GLODAPv2, 2020 – the second update of GLODAPv2

Are Olsen 1, Nico Lange 2, Robert M. Key 3, Toste Tanhua 2, Henry C. Bittig 4, Alex Kozyr 5, Marta Álvarez 6, Kumiko Azetsu-Scott 2, Susan Becker 1, Peter J. Brown 2, Brendan R. Carter 3,4, Leticia Cotrim da Cunha 2, Richard A. Feely 3,4, Steven van Heuven 1, Mario Hoppema 10, Masao Ishii 21, Emil Jeansson 17, Sara Jutterström 17, Camilla S. Landa 1, Siv K. Lauvset 10, Patrick Michaelis 2, Akihiko Murata 1, Fiz F. Pérez 2, Benjamin Pfeil 1, Carsten Schirnack 7, Reiner Steinfeldt 19, Toru Suzuki 30, Bronte Tilbrook 22, Anton Velo 18, Rik Wanninkhof 22, Ryan J. Woosley 23

1 Geophysical Institute, University of Bergen and Bjerknes Centre for Climate Research, Bergen, Norway
2 Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, 08540, USA
3 Sekken Institute for Baltic Sea Research Warnemünde, Rostock, Germany
4 Joint Institute for the Study of the Atmosphere and Ocean, University Washington, Seattle, Washington, USA
5 National Oceanography Centre, Southampton, UK
6 Faculdade de Oceanografia, Universidade do Estado do Rio de Janeiro, Rio de Janeiro (RJ), Brazil
7 Centre for Isotope Research, Faculty of Science and Engineering, University of Groningen, Groningen, the Netherlands
8 Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
9 Oceanography and Geochemistry Research Department, Meteorological Research Institute, Japan Meteorological Agency, Tsukuba, Japan
10 Institute of Climate and Space Research, CSIRO, Newcastle, Australia
11 National Oceanography Centre, Plymouth, UK
12 NOAA National Centers for Environmental Information, Silver Spring, MD, USA
13 GLODAPv2
14 Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, Seattle, Washington, USA
15 UC San Diego, Scripps Institution of Oceanography, San Diego CA 92093, USA
16 National Oceanography Centre, Southampton, UK
17 Geophysical Institute, University of Bergen and Bjerknes Centre for Climate Research, Bergen, Norway
18 National Oceanography Centre, Southampton, UK
19 Institute of Climate and Space Research, CSIRO, Newcastle, Australia
20 Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
21 National Oceanography Centre, Southampton, UK
22 Marine Information Research Center, Japan Hydrographic Association, Tokyo, Japan
23 OECD Centre, Paris, France
24 Joint Institute for the Study of the Atmosphere and Ocean, University Washington, Seattle, Washington, USA
25 Baltic Environmental Research Centre, University of Helsinki, Helsinki, Finland
26 Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
27 CIRES, University of Colorado, Boulder, CO, USA
28 National Oceanography Centre, Southampton, UK
29 Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
30 Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
31 Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
32 Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
33 Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
34 Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
35 Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany

Correspondence to: Are Olsen (are.olsen@uib.no)
Abstract. The Global Ocean Data Analysis Project (GLODAP) is a synthesis effort providing regular compilations of surface to bottom ocean biogeochemical data, with an emphasis on seawater inorganic carbon chemistry and related variables determined through chemical analysis of water samples. GLODAPv2 2020 is an update of the previous version, GLODAPv2.2019. The major changes are: data from 106 more cruises added, extension of time coverage until 2019, and the inclusion of available discrete fugacity of CO2 (fCO2) values in the merged product files. GLODAPv2.2020 includes measurements from more than 1.2 million water samples from the global oceans collected on 216 cruises. The data for the 12 GLODAP core variables (salinity, oxygen, nitrate, silicate, phosphate, dissolved inorganic carbon, total alkalinity, pH, CFC-11, CFC-12, CFC-113, and CCL3) have undergone extensive quality control, especially systematic evaluation of bias. The data are available in two formats: (i) as submitted by the data originator but updated to WOCE exchange format and (ii) as a merged data product applied to minimize bias. These adjustments were derived by comparing the data from the 116 new cruises with the data from the 210 quality-controlled cruises of the GLODAPv2 2019 data product. They correct for errors related to measurement, calibration, and data handling practices, while taking into account any known or likely time trends or variations in the variables evaluated. The compiled and adjusted data product is believed to be consistent to better than 0.005 in salinity, 1% in oxygen, 2% in nitrate, 2% in silicate, 2% in phosphate, 4 µmol kg⁻¹ in dissolved inorganic carbon, 4 µmol kg⁻¹ in total alkalinity, 0.01–0.02, depending on region, in pH, and 5% in the halogenated transient tracers. The other variables included in the compilation, such as isotopic tracers, and discrete fCO2, were not subjected to bias comparison or adjustments. The original data, their documentation and doi codes are available at the Ocean Carbon Data System of NOAA NCEI ([https://www.nodc.noaa.gov/ocads/oceans/GLODAPv2-2020/, last access: 20 June 2020]). This site also provides access to the merged data product, which is provided as a single global file and as four regional ones – the Arctic, Atlantic, Indian, and Pacific oceans – under https://doi.org/10.25921/2c9h-sa89 (Olsen et al., 2020). The bias corrected product files also include significant ancillary and approximated data. These were obtained by interpolation of, or calculation from, measured data. This living data update documents the GLODAPv2 2020 methods and provides a broad overview of the secondary quality control procedures and results.

1 Introduction

The oceans mitigate climate change by absorbing atmospheric CO2, corresponding to a significant fraction of anthropogenic CO2 emissions (Friedlingstein et al., 2019; Gruber et al., 2019) and most of the excess heat in the Earth System caused by the enhanced greenhouse effect (Cheng et al., 2020; Cheng et al., 2017). The objective of GLODAP (Global Ocean Data Analysis Project, www.gladap.info, last access: 25 May 2020) is to ensure provision of high quality and bias-corrected water column bottle data from the ocean surface to bottom that document the state and the evolving changes in physical and chemical ocean properties, e.g., the inventory of the excess CO2 in the ocean, natural oceanic carbon, ocean acidification, ventilation rates, oxygen levels, and vertical nutrient transport. The GLODAP core variables, which are quality controlled and bias corrected, are salinity, dissolved oxygen, inorganic macronutrients (nitrate, silicate, and phosphate), seawater CO2 chemistry variables (dissolved inorganic carbon – TCO2, total alkalinity – TAk, and pH on the total H⁺ scale), and the halogenated transient tracers CFC-11, CFC-12, CFC-113, and CCL3.

Other chemical tracers are usually also measured on the cruises included in GLODAP. A subset of these data is distributed as part of the product but has not been extensively quality controlled or checked for measurement biases in this effort. For some of these variables, better sources of data may exist, for example the product by Jenkins et al. (2019).
for helium isotope and tritium data, GLODAP also includes derived variables to facilitate interpretation, such as potential density anomalies and apparent oxygen utilization (AOU). A full list of variables included in the product is provided in Table 1.

The oceanographic community largely adheres to principles and practices for ensuring open access to research data, such as the FAIR (Findable, Accessible, Interoperable, Reusable) initiative (Wilkinson et al., 2016), but the plethora of file formats and different levels of documentation combined with the need to retrieve data on a per cruise basis from different access points limits the realization of their full scientific potential. For biogeochemical data there is the added complexity of different levels of standardization and calibration, and even different units used for the same variable, such that the comparability between data sets is often poor. Standard operating procedures have been developed for some variables (Dickson et al., 2007; Hood et al., 2010; Hydes et al., 2012) and certified reference materials (CRM) exist for seawater TCO$_2$ and TA$_{alk}$ measurements (Dickson et al., 2003) and for nutrients in seawater (CRMNS, Aoyama et al., 2012; Ota et al., 2010). Still biases in data occur. These can arise from poor sampling and general operation practices, calibration procedures, instrument design, and inaccurate calculations. The use of CRMs does not by itself ensure accurate measurements of seawater CO$_2$ chemistry (Bockmon and Dickson, 2015), and the CRMNS have only become available recently and are not universally used. For salinity and oxygen, lack of – or improper – conductivity-temperature-depth (CTD) sensor calibration is an additional and widespread problem (Olson et al., 2016). For halogenated transient tracers, uncertainties in the standard gas composition, extracted water volume, and purge efficiency typically provide the largest sources of uncertainty. In addition to bias, occasional outliers occur. In rare cases poor precision can render a set of data unusable. GLODAP deals with these issues by presenting the data in a uniform format, by including any documentation that was either submitted by the data originator or could be attained, and by subjecting the data to primary and secondary quality control assessments, focusing on precision and consistency, respectively. Adjustments are applied on the data to minimize severe cases of bias.

GLODAPv2.2020 builds on earlier synthesis efforts for biogeochemical data obtained from research cruises, GLODAPv1.1 (Key et al., 2004; Sabine et al., 2005). Carbon dioxide in the Atlantic Ocean (CARINA) (Key et al., 2010), Pacific Ocean Interior Carbon (PACIFICA) (Suzuki et al., 2013), and notably GLODAPv2 (Olson et al., 2016), GLODAPv1.1 combined data from 115 cruises with biogeochemical measurements from the global ocean. The vast majority of these were the sections covered during the World Ocean Circulation Experiment and the Joint Global Ocean Flux Study (WOCE/JGOFS) in the 1990s, but also included data from important “historical” cruises, such as from the Geochemical Ocean Sections Study (GEOSECS), Transient Traces in the Ocean (TTO), and South Atlantic Ventilation Experiment (SAVE). GLODAPv2 was released in 2016 (Key et al., 2015; Lauvset et al., 2016; Olson et al., 2016) with data from 724 scientific cruises: those included in GLODAPv1.1, those amassed for the Carbon in the Atlantic Ocean (CARINA) data synthesis (Key et al., 2010), those amassed for the Pacific Ocean Interior Carbon (PACIFICA) synthesis (Suzuki et al., 2013), and data from 168 additional cruises. The additional cruises include many collected within the framework of the “repeat hydrography” program (Talley et al., 2016), instigated in the early 2000s as part of CLIVAR and since 2007 organized as the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) (Sloyan et al., 2019). GLODAPv2 is now updated regularly using the format of “living data format” of Earth System Science Data to document significant additions and changes to the dataset. This is the second regular update and adds data from 106 new cruises to the last update GLODAPv2.2019 (Olson et al., 2019).

2 Key features of the update

GLODAPv2.200 (Olson et al., 2020) contains data from 946 cruises, covering the global ocean from 1972 to 2019, compared to 840 for the period 1972-2017 for GLODAPv2.2019. Information on the 106 cruises added to this version is
provided in Table A1 in the Appendix. Their sampling locations are shown alongside those of GLODAPv2:2019 in Fig. 1, while the coverage in time is shown in Fig. 2. The added cruises are from the years 2004-2019 with most more recent than 2010. The majority of the new data were obtained from the two vessels RV *Keili Maru II* and RV *Ryūfū Maru III*, which are operated by the Japan Meteorological Agency in the western North Pacific (Oka et al., 2018; Oka et al., 2017). The data collected across the Davis Strait from 10 cruises between 2004-2015 through a collaboration between the Bedford Institute of Oceanography, Canada and the University of Washington, USA (Azetsu-Scott et al., 2012) is another important addition. Other cruises from the Atlantic include those carried out on the RV *Maria S. Merian* and RV *Meteor* with transient tracer but not nutrients or seawater CO₂ chemistry data; the 2016 occupation of the OVIDE line (Pérez et al., 2018); the 2019 occupation of A17 onboard RV *Hesperides*; the 2018 occupation of A9.5 onboard RSS *James Cook* (King et al., 2019); and A02 on the RV *Celtic Explorer* in 2017 (McGrath et al., 2019). Two older North Atlantic cruises that did not find their way into GLODAPv2 have been added, a 2008 occupation of AR07W including more extensive subpolar NA sampling (35TH20080825) and a 2007 RV *Pelagia* cruise (64PE20071026) covering the Northeast Atlantic. The final Atlantic cruise is 29GD20120910 onboard RV *García del Cid*, which has measurements for stable isotopes of carbon and oxygen (δ¹³C and δ¹⁸O) off the Iberian Peninsula (Voelker et al., 2015) but no data for nutrients, seawater CO₂ chemistry, or transient tracers. Two new cruises are included for the Indian Ocean, both in the far south, in the Indian sector of the Southern Ocean: an Argo deployment cruise south and west of Kerguelen Island onboard the RV *S. A. Agulhas I*, and the 2018 occupation of GO-SHIP line SR03 onboard the RV *Investigator*. The JOIS cruise in 2015 is the sole addition for the Arctic. Finally, the data along the US west coast are from two cruises conducted on board the RVs *Wecoma* (WCOA2011, 32WC20110812) and *Ronald H. Brown* (WCOA2016, 33RO20160505) as part of NOAA’s ocean acidification program.

All new cruises were subjected to primary (Sect. 3.1) and secondary (Sect. 3.2) quality control (QC). These procedures are essentially the same as previously, aiming to ensure the consistency of the data from the 406 new cruises to the previous release of this data product (the GLODAPv2:2019 adjusted data product). A full-blown consistency analysis of the entire GLODAPv2:2020 product (as done with the original GLODAPv2 product) has not been carried out, as it is too demanding in terms of time and resources to allow for frequent updates, particularly in terms of application of inversion results. The QC of GLODAPv2:2019 produced a sufficiently accurate data product that can serve as a reliable reference (this is in fact already done by some investigators to test their newly collected data; e.g. Panassa et al. 2018). The aim is to conduct a full analysis (i.e., including an inversion) again after the completion of the third GO-SHIP survey, currently scheduled for completion by 2023. Until that time, intermediate products like this are released regularly (every year or two years). A naming convention has been introduced to distinguish intermediate from full product updates. For the latter the version number will change, while for the former the year of release is added.

3 Methods

3.1 Data assembly and primary quality control

The data for the 406 new cruises were retrieved from data centers (typically CCHDO, NCEI, PANGAEA) or submitted directly to us. Each cruise is identified by an EXPOCODE. The EXPOCODE is guaranteed to be unique and constructed by combining the country code and platform code with the date of departure in the format YYYYMMDD. The country and platform codes were taken from the ICES (International Council for the Exploration of the Sea) library (https://vocab.ices.dk/, last access: 20 June 2020).
The individual cruise data files were converted to WOCE exchange format: a comma delimited ASCII format for CTD and bottle data from hydrographic cruises. GLODAP deals only with bottle data and CTD data at bottle trip depths, and their exchange format is briefly reviewed here with full details provided in Swift and Díaz (2008). The first line of each exchange file specifies the data type, in the case of GLODAP this is “BOTTLE”, followed by a date and time stamp and identification of the person/group who prepared the file, e.g., “PRINUNIVRMK” is Princeton University, Robert M. Key. Next follows the README section. This provides brief cruise specific information, such as dates, ship, region, method and quality notes for each variable measured, citation information, and references to any papers that used or presented the data. The README information was typically assembled from the information contained in the metadata submitted by the data originator. In some cases, issues noted during the primary QC and other information such as file update notes are included. The only rule for the README section is that it be concise and informative. The README is followed by data column headers, units, and then the data. The headers and units are standardized and provided in Table 1 for the variables included, Exchange file preparation entailed units conversion in some cases, most frequently from milliliters per liter (mL L\(^{-1}\); oxygen) or micromoles per liter (µmol L\(^{-1}\); nutrients) to micromoles per kilogram of seawater (µmol kg\(^{-1}\)). The default procedure for nutrients was to use seawater density at reported salinity, an assumed measurement-temperature of 22 °C, and pressure of 1 atm. For oxygen, the factor 44.66 was used for the milliliter to micromole conversion, while for the per liter to per kilogram conversion density based on reported salinity and draw temperatures was preferred, but draw temperature was frequently not reported and potential density was used instead. The potential errors introduced by any of these procedures are insignificant. Missing numbers are indicated by -999, with trailing zeros to comply with the number format for the variable in question, as specified in Swift and Díaz (2008).

Each data column (except temperature and pressure, which are assumed “good” if they exist) has an associated column of units, and then the data. The headers and units are standardized and provided in Table 1 for the variables included. Exchange file preparation entailed units conversion in some cases, most frequently from milliliters per liter (mL L\(^{-1}\); oxygen) or micromoles per liter (µmol L\(^{-1}\); nutrients) to micromoles per kilogram of seawater (µmol kg\(^{-1}\)). The default procedure for nutrients was to use seawater density at reported salinity, an assumed measurement-temperature of 22 °C, and pressure of 1 atm. For oxygen, the factor 44.66 was used for the milliliter to micromole conversion, while for the per liter to per kilogram conversion density based on reported salinity and draw temperatures was preferred, but draw temperature was frequently not reported and potential density was used instead. The potential errors introduced by any of these procedures are insignificant. Missing numbers are indicated by -999, with trailing zeros to comply with the number format for the variable in question, as specified in Swift and Díaz (2008).

3.2 Secondary quality control

The aim of the secondary QC was to identify and correct any significant biases in the data from the 406 new cruises relative to GLODAPv2,2019, while retaining any signal due to temporal changes. To this end, secondary QC in the form of consistency analyses was conducted to identify offsets in the data. All identified offsets were scrutinized by the GLODAP reference group through a series of teleconferences during March and April 2020 in order to decide the adjustments to be applied to correct for the offset (if any). To guide this process, a set of initial minimum adjustment limits was established (Table 3). These are set according to the expected measurement precision for each variable, and are the same as those used for GLODAPv2,2019. In addition to the magnitude of the offset, factors such as its precision, persistence towards the various cruises used in the comparison, regional dynamics, and the occurrence of time trends or other variations were considered. Thus, not all offsets larger than the initial minimum limits have been adjusted for. A guiding principle for these considerations was to not apply an adjustment whenever in doubt. Conversely, in some cases, data and offsets were very precise and the cruise had been conducted in a region where variability is expected to be small, adjustments lower than the minimum limits were applied. Any adjustment was applied uniformly to all values for a given cruise.
variable and cruise, i.e., an underlying assumption is that cruises suffer from either no or a single and constant measurement bias. Except where explicitly noted (Sect. 3.3.1), adjustments were not changed for data previously included in GLODAPv2.

Crossover comparisons, multi-linear regressions (MLR), and comparison of deep-water averages were used to identify offsets for salinity, oxygen, nutrients, TCO$_2$, TAlk and pH (Sect. 3.2.2 and 3.2.3); in contrast to GLODAPv2 and GLODAPv2.2019, evaluation of the internal consistency of the seawater CO$_2$ chemistry variables was not used for the evaluation of pH (Sect. 3.2.4). New to the present version is the more extensive use of CANYON-B and CONTENT predictions for the evaluation of offsets in nutrients and seawater CO$_2$ chemistry data (Section 3.2.5). For the halogenated transient tracers, examination of surface saturation levels and the relationship among the tracers were used to assess the data consistency (Sect. 3.2.6). For salinity and oxygen, CTD and bottle values were merged into a “hybrid” variable prior to the consistency analyses (Sect. 3.2.1).

### 3.2.1 Merging of sensor and bottle data

Salinity and oxygen data can be obtained either by analysis of water samples (bottle data) and/or directly from the CTD sensor pack. These two types are merged and presented as a single variable in the product. The merging procedures were only applied to the bottle data files, which commonly include values recorded by the CTD at the pressures of the upcast when the water samples are collected. Whenever both CTD and bottle data were present in a data file, the merging step considered the deviation between the two and calibrated the CTD values if required and possible. Altogether seven scenarios are possible, where the fourth (see below) never occurred during our analyses, but is included to maintain consistency with GLODAPv2.

1. No data are available: no action needed.
2. No bottle values: use CTD values.
3. No CTD values: use bottle values.
4. Too few data of both types for comparison and more than 80% of the records have bottle values: use bottle values.
5. The CTD values do not deviate significantly from bottle values: replace missing bottle values with CTD values.
6. The CTD values deviate significantly from bottle values: calibrate CTD values using linear fit with respect to bottle data and replace missing bottle values with the so-calibrated CTD values.
7. The CTD values deviate significantly from bottle values, and no good linear fit can be obtained for the cruise: use bottle values and discard CTD values.

The number of cases encountered for each scenario is summarized in Sect. 4.1.

### 3.2.2 Crossover analyses

The crossover analyses were conducted with the MATLAB toolbox prepared by Lauvset and Tanhua (2015) and with the GLODAPv2.2019 data product as reference. In areas where a strong trend in salinity was present, the TAlk and TCO$_2$ data were salinity normalized before crossover analysis, following Friis et al. (2003). The toolbox implements the ‘running-cluster’ crossover analysis first described by Tanhua et al. (2010). This analysis compares data from two cruises on a station-by-station basis and calculates a weighted mean offset between the two and its weighted standard deviation. The weighting is based on the scatter in the data such that data that have less scatter have larger influence on the comparison than data with more scatter. Whether the scatter reflects actual variability or data...
precision is irrelevant in this context as increased scatter regardless decreases the confidence in the comparison. Stations that are compared must be within 2° arc distance (~200 km) of each other, and only deep data are used. This minimizes effects of natural variability. As default, we used 1500 dbar as the upper depth limit, but in regions where deep mixing or convection occurs (such as the Nordic, Labrador, and Irminger seas) a more conservative limit of 2000 dbar was applied. The deeper limit was also applied to the majority of the northern Pacific cruises on the RV Keiō Maru II and RV Ryōtu Maru III due the great abundance of deep data of the new- and reference cruises. As an example, the crossover for TCO$_2$ measured on the two cruises 49UP20160109 and 49UP20160703 is shown in Fig. 3. For TCO$_2$, the offset is determined as the difference. This is also the case for salinity, TAlk, and pH. For the nutrients, oxygen, and the halogenated transient tracers, ratios are used. This in accordance with the procedures followed for GLODAPv2. The TCO$_2$ values from 49UP20160109 are higher, with a weighed mean offset of 3.62 ± 2.67 µmol kg$^{-1}$, compared to those measured at 49UP20160703.

For each of the 106 new cruises, such a crossover comparison was conducted against all cruises possible in GLODAPv2, i.e., all cruises that had stations closer than 2° arc distance to any station for the cruise in question. The summary figure for TCO$_2$ at 49UP20160109 is shown in Fig. 4. The TCO$_2$ data measured at this cruise are high when compared to the data measured at all nearby cruises included in GLODAPv2 2019, by 3.68 ± 0.83 µmol kg$^{-1}$. This is slightly less than the initial minimum adjustment limit for TCO$_2$ of 4 µmol kg$^{-1}$ (Table 3), but the offset is present against all cruises and there is no obvious time trend, particularly important for TCO$_2$), and as such qualifies for an adjustment of the data in the merged data product. In this case -3 µmol kg$^{-1}$ was applied, in order to bring the TCO$_2$ data from 49UP20160109 into consistency with GLODAPv2 2019.

Two exceptions to the above-described procedure exist: In the Japanese Sea six new cruises were added. In this region, there are only data from two cruises in GLODAPv2 2019. Therefore, all eight cruises were compared against each other and strong outliers were adjusted accordingly, instead of adjusting the six new cruises towards the two existing. A similar approach was used for the 10 new Davis Strait cruises; in this region no data were available in GLODAPv2 2019. Due to the complex hydrography and differences in sampling locations it was very problematic to fully quality control these data, however, so most have been labeled -888, i.e., they are included in the product but with a secondary QC flag of 0 (Sect. 6).

### 3.2.3 Other consistency analyses

A few new cruises had no or very few valid crossovers with GLODAPv2 data. In that situation two other consistency analyses were carried out for salinity, oxygen, nutrients, TCO$_2$, and TAlk data, namely MLR analyses and deep water averages, broadly following Jutterström et al. (2010). For the MLRs, the presence of bias in the data for the cruise in question was identified by comparing the MLR generated with the measured values. These methods were useful in the data-sparse Arctic and Southern oceans. Both analyses were conducted on samples collected deeper than the 1500 or 2000 dbar pressure level to minimize the effects of natural variations, and both used available GLODAPv2 2019 data from within 2° of the cruise in question to generate the MLR or deep water average. The lower depth limit was set to the deepest sample for the cruise in question. For the MLRs, all of the above mentioned variables could be included among the independent variables (e.g., for a TAlk MLR, salinity, oxygen, nutrients, and TCO$_2$ were allowed), with the exact selection determined based on the statistical robustness of the fit, as evaluated using the coefficient of determination ($r^2$) and root mean square error (RMSE). MLRs based on variables that were suspect for the cruise in question were avoided (e.g., if oxygen appeared biased it was not included as an independent variable). The MLRs could be based on 10 to 500
samples, and the robustness of the fit ($r^2$, RMSE) and quantity of fitting data were considered when using the results to guide whether to apply a correction. The same applies for the deep-water averages (i.e., the standard deviation of the mean). MLR and deep-water average results showing offsets above the minimum adjustment limits were carefully scrutinized, along with any crossover and CANYON-B and CONTENT results that existed, to determine whether or not to apply an adjustment.

### 3.2.4 pH scale conversion and quality control

All together 82 of the 106 new cruises included pH data. For one of these, the pH data were not supplied on the total scale or at 25°C and 0 dbar pressure, which is the GLODAP standard, and were thus converted. The conversion was conducted using CO2SYS (Lewis and Wallace, 1998) for MATLAB (van Heuven et al., 2011) with reported pH and TAlk as inputs, and generating pH output values at total scale at 25°C and 0 dbar pressure (named phTs25p0 in the product). Missing TAlk data were approximated as 67 times salinity. The proportionality (67) is the mean ratio of TAlk to salinity in GLODAPv2 data. This is sufficiently accurate for scale-temperature-pressure conversions. Data for phosphate and silicate are also needed, and were, whenever missing, determined using CANYON-B (Bittig et al., 2018). The conversion was conducted with the carbonate dissociation constants of Lueker et al. (2000), the bisulfate dissociation constant of Dickson (1990), and the borate-to-salinity ratio of Uppström (1974). These procedures are the same as used for GLODAPv2.2019 (Olsen et al., 2019).

Internal consistency of CO$_2$ system variables were not used for the secondary quality control of the pH data of the 106 new cruises, but only crossover analysis supplemented by CONTENT and CANYON-B (Sect. 3.2.5). This avoids uncertainties in the quality control owing to incomplete understanding of the thermodynamic constants, major ion concentrations, measurement biases, and potential contribution of organic compounds to alkalinity (Álvarez et al., 2020; Takeshita et al., 2020). However, this applies only to the new cruises. The pH data of 840 of the 936 cruises in GLODAPv2.2020 were QC’d for GLODAPv2 and GLODAPv2.2019, and for these earlier products internal consistency of CO$_2$ system was used for secondary QC of pH. Therefore the level of consistency between these 936 cruises remains at 0.01 to 0.02 pH units, as more thoroughly discussed in Olsen et al. (2019).

#### 3.2.5 CANYON-B and CONTENT analyses

CANYON-B and CONTENT (Bittig et al., 2018) were used to support decisions regarding application of adjustments (or not) from the analyses described above. CANYON-B is a neural network for estimating nutrients and seawater CO$_2$ chemistry variables from temperature, salinity, and oxygen. CONTENT additionally considers the consistency among the estimated CO$_2$ chemistry variables to further refine them. These approaches were developed using the data included in the GLODAPv2 data product. Their advantage compared to crossover analyses for evaluating consistency among cruise data is, that effects of water mass changes on ocean properties are represented in the non-linear relationships in the underlying neural network. For example, if elevated nutrient values are measured on a cruise but are not due to a measurement bias but actual aging of the water mass(es) that have been sampled and as such accompanied by a decrease in oxygen concentrations, the measured values and the CANYON-B estimates will be similar. Vice-versa, if the nutrient values are biased, the measured values and CANYON-B predictions will be dissimilar. Of course, we kept in mind that this relies on the accuracies of the T, S and O$_2$ data and of CANYON-B and CONTENT in themselves. Used in the correct way and with caution this tool is a powerful supplement to the traditional crossover analyses. As an example, the CANYON-B/CONTENT analyses of the data obtained at 49U/P20160109 are presented in Fig. 5. The CANYON-B and CONTENT...
results confirmed the positive offset in the TCO$_2$ values revealed in the crossover comparisons discussed in Sect. 3.2.2. The magnitude of the inconsistencies for the CANYON-B estimate was 3.4 µmol kg$^{-1}$, i.e., slightly less than that the weighted mean crossover offset of 3.7 µmol kg$^{-1}$, while the CONTENT estimate gave an inconsistency of 2.7 µmol kg$^{-1}$.

The differences between these consistency estimates owes to differences in the actual approach, the weighting across stations, considered (i.e., crossover comparisons use only stations within ~200 km of each other, while CANYON-B and CONTENT considers all stations where necessary variables are sampled, and depth range considered (≥500 dbar for CANYON-B and CONTENT vs. ≥1500/2000 dbar for crossovers). The specific difference between the CANYON-B and CONTENT estimates is a result of the seawater CO$_2$ chemistry considerations by the latter. For the other variables, the inconsistencies are low and agree with the crossover results (not shown here but results can be accessed through the Adjustment Table) with the exception of pH. The pH results are further discussed in Sect. 4.2. Another advantage of CANYON-B and CONTENT is that by considering the each data point in it self, primary QC issues has been revealed and corrected for some of the cruises.

### 3.2.6 Halogenated transient tracers

For the halogenated transient tracers (CFC-11, CFC-12, CFC-113, and CCl$_4$; CFCs for short) inspection of surface saturation levels and evaluation of relationships between the tracers for each cruise were used to identify biases, rather than crossover analyses. Crossover analysis is of limited value for these variables given their transient nature and low deep-water concentrations. As for GLODAPv2, the procedures were the same as those applied for CARINA (Jeansson et al., 2010; Steinfeldt et al., 2010).

### 3.3 Merged product generation

The merged product file for GLODAPv2, $v2.2019$ was created by correcting known issues in the GLODAPv2, $v2.2019$ merged file, and then appending a merged and bias-corrected file containing the $31$ new cruises to this error-corrected GLODAPv2, $v2.2019$ file.

### 3.3.1 Updates and corrections for GLODAPv2, $v2.2019$

Several minor omissions and errors have been identified in the GLODAPv2 and $v2.2019$ data products since their release in 2016 and 2019, respectively. Most of these have been corrected in this release. In addition, some recently available data have been added for a few cruises. The changes are:

- For cruise 33RR20160208, the CFC-113 data of station 31 were found to be bad and have been removed. Additionally, the flags for CFC-11, CFC-12, SF$_6$, and CCl$_4$ were replaced with new ones received from the Principal Investigator, and recently published data for δ$^{13}$C and δ$^{14}$C have been added to the product file.

- For 18HU20150504, the pH data measured at stations 196, 200, and 203 were found offset by approximately +0.1 units, because such large offset points to general data quality problems, these data have been removed.

- For 32PO20130829, pH values of station 133 cast 1 were in the wrong order in the file. This has been amended. Additionally, pH values from cast 2 at this station were deemed questionable and have been removed.

- For 33RR20050509, the δ$^{13}$C values of station 7 bottle 32 and station 16 bottle 22 were found bad (values were less than -6 %) and have been removed from the product file.

- For 35MF19850224, the δ$^{13}$C value of station 21 cast 3 bottle 4 was found bad and has been removed.

- For 74JC20100319 the δ$^{13}$C value at station 37 bottle 7 was found bad and has been removed.

- For 49JC20100319 the δ$^{13}$C value at station 49 bottle 1 was found bad and has been removed.

- For 49JC20100319 the pH data measured at stations 196, 200, and 203 were found offset by approximately +0.1 units, because such large offset points to general data quality problems, these data have been removed.

- For 33RR20160208, the CFC-113 data of station 31 were found to be bad and have been removed. Additionally, the flags for CFC-11, CFC-12, SF$_6$, and CCl$_4$ were replaced with new ones received from the Principal Investigator, and recently published data for δ$^{13}$C and δ$^{14}$C have been added to the product file.

- For 18HU20150504, the pH data measured at stations 196, 200, and 203 were found offset by approximately +0.1 units, because such large offset points to general data quality problems, these data have been removed.
All δ¹³C values from the large volume Gerard barrels (identified by bottle number greater than 80) were removed from the product files as these often have poor precision and accuracy related to gas extraction procedures.

For 33HQ20150809, temperatures of station 52 cast 1 were found bad (less than -2 °C) and have been removed, hence all other samples were removed for this cast as well (the same depths and variables were sampled at the other casts, however). Temperatures for casts 2 and 8 were replaced with updated values; these changes are very minor, on the order of 0.001 °C.

For cruises 33RO20110926, 33RO20150525, and 33RO20150410, δ¹³C and δ¹⁴C data have become available and added to the product.

Ship code for all RV *Maria S. Merian* cruises have been changed from MM to M2.

For cruises 49SH20081021 and 49UF20121024, an adjustment of +6 μmol kg⁻¹ is now applied to the TCO₂ values.

Additional primary QC have been applied to the cruises with *Keifu Maru II* and *Ryofu Maru III* that were included in GLODAPv2.2019.

Discrete fugacity of CO₂ (fCO₂) data are now included in the product files whenever available. Discrete fCO₂ is one of the four variables that describes seawater CO₂ chemistry, but is rarely measured and has not been included in GLODAP product files before, in particular as a result of apparent quality issues that were not fully understood during the secondary QC for GLODAPv1.1 (Sabine et al., 2005). However, for some cruises fCO₂ data were included indirectly in both GLODAPv1.1 and GLODAPv2 as they had been used to calculate TAlk, in combination with TCO₂. These calculated TAlk values were, however, not included in v2.2019. We have now chosen to include the discrete fCO₂ data in the product files. This increases transparency and traceability of the product; the fCO₂ data are also highly relevant for ongoing efforts toward resolving recently identified inconsistencies in our understanding of the relationships among the four seawater CO₂ chemistry variables (Carter et al., 2018; Fong and Dickson, 2019; Takeshita et al., 2020; Álvarez et al., 2020). A total of 33924 discrete fCO₂ measurements from 34 cruises conducted between 1983-2014 are now included. All values were converted to 20 °C and 1 atm pressure using CO2SYS for MATLAB (van Heuven et al., 2011). This was also used for the conversion of partial pressure of CO₂ (pCO₂) to fCO₂ for the 20 cruises where pCO₂ was reported. The procedures for these conversions, in terms of dissociation constants and approximation of missing variables, were the same as for the pH conversions (Sect. 3.2.4). These fCO₂ data have not been subjected to secondary QC. The inclusion of discrete fCO₂ data has led to some changes in the calculations of missing seawater CO₂ chemistry variables; these are described towards the end of the next section.

### 3.3.2 Merging

The new data were merged into a bias-minimized product file following the procedures used for GLODAPv1.1 (Key et al., 2004; Sabine et al., 2005), CARINA (Key et al., 2010), PACIFICFA (Suzuki et al., 2013), GLODAPv2 (Olsen et al., 2016), and GLODAPv2.2019 (Olsen et al., 2019), with some modifications:

Data from the 106 new cruises were merged and sorted according to EXPOCODE, station, and pressure. GLODAP cruise numbers were assigned consecutively, starting from 2001, so they can be distinguished from the GLODAPv2.2019 cruises that ended at 1116.
- For some cruises the combined concentration of nitrate and nitrite was reported instead of nitrate. If explicit nitrite concentrations were also given, these were subtracted to get the nitrate values. If not, the combined concentration was renamed to nitrate. As nitrite concentrations are very low in the open ocean, this has no practical implications.

- When bottom depths were not given, they were approximated as the deepest sample pressure + 10 dbar or extracted from ETOPO1 (Amane and Eakins, 2009), whichever was greater. For GLDAPv2, bottom depths were extracted from the Terrain Base (National Geophysical Data Center/NESDIS/NOAA/U.S. Department of Commerce, 1995). The intended use of this variable is only drawing approximate bottom topography for sections.

- Whenever temperature was missing in the original data file, all data for that record were removed and their flags set to 9. The same was done when both pressure and depth were missing. For all surface samples collected using buckets or similar, the bottle number was set to zero. There are some exceptions to this, in particular for cruises that also used Gerard barrels for sampling. These may have valuable tracer data not accompanied by a temperature, so such data have been retained.

- All data with WOCE quality flags 3, 4, 5, or 8 were excluded from the product files, and their flags set to 9. Hence, in the product files a flag 9 can indicate not measured (as is also the case for the original exchanged quality flag files) or excluded from the product; in any case, no data value appears. All flags 6 (replicate measurement) and 7 (manual chromatographic peak measurement) were set to 2.

- Missing sampling pressures or depths were calculated following UNESCO (1981).

- For both oxygen and salinity, CTD and bottle values were merged following procedures summarized in Sect. 3.2.1.

- Missing salinity, oxygen, nitrate, silicate, and phosphate values were vertically interpolated whenever practical, using a quasi-Hermitian piecewise polynomial. “Whenever practical” means that interpolation was limited to the vertical data separation distances given in Table 4 in Key et al. (2010). Interpolated values have been assigned a WOCE quality flag 8.

- The data for the 12 core variables were corrected for bias using the adjustments determined during the secondary QC. For each of these variables the data product also has separate columns of secondary QC flags, indicating by cruise and variable whether (“1”) or not (“0”) data successfully received secondary QC. A 0 flag here means that data were too shallow or geographically too isolated for consistency analyses or that these analyses were inconclusive, but that we have no reasons to believe that the data in question are of poor quality.

- Values for potential temperature and potential density anomalies (referred to 0, 1000, 2000, 3000, and 4000 dbar) were calculated using Letelier and Fofonoff (1984) and Bryden (1973). Neutral density was calculated using Sérzin (2011). Apparent oxygen utilization was determined using the combined fit in Garcia and Gordon (1992).

- Partial pressures for CFC-11, CFC-12, CFC-113, CCLs, and SFs were calculated using the solubilities by Warner and Wassmann (1985), Bu and Warner (1995), Bullister and Wiesgarver (1998), and Bullister et al. (2002).

- Missing seawater CO2 chemistry variables were calculated, whenever possible. The procedures for these calculations have been slightly altered as the product now contains four such variables; earlier versions of GLDAPv2 (Olsen et al., 2016; Olsen et al., 2019) included only three, so whenever two were included the one to calculate was unequivocal. Four CO2 chemistry variables gives more degrees of freedom in this respect, e.g., a particular record may have measured data for TCO2, TAlk, and pH, and then a choice needs to be made with regard to which pair to use for the calculation of CO2. We followed two simple principles. First, TCO2 and TAlk was the preferred pair to calculate pH and CO2 because we have higher confidence in the TCO2 and TAlk data.
than pH (given the issues summarized in Sect. 3.2.4) and $\delta^{13}C\text{O}_2$ (because it was not subjected to secondary QC). Second, if either TCO$_2$ or TAlk was missing and both pH and $\delta^{13}C\text{O}_2$ data existed, pH was preferred (because $\delta^{13}C\text{O}_2$ has not been subjected to secondary QC). All other options involve only two measured variables. The calculations were conducted using CO2SYS (Lewis and Wallace, 1998) for MATLAB (van Heuven et al., 2011), with the constants set as for the pH conversions (Sect. 3.2.4). For calculations involving TCO$_2$, TAlk, and pH, if the number of measured values for a specific cruise were less than half the number of calculated, then all measured values were replaced by calculated values. Such replacements were not done for calculations involving $\delta^{13}C\text{O}_2$ as this would tend to overwrite all measured $\delta^{13}C\text{O}_2$ values or entail replacing a measured variable that has been subjected to secondary QC (i.e., TCO$_2$, TAlk, or pH) with one calculated from a variable that has not been subjected to secondary QC (i.e., $\delta^{13}C\text{O}_2$). Calculated values have been assignedWOCE flag 0.

- The resulting merged file for the 106 new cruises was appended to the merged product file for GLODAPv2.2019. A very small fraction of the data is adjusted. This is similar to the GLODAPv2.2019 results.

### 4 Seconda quality control results and adjustments

All material produced during the secondary QC is available at the online GLODAP Adjustment Table hosted by GEOMAR, Kiel, Germany at https://glodapv2-2020.geomar.de (last access: 18 June 2020), and which can also be accessed through www.glodap.info. This is similar in form and function to the GLODAPv2 Adjustment Table (Olsen et al., 2016) and includes a brief written justification for any adjustments applied.

#### 4.1 Sensor and bottle data merge for salinity and oxygen

Table 4 summarizes the actions taken for the merging of the CTD and bottle data for salinity and oxygen. For 81 % of the 106 cruises added with this update, both CTD and bottle data were included for salinity in the original cruise data files and for all these cruises the two data types were found to be consistent. For oxygen, only 25 % of the cruises included both CTD $O_2$ and bottle values; this is much less than for GLODAPv2.2019 where 58 % of the cruises included both. Having both CTD and bottle values in the data files is highly preferred as the information is valuable for quality control (bottle mistrips, leaking niskin bottles, and oxygen sensor drift are among the issues that can be revealed). The extent to which the bottle data (i.e., OXYGEN in the individual cruise exchange files) in reality is mislabeled CTD data (i.e., should be CTDOXY) is uncertain. Regardless, the large majority of the CTD and bottle oxygen were consistent and did not need any further calibration of the CTD values (23 out of 25 cruises), while for two cruises no good fit could be obtained and their CTD $O_2$ data are not included in the product.

#### 4.2 Adjustment summary

The secondary QC actions for the 12 core variables and distribution of adjustments applied are summarized in Table 5, and Fig. 6, respectively. A very small fraction of the data is adjusted for most variables. None of the salinity data are adjusted, for oxygen and nitrate 1% of the data are adjusted, 2 % for TCO$_2$, 5 % for TAlk, 7 % for phosphate, and 9 % for silicate. For the CFCs, data from one of 16 cruises with CFC-11 is adjusted, while the fractions are two of 21 for CFC-12, and one out of three for CFC-113. The adjustments for the variables are also fairly small, overall. Thus the tendency observed during the production of GLODAPv2.2019 remains, namely, that the data collected at the large majority of recent cruises are consistent with earlier releases of this product.
The western control of pH data proved challenging for this version. The large majority had been collected in the northwestern Pacific, at the cruises conducted by the Japan Meteorological Agency. Figure 7 shows the distribution of pH crossover offsets vs. GLODAPv2.2019. Most of the pH values are higher, some by up to 0.02 units, which is considerable, particularly as the data that are compared are from deeper than 2000 dbar where no changes due to ocean acidification are expected. The challenging aspect lies in the fact that the data that are being added are comparatively many (~70 cruises vs. ~130 already included in v2.2019) and also are more recent (2010-2018 vs. 1993-2016). As such they might be of higher quality given advances in pH measurement techniques over the years. Adjusting a large fraction of the new cruises down (by the adjustment limit of 0.01) is not advisable. We therefore chose to not adjust any pH data, but to exclude the most serious outliers from the product file (using a limit of 0.015%) and include the rest of the data as is.

This is the reason that the number of adjusted cruises for pH is zero (Table 5). We expect that a crossover and inversion analysis of all pH data in the northwestern Pacific will provide more information on the consistency among the cruises, and such an analysis will be conducted for the next update. This might result in re-inclusion of these data, the formal decision for these are therefore “suspend” (Table 5). For now, some caution should be exercised if looking at trends in ocean pH in that region using these data.

For the nutrients, the adjustments were applied to maintain consistency with data included in GLODAPv2 and GLODAPv2.2019. An alternative goal for the adjustments would be maintaining consistency with data from cruises that employed CRMNS to ensure accuracy of nutrient analyses. Such a strategy was adopted by Aoyama (2020) for preparation of the Global Nutrients Dataset 2013 (GND13), and is being considered for GLODAP as well. However, as it would require a re-evaluation of the entire data set, this will not occur until the next full update of GLODAP, i.e., GLODAPv3. For now, we note the overall agreement between the adjustments applied in these two efforts (Aoyama, 2020), and that most disagreements appear to be related to cases where no adjustments were applied in GLODAP. This can be related to the strategy followed for nutrients for GLODAPv2, where data from GO-SHIP lines were considered a priori more accurate than other data. CRMNS are used for nutrients on most GO-SHIP lines.

The improvement in data consistency is evaluated by comparing the weighted mean of the absolute offsets for all crossovers before and after the adjustments have been applied. This “consistency improvement” for core variables is presented in Table 6. The data for CFCs were omitted for previously discussed reasons (Sect. 3.2.6). Globally, the improvement is modest. Considering the initial data quality, this result was expected, but this does not imply that the data initially were consistent everywhere. Rather, for some regions and variables there are substantial improvements when the adjustments are applied. For example, Arctic Ocean phosphate, Indian Ocean silicate and TCO₂, and Pacific Ocean pH data all show considerable improvements.

The various iterations of GLODAP provide insight into initial data quality covering more than 4 decades. Figure 8 summarizes the applied absolute adjustment magnitude per decade. These distributions are broadly unchanged compared to GLODAPv2.2019 (Fig. 6 in Olsen et al., 2019). For several variables improvement is evident over time. Most TCO₂ and TALK data from the 1970s needed an adjustment, but this fraction steadily declines until only a small percentage is adjusted. This is encouraging and demonstrates the value of standardizing sampling and measurement practices (Dickson et al., 2007), the widespread use of CRMs (Dickson et al., 2003), and instrument automation. The pH adjustment frequency also has a downward trend; however, there remains issues with the pH adjustments and this a topic for future development in GLODAP, with the support from the OCB Carbonate System Intercomparison Forum (CSIF, https://www.us-ocb.org/ocean-carbonate-system-intercomparison-forum/, last accessed: 20 June 2020) working group (Alvarez et al., 2020). For the nutrients and oxygen, only the phosphate adjustment frequency decreases from decade to decade...
decade. However, we do note that the more recent data, from the 2010s, receive the fewest adjustments. This may reflect recent increased attention that seawater nutrient measurements have received through an operation manual (Becker et al., 2019; Hydes et al., 2012) availability of CRMNS (Aoyama et al., 2012; Ota et al., 2010), and the SCOR working group #147. Towards comparability of global oceanic nutrient data (COMPONUT). For silicate, the fraction of cruises receiving adjustments peaks in the 1990s and 2000s. This is related to the 2% offset between US and Japanese cruises in the Pacific Ocean that was revealed during production of GLODAPv2 and discussed in Olsen et al. (2016). For salinity and the halogenated transient tracers, the number of adjusted cruises is small in every decade.

5 Data availability

The GLODAPv2.2020 merged and adjusted data product is archived at NOAA NCEI under https://doi.org/10.25921/2c8h-sa89 (Olsen et al., 2020). These data and ancillary information are also available via our web pages https://www.glodap.info and https://www.nodc.noaa.gov/ocads/oceans/GLODAPv2_2020/ (last access: 22 June 2020). The data are available as comma-separated ascii files (*.csv) and as binary MATLAB files (*.mat). Regional subsets are available for the Arctic, Atlantic, Pacific, and Indian oceans. There are no data overlaps between regional subsets and each cruise exists in only one basin file even if data from that cruise crosses basin boundaries. The station locations in each basin file are shown in Fig. 9. The product file variables are listed in Table 1. A lookup table for matching the EXPCODE of a cruise with GLODAP cruise number is provided with the data files. In the MATLAB files this information is also available as a cell array. A “known issues document” accompanies the data files and provides an overview of known errors and omissions in the data product files. It is regularly updated, and users are encouraged to inform us whenever any new issues are identified. It is critical that users consult this document whenever the data products are used.

The original cruise files are available through the GLODAPv2 cruise summary table (CST) hosted by NOAA NCEI: https://www.nodc.noaa.gov/ocads/oceans/GLODAPv2_2020/ (Last access: 22 June 2020). Each of these files has been assigned a doi, but these are not listed here. The CST also provides brief information on each cruise and access to metadata, cruise reports, and its Adjustment Table entry.

While GLODAPv2 is made available without any restrictions, users of the data should adhere to the fair data use principles:

- For investigations that rely on a particular (set of) cruise(s), recognize the contribution of GLODAP data contributors by at least citing the articles where the data are described and, preferably, contacting principal investigators for exploring opportunities for collaboration and co-authorship. To this end, relevant articles and principle investigator names are provided in the CST. Contacting principle investigators comes with the additional benefit that the principal investigators often possess expert insight into the data and/or particular region under investigation. This can improve scientific quality and promote data sharing.

This paper should be cited in any scientific publications that result from usage of the product. Citations provide the most efficient means to track the use of this product, which is important for attracting funding to enable the preparation of future updates.
6 Summary

GLODAPv2.2020 is an update of GLODAPv2.2019. Data from 106 new cruises have been added to supplement the earlier release and extend temporal coverage by 2 years. GLODAP now includes 247 years, 1972–2019, of global interior ocean biogeochemical data from 246 cruises. Figure 10 illustrates the seasonal distribution of the data. As for previous versions there is a bias around summertime in the data in both hemispheres; most data are collected during April through November in the Northern Hemisphere while most data are collected during November through April in the Southern Hemisphere. These tendencies are strongest for the poleward regions and reflect the harsh conditions during winter months, which make fieldwork difficult. Figure 11 illustrates the distribution of data with depth. The upper 100 m is the best sampled part of the global ocean, both in terms of number (Fig. 11a) and density (Fig. 11b) of observations. The number of observations steadily declines with depth. In part, this is caused by the reduction of ocean volume towards greater depths. Below 1000 m the density of observations stabilizes and even increases between 5000 and 6000 m; the latter is a zone where the volume of each depth surface decreases sharply (Weatherall et al., 2015). In the deep trenches, i.e., areas deeper than –6000 m, both number and density of observations are low.

 Except for salinity and oxygen, the core data were collected exclusively through chemical analyses of individually collected water samples. The data of 12 core variables: salinity, oxygen, nitrate, silicate, phosphate, TCO₂, TA, pH, CFC-11, CFC-12, CFC-113, and CCl₄ were subjected to primary quality control to identify questionable or bad data points (flags) and secondary quality control to identify systematic measurement biases. The data are provided in two ways: as a set of individual exchange formatted original cruise data files with assigned WOCE flags, and as globally and regionally merged data product files with adjustments applied to the data according to the outcome of the consistency analyses. Importantly, no adjustments were applied to data in the individual cruise files.

The consistency analyses were conducted by comparing the data from the 106 new cruises to GLODAPv2.2019. Adjustments were only applied when the offsets were believed to reflect biases relative to the earlier data product release related to measurement, calibration, and/or data handling practices, and not natural variability or anthropogenic trends. The Adjustment Table at https://glodap2020.geomar.de (last access: 18 June 2020) lists all applied adjustments and provides a brief justification for each. The consistency analyses rely on deep ocean data (>1500 or 2000 dbar depending on region), but supplementary CANYON-B and CONTENT analyses considers data below 500 dbar. Data consistency for cruises with exclusively shallow sampling was not examined.

Secondary QC flags are included for the 12 core variables in the product files. These flags indicate whether (1) or not (0) the data successfully received secondary QC. A secondary QC flag of 0 does not by itself imply that the data are of lower quality than those with a flag of 1. It means these data have not been as thoroughly checked. For δ¹³C, the QC results by Becker et al. (2016) for the North Atlantic were applied, and a secondary QC flag was therefore added to this variable.

The primary, WOCE, QC flags in the product files are simplified (e.g., all questionable and bad data were removed). For salinity, oxygen, and the nutrients, any data flagged 0 are interpolated rather than measured. For TCO₂, TA, pH, and δ¹³C, any data flagged 0 are calculated from two measured seawater CO₂ variables. Finally, while questionable (WOCE flag =3) and bad (WOCE flag =4) data have been excluded from the product files, some may have gone unnoticed through our analyses. Users are encouraged to report on any data that appear suspicious.

Based on the initial minimum adjustment limits and the improvement of the consistency from the adjustments (Table 6), the data subjected to consistency analyses are believed to be consistent to better than 0.005 in salinity, 1 % in oxygen, 2 % in nitrate, 2 % in silicate, 2 % in phosphate, 4 µmol kg⁻¹ in TCO₂, 5 µmol kg⁻¹ in TA, and 5 % for the halogenated transient tracers. For pH, the consistency among all data is estimated as 0.01–0.02, depending on region.
Author contributions.

AO and TT led the team that produced this update. RMK, AK, and BP compiled the original data files. NL conducted the secondary QC analyses. HCB conducted the CANYON-B and CONTENT analyses. CSL manages the Adjustment Table e-infrastructure. AK maintains the GLODAPv2 webpages at NCEI/OCADS while PM prepared PYTHON scripts for the merging of the data. All authors contributed to the interpretation of the secondary QC results and decisions on whether to apply actual adjustments. Many conducted ancillary QC analyses. AO wrote the manuscript with input from all authors.

Competing interests

The authors declare that they have no competing interests.

Acknowledgements

GLODAPv2.2020 would not have been possible without the effort of the many scientists who secured funding, dedicated time to collect, and shared the data that are included. Chief scientists at the various cruises and principal investigators for specific variables are listed in the online cruise summary table. NL was funded by EU Horizon 2020 through the EuroSea action (grant agreement 862626). LCC was supported by Procienica/UEIRJ grant 2019-2021. MA was supported by IEO RADIALES and RADPROF projects. PJL was part-funded by the UK Climate Linked Atlantic Sector Science (CLASS) NERC National Capability Long-term Single Centre Science Programme (Grant NE/R015953/1). AV & FP were supported by the BOCATS2 Project (PID2019-104279GB-C21) co-funded by the Spanish Government and the Fondo Europeo de Desarrollo Regional (FEDER). RW and BRC acknowledge the NOAA Global Observations and Monitoring Division (fund reference 100007298) and the Office of Oceanic and Atmospheric Research of NOAA. HCB gratefully acknowledges financial support by the BONUS INTEGRAL project (Grant No. 03F0773A). We acknowledge funding from the Initiative and Networking Fund of the Helmholtz Association through the project "Digital Earth" (ZT-0025). This is JISAO and PMEL contribution numbers 2020-1074 and 5112, respectively. This activity is supported by the IOCCP.

References

Alvarez, M., Fajar, N. M., Carter, B. R., Guallart, E. F., Pérez, F. F., Wooley, R. J., and Murata, A.: Global ocean spectrophotometric pH assessment: consistent inconsistencies, Environ. Sci. Technol., doi: 10.1021/acs.est.9b06932, 2020.

Amante, C. and Eakins, B. W.: ETOPO1 Arc-minute global relief model: procedures, data sources and analysis, NOAA Technical Memorandum NESDIS NGDC-24, National Geophysical Data Center, Marine Geology and Geophysics Division, Boulder, CO, U.S.A., 2009.

Aoyama, M.: Global certified-reference-material- or reference-material-scaled nutrient gridded dataset GND13, Earth Syst. Sci. Data, 12, 487-499, 2020.

Aoyama, M., Ota, H., Kimura, M., Kitao, T., Mitsuda, H., Murata, A., and Sato, K.: Current status of homogeneity and stability of the reference materials for nutrients in Seawater, Anal. Sci., 28, 911-916, 2012.

Aucet-Scott, K., Petrie, B., Yeats, P., and Lee, C.: Composition and fluxes of freshwater through Davis Strait using multiple chemical tracers, J. Geophys. Res.-Oceans, 117, 2012.

Becker, M., Andersen, N., Erlenkeuser, H., Humphreys, M. P., Tanhua, T., and Körtzinger, A.: An internally consistent dataset of δ¹⁸O-DIC in the North Atlantic Ocean – NAC13v1, Earth Syst. Sci. Data, 8, 559-570, 2016.

Becker, S., Aoyama, M., Woodward, E. M. S., Bakker, K., Coverly, S., Mahaffey, C., and Tanhua, T.: GO-SHIP repeat hydrography nutrient manual: The precise and accurate determination of dissolved inorganic nutrients in seawater. 2020.
using Continuous Flow Analysis methods. In: The GO-SHIP Repeat Hydrography Manual: A Collection of Expert Reports and Guidelines, Hood, E. M., Sabine, C., and Sloyan, B. M. (Eds.), IOCCP Report Number 14, ICPO Publication Series Number 134, 2019.

Bittig, H. C., Steinhoff, T., Claustre, H., Pfeiler, B., Williams, N. L., Saussier, R., Körtzinger, A., and Gattuso, J.-P.: An alternative to state climatologies: Robust estimation of open ocean CO₂ variables and nutrient concentrations from T, S, and O₂ data using Bayesian Neural Networks, Frontiers in Marine Science, 5, 2018.

Bockman, E. E. and Dickson, A. G.: An inter-laboratory comparison assessing the quality of seawater carbon dioxide measurements, Mar. Chem., 171, 36-43, 2015.

Bryden, H. L.: New polynomials for thermal-expansion, adiabatic temperature gradient and potential temperature of seawater, Deep-Sea Res., 20, 401-408, 1973.

Bu, X. and Warner, M. J.: Solubility of chlorofluorocarbon-113 in water and seawater, Deep-Sea Res. Pt I, 42, 1151-1161, 1995.

Bullister, J. L. and Wisegarver, D. P.: The solubility of carbon tetrachloride in water and seawater, Deep-Sea Res. Pt I, 45, 1285-1302, 1998.

Bullister, J. L., Wisegarver, D. P., and Menzina, F. A.: The solubility of sulfur hexafluoride in water and seawater, Deep-Sea Res. Pt I, 49, 175-187, 2002.

Carrié, B. R., Feely, R. A., Williams, N. L., Dickson, A. G., Fong, M. B., and Takahashi, Y.: Updated methods for global locally interpolated estimation of alkalinity, pH, and nitrate, Limnol. Oceanogr. -Meth., 16, 119-131, 2018.

Cheng, L. J., Abraham, J., Zhu, J., Trembeth, K. E., Sasuilo, J., Boyer, T., Locarnini, R., Zhang, B., Yu, F. J., Wan, L. Y., Chen, X. R., Song, X. Z., Liu, Y. L., and Mann, M. E.: Record-setting ocean warmth continued in 2019, Adv. Atmos. Sci., 37, 137-147, 2020.

Cheng, L. J., Trembeth, K. E., Sasuilo, J., Boyer, T., Abraham, J., and Zhu, J.: Improved estimates of ocean heat content from 1960 to 2015, Sci. Adv., 3, 2017.

Dickson, A. G.: Standard potential of the reaction: AgCl(s) + ½H₂(g) = Ag(s) + HCl(aq) and the standard acidity constant of the ion HSO₃⁻ in synthetic sea water from 273.15 to 318.15 K, J. Chem. Thermodyn., 22, 113-127, 1990.

Dickson, A. G., Asah, J. D., and Anderson, G. C.: Reference materials for ocean CO₂ analysis: a method for the certification of total alkalinity, Mar. Chem., 80, 185-197, 2003.

Dickson, A. G., Sabine, C. L., and Christian, J. R.: Guide to Best Practices for Ocean CO₂ measurements, PICES Special Publication 3, 191 pp., 2007.

Fofonoff, N. P.: Computation of potential temperature of seawater for an arbitrary reference pressure, Deep-Sea Res., 24, 489-491, 1977.

Fong, M. B. and Dickson, A. G.: Insights from GO-SHIP hydrography data into the thermodynamic consistency of CO₂ system measurements in seawater, Mar. Chem., 211, 52-63, 2019.

Freelandtstein, P., Jones, M. W., O’ Sullivan, M., Andrew, R. M., Hueck, J., Peters, G. P., Peters, W., Pouтрат, J., Stich, S., Le Quere, C., Bakker, D. C. E., Canadell, J. G., Ciais, P., Jackson, R. B., Andisoni, P., Barbera, L., Bastos, A., Bastrakov, V., Becker, M., Bopp, L., Buitenhuis, E., Chandra, N., Chevallier, F., Chini, L. P., Currie, K. I., Feely, R. A., Gehlen, M., Giffillan, D., Gkritzalis, T., Golli, D. S., Gruber, N., Gatekust, S., Harris, L., Haverd, V., Houghton, R. A., Hurtt, G., Ilyina, T., Jain, A. K., Joetzjer, E., Kaplan, J. O., Kato, E., Goldewijk, K. K., Korsbakken, J. L., Landschutzer, P., Lauvset, S. K., Law, K. S., Lefevre, N., Lenton, A., Lienert, S., Lombardozzi, D., Marland, G., McGuire, P. C., Milton, J. R., Metzl, N., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S. I., Neill, C. C., Omar, A. M., Ono, T., Peregon, A., Pierrot, D., Poulet, R., Rehder, G., Respandi, L., Robertson, E., Rodenbeck, C., Seferian, R., Schwinger, J., Smith, N., Tans, P. P., Tian, H. Q., Tilbrook, B., Tubiello, F. N., van der Werf, G. R., Wilshire, A. J., and Zaehle, S.: Global Carbon Budeat 2019, Earth Syst. Sci. Data, 11, 1783-1838, 2019.

Fris, K., Körtzinger, A., and Wallace, D. W.: R: The salinity normalization of marine inorganic carbon chemistry data, Geophys. Res. Lett., 30, 2003.

Garcia, H. E. and Gordon, L. I.: Oxygen solubility in seawater - Better fitting equations, Limnol. Oceanogr., 37, 1307-1312, 1992.

Gruber, N., Clement, D., Carter, B. R., Feely, R. A., van Heuven, S., Hoppema, M., Ishii, M., Key, R. M., Koyzi, A., Lauvset, S. K., Lo Coa, M., Mathis, J. T., Murata, A., Olsen, A., Perez, F. F., Sabine, C. L., Tanhua, T., and Wanninkhof, R.: The oceanic sink for anthropogenic CO₂ from 1994 to 2007, Science, 363, 1193-1199, 2019.

Hood, E. M., Sabine, C. L., and Sloyan, B. M.: The GO-SHIP hydrography manual: A collection of expert reports and guidelines, 2010.

Hydes, D. J., Aoyama, A., Aminot, A., Bakker, K., Becker, S., Coverly, S., Daniel, A., Dickson, A. G., Grosso, O., Keronen, R., van Ooijen, J., Sato, K., Tanhua, T., Woodward, E. M. S., and Zhang, J.-Z.: Determination of dissolved nutrients in seawater with high precision and intercomparability using gas-segmented continuous flow analysers. In: The GO-SHIP Repeat Hydrography Manual: A Collection of Expert Reports and Guidelines, Hood, E. M., Sabine, C., and Sloyan, B. M. (Eds.), IOCCP Report Number 14, ICPO Publication Series Number 134, 2012.

Jeannin, E., Olsson, K. A., Tanhua, T., and Bullister, J. L.: Nordic Seas and Arctic Ocean CFC data in CARINA, Earth Syst. Sci. Data, 2, 79-97, 2010.
Pérez, F. F., Fontela, M., García Panassa, E., Santana Ota, H., Mitsuda, H., Kimura, M., and Kitao, T.: Reference materials for nutrients in seawater: Their development and
Olsen, A., Lange, N., Key, R. M., Kozyr, A., van Heuven, S., Kozyr, A., Lin, X., Velo, A., Wallace, D. W. R., and Münster, L.: The CARINA data synthesis project: introduction and overview, Earth Syst. Sci. Data, 2, 105-121, 2010.

King, B., Sanchez-Franques, X., Firing, Y. et al.: RRS James Cook Cruise JC159 28 February - 11 April 2018.
Hydrographic sections from the Brazil to the Beninulfa Current across 25S in the Atlantic National Oceanography Centre Cruise Report, 60, National Oceanography Centre, Southampton, 193 pp., 2019.

Laursen, T., and Tanhua, T.: A toolbox for secondary quality control on ocean chemistry and hydrographic data, Limnol. Oceanogr.-Meth., 13, 601-608, 2015.

Lewis, E. and Wallace, D. W. R.: Program developed for CO₂ system calculations, ORNL/CDIAC-105, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, U.S.A., 1998.

Lueker, T. J., Dickson, A. G., and Keeling, C. D.: Ocean pCO₂ calculated from dissolved inorganic carbon, alkalinity, and equations for K-1 and K-2: validation based on laboratory measurements of CO₂ in gas and seawater at equilibrium, Mar. Chem., 70, 105-119, 2000.

McCrath, T., Cronin, M., Kerrijman, E., Wallace, D., Gregory, C., and McGovern, E.: A rare intercomparison of nutrient analysis at sea: lessons learned and recommendations to enhance comparability of ocean nutrient data, Earth Syst. Sci. Data, 11, 355-374, 2019.

Oka, E., Ishii, M., Nakano, T., Suga, T., Kouketsu, S., Miyamoto, M., Nakano, H., Qiu, B., Sugimoto, S., and Takatani, Y.: Fifty years of the 137A degrees E repeat hydrographic section in the western North Pacific Ocean, J. Oceanogr., 74, 115-145, 2018.

Oka, E., Katsura, S., Inoue, H., Kojima, A., Kitamoto, M., Nakano, T., and Suga, T.: Long-term change and variation of salinity in the western North Pacific subtropical gyre revealed by 50-year long observations along 137 degrees E, J. Oceanogr., 74, 479-490, 2018.

Olsen, A., Key, R. M., van Heuven, S., Lauvset, S. K., Velo, A., Lin, X. H., Schirnick, C., Kozyr, A., Tanhua, T., Hoppema, M., Jutterström, S., Steinfieldt, R., Jeansson, E., Ishii, M., Perez, F. F., and Suzuki, T.: The Global Ocean Data Analysis Project version 2 (GLODAPv2) - an internally consistent data product for the world ocean, Earth Syst. Sci. Data, 8, 297-322, 2016.

Olsen, A., Lange, N., Key, R. M., Tanhua, T., Bittig, H. C., Kozyr, A., Alvarez, M., Azetsu-Scott, K., Becker, S., Brown, P. J., Carrier, B. R., Cotrim da Cunha, L., Feely, R. A., van Heuven, S., Hoppema, M., Ishii, M., Jeansson, E., Jutterström, S., Landa, C. S., Lauvset, S., Michaelis, P., Murata, A., Pérez, F. F., Pfeil, B., Schirnick, C., Steinfieldt, R., Suzuki, T., Tilbrook, B., Velo, A., Wanninkhof, R., and Woosley, R. J.: Global ocean data analysis project version 2/2020 (GLODAPv2.2020), NOAA, National Centers for Environmental Information, https://doi.org/10.25921/2c8hsa89. 2020.

Olsen, A., Lange, N., Key, R. M., Tanhua, T., Alvarez, M., Becker, S., Bittig, H. C., Carter, B. R., da Cunha, L. C., Feely, R. A., van Heuven, S., Hoppema, M., Ishii, M., Jeansson, E., Jutterström, S., Landa, C. S., Lauvset, S., Michaelis, P., Murata, A., Perez, F. F., Pfeil, B., Schirnick, C., Steinfieldt, R., Suzuki, T., Tilianski, M., Tilbrook, B., Velo, A., and Wanninkhof, R.: GLODAPv2.19-an update of GLODAPv2, Earth Syst. Sci. Data, 12, 1437-1461, 2019.

Ota, H., Misuda, H., Kimura, M., and Kitao, T.: Reference materials for nutrients in seawater: Their development and present homogeneity and stability. In: Comparability of nutrients in the world's oceans, Aoyama, A., Dickson, A. G., Hydes, D. J., Murata, A., Oh, J. R., Roose, P., and Woodward, E. M. S. (Eds.), Mother Tank, Tsukuba, Japan, 2010.

Patanea, E., Santamaria-Cassano, F. M., Gonzalez-Dievola, M., Hoppema, M., van Heuven, S., Villier, C., Wolf-Gladrow, D., and Hauck, J.: Variability of nutrients and carbon dioxide in the Antarctic Intermediate Water between 1990 and 2014, Ocean Dyn., 68, 295-308, 2018.

Pérez, F. F., Fontela, M., García-Bañez, M. I., Mercier, H., Velo, A., Lhermitier, P., Zunino, P., de la Paz, M., Alonso-Pérez, F., Guillaum, E. F., and Patid, X. A.: Meridional overturning circulation conveys fast acidification to the deep Atlantic Ocean, Nature, 554, 515-518, 2018.

Sabine, C., Key, R. M., Kozyr, A., Feely, R. A., Wanninkhof, R., Millero, F. J., Peng, T.-H., Bullister, J. L., and Lee, K.: Global Ocean Data Analysis Project (GLODAP): Results and Data, ORNL/CDIAC-145, NDP-083, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, U.S.A., 2003.

Sérazin, G.: An approximate neutral density variable for the World's oceans, Master's Thesis, Ecole Centrale, Lyon, Écully, France, 2011.
Sloyan, B. M., Wanninkhof, R., Rintoul, R., Johnson, G. C., Talley, L. D., Tanhua, T., McDonagh, E., Cusack, C., O’Rourke, E., McGovern, E., Katsumata, K., Dugan, S., Hummon, J., Ishii, M., Azetsu-Scott, K., Boss, E., Aigubo, I., Perez, F. F., Mercier, H., Williams, M. J. M., Anderson, L. E., Lee, J. H., Murata, A., Kosakai, S., Jeannin, E., Honjo, M., and Campos, E.: The Global Ocean Shin-Based Hydrographic Investigations Program (GO-SHIP): A Platform for Integrated Multidisciplinary Ocean Science, Frontiers in Marine Science, 6, 2019.

Steinfeldt, R., Tanhua, T., Bullister, J. L., Key, R. M., Rhein, M., and Köhler, J.: Atlantic CFC data in CARINA, Earth Syst. Sci. Data, 2, 1-15, 2010.

Suzuki, T., Ishii, M., Aoyama, A., Christian, J. R., Enyo, K., Kawaiwa, T., Key, R. M., Kosugi, N., Kozyr, A., Miller, L. A., Murata, A., Nakano, T., Ono, T., Saino, T., Sasaki, K., Sasano, D., Takatani, Y., Wakita, M., and Sabine, C.-L.: PACIFIC Data Synthesis Project, ORNL/CDIAC-159, NPD-092, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U. S. Department of Energy, Oak Ridge, TN, U.S.A., 2013.

Swift, J. and Digs, S. C.: Description of WHF exchange format for CTD/Hydrographic data. CLIVAR and Carbon Hydrographic Data Office, UCSD Scripps Institution of Oceanography, San Diego, CA, US, 2008.

Takeda, Y., Johnson, K. S., Coletti, L., J., Janusch, H. W., Walz, P. M., and Warren, J. K.: Assessment of pH dependent errors in spectrophotometric pH measurements of seawater, Mar. Chem., 223, 103801, 2020.

Talley, L. D., Feely, R. A., Sloyan, B. M., Wanninkhof, R., Barringer, M. O., Bullister, J. L., Carlson, C. A., Doney, S. C., Fine, R. A., Firing, E., Gruber, N., Hansell, D. A., Ishii, M., Johnson, G. C., Katsurama, K., Key, R. M., Knapp, M., Laidog, C., Macdonald, A. M., Mathis, J. T., McDonagh, E. L., Mecking, S., Millero, F. J., Mordy, C. W., Nakano, T., Sabine, C. L., Smethie, W. M., Swift, J. H., Tanhua, T., Thurnherr, A. M., Warner, M. J., and Zhang, J. Z.: Changes in ocean heat, carbon content, and ventilation: A review of the first decade of GO-SHIP global repeat hydrography, Annu. Rev. Mar. Sci., 8, 185-213, 2016.

Tanhua, T., van Heuven, S., Key, R. M., Velo, A., Olsen, A., and Schirnick, C.: Quality control procedures and methods of the CARINA database, Earth Syst. Sci. Data, 3, 25-49, 2010.

UNESCO: Tenth report of the joint panel on oceanographic tables and standards, UNESCO Technical Paper in Marine Science, 36, 13-21, 1981.

Van den Brink, J. R.: Boron Chlorinity ratio of deep-sea water from Pacific Ocean, Deep-Sea Res., 21, 161-162, 1974.

van Heuven, S., Pierrot, D., Rae, J. W. B., Lewis, E., and Wallace, D. W. R.: MA Uppström, L. R.: Boron/Chlorinity ratio of deep sea water from Pacific Ocean, Deep-Sea Res., 21, 161-162, 1974.

van Heuven, S., Pierrot, D., Rae, J. W. B., Lewis, E., and Wallace, D. W. R.: MA Uppström, L. R.: Boron/Chlorinity ratio of deep sea water from Pacific Ocean, Deep-Sea Res., 21, 161-162, 1974.

Van Heuven, S., Pierrot, D., Rae, J. W. B., Lewis, E., and Wallace, D. W. R.: MA Uppström, L. R.: Boron/Chlorinity ratio of deep sea water from Pacific Ocean, Deep-Sea Res., 21, 161-162, 1974.

Van Heuven, S., Pierrot, D., Rae, J. W. B., Lewis, E., and Wallace, D. W. R.: MA Uppström, L. R.: Boron/Chlorinity ratio of deep sea water from Pacific Ocean, Deep-Sea Res., 21, 161-162, 1974.
| Variable                                      | Units       | Product file name | WOCE flag name* | 2nd QC flag name* | Exchange file name |
|----------------------------------------------|-------------|------------------|-----------------|-------------------|-------------------|
| Assigned sequential cruise number            | cruise      |                  |                 |                   |                   |
| Station                                      | station     |                  |                 |                   |                   |
| Cast                                         | cast        |                  |                 |                   |                   |
| Year                                         | year        |                  |                 |                   |                   |
| Month                                        | month       |                  |                 |                   |                   |
| Day                                          | day         |                  |                 |                   |                   |
| Hour                                         | hour        |                  |                 |                   |                   |
| Minute                                       | minute      |                  |                 |                   |                   |
| Latitude                                     | latitude    |                  |                 |                   |                   |
| Bottom depth                                 | m           | bottomdepth      |                 |                   |                   |
| Pressure of the deepest sample               | dbar        | maxsampdepth     |                 |                   |                   |
| Niskin bottle number                         | bottle      |                  |                 |                   |                   |
| Sampling pressure                            | dbar        | pressure          |                 |                   |                   |
| Sampling depth                               | m           | depth             |                 |                   |                   |
| Temperature                                  | °C          | temperature      |                 |                   |                   |
| potential temperature                        | °C          | theta             |                 |                   |                   |
| Salinity                                     | salinity    |                  | salinityf       | salinityqc        |                   |
| Potential density anomaly                    | kg m⁻³      | sigma0           | (salinityf)     |                   |                   |
| Potential density anomaly, ref 1000 dbar     | kg m⁻³      | sigma1           | (salinityf)     |                   |                   |
| Potential density anomaly, ref 2000 dbar     | kg m⁻³      | sigma2           | (salinityf)     |                   |                   |
| Potential density anomaly, ref 3000 dbar     | kg m⁻³      | sigma3           | (salinityf)     |                   |                   |
| Potential density anomaly, ref 4000 dbar     | kg m⁻³      | sigma4           | (salinityf)     |                   |                   |
| Neutral density anomaly                      | kg m⁻³      | gamma            | (salinityf)     |                   |                   |
| Oxygen                                       | µmol kg⁻³   | oxygen           | oxygenf         | oxygenqc          |                   |
| Apparent oxygen utilization                 | µmol kg⁻³   | aou              | aouf            |                   |                   |
| Nitrate                                      | µmol kg⁻³   | nitrate          | nitratef        | nitratqc          | NITRAT            |
| Nitrite                                      | µmol kg⁻³   | nitrite          | nitritef        |                   | NITRIT            |
| Silicate                                     | µmol kg⁻³   | silicate         | silicatef       | silicatqe         | SILCAT            |
| Phosphate                                   | µmol kg⁻³   | phosphate        | phosphateref    | phosphatqeq       | PHOSPH            |
| TCO₂                                         | µmol kg⁻³   | tco2             | tco2f           | tco2qc            | TCARBON           |
| TALK                                         | µmol kg⁻³   | talk             | talkf           | talkqc            | ALKALI            |
| pH on total scale, 25°C and 0 dbar of pressure |             | phntot           | phntotf         | phntoqc           | PH_TOT            |

| Table 1 | Variables in the GLDAPv2.2020 comma separated (csv) product files, their units, short and flag names, and corresponding names in the individual cruise exchange files. In the MATLAB product files that are also supplied a "G2" has been added to every variable name. |
| Property                               | Unit       | Description          |
|----------------------------------------|------------|----------------------|
| pH on total scale, in situ             |            | phinsitup            |
| Temperature and pressure               |            | phinquip             |
| l-CO₂-qi 20 °C and 0 dbar of pressure  |            | phinquip             |
| CDOM temperature                       | °C         | phinquip             |
| CFC-11                                 | pmol kg⁻¹ | cfc11                |
| pCFC-11                                | ppt        | pcfc11               |
| CFC-12                                 | pmol kg⁻¹ | cfc12                |
| pCFC-12                                | ppt        | pcfc12               |
| CFC-131                                | pmol kg⁻¹ | cfc131               |
| pCFC-131                               | ppt        | pcfc131              |
| CCl₄                                   | pmol kg⁻¹ | ccl4                 |
| pCCl₄                                  | ppt        | pccl4                |
| SF₆                                    | fmol kg⁻¹ | sf6                  |
| pH                                     |            | phf                  |
| δ¹³C                                  | ‰          | δc13                 |
| δ¹⁵N                                  | ‰          | δc15                 |
| δ¹⁶O                                  | ‰          | δo18                 |
| Total organic carbon                   | µmol L⁻¹  | toct                 |
| Dissolved organic carbon               | µmol L⁻¹  | doc                  |
| Dissolved organic nitrogen             | µmol L⁻¹  | don                  |
| Dissolved total nitrogen               | µmol L⁻¹  | tdn                  |
| Chlorophyll a                          | µg kg⁻¹   | chlaf                |

- The only derived variable assigned a separate WOCE flag is AOU as it depends strongly on both temperature and oxygen (and less strongly on salinity). For the other derived variables, the applicable WOCE flag is given in parenthesis. Secondary QC flags indicate whether data have been subjected to full secondary QC (1) or not (0), as described in Sect. 3, *formatted for clarity, is 20 °C for all occurrences. Units have not been checked, some values in micromoles per kilogram (for TOC, DOC, DON, TDN) or microgram per liter (for Chl a) are probable.
| WOCE Flag Value | Original data exchange files | Interpretation | Merged product files |
|-----------------|-----------------------------|----------------|---------------------|
| 0               | Not used                    | Interpolated or calculated value | Not used* |
| 1               | Data not received           | Not used*      | Not used* |
| 2               | Acceptable                  | Acceptable     | Acceptable         |
| 3               | Questionable                | Not used*      | Not used* |
| 4               | Bad                         | Not used*      | Not used* |
| 5               | Value not reported          | Not used*      | Not used* |
| 6               | Average of replicate        | Not used*      | Not used* |
| 7               | Manual chromatographic peak measurement | Not used* | Not used* |
| 8               | Irregular digital peak measurement | Not used* | Not used* |
| 9               | Sample not drawn            | No data        | No data             |

*Flag set to 9 in product files
*Data are not included in the GLODAPv2,2020 product files and their flags set to 9.
*Data are included, but flag set to 2
### Table 3. Initial minimum adjustment limits.

| Variable | Minimum Adjustment |
|----------|--------------------|
| Salinity | 0.005              |
| Oxygen   | 1 %                |
| Nutrients| 2 %                |
| TCO₂     | 4 µmol kg⁻¹        |
| TAlk     | 4 µmol kg⁻¹        |
| pH       | 0.01               |
| CFCs     | 5 %                |
| Case | Description                                                                 | Salinity | Oxygen |
|------|------------------------------------------------------------------------------|----------|--------|
| 1    | No data are available: no action needed.                                     | 0        | 0      |
| 2    | No bottle values present: use CTD derived values.                            | 5        | 3      |
| 3    | No CTD values present: use bottle data.                                     |          |        |
| 4    | Too few data of both types for comparison and >80% of records have bottle    | 0        | 0      |
|      | values: use bottle values.                                                   |          |        |
| 5    | The CTD values do not deviate significantly from bottle values: replace      |          |        |
|      | missing bottle values with CTD values.                                       |          |        |
| 6    | The CTD values deviate significantly from bottle values: calibrate these     |          |        |
|      | using linear fit and replace missing bottle values with calibrated CTD       |          |        |
|      | values.                                                                      |          |        |
| 7    | The CTD values deviate significantly from bottle values, and no good linear   | 0        | 1      |
|      | fit can be obtained for the cruise: use bottle values and discard CTD values. |          |        |

Table 4. Summary of salinity and oxygen calibration needs and actions; number of cruises with each of the scenarios identified.
Table 5. Summary of secondary QC results for the 306 new cruises, in number of cruises per result and per variable.

| Variable | Sal. | Oxy. | NO3 | Si | PO4 | TCO2 | TAik | pH | CFC-11 | CFC-12 | CFC-113 | CCl4 |
|----------|------|------|-----|----|-----|------|------|----|--------|--------|---------|------|
| With data | 186 | 201 | 87 | 39 | 44 | 68 | 40 | 24 | 98 | 65 | 203 | 106 |
| No data | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Unadjusted | 29 | 35 | 27 | 7 | 8 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Adjusted | 2 | 4 | 3 | 3 | 4 | 4 | 3 | 2 | 2 | 2 | 2 | 2 |
| 186' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| .777 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |

1. The data are included in the data product file as is, with a secondary QC flag of 1.
2. The adjusted data are included in the data product file with a secondary QC flag of 1.
3. Data appear of good quality but have not been subjected to full secondary QC. They are included in data product with a secondary QC flag of 0.
4. Data are of uncertain quality and suspended until full secondary QC has been carried out; they are excluded from the data product.
5. Data are of poor quality and excluded from the data product.
Table

Improvements resulting from quality control of the 196 new cruises, per basin and for the global data set. The numbers in the table are the weighted mean of the absolute offset of unadjusted and adjusted data versus GLODAPv2.2019, n is the total number of valid crossovers in the global ocean for the variable in question.

|          | ARCTIC | ATLANTIC | INDIAN | PACIFIC | GLOBAL |
|----------|--------|----------|--------|---------|--------|
|          | Unadj  | Adj      | Unadj  | Adj     | Unadj  | Adj    | Unadj  | Adj    |
| Sal (x1000) | 4.7 | 3.7 | 5.0 | 4.0 | 3.9 | 3.9 | 4.3 | 4.2 |
| Oxy (%)     | 0.8  | 0.8  | 0.7  | 0.7  | 0.5  | 0.5  | 0.4  | 0.4  |
| NO2 (%)     | 2.9  | 2.9  | 2.6  | 1.6  | 0.6  | 0.6  | 0.6  | 0.6  |
| Si (%)       | 0.6  | 0.6  | 2.6  | 2.4  | 1.9  | 1.9  | 1.1  | 1.1  |
| PO4 (%)     | 0.8  | 0.8  | 0.9  | 0.9  | 0.5  | 0.5  | 0.5  | 0.5  |
| TAlk (μmol/kg) | 3.4 | 3.4 | 3.6 | 3.6 | 3.9 | 3.9 | 3.9 | 3.9 |
| pH (x1000)  | 8.4  | 8.4  | 8.5  | 8.5  | 8.4  | 8.4  | 8.3  | 8.3  |

Summary of the distribution of applied...
### Table A1: Cruises included in GLODAPv2 2020 that did not appear in GLODAPv2 2019

Complete information on each cruise, such as variables included, and chief scientist and principal investigator names is provided in the cruise summary table at [https://www.nodc.noaa.gov/ocads/oceans/GLODAPv2_2020/cruise_table_2020.html](https://www.nodc.noaa.gov/ocads/oceans/GLODAPv2_2020/cruise_table_2020.html).

| No | EXPCODE | Region | Atlas | Start | End | Ship |
|----|---------|--------|-------|-------|-----|------|
| 2001 | p02M232130625 | Atlantic | BSMU12 | 20120205 | 20120724 | Maria S. Merian |
| 2002 | p02M2321306419 | Atlantic | BSM27 | 20130419 | 20130506 | Maria S. Merian |
| 2003 | p02M232130509 | Atlantic | BSM28 | 20130509 | 20130526 | Maria S. Merian |
| 2004 | p02M232140597 | Atlantic | BSM38 | 20140507 | 20140605 | Maria S. Merian |
| 2005 | p02M232150502 | Atlantic | BSM42 | 20150228 | 20150232 | Maria S. Merian |
| 2006 | p02M232160604 | Atlantic | BSMU2 | 20160207 | 20160207 | Meteo |
| 2007 | p02M232170501 | Atlantic | BSMU2 | 20170204 | 20170216 | Meteo |
| 2008 | p02M232180605 | Atlantic | BSMU2 | 20180204 | 20180216 | Meteo |
| 2009 | p02M232190502 | Atlantic | BSMU2 | 20190204 | 20190216 | Meteo |

**Notes:**
- Deleted: 20200213
- Moved: 20190201
- Formatted: 20200213

**References:**
- Olsen, Are (2020). GLODAPv2 Data and Documentation. NOAA Oceanic Carbon Program, National Data Center. [https://www.nodc.noaa.gov/ocads/oceans/GLODAPv2_2020/cruise_table_2020.html](https://www.nodc.noaa.gov/ocads/oceans/GLODAPv2_2020/cruise_table_2020.html)
Figure 1. Location of stations in (a) GLODAPv2,2019 and for (b) the new data added in this update.

Figure 2. Number of cruises per year in GLODAPv2, GLODAPv2,2019, and GLODAPv2,2020.

Figure 3. Example crossover figure, for CO₂ for cruises 49UP20160109 (blue) and 49UP20160706 (red), as it was generated during the crossover analysis. Panels (a) and (b) show the station positions, Panel (c) shows the data below the upper depth limit (in this case 2000 dbar) as points and the interpolated profiles as lines. Non-interpolated data either did not meet minimum depth separation requirements (Table 4 in Key et al., 2010) or are the deepest sampling depth. The interpolation does not extrapolate. Panel (c) shows the mean difference, profile (black, dots) with its standard deviation, and also the weighted mean offset (straight, red) and weighted standard deviation. Summary statistics are provided in Table 4.

Figure 4. Example summary figure, for CO₂ crosses for 49UP20160109 versus the cruises in GLODAPv2,2019 (with cruise CANYON-B) listed on x-axis sorted according to the year the cruise was conducted. The black dots and vertical error bars show the weighted mean offset and standard deviation for each crossover. The black dashed line and standard deviation are shown in the red line and the 3.68 ± 0.03 mol kg⁻¹. The black dashed line is the reference line for a 4 µmol kg⁻¹ offset (the corresponding line for a 4 µmol kg⁻¹ offset is right on top of x-axis and not visible).

Figure 5. Example summary figure for CONTENT and CANYON-B analyses for 49UP20160109. Any data from regions where CONTENT and CANYON-B were not trained are excluded (in this case, the Sea of Japan). The top row shows the nutrients and the bottom row the seawater CO₂ chemistry variables (Note, different abbreviations for TCO₂ (CT) and TAI). Black dots are the measured data. Blue dots are CANYON-B estimates and red dots are the CONTENT estimates. Each variable has two figure panels. The left shows the depth profile while the right shows the absolute difference between measured and estimated values divided by the CONTENT uncertainty estimate, which is determined for each estimated value. A value below 1 indicates a good match between the two as it means that the difference between measured and estimated values is less than the uncertainty of the latter. The statistics in each panel are for all data deeper than 300 dbar and N is the number of samples considered. A gain ratio and its interquartile range is given for the nutrients. For the seawater CO₂ chemistry variables the numbers on each panel are the median difference between measured and estimated values for CANYON-B (upper) and CONTENT (lower). Both are given with their interquartile range.

Figure 6. Distribution of applied adjustments for each core variable that received secondary QC. Grey areas depict the initial minimum adjustment limits. The figure includes numbers for data subjected to secondary quality control only. Note also that the x-axis scale is set to render the number of adjustments to be visible, so the bar showing zero offset (the 0 bar) for each variable is cut off (see Table 5 for these numbers).

Figure 7. Distribution of pH offsets for the cruises from Japan Meteorological Agency added in GLODAPv2,2020.

Figure 8. Distribution of applied adjustments per decade for the 346 cruises included in GLODAPv2,2020. Dark blue: not adjusted; light blue: absolute adjustment is smaller than initial minimum adjustment limit (Table 4); orange: absolute adjustment is between limit and 2 times the limit, red: absolute adjustment is larger than 2 times the limit.

Figure 9. Locations of stations included in the (a) Arctic, (b) Atlantic, (c) Indian, and (d) Pacific Ocean product files for the complete GLODAPv2,2020 dataset.

Figure 10. Distribution of data in GLODAPv2,2020 in (a) December–February, (b) March–May, (c) June–August, (d) September–November, and (e) number of observations for each month north of 45º N (red), north of equator to 45º N (orange), equator to 45º S (light blue), and south of 45º S (dark blue).

Table 1. Number (a) and density (b) of observations in 100 m depth layers. The latter was calculated by dividing the number of observations in each layer by its global volume calculated from ETOPO2 (National Geophysical Data Center, 2006). For example, in the layer between 0 and 100 m there are on average 0.0075 observations per cubic kilometer. One observation is one water sampling point and has data for several variables.
Figure 1

Locations of stations included in the (a) Arctic, (b) Atlantic, (c) Indian, and (d) Pacific Ocean product files for the whole GLODAPv2.2019 dataset.
Figure 2
Figure 3
Figure 7
Figure 10
Figure 11
6 Leibniz Institute for Baltic Sea Research Warnemünde, Rostock, Germany
CO₂ corresponding to a significant fraction of anthropogenic CO₂ emissions (Gruber et al., 2019; Le Quéré et al., 2018) and most of the excess heat in the Earth System caused by the enhanced greenhouse effect resulting from the fraction of CO₂ and other greenhouse gases remaining in the atmosphere (Cheng et al., 2017). The objective of GLODAP (Global Ocean Data Analysis Project, www.glodap.info, last access: 17 September 2019)

Examples include stable isotopes of carbon and oxygen (δ¹³C and δ¹⁸O), radioisotopes (¹⁴C, ³H, ³He), noble gases (He, Ne), and organic material including total organic carbon (TOC), dissolved organic carbon (DOC), total dissolved nitrogen (TDN), and chlorophyll a (Chl a).

The first version of GLODAP, GLODAPv1.1, was released in 2005 (Key et al., 2004; Sabine et al., 2005). It contains data from 115 cruises with biogeochemical measurements from the global ocean. The vast majority of these are the sections covered during the World Ocean Circulation Experiment and the Joint Global Ocean Flux Study (WOCE/JGOFS) in the 1990s, but data from important “historical” cruises were also included, such as from the Geochemical Ocean Sections Study (GEOSECS), Transient Traces in the Ocean (TTO), and South Atlantic Ventilation Experiment (SAVE). The second version of GLODAP, GLODAPv2, was released in 2016 (Key et al., 2015; Lauvset et al., 2016; Olsen et al., 2016) with data from 724 scientific cruises: those included in GLODAPv1.1, those amassed for the Carbon in the Atlantic Ocean (CARINA) data synthesis (Key et al., 2010), those amassed for the Pacific Ocean Interior Carbon
(PACIFICA) synthesis (Suzuki et al., 2013), and data from 168 additional cruises. The additional cruises include many collected within the framework of the “repeat hydrography” program (Talley et al., 2016), instigated in the early 2000s as part of CLIVAR and since 2007 organized as the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP). Both GLODAPv1.1 and GLODAPv2 data were released in three formats: (i) as submitted by the data originator but reformatted to WOCE exchange format (Swift and Diggs, 2008) and subjected to primary quality control to flag outliers, (ii) as a merged data product with bias minimization adjustments applied, and (iii) as globally mapped climatological distributions. We refer to the first as the original data, to the second as the data product, and to the third as the mapped product.

The GLODAP products have been widely used. The first version formed the basis for the first data-based estimate of the global ocean inventory of anthropogenic carbon (Sabine et al., 2004), and the descriptive paper on GLODAPv1.1 (Key et al., 2004) has been cited more than 800 times according to Web of Science (Clarivate Analytics). For GLODAPv2, we have registered more than 120 applications. Examples include model evaluation (Beadling et al., 2018; Goris et al., 2018; Tjiputra et al., 2018; Ward et al., 2018), model initialization (Orr et al., 2017), water mass analyses (Jeansson et al., 2017; Peters et al., 2018; Rae and Broecker, 2018), ocean acidification (Fassbender et al., 2017; García-Ibáñez et al., 2016; Perez et al., 2018), calibration of Argo biogeochemical sensor measurements (Bushinsky et al., 2017; Johnson et al., 2017), calibration of multiple linear regression (MLR) and neural-network-based methods for biogeochemical data estimation (Bittig et al., 2018; Carter et al., 2018; Fry et al., 2016; Sauzède et al., 2017), contextualization of paleo-oceanographic data (Glock et al., 2018; Sessford et al., 2018), and calculation of inventory, transport, and variability of ocean carbon (DeVries et al., 2017; Fröb et al., 2018; Fröb et al., 2016; Gruber et al., 2019; Panassa et al., 2018; Pardo et al., 2017; Quay et al., 2017). A full list of GLODAPv2 citations is provided at https://www.glodap.info/index.php/glodap-impact/ (last access: 17 September 2019).

Principles
to annual-to-decadal changes in ocean circulation (Fröb et al., 2016; Landschützer et al., 2015), ocean acidification is progressing at unprecedented rates and already causing carbonate mineral undersaturation in some regions (Feely et al., 2008; Qi et al., 2017), oxygen minimum zones are rapidly expanding (Breitburg et al., 2018), and declining nutrient supply to the euphotic zone is potentially changing phytoplankton composition in certain large ocean regions (Rousseaux and Gregg, 2015). In addition, improvements in data management practices and increased computational resources are transforming approaches to, and expectations for, integrated data products. The Surface Ocean CO$_2$ Atlas (SOCAT) is a prominent example in this regard with annual releases and rapid use in global carbon budgets (Bakker et al., 2016; Bakker et al., 2014; Le Quéré et al., 2018; Pfeil et al., 2013). GLODAP is also becoming an important source of calibration and validation data for the biogeochemical sensors that are now deployed on autonomous platforms. Altogether, regular and rapid updates are important.

This contribution documents the first such regular update of GLODAP, which adds data from 116 new cruises to the 724 included in GLODAPv2 and corrects errors and omissions in GLODAPv2. It also forms the basis for the documentation of future updates, adopting the Earth System Science Data “living data” format for evolving data sets.

GLODAPv2.2019 (Olsen et al., 2019) contains data from 840 cruises, covering the global ocean from 1972 to 2017. The sampling locations of the 116 cruises added in this update are shown alongside those of GLODAPv2 in Fig. 1, while the coverage in time is shown in Fig. 2. Compared to GLODAPv2, the added data are mostly repeat observations and extend the coverage in time. Information on cruises added to this version is provided in Table A1 in the Appendix.

The crossover analyses were conducted with the Matlab toolbox prepared by Lauvset and Tanhua (2015) and with the GLODAPv2 data product as reference. In areas where a strong trend in salinity was present, the TAlk and TCO$_2$ data were salinity normalized following Friis et al. (2003), before crossover analysis. The toolbox implements the ‘running-cluster’ crossover analysis first described by Tanhua et al. (2010).
Typically

.12 ± 0.016 times

116
77 of the 116 new cruises included pH data. For about 30% of these, the pH data were not supplied on the total scale, and at 25°C and 0 dbar pressure, which is the GLODAP standard. These data were converted to total pH scale and temperature and pressure of 25°C and 0 dbar. The conversions were conducted by using CO2SYS (Lewis and Wallace, 1998) for MATLAB (van Heuven et al., 2011) with reported pH and TAlk as inputs, and generating pH output values at total scale at 25°C and 0 dbar of pressure (named ph525p0 in the product). Whenever TAlk data were missing, these values were approximated as 67 times salinity. The proportionality (67) is the mean ratio of TAlk to salinity in the GLODAPv2 data. This is sufficiently accurate for scale-temperature-pressure conversions. Data for phosphate and silicate are also needed, and were, whenever missing, determined using CANYON-B (Bittig et al., 2018). The conversion was conducted with the carbonate dissociation constants of Lueker et al. (2000), the bisulfate dissociation constant of Dickson (1990), and the borate-to-salinity ratio of Uppström (1974). These procedures are the same as used for GLODAPv2 (Olsen et al., 2016), except for the CANYON-B estimation of phosphate and silicate.

The secondary quality control of the pH data also followed previous procedures, using a combination of crossovers and internal consistency calculations. The latter were conducted when a cruise had data for TCO₂ and TAlk, in addition to pH. Note that internal consistency was only considered for the secondary
QC of pH, and not for the secondary QC of TCO₂ and TAlk. Hence, the adjustments applied for pH are not only a bias correction but also a seawater CO₂ chemistry consistency correction. This is one factor that makes the secondary quality control of pH data problematic, in particular with regard to the application of a uniform correction for an entire cruise or leg based on offsets in deep data. pH dependent offsets between pH determined spectrophotometrically with purified dyes and pH calculated from TCO₂ and TAlk have recently been found. For example, at a pH of 7.6 the calculated pH is higher by ~ 0.01 than measured pH (Carter et al., 2018). The causes of these discrepancies are not entirely clear, suggestions include deficiencies in dissociation constants used for the seawater CO₂ chemistry calculations, errors in the total boron-to-salinity ratio, and unknown protolytes affecting the TAlk (Carter et al., 2018; Fong and Dickson, 2019). Such low pH values exist only in the deep North Pacific Ocean. Here, application of pH corrections based on seawater CO₂ consistency considerations could impact the correction. Broadly speaking, the pH data in GLODAP have been obtained using a variety of methods (e.g. potentiometric measurements, and spectrophotometric measurements with purified or impure dyes). The pH values produced by these different approaches have documented pH-dependent offsets from one another (Carter et al., 2013; Liu et al., 2011; Patsavas et al., 2015; Yao et al., 2007) that challenge the viability of the uniform adjustments applied (Carter et al., 2018). While we have continued to apply such uniform offsets for this update, we have chosen the higher initial minimum adjustment limit of 0.01, which is twice that used for GLODAPv2 (0.005), to minimize the possibility of false corrections. The full ramifications and a revised strategy for identifying and minimizing bias in pH data is a topic for future development of the GLODAP data synthesis procedures. The full collection of pH values in GLODAPv2.2019 should only be considered to be consistent between cruises to 0.01 to 0.02 pH units.

3.2.5

Values for potential temperature and potential density anomalies (referenced to 0, 1000, 2000, 3000, and 4000 dbar) were calculated using Fofonoff (1977) and Bryden (1973). Neutral density was calculated using Sérazin (2011). Apparent oxygen utilization was determined using the combined fit in Garcia and Gordon (1992).

Partial pressures for CFC-11, CFC-12, CFC-113, CCl₄, and SF₆ were calculated using the solubilities by Warner and Weiss (1985), Bu and Warner (1995), Bullister and Wisegarver (1998), and Bullister et al. (2002).

Whenever only two seawater CO₂ chemistry variables were reported, the third was calculated using CO2SYS (Lewis and Wallace, 1998) for Matlab (van Heuven et al., 2011), with the constants set as for the pH conversions (Sect. 3.2.4). If this resulted in a mix of measured and calculated values for a certain CO₂ system variable for a specific cruise, and if the number of calculated values were equal to or exceeded twice the number of measured, then all measured were replaced by calculated values. Calculated values have been assigned WOCE flag 0.
However, more than a third (38%) had uncalibrated CTD $O_2$ values. For comparison, half of the

Page 12: [42] Deleted
are Olsen
31/07/20 11:42
For data files that only contain bottle values for either or both variables, the tallies are somewhat uncertain, as some CTD values might have been mislabeled by the data originators.

Page 13: [43] Deleted
are Olsen
31/07/20 11:42

1 % compared to 5 % for the 724 GLODAPv2 cruises), for the halogenated transient tracers (0 %–3 %
adjusted, depending on variable, compared to 6 %–10 % for GLODAPv2), and for $TCO_2$ (two cruises, i.e.,
2 % compared to 17 % for GLODAPv2).

The distributions of the magnitude of adjustments applied are presented in Fig. 5 and Table 6. For salinity, oxygen, and silicate, adjustments between 1 and 2 times the initial minimum adjustment limit are most prevalent. For nitrate, phosphate, CFC-11, and CFC-12, adjustments equal to or larger than 2 times the limit are most prevalent. For the salinity and oxygen this reflects that any biases in the data tends to be between 1 and 2 times the limit, while for CFC-11 and CFC-12 it also likely reflects limitations in our ability to confidently identify small biases. These limitations are related to the strongly transient nature of the CFCs. For $TCO_2$ and TAlk, none of the adjustments are larger than 2 times the adjustment limit, and for both properties half of the adjustments applied are below the limit. For TAlk, this distribution of adjustments supports the lowered minimum adjustment limit of 4 µmol kg$^{-1}$ (instead of 6 µmol kg$^{-1}$); these data have sufficient precision to enable the identification of such small adjustments.

For TAlk, seven out of eight adjustments are positive (i.e., the data are biased low), for pH nine out of 10 adjustments are positive, and for oxygen six out of seven are positive. The adjustments for other variables were more distributed around zero. For TAlk, prevalence of a negative bias was also observed in the inter-laboratory comparison reported by Bockmon and Dickson (2015), who suggested the cause being the use of end point titrations rather than the (preferred) equivalence point titrations. However, 6 out of 7 of the negative bias cruises were Japanese. A tendency for bias in Japanese cruises to be negative was also identified in GLODAPv2 and may be due to the use of internal reference material. We note that the TAlk data from 23 out of 29 Japanese cruises with viable deep crossover checks had no apparent deep offset, so the majority of new TAlk data from Japan were consistent with GLODAPv2 even with the lowered threshold.

The prevalence of positive pH adjustments may relate to the fact that at low pH (as is common in the deeper waters where crossover analyses are done), measurements made with purified dyes tend to be lower than pH determined using electrodes, using impure spectrophotometric dyes with older dye coefficients (Clayton and Byrne, 1993), or calculated from $TCO_2$ and TAlk (Carter et al., 2018). The latter three types of pH data constitute the bulk of the reference data for the consistency checks, so the prevalence of a modern negative bias may be a consequence of limitations in the approaches used for the secondary quality control of the pH data in GLODAP. As mentioned above, refining these should be a priority in the future.
Here, we acknowledge the issue and believe that a realistic estimate of the consistency of the pH data in the product is approximately 0.01–0.02.

Crossover comparison is conducted on deep-water samples so atmospheric exchange during sample collection on the new cruises is not a viable explanation for the trend of positive oxygen adjustments. Atmospheric contamination would usually increase deep-water oxygen concentrations since deep oxygen levels are usually low. The data are not collected in any particular region, or associated with any specific laboratory, country, or method. Consequently, no particular explanation can be offered for the prevalence of positive adjustments.

Ocean silicate for the adjusted data is 11.1 % and that for salinity is 10 ppm (i.e., a salinity of 0.01). This can be ascribed to two cruises, 58GS20130717 and 58GS20160802, conducted in the Greenland Sea where an increasing presence of Arctic sourced deep waters generates changes in these properties (Blindheim and Rey, 2004; Lauvset et al., 2018; Olafsson and Olsen, 2010; Olsen et al., 2009) that have not been corrected for. The impact of northern variability on the final consistency estimate can be determined for the Atlantic Ocean by excluding all data north of 50° N from the analysis. This gives a much better initial and final consistency, on par with that for the Indian and Pacific Oceans (Table 8).

(Dickson et al., 2007), the widespread use of CRMs (Dickson et al., 2003), and instrument automation. pH adjustment frequency also has a downward trend; however, the situation is far from ideal and a topic for future development in GLODAP. For the nutrients and oxygen, only

and 5 % for the halogenated transient tracers. For TAlk the stated consistency for GLODAPv2 is 6 µmol kg⁻¹ (Olsen et al., 2016). We now believe this is better, 4 µmol kg⁻¹, not only for the 116 new cruises, but for all data in GLODAPv2 from 2016 as well. This is based on the global average absolute offset for TAlk in the adjusted GLODAPv2 data product of 2.8 µmol kg⁻¹ (Table 5 in Olsen et al. (2016)) and the use of the initial minimum adjustment limit of 4 µmol kg⁻¹ for the cruises added with the present version. For pH on the other hand, the consistency among all data is likely not better than 0.01–0.02

Amante, C. and Eakins, B. W.: ETOPO1 1 Arc-minute global relief model: procedures, data sources and analysis, NOAA Technical Memorandum NESDIS NGDC-24, National Geophysical Data Center, Marine Geology and Geophysics Division, Boulder, CO, U.S.A., 2019.
Aoyama, M., Ota, H., Kimura, M., Kitao, T., Mitsuda, M., Murata, A., and Sato, K.: Current status of homogeneity and stability of the reference materials for nutrients in Seawater, Anal. Sci., 28, 911–916, 2012.
Bakker, D. C. E., Pfeil, B., Landa, C. S., Metzl, N., O'Brien, K. M., Olsen, A., Smith, K., Cosca, C., Harasawa, S., Jones, S. D., Nakaoka, S., Nojiri, Y., Schuster, U., Steinhoff, T., Sweeney, C., Takahashi, T., Tilbrook, B., Wada, C., Wanninkhof, R., Alin, S. R., Balestrini, C. F., Barbero, L., Bates, N. R., Bianchi, A. A., Bonou, F., Boutin, J., Bozec, Y., Burger, E. F., Cai, W. J., Castle, R. D., Chen, L. Q., Chierici, M., Currie, K., Evans, W., Featherstone, C., Feely, R. A., Fransson, A., Goyet, C., Greenwood, N., Gregor, I., Hankin, S., Hardman-Mountford, N. J., Harlay, J., Hauck, J., Hoppema, M., Humphreys, M. P., Hunt, C.,
Clayton, T. D. and Byrne, R. H.: Spectrophotometric seawater pH measurements - Total hydrogen-ion concentration scale calibration of m-cresol purple and at-sea results, Deep-Sea Res Pt I, 40, 2115-2129, 1993.

DeVries, T., Holzer, M., and Primeau, F.: Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning, Nature, 542, 215-218, 2017.

Dickson, A. G.: Standard potential of the reaction: AgCl(s) + ½H₂(g) = Ag(s) + HCl(aq) and the standard acidity constant of the Ion HSO₄⁻ in synthetic sea water from 273.15 to 318.15 K, J Chem Thermodyn, 22, 113-127, 1990.

Dickson, A. G., Afgan, J. D., and Anderson, G. C.: Reference materials for oceanic CO₂ analysis: a method for the certification of total alkalinity, Mar Chem, 80, 185-197, 2003.

Dickson, A. G., Sabine, C. L., and Christian, J. R.: Guide to Best Practices for Ocean CO₂ measurements, PICES Special Publication 3, 191 pp., 2007.

Fassbender, A. J., Sabine, C. L., and Palevsky, H. I.: Nonuniform ocean acidification and attenuation of the ocean carbon sink, Geophys Res Lett, 44, 8404-8413, 2017.

Feely, R. A., Sabine, C. L., Hernandez-Ayon, J. M., Ianson, D., and Hales, B.: Evidence for upwelling of corrosive "acidified" water onto the continental shelf, Science, 320, 1490-1492, 2008.

Fofonoff, N. P.: Computation of potential temperature of seawater for an arbitrary reference pressure, Deep-Sea Research, 24, 489-491, 1977.

Fong, M. B. and Dickson, A. G.: Insights from GO-SHIP hydrography data into the thermodynamic consistency of CO₂ system measurements in seawater, Mar Chem, doi: https://doi.org/10.1016/j.marchem.2019.03.006, 2019.

Friis, K., Körtzinger, A., and Wallace, D. W. R.: The salinity normalization of marine inorganic carbon chemistry data, Geophys Res Lett, 30, 2003.

Fröb, F., Olsen, A., Becker, M., Chafik, L., Johannessen, T., Reverdin, G., and Omar, A.: Wintertime fCO(2) Variability in the Subpolar North Atlantic Since 2004, Geophys Res Lett, 46, 1580-1590, 2019.

Fröb, F., Olsen, A., Pérez, F. F., García-Ibáñez, M. I., Jeansson, E., Omar, A., and Lauvset, S. K.: Inorganic carbon and water masses in the Irminger Sea since 1991, Biogeoosciences, 15, 51-72, 2018.

Fröb, F., Olsen, A., Vage, K., Moore, G. W. K., Yashayaev, I., Jeansson, E., and Rajasakaren, B.: Irminger Sea deep convection injects oxygen and anthropogenic carbon to the ocean interior, Nat Commun, 7, 2016.

Fry, C. H., Tyrrell, T., and Achterberg, E. P.: Analysis of longitudinal variations in North Pacific alkalinity to improve predictive algorithms, Global Biogeochem Cy, 30, 1493-1508, 2016.

García, H. E. and Gordon, L. I.: Oxygen solubility in seawater - Better fitting equations, Limnol Oceanogr, 37, 1307-1312, 1992.

García-Ibáñez, M. I., Zunino, P., Froh, F., Carracedo, L. I., Rios, A. F., Mercier, H., Olsen, A., and Perez, F. F.: Ocean acidification in the subpolar North Atlantic: rates and mechanisms controlling pH changes, Biogeoosciences, 13, 3701-3715, 2016.

Glock, N., Erdem, Z., Wallmann, K., Somes, C. J., Liebetrau, V., Schonfeld, J., Gorb, S., and Eisenhauer, A.: Coupling of oceanic carbon and nitrogen facilitates spatially resolved quantitative reconstruction of nitrate inventories, Nat Commun, 9, 10, 2018.

Goris, N., Tipputra, J. F., Olsen, A., Schwinger, J., Lauvset, S. K., and Jeansson, E.: Constraining projection-based estimates of the future North Atlantic carbon uptake, J Climate, 31, 3959-3978, 2018.

Gruber, N., Clement, D., Carter, B. R., Feely, R. A., van Heuven, S., Hoppema, M., Ishii, M., Key, R. M., Kozyr, A., Lauvset, S. K., Lo Monaco, C., Mathis, J. T., Murata, A., Olsen, A., Perez, F. F., Sabine, C. L., Tanhua, T., and Wanninkhof, R.: The oceanic sink for anthropogenic CO₂ from 1994 to 2007, Science, 363, 1193-1199, 2019.

Hood, E. M., Sabine, C. L., and Sloyan, B. M.: The GO-SHIP hydrography manual: A collection of expert reports and guidelines. , 2010.

Hydes, D. J., Aoyama, A., Aminot, A., Bakker, K., Becker, S., Coverly, S., Daniel, A., Dickson, A. G., Grosso, O., Kerouel, R., van Ooijen, J., Sato, K., Tanhua, T., Woodward, E. M. S., and Zhang, J.-Z.: Determination of dissolved nutrients in seawater with high precision and intercomparability using gas-segmented continuous flow analysers. In: The GO SHIP Repeat Hydrography Manual: A Collection of Expert Reports and Guidelines, Hood, E. M., Sabine, C., and Sloyan, B. M. (Eds.), IOCCP Report Number 14, ICPO Publication Series Number 134, 2012.

Jeansson, E., Olsen, A., and Jutterström, S.: Arctic Intermediate Water in the Nordic Seas, 1991–2009, Deep Sea Research Part I: Oceanographic Research Papers, 128, 82-97, 2017.
Jeansson, E., Olsson, K. A., Tanhua, T., and Bullister, J. L.: Nordic Seas and Arctic Ocean CFC data in CARINA, Earth Syst. Sci. Data, 2, 79-97, 2010.

Jenkins, W. J., Doney, S. C., Fendrock, M., Fine, R., Gamo, T., Jean-Baptiste, P., Key, R., Klein, B., Lupton, J. E., Rhein, M., Roether, W., Sano, Y., Schlitzer, R., Schlosser, P., and Swift, J.: A comprehensive global oceanic dataset of helium isotope and tritium measurements, Earth Syst. Sci. Data Discuss., 2018, 1-26, 2018.

Johnson, K. S., Plant, J. N., Coletti, L. J., Jannasch, H. W., Sakamoto, C. M., Riser, S. C., Swift, D. D., Williams, N. L., Boss, E., Haenjens, N., Talley, L. D., and Sarmiento, J. L.: Biogeochemical sensor performance in the SOCCOM profiling float array, J Geophys Res-Oceans, 122, 6416-6436, 2017.

Jutterström, S., Anderson, L. G., Bates, N. R., Bellerby, R., Johannessen, T., Jones, E. P., Key, R. M., Lin, X., Olsen, A., and Omar, A. M.: Arctic Ocean data in CARINA, Earth Syst. Sci. Data, 2, 71-78, 2010.

Key, R. M., Kozyr, A., Sabine, C. L., Lee, K., Wanninkhof, R., Bellerby, J. L., Feely, R. A., Millero, F. J., Mordy, C., and Peng, T. H.: A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAP), Global Biogeochem Cy, 18, 2004.

Key, R. M., Olsen, A., van Heuven, S., Lauvset, S. K., Velo, A., Lin, X., Schirnick, C., Kozyr, A., Tanhua, T., Hoppema, M., Jutterstrom, S., Steinfeldt, R., Jeansson, E., Ishii, M., Perez, F. F., and Suzuki, T.: Global Ocean Data Analysis Project, Version 2 (GLODAPv2), ORNL/CDIAC-162, ND-P093, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tennessee., 2015.

Key, R. M., Tanhua, T., Olsen, A., Hoppema, M., Jutterström, S., Schirnick, C., van Heuven, S., Kozyr, A., Lin, X., Velo, A., Wallace, D. W. R., and Mintrop, L.: The CARINA data synthesis project: introduction and overview. Earth Syst. Sci. Data, 2, 105-121, 2010.

Landschützer, P., Gruber, N., Haumann, A., Rodenbeck, C., Bakker, D. C. E., van Heuven, S., Hoppema, M., Metzl, N., Sweeney, C., Takahashi, T., Tilbrook, B., and Wanninkhof, R.: The reinvigoration of the Southern Ocean carbon sink, Science, 349, 1221-1224, 2015.

Lauvset, S. K., Brakstad, A., Vage, K., Olsen, A., Jeansson, E., and Mork, K. A.: Continued warming, salinification and oxygenation of the Greenland Sea gyre, Tellus A, 70, 1-9, 2018.

Lauvset, S. K., Key, R. M., Olsen, A., van Heuven, S., Velo, A., Lin, X. H., Schirnick, C., Kozyr, A., Tanhua, T., Hoppema, M., Jutterstrom, S., Steinfeldt, R., Jeansson, E., Ishii, M., Perez, F. F., Suzuki, T., and Watelet, S.: A new global interior ocean mapped climatology: the 1° x 1° GLODAP version 2, Earth Syst Sci Data, 8, 325-340, 2016.

Lauvset, S. K. and Tanhua, T.: A toolbox for secondary quality control on ocean chemistry and hydrographic data. Limnology and Oceanography: Methods, 13, 601-608, 2015.

Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., Pickers, P. A., Korsbakken, J. I., Peters, G. P., Canadell, J. G., Arneth, A., Arora, V. K., Barbero, L., Bastos, A., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Doney, S. C., Gkritzalis, T., Goll, D. S., Harris, I., Haverd, V., Hoffman, F. M., Hoppema, M., Houghton, R. A., Hurtt, G., Ilyina, T., Jain, A. K., Johannessen, T., Jones, C. D., Kato, E., Keeling, R. F., Goldewijk, K. K., Landschützer, P., Lefèvre, N., Lienert, S., Liu, Z., Lombardozi, D., Metzl, N., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S., Neill, C., Olsen, A., Ono, T., Patra, P., Peregon, A., Peters, W., Peylin, P., Pfeil, B., Poulter, B., Rehder, G., Resplandy, L., Robertson, E., Roether, M., Rodenbeck, C., Schulz, U., Schwinger, J., Seferian, R., Skjelvan, I., Steinhoff, T., Sutton, A., Tans, P. P., Tian, H. Q., Tilbrook, B., Tubiello, F. N., van der Laan-Luijkx, I. T., van derWerf, G. R., Viiv, N., Walker, A. P., Wiltshire, A. J., Wright, R., Zaehe, S., and Zheng, B.: Global Carbon Budget 2018, Earth Syst Sci Data, 10, 2141-2194, 2018.

Lewis, E. and Wallace, D. W. R.: Program developed for CO$_2$ system calculations, ORNL/CDIAC-105, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, U.S.A., 1998.

Liu, X. W., Patsavas, M. C., and Byrne, R. H.: Purification and characterization of meta-cresol purple for spectrophotometric seawater pH measurements, Environ Sci Technol, 45, 4862-4868, 2011.

Lueker, T. J., Dickson, A. G., and Keeling, C. D.: Ocean pCO$_2$ calculated from dissolved inorganic carbon, alkalinity, and equations for K-1 and K-2: validation based on laboratory measurements of CO$_2$ in gas and seawater at equilibrium, Mar Chem, 70, 105-119, 2000.

Olafsson, J. and Olsen, A.: Nordic Seas nutrients data in CARINA, Earth Syst. Sci. Data, 2, 205-213, 2010.

Olsen, A., Key, R. M., Jeansson, E., Falck, E., Olafsson, J., van Heuven, S., Skjelvan, I., Omar, A. M., Olsson, K. A., Anderson, L. G., Jutterström, S., Rey, F., Johannessen, T., Bellerby, R. G. J., Blindheim, J.,
Bullister, J. L., Pfeil, B., Lin, X., Kozyr, A., Schirnick, C., Tanhua, T., and Wallace, D. W. R.: Overview of the Nordic Seas CARINA data and salinity measurements, Earth Syst. Sci. Data, 1, 25-34, 2009.

Olsen, A., Key, R. M., van Heuven, S., Lauvset, S. K., Velo, A., Lin, X. H., Schirnick, C., Kozyr, A., Tanhua, T., Hoppema, M., Jutterstrom, S., Steinfeldt, R., Jeansson, E., Ishii, M., Perez, F. F., and Suzuki, T.: The Global Ocean Data Analysis Project version 2 (GLODAPv2) - an internally consistent data product for the world ocean, Earth Syst Sci Data, 8, 297-323, 2016.

Olsen, A., Lange, N., Key, R. M., Tanhua, T., Alvarez, M., Becker, S., Bittig, H. C., Carter, B. R., Cotrim da Cunha, L., Feely, R. A., van Heuven, S., Hoppema, M., Ishii, M., Jeansson, E., Jones, S. D., Jutterström, S., Karlsen, M. K., Kozyr, A., Lauvset, S. K., Lo Monaco, C., Murata, A., Pérez, F. F., Pfeil, B., Schirnick, C., Steinfeldt, R., Suzuki, T., Telszewski, M., Tilbrook, B., Velo, A., and Wanninkhof, R.: Global Ocean Data Analysis Project, version 2.2019 (GLODAPv2.2019). NOAA National Centers for Environmental Information, https://doi.org/10.25921/xnme-wr20, 2019.

Orr, J. C., Najjar, R. G., Aumont, O., Bopp, L., Bullister, J. L., Danabasoglu, G., Doney, S. C., Dunne, J. P., Dutay, J. C., Graven, H., Griffies, S. M., John, J. G., Joos, F., Levin, I., Lindsay, K., Matear, R. J., McKinley, G. A., Mouchet, A., Oschlies, A., Romanou, A., Schlitzer, R., Tagliabue, A., Tanhua, T., and Yool, A.: Biogeochemical protocols and diagnostics for the CMIP6 Ocean Model Intercomparison Project (OMIP), Geosci Model Dev, 10, 2169-2199, 2017.

Ota, H., Mitsuda, H., Kimura, M., and Kitao, T.: Reference materials for nutrients in seawater: Their development and present homogeneity and stability. In: Comparability of nutrients in the world’s oceans, Aoyama, A., Dickson, A. G., Hydes, D. J., Murata, A., Muñoz, J. R., Roose, P., and Woodward, E. M. S. (Eds.), Mother Tank, Tsukuba, Japan, 2010.

Panassa, E., Santana-Casiano, J. M., Gonzalez-Davila, M., Hoppema, M., van Heuven, S., Völker, C., Wolf-Gladrow, D., and Hauck, J.: Variability of nutrients and carbon dioxide in the Antarctic Intermediate Water between 1990 and 2014, Ocean Dyn., 68, 295-308, 2018.

Pardo, P. C., Tilbrook, B., Langlais, C., Trull, T. W., and Rintoul, S. R.: Carbon uptake and biogeochemical change in the Southern Ocean, south of Tasmania, Biogeosciences, 14, 5217-5237, 2017.

Patsavas, M. C., Byrne, R. H., Wanninkhof, R., Feely, R. A., and Cai, W. J.: Internal consistency of marine carbon system measurements and assessments of aragonite saturation state: Insights from two US coastal cruises, Mar Chem, 176, 9-20, 2015.

Perez, F. F., Fontela, M., Garcia-Ibanez, M. I., Mercier, H., Velo, A., Lherminier, P., Zunino, P., de la Paz, M., Alonso, Pérez, F., Guallart, E. E., and Padin, X. A.: Meridional overturning circulation convey fast acidification to the deep Atlantic Ocean, Nature, 554, 515-518, 2018.

Peters, B. D., Jenkins, W. J., Swift, J. H., German, C. R., Moffett, J. W., Cutter, G. A., Brzezinski, M. A., and Casciotti, K. L.: Water mass analysis of the 2013 US GEOTRACES eastern Pacific zonal transect (GP16), Mar Chem, 201, 6-19, 2018.

Pfeil, B., Olsen, A., Bakker, D. C. E., Hankin, S., Koyuk, H., Kozyr, A., Malczynk, J., Manke, A., Metzl, N., Sabine, C. L., Akl, J., Alin, S. R., Bates, N., Bellerby, R. G. J., Borges, A., Boutin, J., Brown, P. J., Cai, W. J., Chavez, F. P., Chen, A., Cosca, C., Fassbender, A. J., Feely, R. A., Gonzalez-Davila, M., Goyet, C., Hales, B., Hardman-Mountford, N., Heinze, C., Hood, M., Hoppema, M., Hunt, C. W., Hydes, D., Ishii, M., Johannesen, T., Jones, S. D., Key, R. M., Kortzinger, A., Landschutzer, P., Lauvset, S. K., Lefevre, N., Lentz, A., Lourantou, A., Merlivat, L., Midorikawa, T., Minton, L., Miyazaki, C., Murata, A., Nakadate, A., Nakano, Y., Nakaoka, S., Nojiri, Y., Omar, A. M., Padin, X. A., Park, G. H., Paterson, K., Perez, F. F., Pierrot, D., Poisson, A., Rios, A. F., Santana-Casiano, J. M., Salisbury, J., Sarma, V. V. S. S., Schlitzer, R., Schneider, B., Schuster, U., Sieger, R., Skjelvan, I., Steinhoff, T., Suzuki, T., Takahashi, T., Tedesco, K., Telszewski, M., Thomas, H., Tilbrook, B., Tipputra, J., Vandemark, D., Veness, T., Wanninkhof, R., Watson, A. J., Weiss, R., Wong, C. S., and Yoshikawa-Inoue, H.: A uniform, quality controlled Surface Ocean CO2 Atlas (SOCAT), Earth Syst Sci Data, 5, 125-143, 2013.

Qi, D., Chen, L., Chen, B., Gao, Z., Zhong, W., Feely, Richard A., Anderson, Leif G., Sun, H., Chen, J., Chen, M., Zhan, L., Zhang, Y., and Cai, W.-J.: Increase in acidifying water in the western Arctic Ocean, Nat Clim Change, 7, 195, 2017.

Quay, P., Somerup, R., Munro, D., and Sweeney, C.: Anthropogenic CO2 accumulation and uptake rates in the Pacific Ocean based on changes in the 14C/12C of dissolved inorganic carbon, Global Biogeochem Cy, 31, 59-80, 2017.

Rae, J. W. B. and Broecker, W.: What fraction of the Pacific and Indian oceans' deep water is formed in the Southern Ocean?, Biogeosciences, 15, 3779-3794, 2018.
Rousseaux, C. S. and Gregg, W. W.: Recent decadal trends in global phytoplankton composition, Global Biogeochem Cy, 29, 1674-1688, 2015.

Sabine, C., Key, R. M., Kozyr, A., Feely, R. A., Wanninkhof, R., Millero, F. J., Peng, T.-H., Bullister, J. L., and Lee, K.: Global Ocean Data Analysis Project (GLODAP): Results and Data, ORNL/CDIAC-145, NDP-083, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, U.S.A., 2005.

Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., Wanninkhof, R., Wong, C. S., Wallace, D. W. R., Tilbrook, B., Millero, F. J., Peng, T. H., Kozyr, A., Ono, T., and Rios, A. F.: The oceanic sink for anthropogenic CO₂, Science, 305, 367-371, 2004.

Sauzède, R., Bittig, H. C., Claustre, H., Pasqueron de Fommervault, O., Gattuso, J.-P., Legendre, L., and Johnson, K. S.: Estimates of water-column nutrient concentrations and carbonate system parameters in the global ocean: A novel approach based on neural networks, Frontiers in Marine Science, 4, 2017.

Sérazin, G.: An approximate neutral density variable for the World’s oceans, Master’s Thesis, École Centrale, Lyon, Écule, France, 2011.

Sessford, E. G., Tisserand, A. A., Risebrough, B., Andersson, C., Dokken, T., and Jansen, E.: High-resolution benthic Mg/Ca temperature record of the intermediate water in the Denmark Strait across D-O stadial-interstadial cycles, Paleoceanogr. Paleoclimatol., 33, 1169-1185, 2018.

Steinfeldt, R., Tanhua, T., Bullister, J. L., Key, R. M., Rhein, M., and Köhler, J.: Atlantic CFC data in CARINA, Earth Syst. Sci. Data, 2, 1-15, 2010.

Suzuki, T., Ishii, M., Aoyama, A., Christian, J. R., Enyo, K., Kawano, T., Key, R. M., Kosugi, N., Kozyr, A., Miller, L. A., Murata, A., Nakano, T., Ono, T., Saino, T., Sasaki, K., Sasano, D., Takatani, Y., Wakita, M., and Sabine, C.: PACIFICA Data Synthesis Project, ORNL/CDIAC-159, NDP-092, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U. S. Department of Energy, Oak Ridge, TN, U.S.A., 2013.

Swift, J. and Diggs, S. C.: Description of WHP exchange format for CTD/Hydrographic data, CLIVAR and Carbon Hydrographic Data Office, UCSD Scripps Institution of Oceanography, San Diego, Ca, US, 2008.

Talley, L. D., Feely, R. A., Sloyan, B. M., Wanninkhof, R., Baringer, M. O., Bullister, J. L., Carlsson, C. A., Doney, S. C., Fine, R. A., Firing, E., Gruber, N., Hansell, D. A., Ishii, M., Johnson, G. C., Katsumata, K., Key, R. M., Kramp, M., Langdon, C., Macdonald, A. M., Mathis, J. T., McDonagh, E. L., Mecking, S., Millero, F. J., Mordy, C. W., Nakano, T., Sabine, C. L., Smethie, W. M., Swift, J. H., Tanhua, T., Thurnherr, A. M., Warner, M. J., and Zhang, J. Z.: Changes in ocean heat, carbon content, and ventilation: A review of the first decade of GO-SHIP global repeat hydrography, Annual Review of Marine Science, Vol 8, 8, 185-215, 2016.

Tanhua, T., van Heuven, S., Key, R. M., Velo, A., Olsen, A., and Schirnick, C.: Quality control procedures and methods of the CARINA database, Earth Syst. Sci. Data, 2, 35-49, 2010.

Tjiputra, J. F., Goris, N., Lauvset, S. K., Heinze, C., Olsen, A., Schwinger, J., and Steinfeldt, R.: Mechanisms and Early Detections of Multidecadal Oxygen Changes in the Interior Subpolar North Atlantic, Geophys Res Lett, 45, 4218-4229, 2018.

UNESCO: Tenth report of the joint panel on oceanographic tables and standards, UNESCO Technical Paper in Marine Science, 36, 13-21, 1981.

Uppström, L. R.: Boron/Chlorinity ratio of deep-sea water from Pacific Ocean, Deep-Sea Research, 21, 161-162, 1974.

van Heuven, S., Pierrot, D., Rae, J. W. B., Lewis, E., and Wallace, D. W. R.: MATLAB program developed for CO₂ system calculations, ORNL/CDIAC-105b, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, U.S.A., 2011.

Ward, B. A., Wilson, J. D., Death, R. M., Monteiro, F. M., Yool, A., and Ridgwell, A.: EcoGEnIE 1.0: plankton ecology in the cGEnIE Earth system model, Geosci Model Dev, 11, 4241-4267, 2018.

Warner, M. J. and Weiss, R. F.: Solubilities of chlorofluorocarbon-11 and chlorofluorocarbon-12 in water and seawater, Deep-Sea Res, 32, 1485-1497, 1985.

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crossas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., Gonzalez-Bertalan, A., Gray, A. J. G., Groth, P., Goble, C., Grethe, J. S., Heringa, J., ‘t Hoen, P. A. C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S. J., Martone, M. E., Mons, A., Packer, A. L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M. A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., and
Mons, B.: The FAIR Guiding Principles for scientific data management and stewardship, Scientific Data, 3, 160018, 2016.
Yao, W. S., Liu, X. W., and Byrne, R. H.: Impurities in indicators used for spectrophotometric seawater pH measurements: Assessment and remedies, Mar Chem, 107, 167-172, 2007.
Table 1. Variables in the GLODAPv2.2019

| Page 20: [48] Formatted Table | Are Olsen | 31/07/20 11:42 |
|--------------------------------|-----------|----------------|

Formatted Table

| Page 20: [49] Formatted    | Are Olsen | 31/07/20 11:42 |
|----------------------------|-----------|----------------|

None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

| Page 20: [50] Formatted    | Are Olsen | 31/07/20 11:42 |
|----------------------------|-----------|----------------|

None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

| Page 20: [51] Formatted    | Are Olsen | 31/07/20 11:42 |
|----------------------------|-----------|----------------|

Right: -0 cm, Tabs: 17.25 cm, Left

| Page 20: [52] Formatted    | Are Olsen | 31/07/20 11:42 |
|----------------------------|-----------|----------------|

None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

| Page 20: [53] Formatted    | Are Olsen | 31/07/20 11:42 |
|----------------------------|-----------|----------------|

Right: -0 cm, Tabs: 17.25 cm, Left

| Page 20: [54] Formatted    | Are Olsen | 31/07/20 11:42 |
|----------------------------|-----------|----------------|

None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

| Page 20: [55] Formatted    | Are Olsen | 31/07/20 11:42 |
|----------------------------|-----------|----------------|

Right: -0 cm, Tabs: 17.25 cm, Left

| Page 20: [56] Formatted    | Are Olsen | 31/07/20 11:42 |
|----------------------------|-----------|----------------|

None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

| Page 20: [57] Formatted    | Are Olsen | 31/07/20 11:42 |
|----------------------------|-----------|----------------|

None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

| Page 20: [58] Formatted    | Are Olsen | 31/07/20 11:42 |
|----------------------------|-----------|----------------|

Right: -0 cm, Tabs: 17.25 cm, Left

| Page 20: [59] Formatted    | Are Olsen | 31/07/20 11:42 |
|----------------------------|-----------|----------------|

None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

| Page 20: [60] Formatted    | Are Olsen | 31/07/20 11:42 |
|----------------------------|-----------|----------------|
Right: -0 cm, Tabs: 17.25 cm, Left

Page 20: [61] Formatted Are Olsen 31/07/20 11:42
None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

Page 20: [62] Formatted Are Olsen 31/07/20 11:42
None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

Page 20: [63] Formatted Are Olsen 31/07/20 11:42
Right: -0 cm, Tabs: 17.25 cm, Left

Page 20: [64] Formatted Are Olsen 31/07/20 11:42
None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

Page 20: [65] Formatted Are Olsen 31/07/20 11:42
Right: -0 cm, Tabs: 17.25 cm, Left

Page 20: [66] Formatted Are Olsen 31/07/20 11:42
None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

Page 20: [67] Formatted Are Olsen 31/07/20 11:42
Right: -0 cm, Tabs: 17.25 cm, Left

Page 20: [68] Formatted Are Olsen 31/07/20 11:42
None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

Page 20: [69] Formatted Are Olsen 31/07/20 11:42
Right: -0 cm, Tabs: 17.25 cm, Left

Page 20: [70] Formatted Are Olsen 31/07/20 11:42
None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

Page 20: [71] Formatted Are Olsen 31/07/20 11:42
None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

Page 20: [72] Formatted Are Olsen 31/07/20 11:42
Right: -0 cm, Tabs: 17.25 cm, Left
None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

**Page 20: [74] Formatted**  
Are Olsen  
31/07/20 11:42
Right: -0 cm, Tabs: 17.25 cm, Left

**Page 20: [75] Formatted**  
Are Olsen  
31/07/20 11:42
None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

**Page 20: [76] Formatted**  
Are Olsen  
31/07/20 11:42
None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

**Page 20: [77] Formatted**  
Are Olsen  
31/07/20 11:42
Right: -0 cm, Tabs: 17.25 cm, Left

**Page 20: [78] Formatted**  
Are Olsen  
31/07/20 11:42
None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

**Page 20: [79] Formatted**  
Are Olsen  
31/07/20 11:42
Right: -0 cm, Tabs: 17.25 cm, Left

**Page 20: [80] Formatted**  
Are Olsen  
31/07/20 11:42
None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

**Page 20: [81] Formatted**  
Are Olsen  
31/07/20 11:42
None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

**Page 20: [82] Formatted**  
Are Olsen  
31/07/20 11:42
Right: -0 cm, Tabs: 17.25 cm, Left

**Page 20: [83] Formatted**  
Are Olsen  
31/07/20 11:42
None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

**Page 20: [84] Formatted**  
Are Olsen  
31/07/20 11:42
Right: -0 cm, Tabs: 17.25 cm, Left

**Page 20: [85] Formatted**  
Are Olsen  
31/07/20 11:42
None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left
| Page 22: [214] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left |

| Page 22: [215] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| Right: -0 cm, Tabs: 17.25 cm, Left |

| Page 22: [216] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left |

| Page 22: [217] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left |

| Page 22: [218] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| Right: -0 cm, Tabs: 17.25 cm, Left |

| Page 22: [219] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left |

| Page 22: [220] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left |

| Page 22: [221] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| Right: -0 cm, Tabs: 17.25 cm, Left |

| Page 22: [222] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left |

| Page 22: [223] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left |

| Page 22: [224] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| Right: -0 cm, Tabs: 17.25 cm, Left |

| Page 22: [225] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left |

| Page 22: [226] Formatted | Are Olsen | 31/07/20 11:42 |
Summary of the distribution of applied adjustments per variable, in number of adjustments applied for each variable.

| Variable | Adj.< limit | Limit ≤ adj. < 2 x limit | 2 x limit ≤ adj. |
|----------|-------------|--------------------------|-----------------|
| Salinity | 0           | 1                        | 0               |
| Oxygen   | 0           | 5                        | 2               |
|        |   0  |   2  |   4  |
|--------|------|------|------|
| NO3    | 0    | 2    | 4    |
| Si     | 3    | 6    | 4    |
| PO4    | 1    | 4    | 5    |
| TCO2   | 1    | 1    | 0    |
| TAik   | 4    | 4    | 0    |
| pH     | 2    | 6    | 2    |
| CFC-11 | 0    | 0    | 1    |
| CFC-12 | 0    | 1    | 2    |
| CFC-113| 0    | 0    | 0    |
| CCl4   | 0    | 0    | 0    |
Table

| Page 26: [252] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| Font: 10 pt, Not Bold, Font color: Auto |

| Page 26: [253] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| Right: -0 cm, Tabs: 17.25 cm, Left |

| Page 26: [254] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| Font: 9 pt, Font color: Auto |

| Page 26: [255] Deleted | Are Olsen | 31/07/20 11:42 |
|------------------------|-----------|----------------|
| 7.                     |

| Page 26: [255] Deleted | Are Olsen | 31/07/20 11:42 |
|------------------------|-----------|----------------|
| 7.                     |

| Page 26: [256] Formatted Table | Are Olsen | 31/07/20 11:42 |
|------------------------------|-----------|----------------|
| Formatted Table              |

| Page 26: [257] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left |

| Page 26: [258] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| Right: -0 cm, Tabs: 17.25 cm, Left |

| Page 26: [259] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left |

| Page 26: [260] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| Right: -0 cm, Tabs: 17.25 cm, Left |

| Page 26: [261] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left |

| Page 26: [262] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| Right: -0 cm, Tabs: 17.25 cm, Left |

| Page 26: [263] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left |

| Page 26: [264] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| Right: -0 cm, Tabs: 17.25 cm, Left |
Table 8. Improvements resulting from the quality control of Atlantic cruises south of 50°N

|       | unadj | adj |
|-------|-------|-----|
| Sal [x1000] | 3.2 => 3.1 |
| Oxy [%]     | 0.8 => 0.6 |
| NO₃ [%]     | 2.1 => 1.3 |
| Si [%]      | 2.2 => 1.7 |
| PO₄ [%]     | 1.2 => 0.9 |
| TCO₂ µmol/kg| 1.8 => 1.8 |
| TAalk µmol/kg| 2.5 => 1.7 |
| pH [x1000]  | 9.7 => 6.0 |
Right, None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left

Right: -0 cm, Tabs: 17.25 cm, Left

None, Right: -0 cm, Space Before: 0 pt, Don't keep with next, Don't keep lines together, Tabs: 17.25 cm, Left
| Page | Action | Number | Title | Date |
|------|--------|--------|-------|------|
| 27   | Formatted | [278] | Are Olsen | 31/07/20 11:42 |
|      | Font:Italic | | | |
| 27   | Formatted | [279] | Are Olsen | 31/07/20 11:42 |
|      | Font:Italic | | | |
| 27   | Deleted | [280] | Are Olsen | 31/07/20 11:42 |
| | | | | |
| 27   | Moved from page 27 (Move #7) | [281] | Are Olsen | 31/07/20 11:42 |
| | | | | 2006 |
| 27   | Formatted Table | [282] | Are Olsen | 31/07/20 11:42 |
| | | | | Formatted Table |
| 27   | Moved from page 27 (Move #8) | [283] | Are Olsen | 31/07/20 11:42 |
| | | | | 20150525 |
| 27   | Formatted | [284] | Are Olsen | 31/07/20 11:42 |
| | | | | Font:Italic |
| 27   | Moved from page 27 (Move #9) | [285] | Are Olsen | 31/07/20 11:42 |
| | | | | 20100804 |
| 27   | Formatted | [286] | Are Olsen | 31/07/20 11:42 |
| | | | | Font:Italic |
| 27   | Moved from page 27 (Move #10) | [287] | Are Olsen | 31/07/20 11:42 |
| | | | | Indian |
| 27   | Moved from page 27 (Move #11) | [288] | Are Olsen | 31/07/20 11:42 |
| | | | | Investigator |
| 27   | Formatted Table | [289] | Are Olsen | 31/07/20 11:42 |
| | | | | Formatted Table |
| 27   | Moved from page 27 (Move #12) | [290] | Are Olsen | 31/07/20 11:42 |
| | | | | Hudson |
| 27   | Formatted | [291] | Are Olsen | 31/07/20 11:42 |
| | | | | Font:Italic |
| 27   | Moved from page 13 (Move #2) | [292] | Are Olsen | 31/07/20 11:42 |
| | | | | Arctic |
| 27   | Formatted | [293] | Are Olsen | 31/07/20 11:42 |
| | | | | Font color: Black |
| Page 27: [294] Moved from page 27 (Move #13) Are Olsen | 31/07/20 11:42 |
|-------------------------------------------------------|----------------|
| Sarmiento de Gamboa                                    |                |

| Page 27: [295] Formatted Are Olsen | 31/07/20 11:42 |
|------------------------------------|----------------|
| Font: Italic, Font color: Black    |                |

| Page 27: [296] Formatted Table Are Olsen | 31/07/20 11:42 |
|------------------------------------------|----------------|
| Formatted Table                          |                |

| Page 27: [297] Formatted Are Olsen | 31/07/20 11:42 |
|------------------------------------|----------------|
| Font color: Black                  |                |

| Page 27: [298] Deleted Are Olsen | 31/07/20 11:42 |
|---------------------------------|----------------|
| Font: Italic                    |                |
| Font: Italic, Font color: Black |                |

| Page 27: [299] Formatted Are Olsen | 31/07/20 11:42 |
|------------------------------------|----------------|
| Formatted Table                    |                |

| Page 27: [300] Formatted Table Are Olsen | 31/07/20 11:42 |
|------------------------------------------|----------------|
| Formatted Table                          |                |

| Page 27: [301] Formatted Are Olsen | 31/07/20 11:42 |
|------------------------------------|----------------|
| Font: Italic                        |                |

| Page 27: [302] Formatted Are Olsen | 31/07/20 11:42 |
|------------------------------------|----------------|
| Font: Italic, Font color: Black    |                |

| Page 27: [303] Formatted Are Olsen | 31/07/20 11:42 |
|------------------------------------|----------------|
| Font: Italic                        |                |

| Page 27: [304] Formatted Are Olsen | 31/07/20 11:42 |
|------------------------------------|----------------|
| Font: Italic                        |                |

| Page 27: [305] Deleted Are Olsen | 31/07/20 11:42 |
|---------------------------------|----------------|
| 1034 317W20130803 Pacific WCOA2013 20130803 20130829 Fairweather |                |
| 1035 318M20130321 Pacific GOSHIP_P02 20130321 20130501 Melville |                |
| Page 27: [306] Moved to page 28 (Move #26) Are Olsen 31/07/20 11:42 | Pacific |
| --- | --- |
| Page 27: [306] Moved to page 28 (Move #26) Are Olsen 31/07/20 11:42 | Pacific |
| Page 27: [307] Formatted Table Are Olsen 31/07/20 11:42 | Formatted Table |
| Page 27: [308] Formatted Are Olsen 31/07/20 11:42 | Font color: Black |
| Page 27: [309] Formatted Are Olsen 31/07/20 11:42 | Font:Italic |
| Page 27: [310] Deleted Are Olsen 31/07/20 11:42 | ThalassaPourquoi Pas? |
| Page 27: [311] Formatted Table Are Olsen 31/07/20 11:42 | Formatted Table |
| Page 27: [312] Moved from page 27 (Move #16) Are Olsen 31/07/20 11:42 | Thalassa |
| Page 27: [313] Formatted Are Olsen 31/07/20 11:42 | Font:Italic |
| Page 27: [314] Formatted Are Olsen 31/07/20 11:42 | Font color: Black |
| Page 27: [315] Formatted Are Olsen 31/07/20 11:42 | Font:Italic |
| Page 27: [316] Moved from page 28 (Move #18) Are Olsen 31/07/20 11:42 | 20101222 |
| Page 27: [317] Moved from page 28 (Move #19) Are Olsen 31/07/20 11:42 | 20111205 |

| 1036 | 320620140320 | Pacific | P16S_2014 | 20140320 | 20140505 | Nathaniel B. Palmer |
| --- | --- | --- | --- | --- | --- | --- |
| 1037 | 320620151206 | Pacific | OOISO; NBP15_11 | 20151206 | 20160102 | Nathaniel B. Palmer |
| 1038 | 325020131025 | Pacific | TGT303, P21_2013 | 20131025 | 20131220 | Thomas G. Thompson |
| 1039 | 32P020130829 | Pacific | WCOA2013 | 20130821 | 20130829 | Point Sur |
| 1040 | 33HQ20150809 | Arctic | HLY1502, GN01, ARC01 | 20150809 | 20151013 | Healy |
| 1041 | 33RO201308033 | Atlantic | A16_N_Davis Strait 2013, KN213-02 | 2013080320 | 201310012013 | Ronald H. Brown |
| 2022 | 16N20130914 |  |  | 130914 | 1003 |  |

| 1045 | 33RO20161119 | Pacific | RB1606, P18_2016, SOCCOM | 20161119 | 20170203 | Ronald H. Brown |
| 1046 | 33RR20160208 | Indian | I08S_2016 | 20160208 | 20160316 | Roger Revelle |
| 1047 | 35PK201405153 | Atlantic | OVIDE_2014, A01W_2014, | 2014051520 | 201406302008 | ThalassaPourquoi Pas? |
| 2026 | 5TH20080825 |  | A25_2014SUBPOLAR08_0 | 080825 | 0915 |  |
| Page 28: [383] Formatted | Are Olsen | 31/07/20 11:42 |
|--------------------------|-----------|----------------|
| Page 28: [384] Formatted | Are Olsen | 31/07/20 11:42 |
| Page 28: [385] Formatted | Are Olsen | 31/07/20 11:42 |
| Page 29: [386] Formatted | Are Olsen | 31/07/20 11:42 |
| Page 29: [387] Moved from page 27 (Move #6) | Are Olsen | 31/07/20 11:42 |
|                           |           | 20170201       |
| Page 29: [388] Formatted | Are Olsen | 31/07/20 11:42 |
| Page 29: [389] Formatted | Are Olsen | 31/07/20 11:42 |
| Page 29: [390] Formatted | Are Olsen | 31/07/20 11:42 |
| Page 29: [391] Formatted | Are Olsen | 31/07/20 11:42 |
| Page 29: [392] Formatted | Are Olsen | 31/07/20 11:42 |
| Page 29: [393] Formatted | Are Olsen | 31/07/20 11:42 |
| Page 29: [394] Formatted | Are Olsen | 31/07/20 11:42 |
| Page 29: [395] Formatted | Are Olsen | 31/07/20 11:42 |
| Page 29: [396] Deleted  | Are Olsen | 31/07/20 11:42 |
| Page 29: [397] Formatted Table | Are Olsen | 31/07/20 11:42 |

Formatted Table
| Page 29: [398] Deleted | Are Olsen | 31/07/20 11:42 |
|------------------------|-----------|----------------|
| 1107  74D120110606   | Atlantic  | UKOA_D366     | 20110606 | 20110709 | Discovery |
| 1108  74D120120731   | Atlantic  | EEL_2012, D379, AR07E_2012 | 20120731 | 20120817 | Discovery |
| 1109  74EQ20151206   | Atlantic  | A05_2015      | 20151206 | 20160122 | Discovery |
| 1110  74JC199903157   | Atlantic  | JR40, Albatross, A23JC159 | 1999031520 | 199904232018 | James Clark RossCook |
| 2105  40H20180228     | Atlantic  | JR40, Albatross, A23JC159 | 180228 | 0410 |

Page 29: [399] Formatted Table | Are Olsen | 31/07/20 11:42 |

Page 29: [400] Formatted | Are Olsen | 31/07/20 11:42 |
Font color: Black

Page 29: [401] Formatted | Are Olsen | 31/07/20 11:42 |
Font: Italic

Page 29: [402] Moved from page 27 (Move #17) Are Olsen | 31/07/20 11:42 |
Indian

Page 29: [403] Deleted | Are Olsen | 31/07/20 11:42 |
|------------------------|-----------|----------------|
| 1112  74JC20071231   | Atlantic  | JR177         | 20071231 | 20080216 | James Clark Ross |
| 1113  74JC20150110   | Atlantic  | JR306         | 20150110 | 20150122 | James Clark Ross |
| 1114  74JC20151217   | Atlantic  | JR15003       | 20151217 | 20151229 | James Clark Ross |
| 1115  74JC20161110   | Atlantic  | JR16002, SR1B | 20161110 | 20161203 | James Clark Ross |
| 1116  77DN20070812   | Arctic    | LOMROG        | 20070812 | 20070919 | Oden |

Page 29: [404] Formatted | Are Olsen | 31/07/20 11:42 |
Right: -0 cm, Tabs: 17.25 cm, Left

Page 30: [405] Deleted | Are Olsen | 31/07/20 11:42 |

Page 30: [406] Deleted | Are Olsen | 31/07/20 11:42 |

Page 30: [406] Deleted | Are Olsen | 31/07/20 11:42 |

Page 30: [406] Deleted | Are Olsen | 31/07/20 11:42 |

Page 30: [406] Deleted | Are Olsen | 31/07/20 11:42 |

Page 30: [406] Deleted | Are Olsen | 31/07/20 11:42 |

Page 30: [406] Deleted | Are Olsen | 31/07/20 11:42 |
Figure 5.

Locations of stations included in the (a) Arctic, (b) Atlantic, (c) Indian, and (d) Pacific Ocean product files for the whole GLODAPv2.2019 dataset.
