Supplementary information about the modelling approach.

Here we use a Total Matrix Intercomparison (TMI; Gebbie and Huybers, 2010) model to study the effect of circulation and biological cycling on Ni cycling. The TMI is a global water mass decomposition that avoids subjective definitions of ocean interior water mass end-members by tracing the ocean interior waters back to their surface origins (Gebbie and Huybers, 2010). The TMI solution is constrained by observational climatologies of hydrographic and biogeochemical parameters as described by Gebbie and Huybers (2010). The TMI circulation is presented on a 4°×4° grid with 33 depth levels.

We first model the distribution of Ni and its isotopes only in terms of ocean circulation:

(1)

(2)

where the concentrations of Ni () and 60Ni () in the ocean are modelled by propagating their surface boundary conditions (and respectively) using the circulation pathway matrix A. The resulting Nipre and 60Nipre fields represent the preformed component of the dissolved pool.

We derive the surface boundary condition using the surface (<100 m) Ni concentration data of the GEOTRACES IDP2021 (GEOTRACES Intermediate Data Product Group, 2021). We subdivide and average the data according to the surface ocean patches defined by TMI. In the high latitude surface regions including the Antarctic and Subantarctic Zones of the Southern Ocean, subpolar North Atlantic, subpolar North Pacific and Arctic, we use the data-based average Ni concentrations for the boundary condition. In the surface low latitude regions (~40°S to ~40°N; see Gebbie and Huybers, 2010), we take the boundary condition to be 2 nmol/L, which is the concentration found in these regions (Takano et al., 2017; Archer et al., 2020; Yang et al., 2020, 2021). The uncertainties on the boundary conditions of Ni concentration are propagated through the model (Fig. S1).

We then calculate the isotopic surface boundary condition as:

 (3)

Where δ60Nib is the 60Ni/58Ni ratio in δ-notation, 0.3852 is the 60Ni/58Ni ratio of reference material NIST SRM 986 and 0.68 is the natural abundance of 58Ni. Presently, there is not enough δ60Ni data to define the isotopic boundary condition (δ60Nib) for each surface patch of TMI (Fig. S2). However, published studies suggest that surface waters in high latitudes have δ60Ni values similar to the uniform deep ocean (Cameron and Vance, 2014; Wang et al., 2019), so we assign them a δ60Ni value of +1.33 ‰ (world ocean average). In the low latitude surface, existing data converge to a heavy δ60Ni value of ~+1.7 ‰ (Archer et al., 2020; Takano et al., 2017; Yang et al., 2021, 2020), which we assign to the surface low latitude patches in TMI. In the model we assume the uncertainty of the surface δ60Ni boundary condition is ±0.07 ‰ (2σ) which is our analytical error. This error is then propagated through the model (Fig. S1).

We cannot explicitly model surface Ni biological cycling because TMI treats the surface as a boundary condition. However, we can add an interior biological cycling term by linking Ni remineralisation to that of PO43-:

(4)

(5)

where ΔPO4 refers to the remineralised PO43- determined by the TMI from PO43- and O2 concentrations, rNi/PO4 and r60Ni/PO4 are the stoichiometric coefficients of Ni and 60Ni to PO43-. In the high latitudes, we assign a value of 0.52 mmol/mol to rNi/PO4 based on the Ni quota in diatoms, while in the low latitudes, we assign a value of 3.4 mmol/mol to rNi/PO4 based on the Ni quota in cyanobacteria (Twining et al., 2012). In this way we try to simply capture the influence of the different ecosystems in the high and low latitude regions. For Ni isotopes, similar to equation (3) we have

 (6)

where δ60Nir is the isotope composition of remineralised Ni.

Model results generally reproduce the structure of the observations (Fig. 2; Figs. S1, S5). The root-mean square error (RMSE) of modelled δ60Ni compares very well to the analytical error on isotope measurements (0.09 and 0.07 ‰, respectively; n=308). The RMSE of modelled Ni concentration, of 1.44 nmol/L, is computed against all the data in IDP2021 (n=8426; GEOTRACES Intermediate Data Product Group, 2021), i.e. representing much more data than we use for δ60Ni. This error is relatively high because the model underestimates Ni concentrations in the deep Pacific. The error can be reduced, if we use a rNi/PO4 ratio higher than the reported cyanobacterial Ni quota which will increase the amount of remineralised Ni. Alternatively, there may be a benthic source of Ni from the sediments that is not included in the model (Little et al., 2020; Gueguen and Rouxel, 2021). Along the GEOVIDE transect, modelled Ni concentrations are underestimated at depths of 100–400 m and 4000–4500 m in low latitude waters, with the latter depth range subject to Southern Ocean influence (Fig. 2a). Modelled Ni concentrations are also generally overestimated for the high latitude North Atlantic (Fig. 2c). This data-model difference likely stems from our assumption that uptake in the entire high latitude ocean has the same rNi/PO4 ratio of 0.52 mmol/mol based on reported diatom Ni quotas (Twining et al., 2012), almost certainly an over-simplification. The data-model difference can be reduced by increasing the rNi/PO4 ratio in the Southern Ocean while decreasing the rNi/PO4 ratio in the North Atlantic. This is not unexpected given that phytoplankton communities in the two high latitude regions are not identical, though both are dominated by diatoms.

Figure S1.

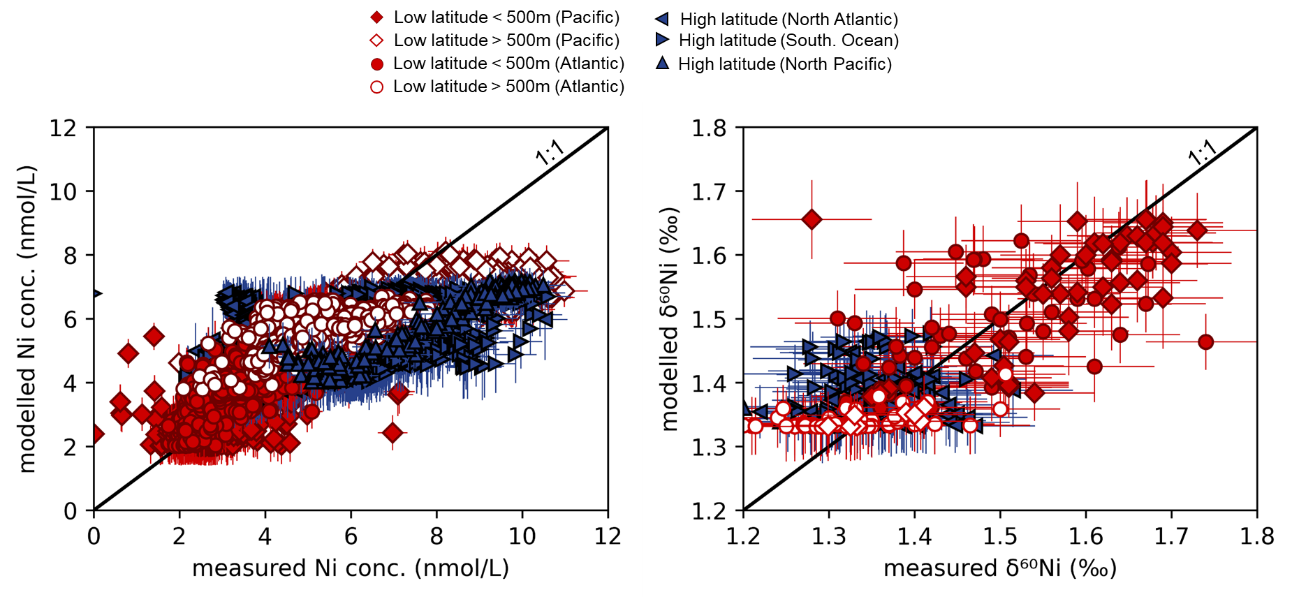


Fig. S1: Modelled versus measured Ni concentrations (for stations for which data are available in the IDP2021; left panel) and Ni isotope compositions (for stations where δ60Ni data are available; right panel). Model results are from our standard model and identical to those shown in Fig. 6 of the main text. The model uncertainties for both Ni concentration and δ60Ni are explained in the text.

Figure S2.

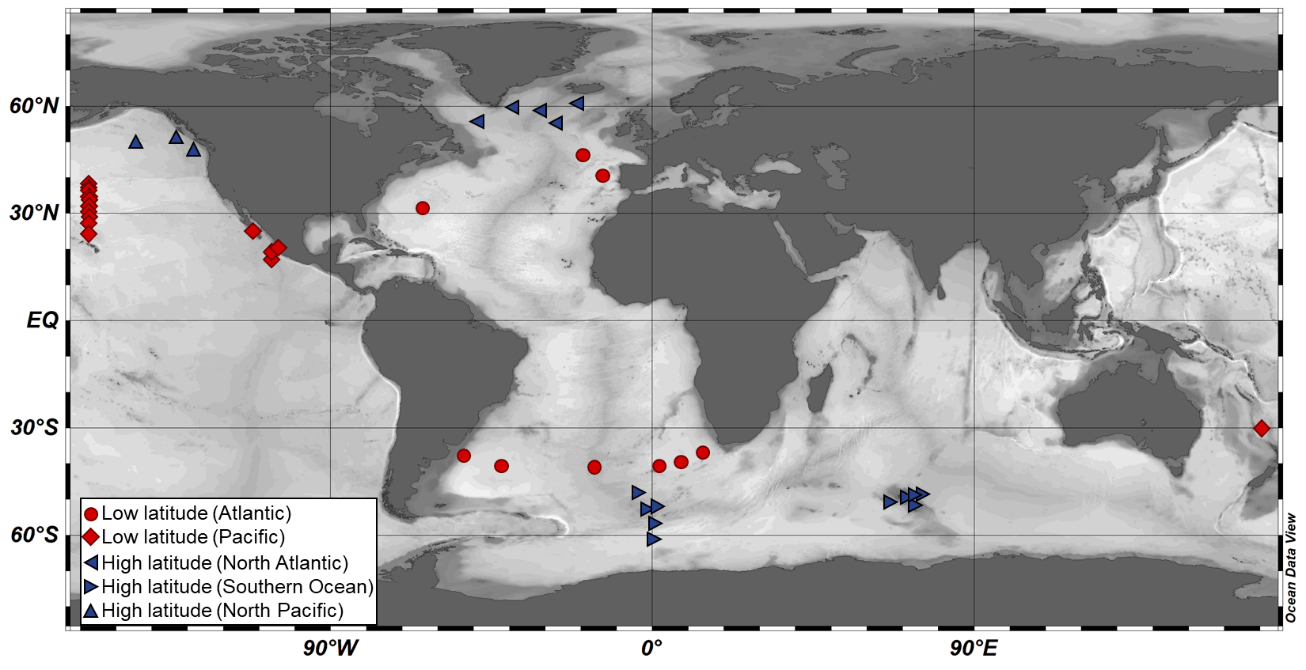


Fig. S2: Stations from this study (GEOVIDE) and from the world ocean where Ni concentrations and δ60Ni are available (Cameron and Vance, 2014; Takano et al., 2017; Wang et al., 2019; Archer et al., 2020; Yang et al., 2020, 2021). Stations from the low latitude ocean are indicated by red symbols while stations from the high latitude ocean are indicated by blue symbols. The separation between both regions is set by the latitude 47° in the northern and southern hemispheres. A distinction is made between the subpolar North Atlantic (triangles pointing towards the left), the Southern Ocean (triangles pointing towards the right), the subpolar North Pacific (triangles pointing upwards), the low latitude Atlantic Ocean (circles) and the low latitude Pacific Ocean (diamonds).

Figure S3.

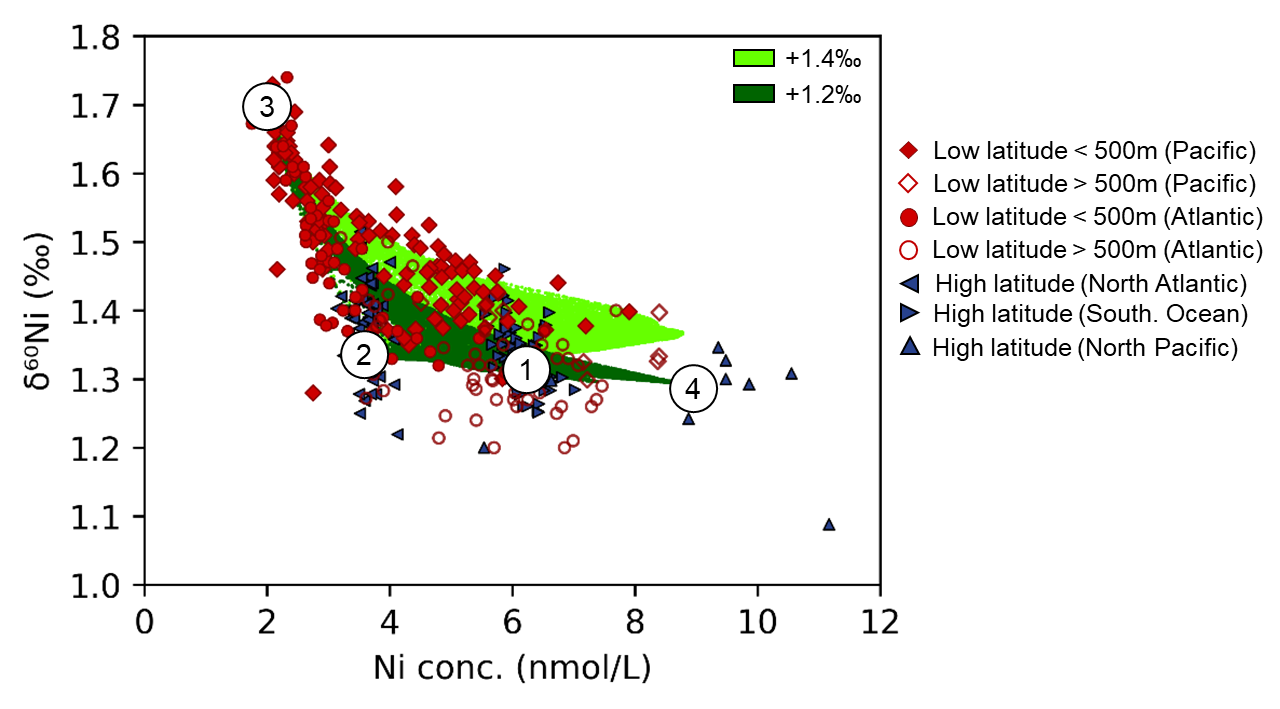
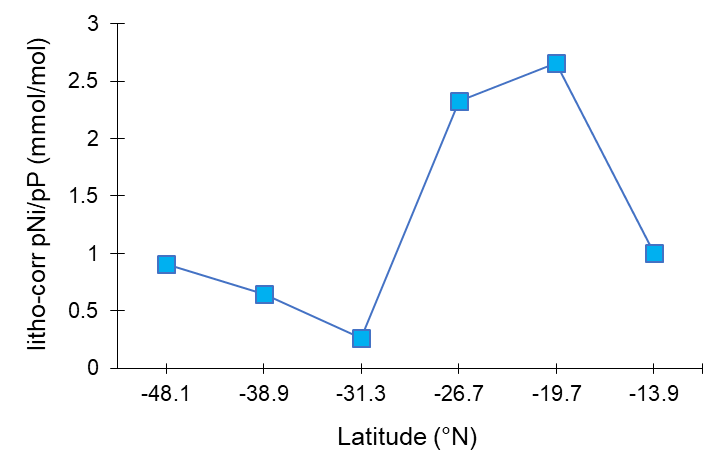


Fig. S3: Comparison of the dissolved Ni-δ60Ni systematics observed in the world ocean (in blue and red, see previous captions) with the results of the Total Matrix Intercomparison model, simulating both the physical circulation and remineralisation. The results are shown for two different isotope compositions for the regenerated pool in the low latitudes, at +1.2 ‰ and +1.4 ‰ (the high latitude remineralised δ60Ni remains +1.33 ‰). End-member 3 represents the surface low latitude region; end-member 2 represents the subpolar North Atlantic region; end-member 1 represents the Southern Ocean; and end-member 4 represents the North Pacific.

Figure S4.



**Fig. S4:** Latitudinal variation of the lithogenic-corrected particulate Ni/P ratios (pNi/pP) along the GEOVIDE transect, with particulate data obtained from in-situ pumps (Lemaitre et al., 2020). The trend is confirmed by GoFlo data (Planquette et al., personal communication).

Figure S5.

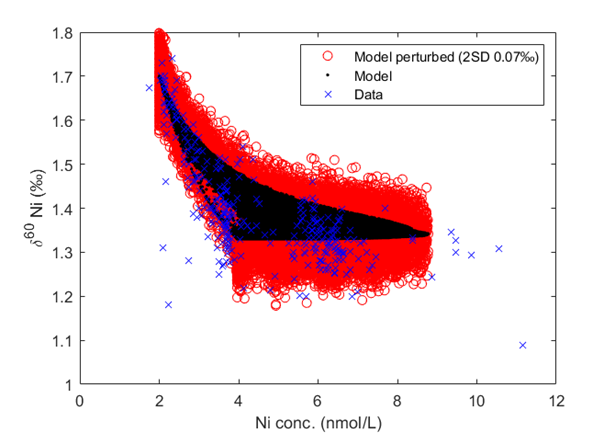


Fig. S5: Comparison of the dissolved Ni-δ60Ni systematics from the world ocean (in blue) with the results of the Total Matrix Intercomparison model, simulating both the physical circulation and remineralisation (in black, see Figure S1 and Fig. 6 of the main text). Red circles represent model output (black) perturbed with normally-distributed noise (2SD ±0.07 ‰) in order to represent the observational data expected if the model distribution were sampled with current analytical uncertainty. This comparison shows that our standard model output is consistent with the vast majority of data within analytical uncertainty on δ60Ni.

Figure S6.

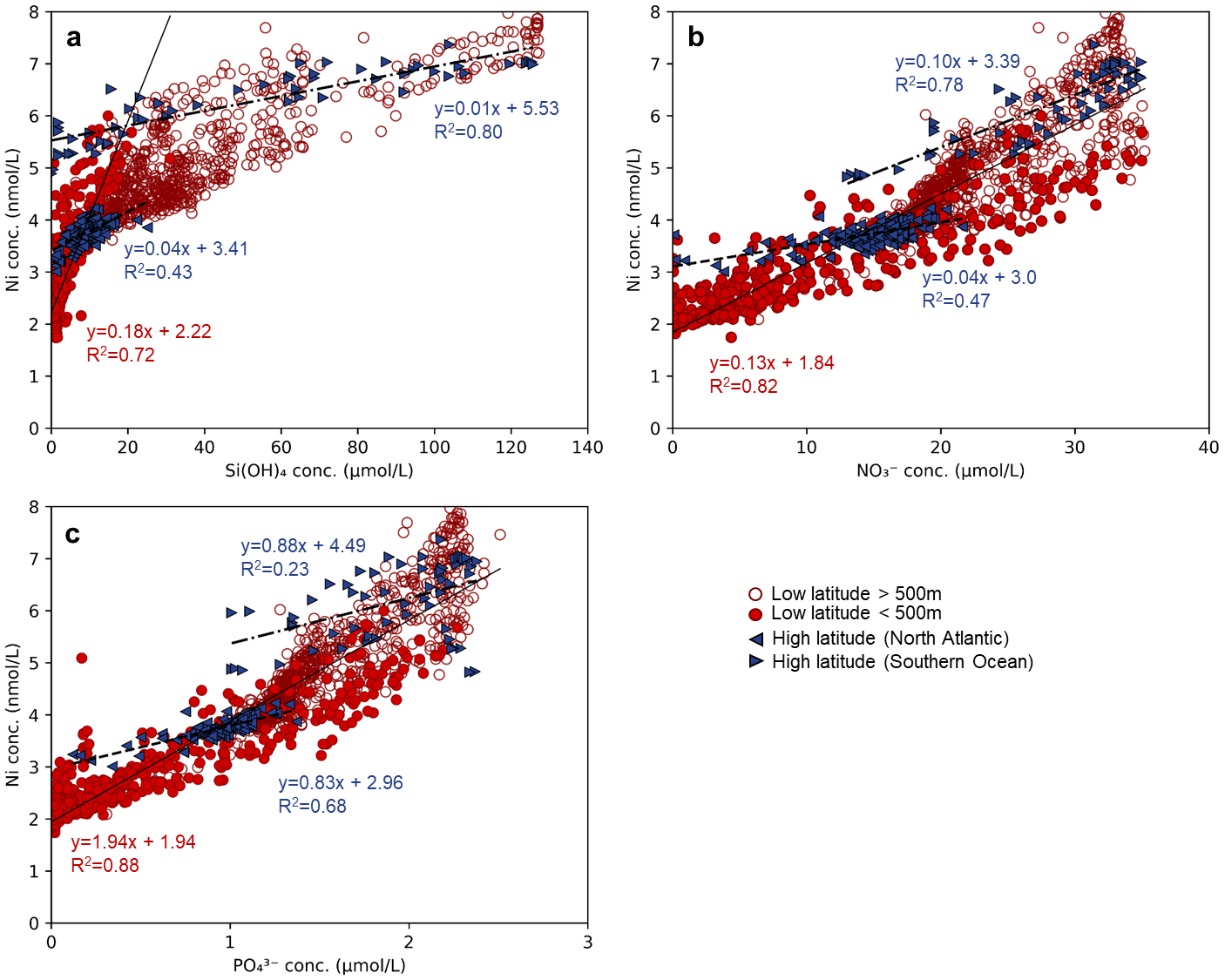


Fig. S6: Ni concentrations against Si(OH)4 (a), NO3- (b) and PO43- (c) concentrations in the Atlantic ocean (from the GEOVIDE, GA02, GA03, ANT XXIV/3, GA10, and RRS 354 cruises; GEOTRACES Intermediate Data Product, 2021). Red circles indicate stations from the low latitude ocean (filled symbols for depths <500 m) while blue triangles indicate stations from the high latitude ocean (triangles pointing towards the right for the Southern Ocean and triangles pointing towards the left for the subpolar North Atlantic). Correlations between data are also indicated: the continuous thin black line for low latitude stations (only for the upper 500 m for the Ni-Si(OH)4 relationship), the dashed black lines for subpolar stations.

Table S1. Dissolved δ60Ni, Ni concentrations, silicate (Si(OH)4), nitrate (NO3-), temperature and salinity for 6 stations across the GEOVIDE transect. There are no PO43- data available for GEOVIDE.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Depth | δ60Ni | 2SD | [Ni] | NO3- | SiOH4 | Temperature | Salinity |
| m | ‰ | ‰ | nmol/L | µmol/L | µmol/L | °C | psu |
|  |  |  |  |  |  |  |  |
| ***Station 13: 41.4°N, -13.9°E, Bottom depth 5345m*** | | | | | |  |  |
| 15 | 1.64 | 0.08 | 2.14 | 0.1 | 0.5 | 15.46 | 35.85 |
| 60 | 1.60 | 0.08 | 2.45 | 2.9 | 0.9 | 13.27 | 35.76 |
| 99 | 1.52 | 0.08 | 2.63 | 6.8 | 1.8 | 12.88 | 35.74 |
| 149 | 1.45 | 0.06 | 2.74 |  |  | 12.75 | 35.73 |
| 199 | 1.47 | 0.04 | 2.72 | 7.8 | 2.3 | 12.56 | 35.70 |
| 298 | 1.54 | 0.03 | 2.80 | 10.3 | 3.1 | 12.20 | 35.66 |
| 495 | 1.38 | 0.09 | 3.06 | 11.6 | 3.7 | 11.69 | 35.62 |
| 595 | 1.51 | 0.08 | 3.20 | 13.9 | 5.0 | 11.31 | 35.59 |
| 790 | 1.36 | 0.04 | 3.66 | 18.4 | 8.7 | 10.76 | 35.73 |
| 990 | 1.39 | 0.09 | 3.84 |  |  | 9.26 | 35.64 |
| 1187 | 1.33 | 0.06 | 3.84 | 18.0 | 10.6 | 9.30 | 35.84 |
| 1975 | 1.42 | 0.05 | 3.97 | 19.1 | 16.3 | 3.97 | 35.03 |
| 2466 | 1.46 | 0.08 | 4.37 | 20.2 | 23.8 | 3.30 | 34.98 |
| 2952 | 1.35 | 0.06 | 4.88 | 21.4 | 33.3 | 2.85 | 34.95 |
| 3932 | 1.30 | 0.08 | 5.68 | 23.0 | 43.4 | 2.53 | 34.91 |
| 4904 | 1.32 | 0.05 | 5.46 | 23.3 | 46.5 | 2.52 | 34.90 |
| 5330 | 1.34 | 0.04 | 5.39 | 23.3 | 47.0 | 2.57 | 34.90 |
|  |  |  |  |  |  |  |  |
| ***Station 21: 46.5°N, -19.7°E, Bottom depth 4518m*** | | | | | |  |  |
| 20 | 1.67 | 0.04 | 1.75 | 4.4 | 1.6 | 13.78 | 35.66 |
| 50 | 1.60 | 0.03 | 2.62 | 4.4 | 1.6 | 12.69 | 35.61 |
| 100 | 1.39 | 0.09 | 2.86 | 8.6 | 2.9 | 12.48 | 35.64 |
| 199 | 1.53 | 0.06 | 2.71 | 9.8 | 3.4 | 12.04 | 35.63 |
| 298 | 1.53 | 0.05 | 3.00 | 10.2 | 3.6 | 11.76 | 35.59 |
| 397 | 1.38 | 0.09 | 2.96 | 12.4 | 4.5 | 11.32 | 35.54 |
| 495 | 1.47 | 0.03 | 3.00 | 11.4 | 4.1 | 10.96 | 35.49 |
| 790 | 1.42 | 0.04 | 3.65 | 17.4 | 8.0 | 9.20 | 35.34 |
| 990 | 1.41 | 0.05 | 3.75 | 19.2 | 10.8 | 7.61 | 35.33 |
| 1237 | 1.38 | 0.05 | 3.79 | 18.8 | 11.0 | 5.76 | 35.15 |
| 1483 | 1.34 | 0.06 | 3.75 | 18.4 | 10.9 | 4.52 | 35.00 |
| 1975 | 1.31 | 0.06 | 3.74 | 18.3 | 12.2 | 3.71 | 34.93 |
| 2268 | 1.28 | 0.04 | 3.90 | 18.3 | 13.3 | 3.40 | 34.92 |
| 2759 | 1.27 | 0.05 | 3.61 | 18.5 | 15.9 | 3.07 | 34.94 |
| 3442 | 1.21 | 0.07 | 4.80 | 21.8 | 37.0 | 2.71 | 34.93 |
| 4415 | 1.29 | 0.04 | 5.41 | 22.9 | 43.7 | 2.56 | 34.91 |
| 4507 | 1.29 | 0.08 | 5.35 | 23.3 | 45.6 | 2.57 | 34.91 |

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Depth | δ60Ni | 2SD | [Ni] | NO3- | SiOH4- | Temperature | Salinity |
| m | ‰ | ‰ | nmol/L | µmol/L | µmol/L | °C | psu |
|  |  |  |  |  |  |  |  |
| ***Station 32: 55.5°N, -26.7°E, Bottom depth 3234m*** | | | | | |  |  |
| 30 | 1.33 | 0.05 | 3.24 | 9.2 | 2.2 | 10.34 | 35.12 |
| 50 | 1.39 | 0.08 | 3.36 |  |  | 8.46 | 35.04 |
| 99 | 1.42 | 0.09 | 3.20 | 9.5 | 2.0 | 8.71 | 35.13 |
| 198 | 1.31 | 0.06 | 3.45 | 13.9 | 5.8 | 8.12 | 35.11 |
| 298 | 1.37 | 0.09 | 3.97 | 15.5 | 7.5 | 6.65 | 34.92 |
| 397 | 1.41 | 0.03 | 3.87 | 16.5 | 8.4 | 6.77 | 35.06 |
| 496 | 1.30 | 0.04 | 3.83 | 19.0 | 10.8 | 5.71 | 34.99 |
| 792 | 1.28 | 0.04 | 3.78 | 17.7 | 9.8 | 4.47 | 34.94 |
| 990 | 1.44 | 0.08 | 3.69 | 17.1 | 9.6 | 4.11 | 34.92 |
| 1236 | 1.46 | 0.10 | 3.71 | 16.9 | 9.8 | 3.90 | 34.91 |
| 1482 | 1.41 | 0.07 | 3.65 | 17.0 | 10.5 | 3.78 | 34.92 |
| 1973 | 1.39 | 0.06 | 3.65 | 17.6 | 11.9 | 3.45 | 34.93 |
| 2953 | 1.47 | 0.06 | 4.00 | 18.2 | 22.3 | 2.90 | 34.97 |
| 3177 | 1.40 | 0.08 | 3.79 |  |  | 2.85 | 34.99 |
| 3218 | 1.39 | 0.05 | 3.85 | 18.5 | 25.1 | 2.86 | 34.99 |
|  |  |  |  |  |  |  |  |
| ***Station 38: 58.8°N, -31.3°E, Bottom depth 1341m*** | | | | | |  |  |
| 19 | 1.40 | 0.03 | 3.29 | 7.1 | 0.5 | 9.24 | 35.06 |
| 50 | 1.36 | 0.04 | 3.33 | 8.8 | 1.2 | 7.94 | 35.07 |
| 98 | 1.40 | 0.05 | 3.35 | 14.3 | 5.9 | 7.51 | 35.10 |
| 197 | 1.39 | 0.03 | 3.41 | 14.6 | 6.4 | 7.34 | 35.11 |
| 297 | 1.42 | 0.03 | 3.42 | 14.8 | 6.6 | 7.12 | 35.09 |
| 397 | 1.37 | 0.05 | 3.49 | 15.0 | 6.6 | 6.78 | 35.06 |
| 495 | 1.38 | 0.04 | 3.56 | 16.6 | 8.3 | 6.58 | 35.07 |
| 792 | 1.35 | 0.04 | 3.66 | 17.8 | 10.3 | 5.17 | 35.03 |
| 940 | 1.41 | 0.04 | 3.63 | 17.2 | 10.3 | 4.54 | 34.99 |
| 1149 | 1.36 | 0.05 | 3.64 |  |  | 4.03 | 34.99 |
| 1285 | 1.37 | 0.03 | 3.64 | 16.8 | 10.6 | 4.01 | 34.99 |
| 1337 | 1.28 | 0.06 | 3.69 | 16.7 | 10.9 | 4.01 | 34.99 |

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Depth | δ60Ni | 2SD | [Ni] | NO3- | SiOH4- | Temperature | Salinity |
| m | ‰ | ‰ | nmol/L | µmol/L | µmol/L | °C | psu |
|  |  |  |  |  |  |  |  |
| ***Station 44: 59.6°N, -38.9°E, Bottom depth 2928m*** | | | | | |  |  |
| 20 | 1.51 | 0.03 | 3.52 | 16.5 | 8.1 | 6.79 | 34.85 |
| 50 | 1.43 | 0.03 | 3.55 |  |  | 4.97 | 34.86 |
| 159 | 1.49 | 0.04 | 3.52 | 16.4 | 8.0 | 4.14 | 34.90 |
| 199 | 1.33 | 0.04 | 3.74 | 16.5 | 8.2 | 4.06 | 34.90 |
| 297 | 1.41 | 0.04 | 3.72 | 16.3 | 8.1 | 3.97 | 34.90 |
| 466 | 1.32 | 0.04 | 3.76 | 16.3 | 8.3 | 3.86 | 34.89 |
| 595 | 1.34 | 0.04 | 3.72 | 16.4 | 8.4 | 3.68 | 34.87 |
| 694 | 1.45 | 0.05 | 3.65 | 16.4 | 8.4 | 3.62 | 34.87 |
| 890 | 1.40 | 0.06 | 3.70 | 17.1 | 9.4 | 3.58 | 34.86 |
| 1087 | 1.36 | 0.08 | 3.72 | 17.3 | 10.6 | 3.73 | 34.90 |
| 1580 | 1.44 | 0.08 | 3.72 |  | 11.5 | 3.54 | 34.93 |
| 1973 | 1.36 | 0.09 | 3.68 | 17.0 | 12.7 | 3.23 | 34.93 |
| 2217 | 1.39 | 0.09 | 3.76 | 16.9 | 13.6 | 3.04 | 34.93 |
| 2561 | 1.38 | 0.08 | 3.67 | 14.1 | 7.6 | 2.65 | 34.91 |
| 2756 | 1.45 | 0.04 | 3.54 | 13.8 | 7.3 | 1.59 | 34.87 |
| 2851 | 1.36 | 0.05 | 3.52 | 13.8 | 7.4 | 1.34 | 34.88 |
| 2916 | 1.33 | 0.06 | 3.47 | 13.8 | 7.4 | 1.29 | 34.89 |
|  |  |  |  |  |  |  |  |
| ***Station 69: 55.8°N, -48.1°E, Bottom depth 3692m*** | | | | | |  |  |
| 15 | 1.38 | 0.07 | 3.72 | 0.1 | 3.6 | 6.22 | 34.62 |
| 41 | 1.32 | 0.09 | 3.59 | 11.8 | 7.0 | 3.60 | 34.74 |
| 70 | 1.33 | 0.10 | 3.68 | 15.4 | 7.4 | 3.89 | 34.82 |
| 178 | 1.34 | 0.04 | 3.57 | 15.9 | 8.0 | 3.71 | 34.85 |
| 496 | 1.44 | 0.08 | 3.68 | 16.0 | 8.1 | 3.49 | 34.85 |
| 792 | 1.35 | 0.05 | 3.69 | 16.2 | 8.2 | 3.48 | 34.85 |
| 1087 | 1.36 | 0.10 | 3.69 | 16.2 | 8.3 | 3.46 | 34.85 |
| 1580 | 1.31 | 0.07 | 3.76 | 16.8 | 9.1 | 3.62 | 34.89 |
| 2071 | 1.34 | 0.07 | 3.72 | 17.1 | 10.8 | 3.45 | 34.92 |
| 2364 | 1.35 | 0.09 | 3.73 | 17.2 | 11.6 | 3.22 | 34.92 |
| 2756 | 1.39 | 0.08 | 3.64 | 16.8 | 12.5 | 2.93 | 34.92 |
| 3196 | 1.30 | 0.07 | 3.72 | 16.4 | 14.0 | 2.48 | 34.91 |
| 3439 | 1.25 | 0.05 | 3.51 | 15.4 | 11.5 | 2.00 | 34.90 |
| 3635 | 1.27 | 0.06 | 3.59 |  |  | 1.68 | 34.90 |
| 3660 | 1.28 | 0.09 | 3.49 | 14.3 | 8.4 | 1.67 | 34.90 |

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