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Deep Argo Improves the Accuracy and Resolution of Ocean Bathymetry

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Key Points:

- The close agreement between ocean bathymetry using Deep Argo and multibeam demonstrates the scientific value of the Deep Argo data set
- Deep Argo-based ocean bathymetry has low horizontal uncertainty (typically <1.5 km) and high vertical accuracy (3.9–4.2 m)
- The inclusion of Deep Argo bathymetry generates improvements of 50–200 m in abyssal regions of the General Bathymetric Chart of the Oceans (GEBCO) grid

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Ocean bathymetry plays an instrumental role in stirring ocean circulation and ocean mixing, shaping the transport of ocean heat, freshwater, oxygen, and carbon, influencing the propagation of tides and tsunamis, and controlling the dispersion of sediments, nutrients, and planktonic species. The dearth of direct ocean bathymetry measurements from shipboard echo sounders covering only 26% of the ocean floor calls for supplemental data. Satellites can provide bathymetry estimates in poorly-sampled regions, but intrinsic limitations of satellite measurements limit their ability to resolve features at horizontal scale <6 km (1/2 wavelength). Here, profile pressure and float descent rate from Deep Argo floats of the Deep Arvor and Deep SOLO float models were used to infer ∼14,000 ocean bathymetry measurements between 2014 and 2024. Our analysis indicates high consistency, 0.98 and 0.97 correlation coefficient, and small rms difference, 88 and 96 m, between multibeam sounding at 1,500–6,000 m depth and bathymetry measurements from Deep SOLO and Deep Arvor models respectively. The stronger agreement between Deep Argo-derived depths and multibeam data compared to altimetry is consistent with lower spatial uncertainties (<1.5 km for >77% of data coverage) and higher vertical accuracy of the Deep Argo data set (3.9–4.2 m at 4,000–6,000 m depth). The inclusion of the Deep Argo bathymetry in the general bathymetric chart of the ocean shows 50–200 m range improvement in the accuracy of altimetrically derived predicted depths.

Plain Language Summary The backbone mission of Deep Argo is to extend Argo profiling of ocean temperature and salinity to the seafloor in the deepest regions of the world ocean. The objective of this study is to demonstrate the scientific value of a supplemental application of the Deep Argo float array to measure ocean bathymetry without the need of integrating new sensors, changing the float cycle or making modifications to the sampling design. Our analysis demonstrates strong agreement between ocean bathymetry derived using Deep Argo floats and multibeam sounding, confirming Deep Argo's ability to collect high-quality ocean bathymetry measurements and the capacity to increase deep-ocean bathymetry sampling in regions lacking ship sounding tracks. This study highlights the importance of synergies between Deep Argo and satellite observations to improve the accuracy and resolution of ocean bathymetry.

1. Introduction

The shape and depth of the ocean basins are major controlling parameters of preconditioning and triggering of tsunamis (Gales et al., 2023; Schnyder et al., 2016), tidal resonance and dissipation (Wang et al., 2024), storm surge propagation (Qian et al., 2024), and orientation of ocean current pathways (de Boer et al., 2022). Ocean basin morphology also plays a leading role in topographic steering (Mashayek et al., 2017), the transfer of energy among spatial and temporal scales that feeds basin-wide transport of heat, freshwater, carbon and oxygen in the ocean (de Lavergne et al., 2022). Accurate knowledge of the geometry of the ocean floor is of fundamental importance for understanding the plate tectonic evolution (Gómez de la Peña et al., 2022; Tucholke et al., 2023) and to characterize marine habitats near the seafloor (Schneider von Deimling et al., 2023). Detailed knowledge of the morphology of the ocean basins is crucial to identify hazards to navigation such as shallow seamounts and steep seabed morphology (Mavraeidopoulos et al., 2017).

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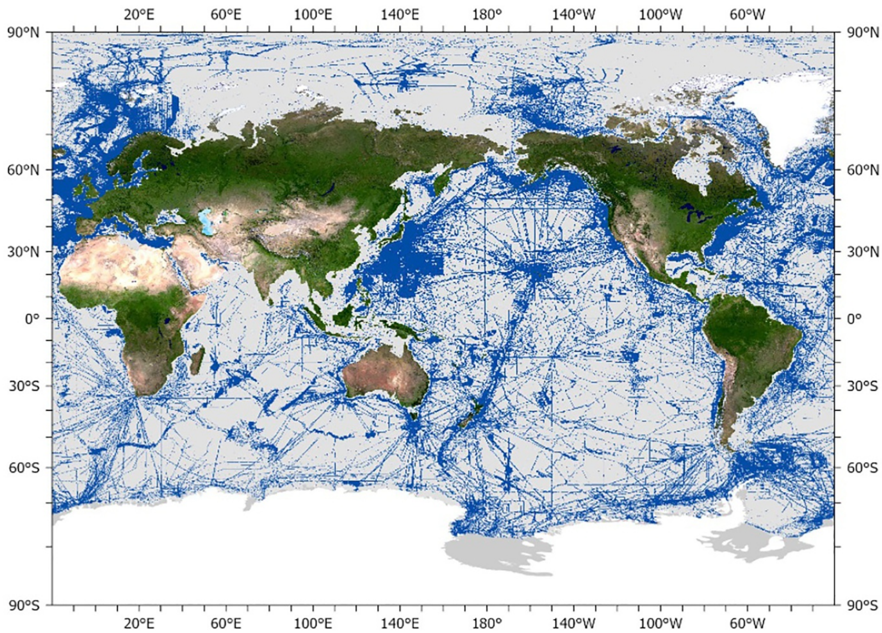

Figure 1. Locations of soundings in the GEBCO_2024 bathymetry. The areas in blue represent grid cells within the GEBCO_2024 Grid that are based largely on directly measured bathymetry data, for example, along ship track. The regions in gray show bathymetry data derived from interpolation using combined direct in situ measurements and satellite gravity observations.

Multibeam echosounders are the state of the art for measuring ocean bathymetry at high accuracy (Mayer et al., 2018) and fine resolution (100–400 m, depending on water depth) but echo sounding measurements are spread out, leaving large uncharted regions between ship tracks in exclusive economic zones and international waters (Wölfl et al., 2019). Only 26% of the ocean floor is currently measured using shipboard sounding data (GEBCO Bathymetric Compilation Group, 2024). Shipboard sounding surveys are mainly opportunistic and provide bathymetry measurements on a narrow swath along the ship transect (Figure 1). About two hundred ship years would be needed to map the ocean below 500 m (Carron et al., 2001; Mayer et al., 2018). In regions where ship sounding is not available, ocean bathymetry can be inferred, albeit with lower resolution (~6–12 km) than ship-based bathymetry, using sea surface slope measured from satellite (Tozer et al., 2019). The combination of satellites of various inclinations and radar altimeters with high-range precision and wide spatial coverage has proven an effective way to improve estimates of the marine gravity field (Sandwell et al., 2021). However, wide spacing between satellite ground tracks, attenuation of the gravitational signal with the ocean depth, altimetry noise due to ocean waves and currents, ubiquitous seafloor roughness, and sediment cover reducing the gravity signal are factors altering the ability of altimeter methods to predict the height, shape, and location of seamounts, and differentiate seamounts from abyssal hills and ridges (Gevorgian et al., 2023; Wessel et al., 2010). Due to the scarcity of echo sounding measurements in many ocean regions, the General Bathymetric Chart of the Oceans (GEBCO) model heavily relies on predicted and interpolated depth using satellite altimetry (Weatherall et al., 2015), for example, in the remote areas of the Southern Hemisphere (Figure 1). It is expected that the inclusion of high-precision altimeters such as SurfaceWater and Ocean Topography Mission (SWOT) will advance the accuracy and spatial resolution of the marine gravity field and therefore improve on predicted bathymetry estimates (Dibarboure et al., 2024). Yu et al. (2024) show that SWOT's ability to resolve smaller-scale seafloor structures is limited by its accuracy of 1.2 mGal and nominal resolution of 4 km per stack of 60+ cycles as estimated over the Foundation Seamounts. Supplemental bathymetry observations are needed in order to validate next-generation altimeters, calibrate bathymetry predictions, and improve topography transfer functions (Sandwell et al., 2022; Tozer et al., 2019).

Deep Argo floats are automated platforms collecting temperature and salinity profiles from the surface to the seafloor in the deepest regions of the ocean every 10 days during an average >5.5-year lifetime (N. V. Zilberman et al., 2023). The size of the Deep Argo fleet has steadily increased since the establishment of the Deep Argo

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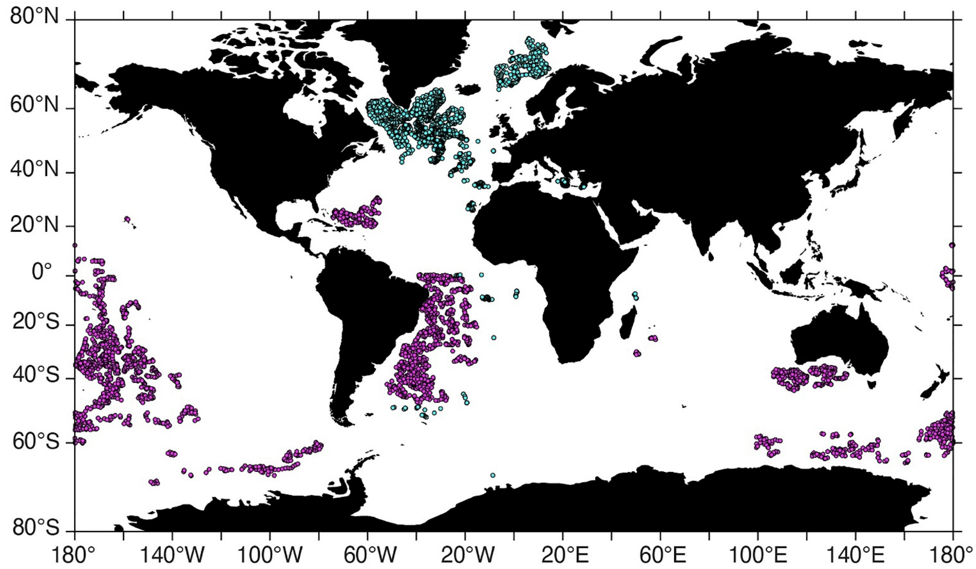

Figure 2. Location of ocean bathymetry measurements from Deep Arvor (light-blue rounded symbols) and Deep SOLO (magenta rounded symbols) floats between 2014 and 2024.

mission in 2015 (N. Zilberman & Maze, 2015; N. Zilberman et al., 2019), reaching >200 active floats in 2024 that are sampling the deepest regions of the global ocean. The main objective of the Deep Argo mission is to improve assessments and projections of the global planetary heat, freshwater, and sea level budgets, and large-scale overturning circulation, but a supplemental capacity of Deep Argo is to collect bathymetry measurements (Figure 2). This emerging application does not necessitate the implementation of additional sensors nor require any changes in Deep Argo sampling. In contrast with shipboard sonar and satellite usage where ocean bathymetry is derived from remote propagation of sound waves and electromagnetic pulses, Deep Argo bathymetry is directly measured when the float reports no change in pressure over a set period of time upon landing on the seafloor (van Wijk et al., 2022).

By design, Deep Argo floats travel vertically through the water column using a hydraulic pump to adjust their buoyancy under pressure. Deep Argo floats are carried horizontally by surrounding ocean currents during their 10-day cycle consisting of descent to programmed maximum profile pressure, drift at parking pressure, ascent to the surface, and drift at the surface. The chronological order of the aforementioned cycle phases may vary depending on the float model (see Section 2.1). Due to their free-drifting characteristic and depending on the strength of the ocean circulation, the position of bathymetry detection may differ from the GPS position recorded at the surface. Deep Argo floats can report location only when the antenna is above the surface and a transmission with satellite is established.

This work introduces the scientific value of using Deep Argo pressure measurements for improving ocean bathymetry in remote regions of the ocean where ship sounding is not available. A publicly available Deep Argo-based bathymetry data set called Argo BathYmetry SenSing (ABYSS) will be maintained at Scripps Institution of Oceanography in collaboration with the Institute of Geophysics and Planetary Physics and with contributions from Deep Argo partners and the GEBCO community. Methods used to infer ocean bathymetry from different Deep Argo float models and assess horizontal displacement of Deep Argo floats between bathymetry detection and surface positioning are described. Validation of Deep Argo-based ocean bathymetry using nearby multibeam sounding data, and comparison with satellite measurements are presented. The impact of using the ABYSS Deep Argo data set in the GEBCO grid is analyzed.

2. Deep Argo Bathymetry

Bathymetry measurements considered in this study were retrieved from Deep Arvor and Deep SOLO float models, which constitute >90% of the active Deep Argo float array. Not included in the current version of the ABYSS product are measurements collected using float designs that are either discontinued, under development,

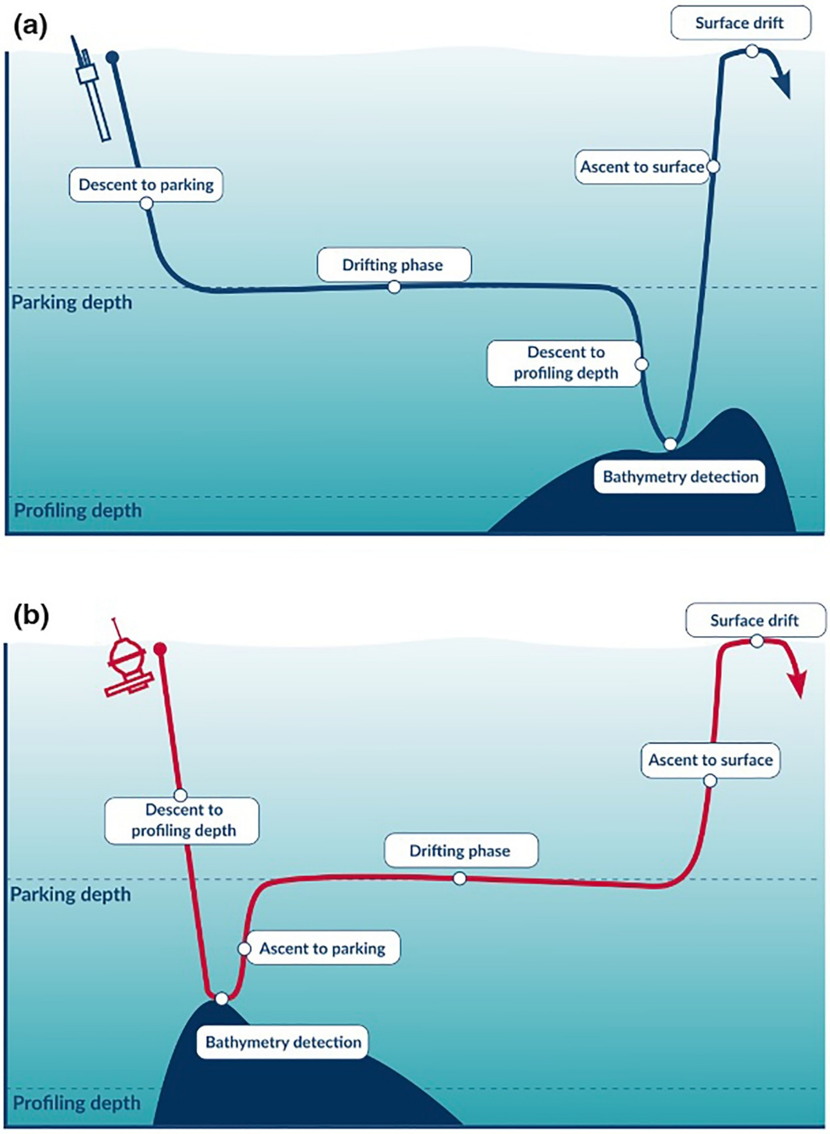

Figure 3. Schematics of the Deep Arvor (a) and Deep SOLO (b) float 10-day cycles when topography is encountered.

or contributing less than 1% of the bathymetry data inferred from Deep Argo. The documentation of ABYSS will be regularly updated on the University of California San Diego website as additional Deep Argo float models become operational and supplemental bathymetry measurements are made available.

2.1. Ocean Bathymetry From Deep Argo Floats

2.1.1. Deep Arvor

Deep Arvor floats (André et al., 2020) have the ability to measure temperature, salinity and pressure to 4,000 dbar. The nominal Deep Arvor float cycle consists of (a) descent to programmed parking pressure, (b) drift at parking pressure for ~9 days, (c) descent to programmed maximum profile pressure, (d) ascent to the surface, and (e) drift at the surface, acquisition of GPS location(s), and data transmission to satellite (Figure 3a). Based on Deep Arvor descending and ascending rates, the times of descent to 4,000 dbar and ascent to the surface are ~0.5-day each. Duration of drift at the surface, GPS location acquisition, and data transmission via Iridium telecommunication system is typically <30 min. Deep Arvor floats monitor themselves for possible detection of ocean bathymetry based on programmed parameters. Measurement codes in Argo trajectory files indicate where in the cycle the location, times and measurements occur (Wong et al., 2025). Pressure is monitored every 5 min during descent from parking to maximum pressure. If, on two consecutives measures, the float does not travel more than 4 dbar, electrovalve actions are triggered to transfer oil into the internal bladder. If the float still does not travel more than 4 dbar after some consecutives electrovalve actions, the grounding is flagged. The number of consecutives electrovalve actions varies with the float's depth and vertical speed and therefore is not a constant. The measurement code (MC) 901 is set by the internal software of the float, following the previous described algorithm. No data processing is involved. Once ocean bathymetry is detected, the Deep Arvor float may stay grounded for a programmed time or start an immediate ascent depending on mission settings. Bottom detection during the parking phase is difficult to determine with confidence due to slow-varying pressure fluctuations and sampling rate (every few hours) significantly sparser than during descent (every few seconds). Changes in horizontal displacement during the parking phase are not measured by Argo floats. Therefore, only bathymetry measurements collected upon descent to maximum pressure are considered in the ABYSS data set. GPS location nearest to bathymetry detection flag is collected in the trajectory file (MC 703). Depth measurements are calculated using pressure and latitude from the TEOS-10 subroutines of the Gibbs-SeaWater Oceanographic toolbox (McDougall & Barker, 2011).

The vertical accuracy of bathymetry measurements from Deep Arvor floats is influenced by two independent factors, the accuracy of the pressure sensor, and the distance between the pressure sensor and the base of the float. The Deep Arvor floats used in this analysis measure pressure from the deep SBE-41 conductivity temperature depth (CTD) sensor manufactured by Sea-Bird scientific (SBS) that is characterized by initial pressure accuracy of ±0.1%, corresponding to approximately 4–4.2 m at 4,000 m depth depending on latitude. The deep SBE-41 CTD is mounted vertically on the Deep Arvor, 1.2-m high on the top cap (Le Reste et al., 2016). Upon bathymetry detection, the distance between the Deep Arvor CTD and seafloor may slightly vary depending on the float orientation relative to the vertical. The orientation of the Deep Arvor float relative to the vertical that is not measured during the float's mission, may induce a systematic shallow bias (where the pressure measurement is shallower than ocean bathymetry) as high as 1.2-m in the case where the Deep Arvor sits vertically upon bathymetry detection.

2.1.2. Deep SOLO

Deep SOLO floats (Roemmich, Sherman, et al., 2019) have the capacity to measure temperature, salinity and pressure to 6,000 dbar. The typical Deep SOLO float cycle consists of (a) descent to programmed maximum profile pressure, (b) ascent to parking pressure, (c) drift at parking pressure for ∼8.5 days, (d) ascent to the surface, and (e) drift at the surface, acquisition of GPS location(s), and data transmission to satellite (Figure 3b). Based on Deep SOLO descending and ascending rates, the times of descent to 6,000 dbar and ascent to the surface are ∼18 hr each. Duration of drift at the surface, GPS location acquisition, and data transmission via Iridium telecommunication system is typically <30 min. Bottom detection of Deep SOLO floats during parking is difficult to determine with confidence for the same reason as Deep Arvor, namely small pressure fluctuations and slow sampling rate. Therefore, only bathymetry measurements collected upon descent to maximum pressure are considered in the ABYSS data set.

Contrary to the Deep Arvor model, time and pressure of bathymetry detection are not directly measured by the Deep SOLO. Assessing whether the Deep SOLO float has encountered bottom upon descent requires determining if pressure and descending rate in the trajectory file meet two criteria. The first criteria is the float has not reached the programmed profile pressure defined in the metafile with the condition that programmed pressure is deeper than 2,000 dbar. Pressure measurements are made throughout the float's cycle, and MCs in the trajectory file indicate what part of the cycle the float is in, along with key transition points when the float moves from one part of the cycle to the next. If the deepest pressure during the descent (MC 190) and before the start of ascent to parking (MCs 390–549) is less than the programmed profile pressure and higher than 2,000 dbar, the first criteria is met. The second criteria is related to changing fall rates at the very bottom of the descending profile that are characteristic of encounters with topography. The vertical resolution of Deep SOLO floats below 2,000 dbar typically varies between 10 and 50 dbar depending on programmed parameters and decreases to 2-dbar within 10 dbar of the programmed maximum profile pressure. Descending rate is calculated at each pressure level within 100-dbar above the deepest pressure. In order to reduce descending rate fluctuations induced by internal wave propagation (Johnson et al., 2022), a three-point running mean window is applied. If the descending rate measured at each pressure level is slowing down compared to the measurement above for over 40% of all data collected within 100 dbar above the deepest pressure, the second criteria is met. Examples of float descending rates for cases where ocean bathymetry is detected (Figures S1 and S2 in Supporting Information S1) and when the float does not reach the seafloor (Figure S3 in Supporting Information S1) are shown in Supplementary Information. Flags of ocean bathymetry detection and no-detection are assigned for each float cycle, with corresponding pressure and timing. GPS location and time nearest to bathymetry detection is recorded in the trajectory file. As for the Deep Arvor, Deep SOLO measurements of ocean bathymetry are determined from pressure and latitude using the TEOS-10 subroutines of the Gibbs-SeaWater Oceanographic toolbox (McDougall & Barker, 2011).

The vertical accuracy of bathymetry measurements from Deep SOLO floats is impacted by the accuracy of the pressure sensor, and the distance between the pressure sensor and ocean bathymetry. The Deep SOLO floats used in our analysis measure pressure from the SBE-61 CTD manufactured by SBS that has initial pressure accuracy of ±0.065%, corresponding to 3.9–4.1 m at 6,000 m depth depending on latitude. The SBE-61 sits horizontally on the bottom cowling of the Deep SOLO float (Roemmich, Sherman, et al., 2019). The distance between the SBE-61 CTD and seafloor will depend on the targeted profiling pressure depth that is programmed in. Deep SOLO floats are equipped with a passive bottom detection system aimed at limiting interaction between the CTD and seafloor, that consists of a 3-m long line hanging below the float. The Deep SOLO pumps a small volume of oil to be neutrally buoyant at its target maximum profiling depth (nominally 6,000 m). Based on the weight of the line, 24 cm would lay on the seafloor to compensate for every 100 m mismatch between the ocean bathymetry and the programmed profiling pressure depth. For instance, when encountering the seafloor at depth 500 m shallower than expected, 1.2 m of the bottom detection line would lay on the seafloor. The length of the Deep SOLO bottom detection line laying on the seafloor that is not measured during the float's mission, may induce a systematic shallow bias as high as 3-m in the case where only the end of the line touches the seafloor.

2.1.3. Horizontal Uncertainty of Deep Argo-Based Ocean Bathymetry

Uncertainty in the position of ocean bathymetry measurements constitutes the main source of error in bathymetry estimates from Deep Argo. A method to correct the positioning of bathymetry measurements using horizontal displacement of Deep Argo floats between ocean bathymetry detection and data transmission to satellites is developed. Duration of horizontal drift below the surface is measured between seafloor detection and nearest float surfacing, which occurs between start and end of ascent for Deep Arvor floats, and between start and end of descent for Deep SOLO floats. Time of horizontal drift at the surface is measured between end-of-ascent and first GPS positioning for the Deep Arvor, and between last GPS positioning and start-of-descent for the Deep SOLO. Velocity fields from the Global Ocean Reanalysis and Simulation GLORYS12 (Lellouche et al., 2021) are combined with duration of float drift below and at the surface to estimate the horizontal displacement of Deep Argo floats.

A series of tests were run to decide if horizontal displacement of Deep Argo floats inferred using GLORYS12 could improve the positioning of ocean bathymetry detection. Float horizontal displacements were calculated using GLORYS daily, monthly, climatology, and 21-year averaged velocity fields between 2000 and 2020. In order to validate our method, Deep Argo bathymetry estimates were compared with multibeam data interpolated at corrected and uncorrected float positions. Using the correction of horizontal displacement from GLORYS12 generates a small (2%) decrease in the correlation between Deep Argo from both Deep SOLO and Deep Arvor float models and multibeam bathymetry shown in Figures 6a and 6b respectively. The limited performance of the correction may be due to limitations of GLORYS12 to predict ocean circulation below 2,000 m. Based on this result, we decided to use horizontal displacement of Deep Argo floats from GLORYS12 as a measure of horizontal uncertainty of ocean bathymetry detection rather than for correcting the positioning of ocean bathymetry measurements. We use 2000–2020 averaged velocity fields instead of daily, monthly, and climatology velocity fields in order to maximize assimilated deep-ocean observations in GLORYS12 simulations.

Using 2000–2020 averaged velocity fields from GLORYS12, the horizontal displacement of Deep Argo floats below the surface typically contributes most of the float displacement between ocean bathymetry detection and data transmission to satellites (>93% for the Deep Arvor and >99% for the Deep SOLO measurements) shown in Figures 4 and 5. Horizontal float displacement between ocean bathymetry detection and data transmission is small (<1.5 km) over wide deep-ocean areas, including the abyssal plains of the Southwest Pacific, Brazil and Argentine basins, around Madagascar and in the interior of the subpolar Atlantic gyre, that represent a large (>77%) fraction of the Deep Argo data set (Figures 4 and 5). In contrast, stronger horizontal displacement rates

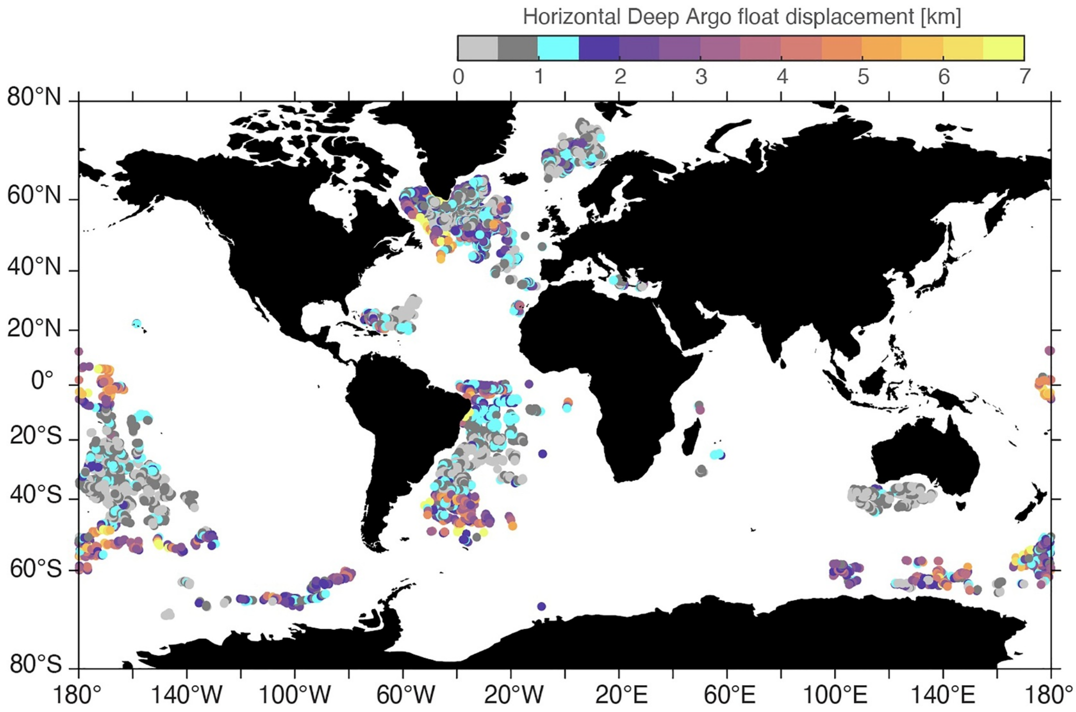

Figure 4. Map showing the estimated horizontal float displacement between bathymetry detection and data transmission to satellites at the surface for Deep SOLO and Deep Arvor ocean bathymetry measurements accumulated between 2014 and 2024.

(1.5–6 km) are seen along equatorial jets of the Pacific and Indian Oceans, the Antarctic Circumpolar Current, and along the Labrador current and the North Atlantic Current. A limited portion (<0.8%) of the Deep Argo data set shows horizontal float displacement larger than 6 km (Figure 5). Depth uncertainty associated with float displacement is calculated at each uncorrected float position as the standard error of GEBCO_2024 bathymetry within the radius of horizontal float displacement. It is acknowledged that since 74% of the GEBCO grid is constrained by satellite measurements, our prediction of Deep Argo depth uncertainty may be underestimated. Depth uncertainty is small (<3 m) over abyssal plains but larger rates (3–14 m) are found over strong ocean bathymetry gradients over ocean ridges, fracture zones, and trenches (Figure S4 in Supporting Information S1). A limited portion (<4%) of the Deep Argo data set shows depth uncertainty larger than 14 m (Figure S5 in Supporting Information S1).

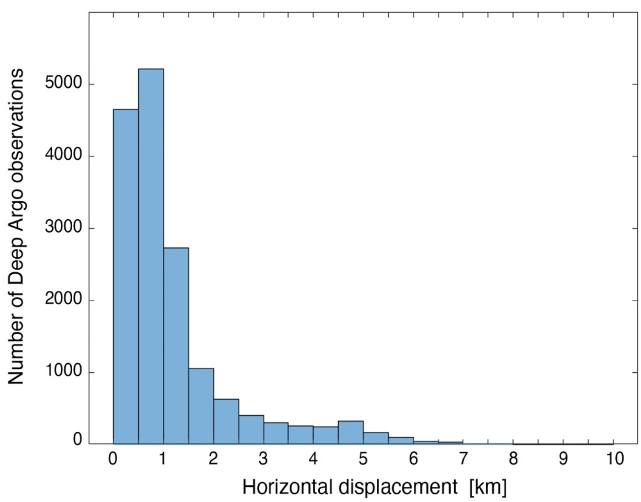

Figure 5. Histogram showing the accumulated number of Deep Arvor and Deep SOLO ocean bathymetry observations as a function of horizontal Deep Argo float displacement between bathymetry detection and data transmission to satellites at the surface.

2.2. GEBCO and SRTM Global Bathymetry Models

Global bathymetry models are used to assess the contributions of the Deep Argo floats to the Seabed2030 effort to map the bathymetry of the oceans by 2030 (Mayer et al., 2018). These models are constructed in layers, with the first layer consisting of gravity-predicted bathymetry (Tozer et al., 2019) having spatial resolution of 8–12 km (1/2 wavelength) and a latitude range of ±80°. With the release of SWOT gravity, the predicted depth resolution will improve to 4–6 km. Spatial coverage and resolution vary between single beam and multibeam echo sounder measurements. A single beam echo sounder measures the shallowest point within a diameter typically half the water depth for a beam width of 30° directly below the vessel (Mayer, 2023). In contrast, multibeam echo sounders collect depth measurements over a swath perpendicular to the direction of travel of the ship, covering a nominal width of the order of 4 times the water depth (Mayer et al., 2018). The spatial resolution provided by the cross products of the transmitted and received beams varies

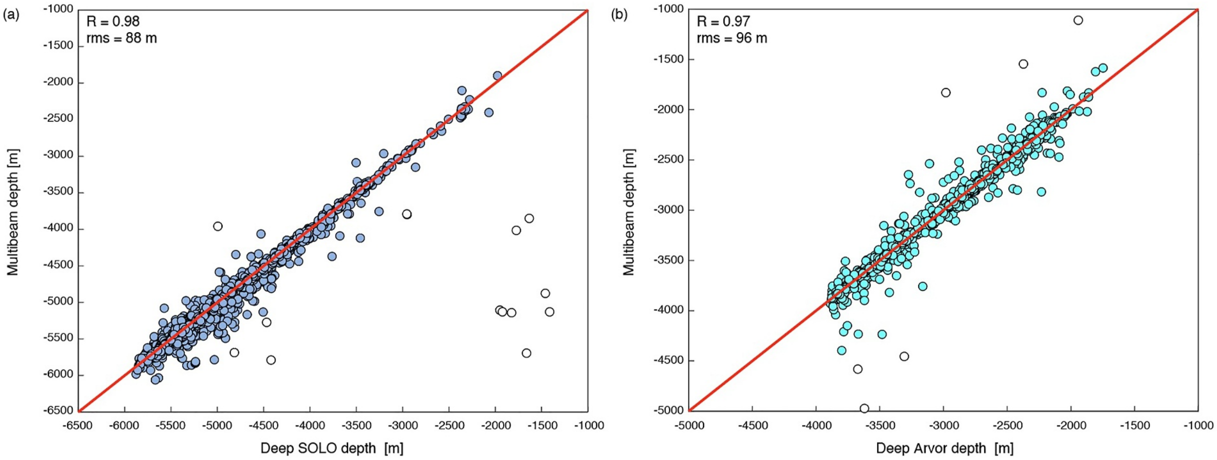

Figure 6. Comparison of bathymetry measured from multibeam echosounders in the GEBCO_2024 data set with (a) Deep SOLO (dark-blue rounded symbols) and (b) Deep Arvor (light-blue rounded symbols) bathymetry measurements. Deep Argo outliers showing bathymetry difference with multibeam data >800 m are shown in white rounded symbols.

with water depth and beam width. For instance, the achievable lateral resolution of a 2 × 2° multibeam system lessens as water depth increases, from 100 to 400 m between 1,000 and 6,000 m depth (Mayer et al., 2018). Sound speed measurement errors induced by ocean temperature, salinity and pressure variability affect the beam vector determination and can generate depth biases that may exceed 0.2%, 8–12 m at 4,000–6,000 m depth (Li et al., 2023; Nistad & Westfeld, 2022). The second layer uses a remove-restore method to force this low-resolution model to match the single-beam and multibeam echo sounder data at a pixel resolution of 1 min. This 1-min model forms the basis for the 15-arcsecond SRTM15_PLUS global grid (Tozer et al., 2019) where a second remove-restore method is used to force the grid to match all higher resolution data (e.g., multibeam, coral reef depths, land topography, arctic topography/bathymetry) from the International Bathymetric Chart of the Arctic Ocean (IBCAO, Jakobsson et al., 2024), International Bathymetric Chart of the Southern Ocean (IBCSO, Dorschel et al., 2022) and some inland lakes. Finally, the SRTM15_PLUS global grid is delivered to the GEBCO group where a third layer of newly acquired and proprietary bathymetry data is added (Weatherall et al., 2015). The pixel resolution of the final grid is 15 arcseconds which is 462 m in latitude and between 462 and ∼100 m in longitude. The SRTM15_PLUS and the GEBCO grids have matching ancillary grids to keep track of the data source (SID) and data type (Type Identifier (TID)) for each pixel. All these grids are updated annually to include improvements in global gravity-predicted depth as well as additional sounding sources such as the Deep Argo data. In the 2024 analysis, an initial release of Deep Argo data was injected into the process similar to the single beam soundings.

3. Results

Ocean bathymetry measurements collected from Deep Argo floats between 2014 and 2024 are validated using the multibeam observations in the GEBCO grid and also compared to the less accurate satellite predicted depth estimates. An analysis of the GEBCO grid with and without integration of Deep Argo bathymetry observations, is used to assess the scientific impact of the Deep Argo data set.

3.1. Validation of Deep Argo Bathymetry Using Multibeam Measurements

The Deep Argo data considered in this analysis comprise 2,664 Deep SOLO depths and 944 Deep Arvor depths located nearby multibeam measurements. Most bathymetry measurements accumulated from Deep Argo floats over the past 11 years, are located in the abyssal regions of the Southwest Pacific, South Atlantic region off South America, and subpolar North Atlantic basins (Figure 4). To enable direct comparisons of Deep Argo bathymetry, multibeam observations are interpolated at positions of Deep Argo float measurements. Comparisons with multibeam data are considered separately for the Deep Arvor and Deep SOLO floats in order to assess the ability of each Deep Argo float model to capture spatial fluctuations in ocean bathymetry (Figures 6a and 6b). Deep Argo measurements demonstrate good agreement with multibeam data. The similar consistency observed for Deep

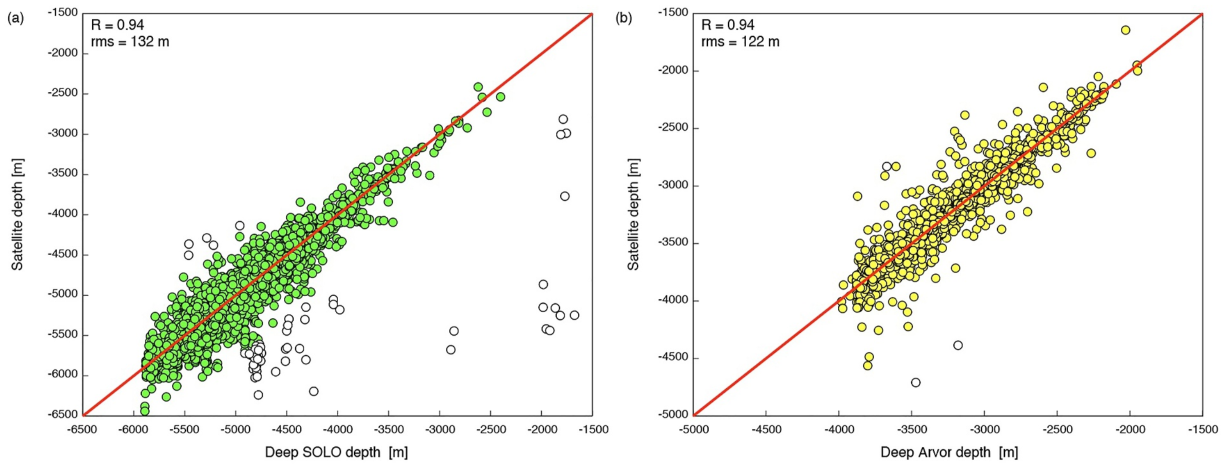

Figure 7. Comparison of satellite-derived bathymetry data in the GEBCO_2024 data set with (a) Deep SOLO (green rounded symbols) and (b) Deep Arvor (yellow rounded symbols) bathymetry measurements. Deep Argo outliers showing bathymetry difference with satellite data >800 m are shown in white rounded symbols.

SOLO (correlation coefficient R of 0.98; rms = 88 m) and Deep Arvor (correlation coefficient R of 0.97; rms = 96 m) measurements is indicative of the good performance of both Deep Argo float models. Most Deep SOLO (89%) and Deep Arvor (85%) bathymetry data show small (<100 m) differences with multibeam. Following GEBCO's guidelines, bathymetry measurements displaying large (>800 m) discrepancies with quality controlled GEBCO grids are flagged as bad. These outliers (white rounded circles in Figures 6a and 6b) represent a limited portion (0.5%) of the Deep Argo data set. Analysis of outliers reveals limited averaged float horizontal displacement (1.1 km) and no evident relationship between float horizontal displacement and the magnitude of discrepancies between Deep Argo and multibeam, suggesting that the misfit is generated by other sources. Deep Argo floats may abort cycles when technical anomalies occur. If the pressure remains unchanged for too long despite pumping actions due to technical difficulties, some cycles can be falsely identified as detection of bathymetry. The float mission parameters stored in the metadata files and the engineering data in the technical files from the global data assembly centers (GDACs) for each float cycle were used in the quality control of the Deep Argo bathymetry data to remove false detection of bathymetry. For the case of ocean-bathymetry measurements collected from Deep SOLO floats built at Scripps Institution of Oceanography and at MRV Systems, 100% of outliers showing large discrepancies (>800 m) with multibeam bathymetry have engineering data indicating stall during descent (flag 2048). This engineering flag is not currently available in the technical files from the GDACs. Future work will consist of continuing advancing the performance of our method to efficiently control the quality of the Deep Argo data set in order to reduce the number of outliers in an automated way.

3.2. Deep Argo Bathymetry Comparison With Satellite Measurements

The Deep Argo data studied here involve 8,481 Deep SOLO depths and 1,711 Deep Arvor depths located nearby satellite measurements. Bathymetry measurements from satellites are interpolated to Deep SOLO and Deep Arvor float positions in order to enable comparisons. Deep Argo bathymetry agrees well with satellite data. The similar consistency observed for Deep SOLO (correlation coefficient R of 0.94; rms = 132 m) and Deep Arvor (correlation coefficient R of 0.94; rms = 122 m) measurements confirms that the performance of Deep Argo bathymetry is independent of the float model (Figures 7a and 7b). The reduced correlation coefficient and increased root mean square difference between Deep Argo and satellite bathymetry compared to multibeam (see Section 3.1) suggests that the supplemental misfit is generated by ocean bathymetry variability that is not resolved by satellites. As in the case of comparisons with multibeam bathymetry, outliers showing large discrepancies (>800 m) between Deep Argo and satellite bathymetry (white rounded circles in Figures 7a and 7b), represent a small portion (0.7%) of the Deep Argo data set. Analysis of outliers reveals limited averaged float horizontal displacement (1.3 km) and no evident relationship between magnitude of float horizontal displacement and discrepancy between floats and satellites, suggesting that the observed misfit is induced by false bathymetry detection. For the case of ocean-bathymetry measurements collected from Deep SOLO floats built at Scripps Institution of Oceanography, 96% of outliers showing large discrepancies (>800 m) with satellite bathymetry

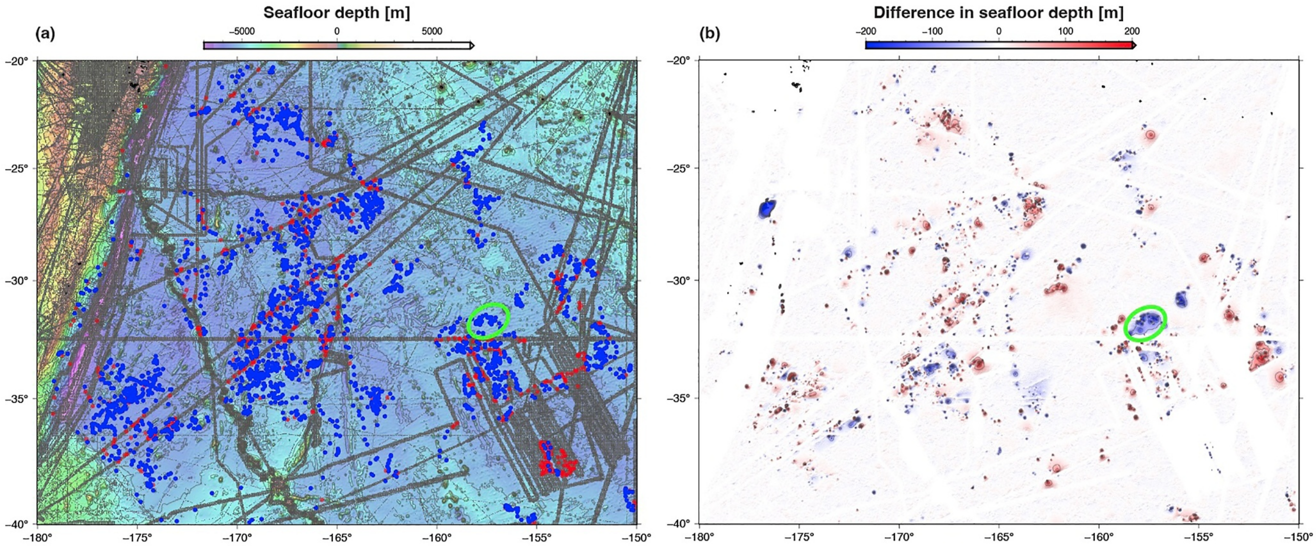

Figure 8. (a) Seafloor depth (contour interval 500 m) from the SRTM15 global grid for a small remote area in the Southwest Pacific. Gray dots show locations of existing multibeam and single beam soundings. There are several large regions (∼50 × 100 km) with no depth soundings so depth is based on a gravity prediction which degrades with distance to the nearest sounding (Marks et al., 2010). Red dots show locations of Deep Argo depth measurement that are within 4 km of an existing sounding and thus not used. Blue dots show locations of Deep Argo depths providing new depth information. (b) Difference between the SRTM15 depth with and without the Deep Argo data at 50 m contour interval (red corresponds to Deep Argo depth shallower than predicted depth). The green circle shown in panels (a) and (b) indicates a region of dense Deep Argo-based bathymetry sampling.

indicate engineering flag 2048. For the case of ocean-bathymetry measurements collected from Deep SOLO floats built at MRV Systems, 92% of outliers showing large discrepancies with satellite bathymetry indicate engineering flag 2048. Based on comparisons between GEBCO quality controlled grids and ocean bathymetry from Deep SOLO floats, it is recommended that the engineering flag 2048 transmitted from Deep SOLO floats, including models built at Scripps Institution of Oceanography and MRV Systems, is captured in the Argo data system in order to facilitate automated removal of false bathymetry detection.

3.3. Contribution of Deep Argo to Bathymetry Grids

The impact of incorporating ABYSS Deep Argo-derived bathymetry data into the 2023 GEBCO grid is investigated for the case of a remote region in the Southwest Pacific Ocean showing heterogeneous multibeam echosounder sampling (Figure 8a). Out of 7,437 Deep Argo bathymetry measurements, 168 data points displaying large (>800 m) discrepancies with nearby soundings and predicted depths from satellites, were marked as bad and excluded from the analysis. We flagged and excluded 1,290 Deep Argo measurements within typical decorrelation length scale of ocean bathymetry, 4 km, of an existing depth sounding, either multibeam or single beam (red rounded symbols in Figure 8a). The remaining 5,979 points (shown as blue rounded symbols in Figure 8a) were treated as high-quality bathymetry measurements and compiled with single-beam, multibeam, and satellite altimetry-derived bathymetry in the SRTM15 database. Here, deviation in GEBCO depth is addressed based on the difference between SRTM15 with and without the integration of Deep Argo-based bathymetry (Figure 8b). Typical improvements are within 50–200 m range and concentrated in areas where single beam and multibeam data are not available. Largest improvements (>100 m) are evident in areas of densest Deep Argo sampling (e.g., region marked in green). This analysis demonstrates that the Deep Argo depth data will be most useful in remote ocean areas having poor sounding coverage.

4. Conclusions

This study explores the capacity of Deep Argo floats to provide ocean bathymetry measurements of scientific value. The estimated vertical accuracy of Deep Argo bathymetry based on the pressure performance of the CTD sensor is 0.065%–0.1%; this is better than nominal sounding accuracy of 0.2% depth. Spatial uncertainty of Deep Argo-derived ocean bathymetry inferred from horizontal float displacement between bathymetry detection and GPS positioning at the surface, is typically <1.5 km, which is coarser than nominal 100–400 m resolution from multibeam echo sounders but about 10 times better than satellite-derived data. It is anticipated that as the performance of numerical models in the deep ocean improves, combined float descent rate and simulated velocity fields will reduce horizontal uncertainties in the position of bathymetry detection from Deep Argo floats. New Deep Argo CTDs, currently under testing to increase the accuracy of Deep Argo pressure to 0.05%, will advance the vertical accuracy of Deep Argo-based ocean bathymetry (N. V. Zilberman et al., 2023).

Our analysis shows high consistency between ocean depths derived from Deep Argo floats and multibeam echo sounders. Depth uncertainty due to horizontal float displacement in Deep Argo bathymetry and sound speed measurement errors in echo sounder estimates are the main sources of discrepancy between the two data sets. The stronger agreement between Deep Argo-derived bathymetry and multibeam (correlation coefficient R of 0.97–0.98; rms = 88–96 m) compared with satellite estimates (correlation coefficient R of 0.94; rms = 122–132 m) is consistent with higher vertical accuracy and lower horizontal uncertainty in the Deep Argo data set than satellites. Integration of ocean depths collected from Deep Argo floats over the last 11 years generates 50–200-m range improvement in the GEBCO grid in regions where Deep Argo observations are available. The high vertical accuracy and low horizontal uncertainty of the Deep Argo data set is likely to play an instrumental role in improving estimates of the height and radius of abyssal hills and seamounts that are not typically well resolved by satellite gravity (Sandwell et al., 2022) and provide a high-quality independent data set to monitor the quality of ocean bathymetry predicted and interpolated using satellite altimetry. Starting in 2025, ocean bathymetry measured from Deep Argo floats will be identified with a TID code of 47 in the GEBCO grids.

On average, 66% of Deep Argo profiles collected between 2014 and 2024 encounter the seafloor and report bathymetry measurements. The possibility of Deep Argo detection of ocean bathymetry is limited by two criteria, the maximum depth range determined by the float model, and the programing of maximum profiling depth by the Deep Argo float owner. Deep Argo deployment strategy is optimized to concentrate floats with higher depth capacity (6,000 m) in deepest regions, and float models with lower (4,000 m) depth ability in shallower areas in order to maximize sampling over the whole water column. The amount of Deep Argo data reaching the seafloor can be increased by setting maximum profiling pressure to exceed the maximum expected depth on a larger number of floats. As the Deep Argo fleet continues to expand, recommended float parking depth will transition from deep-ocean layers to 1,000 m, the parking depth typically used by Argo to facilitate homogeneous horizontal float distribution and sampling coverage (Roemmich, Alford, et al., 2019). The envisioned global Deep Argo 1200-float array will provide profiles at 5° latitude × 5° longitude × 10-day sampling with the backbone objective to reduce errors in trends of sea level and ocean heat content by a factor of 10 (Johnson et al., 2015). Once fully implemented, Deep Argo could accumulate over 30,000 bathymetry measurements per year, rapidly increasing the bathymetry database, and filling large gaps in seafloor coverage in the most remote regions of the abyssal ocean.

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Data Availability Statement

The ABYSS Deep Argo ocean bathymetry data is freely available from N. V. Zilberman et al. (2025). The dataset will be updated every 6 months by NZ and MS.

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