ECCO Version 4 Release 4

Ichiro Fukumori[1], Ou Wang[1], Ian Fenty[1], Gael Forget[2], Patrick Heimbach[3], Rui M. Ponte[4]

[1] Jet Propulsion Laboratory, California Institute of Technology
[2] Massachusetts Institute of Technology
[3] University of Texas at Austin
[4] Atmospheric and Environmental Research, Inc.

24 Apr 2020

Summary

This note provides a brief synopsis of **ECCO Version 4 Release 4 (R4)**, an updated edition to the global ocean state estimate described by *Forget et al.* (2015b, 2016) and *Fukumori et al.* (2017). Release 4 is available at https://ecco.jpl.nasa.gov/drive/files/Version4/Release4.

As of this writing, Version 4 represents the latest ocean state estimate of the Consortium for Estimating the Circulation and Climate of the Ocean (ECCO) (*Wunsch et al.,* 2009; *Wunsch and Heimbach*, 2013) that synthesizes nearly all modern observations with an ocean circulation model (MITgcm, originally described by *Marshall et al.,* 1997) into coherent, physically consistent descriptions of the ocean's time-evolving state covering the era of satellite altimetry. Among its characteristics, Version 4 (*Forget et al.,* 2015b; Release 1 [R1]) is the first multi-decadal ECCO estimate (1992-2011) that is truly global, including the Arctic Ocean. Unlike previous versions, the model uses a nonlinear free surface formulation and real freshwater flux boundary condition, permitting a more accurate simulation of sea level change. In addition to estimating forcing and initial conditions as done in earlier analyses, the Version 4 estimate also adjusts the model's mixing parameters that enables an improved fit to observations (*Forget et al.,* 2015a). The Version 4 synthesis also incorporates a diffusion operator in evaluating model-data misfits (*Forget and Ponte,* 2015) and controls (*Weaver and Courtier*, 2001), accounting for some of the spatial correlation that exist among these elements.

The **Release 2 (R2)** edition of the synthesis (*Forget et al.,* 2016) further incorporated geothermal heating in the model, following the analysis by *Piecuch et al*. (2015) and adjusted global mean precipitation to better match observed global mean sea level time-series observations.

The **Release 3 (R3)** estimate (*Fukumori et al.,* 2017) extended the analysis period to 1992-2015, incorporated new observations (e.g., Aquarius sea surface salinity, GRACE ocean bottom pressure, Arctic hydrographic profiles) and new controls (initial velocity and sea level), and revised the constraints that are employed (e.g., separate anomaly and time-mean constraints).

The present **Release 4 (R4)** synthesis further extends the analysis period to 1992-2017 and incorporates additional changes in the model and estimation as summarized in Table 1 that are further detailed in the sections below.

Changes	Release 4
time period	Extended to 1992-2017
model	Modified chosen algorithm for numerical stability (sea-ice advection scheme, pressure solving criteria).
observations	Updated and expanded observations used (but no new data types)
constraints	Modified weights used for hydrographic profiles (minimize duplicate constraints).
controls	Time-invariant atmospheric controls introduced in Release 3 are no longer separately estimated from time-dependent ones.
output	Includes atmospheric pressure loading; daily output is additionally available.

Table 1: Release 4 Changes from Release 3

1. Time Period

Release 4 covers the period 1992-2017

2. Model

MITgcm's numerical schemes chosen for sea-ice advection and the pressure solver (cg2d) were modified to improve the model's stability. For sea-ice advection, the flux-limited 3rd Order Direct Space and Time (3-DST) scheme is employed in Release 4 (*SEAICEadvScheme* = 33 set in file "data.seaice"), instead of the non-flux limited 3-DST scheme used in Release 3 (*SEAICEadvScheme* = 30).

For *cg2d*, pressure is solved non-dimensionally in Release 4 instead of dimensionally in Release 3; specifically, the parameter specification *cg2dTargetResWunit*=1.E-12 present in Release 3 in the namelist file "data" has been removed in Release 4.

3. Observations

The observations used in R3 (1992-2015) have been updated and extended in time to the 1992-2017 period of R4 (Table 2), where available at the time of computation. In addition, measurements that had not been employed previously have been introduced in the new estimate to better constrain the solution. The new observations include hydrographic data from gliders and moorings. Mean dynamic topography data used has been updated to DTU17MDT.

Variable	Observations
Sea level	TOPEX/Poseidon (1993-2005), Jason-1 (2002-2008), Jason-2 (2008-2017), Jason-3 (2016-2017), Geosat-Follow-On (2001-2007), CryoSat-2 (2011-2017), ERS-1/2 (1992-2001), ENVISAT (2002-2012), SARAL/AltiKa (2013-2017)
Global mean sea level	Average of mean sea level curves from AVISO, CSIRO, NOAA and U.Colorado (1993-2017)
Temperature profiles	Argo floats (1995-2017), XBTs (1992-2017), CTDs (1992-2017), marine mammals (APB 2004-2017), gliders (2003-2017), Ice-Tethered Profilers (ITP, 2004-2017), moorings (1992-2017)
Salinity profiles	Argo floats (1997-2017), CTDs (1992-2017), APB (2004-2017), gliders (2003-2017), ITP (2004-2017), moorings (1992-2017)
Sea surface temperature	AVHRR (1992-2017)
Sea surface salinity	Aquarius (2011-2015)
Sea-ice concentration	SSM/I (1992-2009), SSMIS (2006-2017)
Ocean bottom pressure	GRACE (2002-2016)
TS climatology	World Ocean Atlas 2009
Mean dynamic topography	DTU17MDT

Table 2: Observations employed in Release 4. New items from Release 3 are indicated in red.

3.1 Global mean sea level

Dataset processed by C. Piecuch.

Basic processing follows the description in Fukumori et al. (2018) and includes 60-day smoothing. An updated estimate of the standard error on this 60-day smoothed time series is ~2.7 mm. Series from the following four different processing centers are used:

CSIRO. File “jb_iby_srn_gtn_gin.nc.gz” downloaded from http://www.cmar.csiro.au/sealevel/sl_data_cmar.html on 02/26/2018. The version of the data used for this analysis had IB and GIA corrections made.

NOAA. File "slr_sla_gbl_keep_txj1j2_90.nc" downloaded on 02/26/2018 from https://www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/LSA_SLR_timeseries_global.php. Version of the data used is based on TOPEX and Jason-1,-2, and -3 missions. This version of the data didn't have a GIA correction made, so one was applied post hoc.

AVISO. File MSL_Serie_MERGED_Global_AVISO_GIA_NoAdjust_Filter2m.nc downloaded from https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level/products-images.html on 02/26/2018. File is based on the reference altimetry missions and is corrected for GIA. These series already have a 60-day smoothing applied.

U.Colorado. Data version used here is "2018_rel1" and downloaded from http://sealevel.colorado.edu/files/2018_rel1/sl_global.txt on 02/26/2018. The website notes that important changes from previous releases are (1) now they are basing their estimate on the

RADS database, (2) they are not applying the TOPEX cal-1 mode correction, and (3) they have added Jason-3 GDR cycles 1-70. Details for this data set are given by Nerem et al. (2018).

3.2 *in situ* T and S data

in situ T and S data from several repositories and field programs have been significantly updated in v4r4. In particular, we added data from gliders and instrumented pinnipeds archived in the National Centers for Environmental Information (NCEI) World Ocean Database product

https://www.nodc.noaa.gov/OC5/WOD/pr_wod.html

Maps of the spatial distributions of all *in situ* data constraints and data counts vs. latitude histograms are provided in Appendix A.

3.3 Aquarius

Data provided by N. Vinogradova and R. Ponte

Level 3, version 5.0 data (end of mission release) was originally downloaded on 01/08/2018 from ftp://podaac-ftp.jpl.nasa.gov/allData/aquarius/L3/mapped/V5/monthly/SCI/. Data covered August 2011 to June 2015. Weights used were as in R3 (Fukumori et al., 2018).

3.4 GRACE

Data processed by R. Ponte

Data processing follows exactly that of R3 with details provided in Fukumori et al. (2018). Following files containing JPL RL05 mascon version 2 data were used:

/allData/tellus/L3/mascon/RL05/JPL/CRI/netcdf/GRCTellus.JPL.200204_201706.GLO.RL05M_1.MSCNv02CRIv02.nc (downloaded on 09/28/2017)

/allData/tellus/L3/mascon/RL05/JPL/CRI/mass_variability_time_series/ocean_mass_200204_201701.txt (downloaded 12/15/2017)

Although original data end in June 2017, no data after July 2016 is used because these last months are centered outside of the range of days (12–19) defined to provide a good match between the GRACE month and ECCO model month.

3.5 DTU17MDT

Data processed by R. Ponte

Mean dynamic topography surface DTU17MDT was provided by Per Knudsen on 02/05/2018 (file dtu17mdt2.grd.gz). Details of how DTU17MDT was produced are given by Knudsen et al. (2019). In particular, DTU17MDT is based on the mean sea surface DTU15MSS representing a 20-year mean for the period 1993–2012 and the so-called OGMOC mean geoid (from the Optimal Geoid for Modeling Ocean Circulation project). Processing of data and weights used were as described in Fukumori et al. (2018). DTU17MDT was used to constrain V4r4's mean sea level over the period 1993-2017.

4. Constraints

Weights (data uncertainty estimates) employed in constraining model-data misfits for in situ hydrographic profile data have been revised in Release 4.

4.1 Decimation

Some of the hydrographic data, especially those associated with moorings and gliders, are closely sampled in time compared to typical profiles made by CTDs and Argo floats. For Version 4, which aims to resolve large-scale low-frequency variations of the ocean, data closely sampled in time (e.g., within a day) or space (within 10 km) provide duplicate information. As data error is treated to be uncorrelated in space and time, for computational reasons, such duplicate data would skew the constrained estimate. Thus, for each hydrographic data set, observations were first spatially and temporally decimated by retaining only one profile per day per 10km diameter circle. This decimation process reduces the overall volume of the profile data set by a factor of 2 (Table 3).

Data Set	Before	After
Glider	12.0	0.6
Mooring	5.4	2.3
CTD	11.0	6.9
Argo	11.	10.
ITP	0.7	0.2
APB	11.0	2.3
XBT	13	7
Total	**63**	**30**

Table 3: File size (GB) before and after decimation.

4.2 Additional reweighting

The decimated profile data (Section 4.1) are yet unevenly distributed in space and time. To rectify remaining correlation among the profiles, the data were sorted by space (200kmx200km geodesic bin) and time (month) and weighted such that there is no more than one equivalent profile per area per month across all profile data sets. For instance, data within a geodesic with only daily profiles from a mooring (after decimation in Section 4.1) is assigned a weight of 1/30.

Figure 1 illustrates the weighting factor averaged in time when data is present; regions with high sampling appear with low weights (blue), such as TAO moorings in the tropical Pacific, coastal regions with dense hydrographic sampling (e.g., waters around Japan and the US East Coast), ITP moorings in the Arctic, APB profiles surrounding Antarctica. Geodesics with no available data are shown in black.

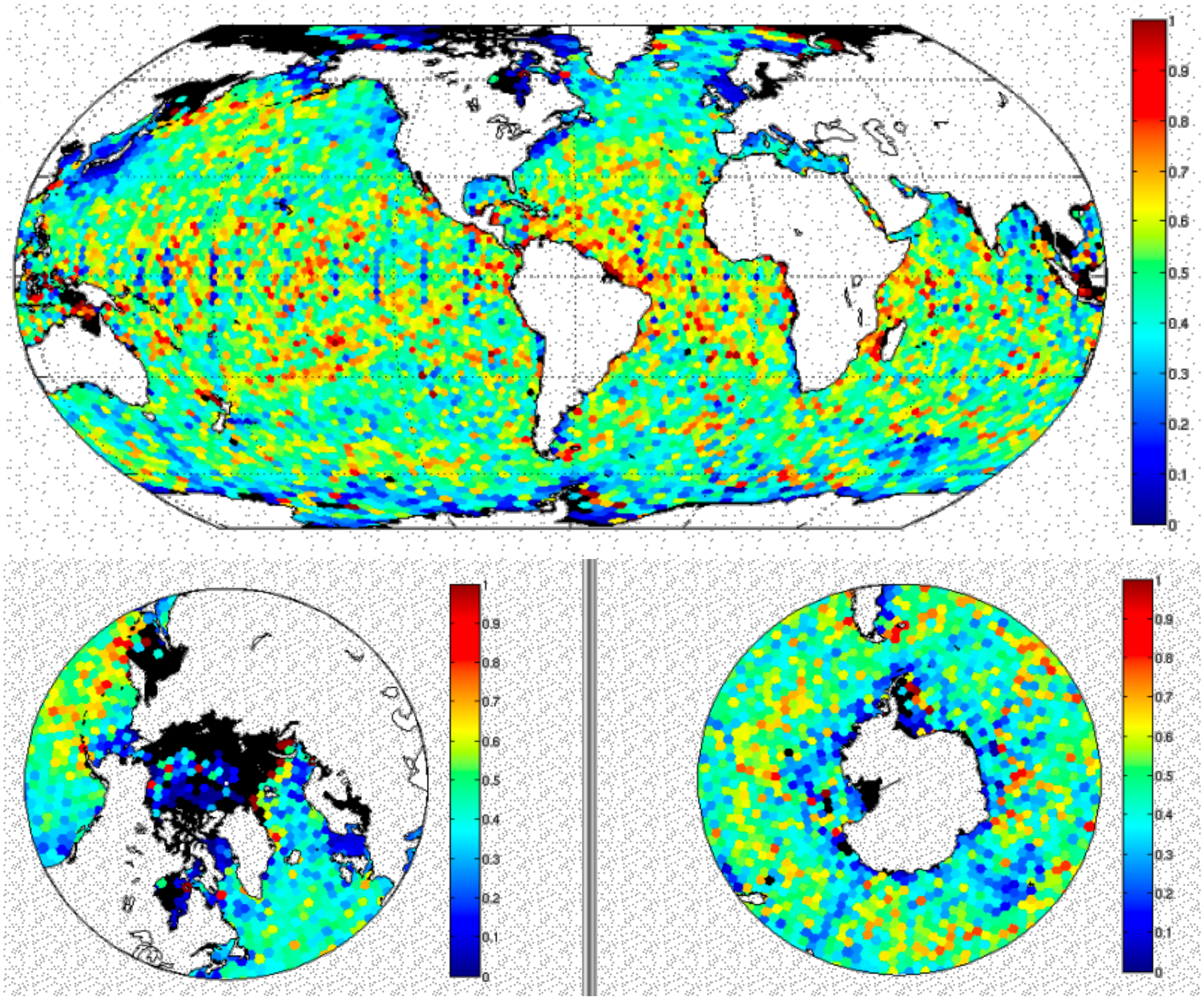


Figure 1: Average weight scaling factor for each geodesic bin.

5. Controls

Time-invariant atmospheric controls first introduced in Release 3 are not separately estimated from time-dependent ones in Release 4. The two were separated to account for temporal correlation in the controls' adjustments. However, continued optimization was not progressing as expected. For the Release 4 estimate, time-mean and time-variable controls were not separately estimated but were optimized as a whole as was performed in R2 and R1, which allowed for a more efficient optimization of model-data misfits.

Note, however, that the time-mean and time-variable split for data constraints introduced in Release 3 is retained in the Release 4 optimization.

6. Output

6.1 Atmospheric Pressure Loading

Although Release 4 ocean state estimation was performed without atmospheric pressure loading, the available output was produced with pressure loading after the fact, so as to allow studies of possible effects of this additional forcing, especially at time-scales shorter than a couple of weeks. The inclusion of atmospheric pressure loading had negligible impact on dynamics and costs at monthly and longer scales, consistent with the largely isostatic (inverse barometer) response expected at these time scales. Dynamic response to pressure loading does affect sub-monthly time scales. In addition, larger initial transients are expected during the first few days of the solution, as part of the initial adjustment to the pressure loading.

The ERA-Interim surface atmospheric pressure fields at 6-hour sampling were used as forcing. To avoid poor resolution of tidal characteristics, the spectral content at 9 tidal frequencies was estimated and removed from the original pressure fields in 3-year moving windows: solar S1 tide (plus four side-bands for seasonal modulations), solar S2 tide (plus two side-bands), and the main semi-diurnal lunar tide M2. The spectral filtering was done by Michael Schindelegger (U. Bonn). Along with the model state, the forcing atmospheric pressure fields, which were not adjusted by the optimization, are provided for reference (e.g., to apply inverse barometer corrections to the model sea level output).

6.2 Daily Mean Output

To allow for studies at sub-monthly time-scales, daily mean fields of the Release 4 solution are available. This is in addition to the monthly means that have been the standard product of previous Version 4 solutions. All fields that are available as monthly means are also available as daily mean fields, including fluxes for budget analyses. Note, however, that Release 4's estimation does not directly control daily variations of the model. For instance, although the estimation evaluates model-data misfits at the measured instances, the optimization adjusts atmospheric forcing only at biweekly intervals (corrections are interpolated in between.)

Subset of daily mean fields available on the ECCO drive

https://ecco.jpl.nasa.gov/drive/files/Version4/Release4

Complete set of daily mean fields on the ECCO Data Portal at NASA Ames

https://data.nas.nasa.gov/ecco/data.php?dir=/eccodata/llc_90/ECCOv4/Release4

Complete set of daily mean files are also online at Ames in the directory
/nobackupp2/dmenemen/public/llc_90/ECCOv4/Release4

Acknowledgments

This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

Forget, G., J. M. Campin, P. Heimbach, C. N. Hill, R. M. Ponte, and C. Wunsch (2015b), ECCO version 4: an integrated framework for non-linear inverse modeling and global ocean state estimation, *Geosci. Model Dev.*, *8*(10), 3071-3104, doi:10.5194/gmd-8-3071-2015.

Forget, G., J.-M. Campin, P. Heimbach, C. N. Hill, R. M. Ponte, and C. Wunsch (2016), ECCO version 4: Second Release, http://hdl.handle.net/1721.1/102062.

Fukumori, I., O. Wang, I. Fenty, G. Forget, P. Heimbach, and R. M. Ponte (2017), ECCO Version 4 Release 3, http://hdl.handle.net/1721.1/110380, doi:1721.1/110380.

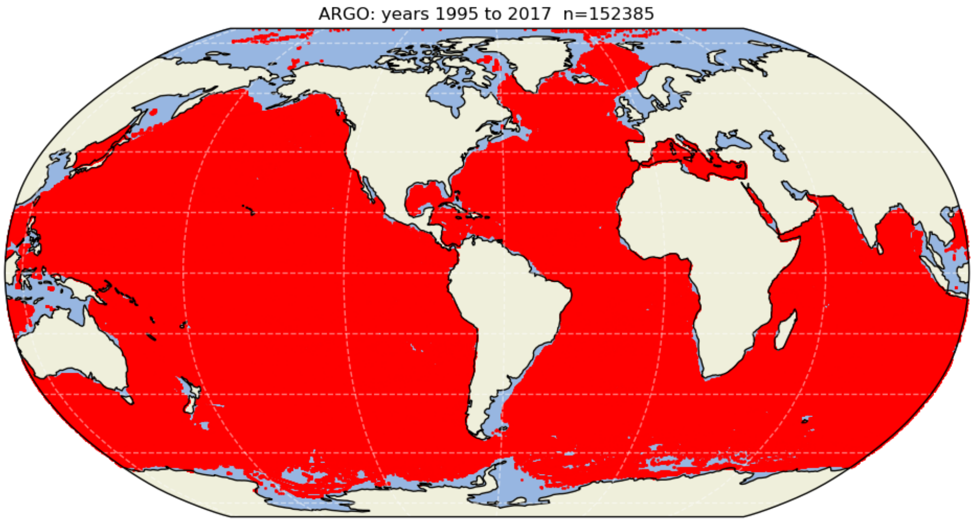
Fukumori, I., I. Fenty, G. Forget, P. Heimbach, C. King, A. Nguyen, C. Piecuch, R. Ponte, K. Quinn, N. Vinogradova, and O. Wang (2018), Data sets used in ECCO Version 4 Release 3, http://hdl.handle.net/1721.1/120472.

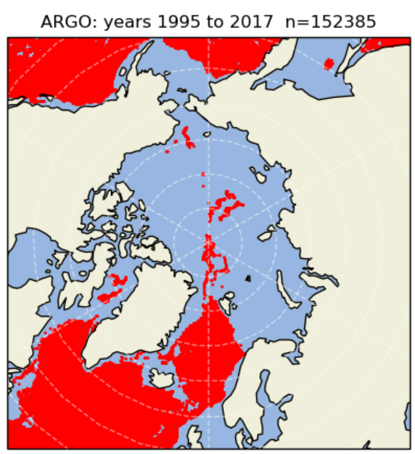
Knudsen, P., O. Andersen, and N. Maximenko (2019) A new ocean mean dynamic topography model, derived from a combination of gravity, altimetry and drifter velocity data, *Advances in Space Research*, https://doi.org/10.1016/j.asr.2019.12.001.

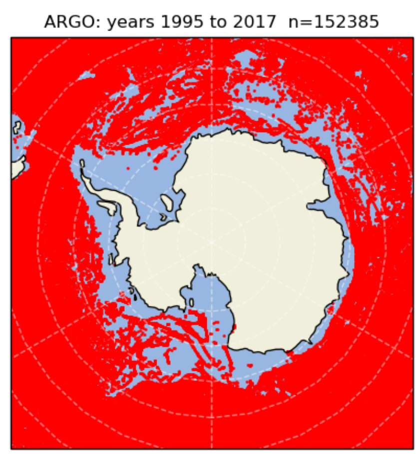
Nerem, R. S., B. D. Beckley, J. T. Fasullo, B. D. Hamlington, D. Masters, and G. T. Mitchum (2018), Climate-change-driven accelerated sea-level rise detected in the altimeter era, *Proc. Natl. Acad. Sci., 115*, 2022-2025, https://doi.org/10.1073/pnas.1717312115.

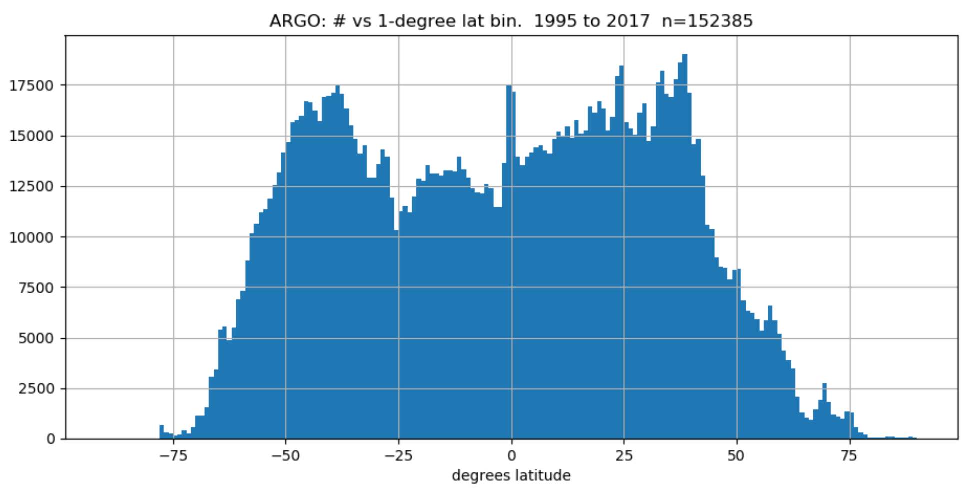
Appendix A: in situ T and S data distributions

Argo

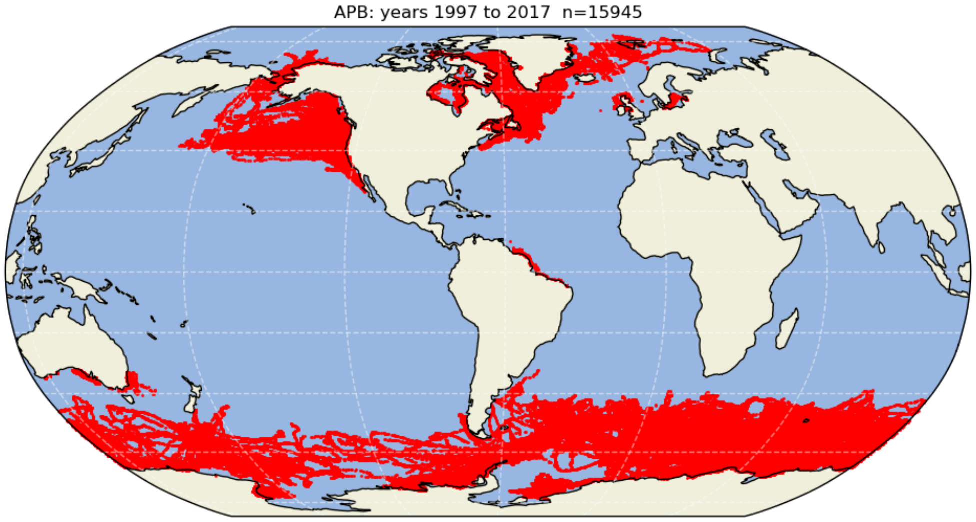


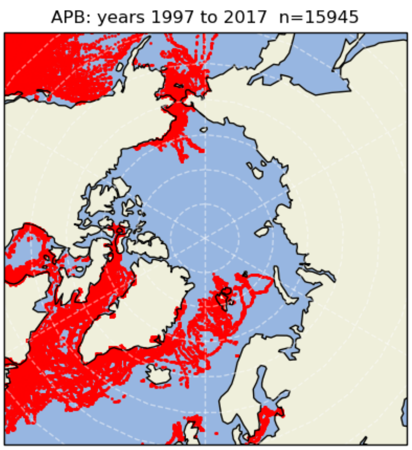


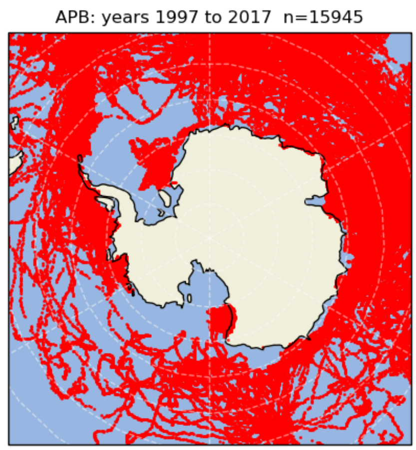


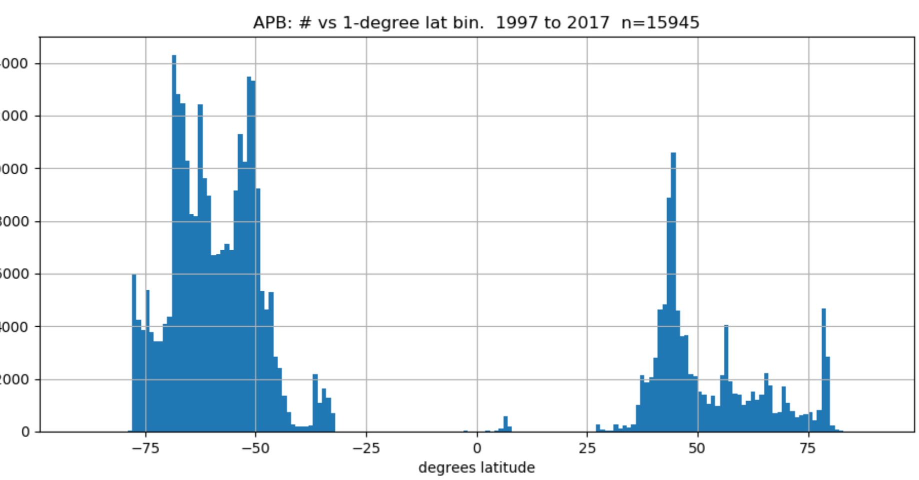


Instrumented Pinnipeds (APB) [NODC]

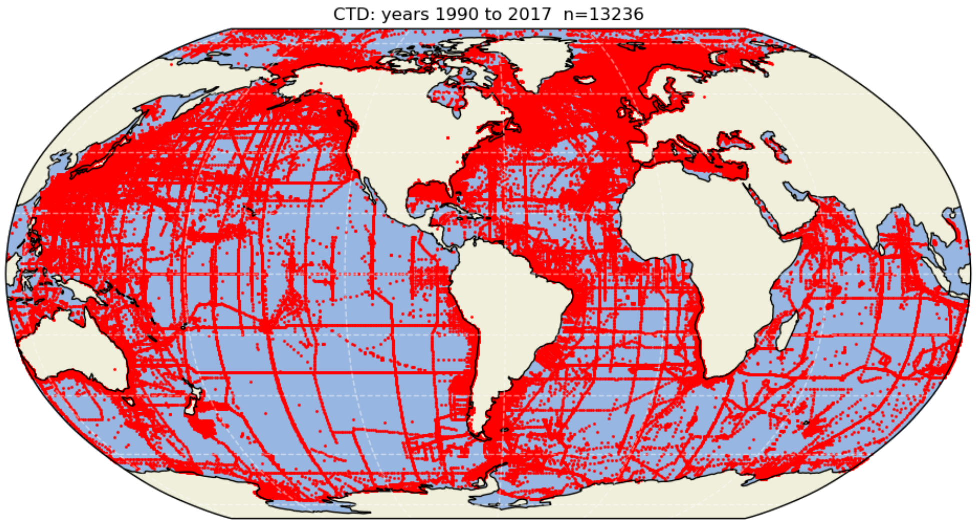


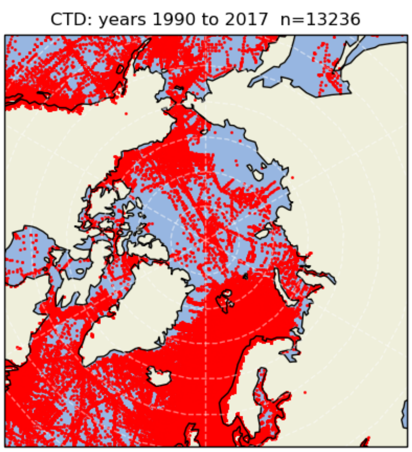


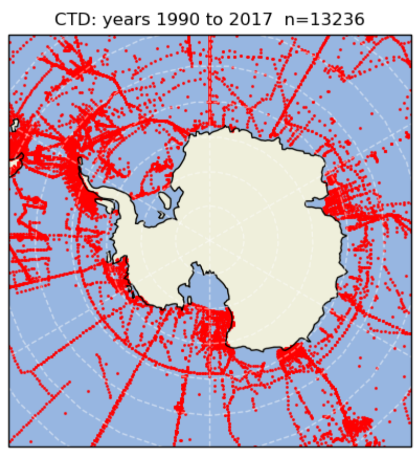


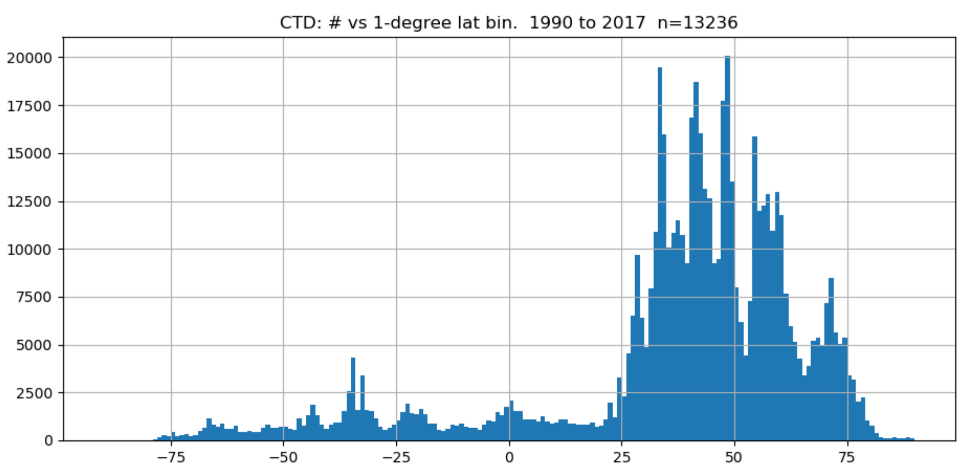


CTD [WOCE/CLIVAR & OTHERS]

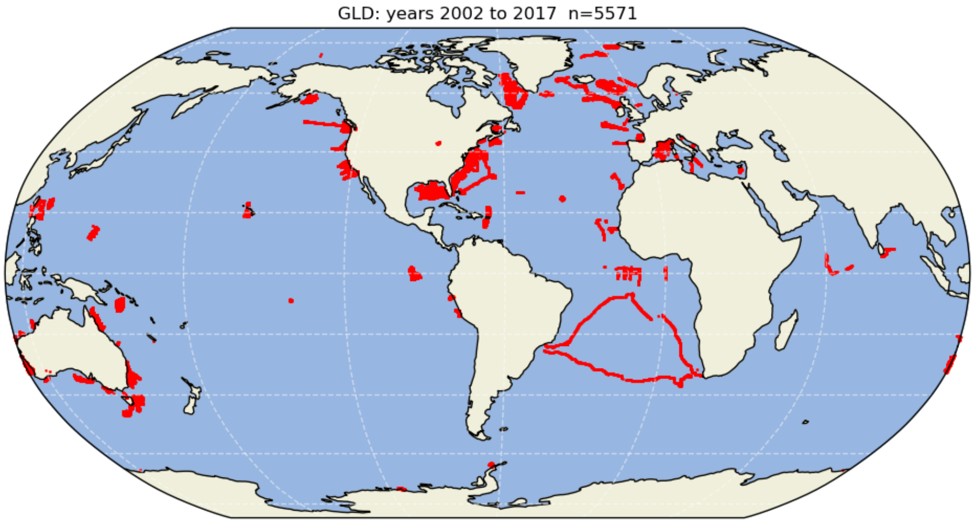


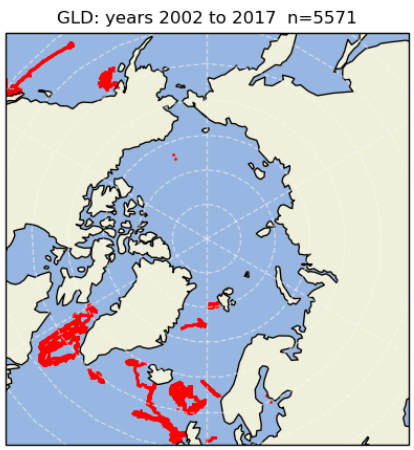


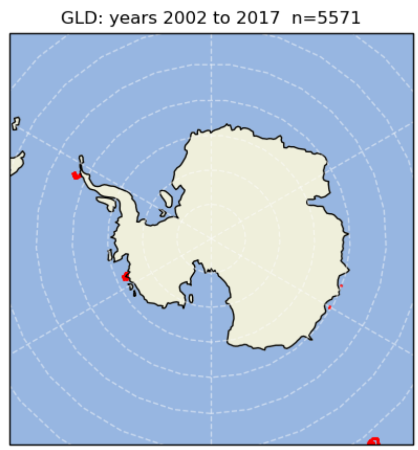


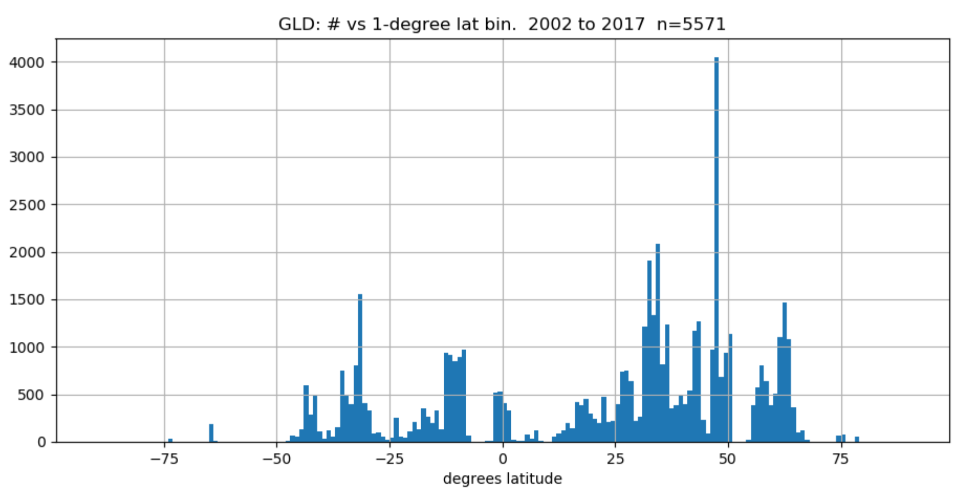


Gliders

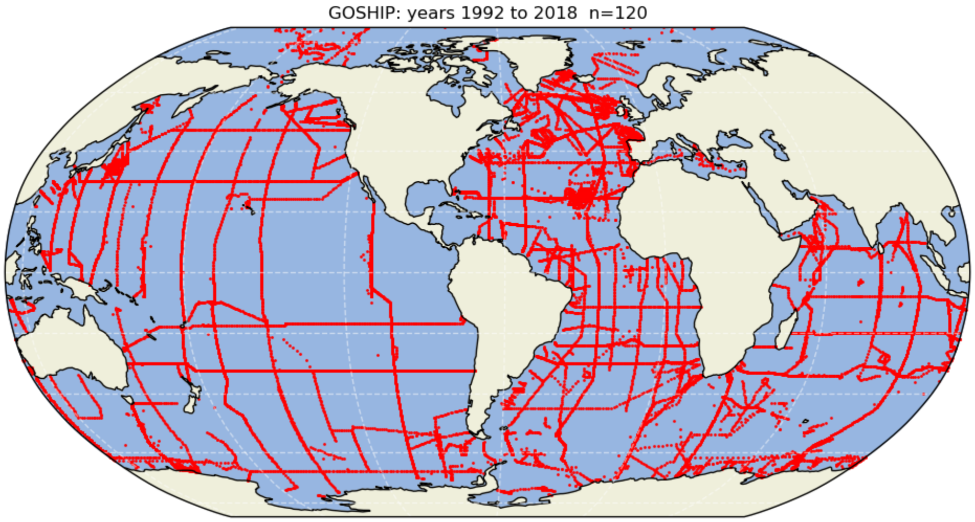

GLD: years 2002 to 2017 n=5571

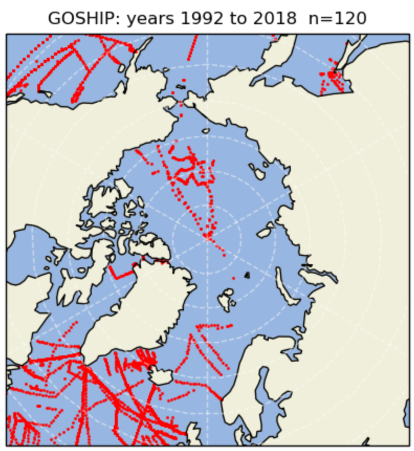

GLD: years 2002 to 2017 n=5571

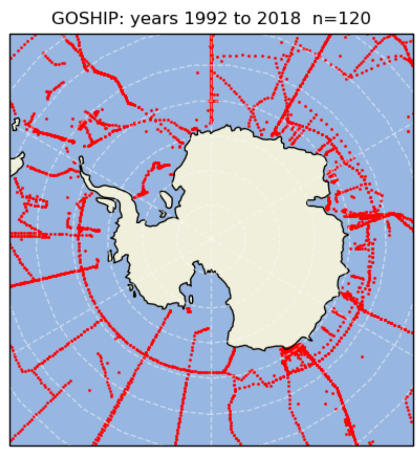

GLD: years 2002 to 2017 n=5571

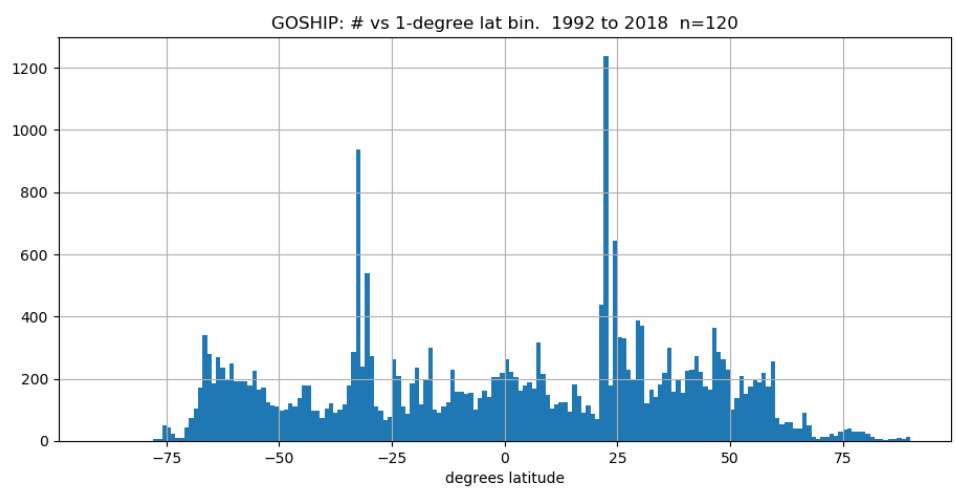

GLD: # vs 1-degree lat bin. 2002 to 2017 n=5571
4000
3500
3000
2500
2000
1500
1000
500
0
−75
−50
−25
0
25
50
75
degrees latitude

GO-SHIP

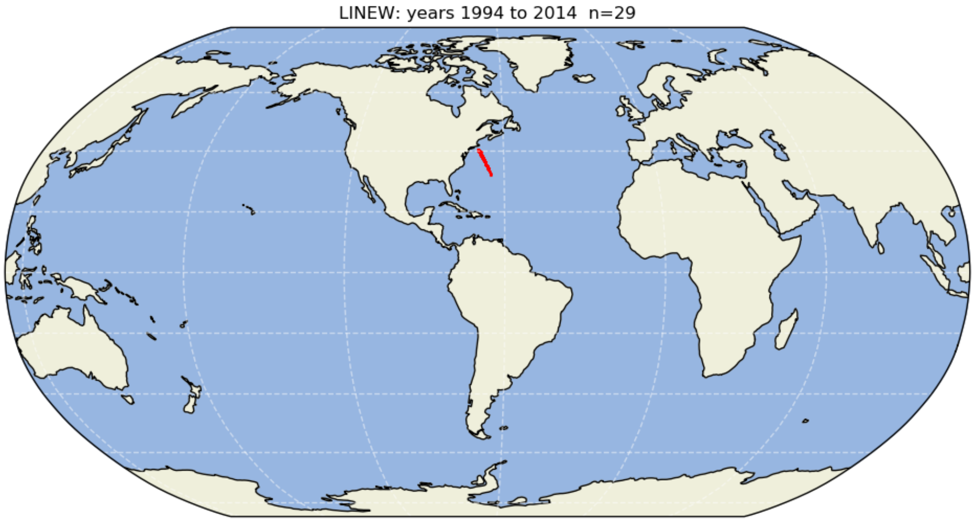

GOSHIP: years 1992 to 2018 n=120

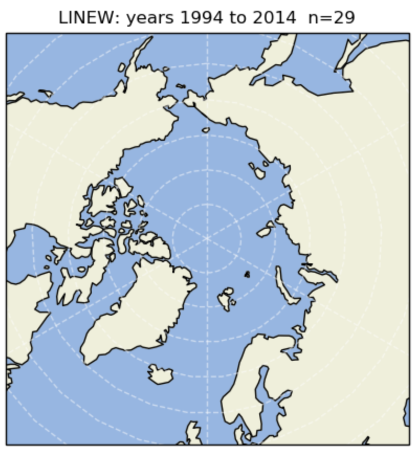

GOSHIP: years 1992 to 2018 n=120

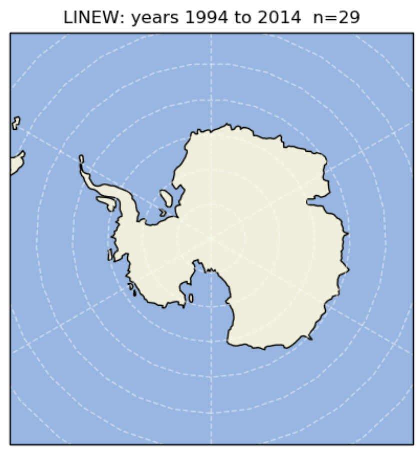

GOSHIP: years 1992 to 2018 n=120

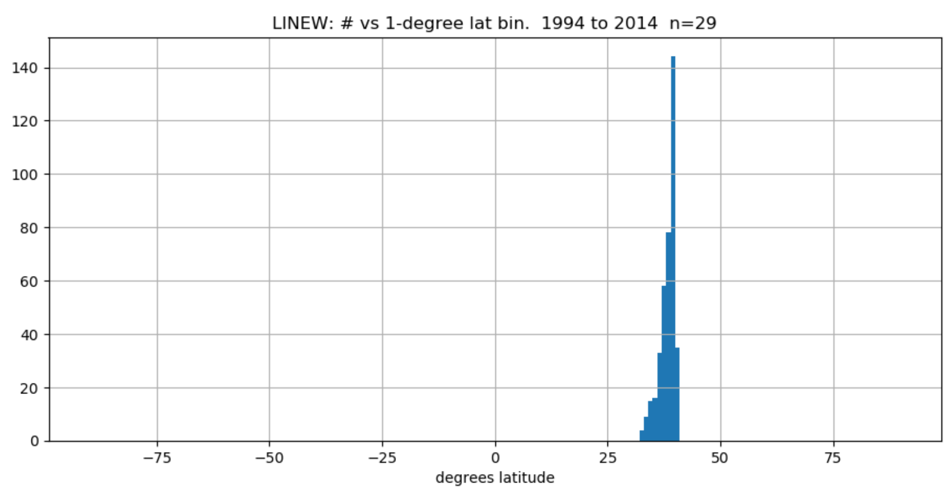

GOSHIP: # vs 1-degree lat bin. 1992 to 2018 n=120
1200
1000
800
600
400
200
0
−75
−50
−25
0
25
50
75
degrees latitude

Line-W

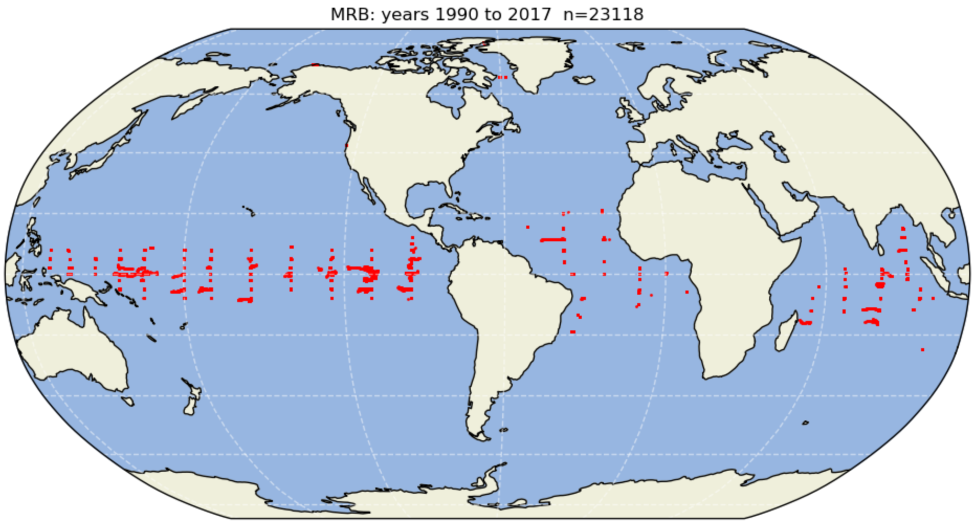

LINEW: years 1994 to 2014 n=29

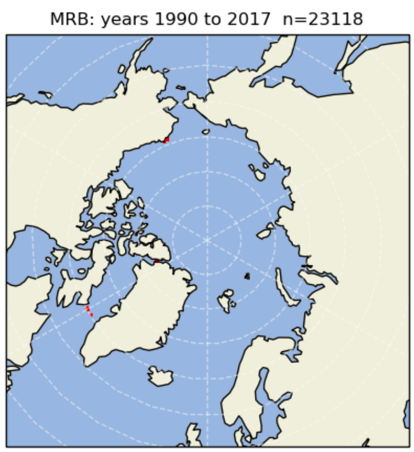

LINEW: years 1994 to 2014 n=29

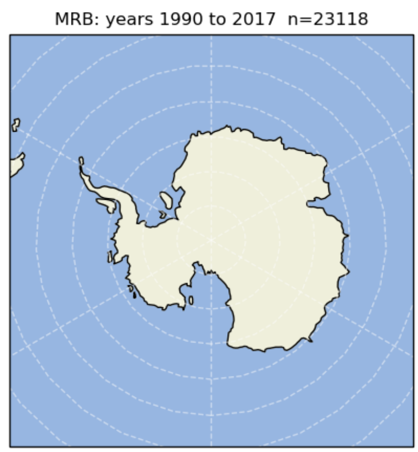

LINEW: years 1994 to 2014 n=29

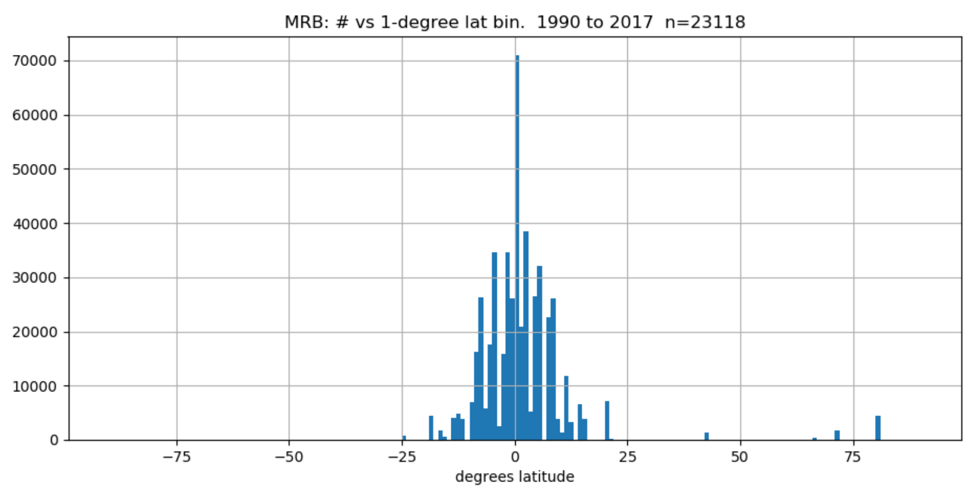

LINEW: # vs 1-degree lat bin. 1994 to 2014 n=29
140
120
100
80
60
40
20
0
−75
−50
−25
0
25
50
75
degrees latitude

Moorings (MRB)

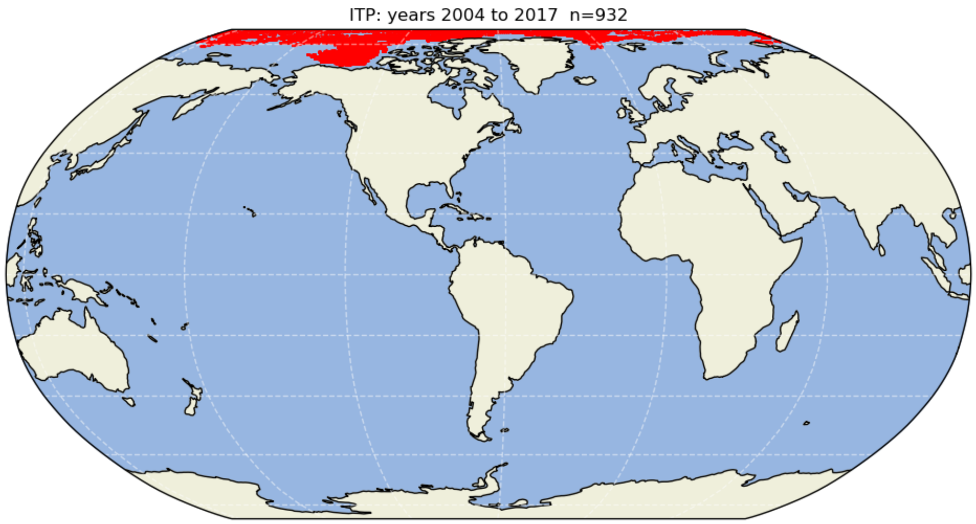


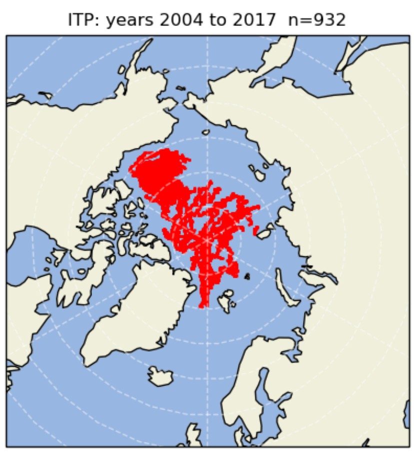


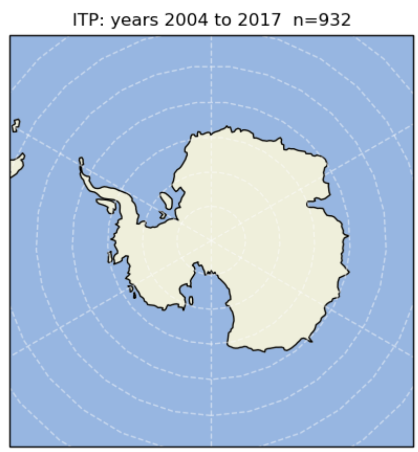


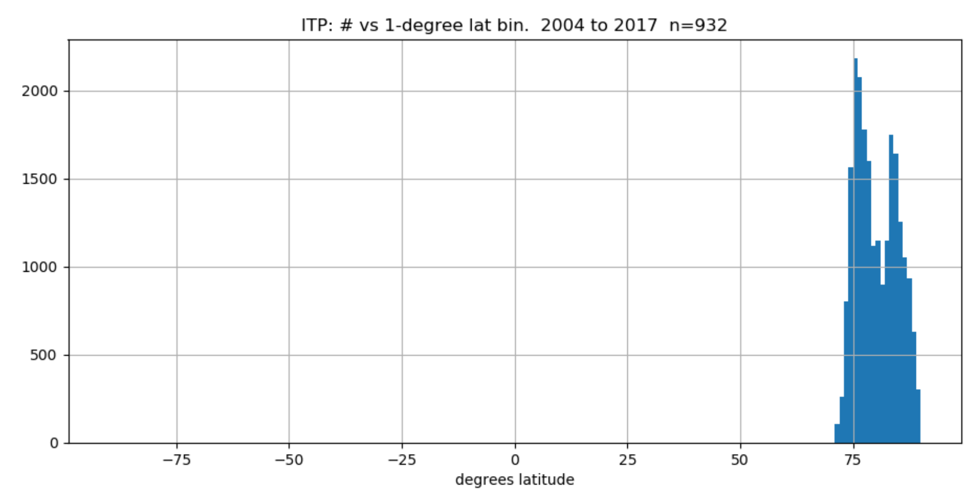


Ice-Tethered Profilers (ITP)

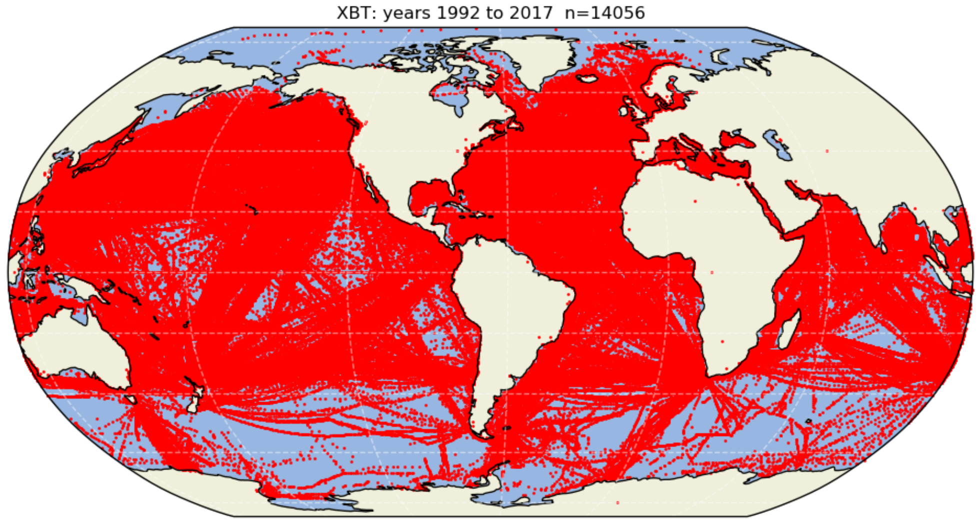


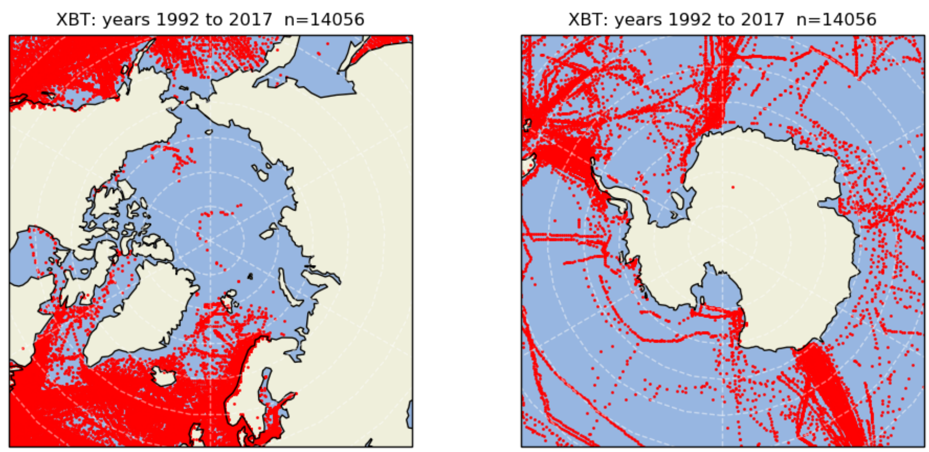


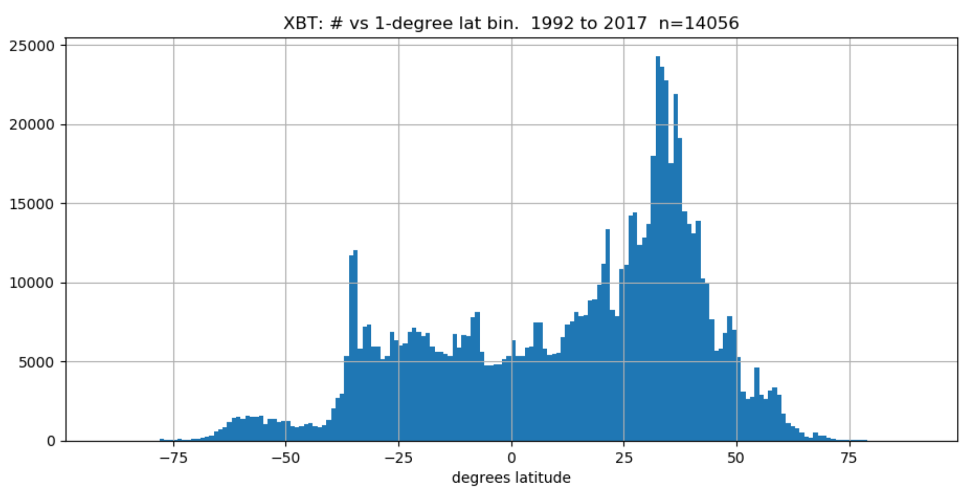




XBT


XBT: years 1992 to 2017 n=14056


XBT: years 1992 to 2017 n=14056
XBT: years 1992 to 2017 n=14056


XBT: # vs 1-degree lat bin. 1992 to 2017 n=14056
25000
20000
15000
10000
5000
0
−75
−50
−25
0
25
50
75
degrees latitude