Effects of the Pandemic on Observing the Global Ocean

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Abstract: The years since 2000 have been a golden age in *in situ* ocean observing with the proliferation and organization of autonomous platforms such as surface drogued buoys and subsurface Argo profiling floats augmenting ship-based observations. Global time series of mean sea surface temperature and ocean heat content are routinely calculated based on data from these platforms, enhancing our understanding of the ocean's role in the Earth's climate system. Individual measurements of meteorological, sea surface and

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subsurface variables directly improve our understanding of the Earth System, weather forecasting, and climate projections. They also provide the data necessary for validating and calibrating satellite observations. Maintaining this ocean observing system has been a technological, logistical, and funding challenge. The global COVID-19 pandemic, which took hold in 2020, added strain to the maintenance of the observing system. A survey of the contributing components of the observing system illustrates the impacts of the pandemic from January 2020 through December 2021. The pandemic did not reduce the short-term geographic coverage (days to months) capabilities mainly due to the continuation of autonomous platform observations. In contrast, the pandemic caused critical loss to longer-term (years to decades) observations, greatly impairing the monitoring of such crucial variables as ocean carbon and the state of the deep ocean. So, while the observing system has held under the stress of the pandemic, work must be done to restore the interrupted replenishment of the autonomous components and plan for more resilient methods to support components of the system that rely on cruise-based measurements.

1. Introduction

The Global Ocean Observing System (GOOS; Lindstroem et al. 2012; Moltmann et al., 2019), structured under the Framework for Ocean Observing (FOO; Lindstroem et al. 2012), consists of the requirements, assessment, design, execution, and utilization/dissemination of networks of measurements of relevant essential ocean variables (EOVs). These are a subset of essential climate variables (ECVs; Bojinksi et al., 2014) used to monitor the environmental conditions immediately above the surface of the ocean, at the surface of the ocean, and throughout the water column down to the ocean/bottom interface. The focus of this work is on the execution of the network as realized in the short and long-term monitoring of ECVs. To clearly delineate this focus from the full system defined under the FOO, we will use the term eGOOS (executed GOOS). Further, the focus here will be on ocean measurements of ECVs rather than EOVs to include marine meteorology measurements and to exclude ocean biological measuring systems, which for the most part, have not achieved FOO mature readiness levels.

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The eGOOS is an evolving (and growing) system of complementary observing networks coordinated through the Observation Coordination Group (OCG) of the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO), with monitoring support from joint World Meteorological Organization (WMO) - IOC OceanOPS center (Revelard et al. 2021). Shipboard measurements allow versatile sampling and high-quality measurements, but come at higher cost and with more human and environmental limitations. Independent platforms allow measurement without immediate ship or proximate human assistance, but require regular maintenance and replenishment. There has been a steady increase in measurements in the global ocean since the end of World War II thanks to dedicated resourcing from countries around the globe. This is due to increased awareness of the importance of ocean observation for weather forecasting and increased interest in protecting marine ecosystems, understanding the ocean's role in the climate system, and exploiting the ocean's economic potential. Technological advances in observing platforms and their sensors have also contributed to this increase in ocean measurements. Today there is an unprecedented availability of data for the global, regional, and coastal oceans, as well as improved data analysis techniques, which gives us the capability to make increasingly reliable weather and climate predictions and to better understand the ocean environment and its changes. Given the increasing importance of ocean observations, it is well worth assessing the impact of the COVID-19 pandemic (hereafter simply pandemic) on the eGOOS. Such an assessment will help to plan and prescribe steps needed to restore the eGOOS, to identify weaknesses in the deployment and maintenance of the system, and to mitigate future unforeseen disruptions. It should be noted that satellites are a vital element of the eGOOS, which are not directly affected by the pandemic (except in the context of resourcing, planning, and launching), but satellites depend on *in situ* data for validation and calibration. The focus of this paper is to determine the repercussions of the pandemic on the *in situ* eGOOS. Specifically, we endeavor to follow up and assess further the risks to the eGOOS identified a few months into the pandemic (Heslop et al., 2020) and the remediation efforts which have unfolded through two years of the pandemic (January 2020-December, 2021).

1.1 Marine Meteorology and ocean surface ECVs

Marine Meteorological (surface atmosphere) ECVs (air temperature, water vapor, surface pressure, wind speed and direction) and ocean surface observations (e.g. sea surface temperature - SST, salinity - SSS, surface currents, sea state) in real-time (RT, public availability within one hour of measurement) and near real-time (NRT; public availability mostly within hours to a couple of days of measurement) are essential for accurate global weather and ocean forecasts, and for satellite data calibration/validation, as well as provision of some climate services, e.g. seasonal forecasting and rapid turnaround event attribution. ECV observations are collected from ships, both dedicated research cruises and Voluntary Observing Ships (VOS) commercial vessels (Smith et al., 2019), and independent platforms such as surface drifters and moored ocean buoys, and recently uncrewed surface vehicles (USVs, e.g. Saildrones). [Note that the remaining surface atmosphere ECVs – precipitation and surface radiation budget, and ocean surface ECVs - surface stress, sea ice, ocean surface flux, sea level, which are not routinely observed from moving platforms, are not addressed here.] The WMO Global Telecommunication System (GTS) is the main mechanism by which these measurements are made available in NRT. For long-term use, data are assembled in databases such as the International Comprehensive Ocean Atmosphere Data Set (ICOADS, Freeman et al. 2017, Liu et al. 2021) and Surface Underway Marine Database (SUMD, Mesick et al., 2020). During the 2020-2021 period of the pandemic the GTS functioned as normal with no major negative consequences. As the major distribution mechanism for weather and climate forecast data, the GTS contains redundancies and safeguards to ensure that the data continue to flow despite short or long-term stressors. Marine meteorological and ocean surface data delivery over the GTS in 2019 (Figure 1a), 2020 (Figure 1b), and 2021 (Figure 1c) show, superficially, the changes in the overall eGOOS.

1.2 Ocean Subsurface ECVs

The subsurface eGOOS is vital for understanding our global climate system both in the physical (temperature, salinity) and the chemical (carbon, oxygen, nutrients, transient tracers, nitrous oxide, ocean colour) domains. Subsurface ECVs temperature and salinity are important inputs for weather and climate models in near-real time. The subsurface eGOOS shares some of the same challenges in building and maintenance as the surface eGOOS, with added difficulties unique to measuring ocean variables at up to 6000 m depth. The subsurface eGOOS ECV

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observations available in the World Ocean Database (WOD; Boyer et al., 2018), mainly from NRT sources, anchored by Argo floats (Wong et al. 2020), exhibited changes through the April - June period in 2019 (Figure 1d), 2020 (Figure 1e) and 2021 (Figure 1f). Most subsurface ECV observations other than temperature and salinity, except those from Argo floats, are not available in NRT due to necessary post-measurement processing and quality assurance. Long-term assembly of data for most ECVs is executed by databases such as the WOD for reuse of the data for climate study. While changes to some elements of the eGOOS are discernable from Figure 1, an exploration of the details of both ship based and independent platform measurement performance is necessary to understand the effects of the pandemic on the eGOOS.

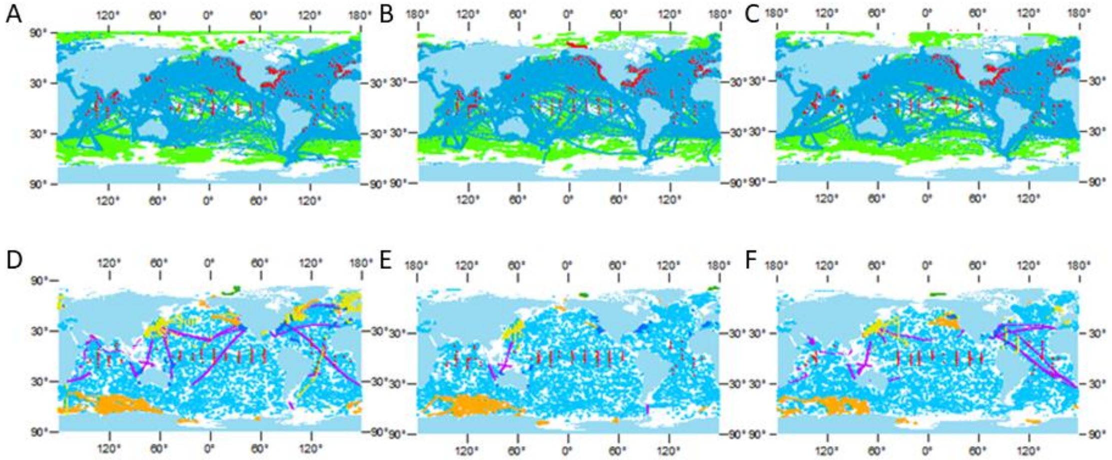

Figure 1. Geographic distribution of marine meteorological and ocean surface observations from ships (blue), moored buoys (red) and drifting buoys (green) for April through June a) 2019, b) 2020, and c) 2021. Subsurface observations (at any depth) from Argo floats (turquoise), Expendable Bathythermographs (purple), ship-based Conductivity-Temperature-Depth (orange), gliders (light blue), tropical moored buoys (red), pinniped mounted sensors (yellow), and ice-tethered profilers (dark green) for April through June: d) in 2019, e) in 2020, and f) in 2021. Note that surface observations from other platforms overlay drifting buoys (green) in a), b), c) while subsurface observations overlay observations from Argo floats (turquoise) in d), e), f). Drifting buoys and Argo floats are well represented, but not visible in all areas outside of marginal seas and high latitudes.

2. Ship-based observations

Historically, ship-based observations have formed the backbone of the eGOOS. Even as technological advances have allowed for the utilization of independent observation platforms, ships are still major contributors to the eGOOS. Cargo and passenger vessels (PVs) contribute NRT marine meteorological, ocean surface, and subsurface measurements of ECVs through the VOS network (Smith et al., 2019). NRT data are utilized in the short-term for weather and climate forecasting and for updating climate data sets. The VOS is the main source of measurements for some marine meteorological variables (e.g. air temperature, relative humidity). The related Ship of Opportunity Programme (SOOP; Goni et al., 2010) focuses on subsurface NRT and ocean (non-weather) focused surface ECVs from volunteer ships. Research vessels (RVs) contribute high quality measurements of ocean and marine meteorological ECVs, indispensable for detection of long-term climate signals both regionally and globally for the deep ocean (below 2000m) and ocean variables for which bottle samples are the most accurate measurements. High quality measurements from RVs are also necessary for maintaining baseline quality standards for NRT measurements and independent platform measurements. RVs extend measurements to geographic regions and ocean depths not readily accessible to other platforms. RVs are the main platform for maintaining long-term climate monitoring for non-NRT subsurface ocean ECVs.

2.1 The VOS network

The number of reporting VOS ships increased steadily from 2016 through the first year of the pandemic to 2021 before declining steadily to the end of 2021 for container/cargo ships as per reports in ICOADS (Figure 2). The pandemic's impact is also shown in the number of ships from the RV and PV fleet (Figure 2) - both decreased significantly in the Spring of 2020. Reporting RVs reached a short-lived minimum (about half of their 2019 numbers) in May 2020, but have rebounded since then due to implementation of safety measure mitigations and the dedication of the research community. Even with that, the RV reports are still about 10% lower than for 2016 - 2019. The number of reporting PVs remained low during the pandemic years (roughly about 60% of its peak in 2019), until a short-lived rebound in mid-2021. The pandemic has led to a steady drop in participating container/cargo ships that were in operation pre-pandemic, but these losses have been partially offset by newly participating VOS ships (Figure 2a, solid vs. dashed lines). Of the marine meteorological measurements, almost all ships are reporting air temperature (AT). SST is reported by roughly 30-70 fewer ships than AT, depending on the year. Water vapor (in the form of relative humidity; RH, not shown) is measured by 30-50 fewer ships than SST, again depending on the year. The curve for the number of ships reporting relative humidity follows the same pattern as SST and AT.

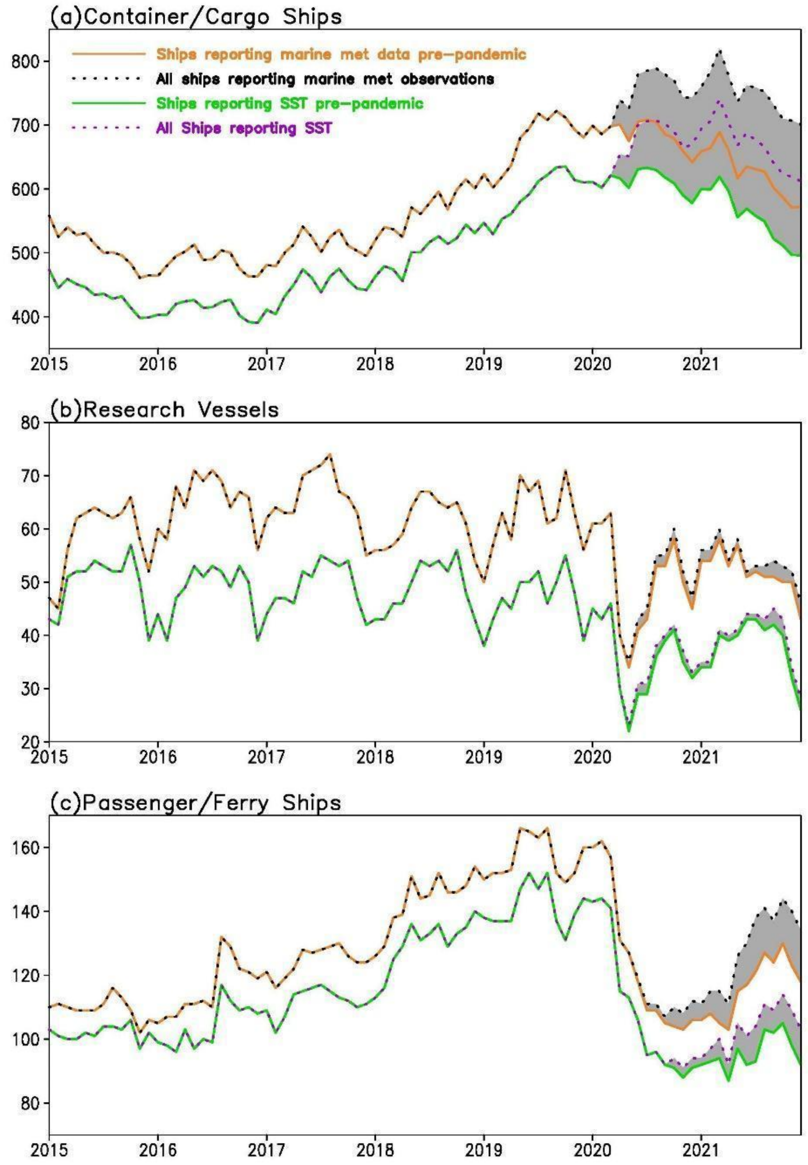

Figure 2. Number of ships with independent WMO call sign numbers since 2015 in the ICOADS R3.0.2 near real-time collection. Top panel (a) is for the container/cargo ships, middle panel (b) for the research vessels/ships, and bottom panel (c) for passenger/ferry ships. The Orange and Black lines are for all ships, compared to the Green and Purple

lines which are for subsets of ships reporting SST measurements. The solid lines are for the number of ships that were reporting data pre-pandemic (defined as March 2020) and have continued since then, while the dashed lines are the total number of ships reporting data during the pandemic.

3.2 SOOP network

The SOOP, closely related to the VOS, also leverages volunteer vessels that routinely transit in strategic shipping routes globally to monitor vital ocean variables, including upper ocean water temperature, using Expendable Bathythermographs (XBT). XBTs were the main component of the subsurface temperature observing system from the 1960s to the advent of the Argo program. They continue to augment Argo by maintaining long time series along particular shipping lines that are chosen because they cross key currents and ocean basins. These XBT surveys are repeated several times a year and at high spatial density, thus providing valuable data to monitor meridional heat transports. The XBT deployment process is largely manual, but increasingly using programmed auto launchers capable of deploying up to 12 XBTs at designated times, and are conducted by the ship crew or by ship riders during a transit. There has been a drop-off in XBT temperature profiles from 2016 to present (Figure 3) due to budget constraints and changes in ship traffic patterns. This trend was accelerated in early 2020 due to the pandemic, recovering somewhat from mid-2020, although not yet approaching pre-pandemic levels by the end of 2021. A continuing problem is the lack of ship-riders due to the logistics of getting to the ship as well as the shipboard infection risk (both for crew and rider). In some cruises, the crew has been taking on ship-rider duties, but usually at a reduced deployment frequency. So, while the number of XBT cruises during the pandemic dropped in 2020 at a steeper rate than the long-term trend, it recovered by the end of 2021 to 2019 levels. However, although the total number of XBTs deployed fell at a much steeper rate in 2020, given fewer deployments per cruise, they were on their way to full recovery to pre-pandemic numbers along many lines by mid-2022. Some long-term lines, notably in the Arabian Sea and the Bay of Bengal, ceased during the pandemic and will be restarted in the near future. SOOP thermosalinograph (TSG) reporting vessels supply high resolution underway SST and SSS measurements, augmenting the VOS NRT

SST (included in Figure 2). The SOOP is integral to surface ocean carbon underway measurements. This is a complex measurement, requiring more processing and quality assurance than temperature or salinity, is available on a limited number of ships, and is consequently more vulnerable to the pandemic.

The Pacific equatorial underway time-series, which has operated via container ships since 1982, has experienced a hiatus of a few years, with travel and access restrictions due to the pandemic prolonging the hiatus**.** Three of the 15 NOAA funded SOOP ships that carry automated surface water CO_2 measurement equipment are cruise ships that have not returned to service as of July 2022, leaving a 1.5 year hiatus. Two other SOOP are cargo vessels that ceased SOOP-CO_2 operations because of restricted boarding for routine maintenance. Some of the 30 % loss of capacity is made up by increased use of RVs and PVs but with changes in geographic coverage.

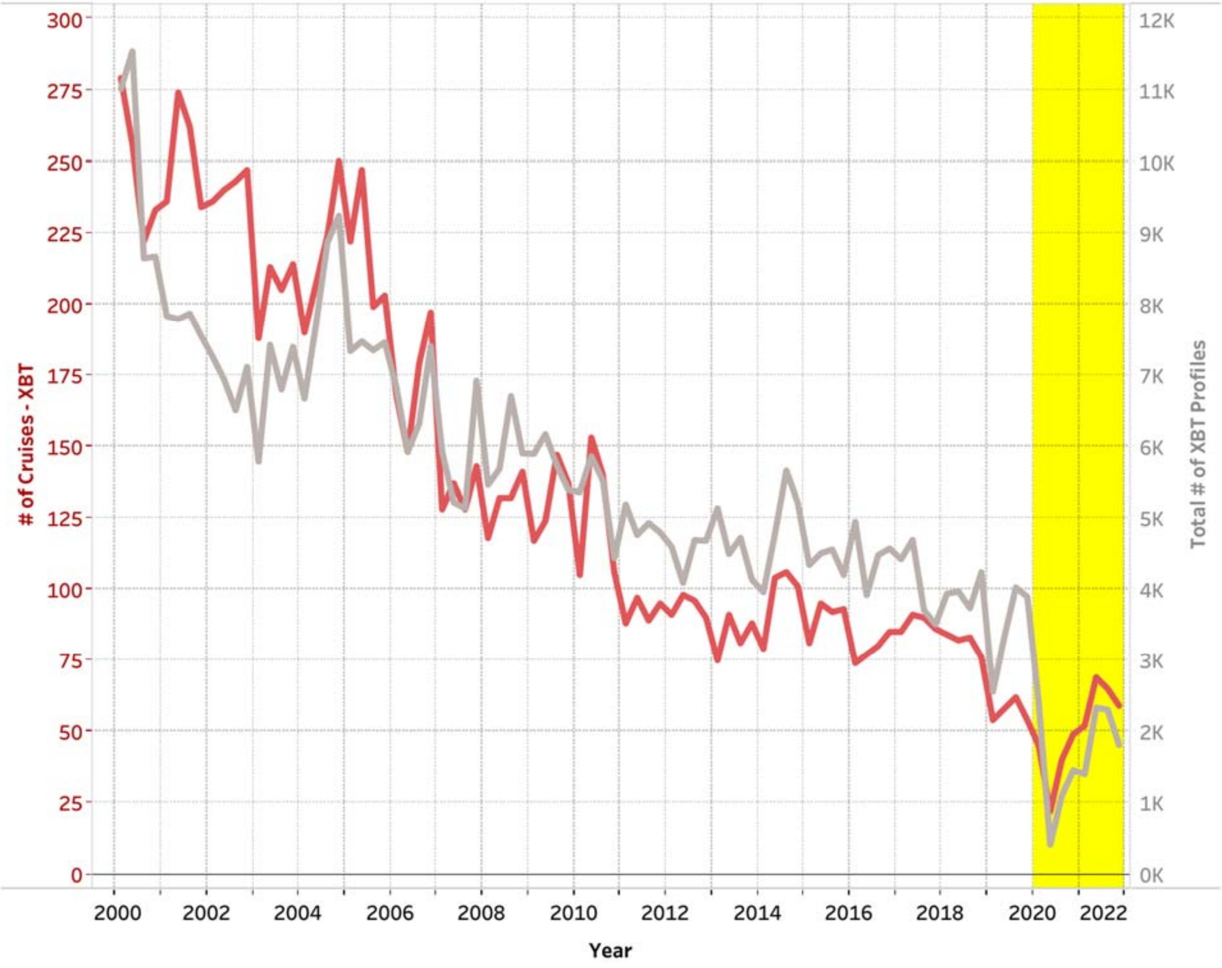

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Figure 3. Expendable Bathythermograph (XBT) cruises 2000- 2021 (red) and total number of XBT profiles (grey) by quarter. Yellow shading for January 1, 2020 – December 31, 2021.

2.3 Research Ships

The Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP; Sloyan et al. 2019) is responsible for coordinating climate quality observations along repeat transects with varying temporal resolution (annual, biennial, decadal, etc.) in the global ocean. During these repeat hydrographic cruises, high (climate) quality referenced measurements of physical, biological, and chemical ocean properties are made from the surface to the ocean's bottom. Additionally, many of these cruises deploy Argo profiling floats, drifting buoys, and are a testbed for new technologies and measurements to probe the ocean. While most measurements are not available in NRT, GO-SHIP cruises are critically important for observing many ocean variables, including carbon, oxygen and nutrient ECVs. Additionally, GO-SHIP cruises help monitor the deep ocean and provide critical information for detecting long-term changes. During 2020, 11 GO-SHIP cruises were scheduled, in which an estimated 1400–1500 oceanographic casts (simultaneous profiles of multiple ECVs) were planned; however, only three of these cruises were completed as planned and contributed roughly 320 casts. Additionally, one US cruise, GO-SHIP line A13.5 was cut short due to the pandemic and made only eight of the planned 128 stations (Figure 4). It was rescheduled for January 2022, but was canceled at the last moment. This resulted in a loss of over three thousand discrete samples in the Eastern South Atlantic, a data-poor region where no high-quality carbon and tracer measurements have been taken since 2010. The rest of the planned GO-SHIP cruises were either postponed by 6-12+ months or canceled. In addition, only 15 of ~80 planned Argo deployments were completed. While some of these cruises may be made up in the future, the knowledge of the state ocean as would have been determined by GO-SHIP for 2020 is irretrievably lost.

While 2020 saw many GO-SHIP cruises outright canceled or delayed due to the pandemic, 2021 cruises experienced their own set of pandemic-related restrictions. While more GO-SHIP cruises were able to set sail in 2021, many of them were restricted in the number of people allowed to partake in the cruise. The reduced number of embarked personnel, coupled with instrument supply chain issues, led to fewer stations being occupied on a given cruise with less information being retrieved from the sea. For example, in some cases physical state variables such as temperature and salinity were observed, but ocean chemistry observations, which are historically much less abundant than physical ocean observations, were unable to be retrieved. In other cases, limited personnel did not allow for full 24 hour rotating shifts, limiting the number of casts able to be taken during a cruise.

In addition to GO-SHIP cruises, research fleets from countries around the world contribute important observations, research, and deployments outside the GO-SHIP repeat transect framework. For example, the U. S. National Oceanographic and Atmospheric Administration (NOAA) currently has 16 active research, survey, and fisheries vessels, which occupy both Atlantic and Pacific waters. The fleet has a wide variety of uses, and many contribute to the global observation system in some manner. Ship days for the fleet went to zero in the April-June quarter of 2020 (Figure 5); however, most vessels returned to at least 66% of their pre-pandemic levels by the end of 2021 and a few have surpassed pre-pandemic levels, bringing the overall NOAA fleet ship days close to 2019 levels. Some national fleets, notably Japan's, continued to go to sea and report temperature and salinity observations in NRT (Figure 1).   Illustrative of the dependence of specific ECVs on RV; among the pandemic canceled RV operations were coastal US cruises supported by NOAA's Ocean Acidification Program, which would have obtained approximately 3000 water samples to study ocean acidification status along the North American Pacific coast. One of the two cruises was successfully completed in summer 2021, but the other has not yet been rescheduled. Coastal ocean acidification cruises along the West Coast of the US, and Gulf of Mexico that occurred in 2021 were also hampered by reduced availability of certified reference materials, travel limitations, and more complicated logistics and quarantine times for participating scientists due to the pandemic.   Pandemic-related supply chain issues have made replacing obsolete and mal-functioning equipment or expanding analytical capacity difficult to impossible. Collectively, these challenges make it difficult to provide partners and stakeholders timely information about ocean carbon and acidification conditions in open ocean, coastal, and estuarine habitats.

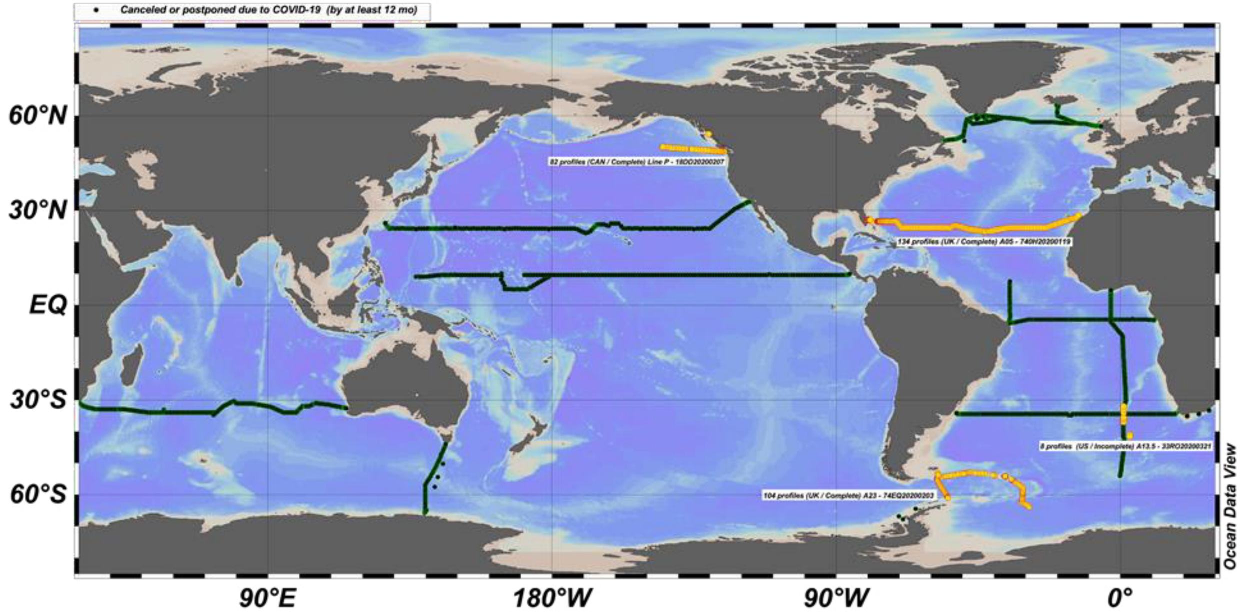

Figure 4. Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP) repeat hydrography cruises planned and/or completed in 2020. Cruises in green were planned, but were subsequently ended prematurely, canceled, or delayed into the future. Orange dots show where profiles were measured in 2020 for completed and partially completed cruises

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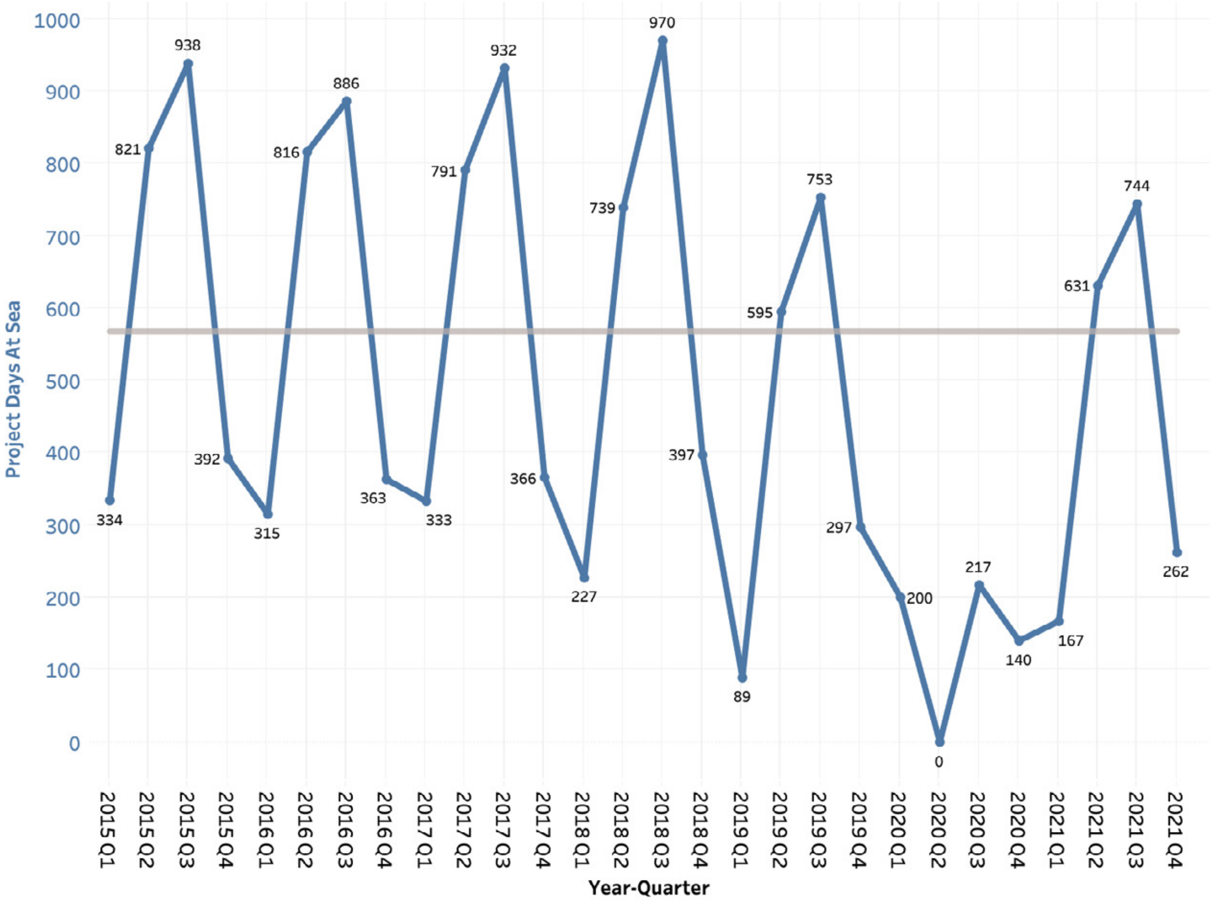


Figure 5. Ship days at sea for the U. S. National Oceanographic and Atmospheric Administration (NOAA) research fleet by quarter, from 2015 through the end of 2021. The blue line represents the total number of project days at sea, with the bold gray indicating the mean quarterly ship days from 2015-2019.

3 Independent platforms

3.1 Surface drifting buoys

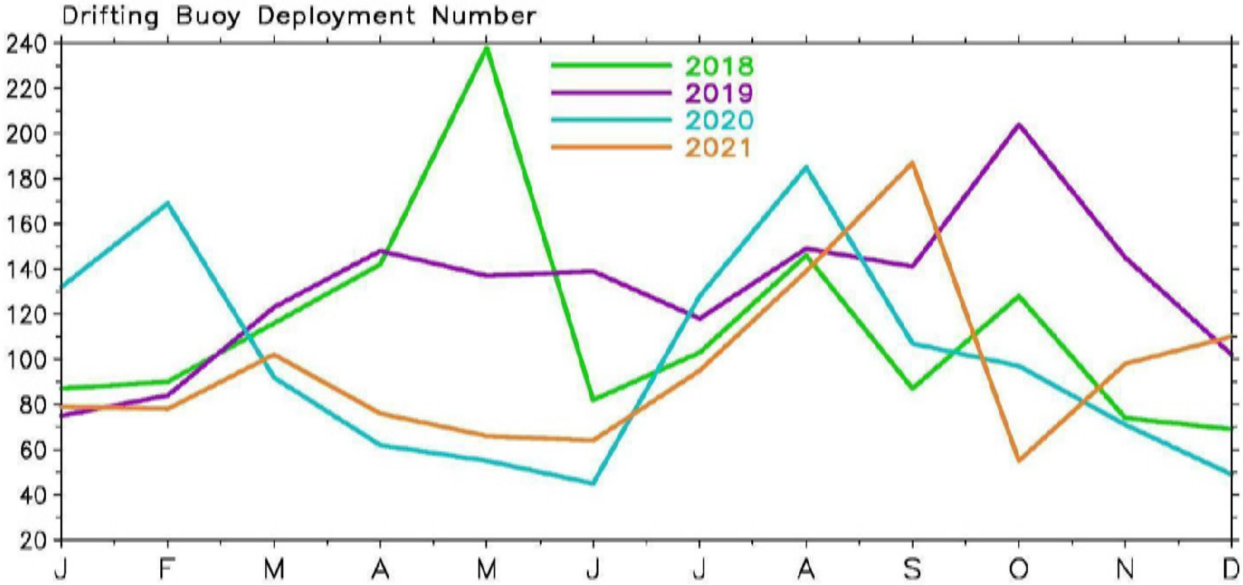


Figure 6. Worldwide monthly surface drifting buoy deployments for years 2018-2021 based on first instance of a buoy found in the International Comprehensive Oceanographic and Atmospheric Data Set (ICOADS R3.0.2; Liu et al. 2021)

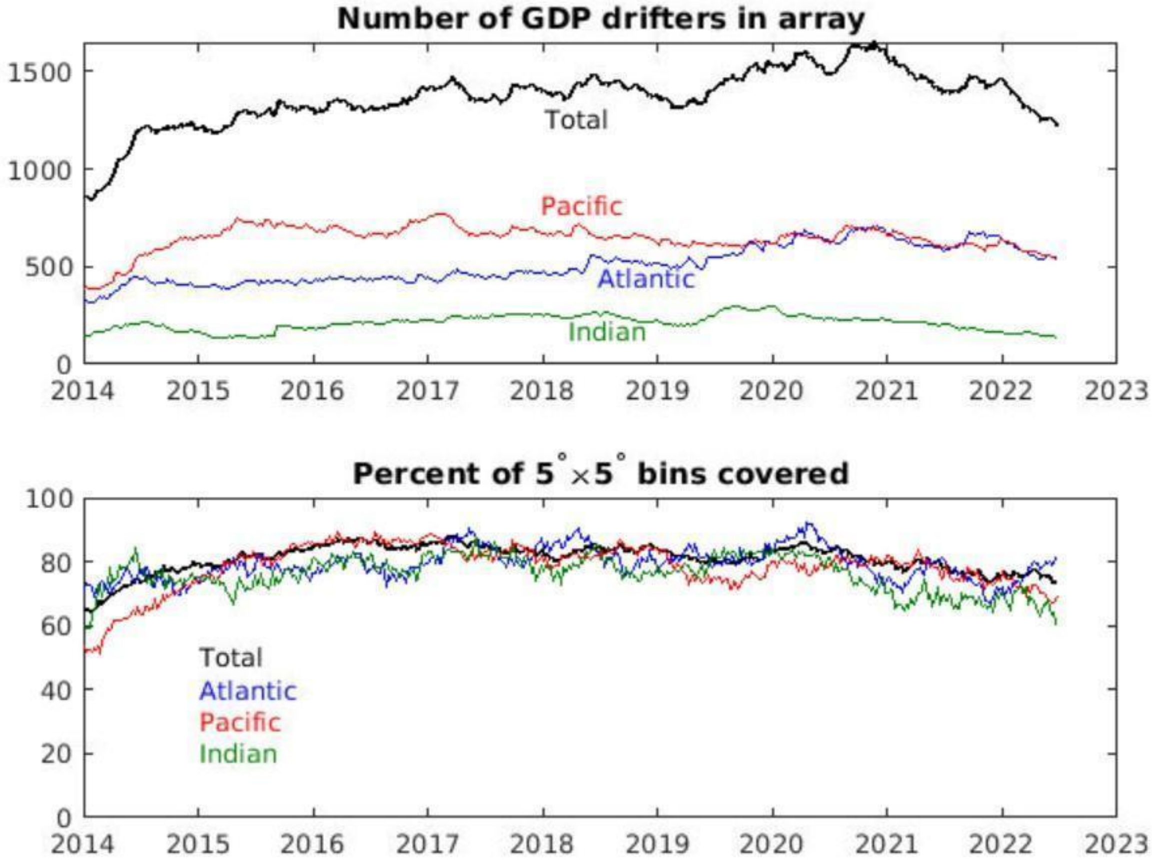


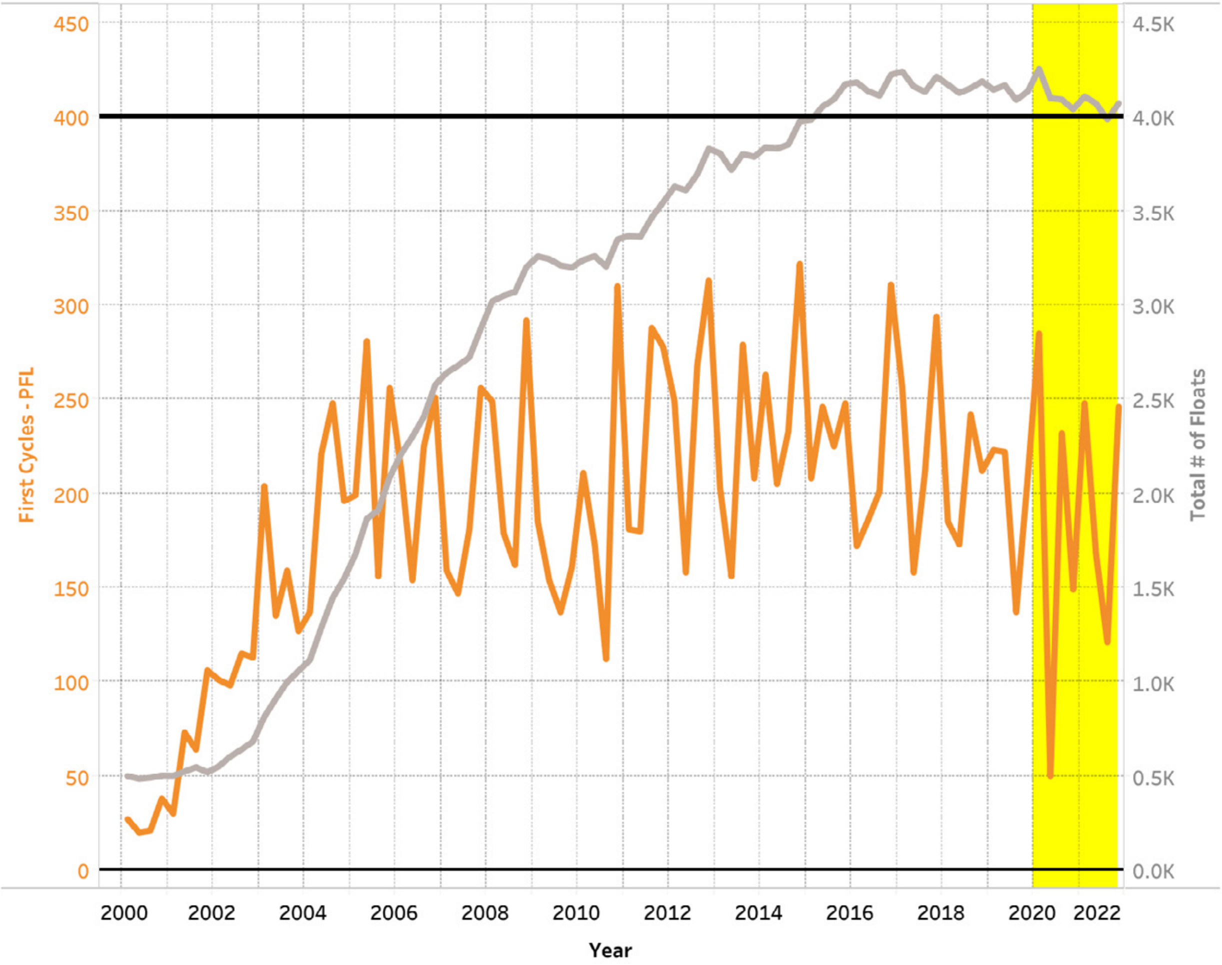
Figure 7. Total active number of surface drifters (top panel) and percentage of ocean spatial coverage in 5x5° lon/lat boxes (bottom panel) maintained by the Global Drifter Program (GDP; https://www.aoml.noaa.gov/phod/gdp/; Lumpkin et al., 2016) based on GOOS criteria for SST and ocean surface current monitoring.

Surface drifting buoys make essential observations of SST, atmospheric (surface) pressure and near-surface ocean currents (calculated from trajectories). All surface drifters measure SST. Drogued buoys, about 50% of all drifters, measure near-surface currents. 50% of surface drifters measure atmospheric pressure. Drifting buoys are deployed globally from RVs, commercial vessels and air drops. Drogued buoys move with the nominal 15 m depth ocean currents. Surface drifters send measurements to communication satellites at approximately hourly time intervals, which are then transmitted to global data collection centers on shore. Drifting buoys have become the main source of spatial and temporal coverage for the *in-situ* surface eGOOS, but have a more limited range of measurements than ships. Surface drifting buoys have an expected lifetime of about 18 months.

Figure 6 shows when the surface drifting buoys in ICOADS (Liu et al., 2021) reported data for the first time after deployment into the ocean. There are seasonal and interannual variations normally. At the pandemic onset in March 2020, the number of new drifter deployments significantly decreased, until early June when special actions were taken to address the decline (Figure 6). Over the course of the pandemic, the Global Drifter Program (GDP; Lumpkin et al., 2016) shifted many deployments from research cruises, which were being delayed or canceled in 2020, to merchant vessels. The difficulty with merchant ship deployments is that these are mainly along major shipping routes, with many important ocean areas left unvisited and consequently in danger of reduction of data coverage. Note that before the pandemic, the GDP had a large number of deployments through the second half of 2019. These deployments, coupled with a doubling of buoy half-life since 2016, resulted in an array maintained in size through 2020. However, many of the 2019 deployments were in dense clusters that did not sustain global spatial coverage. Both float array size and spatial coverage (Figure 7, upper and lower, respectively) have been decreasing in 2021, with notable gaps in the Indian Ocean and the South Atlantic.

3.2 Argo profiling floats

a)



b)

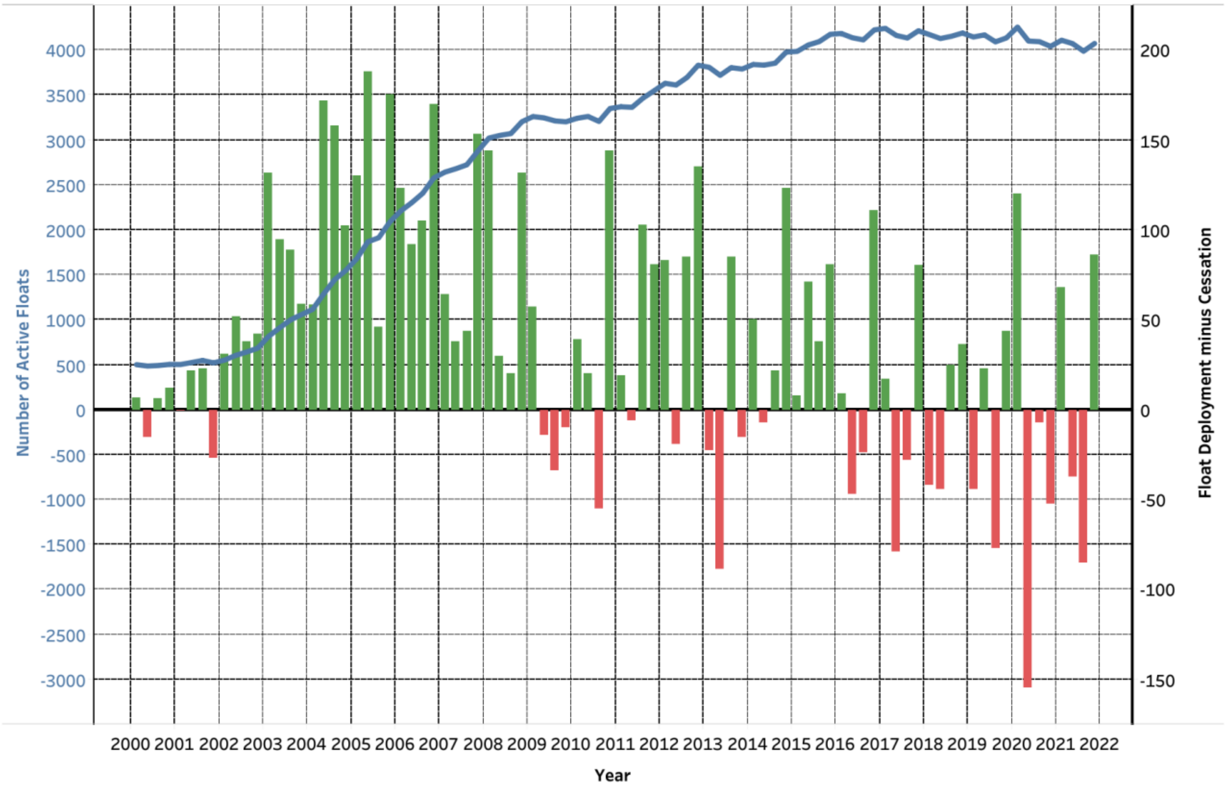


Figure 8. a) Argo float first cycles, 2000-2021 (orange). A first cycle is the first transmitted pressure-temperature-salinity profile set, signifying a newly deployed and actively reporting float. Total reporting Argo floats 2000-2021 (gray). The time period January 1, 2020 – December 31, 2021 shaded yellow. The black line denotes the 4000 reporting floats level. b) Newly deployed minus stopped reporting floats by quarter. Green denotes quarters with more deployments than cessation, red denotes more float cessation than floats deployed.

Argo floats are the backbone of the contemporary subsurface eGOOS, and in many areas and depths, the only observing platform. Furthermore, Argo contributes to the surface eGOOS through the near-surface portion of its sampling scheme. Argo comprises around 4,000 active floats globally, drifting for 10 days at depth, then measuring core variables of pressure/temperature/salinity from 2000 m to the surface. Deep Argo floats take measurements from as deep as 6000 m. Biogeochemical Argo (BGC Argo) floats additionally measure dissolved oxygen, nitrate, pH, chlorophyll fluorescence, and bio-optics. 'First cycles' (Figure 8a) are the first received profiles from a particular float, designating a successful deployment. Floats are deployed mainly from RVs, with some from SOOP merchant ships. The total number of active floats (Figure 8a) dropped slightly over the pandemic as float cessations outnumbered float deployments in all but the first and fourth quarters of 2021 (Figure 8b). A lack of deployment due to pandemic restrictions and rising costs per float may start to create holes in the global coverage of Argo as older floats die and/or disperse out of particular ocean areas. April-June 2020 marked the lowest number of first cycles since the first years of the Argo program. It is important to note that deployments have been trending downward since 2015 due to increased cost per float, and deployments are highly variable by quarter, but the 50 deployments in April-June of 2020 mark a clear low. Extensive work by the Argo community to find deployment opportunities since then has resulted in 230, 139, 237, and 145 first cycles in the third and fourth quarter of 2020 and first and second quarters of 2021. Significant effort was needed to find ships from which to deploy floats during the pandemic, especially in areas such as the South Pacific Ocean which had sparse cruise traffic. Despite these efforts, the total number of active/reporting Argo floats dropped below 4,000 in the fourth quarter of 2020 for the first time since 2015. It is hoped that the excess of deployments over float cessations in the fourth quarter of 2021 marks a return to stable float replenishment.

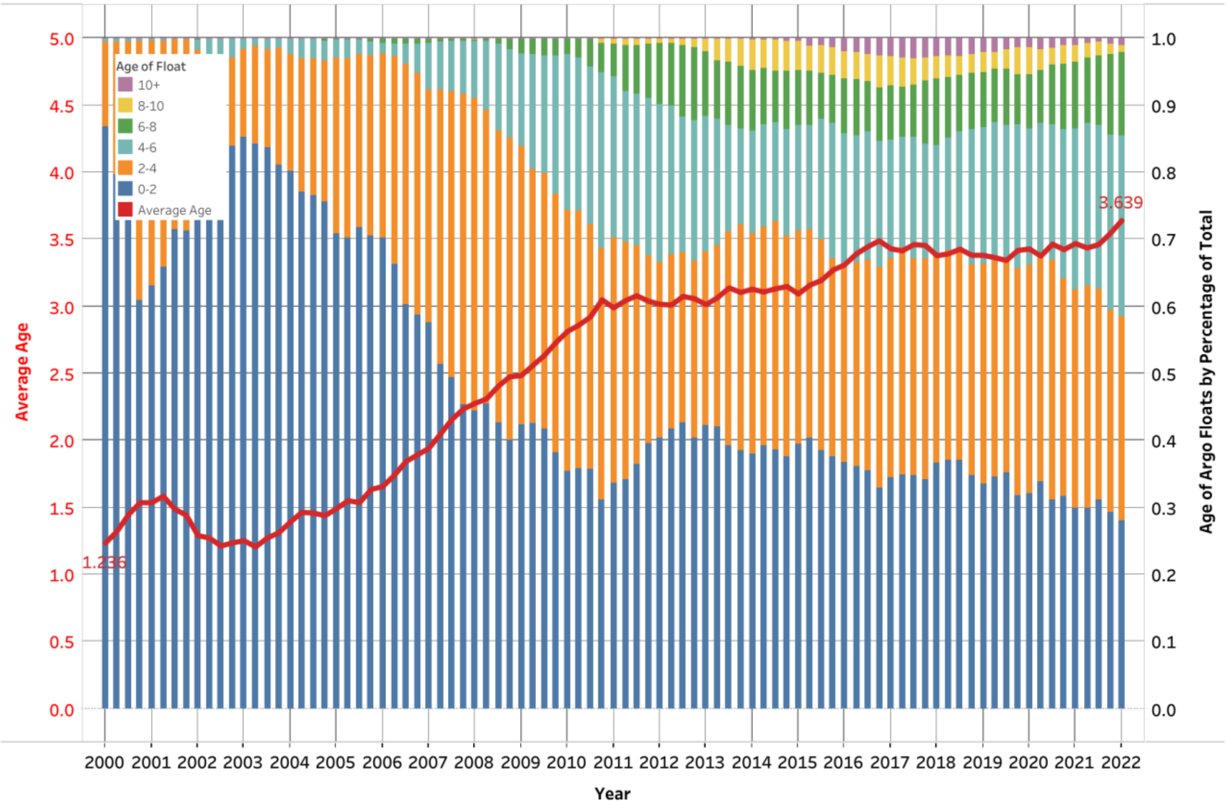


Figure 9. Average age of the Argo fleet (red line) and percent of floats in each age distribution (bars) 2000-2021.

A consideration for Argo floats is that while the number of floats has remained relatively steady through the pandemic due in part to long battery life (Figure 9), instrument performance can deteriorate over time. Therefore, while Argo floats can operate over many years, continual quality assessment of the data is imperative. This is an important issue for Argo salinity, as float measurements are known to be affected by sensor drifts as a result of physical changes in the conductivity cells through time. Historically, when floats approach the age of about 6 years, about 30% of them will require a salinity adjustment of about 0.01 (unitless; Wong et al., 2020). On the other hand, temperature data are known to remain stable through time.

3.3 Moored buoys

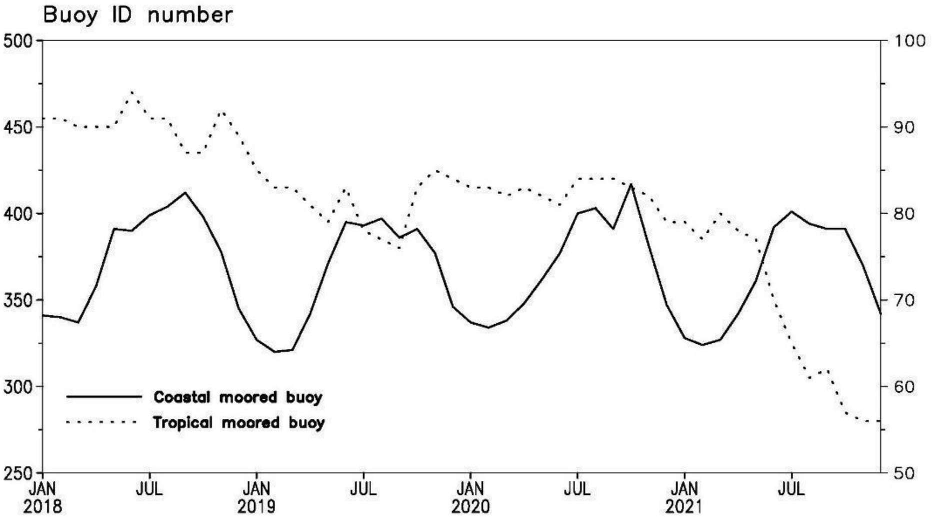


Figure 10. Number of moored buoys in the ICOADS R3.0.2 (Liu et al. 2021) near real-time collection: solid line and left y-axis are for the coastal buoys, and dashed and right y-axis are for the tropical buoys.

Moored buoys are platforms that are anchored to the seafloor at specific geographic locations. Moored buoys typically report marine meteorological readings, surface oceanographic measurements, and in some cases subsurface oceanographic measurements, often at high temporal frequency. Most moored buoys are near-coastal, with the significant exception of the tropical moored buoy arrays, which span the tropical ocean basins. Coastal moored buoys provide data on local conditions while the tropical arrays provide information on tropical phenomena which affect global weather and climate patterns, such as El Nino.

The coastal moored buoy NRT data returns show no discernable drop during the pandemic period in 2020 - 2021 relative to the non-pandemic period in 2018 - 2019 (Figure 10). Coastal moored buoy NRT data have a seasonal pattern, with higher observation counts during the northern hemisphere summer. Non-NRT ECV monitoring from coastal buoys, as with underway data, relies on a smaller highly maintained network. Due to postponements of servicing cruises, NOAA’s Ocean Acidification Observing Network of surface buoys suffered a reduction in data return of 13% compared to pre-pandemic values as sensors failed due to lack of maintenance.

Moored buoys require ship maintenance on site through recovery and re-deployment at regular service cycles. The pandemic has created significant challenges for maintaining open ocean moored buoys. OceanSITES is the collective for research quality deep ocean monitoring sites, most of which include instrumented moored buoy time series of ECVs. The tropical moored buoy arrays are a subset of OceanSITES buoys. Mooring losses in tropical moored buoy arrays, which were already in decline, in 2021 have far exceeded any previous year's losses. In the tropical Pacific, the TAO array (Chen et al., 2018) did have regularly scheduled maintenance. All moorings in RAMA (McPhaden et al., 2009) in the tropical Indian Ocean have been deployed well beyond their 1-year design life. Mooring cruise operations in PIRATA (Bourlès et al., 2019) in the tropical Atlantic have partially resumed, and most of PIRATA has been serviced in 2020-2021 to improve data return rates. However, travel restrictions and cruise cancellations remain a problem for accessing and servicing moorings in RAMA. Figure 10 (dashed line) indicates a dramatic drop of reporting tropical moored buoys, due to extended periods (>2 years) of inability to schedule cruises in the Indian Ocean. Many of the moorings have stopped transmitting due to power loss (design life is 1 year), or have broken free of their anchored positions after wear and tear from extended periods at sea or potential vandalism incidents. However, the first pandemic period RAMA maintenance cruise in over 2 years aboard the Korean ship R/V Isabu in January 2022 has helped to mitigate the declines. Planning for additional cruises in the Indian Ocean is underway. In addition to the impacts of mooring losses, ongoing impacts related to the pandemic also include increasing problems with equipment shipping delays and the emergence of high inflation, which places additional pressures on budgets that do not grow to keep up with inflation. The long-term impacts from data losses in the Indian Ocean array is difficult to quantify since many of the data impacts are only now being realized. However, RAMA data are used extensively to provide accurate weather and monsoon forecasts over south Asia, to improve understanding and impacts of the Madden-Julian Oscillation (MJO), to provide initial conditions for operational global coupled forecasting systems, to provide verification of ocean-atmosphere flux products in the Indian Ocean, among other applications. Documented impacts to each of these applications have been observed by various forecasting centers around the world. An example of pandemic difficulties on a deep ocean mooring is provided by the Stratus Ocean Reference Station at 20° S, 85° deg W under the stratus clouds west of northern Chile. The 2021 cruise was ready to go with personnel already in

Chile, then canceled the day before sailing. Quarantine costs and quadrupled cost of shipping to the pandemic added expenses to the cruise. Time between maintenance allowed for fouling of conductivity cells and consequent low quality upper ocean salinity measurements. Similarly, gooseneck barnacles on sensor heads and propellers affected current velocity measurements. Battery lifetime of 12-14 months was exceeded before maintenance cruise arrival causing loss of data.

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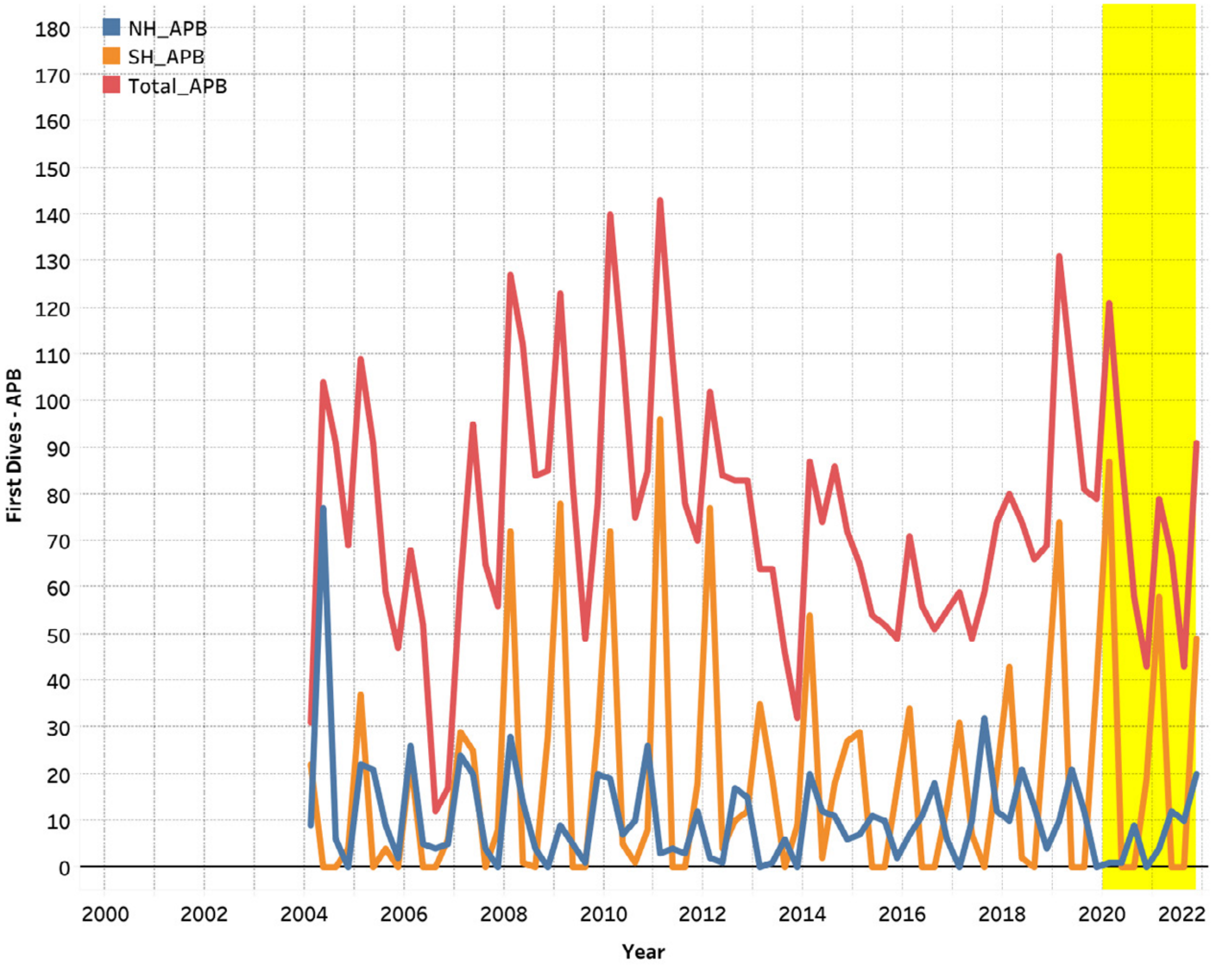

Figure 11. Individual instrumented pinnipeds by quarter 2004-2021 in the northern hemisphere (blue) and the southern hemisphere (orange). Total number of actively reporting instrumented pinnipeds by quarter (red). Yellow shading for January 1, 2020 – December 31, 2021.

3.5 Animal borne ocean sensors (AnIBOS)

Instrumented animals, in particular pinnipeds, are a growing constituent of subsurface temperature observations in the upper ocean (< 1500m) and higher latitudes (75°S - 50°S & > 70°N), augmenting other observing platforms, and in some areas (e.g. Ross Sea), providing some of the only consistent measurements (McMahon et al. 2021). Instrument life mounted on marine animals is limited to one year (McMahon et al. 2021). Since 2015, the number of deployments has remained fairly consistent at approximately 103 instruments total *per annum.* Typically, the instruments are deployed during the hemispheric summers. The 2019-2020 summer

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deployments in the southern hemisphere were completed before the onset of the pandemic (Figure 11). In contrast, in the northern summer 2020 (May - August), i.e. during the height of the first wave of the pandemic, only six pinnipeds were instrumented in the northern hemisphere, well short of previous deployments between 2017-2019. Plans for the 2020-2021 southern hemisphere summer deployments were scaled back to 35 on Kerguelen Island and 25 in the Ross Sea. The total number of active instruments rose after the southern summer 2020-2021 deployments to 79 total reporting pinnipeds globally in the first quarter of 2021. Both northern and southern hemisphere reporting instrumented pinnipeds increased through the end of 2021, though the southern hemisphere instrumenting season was just beginning at the end of the year.

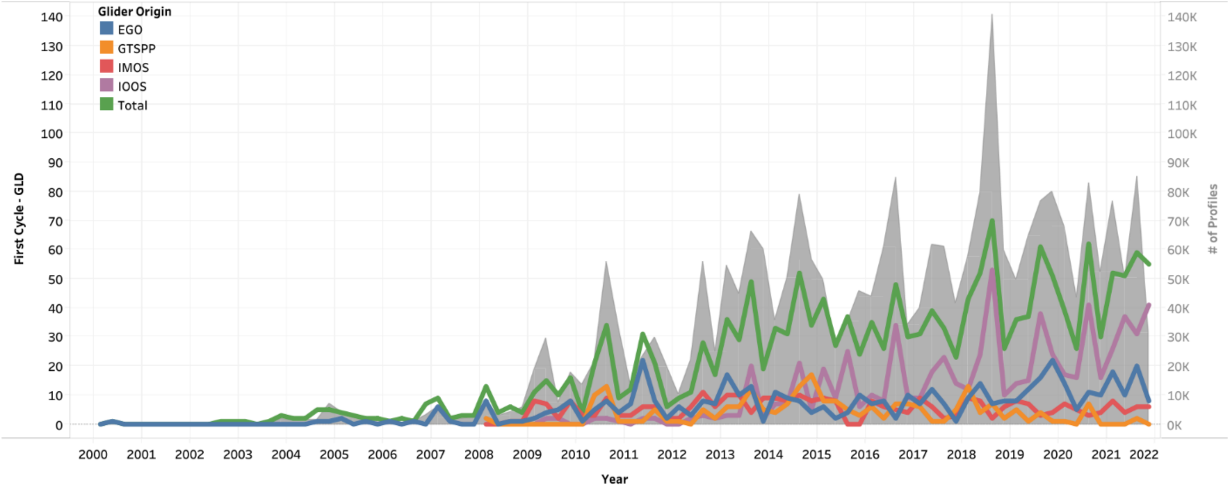
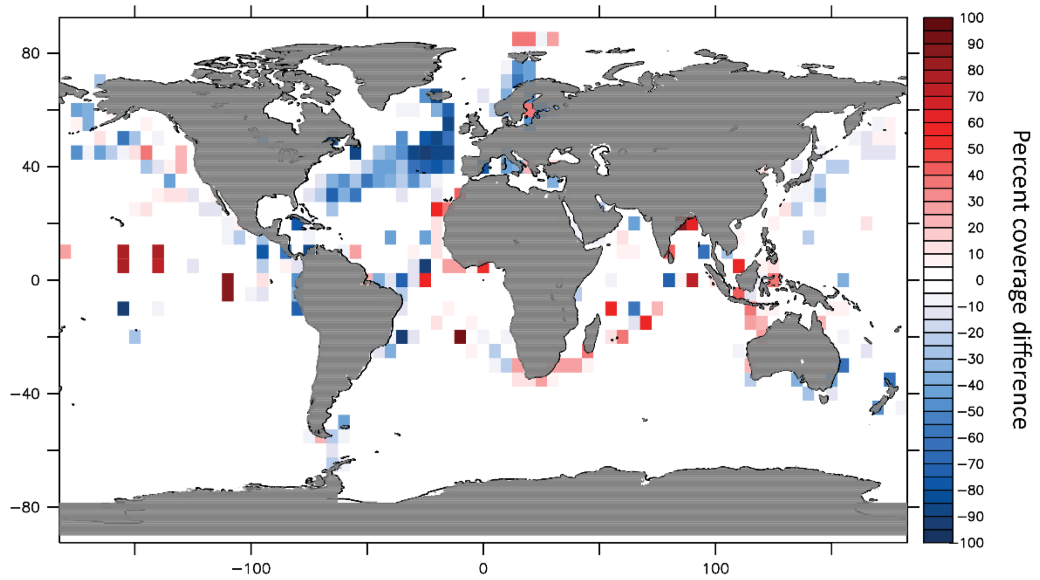


Figure 12. Glider missions 2000-2021 by season as reflected in the three main glider data assembly centers (Everyone's Gliding Observatories, EGO - blue; Australia's Integrated Marine Observing System, IMOS - red; NOAA Integrated Ocean Observing System Glider Data Assembly Center, IOOS, purple) and posted to the Global Telecommunications System (GTS) found in the Global Temperature and Salinity Profile Program (GTSPP, orange). Total number of glider missions in green, total glider cycles in gray shading.

3.4 Uncrewed Systems (UxS)

Gliders are uncrewed buoyancy driven vehicles which are usually deployed for high density limited duration surveys of ocean variables in areas on shelves or near coasts. Glider movements can be guided remotely to some extent from shipboard or land. Glider observations extend the ocean observing system into areas not usually covered by Argo floats and are instrumental in maintaining near coastal time series. The pandemic strongly impacted glider deployment pace with no authorization of deployment at its early stage (April to June 2020). To balance that and to maintain the glider array at an acceptable level, the duration of the missions operational at the time were extended leading to a quasi-normal cumulated number of glider days at sea during this period (Figure 12). Thanks to its capacity to deploy close to the shore from small boats, the deployment pace returned to normal in August 2020. The most prejudicial impact was on long term time series that now have observational gaps. Difficulties in deployment of gliders caused by the pandemic have had an effect on the continuity of the observing network. One example, in the absence of the usual research vessel deployment for the glider line off Trinidad Head, California, a charter vessel was used. This same charter vessel accidentally ran over the glider, resulting in loss of the glider and an irreplaceable gap in the time series of measurements along the line. Uncrewed Surface vehicles (USV) are relatively new platforms, without sufficient history to assess the effects of the pandemic through data receipt. There were, however, tangible effects of the pandemic on USV deployment. Several international USV air-sea CO_2 missions in 2020 and 2021 were postponed as lab facilities were closed and travel restrictions were implemented.

a)



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b)

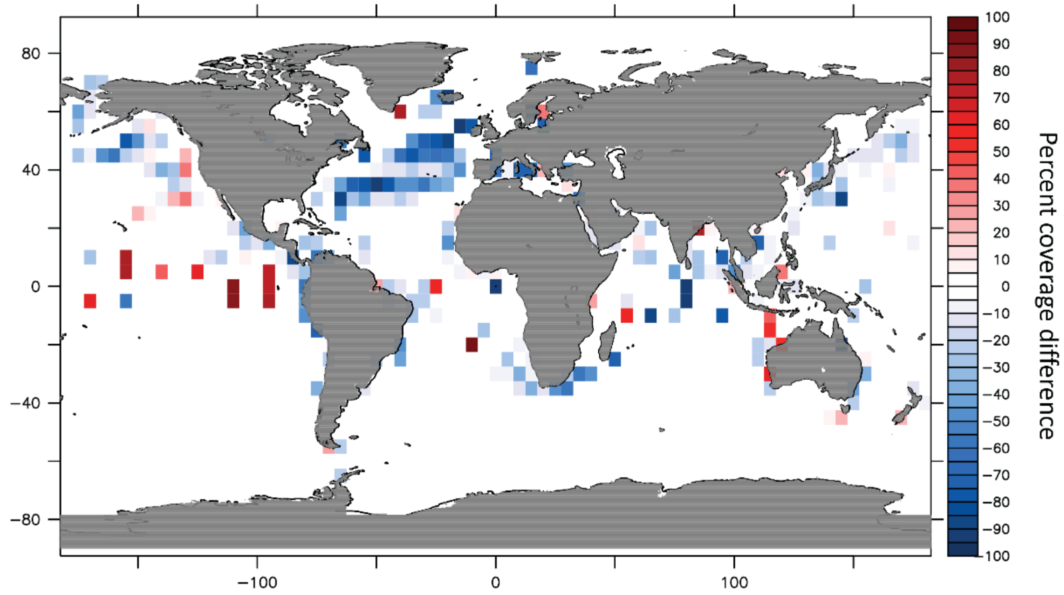

Figure 13. Difference in percentage of weeks, between a) April-June 2020 and April-June, 2019 where there were 25 or more weekly Air Temperature observations from the GTS in a 5x5° lon/lat grid. b) Difference between April-June 2021 and April-June 2019. Blue shading in grid boxes where there were fewer weeks with defined coverage in the later time period, red shading more weeks with defined coverage in the later time period.

4. Effects of the pandemic on global ECV monitoring

The goal of the eGOOS is monitoring and understanding global weather and climate by providing marine meteorological and ocean observations of specific ECVs. The effects of data loss at specific locations and regionally results in the interruption of high quality time series and geographic coverage. On a global scale, the effects of the pandemic can be quantified, or at least defined through specific ECV product sustainment.

4.1 Effects on weather and ocean forecast models

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NRT observations, both marine meteorological as well as SST, SSS, and subsurface temperature and salinity are essential inputs for ocean and atmosphere data assimilation and their loss has direct consequences for real-time monitoring and forecasts (e.g. Vidard et al, 2007; Fujii et al., 2015; and Chen 2020). Ocean state estimation relies heavily on satellite and in situ observations and is used for forecast initialization, validation, and verification. The most immediate impact resulting from the reduction of NRT and RT in situ observations is the constraint they provide during the data assimilation for adjusting drift in the analysis provided by the model. The reduction of available in situ observations certainly impacted the accuracy of the synoptic and seasonal predictions of the ocean and weather state, however the scope of this impact is hard to quantify. Another impact of the reduced observations is their longer term influence on future analyses efforts with advanced data assimilation systems (the so called reanalyses) that are essential for our improved understanding of ocean climate variability and predictability. Effects of the pandemic on eGOOS data flowing through the GTS, and hence on weather and climate models are reflected in changes to the regional volume of marine meteorological data reported (Figure 12), represented most notably by a drop in air temperature reports in the North Atlantic in both 2020 and 2021 and additional data gaps in the South Atlantic and Indian in 2021. Given the relative coverage in the basins, the data loss in the South Atlantic and Indian Oceans may be more critical than the persistent data reduction in the North Atlantic. Ocean observing simulation experiments (Xue et al. 2017; Zhu et al. 2021) in future are needed to quantify the influence in the loss of in situ observations during the pandemic.

4.1 Effects on SST time series

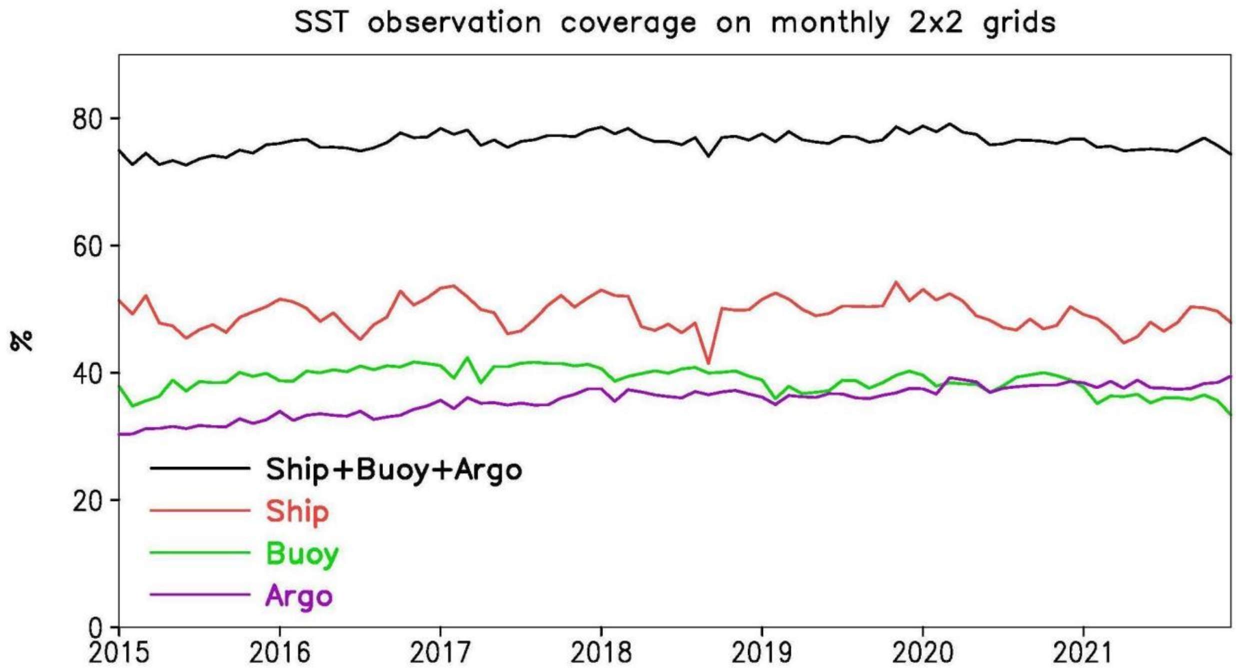

Figure 14. Percent global coverage of monthly sea surface temperature (SST) measurements January 2015 – December, 2021, calculated as the fraction of 2°x2° lon/lat grids with at least one SST report for the month.

SST is a major sea surface variable, influencing short and long-term weather patterns as well as an indicator of decadal cycles and longer-term climate trends. The Extended Reconstruction of Sea Surface Temperature (ERSST; Huang et al. 2017) calculates global SST change from the late 1800s to present. ERSST utilizes the SST observing system on a monthly basis, combining moored/drifting buoys, ship-based observations and Argo profiling floats near-surface measurements. Figure 14 indicates that for the combined ship+buoy+Argo float observations, we saw a slight drop (< 5%) in coverage in early 2020 which has persisted. The slight drop is a combination of a drop in ship coverage starting in early 2020 and a drop in buoy coverage starting in late 2020/early 2021. Argo float coverage was mostly steady with a slight (< 5%) increase during the two year period. Overall, the observational coverage and high quality data receipt needed for ERSST has not been affected globally by the pandemic to date.

4.2 Effects on Ocean heat content (subsurface temperature) time series

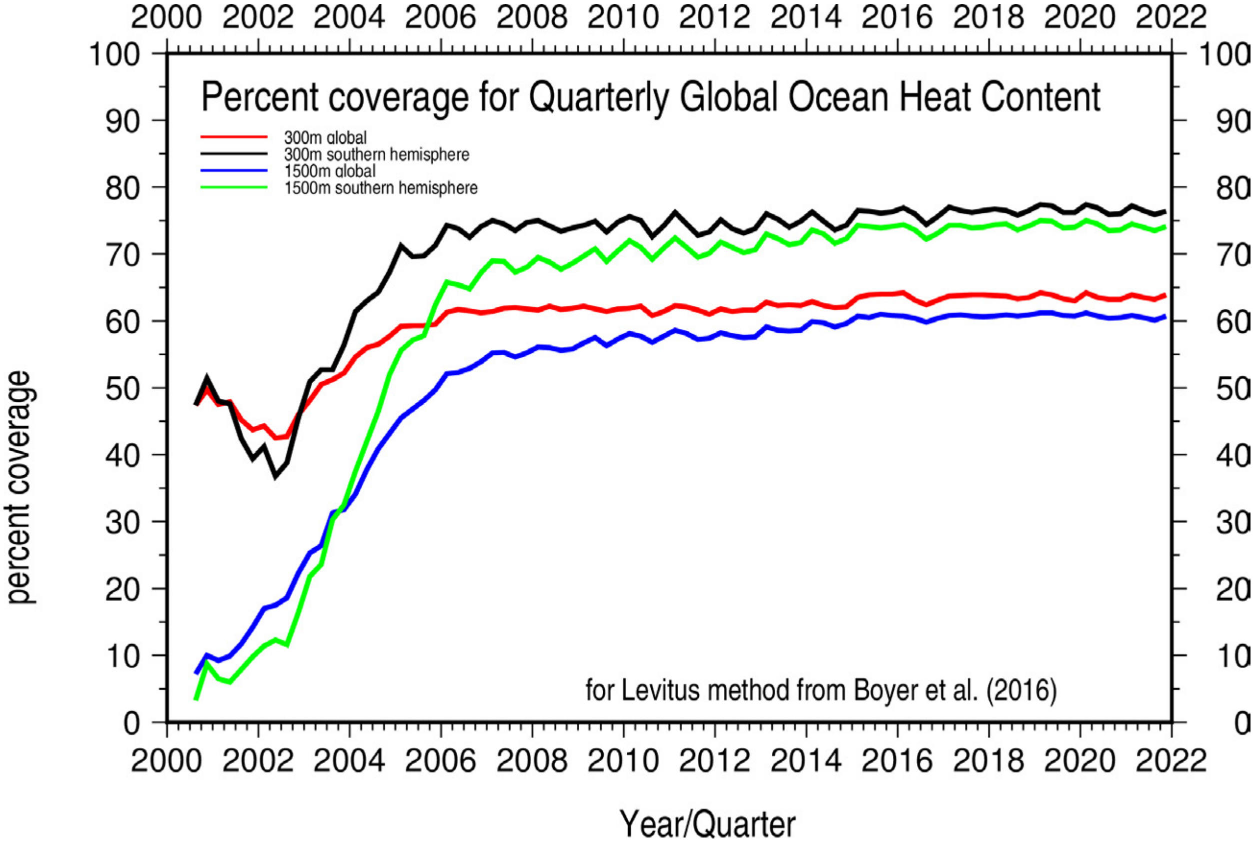

Figure 15. Percent coverage of subsurface temperature data at 300 m and 1500 m depth globally and for the southern hemisphere by season (3-month period) 2000-2021 for the calculation of ocean heat content calculated as fraction of 1°x1° lon/lat grid boxes with at least three temperature measurements within 400 km of the grid-box center.

The ocean absorbs more than 90% of excess heat in the Earth's system, so estimation of ocean heat content (OHC) change is vital to understanding the Earth's Energy Imbalance (EEI) and sea level change (e.g. von Schuckmann et al. 2020). The percent coverage of the global ocean from subsurface temperature data is directly related to uncertainty of the OHC estimate. The percent data coverage has increased rapidly since 2000 (Figure 15) as the Argo array reached global extent around 2006-2007 and has been fairly steady since at around 65% globally. This increase in global subsurface temperature data coverage since year 2000 has led to a decrease in uncertainty in the OHC estimates (Boyer et al., 2016; Johnson et al., 2020). There is no appreciable drop in the percent data coverage in the pandemic period, fluctuations during the pandemic no larger than the fluctuations in previous years, so the observing system has sustained the receipt of quality subsurface temperature measurements in 2020-2021 for the calculation of

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seasonal ocean heat content time series to this point despite the pandemic. Note that the criteria for coverage for SST time series and ocean heat time series are different given the nature of the calculations of the respective ECVs.

4.3 Effects of the pandemic on other ocean ECVs

Of the remaining ocean ECVs, only salinity approaches the volume, distribution, and timeliness of temperature observations. Salinity requires more quality assurance than temperature, including adjustments for sensor drift in the conductivity cells used on Argo floats. Salinity adjustment in Argo is done as part of the delayed-mode data processing procedure, which has been mostly unaffected by the pandemic. However, the loss of ship-based salinity measurements as a result of canceled GO-SHIP cruises during the pandemic is irretrievable. Even though there is no operational freshwater content time series, the salinity equivalent of ocean heat content, ocean salinity is the subject of long-term climate studies (e.g. Durack et al., 2012). SSS are utilized in blended in situ-satellite products (e.g. Xie et al., 2014) at a monthly time scale. Other data products provide subsurface salinity monthly mean global fields at standard ocean depths from Argo data (e.g. Roemmich and Gilson, 2009), and from all observing system data (e.g. Good et al., 2013). For surface ocean carbon, multi-platform air-sea CO_2 data contribute to the Surface Ocean CO_2 Atlas (SOCAT), which is the basis for annual observation-based estimates of ocean CO_2 uptake (Bakker et al. 2016) that inform the annual Global Carbon Budget (Friedlingstein et al. 2021). For the subsurface carbon ECV, as well as for ocean nutrients, monitoring mainly takes the form of long-term climatological means (e.g. the Global Ocean Data Assimilation Project - GLODAP; Lauvset et al. 2021, World Ocean Atlas - WOA; Garcia et al. 2018). Any data loss can be felt in a lack of representativeness of the pandemic years within the overall time period mean, as well as a delay in the accumulation of sufficient data to document global time variations. For ocean dissolved oxygen, global inventory time series are in the research stage (Ito et al., 2017; Grégoire et al., 2021). Operationalizing in situ global dissolved oxygen monitoring will be dependent on the proliferation of BGC Argo and other independent platforms with oxygen sensors and the quality assessment of this sensor data through high quality research cruise data, all of which were affected by the pandemic. Surface ocean currents derived from in situ drifter trajectories are also inventoried yearly (e.g. Lumpkin et al., 2021) and the data are aggregated on one day time periods (Verbrugge et al., 2020).

5. Conclusions

During the course of 2020 and 2021, the pandemic created serious challenges for maintaining the eGOOS to the point that the observing system for ECVs reliant mainly or wholly on research cruises were not sustained. Merchant ships and independent platforms did provide for sustained monitoring of ECVs, but within limitations of deployments, battery life, and instrument reliability over time. These limitations have led to a slow deterioration in the monitoring capabilities for these ECVs, which needs to be addressed.

Lessons from the pandemic for the eGOOS

1. Research cruises are the backbone of the eGOOS in terms of providing high quality measurements for detecting and monitoring climate signals in ECVs, validating and calibrating satellite and NRT in situ measurements, deploying and maintaining independent platforms, and continual development and improvement in end-to-end ECV monitoring systems. The research fleet is not as resilient as the merchant fleet in developing strategies to meet unexpected obstacles. Partly this is due to the economic necessities of merchant ship operation. Strategies for funding and logistics should be implemented to ensure continuity in research cruise operations in the face of unexpected factors such as the pandemic, otherwise monitoring for ECVs cannot be considered sustained.
2. The eGOOS is resilient where independent platforms can be relied upon, within the battery life constraints, instrument constraints, calibration/validation against high quality ship measurements, and maintenance schedules necessary for ensuring high quality measurements. Deployment methods independent of research cruises should be pursued where possible, but with care to ensure high rates of success with the complex instrumentation, where success means not only recording and transmission of measurements, but of high-quality measurements. Battery life extension needs to be accompanied by increased sensor stability.

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3. The augmentation of RV measurements with sensors on independent platforms needs to continue to be emphasized, and accelerated if possible, with specific focus on EOVs such as carbon (pH, alkalinity, dissolved inorganic carbon, and pCO_2), oxygen, and nutrients. This is underway with the growth of BGC and Deep Argo and other programs. Research to validate sustained sensor measurements should be expanded and systematized to provide confidence in the reliability of global sustained ECV monitoring for these variables.
4. Every marine meteorological, surface ocean, and subsurface ocean in situ measurement available in NRT is of value to weather and ocean models. Every measurement can be reused for long-term study and hindcast reanalysis. The data flow of pertinent RV ocean measurements (temperature and salinity) to the GTS in NRT can and should be increased to encompass the entire global RV fleet. The flow of all ECVs from RVs and other platforms to the long-term databases needs to be optimized and sustained to gain full utility of the eGOOS through reuse of the data for climate study.
5. Consolidated monitoring and logistic support of the eGOOS is essential to identifying gaps and coordinating planning for system sustainment.
6. Emerging platforms such as AniBOS and Ocean Gliders, are critical to fill in data gaps in under sampled areas and along the coasts. Other innovative solutions, including new independent systems, as well as enhanced private/public partnerships, could potentially increase data volumes available to research and operational workflows.
7. Securing the supply chain for oceanographic instrumentation and analysis tools is imperative for continuous cost-effective observations.

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Data Availability Statement: All data used in this study are publicly and openly accessible from the archives of the NOAA National Center for Environmental Information (NCEI; ncei.noaa.gov), in aggregated cross-system form in the International Comprehensive Ocean-Atmosphere Data Set (ICOADS; https://icoads.noaa.gov/) and the World Ocean Database (WOD; https://www.ncei.noaa.gov/products/world-ocean-database), in the Observing System Monitoring Center (OSMC; https://www.osmc.noaa.gov/), in the Ocean-Ops monitoring system (https://www.ocean-ops.org/board) as well as the ocean observing system component data management hubs themselves as found in the references.

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