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WORLD OCEAN ATLAS 2001
VOLUME 5: Plankton

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Preface

The oceanographic analyses described by this atlas series expand on earlier works, *e.g.* the *World Ocean Atlas 1998* (WOA98)*, World Ocean Atlas 1994* (WOA94) and *Climatological Atlas of the World Ocean*. Previously published oceanographic objective analyses have proven to be of great utility to the oceanographic, climate research, and operational environmental forecasting communities. Such analyses are used as boundary and/or initial conditions in numerical ocean circulation models and atmosphere-ocean models, for verification of numerical simulations of the ocean, as a form of "sea truth" for satellite measurements such as altimetric observations of sea surface height, for computation of nutrient fluxes by Ekman transport, and for planning oceanographic expeditions.

We have expanded our earlier analyses to include an all-data annual analysis of chlorophyll, monthly analyses of oxygen, and seasonal and monthly analyses of nutrients. Additional data for these variables have become available and there is a need for such analyses of these data in order to:

1) study the role of biogeochemical cycles in determining how the earth's climate system works, particularly the vulnerability of ocean ecosystems to climate change [IPCC (1996)];

2) help verify remotely sensed estimates of chlorophyll (SeaWIFS, ADEOS missions) which requires knowledge of *in situ* variables such as chlorophyll and plankton;

3) provide the most comprehensive set of oceanographic databases and products based on these data to the international research and forecasting communities.

We continue preparing climatological analyses on a one-degree grid. This is because higher resolution analyses are not justified for all the variables we are working with and we wish to produce a set of analyses for which all variables have been analyzed in the same manner. High-resolution analyses as typified by the work of Boyer and Levitus (1997) will be published as separate atlases.

In the acknowledgment section of this publication we have expressed our view that creation of global ocean profile and plankton databases and analyses are only possible through the cooperation of scientists, data managers, and scientific administrators throughout the international scientific community. I would also like to thank my colleagues and the staff of the Ocean Climate Laboratory of NODC for their dedication to the project leading to publication of this atlas series. Their integrity and thoroughness have 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 historical data.

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May 2002

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

The data on which this atlas is based are in *World Ocean Database 2001* and are distributed on-line and CD-ROM by NODC/WDC. Many data were acquired as a result of the NODC *Oceanographic Data Archaeology and Rescue* (NODAR) project, the IOC/IODE *Global Oceanographic Data Archaeology and Rescue* (GODAR) project, and the IOC/IODE *World Ocean Database* project (WOD). At NODC/WDC, "data archaeology and rescue" projects are supported with funding from the NOAA Environmental Science Data and Information Management (ESDIM) Program and the NOAA Climate and Global Change Program which has included support from NASA and DOE. Support for some of the regional IOC/GODAR meetings was provided by the MAST program of the European Union. The European Community has also provided support for the MEDAR/MEDATLAS project which has resulted in the inclusion of substantial amounts of ocean profile data from the Mediterranean and Black Seas into *World Ocean Database 2001.*

We would like to 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. Their efforts have made this and similar works possible.

WORLD OCEAN ATLAS 2001
VOLUME 5: PLANKTON

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ABSTRACT

This atlas contains maps of the distribution of *World Ocean Database 2001* plankton taxonomic groups and biomass on a one-degree grid. Maps for all-data annual and seasonal compositing periods are presented for bacterioplankton, phytoplankton, protist plankton, zooplankton, and plankton biomass. All-data annual maps are also presented for select taxonomic sub-groups within these major categories. Unanalyzed mean fields of annual zooplankton biomass and annual and seasonal calculated zooplankton carbon mass are provided.

1. INTRODUCTION

This atlas is based on all historical plankton biomass and abundance data available from the National Oceanographic Data Center (NODC) and World Data Center (WDC) for Oceanography, Silver Spring, Maryland, plus data gathered as a result of several data management projects including:

a) the Intergovernmental Oceanographic Commission (IOC) *Global Oceanographic Data Archaeology and Rescue* (GODAR) project;

b) the NODC *Oceanographic Data Archaeology and Rescue* (NODAR) project;

c) the IOC *World Ocean Database* project.

Plankton data were first added to the World Ocean Database shortly after the release of *World Ocean Atlas 1994* (WOA94), and first released as part of *World Ocean Database 1998* (WOD98). Since the publication of WOD98, substantial amounts of additional plankton data have become available. However, even with these additional data, we are still hampered in a number of ways by a lack of data. Because of the lack of data, we are forced to examine the annual cycle by compositing all data regardless of the year of observation. In many areas, quality control is made difficult by the limited number of data. Data may exist in an area for only one season, thus precluding any representative annual analysis. In some areas there may be a reasonable spatial distribution of data points on which to base an analysis, but there may be only a few (perhaps only one) data in each one-degree latitude-longitude square. With plankton data, additional issues of the taxonomic coverage (*e.g.,* the quality and quantity of species enumerated) and the sampling methods and biases (*e.g.,* due to sampling depth intervals or net mesh opening) can also make an existing data set not comparable with other data within the same region.

This atlas was modeled after earlier atlases in the World Ocean Atlas series [Levitus and Boyer (1994), Conkright *et al.* (1994), and Conkright *et al.* (1998a,b)], and represents the first efforts at adding a plankton component to these products. This atlas features analysis of mean zooplankton biomass. Adding data to the database is an ongoing process. As more data are added, spatial and temporal coverage will improve, and additional taxonomic groups will be added to the analysis.

2. DATA AND DATA DISTRIBUTION

Data sources and quality control procedures are briefly described below. For further information on the data sources used in *World Ocean Atlas 2001* (WOA01), refer to the *World Ocean Database 2001* (WOD01) series [O'Brien *et al.* (2002)]. General ocean station data quality control procedures, not specific to the plankton data, are also outlined by Conkright *et al.* (2002a).

2.1 Data sources

The historical plankton tows used in this product were obtained from the NODC/WDC archives, and includes all data gathered as a result of the NODAR and GODAR projects. Large amounts of these data were digitized from manuscript and cruise reports, on-site at NODC or through joint efforts with other institutes.

Appendix A shows the geographic distribution of historical bacterioplankton observations. Appendix B shows the geographic distribution of historical phytoplankton observations. Appendix C shows the geographic distribution of historical protist plankton observations. Appendix D shows the geographic distribution of historical zooplankton observations. Appendix E shows the geographic distribution of historical plankton biomass observations. Before each distribution figure, a table summarizes the major taxonomic members of that group.

In all data distribution maps that appear in the appendices, a small dot indicates a one-degree square containing one to four tows and a large dot indicates a square containing five or more tows.

2.2 Data quality control

Quality control of the data is a major task, the difficulty of which is directly related to lack of data (in some areas) upon which to base statistical checks. Consequently certain empirical criteria were applied, and as part of the last processing step, subjective judgment was used. Individual data, and in some cases entire profiles or cruises, have been flagged because these data produced features that were judged to be non-representative or in error (*e.g.,* due to equipment malfunction, sampling bias, or a significant population bloom). As part of our work, we have made available World Ocean Database 2001 (WOD01) which contain all of the plankton data with various quality control flags applied. Our knowledge of the variability of the world ocean now includes a greater appreciation and understanding of the ubiquity of eddies, rings, and patchiness in some parts of the world ocean as well as seasonal and diurnal variability. Therefore, we have simply flagged data, not eliminated them. Thus, individual investigators can make their own decision regarding the representativeness or correctness of the data.

2.2a Duplicate tow elimination

Duplicate data are typically only a minor problem for plankton data. However, some duplication may happen when data are received directly from a project, and also from a regional data center. Sometimes this results in similar data with slightly different time and/or position and/or data values, and hence are not easily identified as duplicate stations. Therefore, our databases were checked for the presence of exact and "near" exact replicates using eight different criteria. The first checks involve identifying stations with exact position/date/time and data values; the next checks involve offsets in position/date/time. Tows identified as duplicates in the checks with a large offset were individually verified to ensure they were indeed duplicate profiles. When a duplicate is found, the duplicating tow is removed from the database.

2.2b Range checks

Broad, taxonomic group-based value range checks were used to flag extremely large or small values within the database. At this time, only a single range (for the entire world ocean) was used, for the major taxonomic groups (Table 1). Future work will divide the ranges into smaller taxonomic sub-groups, and individual oceanographic basins, allowing for tighter automated range checks.

Table 1. WOD01 Broad Taxonomic Group-based Value Range Checks

Group	*Min*	*Max*	*Units*
Bacteria	0.001	5,000	#/ul
Phytoplankton	0.001	50,000	#/ml
Zooplankton	0.001	200,000	#/m^3
Total Displacement Volume	0.005	10.	ml/m^3
Total Settled Volume	0.025	50.	ml/m^3
Total Wet Mass	0.5	10,000	mg/m^3
Total Dry Mass	0.01	500	mg/m^3
Total Ash-free Dry Mass	0.01	100	mg/m^3

2.2c Statistical checks

Statistical checks were used only to highlight suspect values, and were not used to automatically flag any of these values. Observations greater than five standard deviations from the mean were investigated on a case-by-case basis. While natural variability may account for some of these, others were due to sampling gear biases (*e.g.,* a very low diatom count due to a few diatoms being caught in a larger mesh zooplankton tow).

2.2d Subjective flagging of data

The data were averaged by one-degree squares and graphically displayed for visual analysis. Sometimes the one-degree means contained suspicious data contributing to unrealistic distributions, yielding intense bull's-eyes or gradients. Examination of these features indicated that some of them were due to particular oceanographic cruises. In such cases, data from an entire cruise were eliminated from further use by setting a flag on each tow from the cruise. In other cases, individual tows or measurements were found to cause these features. These instances were then flagged and eliminated from the analysis.

2.2e Representativeness of the data

Another quality control issue is data representativeness. The general paucity of data forces the compositing of all historical data to produce "climatological" fields. In a given one-degree square, there may be data from a month or season of one particular year, while in the same or a nearby square there may be data from an entirely different year. If there is large interannual or seasonal variability in a region where scattered sampling in time has occurred, then one can expect the analysis to reflect this. Because the observations are scattered randomly with respect to time, except for a few limited areas, the results cannot, in a strict sense, be considered a true long-term climatological average.

To clarify discussions on the amount of available data, quality control techniques, and the representativeness of the data, the reader should examine in detail the maps showing the distribution of data (Appendices A, B, C, D, E) and the *World Ocean Database 2001* atlas series which shows the distribution of oceanographic stations/profiles as a function of year and instrument type [Conkright *et al.* (2002b), O'Brien *et al.* (2002)],. These maps are provided to give the reader a quick, simple way of examining the historical data distributions.

3. DATA PROCESSING AND PROCEDURES

This atlas features preliminary analysis of total zooplankton biomass. The dominant types of zooplankton biomass estimates available as part of the WOD01 are "total displacement volume" and "total wet mass", with lesser amounts of "total settled volume", "total dry mass" and "total ash-free dry weight" (Appendix E).

For the purposes of creating zooplankton biomass fields for the atlas, the objective was to provide as much spatial coverage as possible while remaining within reasonable parameters for net mesh size and sampling depth interval. The raw data are available within the WOD01 product (online, CD-ROMs) for investigators which wish to define different criteria for their specific needs.

3.1 Choice of spatial grid

A one-degree latitude-longitude spatial grid was selected for these data to put them on a uniform grid with that of the other variables of the WOA98 and WOA01 atlases.

3.2 Choice of Depth Interval

Figure 1 summarizes the depth coverage of all biomass tows in WOD01. The dominant biomass sampling interval, 0 - 200 meters, was selected for the biomass analysis. For single nets, depths of up to 250 meters were allowed to maximize map coverage**.** For multiple net tows, with multiple depth intervals (*e.g., 0-100, 100-200, 200-500, 500-1000)*, the sum of the values only from those nets falling inside of this interval was used to create a new single depth interval (*e.g., 0-100 + 100-200 = "0-200"*).

3.3 Choice of Mesh Size

Figure 2 shows the distribution of sampling mesh sizes deployed in the WOD01 biomass data. Four groupings of mesh sizes are present, 50-275 μm, 300-

400 µm, 450-600 µm, and >800 µm. The distributions of plankton tows using these mesh sizes are plotted in Figures 3-6.

The full range mesh sizes used for this analysis was 150 µm to 500 µm, but dominated heavily by the 300-400 µm mesh size. Supplemental data from 168-200 µm mesh range were used to add coverage to data sparse regions (*e.g.,* the Arctic and Antarctic). Also included was the 505 µm mesh data of the CalCOFI project.

3.4 Calculation of mean biomass

For each 1-degree latitude-longitude grid, the annual mean biomass value was calculated using all unflagged biomass data which satisfied the target depth and mesh intervals. These calculations were performed for each of the major types of biomass (Appendix F).

3.5 Conversion and calculation of mean zooplankton carbon mass

To further improve the spatial and temporal coverage of the WOA01 zooplankton biomass, the five types of plankton biomass were converted to a common biomass type, zooplankton carbon mass (mg-C/m^3), using the conversion factors provided by the ICES Committee on Terms and Equivalents [Cushing *et al.* (1958), Table 2].

Table 2: Conversion of zooplankton biomass to zooplankton carbon mass

Original Biomass Measure	Conversion Factor
Displacement Volume (ml) to Carbon mass (mg-C) [1]	* 96
Wet Mass (mg) to Carbon mass (mg-C) [1]	* 0.12
Dry Mass (mg) to Carbon mass (mg-C) [1]	* 0.60
Settled Volume (ml) to Wet Mass (mg) [1] then to Carbon mass (mg-C) [1]	* 195 * 0.12

[1] per Cushing *et al.* (1958)

Each of the biomass types were converted to carbon mass using the appropriate conversion factor in Table 2. Annual mean calculated zooplankton carbon mass was calculated using all unflagged zooplankton carbon mass values (which satisfied the depth and mesh interval targets). Seasonal mean carbon mass was calculated by using only those biomass data within the specified season. The WOA98 and WOA01 seasons are based on the Northern Hemisphere and defined as follows: Winter = January-March, Spring = April-June, Summer = July-September, and Fall = October-December.

4. RESULTS

4.1 Explanation of figures

The figures in this atlas are available in both a paper (black-and-white) and electronic (color) form. Unlike other atlases of the WOA01 series, the zooplankton biomass data were too sparse to contour. Instead, this atlas utilizes a six-value-category plot in which the size of a graphical circle represents the value range of the biomass at each one-degree grid location. [The online digital (color) atlas uses a 10-value-category plot in which the color of a graphical dot represents the value range.]

4.2 Contents of the World Ocean Atlas 2001 CD-ROM

This atlas presents zooplankton biomass data for the 0-200 meter depth interval. Associated with this atlas is a CD-ROM containing digital fields of zooplankton biomass (the five biomass types (Appendix F) and the calculated zooplankton carbon mass (Appendix G)). Also available is a DVD-ROM with color figures illustrating these data for the world, Pacific, Atlantic and Indian basins. The following is a list of digital fields for the world ocean:

(a) fields containing the number of biomass observations by one-degree squares;

(b) one-degree fields of unanalyzed annual mean zooplankton biomass (all types);

(c) one-degree fields of unanalyzed seasonal mean zooplankton biomass (carbon mass only).

The *World Ocean Atlas 2001* data are available online in addition to the CDROM and/or DVD-ROM format.

5. SUMMARY

In the preceding sections we have described the results of a project to combine historical zooplankton biomass data archived at NODC/WDC, including substantial amounts of data gathered as a result of the NODC and IOC data archaeology and rescue projects. We desire to build a set of climatological analyses that are identical for all variables including relatively data sparse variables such as nutrients and plankton. This provides investigators with a consistent set of analyses to work with.

We have attempted to create unanalyzed mean fields and data sets that can be used as a "black box." We emphasize that some quality control procedures used are subjective. For those users who wish to make their own choices, all the data used in our analyses are available both at standard depth levels as well as observed depth levels (*World Ocean Database 2001* CD-ROM set - Conkright *et al.*, 2002a). The results presented in this atlas show some features that are suspect and may be due to nonrepresentative or incorrect data that were not flagged by the quality control techniques used. Although we have attempted to eliminate as many of these features as possible by flagging the data which generate these features some obviously remain. Some may eventually turn out not to be artifacts but rather to represent real features, not yet capable of being described in a meaningful way due to lack of data.

6. FUTURE WORK

Our analyses will be updated when justified by additional observations. As more data are received and/or digitized at NODC/WDC, we will expand the spatial and temporal coverage of the zooplankton biomass means, ideally tightening the range of mesh sizes, improving coverage for the five biomass types, and improving the conversion equations for calculated zooplankton carbon mass. Table 3 summarizes the WOD01 content by major taxonomic groups. Future work will also include similar analysis of zooplankton and phytoplankton abundance (counts) for some of the major taxa (*e.g.,* copepods, chaetognaths, diatoms, dinoflagellates).

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TABLES and FIGURES

TABLE 3. WOD01 Plankton Content

Code	Group	Total Stations	*Winter (Jan.-Mar.)*	*Spring (Apr.-Jun.)*	*Summer (Jul.-Sep.)*	*Fall (Oct.-Dec.)*	Figure
BACTERIOPLANKTON:							
1000000	ALL BACTERIA SUB-GROUPS	**2,012**	***394***	***392***	***663***	***563***	**A1**
1010000	CYANOBACTERIA	**1,000**	*191*	*153*	*406*	*250*	A2
PHYTOPLANKTON:							
2000000	ALL PHYTOPLANKTON SUB-GROUPS	**24,989**	***5,038***	***7,377***	***8,286***	***4,288***	**B1**
2010000	DIATOMS	**20,363**	*4,272*	*6,067*	*6,573*	*3,451*	B2
2020000	DINOFLAGELLATES	**13,937**	*1,903*	*4,613*	*5,360*	*2,061*	B3
2030000	CHROMOPHYTES	**4,650**	*526*	*1,326*	*1,877*	*921*	-
2040000	CHLOROPHYTES	**1,381**	*202*	*598*	*463*	*118*	-
2050000	COCCOLITHOPHORES	**3,623**	*822*	*1,181*	*1,056*	*564*	B4
PROTIST PLANKTON:							
3000000	ALL PROTIST PLANKTON SUB-GROUPS	**12,871**	***2,385***	***3,416***	***4,319***	***2,751***	**C1**
3010000	MASTIGOPHORA	**290**	*29*	*117*	*135*	*9*	-
3020000	AMEBAS	**42**	*1*	*5*	*32*	*4*	-
3030000	FORAMINIFERA	**4,194**	*858*	*1,046*	*1,360*	*930*	C2
3040000	HELIOZOANS	**80**	*3*	*3*	*45*	*29*	-
3050000	RADIOLARIANS	**3,804**	*765*	*803*	*1,347*	*889*	C3
3060000	CILIOPHORA	**3,799**	*450*	*1,124*	*1,505*	*720*	C4
ZOOPLANKTON:							
4000000	ALL ZOOPLANKTON SUB-GROUPS	**41,178**	***9,321***	***12,102***	***11,206***	***8,549***	**D1**
4020000	PORIFERA	**1,944**	*486*	*503*	*538*	*417*	-
4030000	CNIDARIA	**14,521**	*3,119*	*4,039*	*4,239*	*3,124*	D2
4040000	CTENOPHORA	**3,672**	*897*	*950*	*1,082*	*743*	D3
4060000	PLATYHELMINTHES	**2,037**	*508*	*541*	*557*	*431*	-
4070000	NERMERTEA	**2,330**	*634*	*609*	*636*	*451*	-
4100000	ROTIFERA	**2,131**	*486*	*511*	*681*	*453*	-
4150000	NEMATODA	**2,042**	*520*	*539*	*548*	*435*	-
4170000	BRYOZOA (ECTOPROCTA)	**3,105**	*794*	*817*	*925*	*569*	-
4180000	PHORONIDA	**2,198**	*605*	*607*	*562*	*424*	-
4190000	BRACHIOPODA	**2,005**	*510*	*537*	*529*	*429*	-

TABLE 3. ***(continued)***		**Total Stations**	***Winter (Jan.-Mar.)***	***Spring (Apr.-Jun.)***	***Summer (Jul.-Sep.)***	***Fall (Oct.-Dec.)***	**Figure**
4200000	MOLLUSCA	**15,281**	*3,418*	*3,845*	*4,629*	*3,389*	-
4202500	Gastropods	**12,834**	*2,939*	*3,366*	*3,777*	*2,752*	D4
4205000	Bilvalves	**2,307**	*412*	*526*	*1,002*	*367*	-
4207500	Cephalopods	**4,007**	*1,146*	*883*	*1,280*	*698*	D5
4220000	SIPUNCULA	**2,078**	*524*	*525*	*578*	*451*	-
4240000	ANNELIDA	**12,029**	*2,564*	*3,333*	*3,404*	*2,728*	-
4245000	Polychaetes	**10,264**	*2,306*	*2,849*	*2,871*	*2,238*	D6
4270000	ARTHROPODS (*excluding Crustaceans*)	**2,431**	*707*	*611*	*665*	*448*	-
4280000	CRUSTACEANS	**35,713**	*7,806*	*11,062*	*9,443*	*7,402*	-
4281000	Ostracods	**8,820**	*2,445*	*2,011*	*2,152*	*2,212*	D7
4282000	Copepods	**31,961**	*7,319*	*9,145*	*8,537*	*6,960*	D8
4283000	Cirripedia (barnacles)	**6,920**	*1,335*	*2,359*	*2,196*	*1,030*	-
4284000	Mysidacea	**4,353**	*1,111*	*1,166*	*1,150*	*926*	D9
4286000	Isopods	**3,868**	*1,174*	*913*	*881*	*900*	-
4287000	Amphipods	**14,900**	*3,369*	*4,089*	*3,922*	*3,520*	D10
4288000	Euphausiacea	**16,522**	*3,456*	*5,246*	*4,307*	*3,513*	D11
4289000	Decapoda	**14,343**	*2,363*	*5,513*	*4,225*	*2,242*	D12
4300000	ECHINODERMATA	**5,665**	*1,021*	*1,609*	*2,127*	*908*	-
4310000	CHAETOGNATHA	**23,740**	*5,508*	*6,333*	*6,549*	*5,350*	D13
4320000	HEMICHORDATA	**2,003**	*521*	*519*	*544*	*419*	-
4330000	TUNICATES	**17,629**	*3,756*	*4,993*	*5,089*	*3,791*	D14
5000000	LARVAL FISH	**49,468**	***13,698***	***16,045***	***11,530***	***8,195***	D15
PLANKTION BIOMASS							
-200	ALL BIOMASS TYPES	**98,612**	***24,032***	***28,623***	***27,162***	***18,795***	**E1**
-201	Total Displacement Volume	**62,466**	*17,506*	*18,700*	*14,641*	*11,619*	*F1*
-202	Total Settled Volume	**7,953**	*1,422*	*1,786*	*2,828*	*1,917*	*F2*
-203	Total Wet Mass	**28,944**	*5,105*	*8,430*	*9,972*	*5,437*	*F3*
-204	Total Dry Mass	**928**	*134*	*297*	*378*	*119*	*F4*
-205	Total Ash-free Dry Mass	**260**	-	-	-	*260*	*F5*

Values in the first column indicate the WOD01 Biological Grouping Code (BGC) for the taxonomic group described in the second column.

Figure 1. Frequency of Coverage for WOD01 Biomass Sampling Depth Intervals.

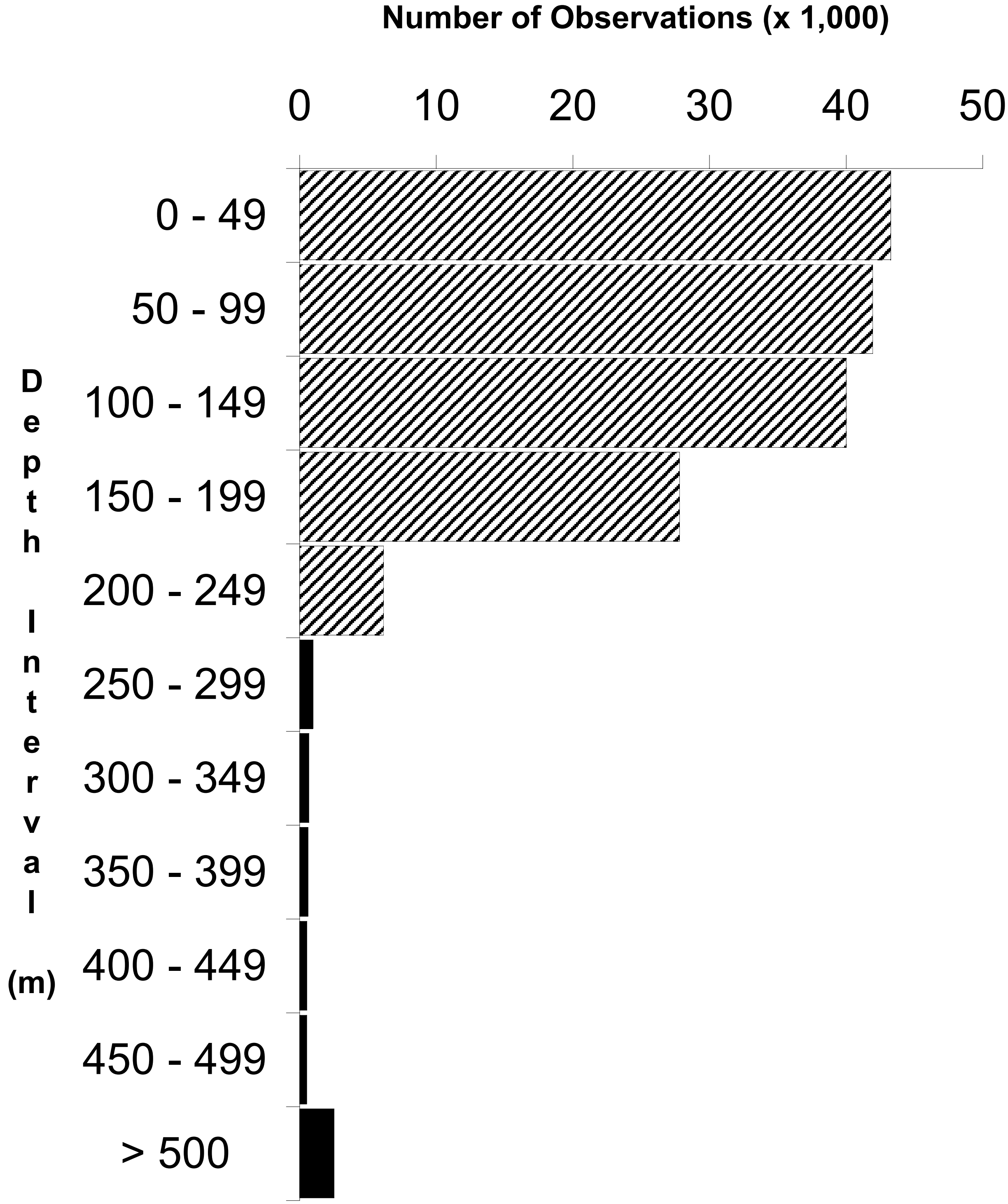
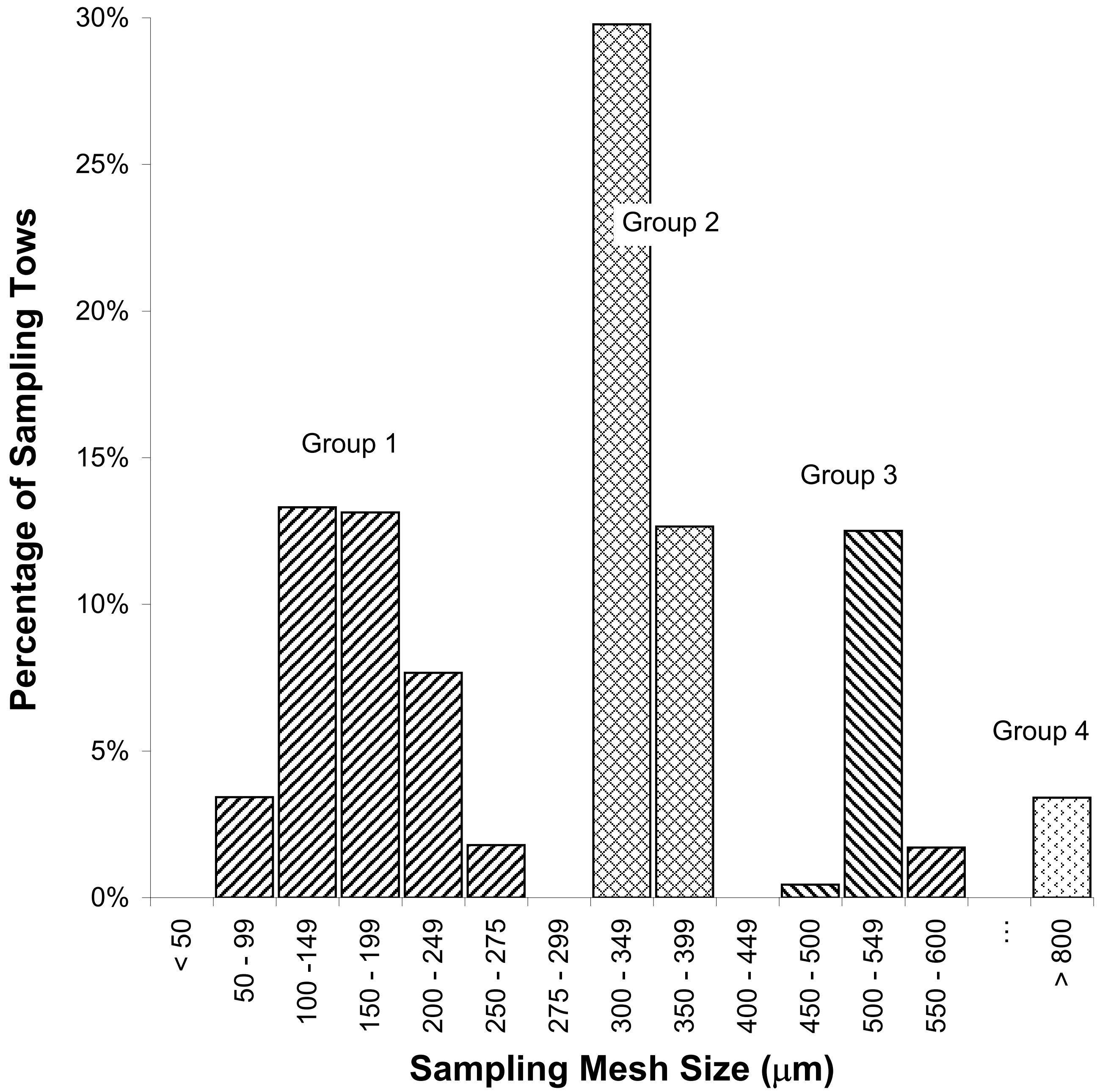


Figure 2. Frequency of WOD01 Biomass Sampling Mesh Size



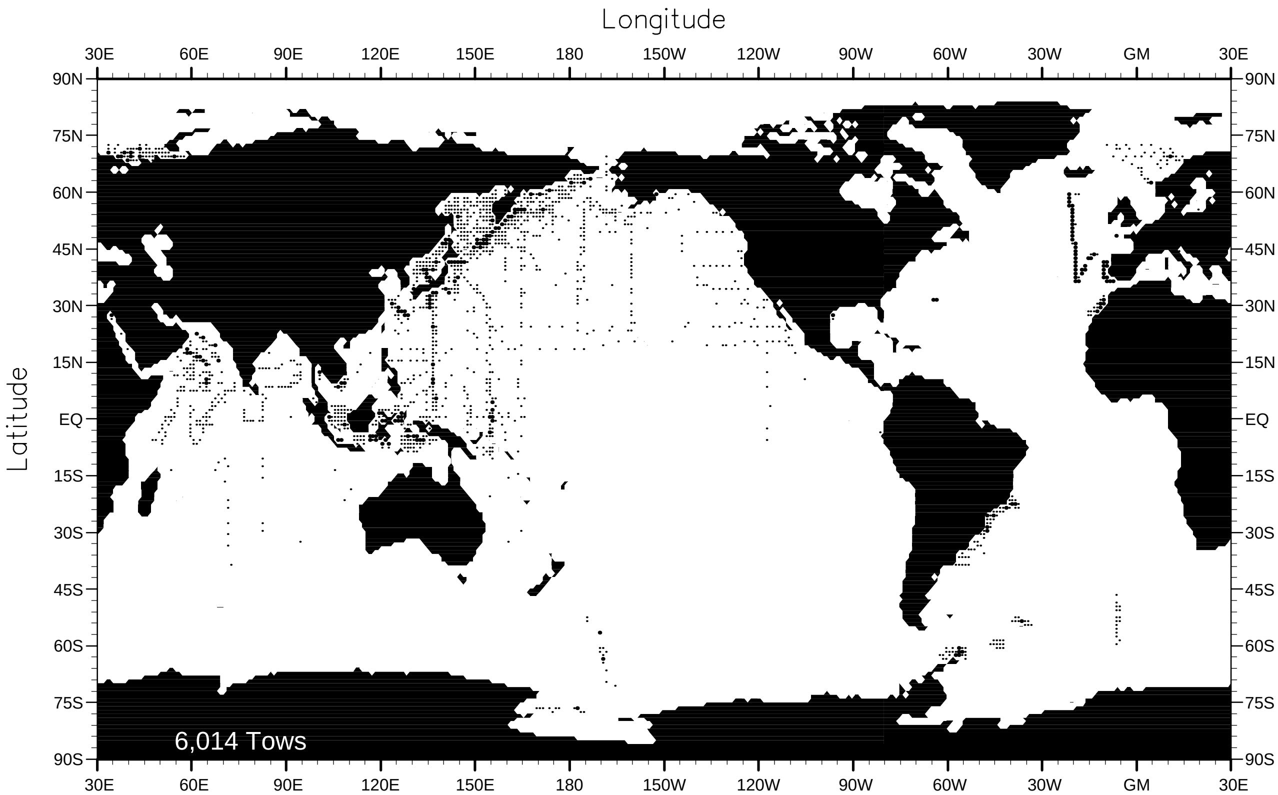


Fig. 3. Distribution of all biomass tows using mesh sizes 50 - 275 µm.

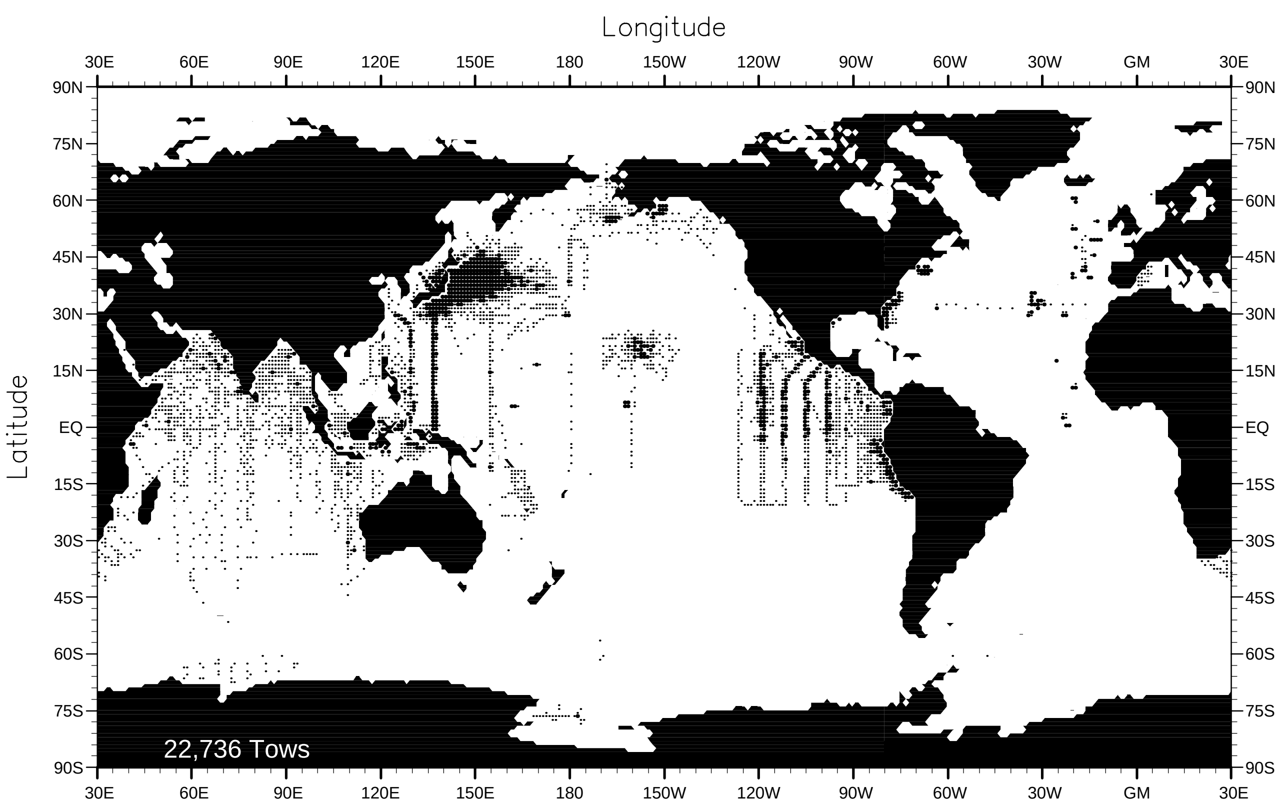


Fig. 4. Distribution of all biomass tows using mesh sizes 300 - 400 µm.

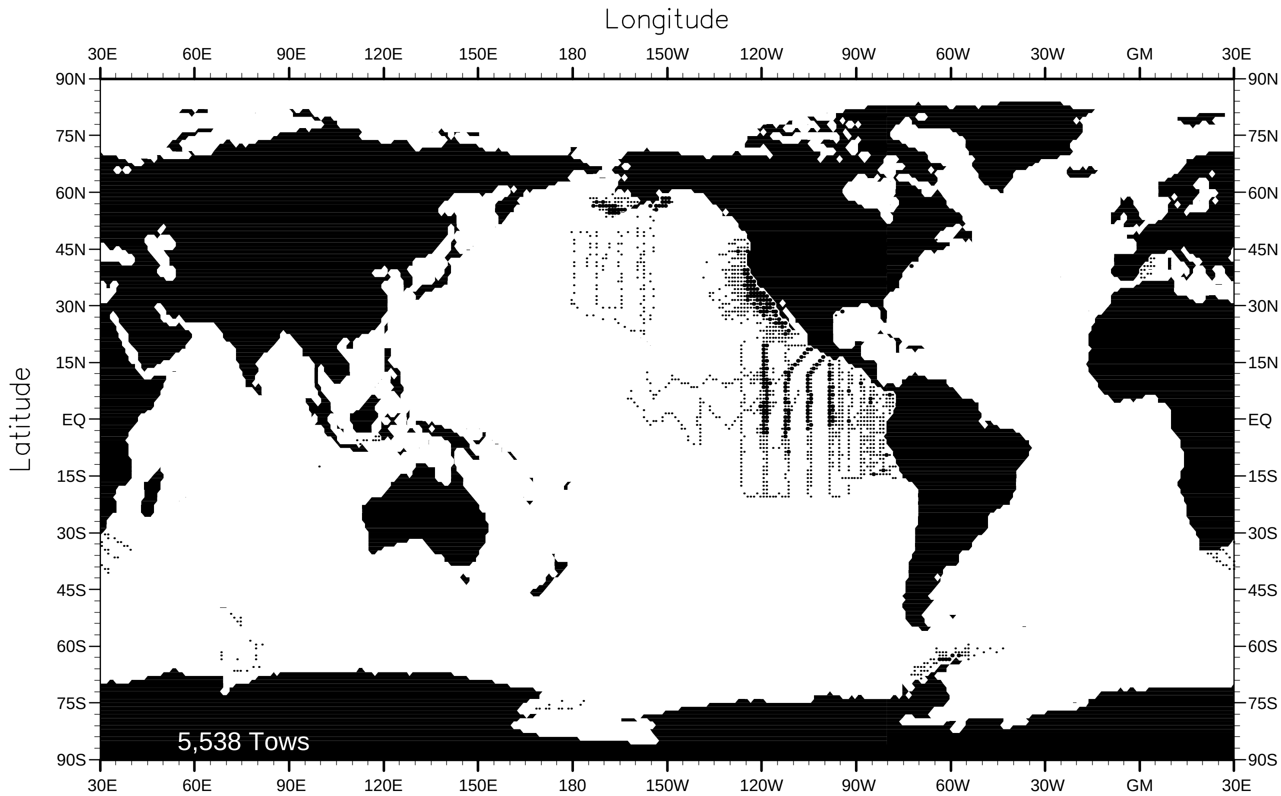


Fig. 5. Distribution of all biomass tows using mesh sizes 450 - 600 µm.

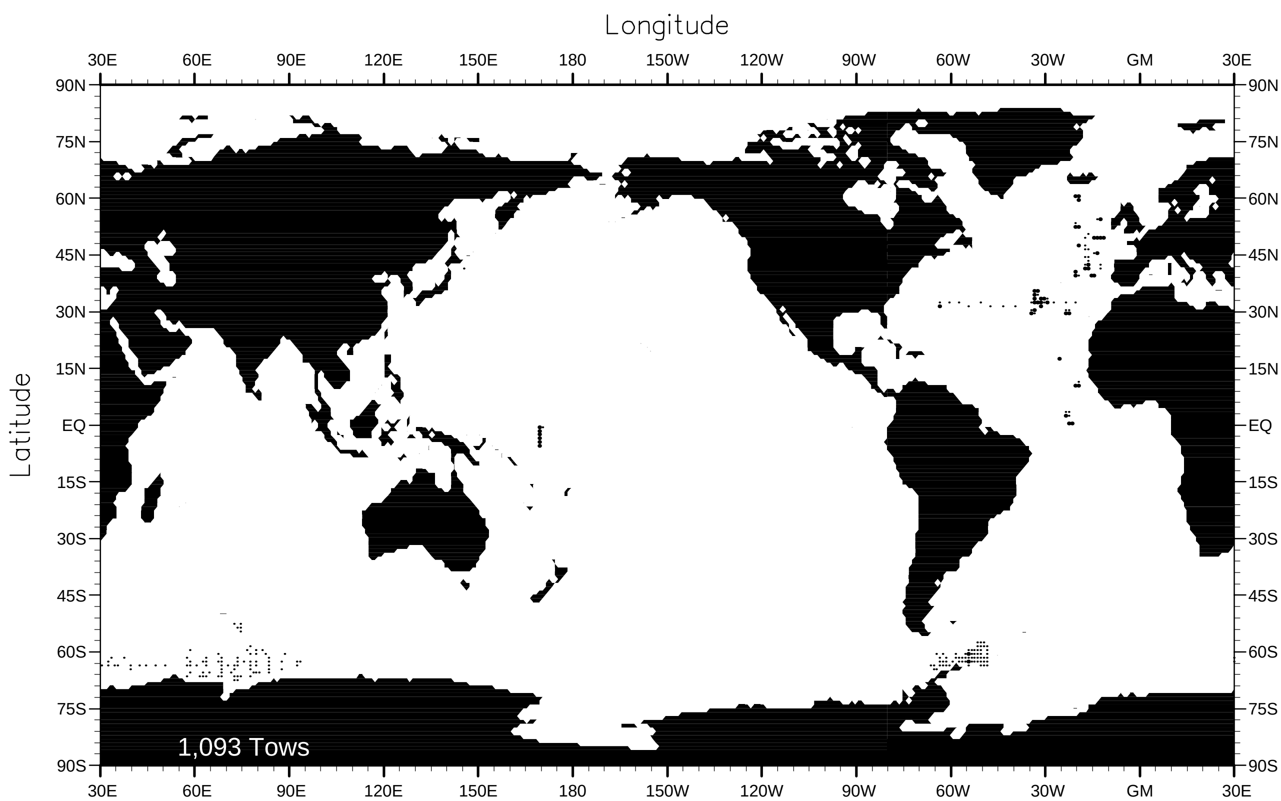


Fig. 6. Distribution of all biomass tows using mesh sizes > 800 µm.