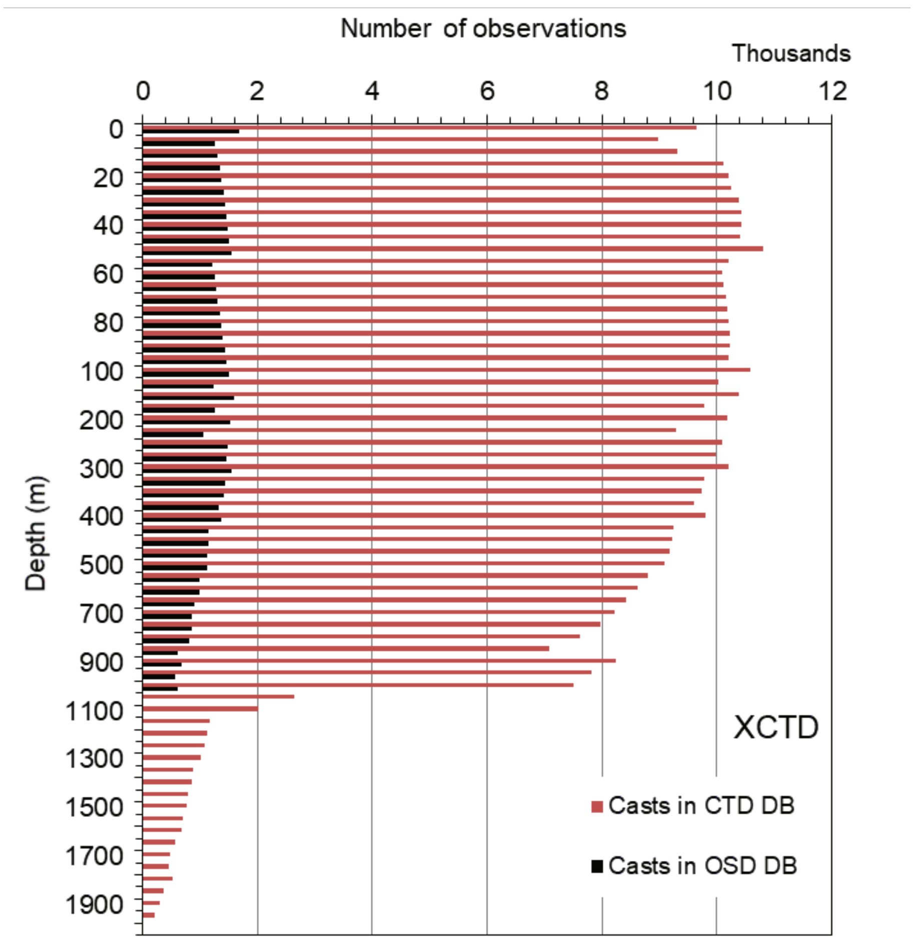

Figure 5.4. Distribution of Expendable Conductivity, Temperature and Depth (XCTD) data at standard depth levels in WOD18.

5.5. RELEVANT WEB SITES

All websites last accessed: 2018-09-19

Global Temperature and Salinity Profile Programme WMO 1770 code table: https://www.nodc.noaa.gov/GTSPP/document/codetbls/wmocodes/table1770.html

International Organization for Standardization (ISO): https://www.iso.org/iso-3166-country-codes.html

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

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

Lockheed Martin, Corp.: https://www.lockheedmartin.com/en-us/products/oceanographic-instrumentation.html , https://www.lockheedmartin.com/content/dam/lockheed-martin/rms/documents/oceanographic-instrumentation/Lockheed%20Martin%20XCTD%20Profiling%20System%20Dat2a%20Sheet.pdf

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

Ship of Opportunity Programme (SOOP): http://www.jcommops.org/sot/soop/index.html

Tsurumi Seiki Co. (TSK): http://www.tsk-jp.com/index.php?page=/product/detail/5/2 , http://www.tsk-jp.com/index.php?page=/product/detail/2/2

Tohoku University, Japan: http://www.tohoku.ac.jp/en/

U.S. Navy, Arctic Submarine Laboratory (ASL): https://www.public.navy.mil/subfor/uwdc/asl/Pages/default.aspx

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CHAPTER 6: PROFILING FLOATS DATA (PFL)

Ricardo A. Locarnini, Tim P. Boyer, Olga K. Baranova, Hernán E. García, Alexey V. Mishonov, James R. Reagan, Melissa M. Zweng

Ocean Climate Laboratory
National Centers for Environmental Information / NOAA
Silver Spring, MD

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 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, nitrate, pH, and chlorophyll-a sensors have also been deployed, as well as transmissometers, optical irradiance sensors, velocity meters, and rainfall and wind speed sensing instrumentation. In addition to the measurements of pressure, temperature, salinity, and oxygen present in previous releases, Table 6.1 shows that measurements of nitrate, pH, chlorophyll-a, and transmissivity from Biogeochemical-Argo (Claustre *et al.*, 2010) are included in the PFL dataset of the *World Ocean Database 2018* (WOD18).

Table 6.1. Variables and profile counts in the PFL WOD18 dataset.

Variable	Number of Profiles
Temperature	1,867,771
Salinity	1,807,538
Oxygen	137,322
Nitrate	22,235
pH	5,699
Chlorophyll-a	49,316
Transmissivity	4,273
Pressure	1,864,815

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

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

6.2. PREDECESSORS OF PROFILING FLOATS

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

6.3. FIRST PROFILING FLOATS

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

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

6.4. PRESENT FLOAT TECHNOLOGY

Further improvements to the P-ALACE float design were made. Float R1, by Webb Research, was introduced at the request of Dr. Steve Riser in 1996 (personal communication, Dan Webb). It was replaced by its successor, the Autonomous Profiling EXplorer (APEX) by Webb Research, which is still in use today. Since 1997, APEX floats have been deployed from merchant vessels moving at speeds up to 25 knots, removing the need to employ research vessels in some areas. Other second-generation floats include the Sounding Oceanographic Lagrangian Observer (SOLO), developed at Scripps Institute of Oceanography. This float replaced the P-ALACE floats' reciprocating high pressure pump with a single stroke hydraulic pump (Davis *et al.*, 2000); the APEX uses a similar pump. This advance allowed the SOLO to more easily reach a desired isobar or isotherm and to cycle between subsurface depths before ascending to the surface. As the P-ALACE was the profiling version of the ALACE float, the PROVOR is the profiling version of the MARVOR float (Loaec *et al.*, 1998), and they have been deployed since 1997.

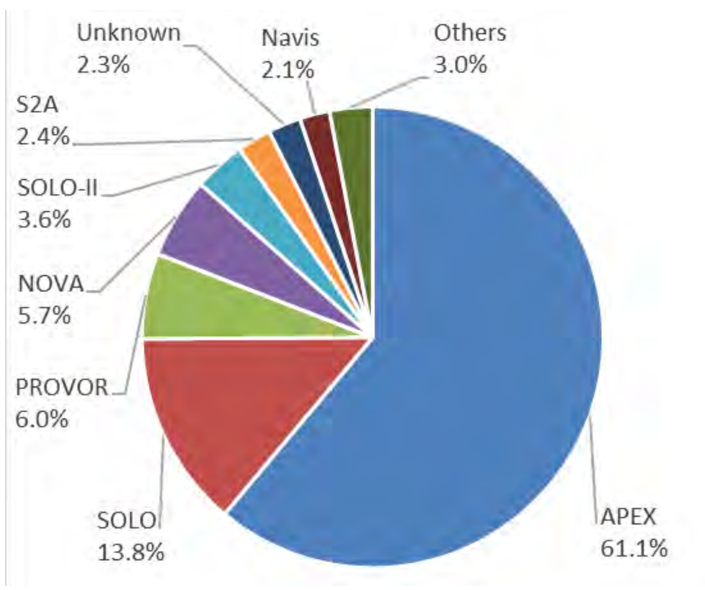

Figure 6.1. Casts from different types of profiling floats (PFL) in WOD18.

Both Martec and MetOcean (Canada) now produce PROVOR floats on the same design. MARVOR and PROVOR floats operate on the same bladder/buoyancy principles as the ALACE floats. PROVOR floats have the added ability to record and store oceanographic profile data on their descent as well as their ascent. The Japanese Agency for Marine-Earth Science and Technology (JAMSTEC) and Tsurumi Seiki Co. (TSK) have developed and deployed the New profilINg floats of JApan (NINJA) (Ando *et al.*, 2003) beginning in 2002. Navigating European Marine Observer (NEMO) floats have been deployed in the Southern

Ocean starting in early 2004 by the Alfred Wegner Institute (AWI, Germany). These floats are based on the SOLO design and are equipped with algorithms based on temperature measurements which help them avoid surfacing in ice covered areas. NEMO floats combine this ability with RAFOS positioning, extending the reach of profiling floats to ice-covered regions. New generations of floats, e.g. SOLO-II, S2A by MRV Systems (USA), NOVA (New generation Oceanographic Variable buoyancy Autonomous) by MetOcean, and Navis by Sea-Bird Scientific (USA), include updated software and features, and form part of the Argo array. Newly designed "Deep" types of profiling floats, e.g. Deep SOLO, Deep APEX, and Deep-Arvor (Le Reste *et al.*, 2016), increase their monitoring capabilities beyond the upper 2000 m of the water column, up to the ocean bottom. Since August 2012, about 80 deep profiling floats have been deployed. WOD18 includes data obtained with an air-deployed profiling ocean float, ALAMO (Air Launched Autonomous Micro Observer). Figure 6.1 shows the relative distribution of different types of profiling floats in WOD18. Most of the data, almost 95%, are known to have been obtained by just seven float types.

6.4.1. The Argo Project

The Argo project is an umbrella project which coordinates the deployment, quality control, and public access for profiling float data. Argo is not an acronym: it refers to the relationship between the Jason satellite altimeter measuring ocean surface topography and the Argo floats revealing the ocean subsurface structure, evoking the mythical Jason and his ship the Argo (Gould, 2005). Since the year 2000, nearly all data from deployed floats are available through this project. Floats are deployed by individual countries, projects, and institutions, usually with some level of coordination with Argo. Float data are captured from the ARGOS and Iridium satellites by the Argo Data Assembly Centers (DACs) and placed on the World Meteorological Organization (WMO) Global Telecommunications System (GTS) within 24 hours. These data are also relayed in near-real-time to the two Argo Global Data Assembly Centers (GDACs): the French Coriolis Center at IFREMER, and the U.S. Global Ocean Data Assimilation Experiment (GODAE) server in Monterrey, California hosted by the U.S. Navy. Within 24 hours the data are made available to the public through these sites as well. Preliminary quality checks are performed at the DACs on the incoming data. These data are the real time data. Further quality control is performed at the DACS, the GDACs, at regional centers, and by the primary investigators responsible for the floats. A delayed mode version of the data is then released. Each float is assigned a WMO identification number for easy identification. Meetings and workshops on data quality control, data access, and scientific research with floats have been held to keep the scientific community informed and coordinate responses and solutions to quality control and access problems. The goal of Argo is to deploy and maintain a global array of profiling floats to monitor the large-scale circulation of the world ocean, as well as its heat and fresh water content. With this stated goal, pressure, temperature and salinity sensors are the only necessary oceanographic sensors, although floats may be equipped with other sensors. Argo has surpassed its goal of 3,000 floats worldwide, with more than 3,500 active floats since late 2012 – about 4,100 floats were active in late 2017, of which only 46 were known to be deep profiling floats. The preference is for the floats to deliver profiles from 2000 decibars, or near the ocean bottom, 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 WOD18 consists of data from the WOCE project, data from the Global Temperature and Salinity Profile Project (GTSPP), which is an archive for data from the GTS, and the Argo U.S. GODAE server. Since the Coriolis and GODAE data are synchronized, there should be no differences between the two data sets. Figure 6.2 shows the relative distribution from each data set for temperature and salinity; the profiling float data in WOD18 for oxygen, nitrate, pH, chlorophyll-a, and transmissivity, are all from the Argo U.S. GODAE server.

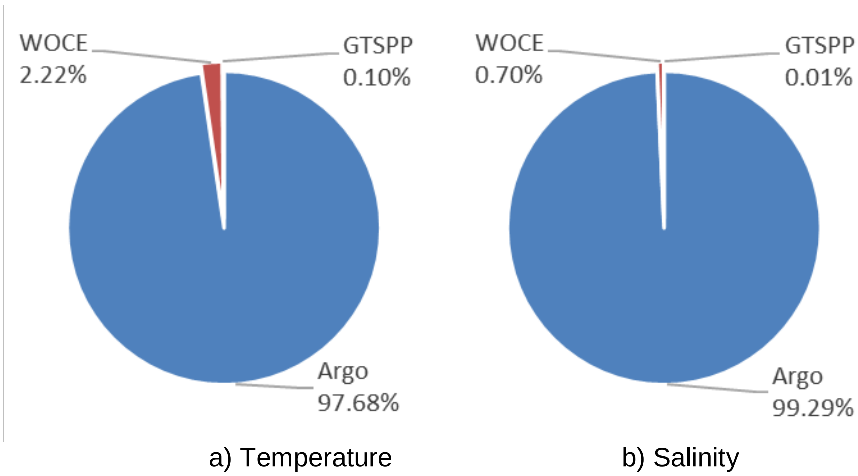

Figure 6.2. PFL data contributions from different sources.

6.5. SENSOR ACCURACY

The temperature and salinity data from the profiling floats come from various CTD sensors. The P-ALACE floats used an YSI 46016 thermistor, with estimated precision of 0.005°C, and a Falmouth Scientific Inc. (FSI) conductivity sensor with an estimated accuracy of 0.01 $mS \cdot cm^{-1}$ (milliSiemens·centimeter^{-1}). The pressure sensor used was a Paine strain gauge sensor. The sensor had hysteresis errors on the order of 5 meters initially, which were later reduced by thermally isolating the sensor (Davis *et al.*, 2001). To reduce pressure reading errors, Sea-Bird 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 Sea-Bird. The Sea-Bird 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). Sea-Bird specifications are for Sea-Bird 41 CTD for ALACE floats.

For oxygen measurements, the Aanderaa 3835 oxygen sensor has an accuracy of 8 µM or 5%, whichever is greater. Accuracy of the Sea-Bird SBE 43 oxygen sensor is 2% of saturation, while that of the SBE 63 is the greater of 3 µmol/kg or 2%. These values are from the product specifications. Körtzinger *et al.* (2005) discuss oxygen measurements from profiling floats. Recent studies show that measurements with the Aanderaa oxygen optodes 3830 and 4330, or any optodes with reliable in-air measurements, and a proposed in-air oxygen measurement routine will result in accuracies close to 1 μmol/kg over the entire lifetime of a float (Bittig and Körtzinger, 2015).

The nitrate data from profiling floats obtained using ultraviolet spectrophotometer nitrate sensors have a reported accuracy of 1 μmol/kg (Johnson *et al.*, 2013). pH data obtained with ion sensitive field effect transistors have an accuracy of 0.01 pH (Johnson *et al.*, 2016). Chlorophyll-a data have an accuracy of the greater of 30% (Fluorescence) and 24% (Radiometer) or 0.03 mg Chl-a/m^3 (Boss *et al.*, 2008; Xing *et al.*, 2011).

6.6. DATA PROBLEMS

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

6.6.1. Sensor problems

The biggest persisting challenge for profiling float sensors is salinity drift. Conductivity cells are calibrated against samples of standard seawater before deployment of the float. However, even over the course of a short oceanographic cruise, the conductivity sensor on a standard winch-deployed CTD can experience slowly increasing unidirectional errors (drift) due to biofouling and small changes in cell geometry. Profiling floats are designed to be almost constantly immersed in the harsh ocean environment for four years. Therefore, it is to be expected that the conductivity sensor on a float will experience drift. Oka (2005) estimated a salinity drift of -0.016 ± 0.006 per year from recalibration of three floats recovered after 2-2.5 years of deployment. From examining the extant float data, some floats can experience much larger drifts, or even abrupt deviations from calibration. A number of algorithms for correcting for drift have been proposed (Wong *et al.*, 2003 [WJO]; Böhme and Send, 2005 [BS]; Durand and Reverdin 2005, Owens and Wong, 2009 [OW]). The Argo delayed-mode data are corrected for drift using the OW, WJO, or BS algorithm, depending on the DAC which is making the correction. Delayed-mode data are available in WOD18. If the pressure adjustment, temperature adjustment, or salinity adjustment variable is present in a cast (variable specific secondary header 19), the cast has delayed-mode quality control applied by the appropriate DAC. This adjustment variable gives the mean change between delayed-mode and real-time values at the same measurement levels for all levels below 500 meters depth. Salinity drift adjustments and most pressure sensor adjustments are uniform over an entire profile so the adjustment variable is usually a good indicator of the profile change at each level from real-time to delayed-mode. However, there are some cases where a single level or a few levels have their values adjusted. In these cases the adjustment variable does not represent the change to each level.

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

Unfortunately, troubling drifts in conductivity sensors continue to be a problem. In early 2018, it was reported that certain Sea-Bird conductivity sensors suffer very early high drifts, which result in a high salinity bias larger than 0.01 two years after deployment (S. Wijffels, J. Gilson, P. Robbins, and A. Wong, Argo, 2018).

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 Sea-Bird 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 WOD18. For those data which could not be corrected, all float cycles are flagged. In early 2009, a problem with the Druck pressure sensor was found (J. Willis and D. Roemmich, Argo Steering Team, 2009). This problem causes pressure sensor drift after deployment. Deployment of new floats was halted temporarily, until the pressure sensor design could be altered. Barker *et al.* (2011) reported that about 57% of the profiles from APEX floats, the predominant type of deployed Argo floats – see Figure 6.1, could be immediately corrected for pressure sensor drift, while only about half of the then uncorrectable APEX profiles could be corrected with the future release of updated metafiles and technical files.

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

Another identified problem is a thermal lag caused because the thermistor and the conductivity cell are located a small distance from each other. If there is a large vertical gradient in temperature, this can cause erroneous spikes in the salinity field. Work has been done to correct this lag problem and corrections are available in the delayed-mode data. However, the error is quite different between different Sea-Bird 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 WOD18.

Table 6.2. 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 Pro-files	Average Correc-tion (m)	Maximum Correc-tion (m)
13857	140	9.4	14.5
13858	48	12.7	12.7
13859	155	6.0	8.4
15819	121	17.9	27.7
15820	174	12.7	13.9
15851	97	13.5	82.8
15852	116	5.8	6.4
15853	120	6.9	8.4
15854	66	11.8	12.9
15855	61	9.7	9.7
31810	124	18.7	19.5
31855	73	13.2	50.3
31856	47	15.4	17.7
31857	109	15.7	52.0
31858	23	15.6	21.1
31859	163	19.9	24.7

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 WOD18**. A list of the floats and the average pressure correction are shown in Table 6.2.

There are no significant identified problems with the temperature sensors. Oka and Ando (2004) found no drift in temperature from three 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. Körtzinger *et al.* (2005) found no instrument problems using the Aanderaa 3830 sensor after 6-9 months deployment. Both Aanderaa and Sea-Bird sensors compare well with Winkler titrated oxygen values and appear to have stable calibration according to recently presented results (Gilbert *et al.*, 2006).

Biofouling of the optical sensors measuring nitrate, pH, chlorophyll-a, and transmissivity has been reduced or eliminated by exposing the sensors to wave action when the floats surface and removing the sensors from the flow stream of the CTD (Johnson *et al.*, 2017).

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 WOD18 if they have not been removed beforehand. But there may be data with errors of this nature which escaped all quality control steps.

6.7. ORIGINATORS FLAGS

The originators flags from the Argo program are kept intact in the WOD18 data. The flags are as follows:

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

Note that not all data marked with originators 3 or 4 are marked with WOD18 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 WOD18 standards, or that the failing test was not performed for WOD18. The user of WOD18 can choose to use the Argo flags, the WOD18 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 WOD18. This grey list is periodically updated. The grey list used to flag data for WOD18 is the version from August 7, 2018.

6.8. PFL DATA DISTRIBUTIONS

Figure 6.3 shows the geographic distribution of profiling float casts for the period 1994-2017. It is clear that Argo has met its goal of full geographic coverage of non-ice covered ocean: there are a total of 1,867,873 PFL casts for the entire World Ocean, closely divided between the southern hemisphere (891,667 casts, or 47.7%) and the northern hemisphere (976,206 casts, or 52.3%). Table 6.3 and Figure 6.4 shows that about 54% of the floats data are of U.S. origin, followed by Japan at about 10%. It also shows that many countries around the world contribute profiling float data. The yearly count in Table 6.4 and Figure 6.5 shows the rapid increase with time of recorded profiling float casts, from less than 15,000 a year before 2002, to more than 115,000 a year by 2008, with around 160,000 casts a year obtained since 2013. The depth distribution, Figure 6.6, shows that many of the surface and near surface values do not exist or are missing: most float sensors are shut down near the surface to avoid biofouling.

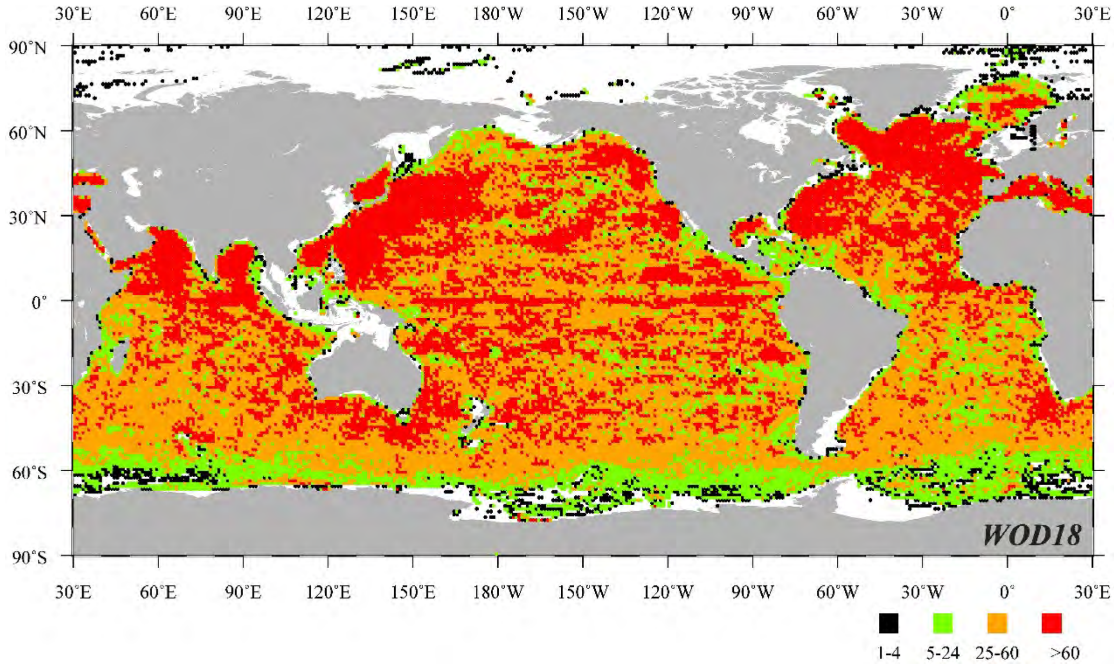

Figure 6.3. Geographic distribution of profiling floats (PFL) casts for the period 1994-2017 in WOD18.

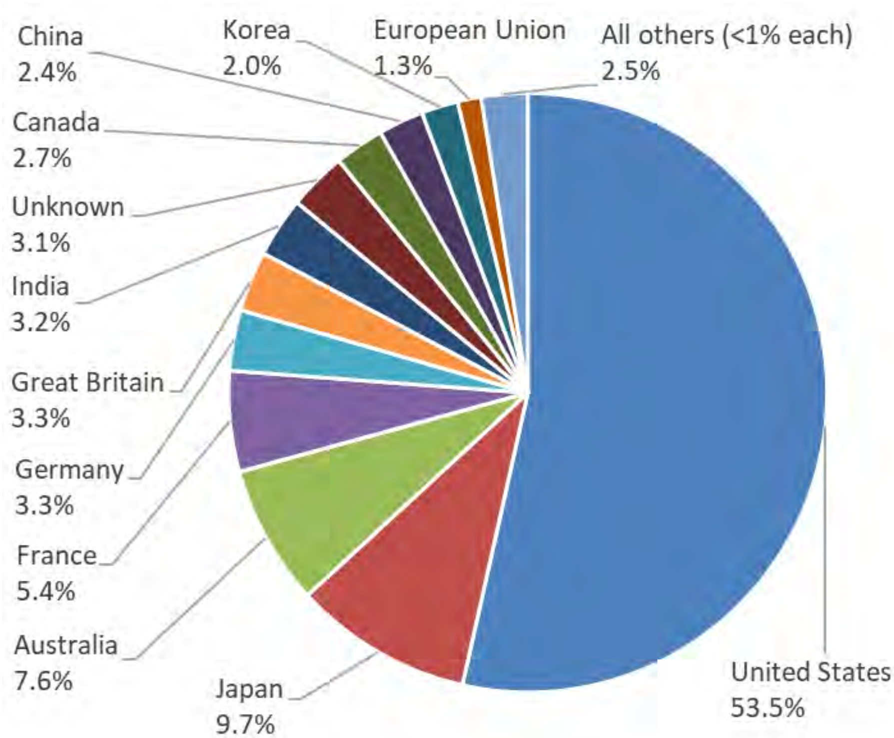

Figure 6.4. Profiling floats (PFL) data contribution by countries in WOD18

Table 6.3. National contribution of PFL casts in WOD18.

ISO[1] Country Code	Country Name	PFL Casts	% of Total
US	United States	999,430	53.51
JP	Japan	180,597	9.67
AU	Australia	141,374	7.57
FR	France	101,367	5.42
DE	Germany	61,225	3.28
GB	Great Britain	60,769	3.25
IN	India	58,939	3.16
99	Unknown	57,171	3.06
CA	Canada	50,008	2.68
CN	China, The People's Republic of	45,708	2.45
KR	Korea, Republic of	37,125	1.99
EU	European Union	23,710	1.27
IT	Italy	18,167	0.97
ES	Spain	8,471	0.45
NO	Norway	4,476	0.24
IE	Ireland	3,163	0.17
CL	Chile	3,053	0.16
FI	Finland	2,309	0.12
TR	Turkey	1,811	0.10
GR	Greece	1,674	0.09
BG	Bulgaria	1,128	0.06
MU	Mauritius	1,030	0.06
BR	Brazil	1,022	0.05
DK	Denmark	897	0.05
NL	Netherlands	897	0.05
PL	Poland	883	0.05
NZ	New Zealand	565	0.03
MX	Mexico	544	0.03
RU	Russian Federation	307	0.02
LB	Lebanon	53	<0.01
	Total	*1,867,873*	*100.0*

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

Table 6.4. The number of Profiling Float Data (PFL) casts as a function of year in WOD18.

Total number of casts = 1,867,873.

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1994	53	2000	13,854	2006	87,293	2012	141,444
1995	1,038	2001	14,677	2007	101,933	2013	155,541
1996	2,557	2002	20,421	2008	116,130	2014	159,317
1997	5,996	2003	31,070	2009	120,810	2015	171,976
1998	11,528	2004	45,097	2010	117,392	2016	174,943
1999	14,230	2005	66,355	2011	128,575	2017	165,643

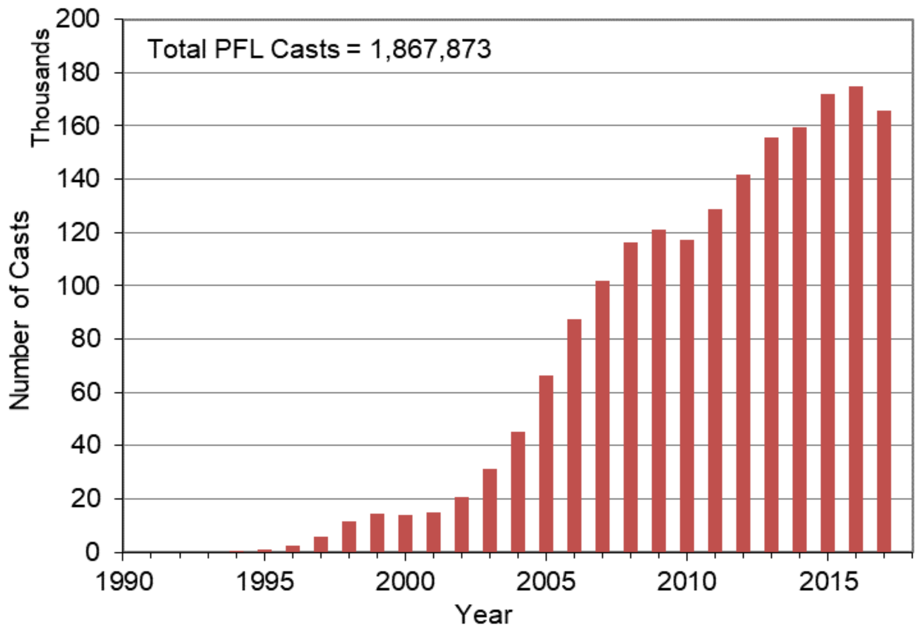

Figure 6.5. Temporal distributions of Profiling Float Data (PFL) casts in WOD18.

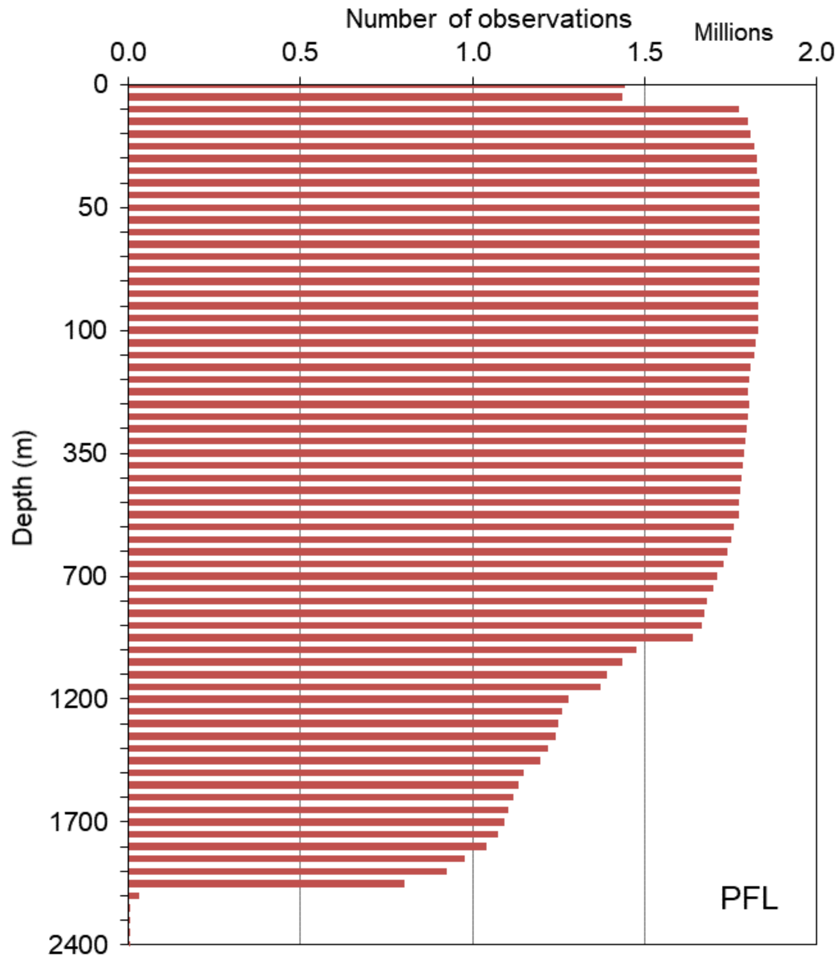

Figure 6.6. Distribution of Profiling Float Data (PFL) data at standard depth levels in WOD18.

6.9. RELEVANT WEB SITES

Aanderaa: http://www.aanderaa.com/index.php.
Argo: http://www.argo.ucsd.edu.
Argo Information Center: http://wo.jcommops.org/cgi-bin/WebObjects/Argo.
BioGeochemical Argo: http://biogeochemical-argo.org/index.php.
FSI Scientific, Inc: http://www.falmouth.com/.
Sea-Bird Scientific: http://www.seabird.com/.
TSK The Tsurumi-Seiki Co., Ltd.: http://tsk-jp.com/.
U.S.A. GODAE: http://www.usgodae.org.

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

CHAPTER 7: MECHANICAL BATHYTHERMOGRAPH DATA (MBT)

Igor V. Smolyar, Alexey V. Mishonov, Tim P. Boyer, Ricardo A. Locarnini

Ocean Climate Laboratory
National Centers for Environmental Information
Silver Spring, MD

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 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. Spilhaus (1987) give a review of the development of the MBT. Couper and LaFond (1970) provide another more comprehensive review.

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).

7.2. MBT ACCURACY

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

7.3. SURFACE DATA ACQUIRED CONCURRENTLY WITH MBT CASTS

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

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

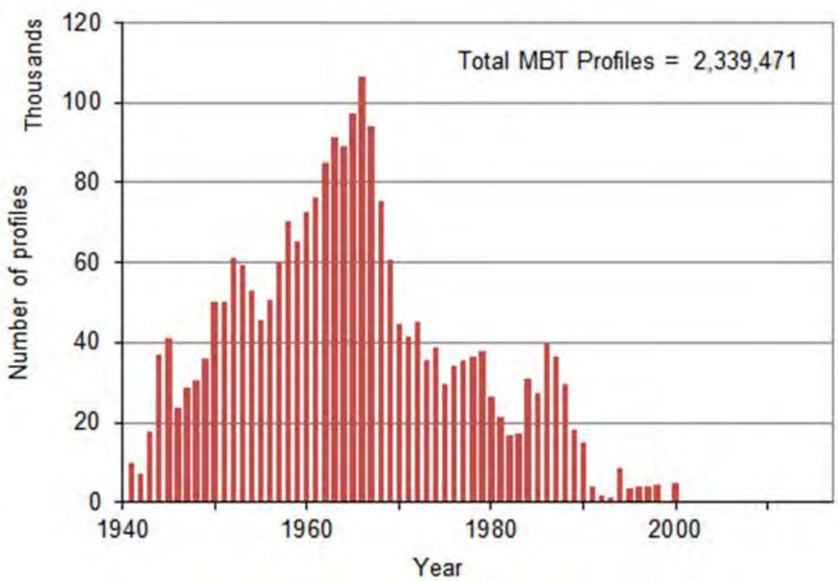

Figure 7.1. Temporal distribution of Mechanical Bathythermograph (MBT) profiles in WOD18.

7.4. MBT PROFILE DISTRIBUTION

Table 7.1 gives the yearly counts of MBT profiles for the World Ocean and Figure 7.1 shows the time series of those yearly totals. Figure 7.2 represents distribution of Mechanical Bathythermograph (MBT) data at standard depth levels. There are a total of 2,339,471 MBT profiles for the entire World Ocean with only about 11% measured in the southern hemisphere and 89% profiles measured in the northern hemisphere (Figure 7.3). Table 7.3 gives national contributions of MBT profiles.

Table 7.1. Number of all MBT profiles as a function of year in WOD18.

Total Number of Profiles = 2,339,471

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1941	9,990	1961	76,417	1981	21,182
1942	7,014	1962	84,853	1982	16,608
1943	17,767	1963	91,213	1983	17,481
1944	36,785	1964	88,951	1984	30,910
1945	41,086	1965	97,112	1985	27,285
1946	23,822	1966	106,585	1986	39,504
1947	28,808	1967	94,162	1987	36,525
1948	30,307	1968	75,372	1988	29,684
1949	36,040	1969	60,830	1989	18,024
1950	50,296	1970	44,886	1990	14,921
1951	50,248	1971	41,386	1991	3,829
1952	61,310	1972	45,353	1992	1,554
1953	59,341	1973	35,533	1993	1,169
1954	52,914	1974	38,586	1994	8,417
1955	45,467	1975	29,808	1995	3,453
1956	50,521	1976	34,360	1996	3,905
1957	60,464	1977	35,455	1997	3,859
1958	70,102	1978	36,608	1998	4,552
1959	65,214	1979	37,806	1999	0
1960	72,656	1980	26,362	2000	4,819

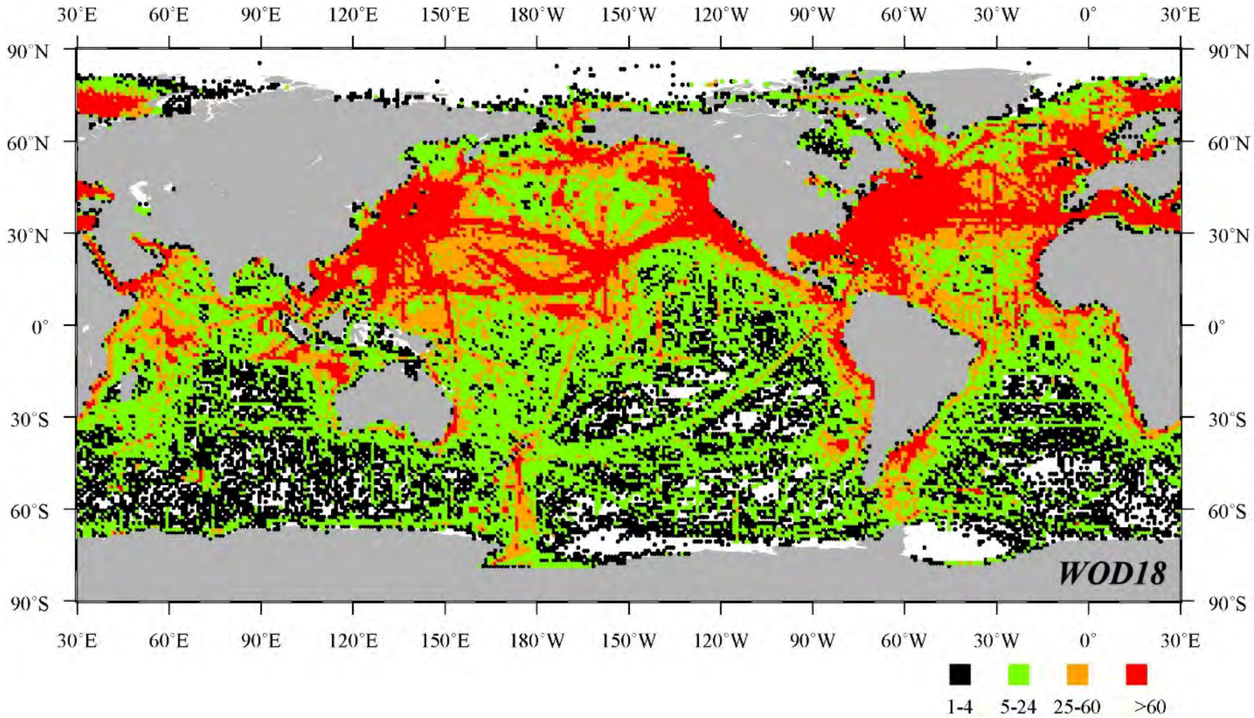

Figure 7.3. Geographic distribution of Mechanical Bathythermograph (MBT) profiles in WOD18.

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

TABLE 2.3. Observations taken with bathythermographs and reversing thermometers			
BT	**No. of stations**	**No. of thermometer observations**	**Standard Deviation of Temperature Differences***
# 1784A (Shallow)	9	20	0.15
# 1258A (Deep)	10	41	0.19
# 514A (Deep)	12	36	0.10

Reproduced from Leipper and Burt (1948).

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

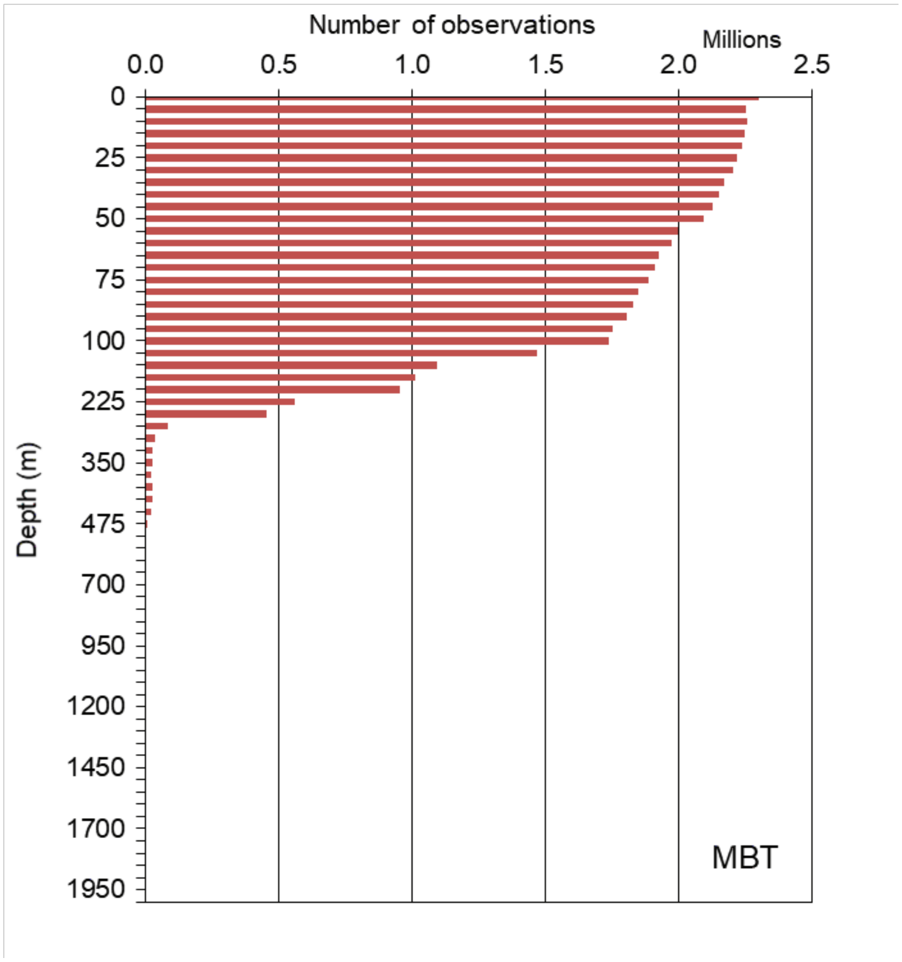

Figure 7.2. Distribution of Mechanical Bathythermograph (MBT) data at standard depth levels in WOD18.

Table 7.3. National contributions of Mechanical Bathythermograph profiles in WOD18.

ISO[1] Country Codes	Country name	MBT Casts	% of Total
US	United States	1,169,350	50.0
SU	Union of Soviet Socialist Republic	449,098	19.2
JP	Japan	296,405	12.7
CA	Canada	184,844	7.9
GB	Great Britain	118,638	5.1
DE	Germany	25,005	1.1
AU	Australia	18,376	0.8
99	Unknown/International	16,386	0.7
FR	France	13,538	0.6
AR	Argentina	10,995	0.5
NL	Netherland	8,088	0.3
IT	Italy	6,267	0.3
PE	Peru	5,212	0.2
CL	Chile	4,161	0.2
PT	Portugal	2,628	0.1
NZ	New Zealand	2,435	0.1
CD	Congo, the Democratic Republic	1,234	0.1
BE	Belgium	1,218	0.1
NO	Norway	913	<0.1
EC	Ecuador	885	<0.1
CO	Colombia	747	<0.1
VE	Uruguay	673	<0.1
IN	India	540	<0.1
MG	Madagascar	405	<0.1
GR	Greece	327	<0.1
SN	Spain	245	<0.1
ES	Estonia	195	<0.1
SL	Russian Federation	187	<0.1
CI	Cote D'Ivoire	99	<0.1
MC	Monaco	97	<0.1
NG	Nigeria	89	<0.1
BR	Brazil	82	<0.1
TH	Thailand	77	<0.1
ZA	South Africa	20	<0.1
GH	Ghana	12	<0.1

[1] ISO = International Organization for Standardization

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CHAPTER 8: DIGITAL BATHYTHERMOGRAPH (DBT) PROFILES

Igor V. Smolyar, Alexey V. Mishonov, Tim P. Boyer, Ricardo A. Locarnini

Ocean Climate Laboratory
National Centers for Environmental Information
Silver Spring, MD

8.1. INTRODUCTION

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

All DBT profiles are stored in the MBT dataset of WOD18.

8.2. DBT ACCURACY

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

8.3. DBT PROFILE DISTRIBUTIONS

Table 8.1 gives the yearly counts of DBT profiles for the World Ocean. Figure 8.1 shows the time series of the yearly totals of Digital Bathythermograph profiles for the World Ocean. There are a total of 80,200 DBT profiles for the entire World Ocean with about 6.0% measured in the southern hemisphere and 94.0% profiles measured in the northern hemisphere. Table 8.2 gives national contributions of DBT data. Figure 8.3 illustrate distribution of Digital Bathythermograph (DBT) data at standard depth levels in WOD18.

Table 8.1. The number of Digital Bathythermograph (DBT) profiles as a function of year in WOD18.

The total number of casts = 80,200.

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1977	27	1984	9,271	1991	4,662	1998	0
1978	234	1985	8,427	1992	2,285	1999	0
1979	1,926	1986	5,255	1993	2,507	2000	1
1980	5,310	1987	4,505	1994	121	2001	73
1981	6,000	1988	5,478	1995	2	2002	19
1982	7,539	1989	3,443	1996	27	2003	23
1983	8,440	1990	4,148	1997	88	2004	389

Table 8.2. National contributions of Digital Bathythermograph (DBT) profiles in WOD18.

ISO[1] Country Codes	Country Name	DRB Casts	% of Total
JP	Japan	69,098	86.2
CA	Canada	11,102	13.8
	Total	*80,200*	*100.00*

[1] ISO = International Organization for Standardization

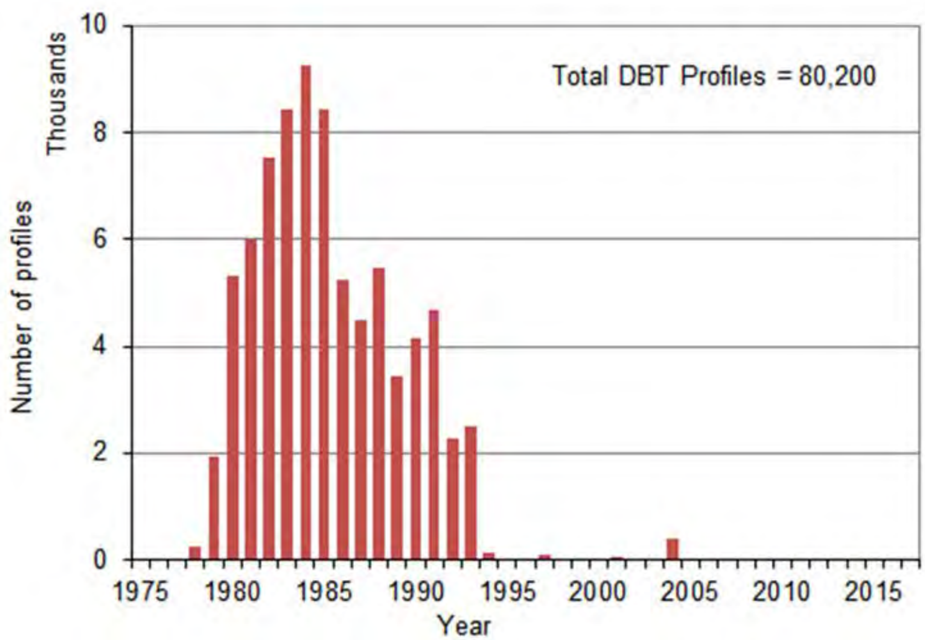

Figure 8.1. Temporal distribution of Digital Bathythermograph (DBT) profiles in WOD18

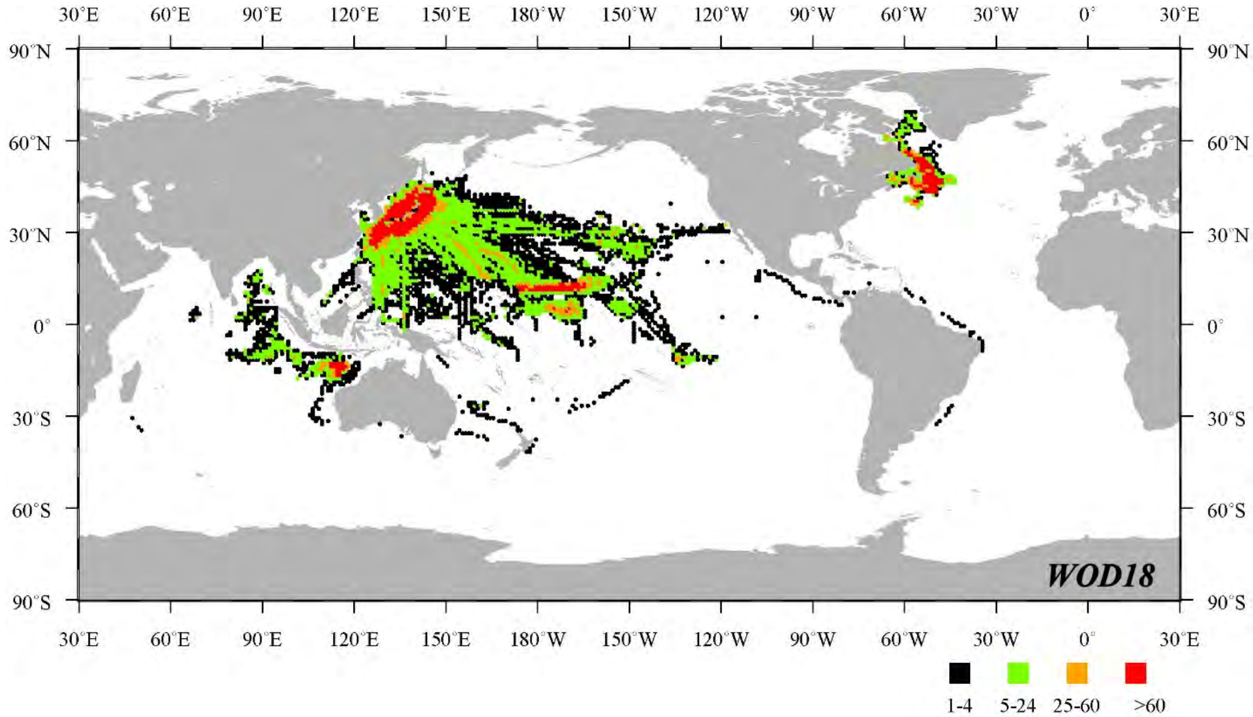

Figure 8.2. Geographic distribution of Digital Bathythermograph profiles in WOD18

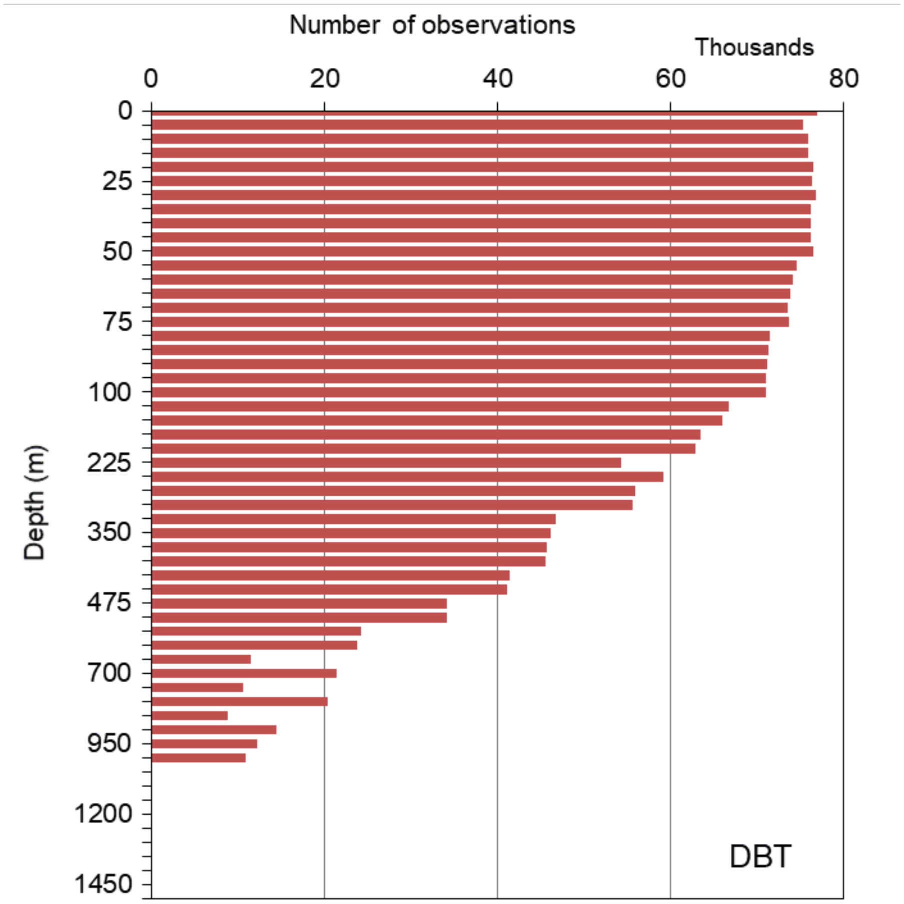

Figure 8.3. Distribution of Digital Bathythermograph data at standard depth levels in WOD18.

8.4. REFERENCES AND BIBLIOGRAPHY

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CHAPTER 9: MOORED BUOY DATA (MRB)

Melissa M. Zweng, Alexey V. Mishonov, Tim P. Boyer, Ricardo A. Locarnini, Dan Seidov

Ocean Climate Laboratory
National Centers for Environmental Information
Silver Spring, MD

9.1. INTRODUCTION

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

- extensive requirements exist for oceanographic and meteorological information to satisfy both operational and research needs in the oceanic and Great Lakes environments;
- automatic, moored buoys were capable of meeting a significant portion of those needs; and that
- a network of such buoys, would be an essential element of an overall environmental information and prediction system (Shea, 1987).

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

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

The WOD18 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 November 3, 1977 to December 31, 2017. The dataset contains a total of 1,585,135 profiles. The majority of data came from ongoing programs. The TAO buoy array collected 544,004 casts. The PIRATA program provided 96,201 casts. The TRITON program collected 81,512 casts and the RAMA project submitted 73,375 casts. Historic data consist of 73,347 casts from three buoys located around Japan and operated by the Japan Meteorological Agency (JMA); 19,444 casts were collected during the MARNET program, and 905 casts were collected during the South China Sea Monsoon Experiment (SCSMEX). Two Arctic data programs contributed a number of profiles: the Arctic-Subarctic Ocean Fluxes (ASOF) project contributed 635,124 casts, and the Circulation of the North Central Chukchi Shelf project provided 43,005 profiles.18,217 casts came from other sources (See Figure 9.1 for percentages and related web-links below for additional information). Please note that sampling frequencies among the observational programs differ; the number of casts depends not only on the number of instruments and the length of the record but also the rate at which the instrument samples, and if the data is averaged or post-processed. As part of the Tropical Ocean-Global Atmosphere (TOGA) program, efforts were made to enhance the real-time ocean observing system in the tropical Pacific Ocean. The Tropical Atmosphere Ocean (TAO) array of moored buoys spans the tropical Pacific from 137°E to 95°W and from 8°S to 8°N. The TAO system began in 1985 as a regional-scale set of meridional arrays on both sides of the Equator at 110°W and 165°E and has steadily expanded to its present size of approximately 70 moorings.

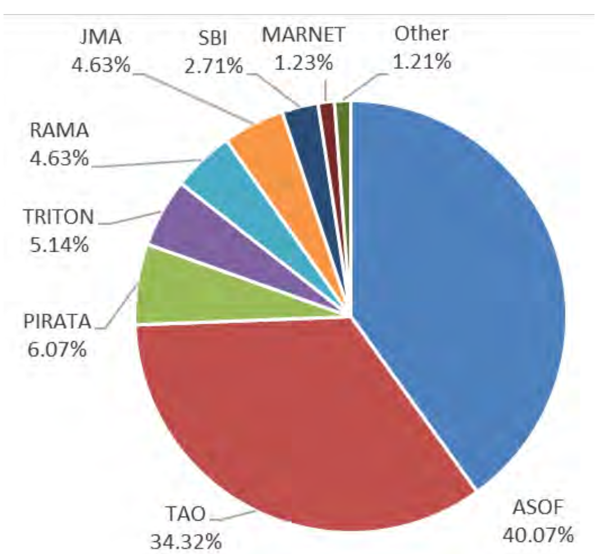

Figure 9.1. Distribution of the moored buoy data among the major research programs.

The buoys in the TAO array are typically separated by 2-3 degrees of latitude and 10-15 degrees of longitude. The array provides surface wind, rain rates, sea surface temperature (SST), upper ocean temperature, as well as subsurface temperatures and salinity down to a depth of 500 meters, and current measurements (Mangum, 1994; Mangum *et al.,* 1994; McPhaden, 1995; McPhaden *et al.,* 1998). The majority of TAO moorings are ATLAS moorings developed at NOAA's Pacific Marine Environmental Laboratory (PMEL) Seattle, WA, in the 1980's (https://www.pmel.noaa.gov/gtmba/pmel-theme/pacific-ocean-tao).

The ATLAS mooring is a taut wire surface mooring with a toroidal float. It is deployed in depths of up to 6000 meters (Milburn *et al.,* 1996). The expansion of this array is the result of international collaboration between scientists from France, Japan, Korea and the USA, and its current support is from the US, Japan and France. The first ATLAS mooring was deployed in December 1984. Collected data are transmitted to shore in real time using the ARGOS System (http://www.argos-system.org/), processed by Collecte Localisation Satellites (CLS, http://www.cls.fr/) or Service ARGOS Inc., and placed on the Global Telecommunication System (GTS, https://public.wmo.int/en/programmes/global-telecommunication-system). 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, https://public.wmo.int/en/programmes/global-climate-observing-system), World Climate Research Programme (WCRP, https://www.wcrp-climate.org/), Climate Variability and Predictability Programme (CLIVAR, http://www.clivar.org/), and the World Weather Watch Programme (WWW, http://www.wmo.int/pages/prog/www/index_en.html).

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). 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 (https://www.pmel.noaa.gov/gtmba/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 moorings and NIO (National Institute of Oceanography, India) began subsurface mooring deployment along the equator (McPhaden *et al.*, 2006). As of 2017 RAMA was 78% complete, with 36 of 46 mooring sites occupied (https://www.pmel.noaa.gov/gtmba/pmel-theme/indian-ocean-ramaThe planned array will consist of 38 surface and 8 subsurface moorings. Mooring equipment, ship time, personnel, and/or logistic support has been provided by several nations including Japan, India, the United States, Indonesia, China, France and the African countries participating in the Agulhas and Somali Current Large Marine Ecosystems (ASCLME) project: Comoros, Mozambique, Kenya, Tanzania, Madagascar, South Africa, Seychelles and Mauritius (McPhaden *et al.*, 2009). Data collected by RAMA buoys are distributed by Service Argos via Global Telecommunications System (GTS) as well as via the PMEL, JAMSTEC and NIO websites (see links below).

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

The Arctic/Subarctic Ocean Fluxes (ASOF) project is a collection of research products from several countries. The ASOF project was established in 2000, and from 2000 to 2008 measurements at several locations in the Arctic and Subarctic was collected with the aim of estimating a freshwater budget for Arctic inflows and outflows. A second phase of the project, since 2008, combines the ongoing scientific work of ASOF I with application of the results to broader questions of science and society. The ASOF mooring data in WOD18 comes from the Canadian Arctic Throughflow Study (CATS), which gathered data in Nares Strait from 2003 to 2006 (Rabe *et al.*, 2010). The moorings were instrumented with Sea-Bird Electronics, Inc. model 37-IM temperature and conductivity sensors at up to 4 depth levels (CATS, 2007).

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

Five countries collected most of the moored buoy data in WOD18: USA, Japan, Germany, Brazil, and France. Significant amounts of data have no country information mostly because of the multi-national nature of its acquisition and processing; those data were obtained from internet-based web-portals of the international research Programs (*i.e.* RAMA, *etc*.) Table 9.1 provide detailed information on each country contribution.

9.2. MRB DATA PRECISION AND ACCURACY

The accuracy of MRB temperature and salinity data depends on the temperature and conductivity sensors used. For TRITON buoys, for example, sensor range and accuracy are: conductivity 0-70/0.003 ms·cm^{-1}; temperature -3.0 – 33.0/0.002°C; depth 0-1000 pounds per square inch absolute (psia) / 0.15% full scale (Kuroda, 2001; Ando *et al.,* 2005). Data acquired during TAO and PIRATA programs were collected from PROTEUS and ATLAS buoys using Sea-Bird Electronics Inc. SEACAT sensors which have sea surface temperature accuracy of 0.01°C for the PROTEUS mooring and 0.03°C for ATLAS moorings; subsurface temperature accuracy is 0.01°C for the PROTEUS mooring and 0.09°C for ATLAS moorings (Freitag *et al.,* 1994; Cronin and McPhaden, 1997). RAMA data are collected mostly from ATLAS and TRITON moorings. In February 2008 JAMSTEC deployed several mini-TRITON buoys with slack-line moorings with all its sensors equipped to measure pressure so data can be interpolated to standard depth (McPhaden *et al.*, 2009).

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

Table 9.1. National contributions of MRB casts in WOD18

ISO[1] Country Code	Country Name	MRB Casts	% of Total
US	United States	1,237,039	78.04
JP	Japan	184,462	11.64
BR	Brazil	49,273	3.11
FR	France	43,231	2.73
99	Unknown / International	45,291	2.86
DE	Germany	19,445	1.23
TW	Taiwan	905	0.06
	Total:	*1,585,135*	*100.00*

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

The moorings from the CATS study, part of the ASOF project, were instrumented with SBE 37-IM temperature/conductivity sensors (Rabe *et al.*, 2010). The temperature measured by this sensor is accurate to 0.002°C, and conductivity to 0.0003 S/m. The measurements from the Circulation of the North Central Chukchi Shelf project were collected using SBE 16 temperature and conductivity sensors. Using this sensor, temperature was measured to 0.005 °C, and conductivity to 0.0005 S/m (CATS, 2007). The sensors were calibrated before deployment and after recovery, and linearly interpolated calibration coefficients were applied to the data during processing (Weingartner, 2007).

The Central and Northern California Ocean Observing System (CeNCOOS) acts as a Data Assembly Center for and Monterey Bay Aquarium Research Institute (MBARI) moorings M1 and M2 in Monterey Bay. The M1 mooring measures temperature at 0, 60 and 100m along with chemical, biological and meteorological information at the surface. Mooring M2 was replaced by the NDBC mooring 46042 in 2011 (CeNCOOS, 2018)

9.3. MRB CAST DISTRIBUTIONS

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

The geographic distribution of the MRB casts for 1977-2017 is shown in Figure 9.3. There are 1,585,135 MRB casts for the entire World Ocean with 780,117 casts (49%) measured in the tropical regions (15°N – 15°S). The TAO, TRITON, PIRATA, and RAMA programs contributed these data. The MARNET and JMA programs have contributed 46,509 casts (3%) measured in the area between 30°N and 60°N. Approximately 4% of all casts (64,356, mostly collected by JMA) were acquired between 15°N -30°N. The ASOF and Circulation of the North Central Chukchi Shelf project collected data in the Arctic Ocean and Canadian Archipelago, contributing 678,129 profiles in total (43%). Only 7,623 profiles were collected in the southern hemisphere south of 15ºS (0.05%).

Table 9.2. The number of MRB casts in WOD18 as a function of year
Total number of casts = 1,585,135

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1977	173	1988	6,965	1999	39,957	2010	37,426
1978	240	1989	8,352	2000	37,685	2011	44,241
1979	1,184	1990	8,517	2001	31,635	2012	36,084
1980	1,307	1991	9,749	2002	30,049	2013	31,630
1981	1,148	1992	23,866	2003	115,912	2014	29,405
1982	931	1993	33,253	2004	240,722	2015	33,333
1983	1,370	1994	47,337	2005	241,326	2016	31,826
1984	1,464	1995	44,286	2006	161,200	2017	28,960
1985	1,951	1996	37,841	2007	33,337		
1986	3,328	1997	32,787	2008	34,460		
1987	4,401	1998	36,851	2009	36,328		

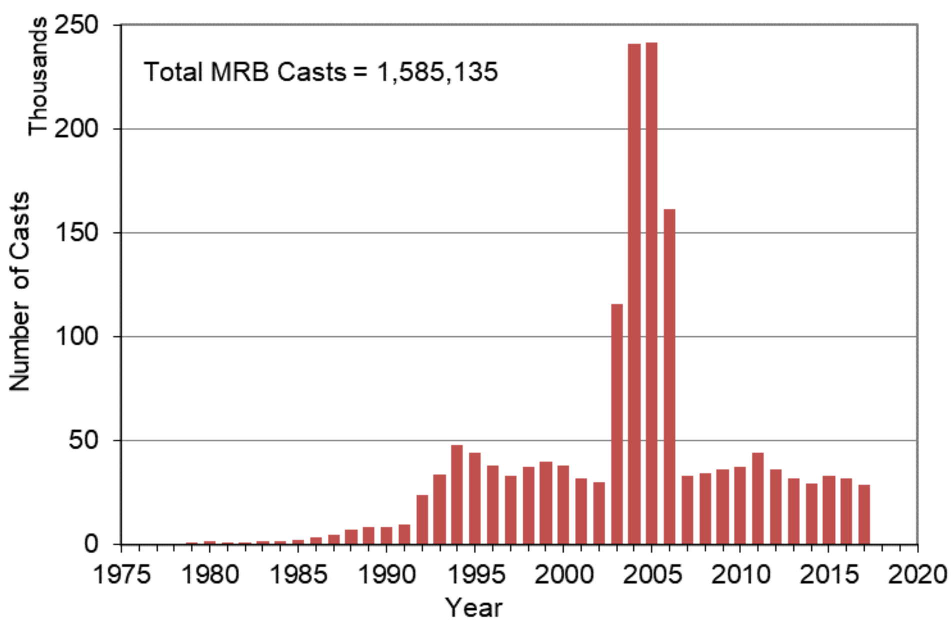

Figure 9.2. Temporal distribution of the Moored Buoys (MRB) casts in WOD18.

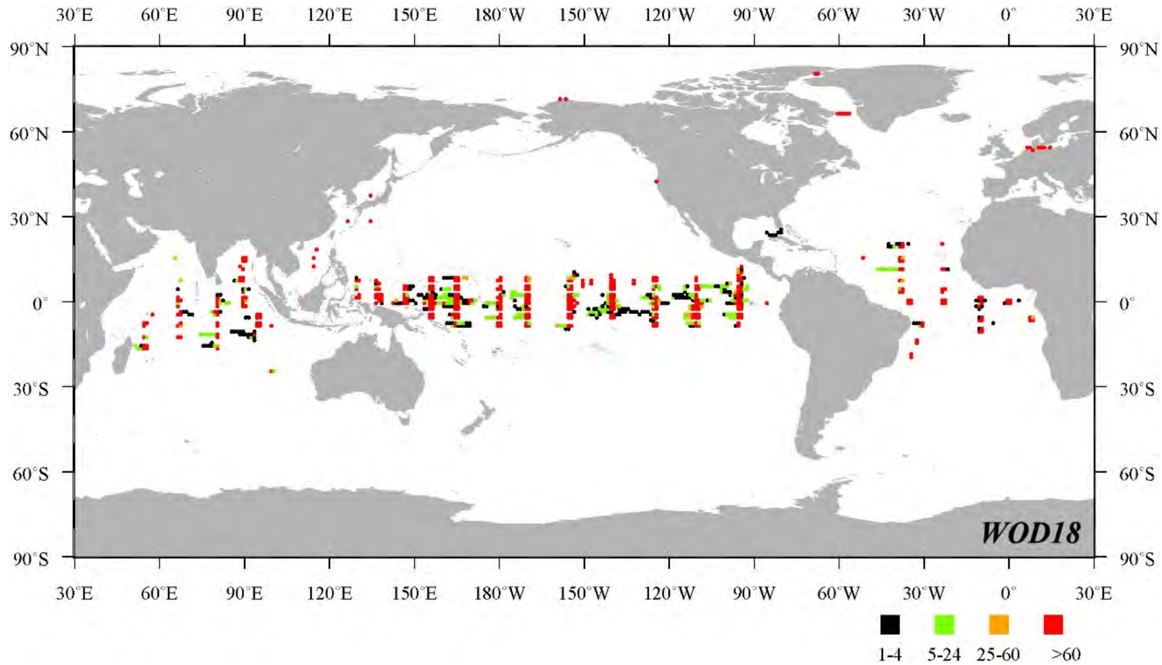

Figure 9.3. Geographic distribution of the Moored Buoys (MRB) casts collected by major research programs in WOD18 by one-degree squares

Figure 9.4 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 750 meters of the water column.

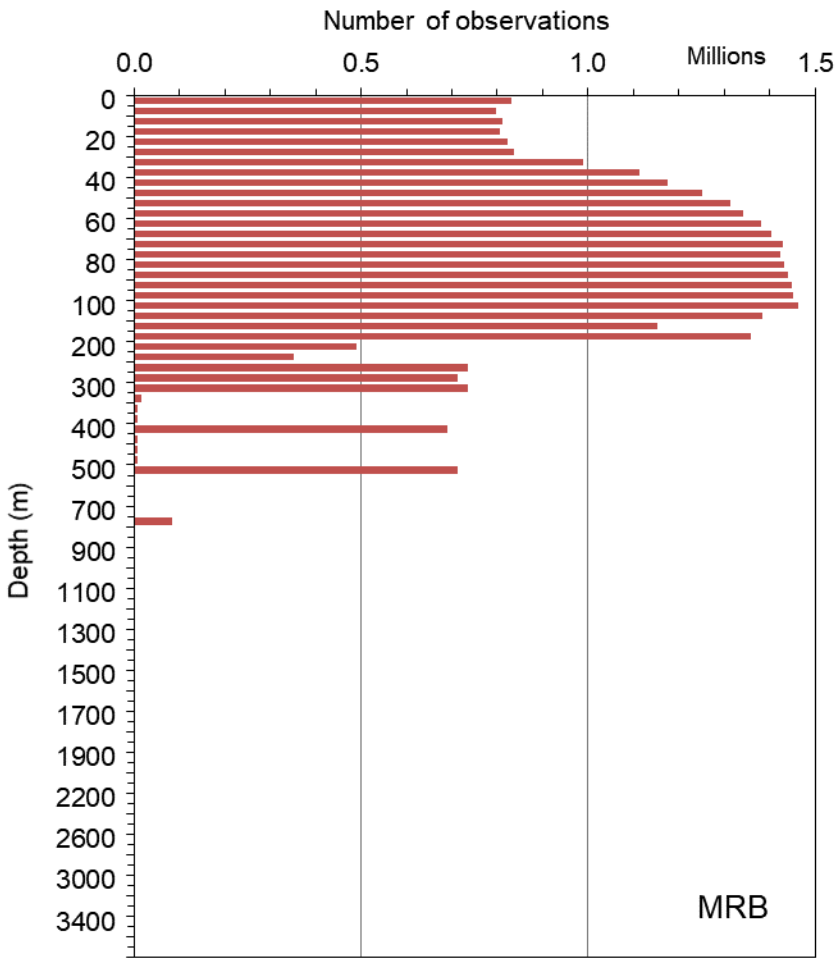

Figure 9.4. Distribution of t**he Moored Buoys (MRB) data at standard depth levels in WOD18**

9.4. RELEVANT WEB SITES

ARGOS Program: http://www.argos-system.org/
Centre national de la recherche scientifique (CNRS): http://www.cnrs.fr/
Canadian Arctic Throughflow Study (CATS):
http://www.udel.edu/CATS/healy_2007/expedition/Cruise_Report.pdf
Central and Northern California Observing System (CeNCOOS):
https://www.cencoos.org/data/buoys/mbari
Diretoria De Hidrografia E Navegação (DHN), Brazil: https://www.marinha.mil.br/dhn/
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/
Instituto Nacional de Pesquisas Espaciais (INPE), Brazil: http://www.inpe.br/
JAMSTEC TRITON Buoy project: http://www.jamstec.go.jp/jamstec/TRITON/real_time/
MARNET description available at:
https://www.bsh.de/EN/TOPICS/Observation_systems/MARNET_monitoring_network/MARNET_monitoring_network_node.html).

METEOSAT: http://www.esa.int/ESA
National Data Buoy Center: https://www.ndbc.noaa.gov/
PIRATA Program: https://www.pmel.noaa.gov/gtmba/pirata
RAMA Program links:

GTS: https://public.wmo.int/en/programmes/global-telecommunication-system
PMEL: https://www.pmel.noaa.gov/tao/drupal/disdel/
JAMSTEC: http://www.jamstec.go.jp/tropicbuoy/index.html
NIO: http://www.nio.org/index/option/com_nomenu/task/show/tid/2/sid/18/id/5

South China Sea Monsoon Experiment:

http://www.pmel.noaa.gov/tao/proj_over/scsmex/scsmex-display.html

Tropical Atmosphere Ocean Project: https://www.pmel.noaa.gov/gtmba/
WMO-IOC Data Buoy Cooperation Panel: http://www.jcommops.org/dbcp/

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CHAPTER 10: DRIFTING BUOY DATA (DRB)

Melissa M. Zweng, Tim P. Boyer, Ricardo A. Locarnini, Alexey V. Mishonov, Dan Seidov

Ocean Climate Laboratory
National Oceanographic Data Center
Silver Spring, MD

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, 2018; IABP, 2018).

The first drifting buoys, drift bottles, were used in the early 1800s in an effort to map surface currents. The bottles were weighted so that they were almost entirely submerged and usually carried a note that recorded launch location and time. Bottles were used because previous attempts at mapping ocean currents using ship drift measurements proved unreliable due to the added effect of wind on the movement of the ships (Lumpkin and Pazos, 2006). With the advent of radio, the position of the drifters could be transmitted from small, low-drag antennae and triangulated from the shore. In the early 1970s, positions started to be gathered via satellites. As technology improved, drifters started to obtain meteorological measurements, sea surface temperatures, as well as oceanographic measurements (IADP, 2018; 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, 2018; GTS, 2018).

Between the years 1985 and 1994, the Arctic Data Buoy Program of the Polar Science Center of the Applied Physics Laboratory at the University of Washington deployed 24 modified data buoys in ice floes on the Arctic Ocean. These were the first buoys, as well as the first sea ice buoys, to be equipped with Seabird CTD sensors for collecting oceanographic data along with the meteorological data. These modified buoys, known as Polar Ocean Profile (POP) buoys, measured subsurface ocean temperature, salinity, and depth. They also measured air temperature and barometric pressure. Measurements were taken at twelve-minute intervals. The direction and velocity of the sea ice floe was interpolated from changes in position from each buoy. Due to being subjected to the stresses and strains of the Arctic pack ice, these buoys varied greatly in their longevity, though the battery pack was designed to last for approximately three years (Rigor, 2002; IABP, 2018; JAMSTEC, 2018).

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

10.1.2. Global Temperature-Salinity Profile Program (GTSPP)

The Marine Environmental Data Service (MEDS, Canada) collects the data from all drifting buoys via the Global Telecommunication System (GTS). MEDS has been a Responsible National Oceanographic Data Center (RNODC) since January 1986 under the auspices of the Intergovernmental Oceanographic Commission (IOC). They acquire, process, quality control, and archive real-time drifting buoy data that is reported over the GTS as well as delayed-mode data that are acquired from other sources. Over 200,000 new records are captured monthly from the GTS by MEDS. The GTSPP program through MEDS only includes data from drifting buoys that send subsurface data. This drifting buoy data includes buoy position, date, time, surface and subsurface water temperature, salinity, air pressure, temperature and wind direction (MEDS, 2018). Currently, buoy data from GTSPP in the WOD18 database comes mostly from the United States, Japan and France. It consists of temperature readings and some have meteorological measurements such as wind speed, wind direction, dry bulb temperature, and barometric pressure.

10.1.3. JAMSTEC Buoys

In the early 1990s, the Japan Marine Science and Technology Center (JAMSTEC) developed a polar ocean profiler buoy, the Ice Ocean Environmental Buoy (IOEB), as a joint project with the Woods Hole Oceanographic Institution (WHOI). This was the first attempt to develop a drifting ice buoy equipped with not only meteorological, sea ice and oceanographic sensors, but also with other sensors, such as optical sensors and time series collection devices, that would determine the activities of marine organisms. The first IOEB was deployed in the Beaufort Sea in April 1992; the second was deployed April 1994 into the Arctic Transpolar Drift. These first buoys lacked mobility and had little consistency in measurements due to the large number of different sensors on them. In addition, the buoys were expensive to assemble and required large camps and lots of equipment and materials to install them in the ice. They also had to be recovered to analyze collected sediment samples (JAMSTEC, 2018).

JAMSTEC and MetOcean Data System Ltd. developed a new drifting buoy in 1999, named J-CAD (JAMSTEC Compact Arctic Drifter), and its mission was to conduct long-term observations in the Arctic Ocean multi-year ice zones as a participant of the International Arctic Buoy Program (IABP). Since 2000, the J-CAD has been used to measure the structure of upper ocean currents and water properties. J-CADs have been installed into the sea ice in various regions of the Arctic Ocean and have been collecting oceanographic and meteorological data. The data J-CAD buoys collect are: air temperature, barometric pressure, wind direction, wind speed, sea surface temperature, platform heading, platform tilt, latitude, longitude, date and time of reading, GPS drift speed, GPS drift direction, CTD sensor depth, pressure, temperature, conductivity, salinity, potential temperature, density, and several ADCP parameters. (The ADCP data are not available through the WOD series.) The sensors measure data at one-hour intervals and the J-CAD deployment location varies by different projects' requirements (JAMSTEC, 2018; Kikuchi *et al.,* 2002).

The total weight of the J-CAD system was designed to be 255 kg or less so it can be deployed using a small, light crane system. The maximum external diameter of the underwater sensors is 28 cm; each sensor can be lowered through a 30 cm hole in the ice that can be drilled with simple equipment. It is equipped with three types of sensors: meteorological, oceanographic, and buoy status sensors. The J-CAD buoys consist of a floatation collar made of foam resin buoyancy material (Surlyn Ionomer resin manufactured by DuPont Co.) enclosed by aluminum. The housing for instruments, also made from aluminum and foam resin, holds the data logger/controller engine (Tattletale model 8) with 48MB flash card memory, a GPS receiver, two satellite communication systems, the GPS interface MetOcean Digital Controller, and two 245 Ah 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, 2018).

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, 2018).

The ocean temperature and conductivity data are obtained from Sea-Bird SBE37IM CT sensors, two of which are equipped with pressure sensors that are part of the CT instrument. On a J-CAD buoy, four CT and two CTD sensors can be mounted. The CT sensors are usually attached at 25m, 50m, 80m, and 180m. The two CTD sensors are usually placed at 120m and 250m. These depths can be adjusted to the sea area under observation. There are also two WorkHorse 300 kHz ADCPs from RD Instruments attached at 12m (facing downward) and at 260m (facing upward/downward) depth 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, 2018; 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 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, 2018).

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. JAMSTEC continues to deploy buoys at a rate of 2 per year for the NPEO. The Pacific Marine Environmental Laboratory (PMEL) also maintains drifting weather buoys as part of this program (NPEO, 2018; Kikuchi *et al.,* 2002).

10.1.4. Ice-Tethered Profiling Buoys (ITP)

In 2006, WHOI developed the ITP buoy platform to effectively map the water column in ice-covered seas with a profiling drifter. This drifter builds off the technology developed for the moored profiler (MP) instrument, also developed at WHOI, and from the innovations of the ARGO profiling floats. Instead of being instrumented at fixed depths like other ice drifters, the ITP platform profiles at high resolution through the water column as the ice floe moves, and returns measurements along with the instrument's position from GPS. The platform is lightweight and able to be deployed by helicopter or Twin Otter aircraft through a standard 25cm hole augured in the ice. The instruments are relatively inexpensive, so they can be considered expendable and several can be deployed at one time (ITP, 2018; Krishfield *et al.*, 2008).

The drifter is composed of two parts: the surface package that sits on the ice surface, and the underwater profiling package on the tether line. The surface package is made from yellow-painted foam and contains the Iridium modem, GPS receiver, data controller, batteries and an interface to the underwater part of the drifter. On the outside of the surface package, a temperature sensor measures air temperature. The surface package is designed to be expandable and support other instrumentation as well as increased power and battery loads in the future. When deployed, the surface package is placed on a wooden pallet to help avoid melting and deformation of the ice floe (ITP, 2018; Krishfield *et al.*, 2008).

Below the surface, a plastic-jacketed wire rope tether line extends up to 800m into the water column. A ballast weight at the bottom of the line keeps it oriented vertically. The profiling package is ballasted to be neutrally buoyant at mid-profile depth. The profiling package moves along the line using a traction drive similar to that used by the moored profiler (MP) buoys. The profiling package is instrumented with a Sea Bird Electronics, Inc. model 41-

CP CTD, the same instrument used by ARGO floats. The package returns data at a sample rate of 1Hz and the surface unit sends it to shore at near-real time over the Iridium link. Two related platforms, the Ice-Tethered Winch (ITW) and Ice-Tethered Micro-mooring (ITM) have also been deployed. The ITW uses a profiling Arctic winch to sample closer to the sea surface. The ITMs, which have instruments at fixed depths, are instrumented with Sea-Bird SBE37-SI microCATs and Nortec Aquadopp current profilers to measure ocean currents (ocean currents data not available in the WOD series) (ITP, 2018; Krishfield *et al.*, 2008).

As of September 2018, 110 individual ITP, ITM and ITW packages have been launched, supporting the Beaufort Gyre Observing System (BGOS), Beaufort Gyre Freshwater Experiment (BGFE), North Pole Environmental Observatory (NPEO), European Union DAMOCLES, Nansen and Amundsen Basins Observational System (NABOS), and Hybrid Arctic/Antarctic Float Observation System (HAFOS) projects in the Arctic and the National Institute of Water and Atmospheric Research (NIWA) project in the Antarctic (ITP, 2018).

10.1.4. PAICEX Russian Drifting Ice Camp data

Data rescue coordinated by the Global Oceanographic Data Archaeology and Rescue (GODAR, 2018) project resulted in a digitization and submission by the P.P Shirshov Institute of Oceanology, Russian Academy of Sciences, of Soviet and Russian drifting ice camp data collected between 1950 and 2009. The April 2007 and April 2009 ice camp data, from the PAICEX project, also featured drifting mooring lines. The camp started at ice-station Barneo, around 89ºN, and drifted along with the ice. The moorings measured temperature and salinity at three depths (75m, 100m and 125m) every 3 minutes for approximately 2 weeks. The PAICEX program also collected bottle profiles; these data are part of the WOD18 OSD dataset (see Chapter 2 of this document).

10.2. DRB ACCURACY

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

The foremost concern of the POP buoy's accuracy was conductivity sensor drift due to fouling. Over a year, it seemed that the normal instrumental drift that occurs with age and use fell to less than one percent of the original accuracy. Because the buoys were not usually recovered or revisited, their approach to minimize fouling was to use light baffling shrouds coated with anti-fouling paint around the conductivity cell. More recently, Sea-Bird has provided anti-fouling tubes on the ends of the conductivity cells. The Arctic environment, being cold and dark for half of the year, is detrimental to the growth of fouling organisms. The few sensors that were recovered showed no evidence of fouling or fouling drift. Over time, fouling was generally found to not be a serious problem in the Arctic, though there were occasional problems with shallow sensors in the summer (Morrison, Pers. Com.; Rigor, 2002). Another problem with the POP buoys was inaccurate surface air temperatures that were caused by the small size of the buoy. The air temperature sensor was inside a fiberglass shroud that created a microcosm that would heat up in the summer and be drifted over and insulated by snow in the winter. This difference in internal and external environments rendered the air temperature readings unfit for scientific use (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, 2018).

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., 2018).

The ITP drifters use the Sea-Bird Electronics, Inc. model 41-CP CTD package to measure temperature, conductivity and pressure at 1 Hz resolution as the instrument profiles the water column. Temperature measurements using the 41-CP are accurate to 0.002°C, and the conductivity sensor has an accuracy of 0.002 (equivalent salinity). Pressure is accurate to within 2 dbar. The instrument demonstrates good stability and is suitable for long deployments with little measurement drift. Some ITP drifters also include a dissolved oxygen sensor, the SBE-43, which is accurate to 2% of saturation (Sea-Bird Electronics Inc., 2018). Also included on select ITP drifters is a Seapoint fluorometer to measure chlorophyll (Seapoint Sensors Inc., 2013). Depending on the water depth, the drifters may take up to 6 profiles per day (Krishfield, 2008). ITM instruments are outfitted with Sea-Bird SBE37-SIP microCATs, which have temperature sensors accurate to ±0.002 ºC, conductivity sensors accurate to ±0.0003 S/m, and pressure sensors accurate to ±0.1% of the range (Sea-Bird Electronics Inc, 2018).

10.3 DRB PROFILE DISTRIBUTIONS

There are data from 227,871 drifting buoy casts in WOD18, which were submitted by five major research programs. The majority of DRB data came from the Ice-Tethered Profiler program, which contributed 93,750 profiles, and surface drifters equipped with thermistor chains via GTSPP data system (82,427 casts). JAMSTEC provided 40,450 casts from J-CAD buoys, the Arctic Ocean Buoy Program (AOPB) submitted 8,240 profiles, and the P.P Shirshov Institute of Oceanology, Russian Academy of Sciences submitted 11,243 casts from the PAICEX project (see Figure 10.1).

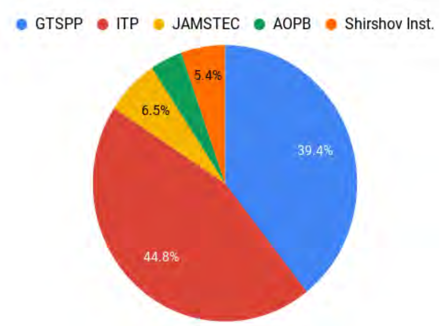

Figure 10.1. Distribution of the Drifting Buoy data in WOD18 among major research programs

The geographic distribution of the DRB casts is illustrated in Figure 10.2a (Global Ocean) and 10.2b (North Polar Area from 50°N). The majority of the DRB casts distributed in the northern hemisphere in Pacific, Atlantic and Arctic oceans, and small amount found in the Southern Ocean. There are also profiles from the Mediterranean Sea, Persian Gulf and Red Sea as well as the northern Indian Ocean, but they are only a minor part of the global DRB profiles 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 WOD18. The total number of profiles = 227,871

YEARS	CASTS	YEARS	CASTS	YEARS	CASTS	YEARS	CASTS	YEARS	CASTS
1985	217	1992	606	1999	4,770	2006	4,655	2013	16,666
1986	482	1993	462	2000	12,611	2007	9,231	2014	12,704
1987	447	1994	532	2001	62,952	2008	7,131	2015	7,077
1988	1,387	1995	0	2002	9,249	2009	12,897	2016	4,444
1989	1,510	1996	0	2003	7,905	2010	5,301	2017	3,341
1990	1,175	1997	0	2004	5,681	2011	6,987		
1991	1,422	1998	3	2005	10,332	2012	14.680		

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

Table 10.2. National contributions of DRB casts in WOD18.

ISO[1] Country Code	Country Name	DRB Casts	% of Total
US	United States	116,600	51.17
FR	France	58,100	25.50
JP	Japan	40,450	17.75
RU	Russian Federation	11,243	4.93
99	Unknown / International	1,477	0.65
AU	Australia	1	<0.01
	Total:	*154,900*	*100.00*

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

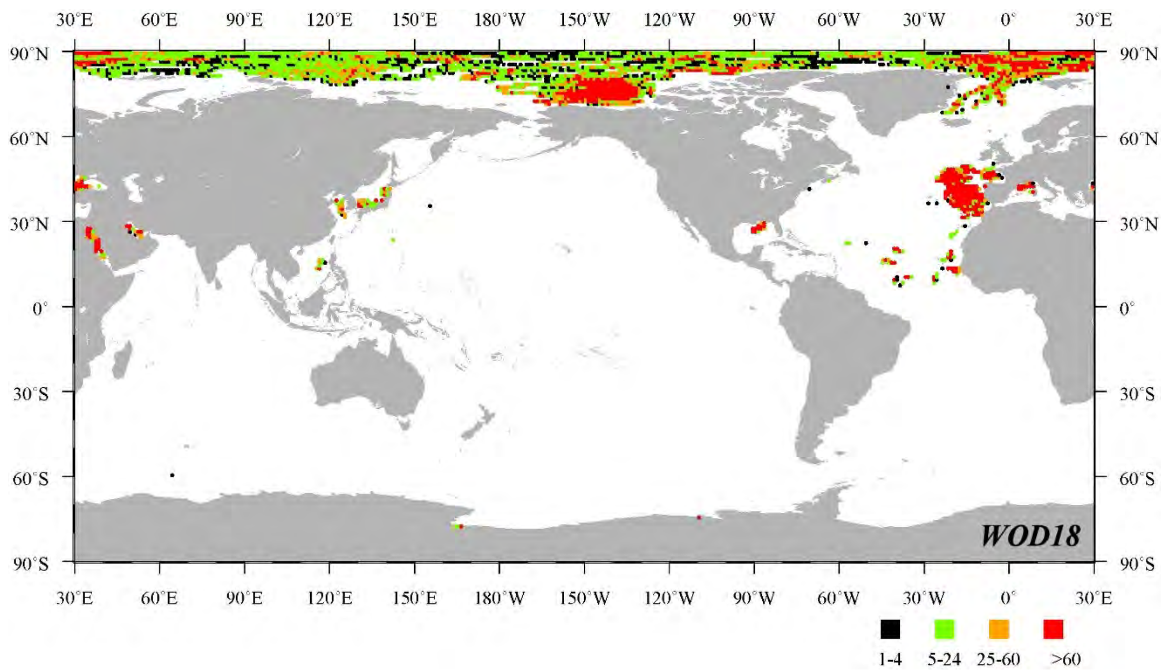

Figure 10.2a. Geographic distribution of the Drifting Buoy (DRB) data (Global Ocean) by one-degree squares in WOD18.

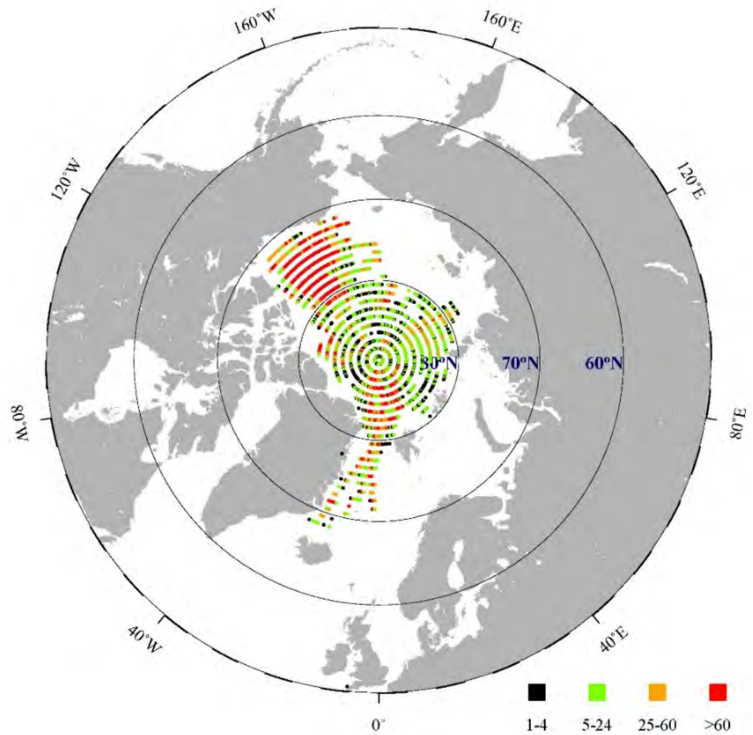

Figure 10.2b. Geographic distribution of the Drifting Buoy (DRB) data (North Polar Area) by one-degree squares in WOD18.

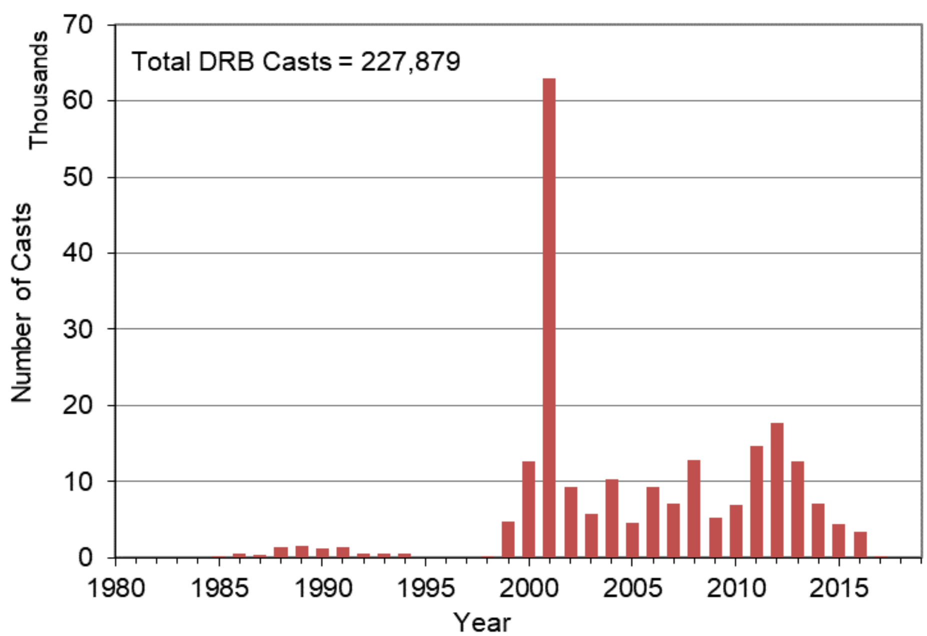

Figure 10.3. Time series of the Drifting Buoy (DRB) casts as a function of year in WOD18.

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

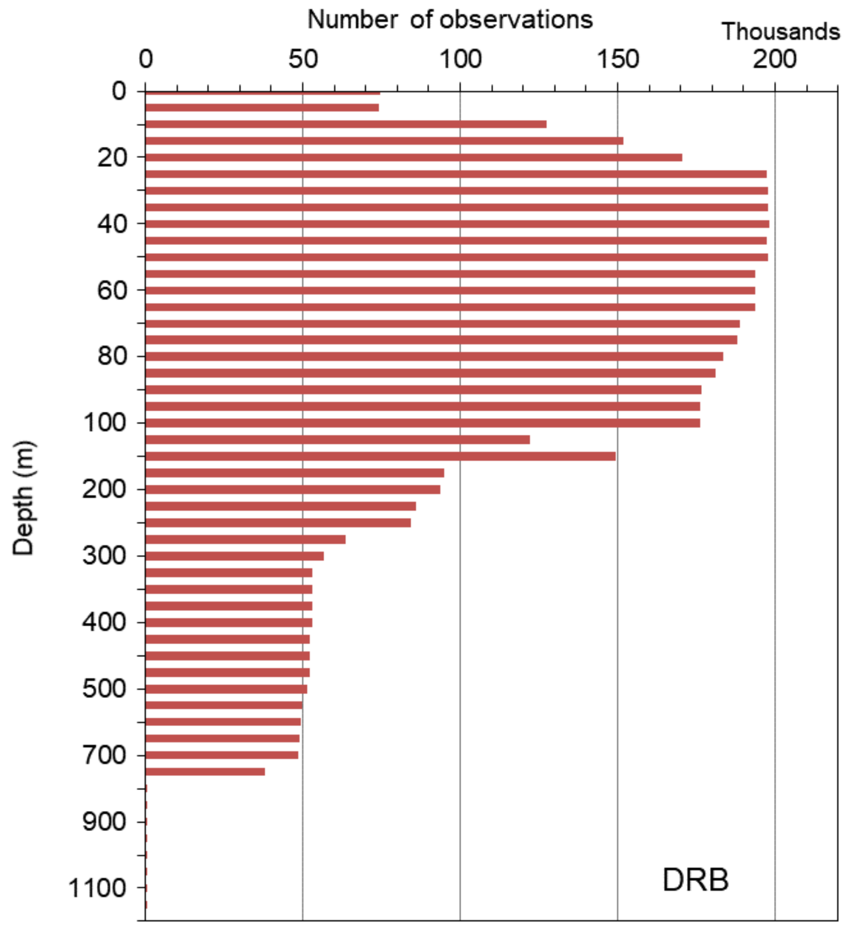

Figure 10.4. Distribution of the Drifting Buoy (DRB) data at standard depth levels in WOD18.

10.4. RELEVANT WEB SITES

DBCP, 2018. Data Buoy Cooperation Panel, Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology, http://www.jcommops.org/dbcp/

GODAR, 2018. https://www.iode.org/index.php?option=com_content&view=article&id=18&Itemid=57

GTS, 2018. The Global Telecommunication System, World Meteorological Organization, https://public.wmo.int/en/programmes/global-telecommunication-system

IABP, 2018. International Arctic Buoy Program, Polar Science Center, Applied Physics Laboratory, University of Washington, Washington, USA, http://iabp.apl.washington.edu and http://iabp.apl.washington.edu/overview_contributions.html

ITP, 2018. Ice-Tethered Profiler, Woods Hole Oceanographic Institution, Massachusetts, USA, http://www.whoi.edu/page.do?pid=20756 .

JAMSTEC, 2018. 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, 2018. Marine Environmental Data Service (MEDS), Department of Fisheries and Oceans, Ontario, Canada, http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/drib-bder/index-eng.html

NDBC, 2018. 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, 2018. The North Pole Environmental Observatory (NPEO) Project, Office of Polar Programs, National Science Foundation, Virginia, USA, http://psc.apl.washington.edu/northpole/index.html.

Sea-Bird Electronics Inc., 2018. http://www.seabird.com.

Seapoint Sensors Inc., 2018. http://www.seapoint.com/scf.htm.

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Morison, J. (Personal Communication, Feb. 2006). Principal Oceanographer, Polar Science Center, Applied Physics Laboratory, U. Washington, Seattle, WA, USA.

Rigor, I.G. and A. Heiberg (1997). International Arctic Buoy Program data report 1. January - 31 December 1995. U. of Washington, Seattle. Applied Physics Laboratory. *Technical memorandum, May 1997*. APL-UW TM 4-97, 173p. + append.

Rigor, I., R. Colony, and S. Martin (2000). Variations in Surface Air Temperature Observations in the Arctic, 1979 - 1997, *J. Clim.*, 13(5): 896-914.

Rigor, I. (2002). IABP 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 RECORDER DATA (UOR)

James R. Reagan, Christopher R. Paver, Tim P. Boyer, Alexey V. Mishonov

Ocean Climate Laboratory
National Centers for Environmental Information
Silver Spring, MD

11.1. INTRODUCTION

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

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

The modern UOR is a self-contained oceanographic sampler which can be towed from research vessels and merchant ships at speeds up to 25 knots. It can be launched and recovered by non-scientist crew members while the vessel is underway. It can be used to carry instrumentation to sample plankton continuously and to measure chlorophyll, radiant energy, temperature, and conductivity, all of which are recorded with depth (Aiken, 1981; Burt, 2000). This technique is often used for large marine ecosystem sampling or frontal zones because of its convenience and uninterrupted data coverage (Williams and Lindley, 1980; 1998; Pollard, 1986) and its ability to sample a large area in a reasonable period of time (Brown *et al.,* 1996). It is also expanding towards a wider set of sensors used, such as light absorption sensors and attenuation meters (Barth and Bogucki, 2000).

The WOD18 UOR dataset consists of temperature, salinity, chlorophyll concentration, pressure, and a small number of oxygen profiles (see Table 11.1 for details) collected by CTD and fluorometer sensors mounted on a SeaSoar-type towed vehicle. The SeaSoar towed vehicle was developed by Chelsea Technologies Group (http://www.chelsea.co.uk) from an original design by the Institute of Oceanographic Sciences (now the Southampton Oceanography Centre, UK). "SeaSoar is capable of undulating from the surface to 500 meters at tow speeds of up to 12 knots (with faired cable) following a controlled and adjustable undulating path through the ocean. Sampled data, obtained from sensors mounted in SeaSoar, are transmitted to the towing vessel for processing, display and storage via a multi-core tow cable" (https://www.chelsea.co.uk/products/marine-science/towed-vehicles/seasoar). For unfaired cable, the depth range is from the surface to 100 meters.

Table 11.1. Profile count for major variables in the WOD18 UOR dataset.

Variables	Profiles
Temperature	127,524
Salinity	125,699
Oxygen	361
Chlorophyll	20,254
Pressure	118,727

Much of the WOD18 UOR data were submitted to NCEI by nine institutions (see Figure 11.1) and collected in the framework of several major international programs (see Figure 11.2) in the Atlantic, Pacific and Indian oceans from 1992 till 2000.

The majority of data (41,485 casts) were collected by the University of Delaware (UD, see Fig. 11.1) during the Delaware Circulation and Dye Experiment (DECADE, see Fig. 11.2). This experiment studied the mixing and secondary circulation in the Delaware River plume. Data were acquired by means of a Scanfish undulating towed vehicle equipped with a Chelsea Ltd. MKIII Aquatracka fluorometer fitted to a Sea Bird SBE-911 CTD (Houghton *et al.*, 2004).

Oregon State University (OSU, Corvallis, OR) has submitted 26,854 UOR casts to NCEI, of which 20,026 casts were taken as part of the international research program "Tropical Ocean Global Atmosphere/ Coupled Ocean Atmosphere Response Experiment" (TOGA/COARE).

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, all of which were a part of the 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 the ~155°E line in 1992 - 1993 (for further details see the TOGA/COARE website at http://www.soest.hawaii.edu/COARE/index.html).A substantial amount of data was provided by the NOAA National Marine Fisheries Service (NMFS) in Seattle, WA, which contributed 9,054 casts measured along the Oregon coast.

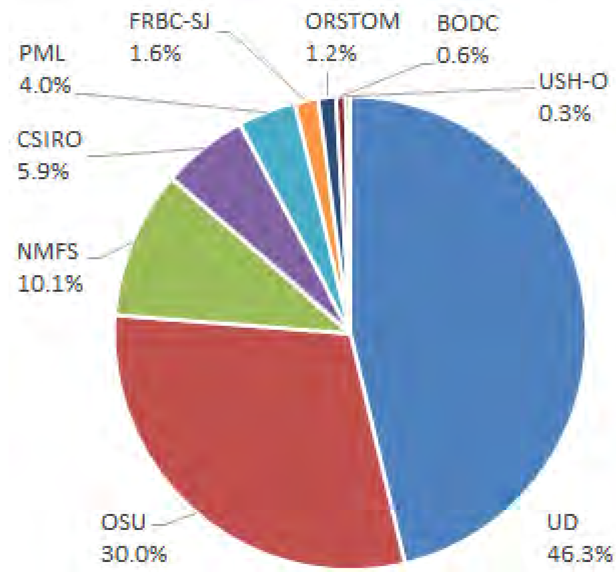

Figure 11.1. Distribution of the UOR data in WOD18 among the known contributing institutions

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

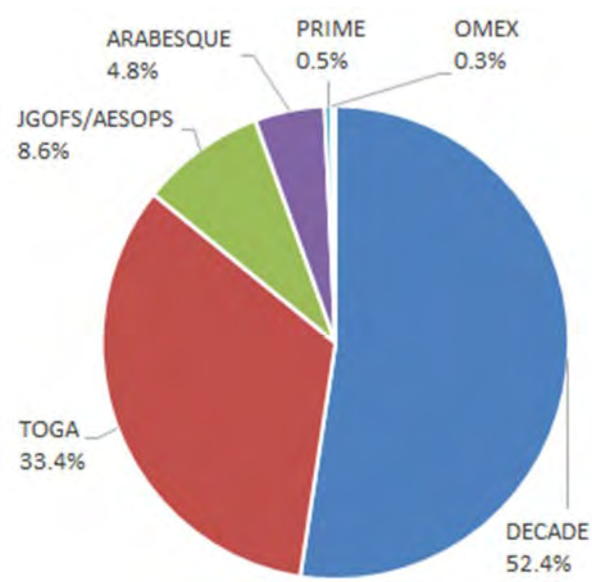

Figure 11.2. Distribution of the UOR data in WOD18 among the known contributing projects

During the U.K. ARABESQUE project in 1994, 3,829 casts were collected in the Indian Ocean by groups from the Plymouth Marine Laboratory (PML, U.K.: 3553 casts) and the

University of Southampton – Department of Oceanography (USH-O, U.K.: 276 casts). The ARABESQUE project aimed to understand the microbial biogeochemistry in the upper ocean of the Arabian Sea. Its focus was to understand how the cycling processes of carbon and nitrogen were linked to climate change. The field program was timed to coincide with the Southwest Monsoon. It also continued from the inter-monsoon period until 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 thematic project funded by the National Environment Research Council of UK (NERC) to study plankton's role in oceanic biogeochemical fluxes. The PRIME data included in WOD18 were collected in the northeast Atlantic in 1996 (http://www.bodc.ac.uk/products/bodc_products/prime/).

BODC also submitted Ocean Margin Exchange (OMEX) project data (218 casts). The aim of the OMEX project was to study, observe, and model the physical, chemical and biological processes and fluxes taking place along the ocean margin, the interface between the open ocean, and the continental shelf. The first phase of the project, OMEX I, concentrated on studying the processes taking place along the northwest European shelf break. (http://www.bodc.ac.uk/products/bodc_products/omex_1/).

More recently (2012), the Fisheries and Oceans Canada – Marine Environmental Data Section (MEDS) submitted 32,937 UOR casts to NCEI, which are new to WOD18. Much of this data is off of the Northeast coast of North America (see Fig. 11.5). This data complements historical data from the Fisheries Research Board of Canada Biological Station in St. John, Newfoundland (FRBC-SJ: 1,439 casts).

It should be noted that the current UOR data holdings in WOD18 is not exhaustive. There exists a substantial amount of UOR data up to the present day that has not been submitted to the National Centers for Environmental Information and is therefore not included in WOD18. If and when the data is submitted to NCEI, the data will then be added to WOD.

11.2. UOR DATA PRECISION AND ACCURACY

The accuracy of UOR data depends on the performance of the sensors used and the post-processing of the data. A SeaSoar undulating vehicle is capable of carrying various instrumental packages. For the data stored in the WOD18 database, the Sea-Bird Electronics SBE 911*plus* CTD instrument was used most often. Please see section 3.2 for CTD accuracy information. It is presumed that UOR data submitted into WOD18 were corrected for effects of: a) variable flow rate (Huyer *et al.,* 1993), b) thermal mass (Lueck, 1990; Morrison *et al.,* 1993), and c) offset between temperature and conductivity data (Larson, 1992; Morrison *et al.,* 1993).

11.3. UOR PROFILE DISTRIBUTIONS

Table 11.2 gives the yearly counts of UOR casts for the World Ocean and Figure 11.3 illustrates this graphically.

Table 11.2. The number of all UOR casts as a function of year in WOD18.
Total number of casts = 127,544

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1976	1	1986	6	1996	2,286	2006	1,385
1977	0	1987	2	1997	8,254	2007	660
1978	0	1988	35	1998	1,429	2008	1,315
1979	0	1989	257	1999	1,634	2009	1,359
1980	0	1990	1,407	2000	10,344	2010	1,232
1981	0	1991	2,387	2001	1,299	2011	1,229
1982	4	1992	13,909	2002	1,391	2012	1,439
1983	1	1993	18,606	2003	4,043	2013	0
1984	2	1994	8,383	2004	39,961	2014	0
1985	0	1995	1,933	2005	1,331	2015	0

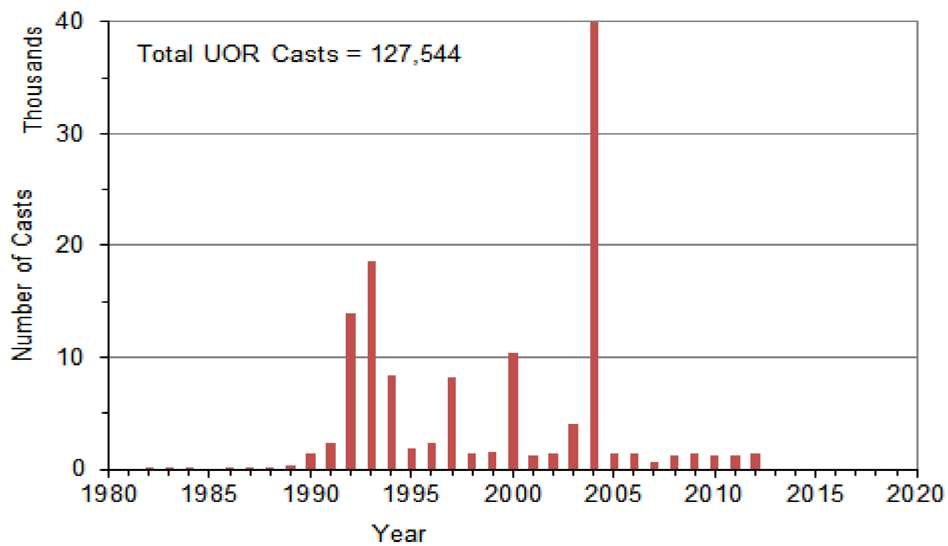

Figure 11.3. Temporal distribution of Undulating Ocean Recorders (UOR) casts in WOD18.

Table 11.3 gives the numerical and percentage contribution from various countries to the UOR dataset (also shown graphically in Figure 11.4). The geographic distribution of UOR casts is shown in Figure 11.5. Much of the data is localized and related to the projects discussed in section 11.1. Figure 11.6 illustrates the distribution of the UOR data as a function of depth at observed depth levels.

Table 11.3. National contributions of UOR casts in WOD18.

ISO[1] Country Code	Country Name	UOR Casts	% of Total
US	United States	77,393	60.68
CA	Canada	34,255	26.86
AU	Australia	5,597	4.39
EE	Estonia	4,650	3.64
GB	United Kingdom	4,410	3.46
FR	France	1,118	0.88
99	Unknown	121	0.09
	Total	*127,544*	*100.00*

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

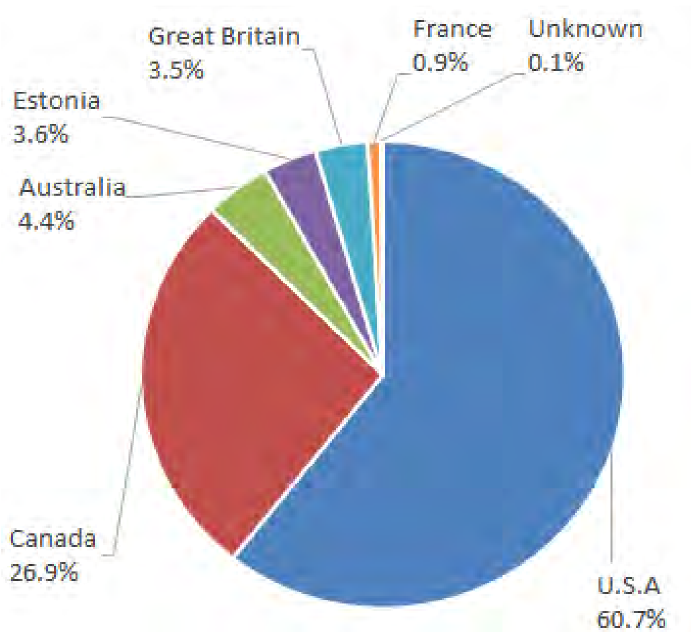

Figure 11.4. Distribution of the Undulating Ocean Recorders (UOR) data in WOD18 among the contributing countries.

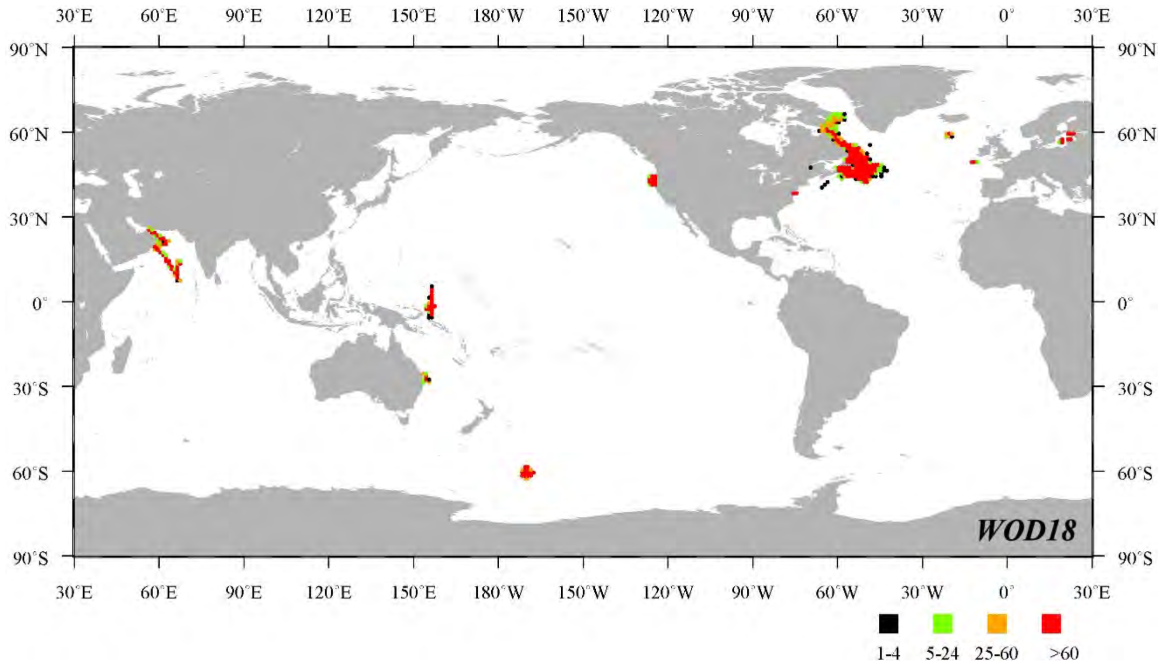

Figure 11.5. Geographic distribution of Undulating Ocean Recorders (UOR) casts in WOD18 by one-degree squares.

11.4. RELEVANT WEB SITES

ARABESQUE Project: http://www.bodc.ac.uk/products/bodc_products/arabesque/

Australian Commonwealth Scientific and Industrial Research Organization (CSIRO): http://www.csiro.au

Chelsea Technologies Group: https://www.chelsea.co.uk/products/marine-science/towed-vehicles

College of Oceanic and Atmospheric Sciences at Oregon State University, Corvallis, OR: http://ceoas.oregonstate.edu/

JGOFS-AESOPS: http://usjgofs.whoi.edu/jg/dir/jgofs/southern/rr-kiwi_6/

Ocean Margin Exchange (OMEX): http://www.bodc.ac.uk/omex/

Plankton Reactivity in the Marine Environment (PRIME): http://www.bodc.ac.uk/projects/uk/prime/

Plymouth Marine Laboratory: http://www.pml.ac.uk/

Tropical Ocean Global Atmosphere/Coupled Ocean Atmosphere Response Experiment (TOGA-COARE):
http://gcmd.nasa.gov/records/GCMD_COARE_ocmix_seasoar.html;
http://www.soest.hawaii.edu/COARE/

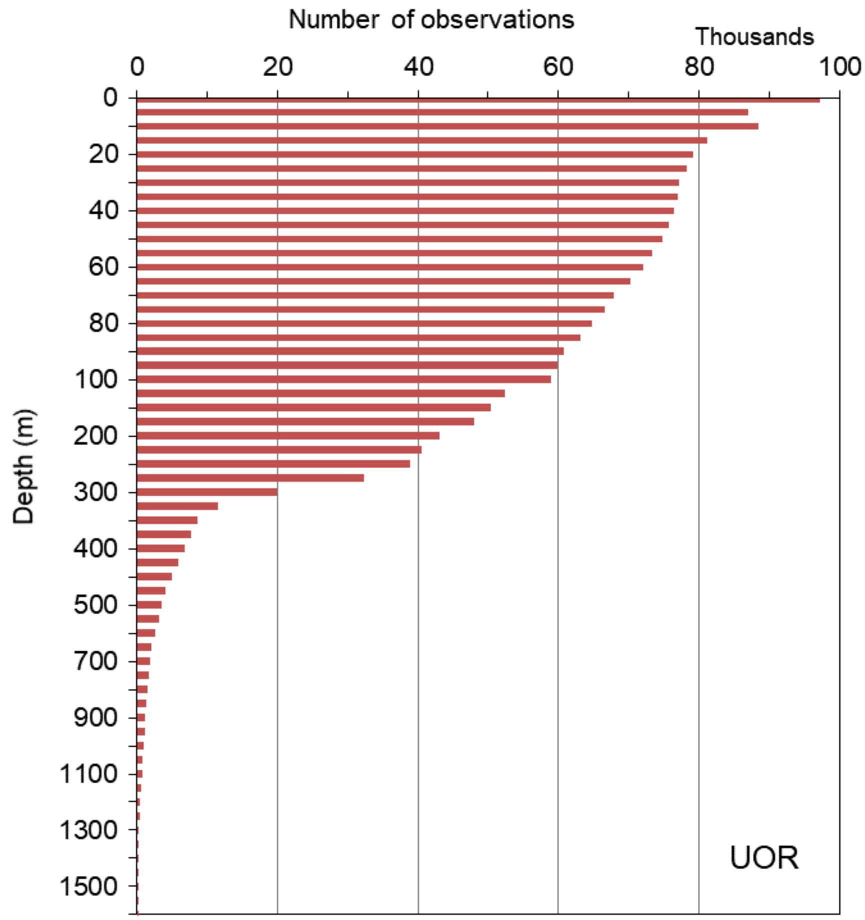

Figure 11.6. Distribution of Undulating Ocean Recorders (UOR) data at standard depth levels in WOD18.

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CHAPTER 12: AUTONOMOUS PINNIPED BATHYTHERMOGRAPH DATA (APB)

Melissa M. Zweng, Olga K. Baranova, Tim P. Boyer, Ricardo A. Locarnini,
Alexey V. Mishonov, Dan Seidov

Ocean Climate Laboratory
National Centers for Environmental Information
Silver Spring, MD

12.1. INTRODUCTION

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

Data from sensor instruments attached to marine animals (instrumented animals) such as sea turtles, sea birds, sharks, tuna, and marine mammals, were initially collected for the principal purpose of studying animal ecology (Le Bœuf *et al.*, 1988; Block, 2005). In addition to animal ecology studies, scientists can use instrumented animals as autonomous ocean profilers to enhance sparse oceanographic observations in specific oceanic regions (McCafferty *et al.,* 1999; Boehlert *et al.,* 2001; Charrassin *et al.*, 2002; Lydersen *et al.*, 2002; Hooker and Boyd, 2003; Fedak, 2004; Ropert-Coudert and Wilson, 2005; Roquet *et al.*, 2009; Padman *et al.*, 2010). The data supplied by instrumented animals could potentially fill data gaps due to harsh environmental conditions in areas such as the Bering Sea, Gulf of Alaska, and the Southern Ocean, especially in winter and in ice-covered waters. These data can also help fill spatial and temporal gaps due to remoteness of some areas such as the southeast Pacific, and spatial gaps between routes of Ships-of-Opportunity (or Voluntary Observing Ships, VOS). The use of instrumented marine animal data has been shown to improve state estimates of under-sampled regions like the Southern Ocean (Roquet et al, 2013).

Temperature profiles from instrumented animals are less expensive than those obtained by traditional instruments such as Expendable Bathythermographs (XBT) (Boehlert *et al.,* 2001). After recovering instruments from animals, the equipment can be re-used. The vertical resolution of the available pinniped data is better than the vertical resolution of bottle station data but generally worse than the resolution of XBT and Conductivity-Temperature-Depth (CTD) data.

The Autonomous Pinniped Bathythermograph (APB) dataset presented in the WOD18 contains *in situ* temperature data from temperature-depth records (TDRs) and conductivity-temperature-depth satellite relay data loggers (CTD-SRDLs) attached to pinnipeds (*e.g.*, elephant seals). The instrumented animals include northern elephant seals (*Mirounga* *angustirostris*), southern elephant seals (*Mirounga leonina*), Weddell seals (*Leptonychotes weddellii*) and narwhals (*Monodon monoceros*).

12.2. DATA SOURCES

The APB data that comprise WOD18 have been acquired through different sources and projects. Table 12.1 shows the contributing projects and number of casts submitted. 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 animal's head using epoxy. The antenna was oriented to be out of the water when the seal surfaced. The PTT transmitted every 34 seconds while the seals were at the surface (Boehlert *et al.,* 2001).

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

The Marine Animals Exploring Pole to Pole (MEOP) consortium, a collaboration of scientists from many countries who work on instrumented marine animals, serves as a Data Assembly Center for instrumented marine animal data. They combine global data from national observing programs (Australia, Brazil, Canada, China, Denmark, France, Germany, Norway, South Africa, Sweden, the United Kingdom, and the USA) and periodically release a quality-controlled database. They also release best practices for collection and data formats and maintain documentation and links to publications that feature the data.

NCEI also received some IMOS, SMRU and SEaOS data in near-real time through the Global Temperature-Salinity Profile Program (GTSPP) system.

The Global Temperature-Salinity Profile Program (GTSPP) system provides NCEI with most near-real time APB profiles. Some programs provide delayed-mode profiles later and WOD replaces the near-real time data when post-processed versions are available. About 105,000 profiles are still near-real time versions from GTSPP.

12.3. INSTRUMENTATION

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

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

Table 12.1. Projects contributing to the WOD18 APB dataset and number or profiles submitted.

Project	Number of casts
Autonomous Pinniped Environmental Samplers (APES)	75,665
Southern Elephant Seals Oceanographic Samplers (SEAOS)	2,129
Integrated Marine Observing System (IMOS)	140,869
Marine Mammals Exploring the Oceans Pole to Pole (MEOP)	330,350
Tagging of Pacific Predators (TOPP)	1,171,943

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

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

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

12.4. GEOGRAPHICAL AND DEPTH DISTRIBUTION OF DATA

The WOD18 has a total of 1,804,605 APB vertical profiles collected between 1997 and 2017 (Table 12.2). Figure 12.1 shows the geographic distribution of the dataset, and Figure 12.2 shows depth distribution of the entire data set.

Table 12.2. The number of all APB casts as a function of year in WOD18. Total number of casts =1,804,605

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1997	19,875	2003	0	2008	254,145	2013	25,307
1998	44,626	2004	162,219	2009	127,882	2014	44,226
1999	11,164	2005	346,045	2010	165,137	2015	30,665
2000	0	2006	137,722	2011	60,602	2016	32,020
2001	0	2007	260,772	2012	51,589	2017	26,070
2002	0						

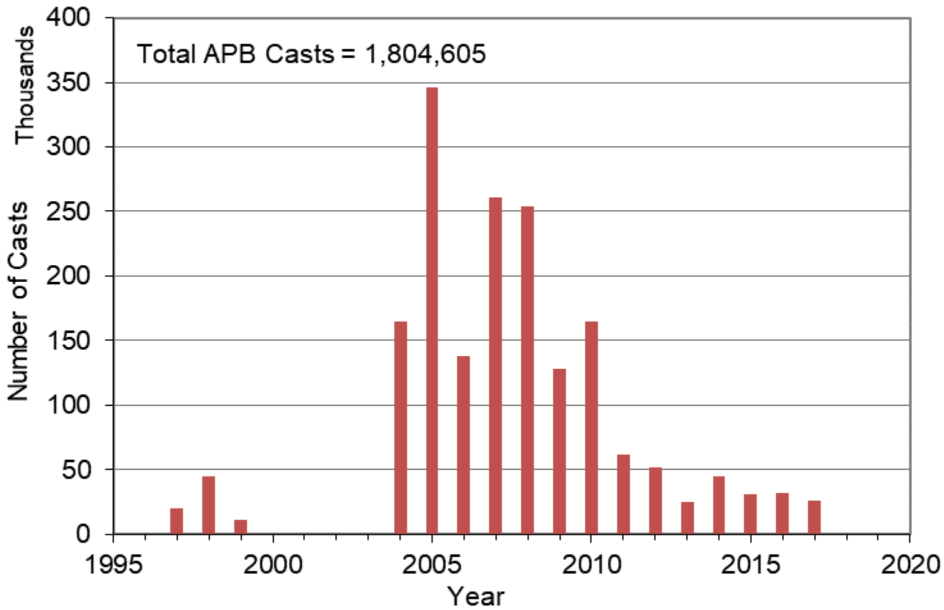

Figure 12.1. Temporal distribution of APB casts in WOD18.

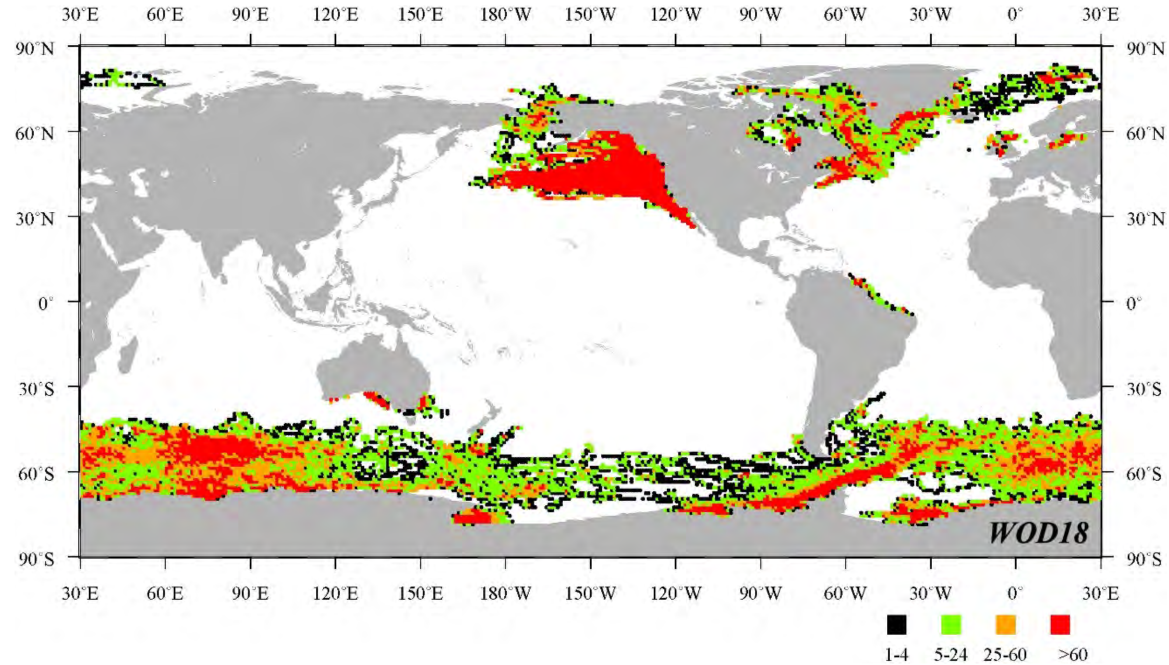

Figure 12.2. Geographical distribution of the Autonomous Pinniped Bathythermograph (APB) data in WOD18 by one-degree squares.

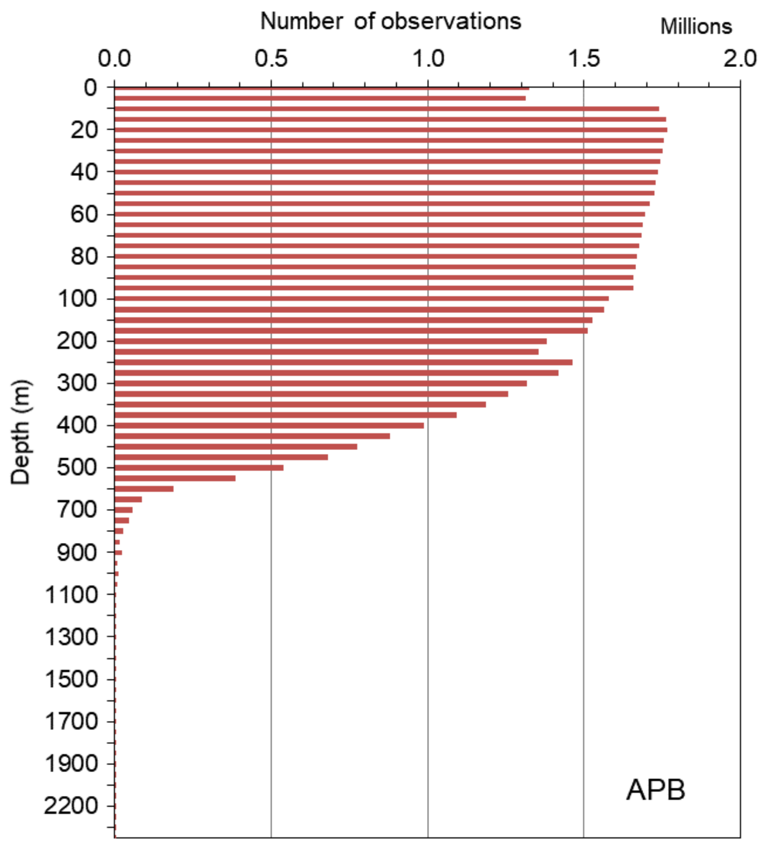

Figure 12.2. Distribution of the Autonomous Pinniped Bathythermograph (APB) data at standard depth levels in WOD18.

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CHAPTER 13: MICRO BATHYTHERMOGRAPH DATA (MICRO BT)

Igor V. Smolyar, Alexey V. Mishonov, Tim P. Boyer, Ricardo A. Locarnini

Ocean Climate Laboratory
National Centers for Environmental Information
Silver Spring, MD

13.1. INTRODUCTION

The Micro Bathythermograph (Micro BT) is a high-accuracy temperature and pressure instrument developed to record and report data electronically. WOD18 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 WOD18.

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 11,136 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 WOD18.
Total Number of Profiles = 11,136

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1992	5,659	1995	642	1998	478	2001	653
1993	354	1996	528	1999	556	2002	643
1994	314	1997	504	2000	662	2003	143

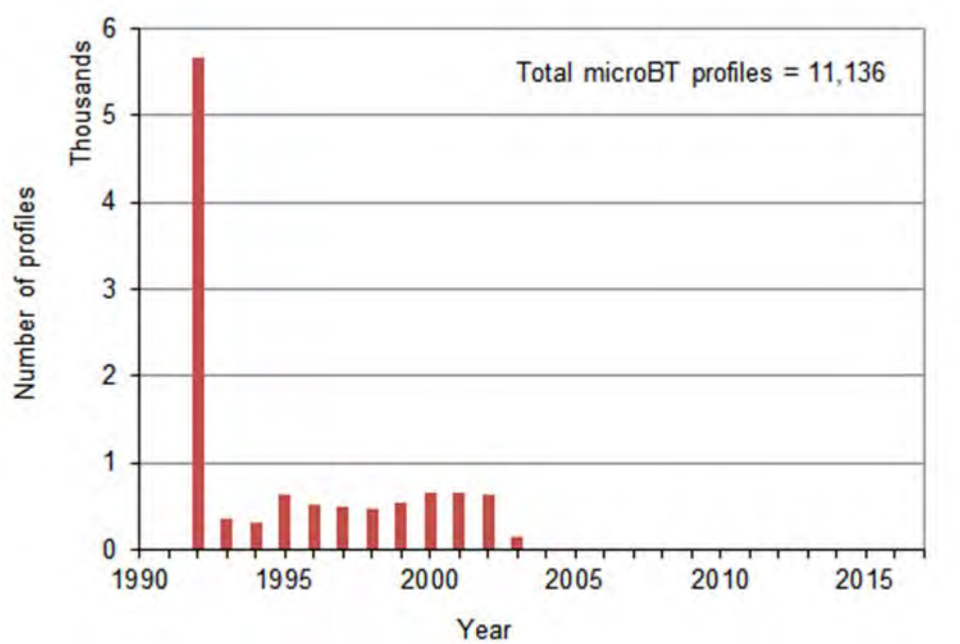

Figure 13.1. Temporal distribution of micro Bathythermograph data in WOD18.

Table 13.2. National contributions of Micro Bathythermograph profiles in WOD18.

ISO[1] Country Code	Country Name	Micro BT Count	% of Total
US	United States	11,136	100.0

[1] ISO = International Organization for Standardization

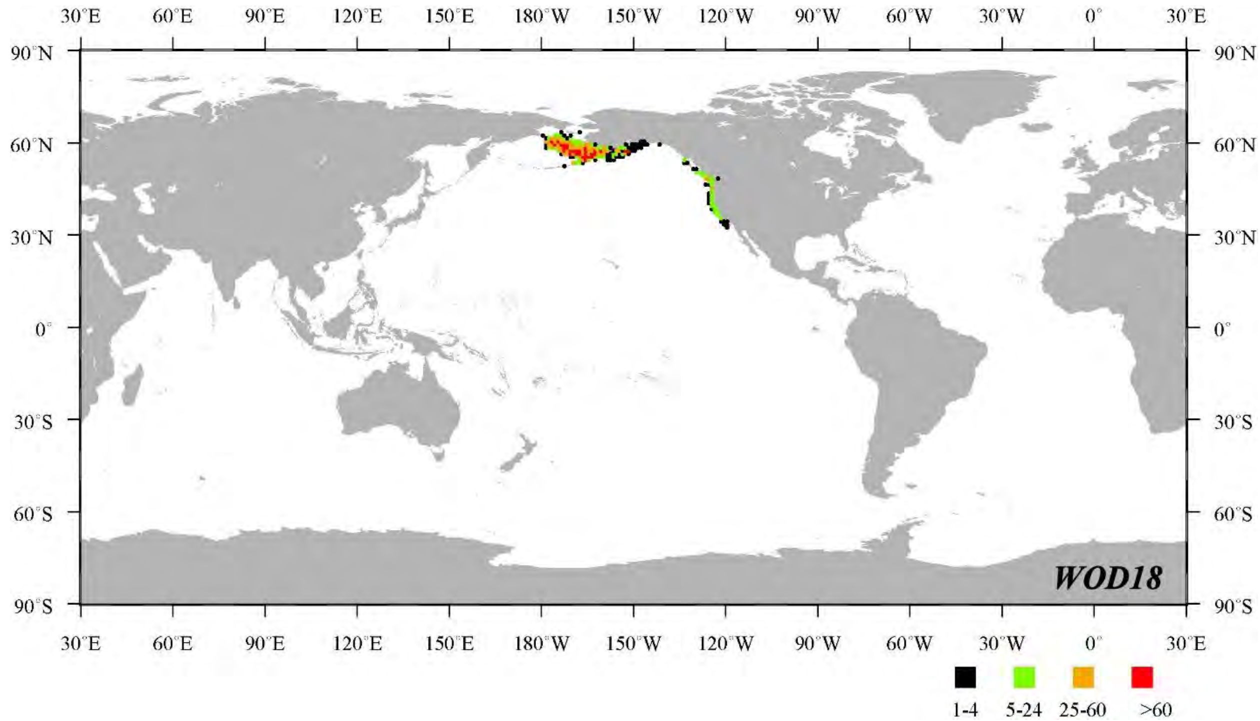

Figure 13.2. Geographic distribution of Micro Bathythermograph data in WOD18.

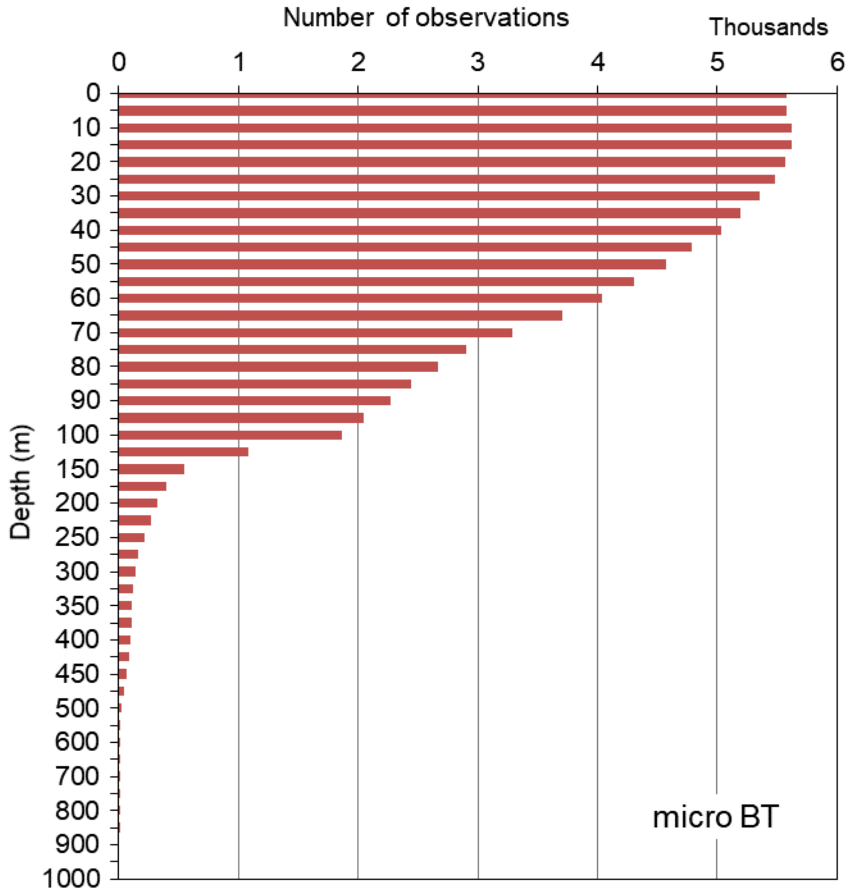

Figure 13.3. Distribution of micro Bathythermograph data at standard depth levels in WOD18.

CHAPTER 14: SURFACE-ONLY DATA (SUR)

James R. Reagan, Igor V. Smolyar, Tim P. Boyer, Alexey V. Mishonov

Ocean Climate Laboratory
National Centers for Environmental Information
Silver Spring, MD

14.1. INTRODUCTION

The major focus of the WOD18 is sub-surface profile data. Therefore, surface data are included in WOD18 only if they were collected together with measurements of oceanographic variables of interest (*e.g.,* chlorophyll, CO_2, pH, etc.; see Table 14.1), or if the data cover under-sampled time periods (*e.g.,* ICES Atlantic data for 1900-1939), or data provided by scientific ship-of-opportunity (SOOP) programs. For example, WOD18 contains many observations from the Institut de Recherche et Développement (IRD), formerly ORSTOM, which provided NCEI with surface salinity data from SOOP for the Tropical Pacific (Henin and Grelet, 1996). It should be noted that surface-only data oriented projects exist, which hold much more comprehensive surface data collections than WOD18. For example, the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) contains more than 455 million individual marine reports (Freeman *et al.,* 2017) and the NCEI-Thermosalinographs Database contains over 310 million (temperature and/or salinity) observations (Z. Wang, 2018). The majority of the SUR data in WOD are salinity, temperature, and mole fraction of CO_2 in seawater (Table 14.1). Table 14.2 lists the number of SUR observations as a function of year of collection since 1867.

14.2. DATA PRECISION

Samples of the sea water may have been collected from the continuous flow of water pumped from subsurface depths (*e.g.,* ship's water intake) or have been drawn from a bucket. A comprehensive review of the sampling techniques and its influence on the collected data precision can be found in Reverdin *et al.* (1994). When data came from bucket samples, the precision of the sea surface salinity is believed to be about ±0.1 (Delcroix and Picaut, 1998; Delcroix *et al.,* 2005). When data were collected by Thermosalinograph (TSG), sea surface salinity and temperature readings were recorded approximately every 10 seconds (Thomas *et al.,* 1999). Data precision of more modern measurements is limited by the characteristics of the instrument (Delcroix *et al.,* 2005). The accuracy of a Sea-Bird SBE 45 MicroTSG (example of a modern day TSG) is ±0.002°C for temperature and ±0.005 for salinity (see: https://www.seabird.com/sbe45-microtsg-thermosalinograph/product?id=54627900541).

Table 14.1. List of parameters and number of observations in the SUR dataset of WOD18.

Parameter [nominal abbreviation]	Reporting unit (nominal abbreviation)	Number of observations
Temperature [t]	Degree centigrade (°C)	506,062
Salinity [S]	Unit less	1,958,361
pH	Unit less	84
Total Chlorophyll [Chl] unless specified	Micro-gram per liter ($\mu g \cdot l^{-1}$)	44,256
Phaeophytin	Micro-gram per liter ($\mu g \cdot l^{-1}$)	119
Primary Production	Micro-gram of Carbon per liter-day ($\mu gC \cdot l^{-1} \cdot day^{-1}$)	119
Alkalinity [TALK]	Milli-equivalent per liter ($meq \cdot l^{-1}$)	84
Partial Pressure of Carbon Dioxide [pCO_2]	Micro-atmosphere (µatm)	37,124
Mole fraction of CO_2 in seawater [XCO_2sea]	Parts per million (ppm)	132,793
Conductivity	Siemens per meter ($S \cdot m^{-1}$)	52,284
CO_2warm [1]	Degree centigrade (°C)	60,262
Mole fraction of CO_2 in atmosphere [XCO_2atm]	Parts per million (ppm)	169,469
Barometric pressure	Milllibar (mb)	164,881
Latitude	Degrees of latitude	2,098,020
Longitude	Degrees of longitude	2,098,020
Julian Day	Day	2,098,020

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

14.3. DATA COVERAGE

The earliest surface temperature data included in WOD18 were collected in 1867 by Norwegian sailors from the ships *Isbjornen* and *Ishavet* in the North Sea, Norwegian Sea, and in the North Atlantic waters around Iceland (Table 14.2). SUR data were routinely collected in the 19th century (Figure 14.1), but most of the SUR data were collected after the late 1990s (Figure 14.1). This SUR dataset consists of 9,257 cruises (Figure 14.2). Surface data collected before 1955 were often bucket samples, data acquired after 1957 were, most often, from thermosalinographs (TSG) and other underway systems.

There are noticeable data gaps after the First World War (1914-1918) and during and after the Second World War (1939-1945). A large increase in surface data (mainly SST and sea surface salinity measurements) occurred in the 1990s. These data were mainly acquired by the TSG instruments mounted on ships-of-opportunity. Data collected over that period contains more than 70% of the entire SUR dataset with almost all data being collected along shipping routes in the Pacific Ocean (Figure 14.2). The major country contributions to the SUR dataset are France (41.8% of all SUR data) and Australia (32.5%). Unlike many other datasets in WOD where temperature dominates the data distribution, salinity dominates the data distribution in SUR (Table 14.1). This is due to many salinity-only data contributions (1,589,463 observations) from the Oceanic Lab of the Institution of French Oceania (Noumea, New Caledonia) during the 1969-1999 time period.

Table 14.3 lists the input of data to the SUR dataset by country of origin. Figure 14.2 shows that the majority of SUR data were collected along the main commercial shipping routes of the Atlantic and Pacific Oceans. In terms of volume of data, about 87% of the observations in SUR were acquired from two main sources: International Council for the Exploration of the Sea (ICES) and the Oceanic Lab of the Institution of French Oceania (Noumea, New Caledonia). The remaining 13% came from the National Institute of Oceanography in India, Scripps Institution of Oceanography, National Institute for Environmental Studies, Institute of Ocean Sciences, Sidney, Australia, the Office of Scientific and Technical Research Overseas (ORSTOM) - New Caledonia (before independence), and several others.

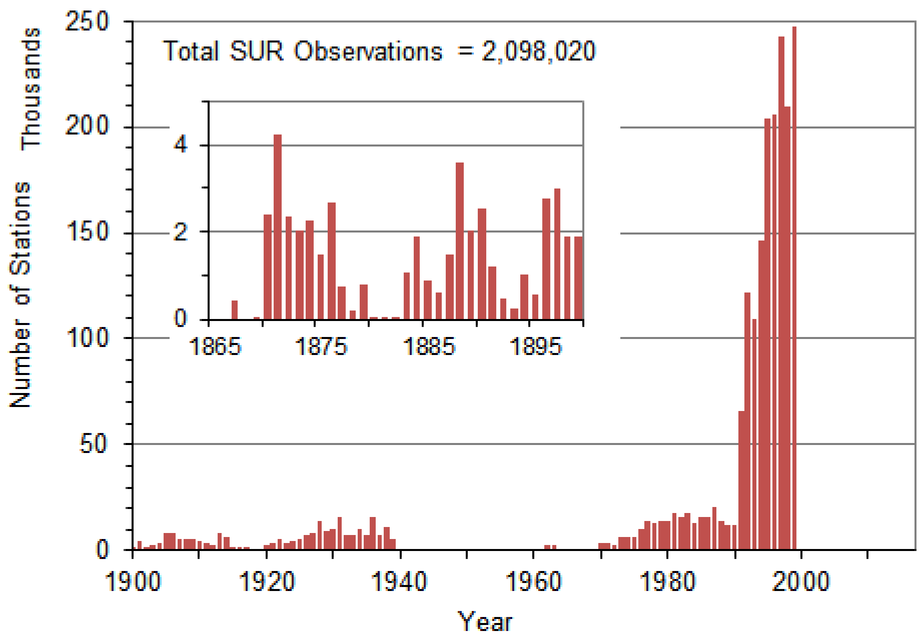

Figure 14.1. Temporal distribution of surface (SUR) observations in WOD18.

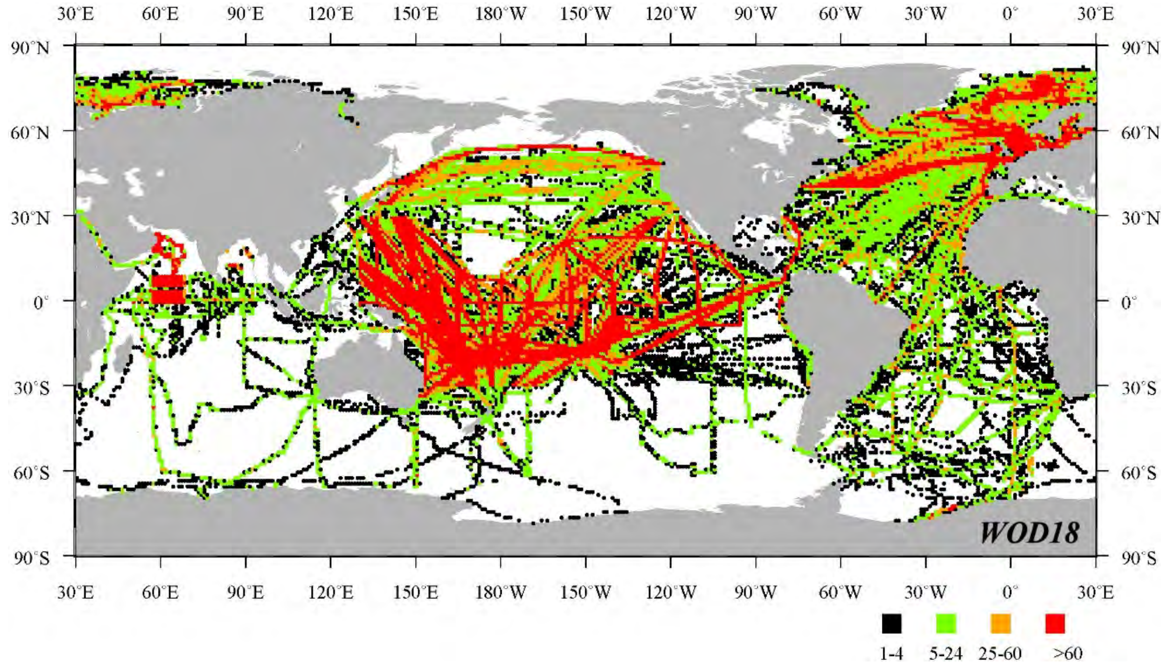

Figure 14.2. Geographic distribution of surface (SUR) observations by one-degree squares in WOD18.

Table 14.2. The number of all SUR observations as a function of year in WOD18.

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

YEAR	COUNT	YEAR	COUNT	YEAR	COUNT	YEAR	COUNT
1867	398	1903	2,242	1939	5,745	1975	6,571
1868	0	1904	3,695	1940	48	1976	10,402
1869	44	1905	8,621	1941	0	1977	13,719
1870	2,421	1906	7,897	1942	0	1978	13,018
1871	4,261	1907	5,781	1943	0	1979	14,033
1872	2,366	1908	5,170	1944	0	1980	13,950
1873	2,029	1909	5,557	1945	0	1981	17,897
1874	2,240	1910	4,502	1946	0	1982	15,412
1875	1,480	1911	3,585	1947	0	1983	17,411
1876	2,691	1912	2,478	1948	0	1984	12,643
1877	725	1913	7,881	1949	0	1985	15,480
1878	187	1914	5,961	1950	0	1986	16,250
1879	780	1915	1,882	1951	0	1987	20,553
1880	68	1916	1,753	1952	26	1988	14,288
1881	41	1917	1,659	1953	22	1989	12,022
1882	15	1918	55	1954	0	1990	11,975
1883	1,075	1919	113	1955	0	1991	66,242
1884	1,884	1920	2,838	1956	0	1992	122,114
1885	861	1921	3,702	1957	839	1993	109,400
1886	601	1922	5,532	1958	0	1994	146,742
1887	1,475	1923	3,945	1959	0	1995	204,435
1888	3,589	1924	4,150	1960	0	1996	206,211
1889	2,013	1925	5,666	1961	555	1997	242,401
1890	2,523	1926	7,143	1962	2,961	1998	209,981
1891	1,197	1927	8,633	1963	2,972	1999	247,364
1892	468	1928	13,579	1964	0	2000	0
1893	214	1929	8,935	1965	0	2001	0
1894	1,003	1930	9,921	1966	0	2002	0
1895	570	1931	15,847	1967	0	2003	0
1896	2,777	1932	6,975	1968	0	2004	0
1897	3,005	1933	7,590	1969	767	2005	0
1898	1,885	1934	10,173	1970	3,159	2006	79
1899	1,885	1935	7,355	1971	3,126	2007	213
1900	1,975	1936	16,058	1972	2,791	2008	196
1901	4,820	1937	7,488	1973	6,504	2009	734
1902	1,294	1938	10,858	1974	6,422	2010	267

Table 14.3. National contributions of observations, and number of cruises by country of origin in the SUR dataset in WOD18.

ISO[1] Country Codes	Country Name	Number of Cruises	Number of Observations	% of Total
FR	France	3,272	876,382	41.77
AU	Australia	85	681,879	32.50
	Unknown	3,378	161,543	7.70
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
FI	Finland	18	2,593	0.12
IN	India	111	1,537	0.07
NL	Netherlands	21	1,309	0.06
SU	Union of Soviet Socialist Republics	1	1,068	0.05
LV	Latvia	38	1,010	0.05
SE	Sweden	15	710	0.03
BE	Belgium	3	283	0.01
PT	Portugal	9	199	0.01
IE	Ireland	27	164	0.01
EE	Estonia	3	84	0.00
	Total:	*9,257*	*2,098,020*	*100.00*

1. [1] ISO = International Organization for Standardization
2. http://www.iso.org/iso/country_codes.htm

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CHAPTER 15: GLIDER DATA (GLD)

Alexey V. Mishonov, Melissa M. Zweng, Tim P. Boyer, Ricardo A. Locarnini, Dan Seidov

Ocean Climate Laboratory
National Centers for Environmental Information/ NOAA
Silver Spring, MD

15.1. INTRODUCTION

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

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

Gliders are equipped with a Global Positioning System (GPS) navigation to locate the vehicle. A satellite data relay is used to send its position and other data to shore-based computers while the operators program the gliders depth and mission. Modern gliders can reach a maximum depth of 1500 m (Table 15.1). Their battery lifetime ranges from a few weeks to several months. Gliders' speed is typically less than 0.5 $m \cdot s^{-1}$ (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.

Table 15.1. Glider capabilities [1]

Glider	Maximum depth, m	Typical speed, $m \cdot sec^{-1}$	Maximum Range, km	Endurance, days
Seaglider	1000	0.25	4600	270
Slocum:				
Alkaline	1000	0.35	1200	50
Rechargeable	1000	0.35	3000	120
Lithium	1000	0.35	13000	500
Spray	1500	0.25	4700	180

[1] Capabilities above based on standard load packages

15.2. GLIDER DESIGN AND OPERATION

Several types of operational gliders shown in Table 15.1 collected data stored in WOD18. The Seaglider (Eriksen *et al.*, 2001) was developed at the University of Washington (UW). Currently, the UW manufactures Seagliders only for UW employees/students, with iRobot and most recently Kongsberg Underwater Technology Incorporated manufacturing Seagliders for those outside of UW (Kongsberg, 2014). The Slocum gliders (Webb *et al.*, 2001) are manufactured by Teledyne Webb Research Corporation. The Spray gliders (Sherman *et al.*, 2001) were developed at the Scripps Institution of Oceanography (Rudnick *et al.*, 2004) under the guidance of Dr. Russ Davis (http://auvac.org/configurations/view/6). Bluefin Robotics licensed the technology from Scripps in 2004 and is the current manufacturer of Spray gliders. Detailed information on gliders specifications and their functions can be found in Rudnick *et al.* (2004), Eriksen *et al.* (2001), Sherman *et al.* (2001), Webb *et al.* (2001), and at the web links provided below.

These gliders have similar features and functionality that can be illustrated by Seaglider-019 (SG-019) (Eriksen *et al.*, 2001). This seaglider is 1.8 m long, has a wing span of 1 m, 1.4 m antenna mast, and weighs 52 kg (Eriksen *et al.*, 2001). It was designed to operate with pitch angles from 10° to 75°. The vehicle alternately dives and climbs to a commanded depth from the surface down to a maximum depth of 1 km and back to the surface every 3 to 9 hours. It remains at the surface for 5 minutes and during that time the Iridium/GPS antenna is raised above the air-sea surface by pitching the vehicle nose down at 45° (Eriksen *et al.*, 2001; Hines, 2005; Rudnick *et al.*, 2004). The seaglider obtains its GPS fixes, transmits collected data at 180 bytes s^{-1}, relays its position, and receives instructions via the Iridium satellite phone network before diving again (Rudnick *et al.*, 2004). It travels at a speed of 0.25 $m \cdot s^{-1}$, 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 (Hines, 2005).

The Seaglider 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/project/project.php?id=seaglider

Spray gliders are capable to dive to 1500m depth with descent angles exceeding 20° and can conduct over 800 dives along 4000 km long trajectory path (http://auvac.org/configurations/view/6).

Slocum gliders are very versatile platform, which can support over 40 different sensors and can be operated remotely or pre-programmed. Its long endurance allows wide data collection range over extended period of time (http://www.teledynemarine.com/slocum-glider).

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

15.3. GLD PROFILE DISTRIBUTIONS

Figure 15.1 illustrates the geographical distribution of 1,148,669 glider casts in WOD18 collected between 2002 and 2018. Data density is illustrated by different colors indication the amount of the profiles found in single 1°x1° latitude-longitude square.

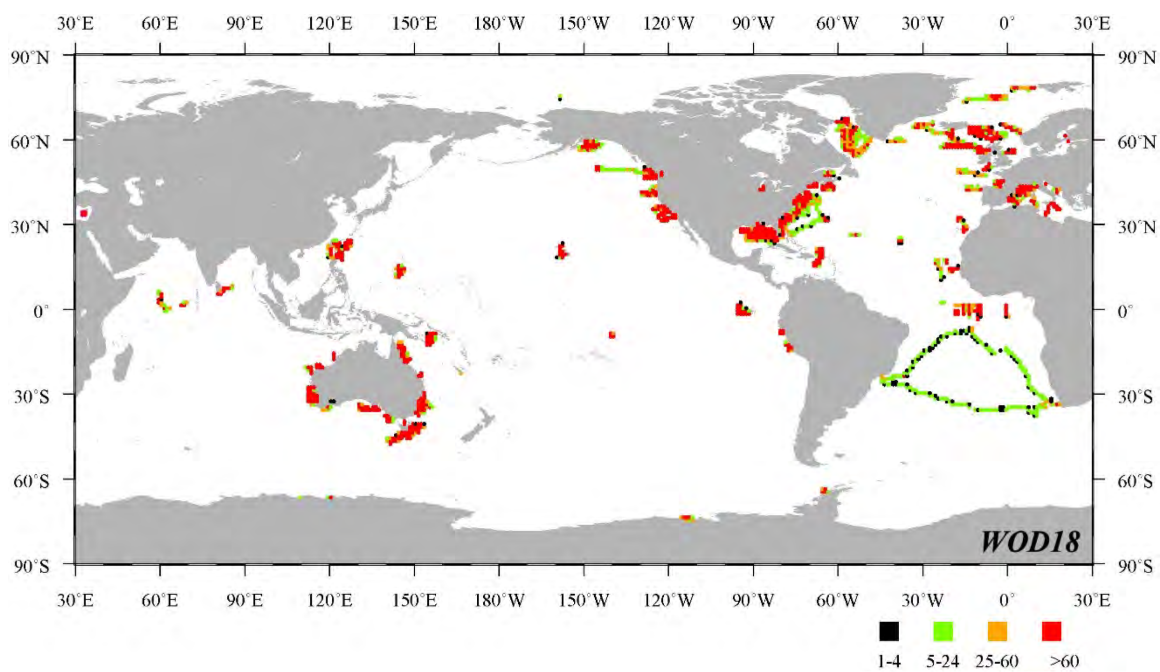

Figure 15.1. Geographical distribution of Glider (GLD) casts in WOD18: number of profiles per 1°square.

Figure 15.2 and Table 15.2 shows the temporal distribution of glider casts in WOD13 over the period of data collection. It should be noted that after initial period of the technology development in 2002-2008, sharp increase in the data collection occurred after 2009 reflects growing interest to the gliders as a convenient and versatile platform for oceanographic research.

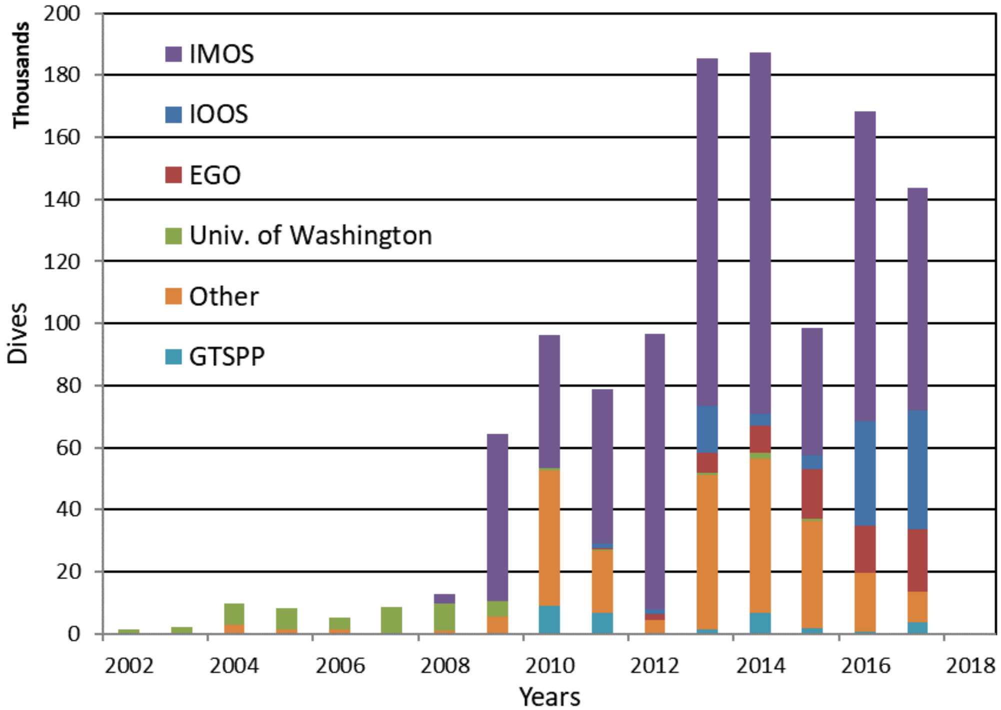

Figure 15.2. Temporal distribution and major sources of Glider (GLD) data in WOD18.

Table 15.2. The number of all Glider (GLD) casts as a function of year in WOD18.

Total Number of Profiles = 1,148,669

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
2002	1,492	2006	5,162	2010	97,244	2014	187,465
2003	2,313	2007	8,599	2011	78,801	2015	98,655
2004	9,620	2008	12,738	2012	96,526	2016	168,339
2005	8,205	2009	64,392	2013	185,301	2017	143,676

Figure 15.3 shows contribution of the glider data made by different programs as a percentage of the total amount. The major contributor of the glider data in WOD18 is Australian Integrated Marine Observing System (IMOS - http://imos.org.au/). Australian Ocean Gliders facility operates a fleet of gliders measuring oceanographic parameters on shelf and boundary currents in Australian waters. It operates a number of Slocum gliders in the Coral Sea, East Australian Current off New South Wales and Tasmania, Southern Ocean. southwest of Tasmania, the Leeuwin and Capes Currents off South Western Australia and the Pilbara and Kimberly regions off North Western Australia (http://imos.org.au/facilities/oceangliders/).

The data submitted by IOOS are collected via the IOOS Underwater Glider Network Map and includes current and historical glider missions dating back to 2005 from Gulf of Mexico (GCOOS), Southern California (SCCOOS), Northern Pacific (NANOOS), Central and

Northern California (CeNCOOS), Great Lakes (GLOS), Mid-Atlantic (MARACOOS), and the Atlantic Oceanographic and Meteorological Lab (AOML). https://gliders.ioos.us/data/.

Data collected by University of Washington from their Seagliders were main source of the glider data in WOD for 2002-2009 years. Now these data submitted to NCEI via IOOS channel. Canada Department of Fisheries via the Global Temperature-Salinity Profile Program (GTSPP) has submitted noticeable volume of glider data in 2010-2017.

It should be noted though, that over 20% of the glider data in WOD18 has no program information provided in the metadata, which make is difficult to credit data collecting/submitting agencies and institutions.

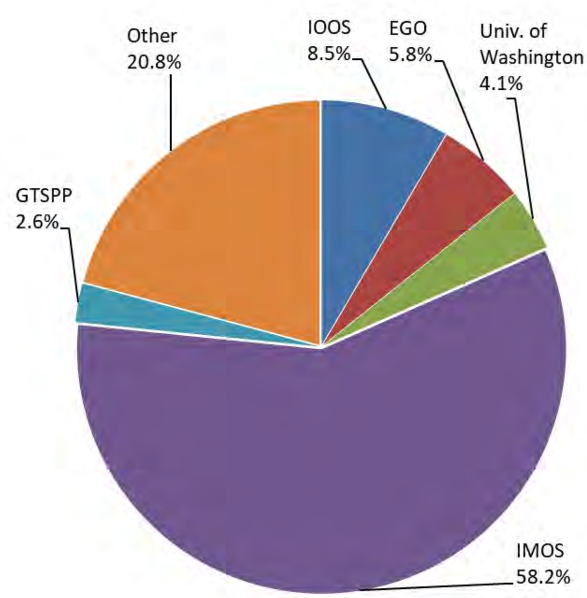

Figure 15.3. Contribution of Glider (GLD) data by different programs in WOD18.

Figure 15.4 shows global geographic distribution of the glider data color-coded according to submitting institutions. This figure allows to clearly seeing that at the current stage of the glider observation technology, majority of the data are collected close to the contributing countries' economic zones with the only exceptions of the RU29 *Challenger* Slocum G2 glider (WOD platform code 10850) operated by Rutgers University' Coastal Ocean Observation Lab (WOD institution code 1512). This glider deployed from Cape Town completed the first circumnavigation of the Atlantic basin in three deployments after 282 days at sea (WOD cruise numbers US-36223, US-36234, and US-37614) (https://marine.rutgers.edu/main/announcements/the-challenger-glider-mission-south-atlantic-mission-complete). With development of the deep-range gliders and advanced battery packs, we expecting the glider data to cover larger areas in the near future.

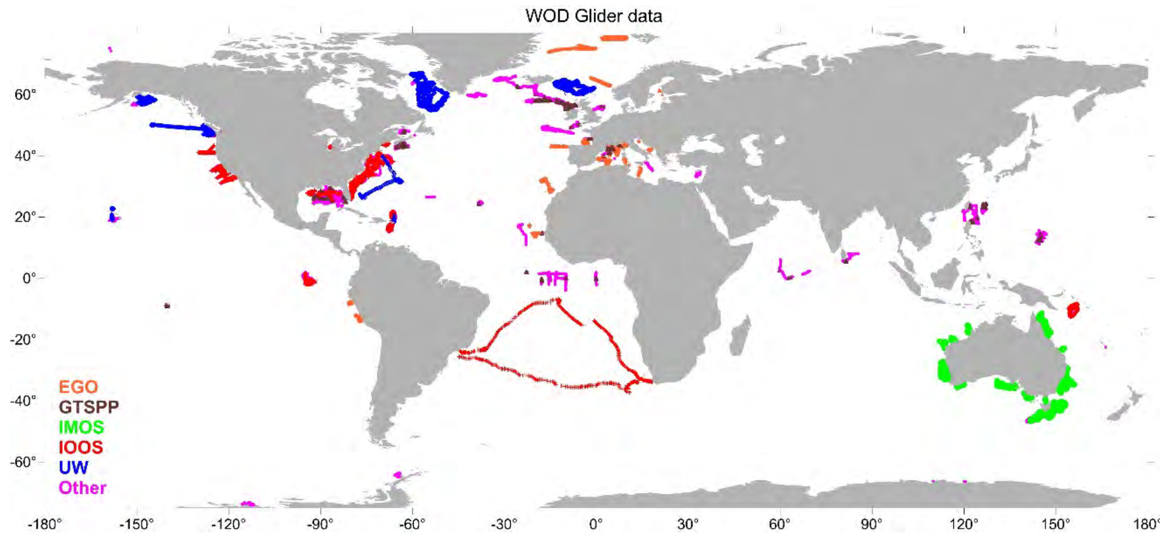

Figure 15.3. Geographical distribution of Glider (GLD) data submitted by different programs in WOD18.

Figure 15.5 shows depth distribution of the glider data at the standard depth levels. The majority of glider data in WOD18 acquired in the upper 1000m layer of the ocean. However, data from deep-ocean gliders, which are under development, are present in WOD18, but they are not visible on Fig. 15.4 because of low volume of such data now. The amount of deep ocean glider data varied from about 1600 to 40 profiles in 1100-5500m depth range.

There are not too many countries capable to manufacture, maintain, support glider operations, and generate constant data stream at this moment. Table 15.3 and Figure 15.5 show the glider data contribution by country. Two major contributors of the glider data to the NCEI archives – Australia (IMOS) and USA (Univ. of Washington and IOOS) are submitted 89.5% of all data stored in WOD18. European Union countries contributed ~7% of the data so far, with France leading the way collecting and submitting 4.26% of all data. Apparently, fast growing "Everyone's Gliding Observations" (EGO) program looks very promising for expanding future data collection in the European waters and further data submission (www.ego-network.org).

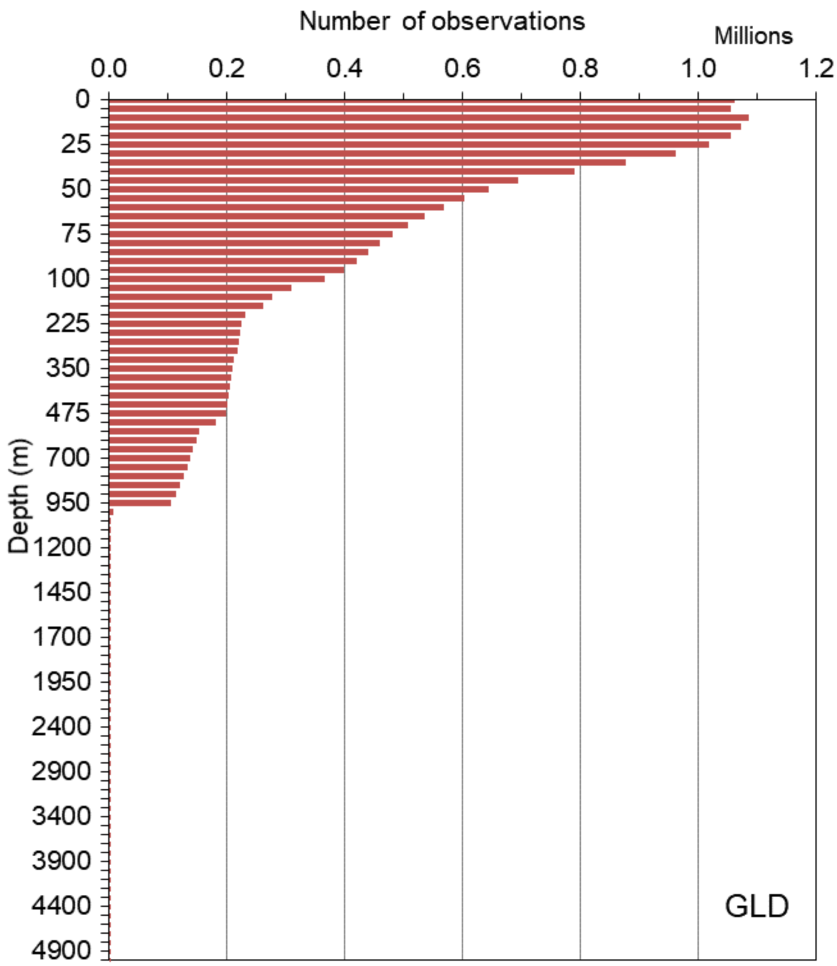

Figure 15.5. Distribution of Glider (GLD) data at standard depth levels in WOD18.

Table 15.3. National contribution of Glider (GLD) profiles in WOD18.

ISO[1] Contry Code	Country Name	GLD Casts	% of Total
AU	Australia	671,215	58.43%
US	United States	355,045	30.91%
FR	France	48,942	4.26%
CA	Canada	26,422	2.30%
99	Unknown	13,480	1.17%
DE	Germany	12,185	1.06%
IT	Italy	8,340	0.73%
GB	Great Britain	6,712	0.58%
ES	Spain	5,019	0.44%
NO	Norway	1,339	0.12%
	Total	***1,148,699***	100.00%

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

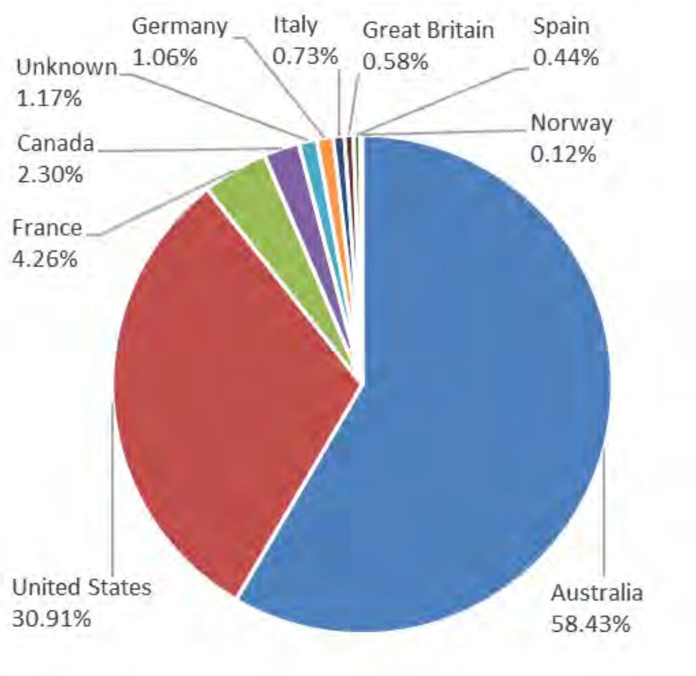

Figure 15.5. Glider (GLD) data contribution by countries in WOD18.

15.4. RELEVANT WEB SITES

Applied Physics Laboratory - University of Washington (Seaglider):
http://www.apl.washington.edu/project/project.php?id=seaglider

Australian Integrated Marine Observing System (IMOS) Ocean Gliders Facility:
http://imos.org.au/facilities/oceangliders/

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

Autonomous Undersea Vehicle Applications Center:
http://auvac.org/

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

Bluefin Robotics (Spray Glider):
http://www.bluefinrobotics.com/products/spray-glider/

Coastal Ocean Observation Lab – Rutgers University:
http://rucool.marine.rutgers.edu/

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

Everyone's Gliding Observatories: www.ego-network.org

Global Temperature and Salinity Profile Programme: https://www.nodc.noaa.gov/GTSPP/

iRobot (Seaglider): http://auvac.org/uploads/configuration_spec_sheets/iRobot_1KA_Seaglider.pdf

Kongsberg Underwater Technology, Inc. (Seaglider): https://www.km.kongsberg.com/

SBE 911 plus CTD: https://www.seabird.com/profiling/sbe-911plus-ctd/family?productCategoryId=54627473769

SCRIPPS Institute of Oceanography (Spray Glider): http://spray.ucsd.edu/

Teledyne Webb Research Corporation (Slocum Glider): http://www.webbresearch.com/slocumglider.aspx

U.S. Integrated Ocean Observing System (IOOS): https://gliders.ioos.us/

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CHAPTER 16: PLANKTON DATA

Olga K. Baranova[1], Todd D. O'Brien[2], Tim P. Boyer[1]

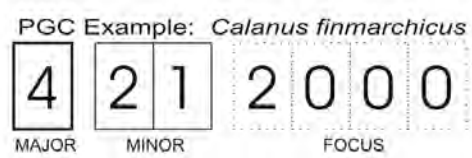
[1] Ocean Climate Laboratory - National Centers for Environmental Information
[2]Office of Science and Technology - National Marine Fisheries Service
Silver Spring, Maryland, USA

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 2018* (WOD18) includes and extends the content of the previously released *World Ocean Database 2013, 2009, 2005* (Baranova *et al.,* 2013, 2009, 2005), *World Ocean Database 2001* (O'Brien *et al.,* 2001), and *World Ocean Database 1998* (Conkright *et al., 1998*). The WOD18 plankton data subset is a collection of measurements from serial bottle and plankton net-tow. The plankton measurements are represented in WOD18 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 WOD18 are stored using the corresponding ITIS (Integrated Taxonomic Information System, https://www.itis.gov) Taxonomic Serial Number (TSN). ITIS TSN's are not available for all plankton descriptions and biomass. WOD18 negative taxonomic codes (sequentially assigned numbers) were developed to preserve the original descriptions. In addition to ITIS or negative taxonomic codes, each plankton description has a *Plankton Grouping Code* (PGC) developed by O'Brien (2007). The PGC code follows the taxonomic hierarchy presented in *The Five Kingdoms* (Margulis & Schwartz 1998). The PGC is an ancillary code which places each taxon into broader groups (*e.g., phytoplankton, diatoms, zooplankton, copepods*) and allows the WOD18 user access to hundreds of individual taxa by using a single PGC code. The PGC is 7-digit code divided into Major group (*e.g. Bacteria, Phytoplankton, Zooplankton*), Minor group (*e.g., cyanobacteria, diatoms,*



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

The typical plankton cast, as represented in WOD18, stores taxon specific and/or biomass data in individual sets, called “Taxa-Record”. Figure 16.1 demonstrates an example of a plankton cast in WOD18.

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 WOD18 documentation (Garcia *et al.,* 2018).

The alternative way to receive plankton data is a “csv” (comma-separated value) output file, which is available only through the WODselect – the online WOD18 database retrieval system (https://www.nodc.noaa.gov/OC5/SELECT/dbsearch/dbsearch.html).

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

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

Taxa-Record # 1
Param_number 85263.000 upper_depth 0 lower_depth 100.000
Taxon_lifestage 25.000 Taxon_count 18.600 Taxon_modifier
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#	**0000772**
Cast Number	**9617720**
Orig_Stat_Num	**7**
Bottom_Depth	**1413.000**
T-S_Probe	**7.000**
NODCorig	**3.000**

Figure 16.1. An example a plankton cast in WOD18 (using provided output software).

```
CAST   ,,9617720,WOD Unique Cast Number,WOD code,,,,,,,,,,

NODC Cruise ID,,06-10438      ,,,,,,,,,,,,

Originators Station ID,,7,,,integer,,,,,,,,,

Originators Cruise ID,,,,,,,,,,,,,,

Latitude,,79.0167,decimal degrees,,,,,,,,,,,

Longitude,,-4.8833,decimal degrees,,,,,,,,,,,

Year,,1991,,,,,,,,,,,,

Month,,6,,,,,,,,,,,,

Day,,9,,,,,,,,,,,,

METADATA,,,,,,,,,,,,,,

Country,,DE,NODC code,GERMANY, FEDERAL REPUBLIC OF,,,,,,,,,

Accession Number,,772,NODC code,,,,,,,,,,,

Project,,435,NODC code,IAPP (International Arctic Polynya Programme),,,,,,,,,,

Platform,,199,OCL code,POLARSTERN,,,,,,,,,,

Institute,,892,NODC code,ALFRED-WEGENER-INSTITUTE (BREMERHAVEN),,,,,,,,,,

Bottom depth,,1413,meters,,,,,,,,,,,

Database origin,,3,WOD code,GODAR Project,,,,,,,,,,

BIOLOGY METADATA,,,,,,,,,,,,,,

Mesh size,,200,microns,,,,,,,,,,,

Type of tow,,2,WOD code,VERTICAL TOW,,,,,,,,,,

Large plankters removed, ,1,WOD code,yes,,,,,,,,,,

Gear,,118,WOD code,Bongo Net,,,,,,,,,,

Net mouth area,,0.3,m2,,,,,,,,,,,

Min length removed,,1,cm,,,,,,,,,,,

Average tow speed,,2,knots,,,,,,,,,,,

BIOLOGY,Upper Z,Lower Z,Measuremnt Type,ORIGINAL VALUE ,F,Orig unit,WOD CBV
value  ,F,_unit,_meth,WOD PGC,ITIS TSN,mod,lif,

1,0. meters,100. meters,Taxon_count,18.6,0,#/m3,18.6,3,
#/m3,70,4282010,CALANUS,MODIFIER=spp.  (multiple species),LIFE STAGE=C1:
COPEPODITE I

2,0. meters,100. meters,Total Dry Mass,3100,0,mg/m2,31,3,mg/m3,69.1,-404,Zooplankton
Dry Mass (mg/unit),,,,,,,,,,,

3,0. meters,100. meters,Taxon_count,0.1,0,#/m3,0.1,3,
#/m3,70,4282010,CALANUS,MODIFIER=spp. (multiple species),LIFE STAGE=C2:
COPEPODITE II

......

END OF BIOLOGY SECTION
```

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

16.2. BASIC QUALITY CONTROL

Plankton numerical abundance and total biomass measurements are stored with the data originator's units in WOD18 (*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 WOD18 documentation, Appendix 5.11, (Garcia *et al.,* 2018). 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. WOD18 broad group-based ranges for plankton abundance.

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

Table 16.3. WOD18 broad group-based ranges for biomass.

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

WOD18 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 WOD18 have been contributed by 37 countries, 142 institutions and more than 50 projects. Significant amounts of data (104,740 casts) have no information about the project. Among them are data provided by the Instituto del Mar del Peru (IMARPE). This contribution (~23,000 casts) comes from a joint data rescue effort with the IMARPE and the Intergovernmental Oceanographic Commission's Global Oceanographic Data Archaeology and Rescue project (GODAR), which digitized over forty-five years of IMARPE phytoplankton monitoring data. Substantial amounts of historical biomass and abundance data are from the archives of the National Centers for Environmental Information (NCEI), former National Oceanographic Data Center (NODC) and the World Data Center for oceanography, Silver Spring.

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

A considerable portion of biomass data (~69,500 casts) was received from Coastal and Oceanic Plankton Ecology Production and Observation Database (COPEPOD)1 as a result of collaboration between NCEI and National Marine Fisheries Service (NMFS).

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1 Data acquired through the COPEPOD database were provided in COPEPOD's format and mainly include data from CalCOFI, ECOMON, and SEAMAP projects.

Table 16.4. National contributions of plankton casts in WOD18.

ISO Country Code	Country Name	# Casts	% of Total
US	United States	130,675	53.3
JP	Japan	41,372	16.9
PE	Peru	22,874	9.3
SU	Union of Soviet Socialist Republics	20,551	8.4
GB	Great Britain	16,253	6.6
ID	Indonesia	2,098	0.9
PT	Portugal	1,611	0.7
NO	Norway	1,422	0.6
FR	France	1,222	0.5
IN	India	970	0.4
DE	Germany	958	0.4
AU	Australia	763	0.3
CA	Canada	733	0.3
RU	Russian Federation	508	0.2
PL	Poland	405	0.2
ZA	South Africa	396	0.2
EC	Ecuador	352	0.2
MX	Mexico	293	0.1
BR	Brazil	216	0.1
KR	Korea Republic of	193	0.1
PH	Philippines	184	0.1
TW	Taiwan	141	0.1
NC	New Caledonia	136	0.1
DK	Denmark	133	0.1
IS	Iceland	133	0.1
CO	Colombia	97	> 0.1
ES	Spain	71	> 0.1
AR	Argentina	64	> 0.1
BE	Belgium	38	> 0.1
CI	Cote d'Ivoire	37	> 0.1
NL	Netherlands	36	> 0.1
SG	Singapore	35	> 0.1
CD	Congo, the Democratic Republic	29	> 0.1
PK	Pakistan	22	> 0.1
NG	Nigeria	12	> 0.1
SE	Sweden	11	> 0.1
TH	Thailand	10	> 0.1
	Total	*245,059*	*100.0*

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 Ecosystem Monitoring Program (EcoMon) and its predecessor Marine Resources Monitoring Assessment and Prediction (MARMAP) program is one of the important contributors of the plankton data (25,981 casts). The NMFS-wide EcoMon program maintains plankton sampling databases for the northeast U.S. continental shelf ecosystem. Sampling was conducted under a number of different programs with varying temporal and spatial scale. The largest and most comprehensive was the Marine Resources Monitoring Assessment and Prediction Program (MARMAP), which sampled the shelf from 1977 to 1987. Data collected over time includes biological surveys of fishes, fish eggs and larvae.

The Ecosystems and Fisheries-Oceanography Cooperative Investigations (EcoFOCI) program contributed a valuable amount of plankton biomass data (13,608 casts). The EcoFOCI is a joint research program between the Alaska Fisheries Science Center and the Pacific Marine Environmental Laboratory. Originally, the FOCI was established by NOAA in 1984 to study walleye pollock in the western Gulf of Alaska. Later on the EcoFOCI has broadened its study to ecosystems research in the North Pacific and Alaskan waters https://www.ecofoci.noaa.gov.

A significant amount of data (11,620 casts) was received through the Southeast Area Monitoring and Assessment Program (SEAMAP). Since its beginning in 1981 SEAMAP monitoring of marine resources within Gulf of Mexico, South Atlantic, and Caribbean regions http://www.seamap.org/ .

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

Another source of data was the Eastern Tropical Pacific Ocean (EASTROPAC) program (5,544 casts). The first EASTROPAC survey (February 1967 through March 1968) was a cooperative effort towards the understanding of the oceanography of the eastern Tropical Pacific Ocean. Participating scientists were primarily from the NMFS, Scripps Institution of Oceanography, and the Inter-American Tropical Tuna Commission.

Kuroshio Exploitation and Utilization Research (KER) project provided 4,234 casts. KER was designed to study the subtropical circulation system, marine ecology, and fishery around Japan. The project was conducted in 1977 – 1995.

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

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

NCEI Project Code	Project Name	# Casts	% of Total
33	*CalCOFI: California Cooperative Oceanic Fisheries Investigation	38,980	27.7
637	*EcoMon: Ecosystem Monitoring Program/MARMAP: Marine Resources Monitoring Assessment and Prediction	25,981	18.5
174	*EcoFOCI: Ecosystems and Fisheries-Oceanography Cooperative Investigations	13,608	9.7
121	*SEAMAP: Southeast Area Monitoring and Assessment Program	11,620	8.3
81	*OCSEAP: Outer continental shelf environmental assessment program	7,920	6.4
3	*EASTROPAC (1967-1968)	5,544	4.5
526	GENERAL FISHERIES RESEARCH (YugNIRO)	5,438	4.5
243	KER: Kuroshio exploitation and utilization research (1977 - 1995)	4,234	3.4
93	BRINE DISPOSAL	4,198	3.4
240	USAP or USARP : United States Antarctic Research Project	3,665	2.9
25	IIOE: International Indian Ocean Expedition	2,045	1.6
344	*POFI: Pacific Oceanic Fisheries Investigations	1,310	1.1
372	OMEX: Ocean margin exchange project	1,234	1.0
367	GLOBEC: Georges Bank Program	951	0.8
361	JGOFS/AESOPS: US JGOFS Antarctic Environments Southern Ocean Process Study	943	0.8
30	ICNAF: International Commission for the Northwest Atlantic Fisheries	851	0.7
345	NORTH SEA PROJECT	827	0.7
241	BIOMASS: Biological Investigations of Marine Antarctic Systems and Stocks	712	0.6
322	*SKIPJACK	684	0.6
365	JGOFS/ARABIAN: Arabian Sea Process Studies	657	0.5
31	CSK: Cooperative Study of the Kuroshio	599	0.5
83	OCS-SOUTH: Texas	533	0.4
275	JGOFS/BATS: Bermuda Atlantic Time Series	495	0.4
325	CINECA: Cooperative Investigations of Northern Part of Eastern Central Atlantic	400	0.3
82	PSERP: Mesa Puget Sound	396	0.3
645	Discovery Investigations	366	0.3
200	JGOFS: Joint Global Ocean Flux Study	363	0.3
273	EASTROPIC: Eastern Tropical Pacific 1955	323	0.3
410	TASC: Trans Atlantic Study of *Calanus*	300	0.2
310	JGOFS/EQPAC: Equatorial Pacific basin study	279	0.2

NCEI Project Code	Project Name	# Casts	% of Total
450	SFRI UPWELLING CRUISE 1969	255	0.2
96	EPA: Buccaneer oil field	214	0.2
321	BOFS: Biogeochemical Ocean Flux Study	180	0.2
422	ICITA - EQUALANT III	177	0.1
443	IMECOCAL: Investigaciones Mexicanas De La Corriente De California	174	0.1
421	ICITA - EQUALANT II	164	0.1
420	ICITA - EQUALANT I	163	0.1
34	MAZATLAN	119	0.1
255	CTZ: Coastal Transition Zone	100	> 0.1
246	BERPAC: Bering and Pacific Russian/US Cooperative Research Program	88	> 0.1
328	SIBEX: Second International Biomass Experiment - Fr	63	> 0.1
312	CEAREX: Coordinated Eastern Arctic Experiment	63	> 0.1
225	WOCE: World Ocean Circulation Experiment	41	> 0.1
435	IAPP: International Arctic Polynya Programme	41	> 0.1
90	ONR: Office of Naval Research	39	> 0.1
71	IDOE/CUEA	30	> 0.1
434	ARCTIC OCEAN SECTION: Canada/U.S. joint expedition	18	> 0.1
77	SCOPE	11	> 0.1
447	Marine Food Chain Research Group	10	> 0.1
444	GSP: Greenland Sea Project	5	> 0.1
	Total	245,059	100.00

16.4. PLANKTON DATA DISTRIBUTIONS

The WOD18 plankton subset consists of 245,059 globally distributed casts (Figure 16.3). The temporal distribution of plankton sampling covers period from 1900 to 2015 year (Figure 16.4). Table 16.6 gives the yearly counts of plankton casts in the WOD18.

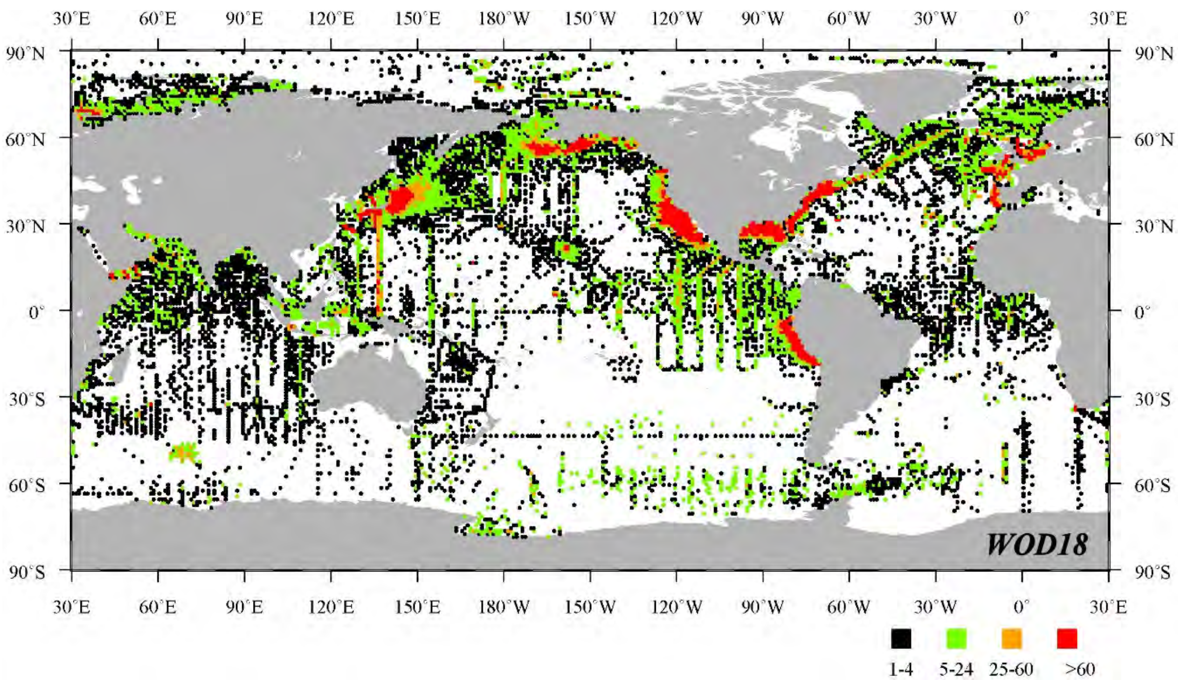

Figure 16.3. Geographic distribution of plankton (245,059 casts) in WOD18.

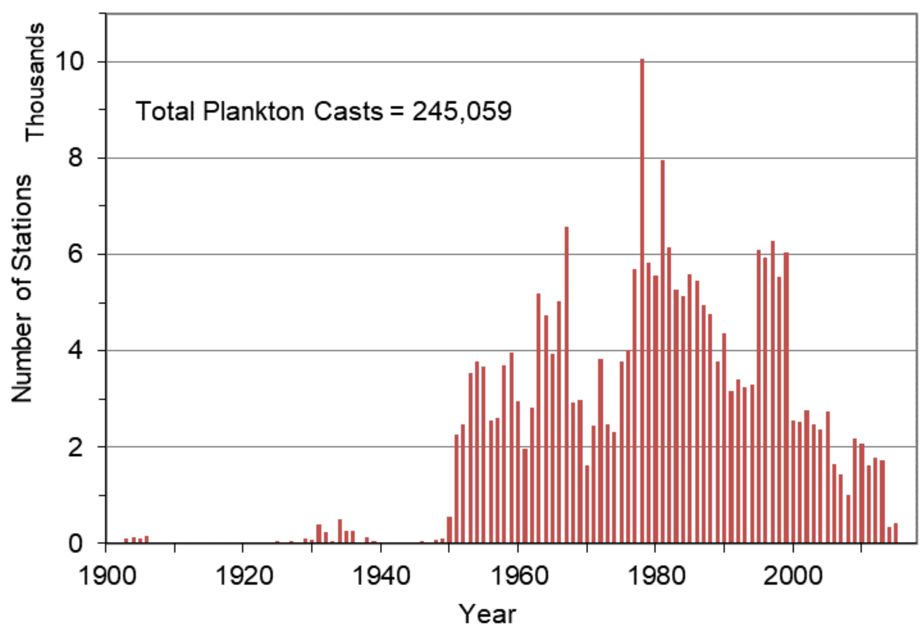

Figure 16.4. Temporal distributions of plankton casts in WOD18 as a function of year.

Table 16.6. Number of plankton casts in WOD18 as a function of year

Total Number of Casts = 245,059

YEAR	CASTS	YEAR	CASTS	YEAR	CASTS	YEAR	CASTS
1900	17	1929	93	1958	3,690	1987	4,949
1901	9	1930	88	1959	3,953	1988	4,759
1902	13	1931	409	1960	2,962	1989	3,767
1903	100	1932	247	1961	1,959	1990	4,370
1904	126	1933	62	1962	2,814	1991	3,162
1905	95	1934	490	1963	5,195	1992	3,399
1906	160	1935	273	1964	4,730	1993	3,254
1907	0	1936	262	1965	3,940	1994	3,308
1908	0	1937	7	1966	5,040	1995	6,082
1909	0	1938	134	1967	6,573	1996	5,937
1910	0	1939	51	1968	2,934	1997	6,275
1911	0	1940	2	1969	2,974	1998	5,527
1912	0	1941	0	1970	1,620	1999	6,045
1913	6	1942	2	1971	2,438	2000	2,562
1914	7	1943	0	1972	3,821	2001	2,531
1915	9	1944	0	1973	2,467	2002	2,768
1916	0	1945	0	1974	2,318	2003	2,483
1917	0	1946	54	1975	3,772	2004	2,367
1918	0	1947	36	1976	4,025	2005	2,745
1919	0	1948	67	1977	5,685	2006	1,644
1920	0	1949	98	1978	10,060	2007	1,444
1921	29	1950	558	1979	5,828	2008	1,002
1922	33	1951	2,266	1980	5,570	2009	2,176
1923	0	1952	2,468	1981	7,952	2010	2,067
1924	2	1953	3,531	1982	6,152	2011	1,627
1925	50	1954	3,783	1983	5,255	2012	1,793
1926	34	1955	3,676	1984	5,145	2013	1,729
1927	46	1956	2,566	1985	5,597	2014	334
1928	35	1957	2,602	1986	5,465	2015	423

16.5. PLANKTON CONTENT

The plankton measurements are represented in WOD18 as descriptive and numeric abundance, and biomass data. The majority (69%) of plankton measurements are total biomass. Contributions of plankton casts by measurement type are shown in Figure 16.5.

16.5.1. Abundance

The majority (83%) of plankton abundance measurements in WOD18 are numeric (*e.g.*, the number of individuals counted per sample or haul), while descriptive abundance measurements (*e.g.*, individual was "rare", "common", or "abundant" in sample or haul) are present in a smaller amount (17 %) of total abundance. The WOD18 plankton abundance content, listed by major plankton groups and sub-groups, is summarized in Table 16.7.

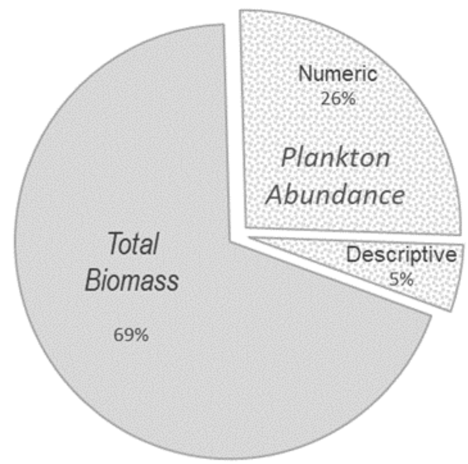

Figure 16.5 Contributions of Plankton casts by measurement type.

Table 16.7 WOD18 abundance measurements content.

PGC	Plankton Group	Numeric abundance (casts #)	Descriptive abundance (casts#)
1000000	**BACTERIA** (*all sub-groups*)	1,986	28
1050000	Cyanobacteria	974	27
2000000	**PHYTOPLANKTON** (*all sub-groups*)	37961	22,471
2030000	Amoebida	44	0
2040000	Granuloreticulosa (Foraminifera)	5,561	147
2070000	Dinomastigota (Dinoflagellata)	14,586	20,563
2080000	Ciliophora (ciliates)	4,893	7,769
2100000	Haptomonada (Coccolithophorids)	5,342	372
2110000	Cryptomonada (Chrytophyta)	1,910	8
2120000	Discomitochondria	1,333	242
2130000	Chrysomonada (Chrysophyta)	5,632	5,772
2160000	Diatoms (Bacillariophyta)	22,877	19,475
2270000	Actinopoda	3,817	436
2280000	Chlorophyta (green algae)	1,223	128
2300000	Ebriida	184	2
4000000	**ZOOPLANKTON** (*all sub-groups*)	46,224	5,805
4020000	Porifera	1,941	3
4030000	Cnidaria (coelenterates)	16,103	2,676
4032000	Hydrozoa	13,843	665
4036000	Stauromedusae	2,381	28
4038000	Antipatharia	2,292	83

PGC	Plankton Group	Numeric abundance (casts #)	Descriptive abundance (casts#)
4040000	Ctenophora (comb jellies)	3,912	370
4050000	Platyhelminthes (flat worms)	2,042	0
4090000	Nemertina (ribbon worms)	2,352	44
4100000	Nematoda	2,053	7
4130000	Rotifera (rotifers)	2,182	623
4180000	Entoprocta	2,157	0
4190000	Arthropoda: Chelicerata	862	154
4200000	Arthropoda: Mandibulata ("insects")	4,881	14
4210000	Arthropoda: Crustacea (*all sub-groups*)	49,737	6,553
4211000	*Crustacea*: Ostracoda	12,781	300
4212000	*Crustacea*: Copepoda	88,658	9,800
4213000	*Crustacea*: Cirripedia (barnacles)	7,091	783
4214000	*Crustacea*: Mysidacea	4,464	55
4216000	*Crustacea*: Isopoda	4,049	60
4217000	*Crustacea*: Amphipoda	22,309	1,718
4218000	*Crustacea*: Euphausiacea	17,227	1,728
4219000	*Crustacea*: Decapoda	15,008	1,159
4220000	Annelida (segmented worms)	26,547	4,716
4230000	Sipuncula	2,075	2
4260000	Mollusca (*all sub-groups*)	19,337	1,896
4262500	*Mollusca*: Gastropoda (snails & slugs)	17,201	1,008
4265000	*Mollusca*: Bivalvia (bivalve molluscs)	3,627	593
4266000	*Mollusca*: Scaphopoda (tusk shell)	85	0
4267500	*Mollusca*: Cephalopoda	4,123	26
4290000	Bryozoa	3,203	137
4300000	Brachiopoda (lamp shells)	2,012	1
4310000	Phoronida	2,202	0
4320000	Chaetognatha (arrow worms)	26,878	3,400
4330000	Hemichordata	3,965	4
4340000	Echinodermata	6,614	1,040
4350000	Urochordata (*all sub-groups*)	19,905	3,579
4352500	*Urochordata*: Ascidiacea (sea squirts)	870	0
4355000	*Urochordata*: Thaliacea (salps & doliolids)	11,385	101
4357500	*Urochordata*: Larvacea / Appendicularia	18,037	1,447
4360000	Cephalochordata / Leptocardia	2,458	17
5000000	**ICHTHYOPLANKTON**	54,286	217

The geographic distribution of numerical abundance casts of major plankton groups for WOD18 is shown in Figures 16.6 – 16.9.

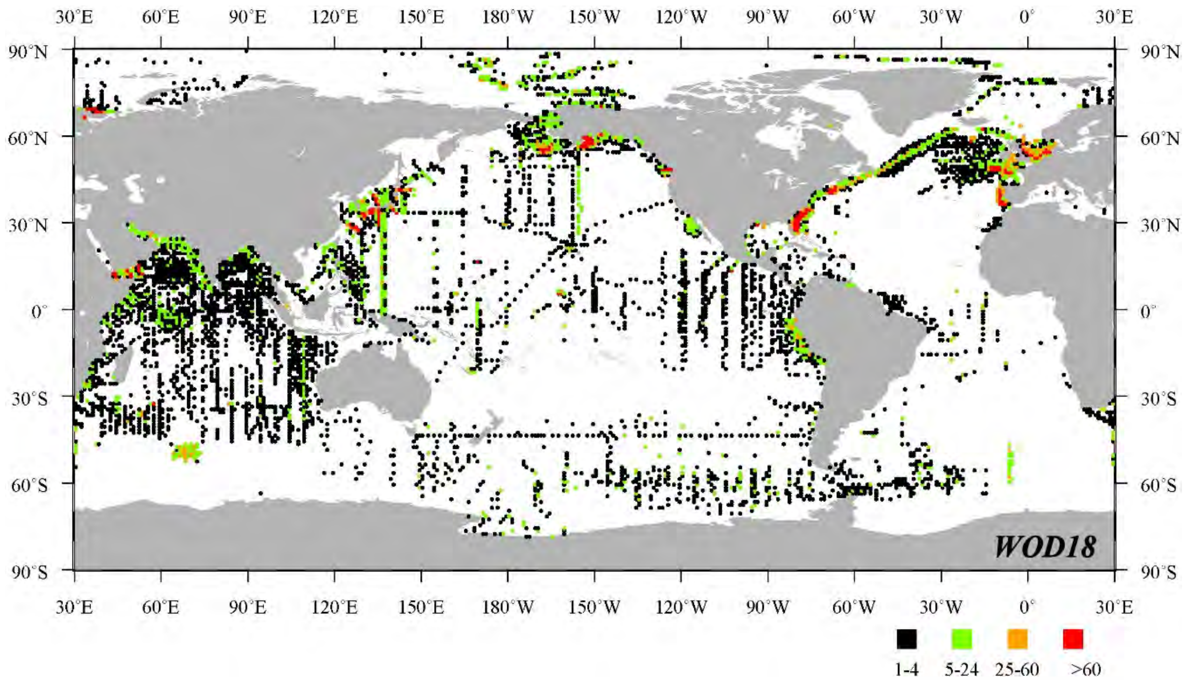

Figure 16.6. Geographic distribution of zooplankton numerical abundance (46,224 casts) in WOD18.

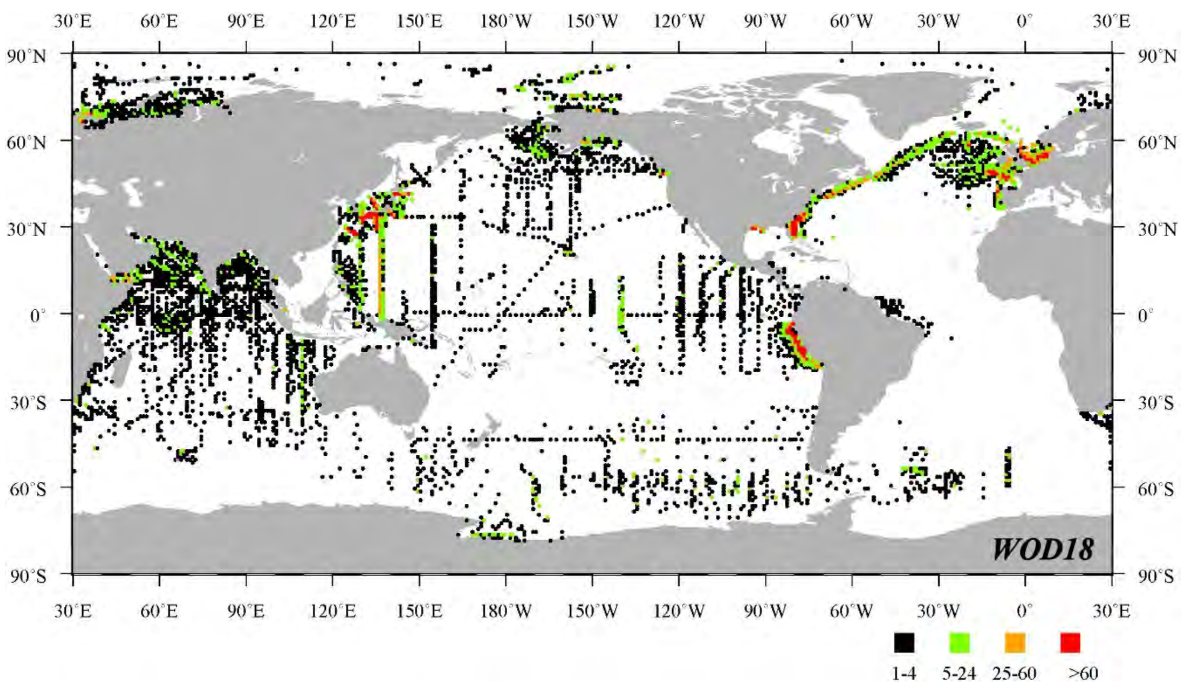

Figure 16.7. Geographic distribution of phytoplankton numerical abundance (37,961 casts) in WOD18.

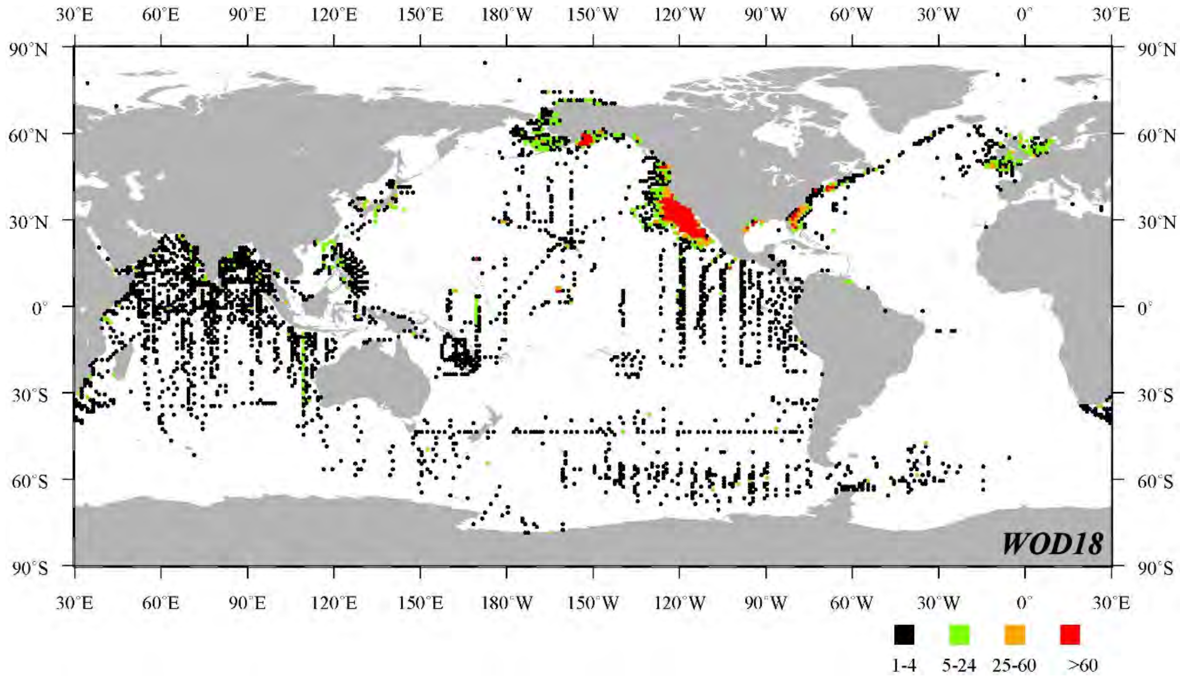

Figure 16.8. Geographic distribution of ichthyoplankton numerical abundance (54,286 casts) in WOD18.

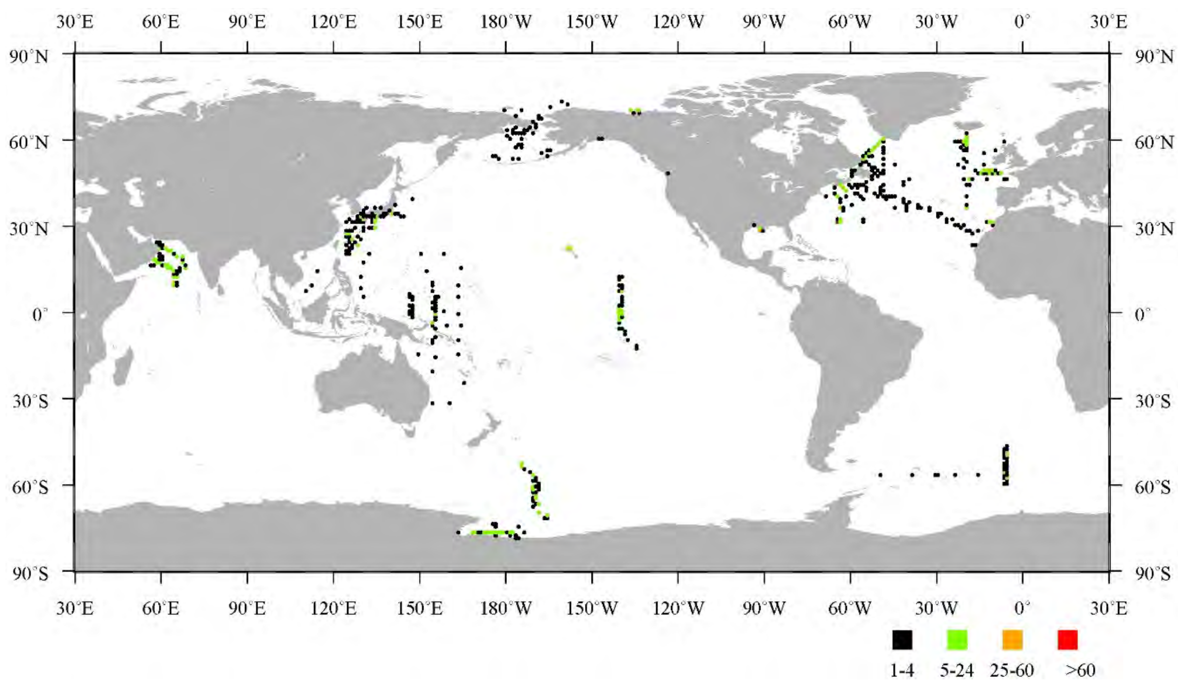

Figure 16.9. Geographic distribution of bacterioplankton numerical abundance (1,986 casts) in WOD18.

16.5.2. Total Biomass

The WOD18 total biomass data type represents measurement for which the entire contents of the plankton net are measured as a single, undifferentiated mass. This "mass" can be quantified by measuring the total settled volume, displacement volume, wet mass, dry mass, or ash-free dry mass of the entire sample. Although the sampling methods of total biomass data represented in the WOD18 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. WOD18 biomass measurements content.

PGC Code	Taxonomic Description	# Casts	% of Total
-401	Total Displacement Volume	125,022	72.68
-402	Total Settled Volume	9,926	5.77
-403	Total Wet Mass	34,075	19.80
-404	Total Dry Mass	2,554	1.49
-405	Total Ash-free Dry Mass	446	0.26

The majority of WOD18 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 WOD18 documentation, Table. 6 (Garcia *et al.,* 2018).

The geographic distribution of biomass casts for WOD18 is shown in Figures 16.10. – 16.14.

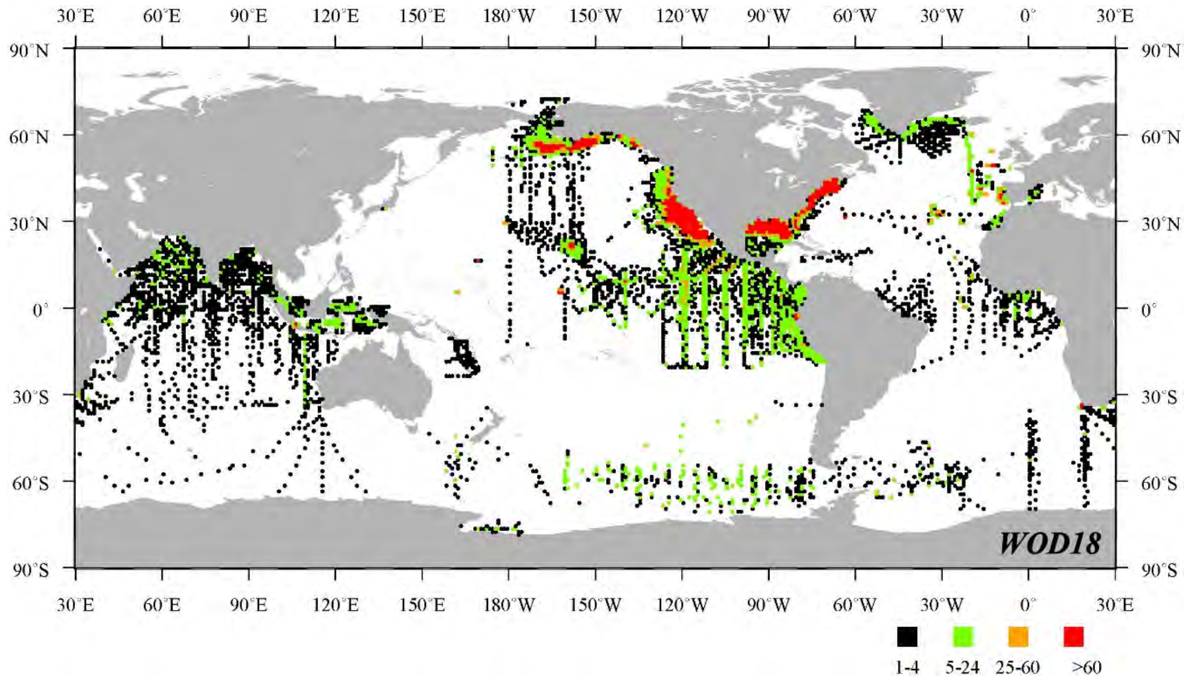

Figure 16.10. Geographic distribution of total displacement volume (125,022 casts) in WOD18.

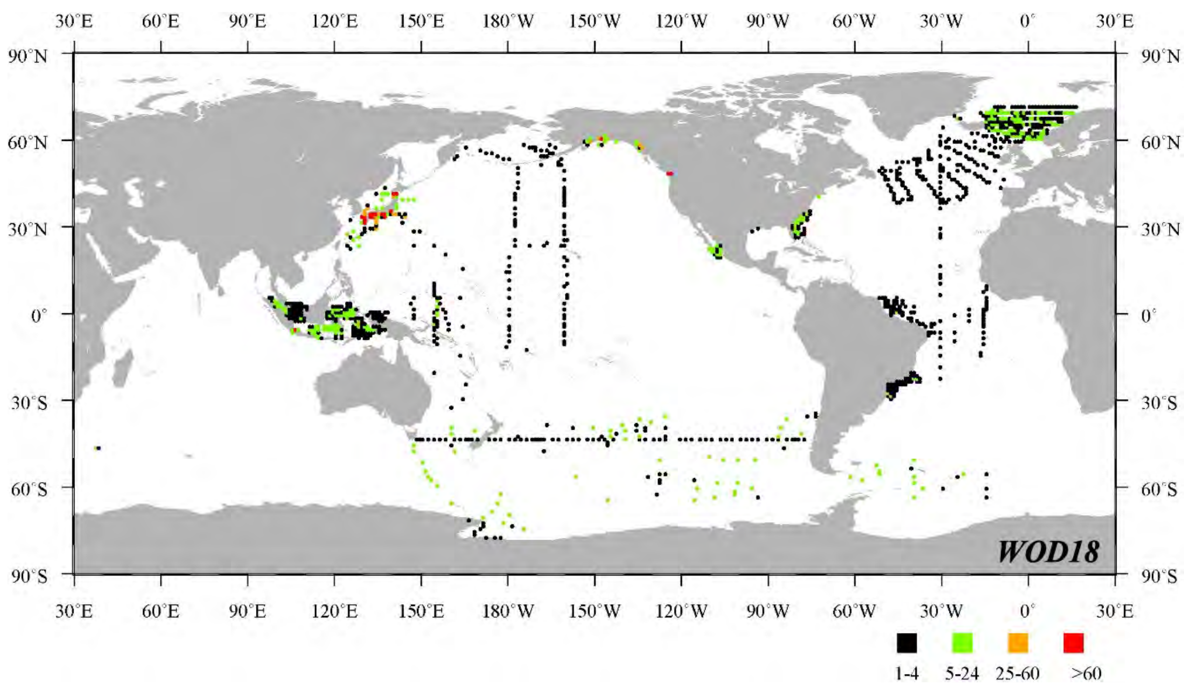

Figure 16.11. Geographic distribution of total settled volume (9,926 casts) in WOD18.

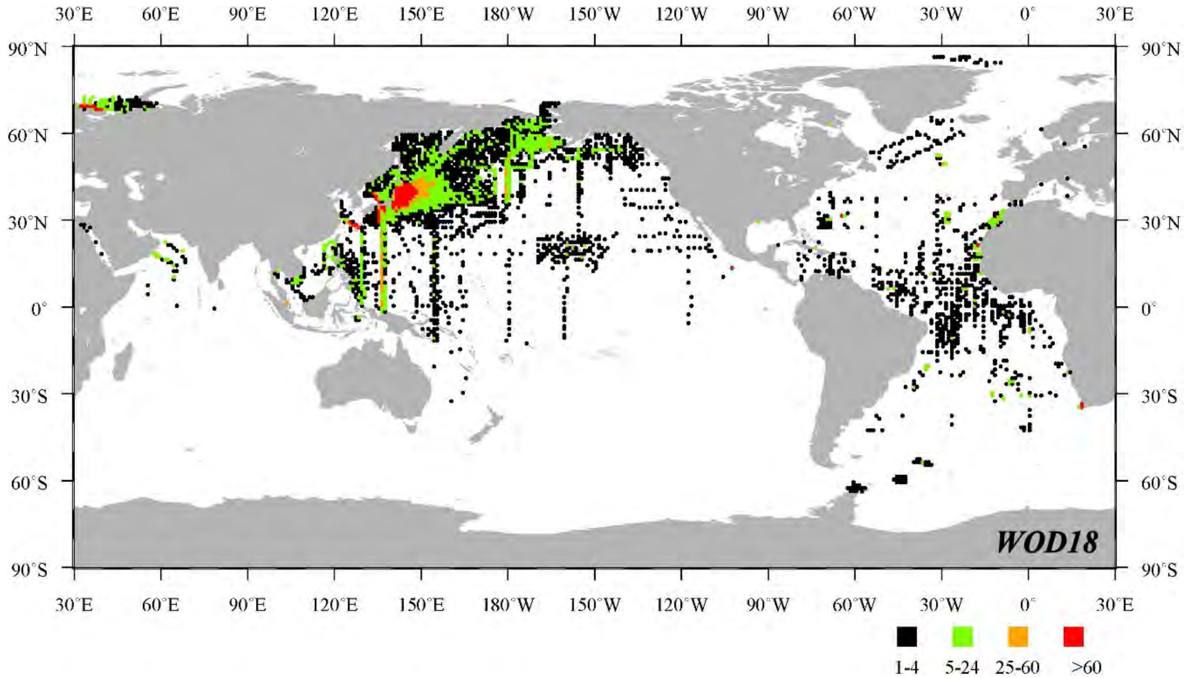

Figure 16.12. Geographic distribution of total wet mass (34,075 casts) in WOD18.

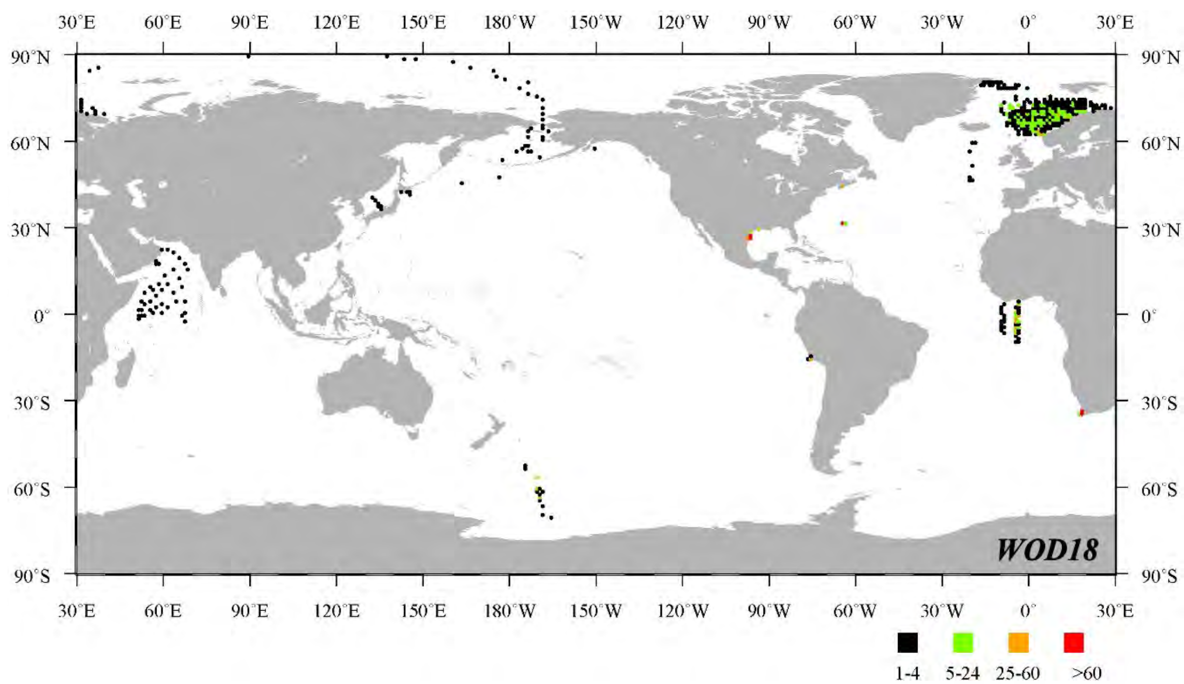

Figure 16.13. Geographic distribution of total dry mass (2,554 casts) in WOD18.

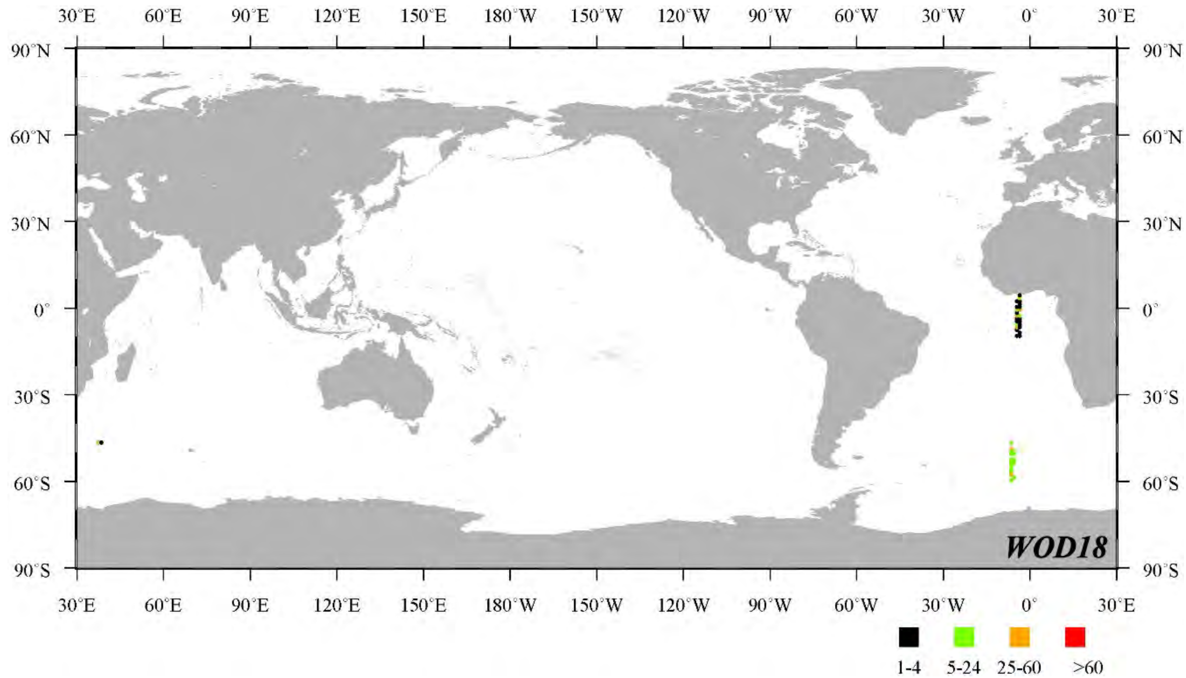

Figure 16.14. Geographic distribution of total ash-free dry mass (446 casts) in WOD18.

16.6. REFERENCES AND BIBLIOGRAPHY

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