Eos

Clues from the Sea Paint a Picture of Earth's Water Cycle

New instrumentation and growing modeling needs in the Earth sciences are driving a renewed effort to compile and curate seawater oxygen isotope data in a centralized, accessible database.

By **Kristine DeLong**, **Alyssa Atwood**, **Andrea Moore,** and **Sara Sanchez**
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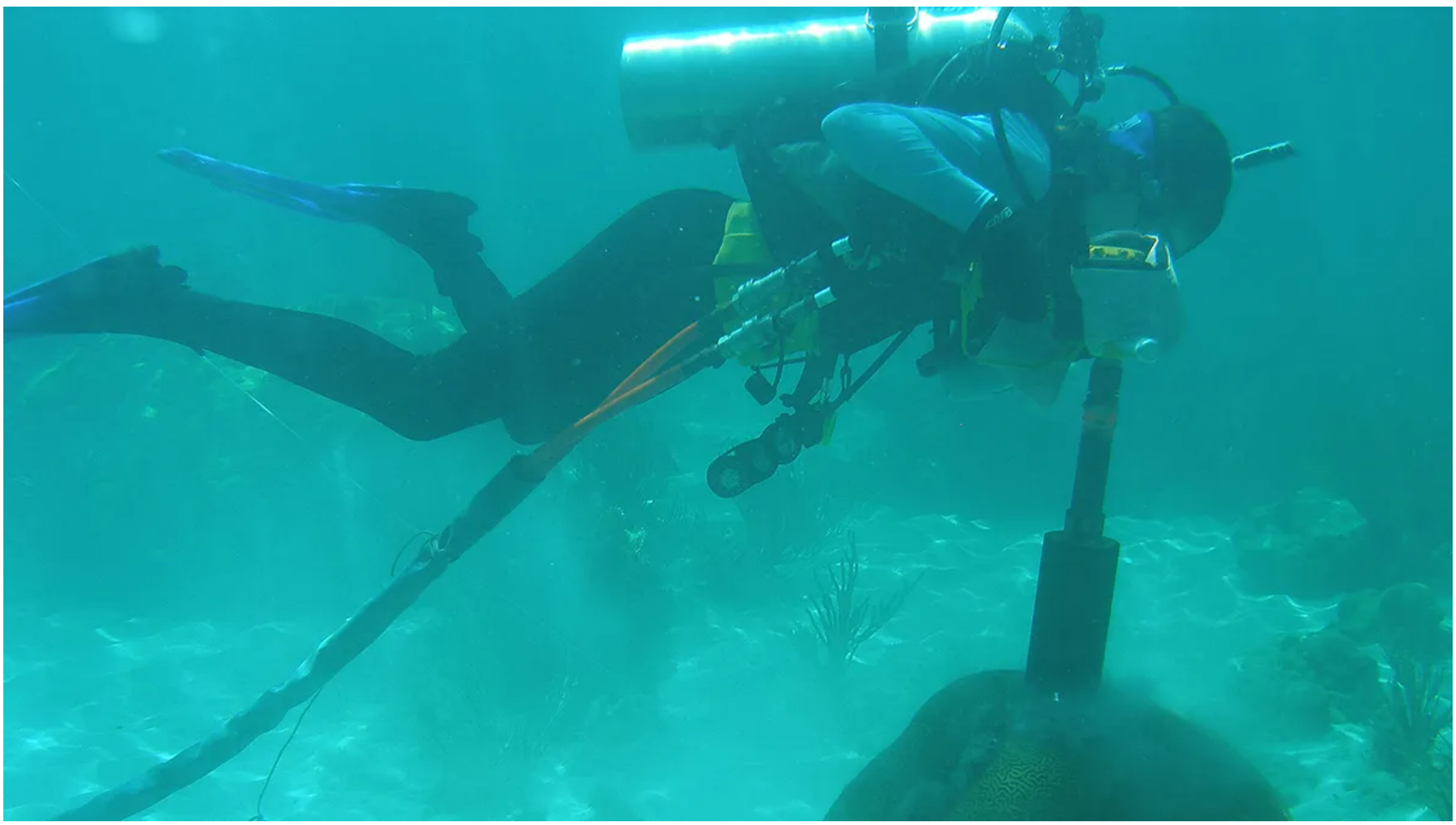

A researcher collects a core from a coral head in Dry Tortugas National Park in the Gulf of Mexico in 2008. Credit: Kristine DeLong

In the global water cycle, water that evaporates from the ocean into the atmosphere is transported as water vapor. Some of this water returns directly to the ocean, while the rest eventually precipitates as rain, snow, or ice on land before much of it is ultimately recycled to the ocean via rivers and other sources. As water changes phase

Science at the Seafloor

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from liquid to vapor, the lighter, more abundant isotope of oxygen (^{16}O) preferentially enters the vapor phase compared with the heavier, less abundant isotope (^{18}O), and the reverse occurs when water vapor condenses to liquid water and ice. This variable partitioning of these stable oxygen isotopes by mass provides a means of tracing water as it moves through the water (hydrologic) cycle—a vital tool in studies of climate, meteorology, oceanography, and more.

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What's Up at the Bottom of the Ocean?

A wide variety of research networks (e.g., the **Global Network of Isotopes in Precipitation**, **Global Network of Isotopes in Rivers**, and **National Ecological Observatory Network**) have measured—and maintain databases of—the oxygen isotope ratios (referred to as $\delta^{18}O$) of water on and above land (namely, in precipitation, rivers, and the atmosphere) to examine the cycling of water between the land and atmosphere. However, no such active observing network exists to document the oxygen isotope ratios of seawater ($\delta^{18}O_{sw}$) needed to understand the cycling of water between the ocean and the atmosphere.

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Measurements of the oxygen isotope ratios of seawater ($\delta^{18}O_{sw}$) provide important information about the modern ocean and its relationship to the water cycle.

Measurements of $\delta^{18}O_{sw}$ provide important information about the modern ocean and its relationship to the **water cycle**. For example, $\delta^{18}O_{sw}$ can inform us about processes related to ocean circulation (upwelling and **advection**), riverine input into the oceans, ocean-atmosphere water exchange through precipitation and evaporation, and continental ice sheet volume on timescales spanning glacial–interglacial periods and longer.

In 2017, the PAGES (Past Global Changes) **CoralHydro2k** project was formed to investigate the variability of temperature and $\delta^{18}O_{sw}$ in the surface ocean during the past 2,000 years. Corals incorporate oxygen from seawater into their calcareous skeletons, thus preserving a record of the environment in which they live, and with the very limited coverage of modern $\delta^{18}O_{sw}$ measurements, corals offer vital information for oxygen isotopic variability in the ocean. The CoralHydro2k investigation combines measurements of $\delta^{18}O$ in corals and of coral strontium-to-calcium ratios (Sr/Ca). Coral Sr/Ca is a seawater temperature proxy, whereas the $\delta^{18}O$ preserved in coral skeletons varies depending on both the water temperature and the $\delta^{18}O_{sw}$ at the time the coral skeleton is formed. Therefore, $\delta^{18}O_{sw}$ can be calculated using the combined measurements of $\delta^{18}O$ and Sr/Ca in corals, given the calibrations for the coral proxies (Sr/Ca and $\delta^{18}O$) to ocean conditions are known, yet verification of these $\delta^{18}O_{sw}$ reconstructions requires

$\delta^{18}O_{sw}$ measurements.

To aid in this effort, we are creating an updated open-access seawater oxygen isotope database of modern $\delta^{18}O_{sw}$ measurements. Here we summarize our crowdsourcing efforts and describe the $\delta^{18}O_{sw}$ database to date.

A Host of Questions Await Isotopic Clues

Measurements of $\delta^{18}O_{sw}$ provide important information about the modern ocean, but they are sparse in space and time. Unlike meteorological observations on land, oceanic observations remained relatively limited and regionally focused until the past few decades. This is because most ocean observations are made by satellite remote sensing or by in situ measurements at coastal and island locations that have the infrastructure to support sustained observations of ocean surface properties.

These ocean observations generally include measurements of salinity; however, they rarely include $\delta^{18}O_{sw}$ because there is no cost-effective, easily deployable instrumentation to measure seawater isotopes in situ. Seawater samples must be taken back to a laboratory for isotopic analysis, and these data are rarely provided publicly in real time as other ocean observations are.

Surface seawater $\delta^{18}O$ covaries with salinity because precipitation and evaporation exert a similar influence on both variables. Lighter isotopes are preferentially evaporated—and heavier isotopes are preferentially precipitated—leaving the ocean isotopically heavier and saltier in regions dominated by evaporation (relative to precipitation) and isotopically lighter and fresher in regions dominated by precipitation. However, the strength of this relationship can vary across time and space, even within individual ocean basins, making salinity an imperfect proxy for $\delta^{18}O_{sw}$ [*Conroy et al.*, 2017]. One reason for this is that $\delta^{18}O_{sw}$ is sensitive to changes in the source and transport pathway of atmospheric water vapor, whereas seawater salinity is not. Thus, measurements of $\delta^{18}O_{sw}$ taken independently of salinity measurements provide additional useful information for models of the ocean-climate system, yielding, for example, more accurate constraints on local moisture budgets and ocean mixing.

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Modern $\delta^{18}O_{sw}$ data are also essential for calibrating proxies of past ocean variability in marine carbonates, **such as corals**, foraminifera, mollusks, ostracods, and coralline algae, that are used in paleoclimate reconstructions. Recent paleoclimate data assimilation efforts such as the **Last Millennium Reanalysis project** [e.g., *Tardif et al.*, 2019] would greatly benefit from a spatial network of $\delta^{18}O_{sw}$ data for training the proxy system models that underlie those efforts. Such reconstruction and assimilation efforts enable scientists to extend climate records back into the preindustrial era, thereby contextualizing anthropogenic climate change and improving the skill of future climate projections.

Additionally, observational $\delta^{18}O_{sw}$ data are needed by climate model researchers running isotope-enabled Earth system models (e.g., NCAR **iCESM**, **iHadCM3**, **ECHAM5-wiso**); these data allow researchers to assess model performance and skill and provide model boundary conditions (in model configurations that include only active atmosphere and land surface). Given these wide-ranging applications, $\delta^{18}O_{sw}$ data are useful to research communities in oceanography, atmospheric science, geology, and geography alike. For these reasons, a comprehensive database of $\delta^{18}O_{sw}$ data that are publicly available and actively maintained is critically needed.

Seawater Isotope Data Enter the FAIR Era

A major effort to gather $\delta^{18}O_{sw}$ data was completed in the 1990s [***Schmidt***, 1999; ***Bigg and Rohling***, 2000], resulting in the NASA Goddard Institute for Space Studies (GISS) **Global Seawater Oxygen-18 Database**, which includes more than 25,500 individual data points. That database was used to construct a global gridded data set of $\delta^{18}O_{sw}$ and to characterize regional relationships between $\delta^{18}O_{sw}$ and salinity [***LeGrande and Schmidt***, 2006]. It has subsequently been used in many studies. However, the support needed to maintain that database has been limited in recent years, and it is no longer being updated—the last $\delta^{18}O_{sw}$ measurements were added more than a decade ago in 2011.

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New isotope analyzers using **cavity ring-down spectroscopy** (an ultrasensitive laser-enabled form of spectroscopy) have reduced analytical costs and rejuvenated the collection and measurement of water $\delta^{18}O$. During the past decade, a growing number of new $\delta^{18}O_{sw}$ data sets, many collected using cavity ring-down spectroscopy, have been published, yet there is no active repository dedicated to archiving these $\delta^{18}O_{sw}$ data. As a result, authors often resort to providing their data in supplemental tables in journal articles or to merging their $\delta^{18}O_{sw}$ measurements with other geochemical data and submitting them to repositories dedicated to those other types of data. Researchers cannot easily find or access these "hidden" data sets, thus limiting their inclusion and usability for further research [***Chamberlain et al.***, 2021]. Other $\delta^{18}O_{sw}$ data sets are publicly available and findable, but they are scattered across a myriad of repositories (e.g., **GISS**, **PANGAEA**, **GEOTRACES**, **Waterisotopes.org**, and **EarthChem**) and thus are not easily collated together for analysis.

CoralHydro2k is building upon previous PAGES 2k efforts, namely, Ocean2k [***Tierney et al.***, 2015] and Iso2k [***Konecky et al.***, 2020], which compiled published coral $\delta^{18}O$ and other data into new machine-readable databases. To aid in the calibration and interpretation of these coral records and in recognition of the value of $\delta^{18}O_{sw}$ data to the broader Earth science community, the CoralHydro2k project is also collecting $\delta^{18}O_{sw}$ data.

We are collating these records in a new, machine-readable, and metadata-rich database consistent with findability, accessibility, interoperability, and reusability (**FAIR**) standards for digital assets. Funding agencies and many publishers are now requiring researchers to archive their data in FAIR-compliant, public repositories, providing yet another reason for the new database, as no such repository exists for seawater oxygen isotopes. Once the first version of the database is made public—slated for spring 2023—it will be accessible (**here**) via the NOAA World Data Service for Paleoclimatology. We are also working with **EarthChem** to set up a **Seawater Oxygen Isotopes Community**, whereby new $\delta^{18}O_{sw}$ data sets can be submitted and each data submission will be assigned a digital object identifier (DOI) so that the researchers who produced the $\delta^{18}O_{sw}$ data can be cited directly when their data are used by other researchers.

Gathering All the Data

As of 1 May 2022, we have collected a total of 77 $\delta^{18}O_{sw}$ data sets and have added 5,664 measurements from 58 of those data sets to our database. Approximately 50% of these measurements are from hidden sources (e.g., journal supplemental tables), 35% are from public repositories (e.g., **PANGAEA**, **Waterisotopes.org**, **EarthChem**), and 15% are currently stored in the NASA Global Seawater Oxygen-18 Database. Nearly all of the measurements (94%) are from the surface ocean (upper 5 meters). We will continue adding to the new database for the coming year and beyond as part of the ongoing CoralHydro2k project, with the goal of including as many $\delta^{18}O_{sw}$ data points as possible from the global ocean. The first phase of the project has prioritized surface ocean data from the tropics; however, the database will ultimately include $\delta^{18}O_{sw}$ data from all depths and regions.

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Our compilation thus far reveals the sparse distribution of surface $\delta^{18}O_{sw}$ observations in both space and time (Figure 1). There are vast ocean regions for which no $\delta^{18}O_{sw}$ measurements are available, including large swaths of the tropical oceans. In places where data exist, there are typically fewer than two measurements. Notable exceptions are Palau and the Galápagos Islands (marked with red circles in Figure 1), where researchers have collected some of the longest $\delta^{18}O_{sw}$ records with weekly sampling maintained for several years [***Conroy et al.***, 2017].

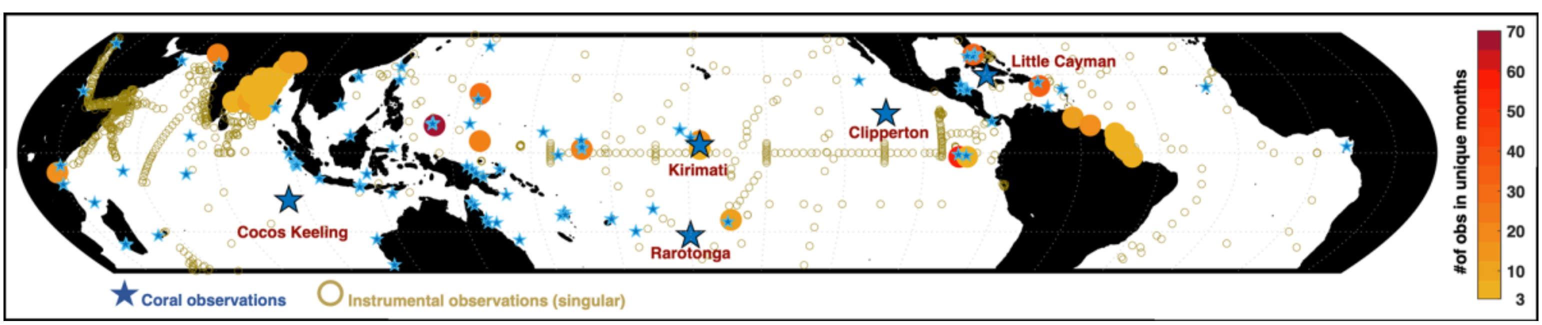

Fig. 1. The locations of all instrumental $\delta^{18}O_{sw}$ in the NASA Global Seawater Oxygen-18 Database and select coral-derived $\delta^{18}O_{sw}$ observations from the CoralHydro2k $\delta^{18}O_{sw}$ Database, binned into 2° × 2° grid boxes, are shown here. Small gold circles indicate grid boxes for which two or fewer distinct months of

$\delta^{18}O_{sw}$ observations are available. Larger solid circles denote locations for which more than two distinct months of observations are available; the color bar corresponds to the number of unique months observed. Blue stars denote the locations where the coral $\delta^{18}O$ records selected for Figure 2 were collected. Click image for larger version.

Comparing $\delta^{18}O_{sw}$ outputs from several isotope-enabled models as well as coral-derived $\delta^{18}O_{sw}$ reconstructions from five coral study sites demonstrates the wide variability of $\delta^{18}O_{sw}$ among the different models and between models and reconstructions (Figure 2). The discrepancies among the models may be due to their structural differences (e.g., in their resolution, subgrid-scale parameterizations, or treatment of atmospheric exchange or ocean mixing processes). To reconcile these discrepancies, more direct measurements of $\delta^{18}O_{sw}$ data are needed to train the models and assess their skill.

Furthermore, at several locations (Little Cayman, Kiritimati, and Rarotonga), the coral-derived $\delta^{18}O_{sw}$ variability exceeds that of nearly all the model estimates (Figure 2). Large variability in coral-based $\delta^{18}O_{sw}$ has also been found relative to an isotope-enabled regional ocean model (isoROMS) [***Stevenson et al.***, 2018]. More $\delta^{18}O_{sw}$ observations are needed to determine whether such model-reconstruction offsets are due to deficiencies in the models, uncertainties in the coral $\delta^{18}O_{sw}$ reconstructions associated with the calculation of $\delta^{18}O_{sw}$ from coral $\delta^{18}O$ and Sr/Ca, or both.

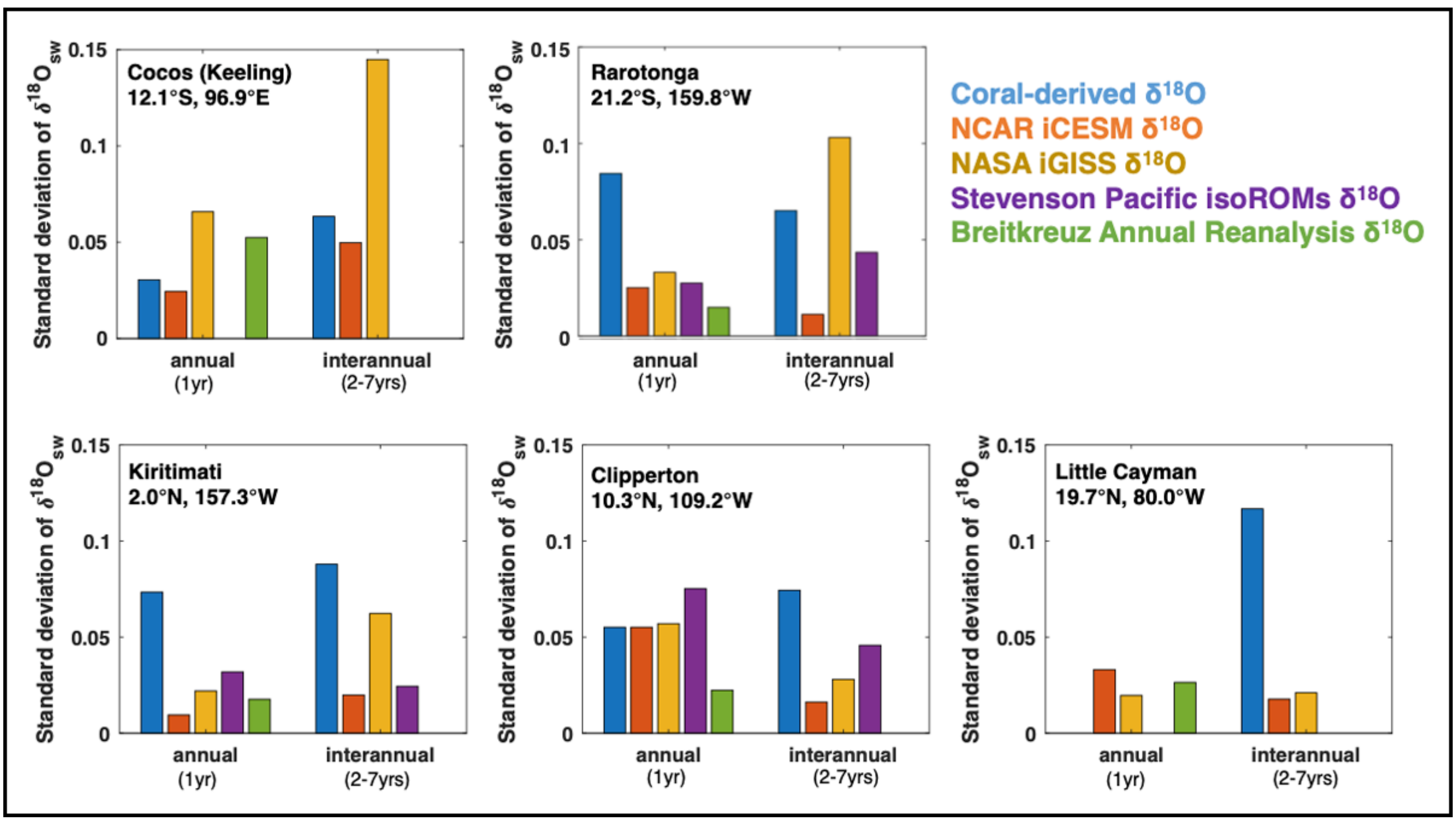

Fig. 2. These plots compare coral-derived $\delta^{18}O_{sw}$ with simulated $\delta^{18}O_{sw}$ from isotope-enabled Earth system models and from a reanalysis product for the five island locations denoted by large blue stars in the map in Figure 1: Cocos (Keeling) in the eastern Indian Ocean, Rarotonga and Kiritimati in the central Pacific Ocean, Clipperton in the eastern Pacific Ocean, and Little Cayman in the Atlantic Ocean. Blue bars show the annual standard deviation of $\delta^{18}O_{sw}$ calculated from the monthly climatology of $\delta^{18}O_{sw}$ at each location in the coral archives. Orange bars show the National Center for Atmospheric Research Community Earth System Model Last Millennium Ensemble (1,000 years) [*Brady et al.*, 2019]. Yellow bars show the NASA Goddard Institute for Space Studies E2-R last millennium simulation (ensemble member E4rhLMgTck; 255 years) [*Colose et al.*, 2016]. Purple bars show the isoROMs Pacific Ocean simulation (44 years)

[*Stevenson et al.*, 2018]. Green bars show the 2018 Breitkreuz reanalysis (monthly climatology constrained by global monthly $\delta^{18}O_{sw}$ data collected from 1950 to 2011 and climatological salinity and temperature data collected from 1951 to 1980 [*Breitkreuz et al.*, 2018a, 2018b]). The interannual standard deviation of $\delta^{18}O_{sw}$ was calculated from the 2- to 7-year bandpass-filtered time series of each data set, except for the Breitkreuz reanalysis data set (for which an interannual standard deviation cannot be calculated from the monthly climatology).

The CoralHydro2k Seawater $\delta^{18}O_{sw}$ Database Project is accepting data submissions as we continue populating the new database. All $\delta^{18}O_{sw}$ observations are welcomed (published and unpublished), regardless of the depth or location where the water samples were collected. We strongly encourage submissions with detailed metadata (analytical precision, standards and instrument used, etc.) as part of our commitment to generating a FAIR-aligned database. Researchers can submit their data to the CoralHydro2k $\delta^{18}O_{sw}$ database via our **Qualtrics survey**, where we also provide a **YouTube video** with instructions on how to submit your data. If you know of $\delta^{18}O_{sw}$ data that should be included in the database, please submit this information along with a DOI or citation via our **Google Form**. Following release of the first version of the database, it will be updated periodically with additional data.

We are confident that this new and growing seawater isotope database will become a vital tool for scientists as they work to paint a clearer picture of Earth's dynamic water cycle and its relationship to the oceans and climate in the past, present, and future.

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