Steps towards a global and interdisciplinary deep ocean observing system

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Characteristics of an optimized deep ocean observing system

- Global full depth (> 200 m or > 2000 m) coverage
- International consensus by agencies and the scientific community
- Synergistic and multidisciplinary
- Sustainable: Cost-effective and adapted to resources
- Key objectives are well defined and adapted to societal needs
- Free and easy data access, available in near real time and delayed mode quality control
- Effective partnership between academic institutions and the industry
- Platforms and sensors compatible with long-term operational use
- Availability of diverse commercial suppliers
- Gradual implementation of new technology after thorough testing in the lab and field
- Products available to facilitate data use
Deep Argo is quickly increasing deep ocean sampling

- 10% of historical temperature and salinity profiles extend below 2000 m
- Deep Argo floats provides seasonally unbiased data
- In <7 years, Deep Argo has accumulated in regional pilot arrays about as many full-depth profiles as ships over the past 70 years (Zilberman et al., 2023)
- Deep Argo data supplement measurements collected from other deep ocean observing systems

Zilberman et al., 2023

GO-SHIP

OceanSITES
Global Implementation of Deep Argo

- Full-depth temperature and salinity data source
- Objective to reduce errors in decadal trends of deep OHC from ±0.04 to ±0.006 W m⁻² dec⁻¹ (Meyssignac et al., 2019), and deep steric sea level from ±0.73 to ±0.1 mm dec⁻¹ (Johnson et al., 2015)
- Assuming an averaged Deep Argo float longevity of 4 years, implementing a 1250-float global array size would require 300 float deployments per year among all international partners

Global 1,250 Deep Argo float array
5° x 5° x 10-day sampling

Johnson et al. (2015)
Deep Argo objectives: Improve Ocean Heat Content (OHC) estimates

- The Earth system has warmed for the past 150 years
- 89% of the excess heat is stored in the ocean, including 8% below 2000 m depth
- Global decadal trends of deep OHC show large uncertainties comparable to signal (0.06 ±0.03 W m$^{-2}$ from 1990 to 2020)
- Earth system and ocean warming are accelerating since 1960. Due to sparse ocean sampling below 2000 m, our ability to measure the deep-ocean contribution is limited.
Ability of Deep Argo to close the Earth Energy Imbalance

- Confidence limits of deep-ocean warming rates from Deep Argo are 10 times tighter than historical data in the Argentine Basin, and 2 times tighter than historical data in the Brazil Basin.

- Deep Argo indicates an acceleration of abyssal warming in the Southwest Pacific in 2010s compared to 1990-2000s and 2000-2010s.

- Deep Argo float measurements show warming to cooling reversal in the deep subpolar Atlantic Ocean in 2014.

Zilberman et al., 2023
The ocean warming contributes to sea-level rise, which is also accelerating. Besides instrument error or noise (Argo and satellite data), sparse sampling of the deep ocean is likely a contributor to the non-closure of the global or regional sea-level budget (Royston et al., 2020; Barnoud et al., 2021).
Ability of Deep Argo to close the sea level budget

Deep Argo based steric sea level in the upper 2000 m and deep ocean below

Deep Argo vs Geodetic sea level estimates of steric sea level over the full ocean depth

- Deep Argo measurements show deep steric sea level contributing up to 40% of full-depth steric sea level
- Interannual variations of steric sea level below 2000 m show no significant correlation with the upper ocean (< 2000 m)
- Measuring steric sea level over the full water column is needed to improve estimates of the steric contribution and close the sea level budget

Zilberman et al., In prep
Deep Argo objectives: Improve ocean model predictions

- The addition of global and frequent deep-ocean observations improves the representation of deep-ocean processes and can prevent unrealistic drifts in ocean model (up to 0.05°C difference in temperature and 0.005 PSS-78 in salinity)

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Gasparin et al., 2020

**Zonally averaged 2009-2013 mean Temperature and Salinity Error**

- **UPPER experiments** = « core Argo » data assimilated
- **FULL experiments** = « deep Argo » data assimilated
Ability of Deep Argo to better constrain and validate deep-ocean variability in ocean reanalysis

- Annual signal in Steric sea level greater in Deep Argo than GLORYS reanalysis. 2-month phase difference
- Both Deep Argo and GLORYS show stronger contribution of temperature compared to salinity
Deep Argo’s new objective: Measure Ocean Bathymetry

Zilberman et al., In prep

- >10,000 Deep Argo based bathymetry comparisons with multibeam show small rms difference of 165 m, high correlation of 0.96, and limited averaged horizontal error of 1.4 km.
- Difference between Deep Argo and original depth highlights the improvements from the Deep Argo dataset. Black lines show 100 m contours with no zero contour. Maximum corrections are ~200 m.
Deep Argo Sensor Development

To manage the progress of sensors from experimental to fully approved, Argo considers sensors and parameters to be in one of three stages (https://argo.ucsd.edu/expansion/framework-for-entering-argo/)

- **Stage I**: Experimental deployments < 10 floats. Data is distributed in Argo auxiliary files.

- **Stage II**: Global Argo Pilot ~ 100 floats. Approved by the Argo Steering Team (AST) based on technological readiness, compelling global design, major benefits to society and a solid implementation plan. Argo general guidelines need to be met and all the meta, technical and profile variables must be defined. QC methods are being developed at this stage. Data are distributed on the main Argo data system with appropriate QC flags.

- **Stage III**: Global Implementation > 1000 floats. Approved by the AST. Need approval from Intergovernmental Oceanographic Commission (IOC) Executive council if new Argo parameter. QC methods are finalized.

**Oxygen** About 30% active Deep Argo floats are equipped with oxygen sensors. Ongoing work focused on improving DO sensor performance to increase ability to resolve fluctuations in the deep ocean signal. Stage II.

**Ocean Mixing** Prototype under development

**Ocean Scattering** Prototype under development
Status of the Deep Argo float array

- 194 Deep Argo floats are currently active
- Deep Argo floats have been deployed in deep areas and nearby dense water mass formation regions
- 95 Deep Argo float deployments planned in 2024
- Objectives beyond 2024 to
  - Maintain and extend existing arrays to lengthen time series
  - Deploy new arrays in key regions to reach global coverage
What is a Deep Argo float?

- Profile temperature and salinity to 4000-6000 m at nominal 10-day sampling
- Since each Deep Argo float replaces a Core Argo float in the OneArgo design, a minimum lifetime of at least 4 years, approaching the averaged 5.5-year Core Argo float longevity, is desired
- Data shared publicly in near real-time and QCed version
- Floats can profile to maximum depth on ascent and/or descent
- Measurements on ascent at least in the upper 1000 m
- Vertical resolution is 2-dbar bin-averaging in the upper 2000 m, and 10-25-dbar below 2000 m
- Transition to parking depth at 1000 m
- Prioritize deployments in deep ocean regions (> 2000 m)
Active Deep Argo float models

- 70% of active Deep Argo floats are capable of profiling to 6000 m
- 30% of the Deep Argo fleet can measure to 4000 m
- 2 additional Deep Argo float models are under development
- Averaged Deep Argo float lifetime has reached 4.7 years
Deep Argo CTD Sensor Status

- Targeted accuracies of temperature, salinity, and pressure ±0.001°C, ±0.002 PSS-78, and ±3 dbar

- 2 Deep Argo CTDs from SeaBird Scientific are operational. A pilot CTD from RBR is under testing

- SBE61 has demonstrated ±0.001°C accuracy in the field

- A method was successfully implemented to reduce salinity bias to ±0.002 PSS-78 on the extended-depth SBE41 and the SBE61

- Pilot SBS61 Deep Argo CTD (SBE61 with Keller pressure sensor) shows ±3 dbar in the field

Testing of the SBS61 on the Deep SOLO float by the Scripps Argo lab
Recommendations for Argo data use

Use of quality flags and adjusted Argo profiles to filter “bad” data

- **Biased raw** Argo salinity leads to **spurious results in global sea level estimates**
- Best ways to ensure that instrument bias is filtered out is to **use delayed mode (adjusted) data**
- Detailed quality control flags, delayed-mode process, validation of the adjusted salinity, and associated uncertainty estimates are described in Wong et al (2023; https://doi.org/10.5194/essd-15-383-2023)

Argo is a living dataset. Need to refresh analysis archives with DMQ Ced Argo data

When using Argo profiles from the GDACs, make sure to stay up to date:
- Download a recent monthly DOI tarball:  [https://doi.org/10.17882/42182](https://doi.org/10.17882/42182)
- Use rsync to keep your local mirror up to date:  [http://www.argodatamgt.org/Access-to-data/Argo-GDAC-synchronization-service](http://www.argodatamgt.org/Access-to-data/Argo-GDAC-synchronization-service)
- Make a selection on the Argo data selection tool:  [https://dataselection.euro-argo.eu/](https://dataselection.euro-argo.eu/)
- Select Argo data via ERDDAP:  [www.ifremer.fr/erddap/index.html](http://www.ifremer.fr/erddap/index.html)

When using an Argo product created by a third party and listed on this webpage  [https://argo.ucsd.edu/data/argo-data-products/](https://argo.ucsd.edu/data/argo-data-products/), be aware that the Argo data in that product may not be up to date. Contact the producers for more information.
Deep Argo RT (real time) corrections and DM (delayed mode) adjustments have largely improved in 2023

- A method correcting conductivity cell compressibility with pressure (Cpcor) was successfully implemented, increasing Deep Argo salinity accuracy to targeted value of ±0.002 PSS-78
- ~ 81 % (vs 48% in 2022) of the salinity profiles have been corrected with a new Cpcor value either in A mode or D mode
- 69 % (vs 26% in 2022) of the Real Time data is adjusted with a new Cpcor value
- Large improvement in Deep Argo data quality control in 2023 compared to 2022, both for near real time and delayed modes

2022
- 329 Deep Argo floats – 30,165 profiles

2023
- 373 Deep Argo floats – 38,529 profiles

** Statistics on 35171 profiles with PROFILE_PSAI_QC # F

from 6 DACs : aoml, bodc, coriolis, csio, csiro, jma
Priority to facilitate usage of Argo data with data products

https://argo.ucsd.edu/

Argo data products

Argo's more than 3500 floats provide 100,000 plus temperature and salinity profiles each year which create a large data set available on the Argo GDACs. As an alternative to using individual profiles from the GDACs, different groups around the world have produced various products based on Argo data. While these products include Argo data, they are not maintained by Argo itself. These products fall into the following categories:

- Gridded fields of temperature, salinity, mixed layer depth, etc.
- Velocity products
- Collections of profiles that have all been interpolated to the same pressure levels (standard depth level profiles)
- Collections of profiles that have been put through additional quality control measures

Below you will find links to the gridded products. Please click the other links above to access other Argo products or visit our operational center page to look at data from model outputs using Argo.

While each producer makes every effort to remove errors from their product, some might still exist. Therefore, users are reminded that these products are to be used cautiously. Please notify the producer if an error is discovered. Please credit the product appropriately.

If you have gridded fields or other products based on Argo data that you would like added to this page, please email argo@ucsd.edu with all the necessary data for the table.

If using one of these products in a publication, please remember to acknowledge Argo data with the following statement and the Argo DOI.
A growing literature demonstrating the value of the Deep-Argo data

- To track uptake and impact, we ask that where Deep Argo data are used (e.g. publication, product, etc) an acknowledgement be given.
- How to cite Deep Argo: Zilberman et al. (2023); OneArgo: Roemmich et al (2019); Argo data: Wong et al. (2020)

59 publications

- **Subpolar North Atlantic**
  North Atlantic Deep Water pathways and decadal property changes (Racapé et al, 2018; Desbruyères et al, 2022; Petit et al, 2022)

- **Brazil and Argentine basins**
  Abyssal warming trends (Johnson et al 2019, 2020, 2022); Circulation and mixing (Johnson and King, 2023)

- **Southwest Pacific**
  Deep geostrophic circulation (Zilberman et al, 2020)

- **Global ocean**
  Internal wave detection (Johnson et al, 2022b)

- **Southern Ocean**
  Antarctic Bottom Water contraction and spatial variability (Kobayashi 2018; Thomas et al, 2020; Foppert et al, 2021)

**Review, design and implementation papers**
- Zilberman et al., 2023
- Johnson and Fassbender, 2023
- Liu et al., 2023
- Owens et al., 2022
- Johnson et al., 2015

**Technology**
- Kobayashi et al., 2021a,b
- André et al., 2020
- Roemmich et al., 2019

**Model prediction/assimilation**
- Gasparin et al., 2020

**Products**
- Trajectory products (Zilberman et al., 2013)
- T/S gridded products (Kolodziejczyk et al., 2023)

To track uptake and impact, we ask that where Deep Argo data are used (e.g. publication, product, etc) an acknowledgement be given.

How to cite Deep Argo: Zilberman et al. (2023); OneArgo: Roemmich et al (2019); Argo data: Wong et al. (2020)

59 publications
Challenges: Resources have not been secured to implement OneArgo

Comprises 4700 floats including:
- 1250 Deep Argo floats
- 1000 Biogeochemical (BGC) Argo floats
- Expansion into seasonal ice zones
- Enhanced sampling in the equatorial, western boundary regions, and marginal seas

Presently the Argo system is in **net decline** and the implementation of OneArgo **has stalled** due to flat funding

Total = 3796/4700 (81%)
Deep = 194/1250 (15%)
Biogeochemical (*>=5 params) = 290/1000 (29%)
Conclusion Part 1 — Deep Argo Data use and Access

- Argo is a living dataset. Use Argo data quality flags and frequently refresh archives prior to performing analysis.
- Products to facilitate the use of the Argo dataset are available on the Argo website. New products are under development.
- Cite the OneArgo review paper from Roemmich et al (2019), Deep Argo implementation paper from Zilberman et al (2023), and Argo data paper from Wong et al (2020) to facilitate tracking of the uptake and impact of the Deep Argo dataset.
Deep Argo can rapidly densify deep-ocean observations to the seafloor.

Deep Argo data resolve deep-ocean heat and freshwater contents, steric sea level, and ocean circulation, increase numerical model performance, and improve ocean bathymetry maps.

200 Deep Argo floats are sampling the ocean every 10 days to 6000 m depth.

Resources have not been secured to implement the OneArgo design. Only 15% of the global implementation of the Deep Argo array is funded.
Conclusion Part 3 — Deep Argo Technology

- Maintaining a diversity of floats and CTD sensors is needed to achieve the global implementation of the Deep Argo array
- 4 Deep Argo floats models are available for purchase. 2 additional models are under development
- Temperature accuracy of 0.001°C was reached on SBE-61. Salinity bias has been reduced from ±0.004 PSS-78 to ±0.002 PSS-78 on 2 operational CTD sensors from SeaBird. A CTD sensor model from RBR is under testing. 2 pressure sensor models are under testing to increase pressure accuracy from ±4.5 dbar to ±3 dbar
- Deep Argo bathymetry data has been validated using multibeam comparisons
- New applications (oxygen, ocean mixing and scattering) are under testing