Observational gaps in our in-situ monitoring of Earth's Energy Imbalance and Marine Heat Waves

Tim Boyer presenting for coauthors, with Boyin Huang additional material on marine heat waves; Ricardo Locarnini, James Reagan, Alexey Mishonov additional material for Earth's Energy Imbalance

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National Centers for Environmental Information

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Effects of the Pandemic on Observing the Global Ocean

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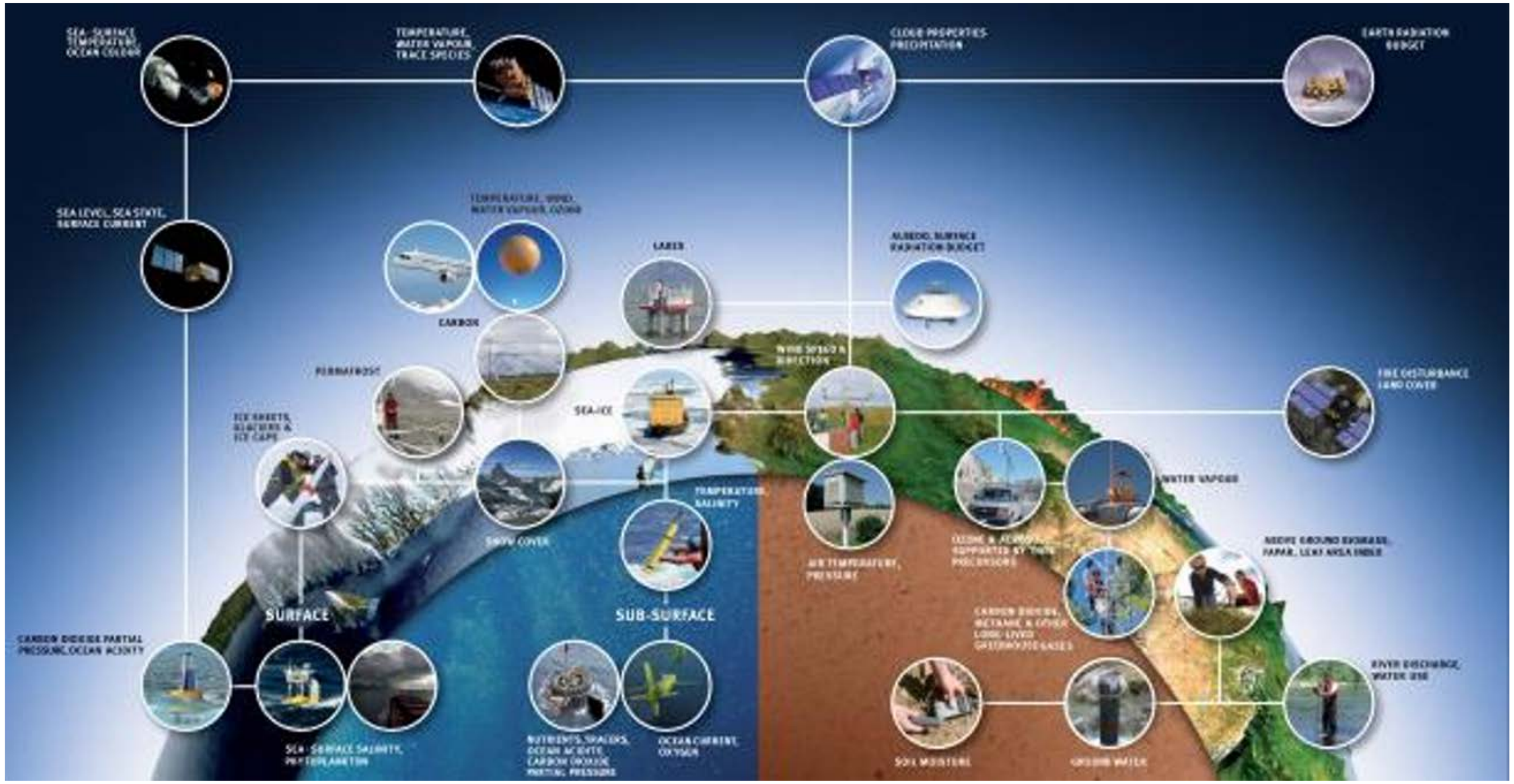
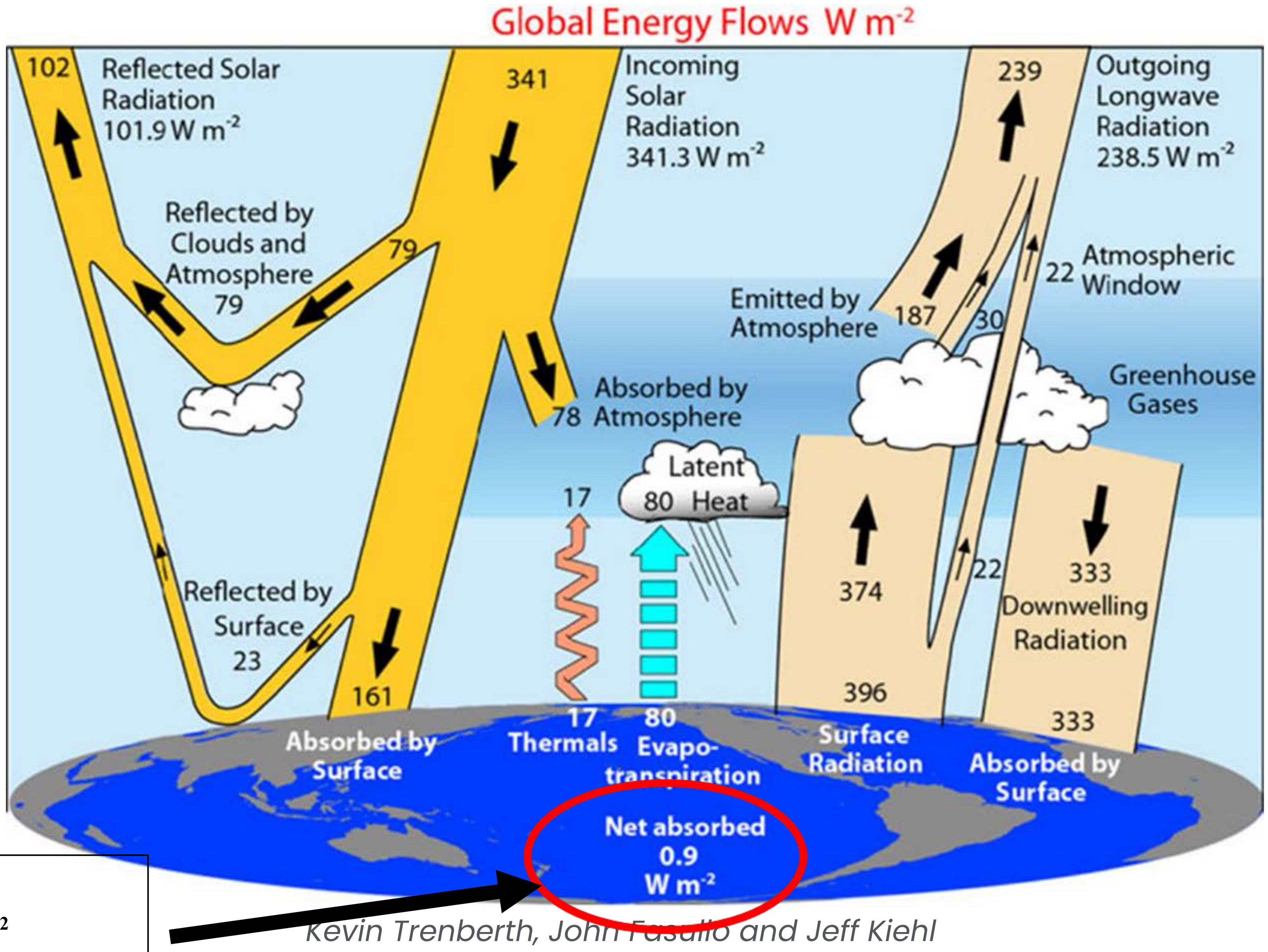
Essential Climate Variables including Essential Ocean Variables of the World Meteorological Office



The Global Ocean Observing System (GOOS), structured under the Framework for Ocean Observing (FOO), consists of the requirements, assessment, design, execution, and utilization/dissemination of networks of measurements of relevant essential ocean variables (EOVs).

The focus here will be on the execution of the GOOS, the measurement of EOVs as seen from the utilization in ocean monitoring products

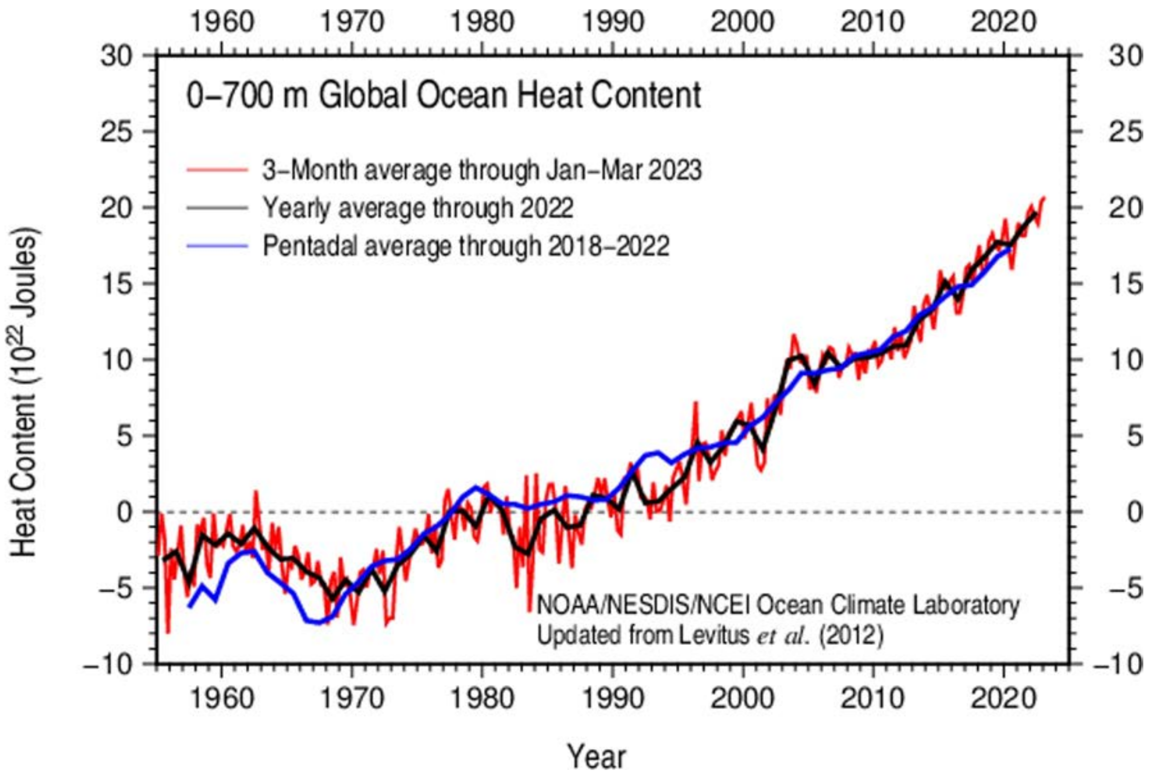
Earth's Energy Imbalance: Incoming Solar Radiation (Yellow) > Outgoing Longwave Radiation (White)

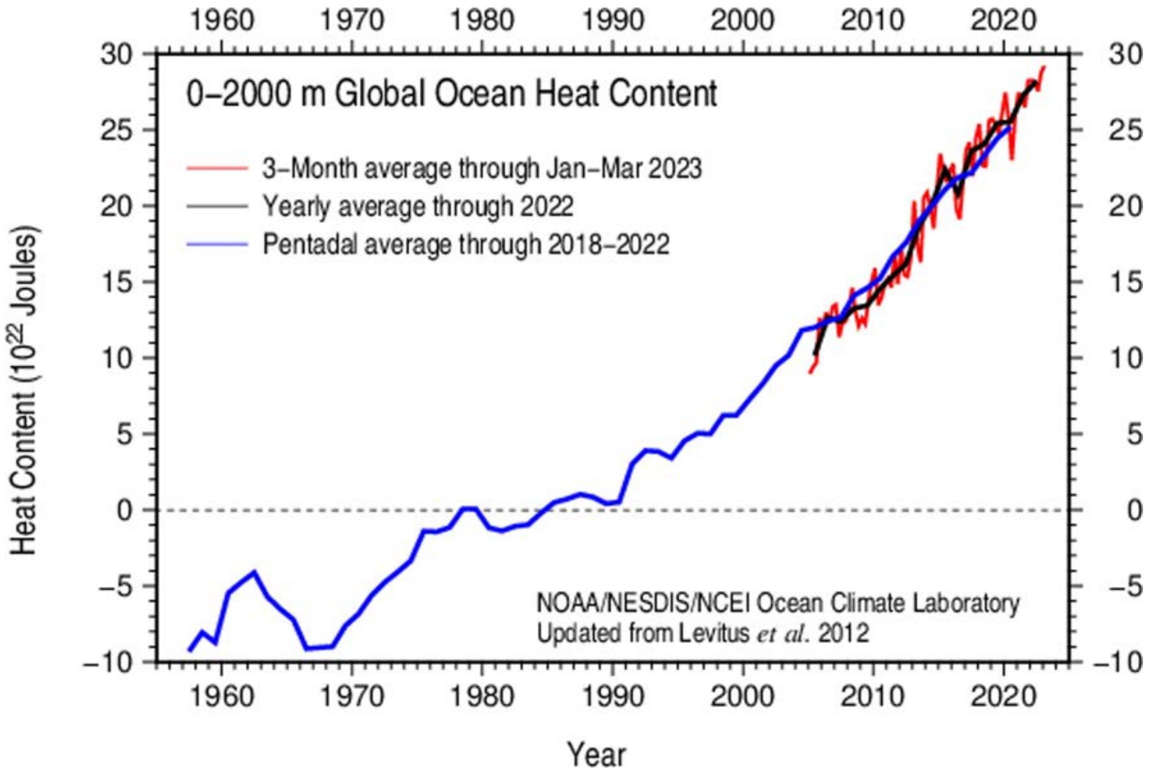


IPCC AR6 prelim:

1971-2018: 0.57 [0.43 to 0.72] W m^{-2}
2006-2018 0.79 [0.52 to 1.06] W m^{-2}

https://scied.ucar.edu/image/radiation-budget-diagram-earth-atmosphere

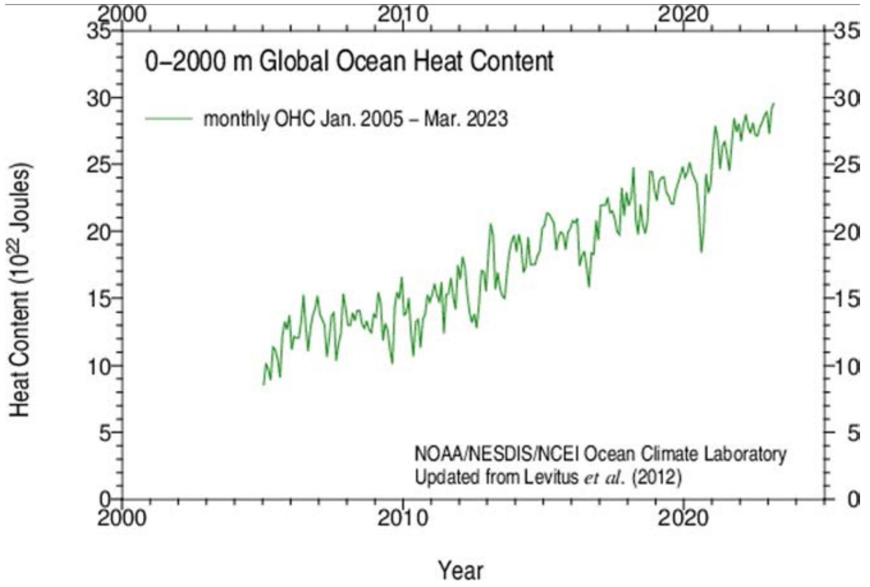


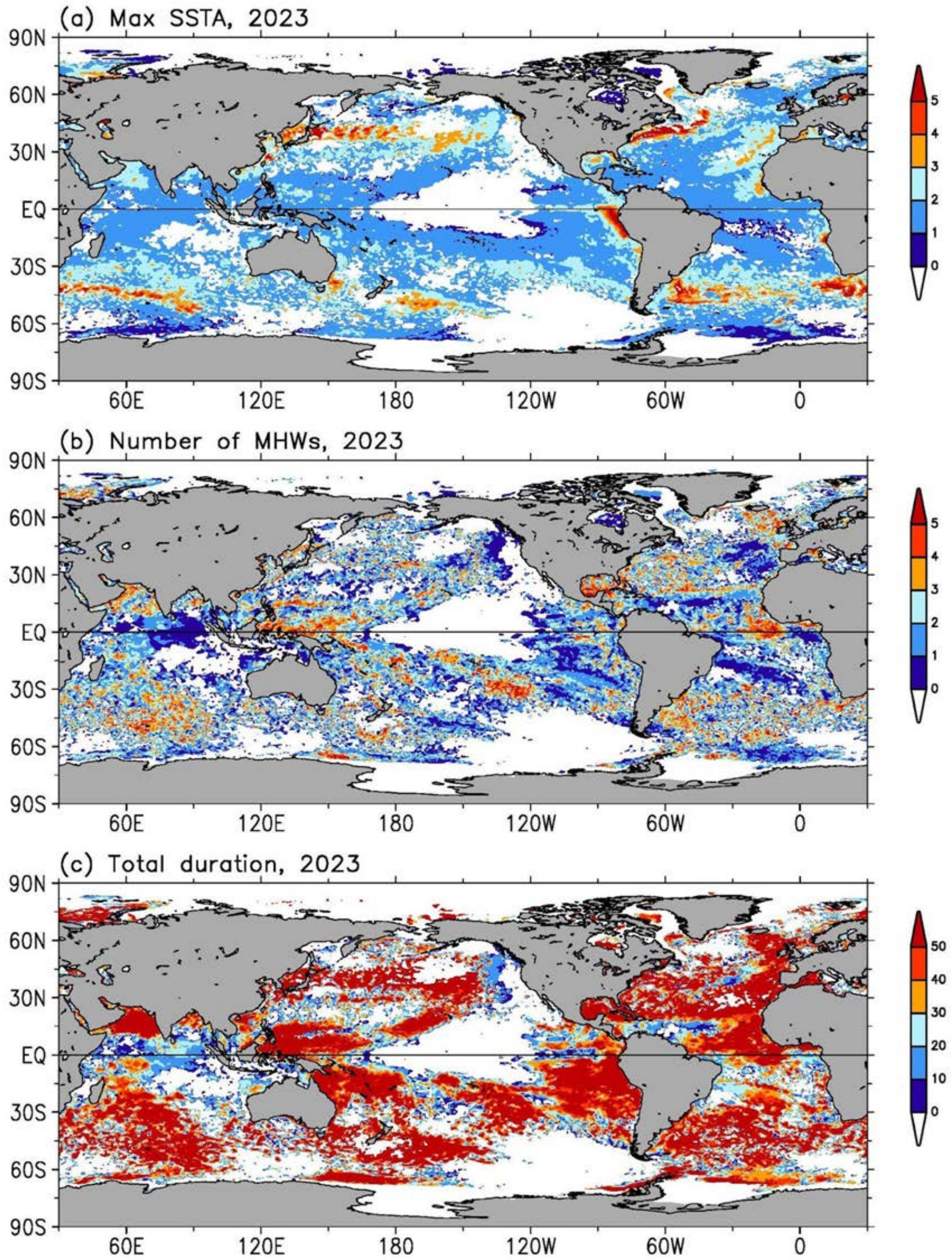


Earth's Energy Imbalance 90% sequestered in the ocean.

Global Ocean Heat Content Anomaly through March 2023 from NCEI five-year, one year, seasonal time series integrated over 1° grids surface to 700 m (top left), surface to 2000m (top right) and monthly surface to 2000m (bottom)

[Note: RFROM in situ + satellite 7 day/1/4°degree)

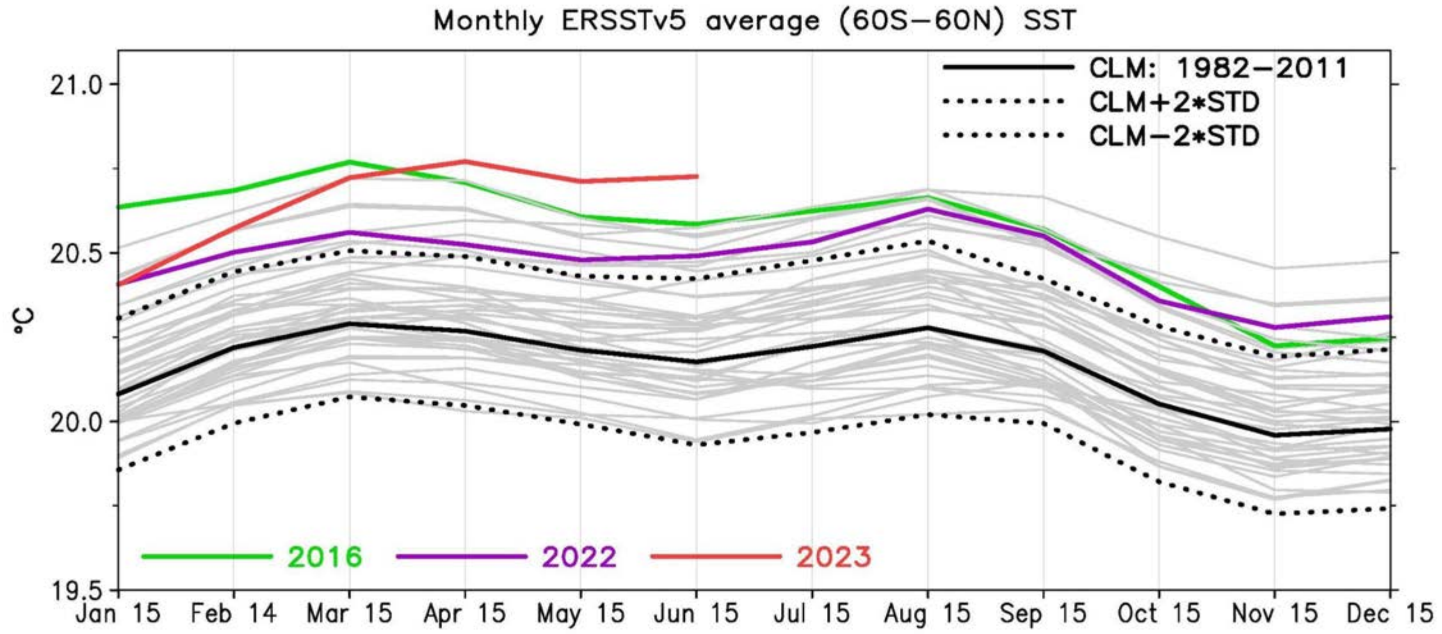


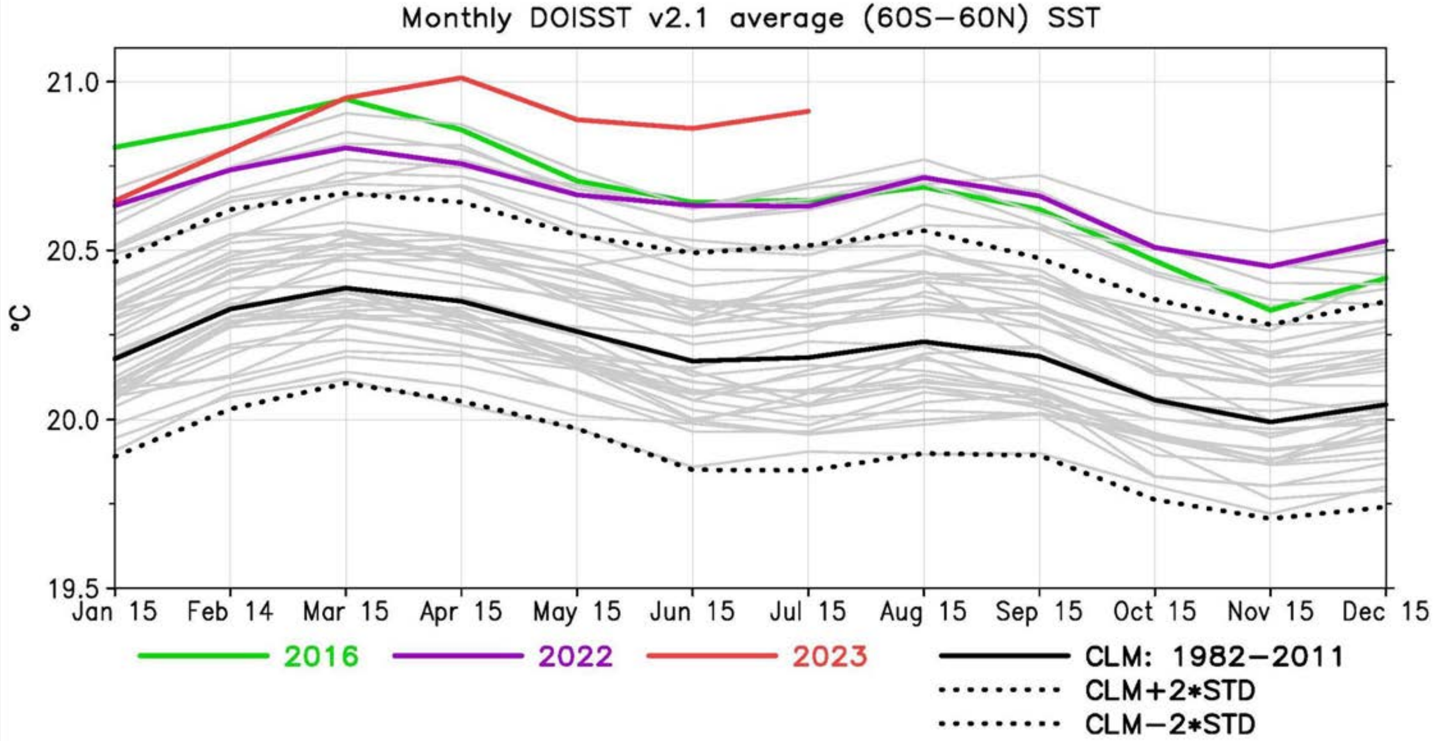


Marine Heatwaves 2023 from DOISST
Maximum Temperature Anomaly in 2023 (°C, top)

Number of Marine Heatwaves in 2023 (middle)

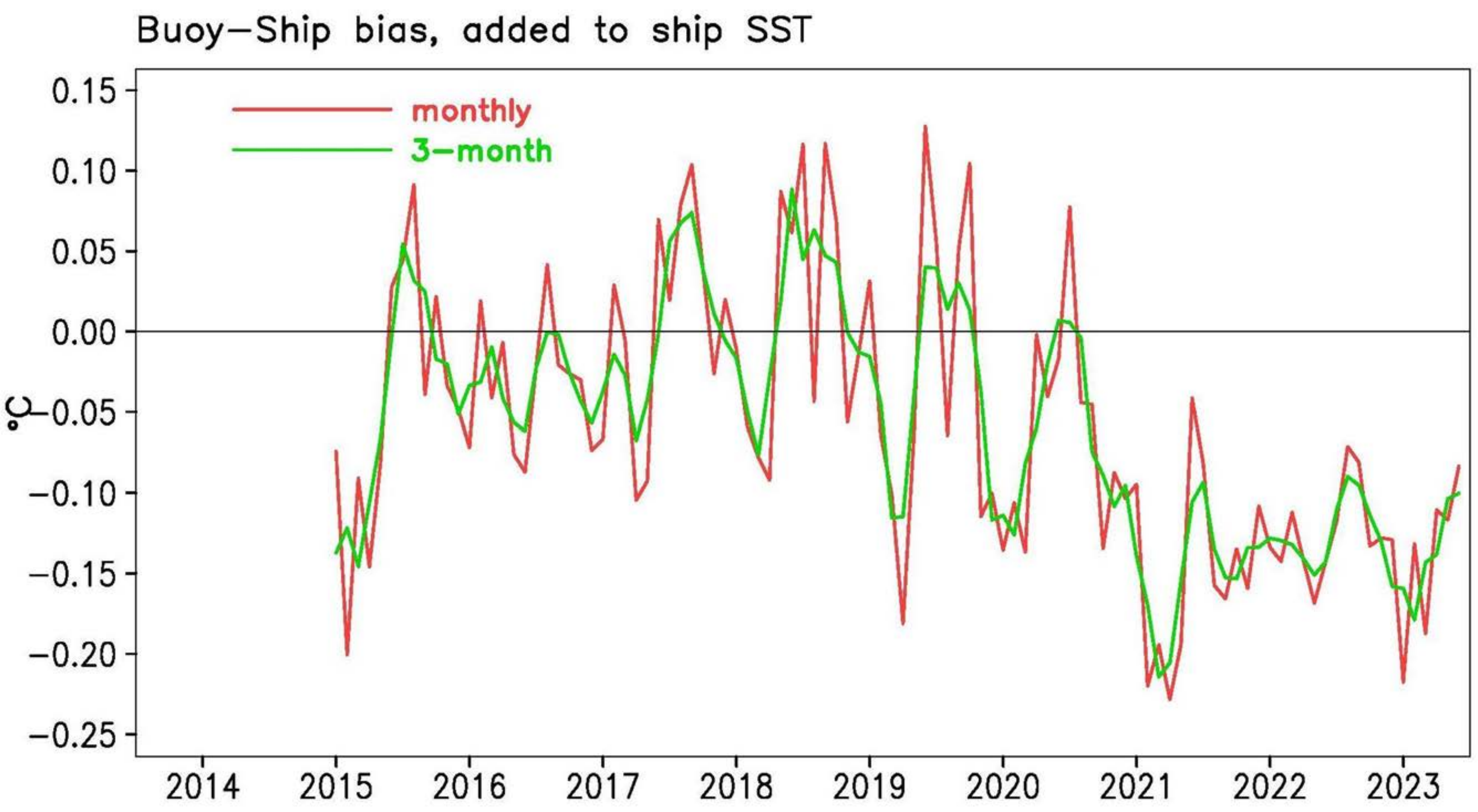
Total duration of Marine Heatwaves in 2023 (days, bottom)





Global Mean SST from Extended Reconstruction of Sea Surface Temperature (ERSST) v5 (top) and from Daily Optimally Interpolated Sea Surface Temperature (DOISST) v2.1(bottom)

Marine Heat Wave: DOISST 1/4° grid with temperature anomaly in the 90th percentile of historic values for 5 or more consecutive days



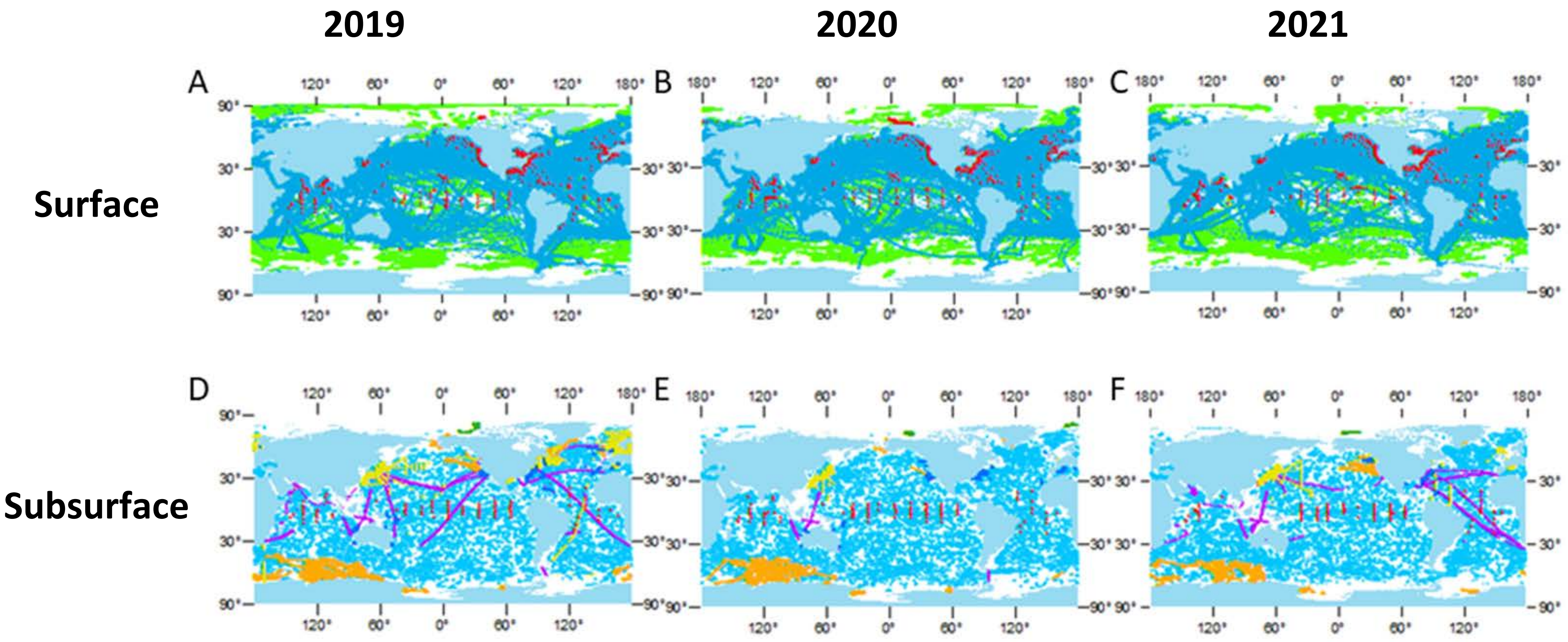
ERSST: All in situ data (ship, Argo, drifting and moored buoys)

Ship bias correction to buoy (figure)

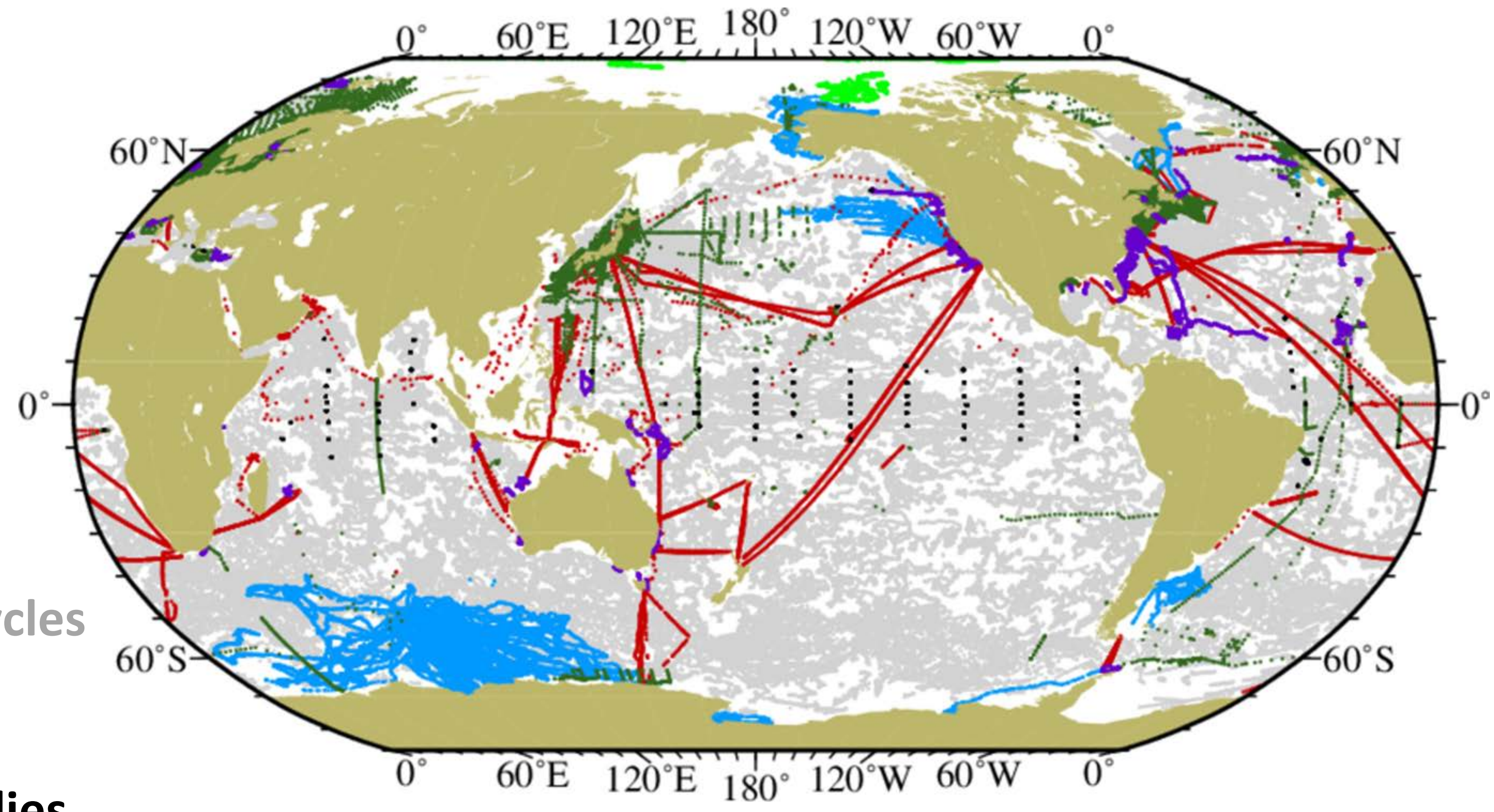
Monthly 2° X 2° gridded

DOISST: All in situ data + satellite data (Pathfinder SST, Navy SST, MetOpA/B after 2019/11/15, and ACSPO after 2021/10/1)

Ship bias correction (0.01°C 2016-2023/5, calculated as in ERSST 2023/7 forward)



Ocean Observing System April – June before and during the pandemic: Ships (blue), moored buoys (red) and drifting buoys (green), 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)



598,938 casts

165,839 Profiling float cycles
18,090 CTD casts
13,807 XBT drops
29,163 moored buoy dailies
21,249 Ice-Tethered Profiler cycles
288,835 glider cycles
62,405 pinniped dives

2019 Subsurface Temperature Observations

318,534 casts

165,942 Profiling float cycles

8,885 CTD casts

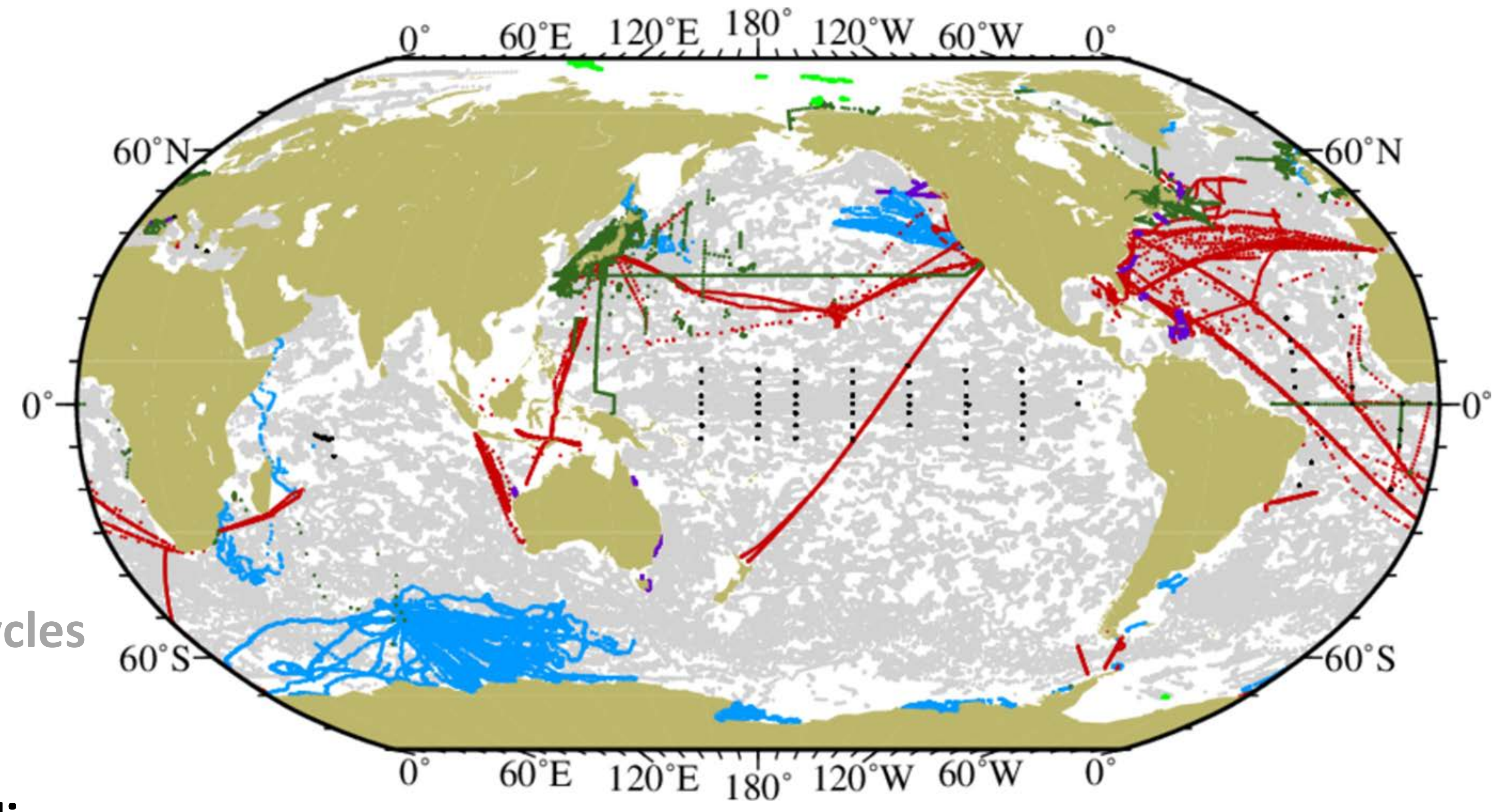
8,348 XBT drops

19,237 moored buoy dailies

1,305 Ice-Tethered Profiler cycles

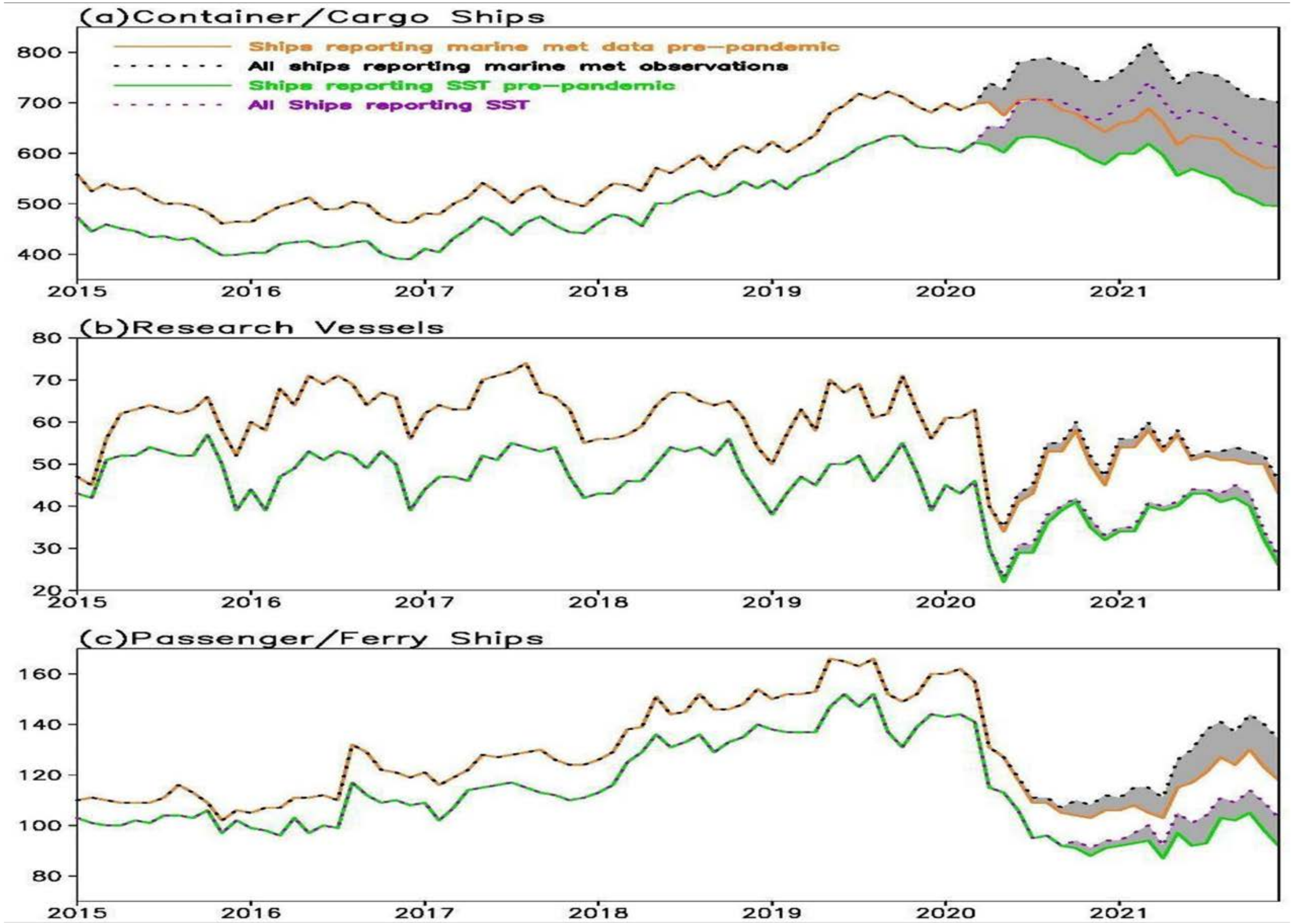
59,104 glider cycles

55,713 pinniped dives



2022 Subsurface Temperature Profiles

Volunteer Observing Ships Reporting Marine Meteorological and Sea Surface Temperature Observations Before and During the Pandemic

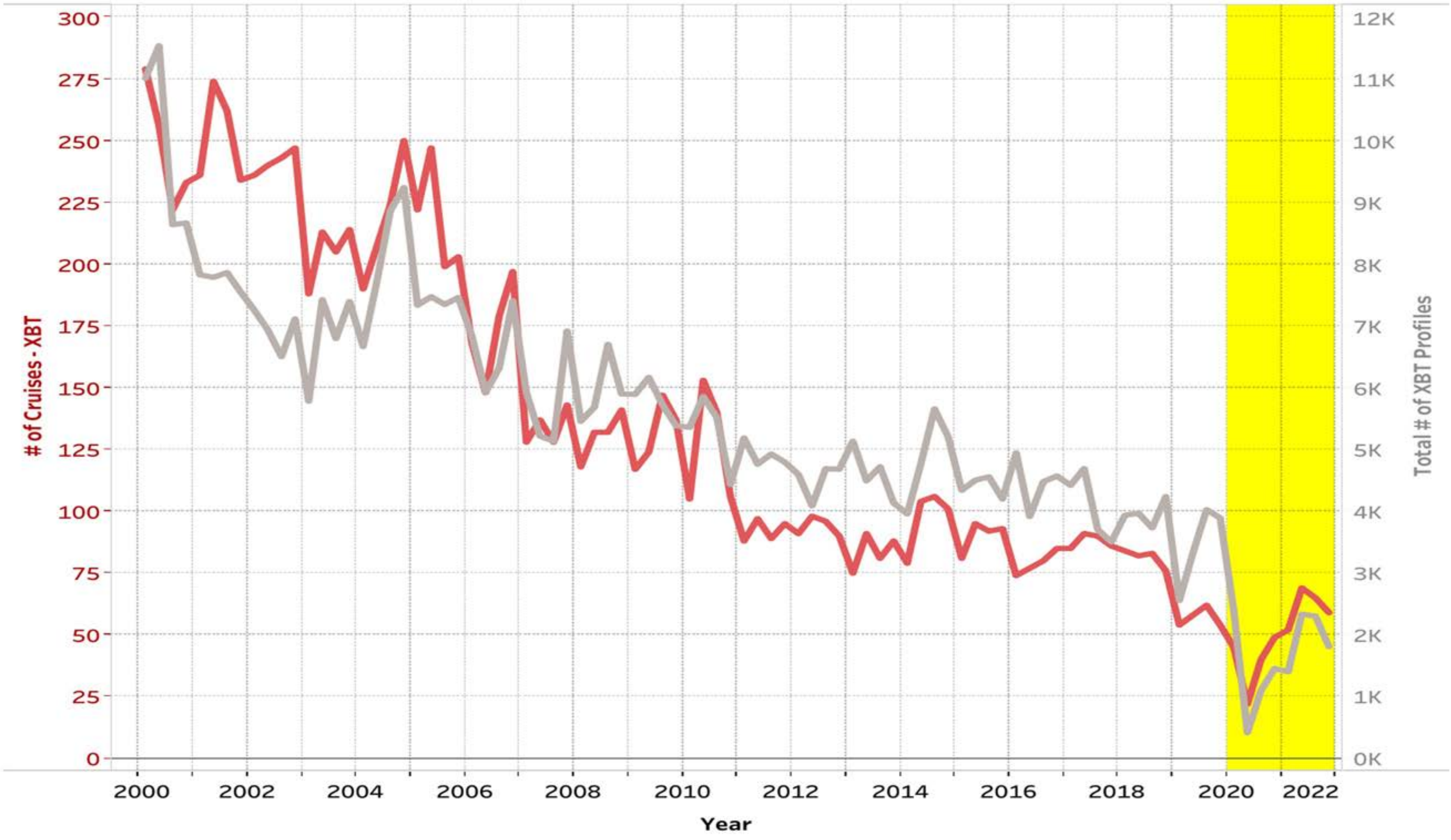


Merchant Ships

Research Vessels

Passenger Ferries

Number of Ship of Opportunity Cruises from which Expendable Bathythermographs (XBTs) were dropped (red) and total number of XBTs dropped (grey) by quarter 2000-2021



Yearly Total Drops:

2019	13,983
2020	5,496
2021	8,423
2022	10,495

Reasons for low levels of XBT drops during the pandemic

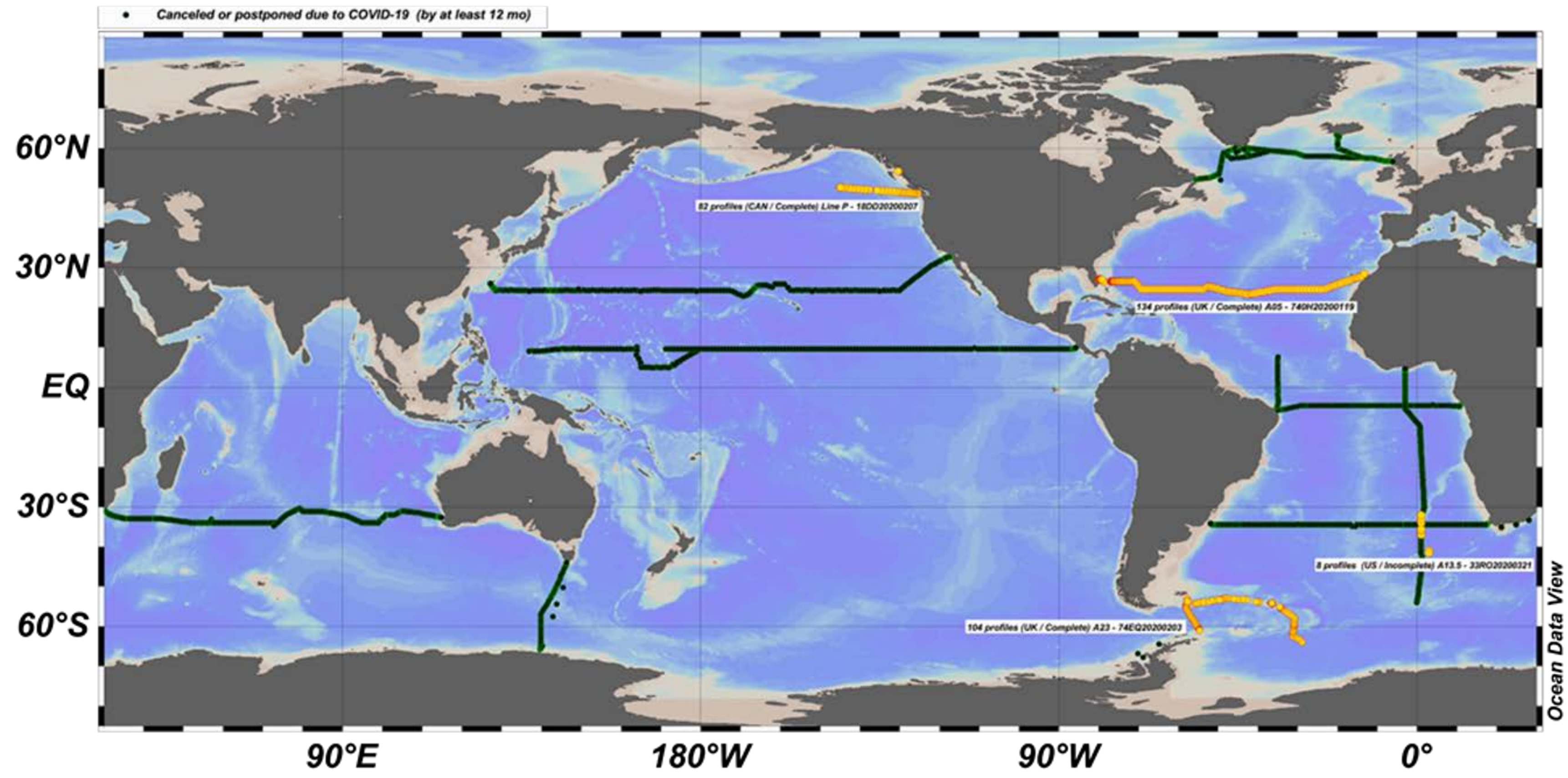
Continuation of recent trend – budget constraints and loss of ship time

Cessation of shipping traffic at the beginning of the pandemic, disruption of existing shipping routes

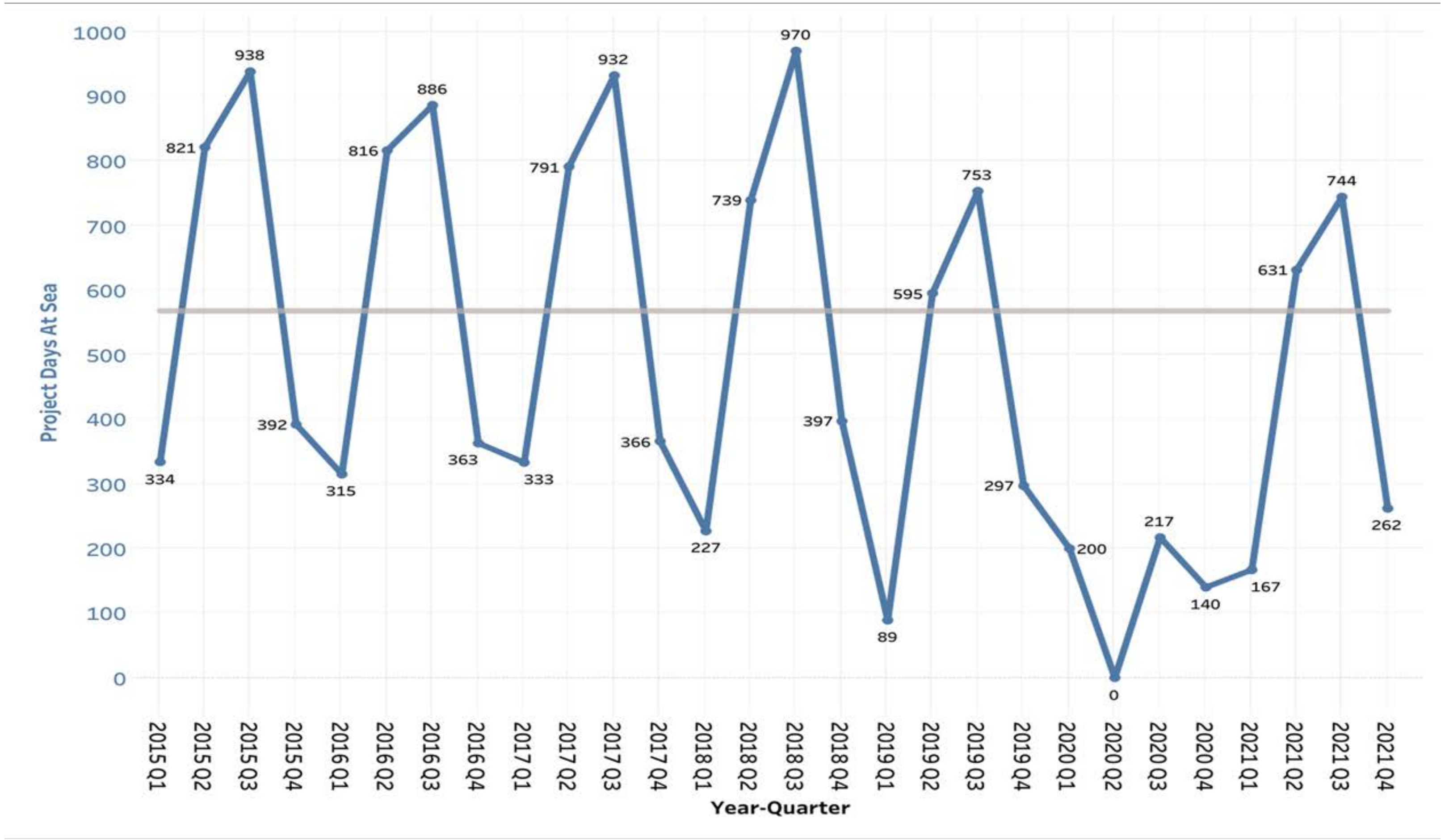
Logistical difficulties in delivering equipment to ships

Safety concerns for ship riders

XBT drop duties transferred to ships crew – less frequent drops

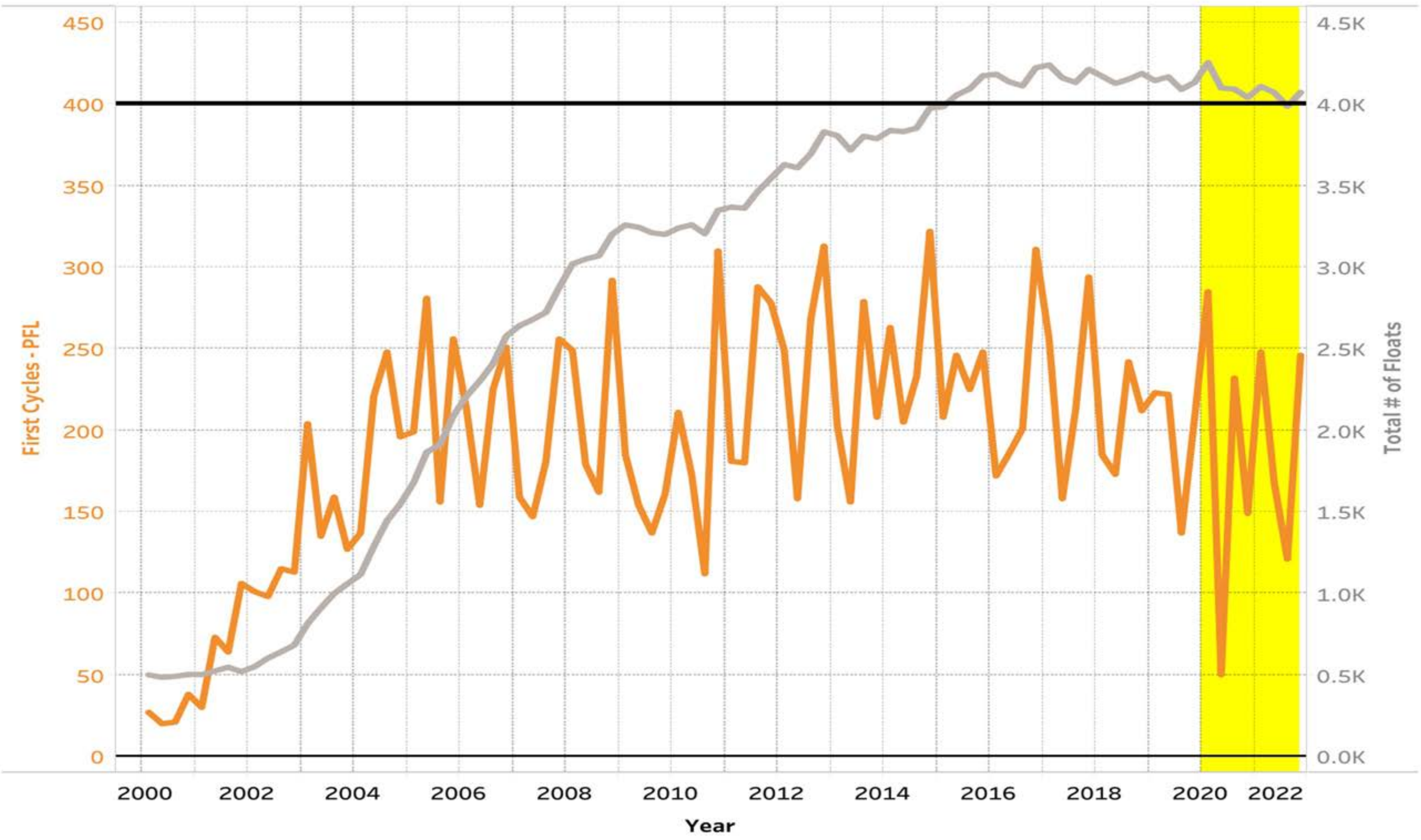


Repeat Hydrography Cruises delayed, cancelled or ended prematurely in 2020 (Green)
Stations completed from full or partial repeat hydrography cruises in 2020 (Yellow)



National Oceanographic and Atmospheric Administration (NOAA) total ship cruise days by quarter 2015-2021
From NOAA Office of Marine and Aviation Operations (OMAO)
16 ships managed by OMAO – from coast surveys to ocean exploration

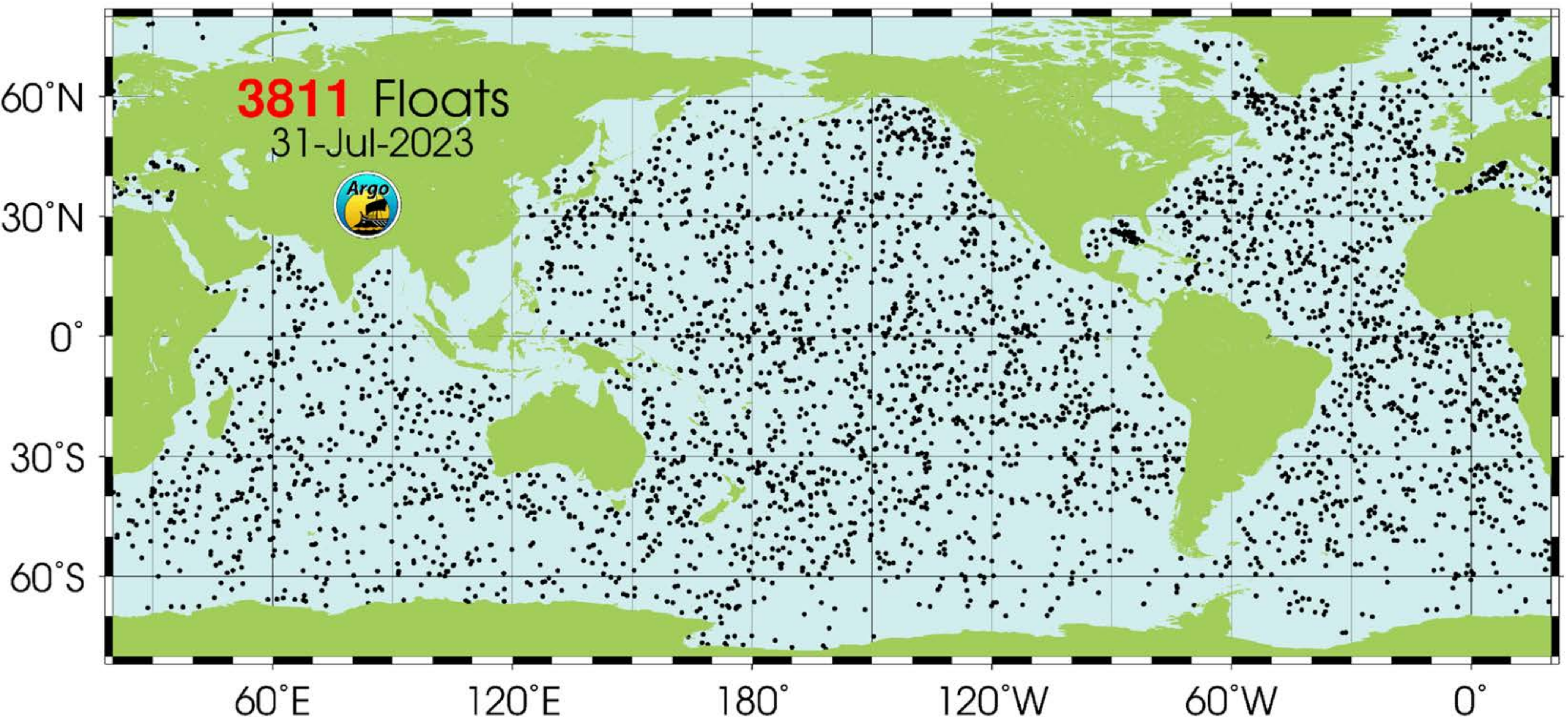
Successful Argo float deployments (first cycles) 2000-2022 (orange)



Briefly (one quarter) dropped below 4000 reporting floats – but float numbers nearly steady through pandemic

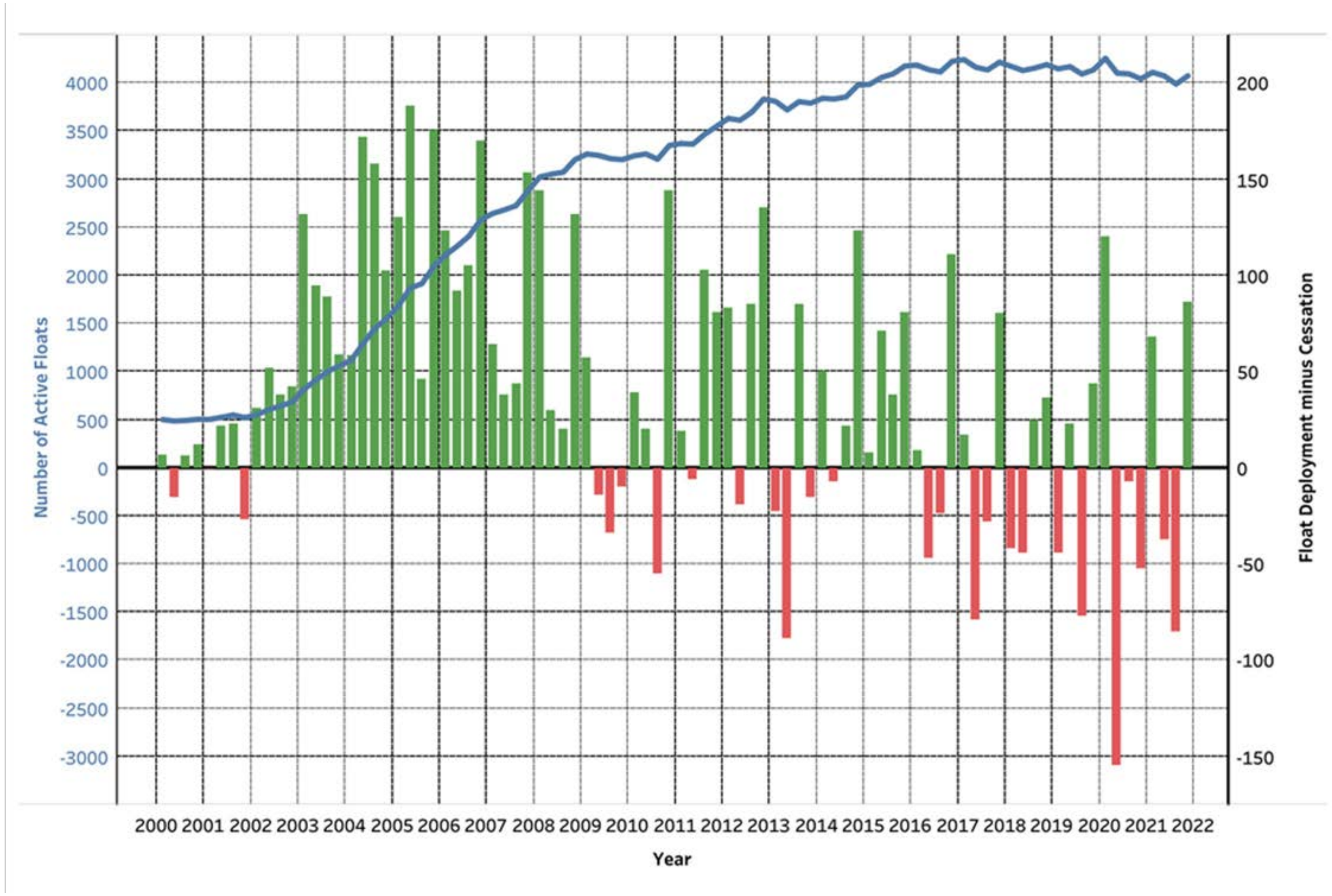
Drop in float deployments in first months of pandemic and in third quarter of 2022

Total number of reporting Argo floats 2000-2022 (grey)



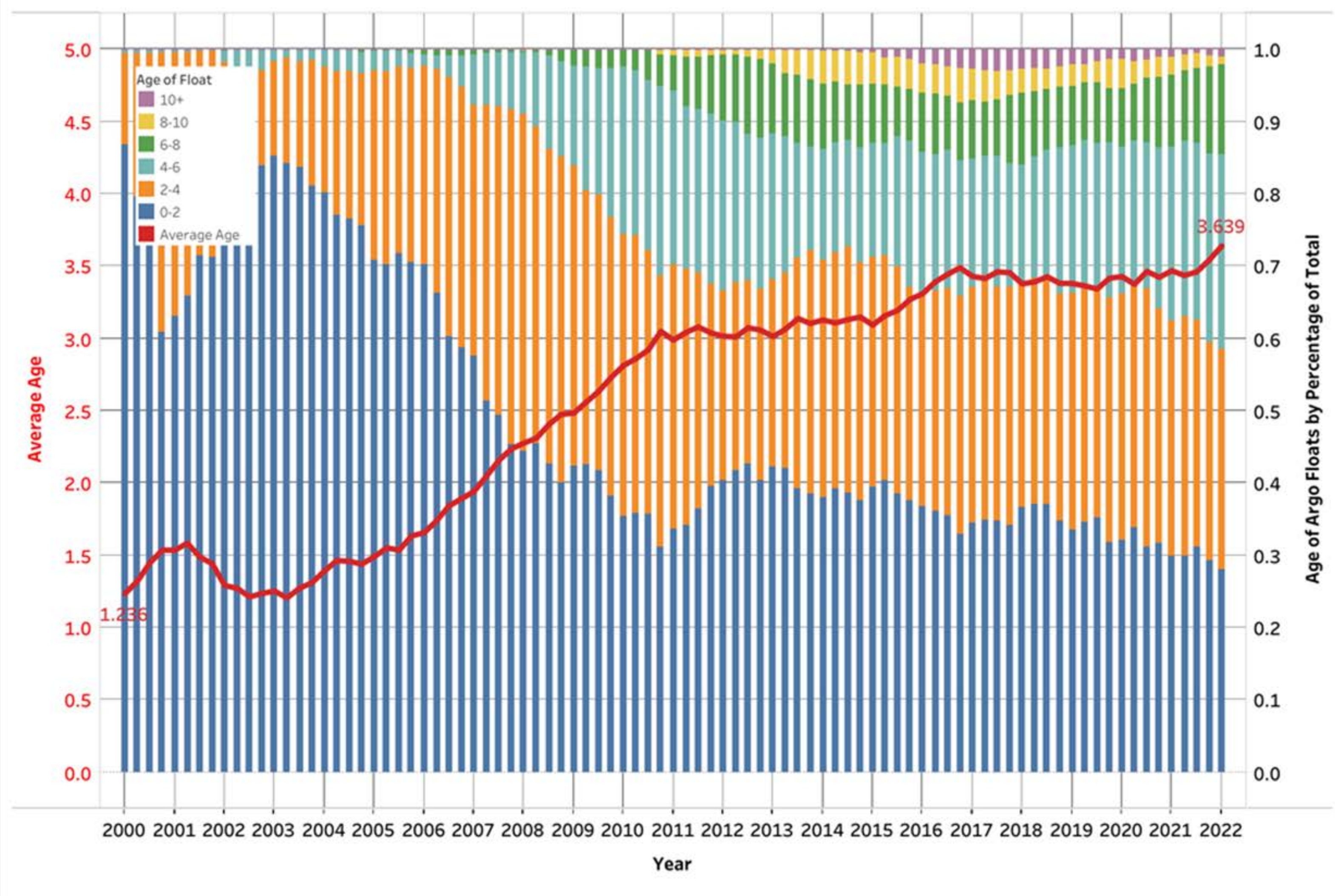
Above: Current Argo status (from https://argo.ucsd.edu/about/status/)
Floats reporting April – June, 2023 (from World Ocean Database) 3,974

Number of floats deployed minus number of floats stopped transmitting (or no valid data)



Gain in total float numbers (green) loss in total float numbers (red)

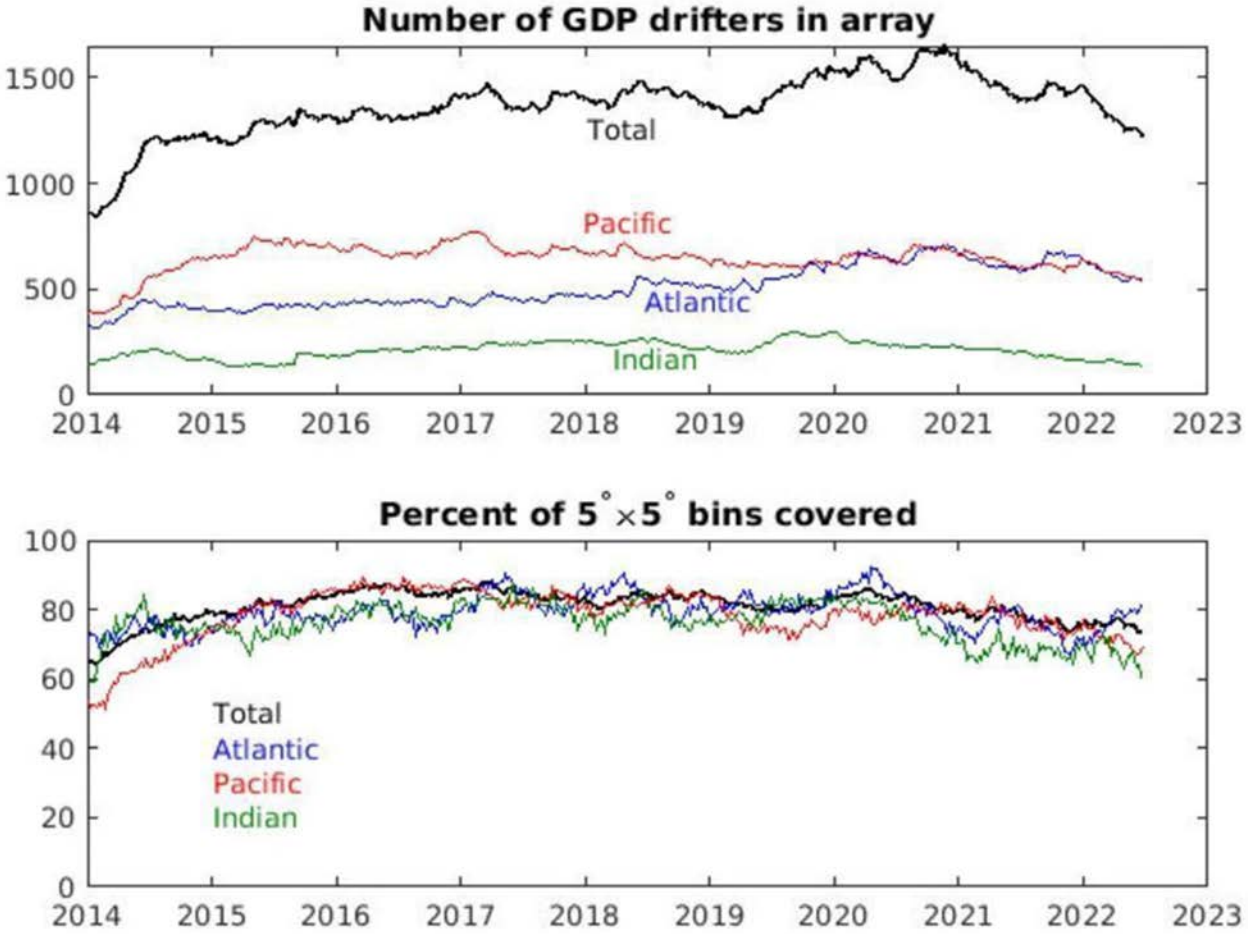
Argo float lifetime: steady increase offsets to some degree need for new deployments



Average age of float increased slightly to 3.7 years during the pandemic

Argo through the pandemic

- Argo float fleet maintained through the pandemic with only a slight drop in total number of floats
- Exhaustive logistics effort needed to find deployment mechanisms due to limited research cruise availability.
- Longer battery life has also contributed to steady total float numbers
- Longer float life can lead to more instances of data quality (less so for temperature than other variables)
- Limited deployment options has led to ‘holes’ opening up in the geographic coverage of floats – most notably in the north Indian Ocean
- In the future it is important to close these holes, add floats where float lifetime is higher than optimal for return of quality data.



Global Drifter Program surface drifters:

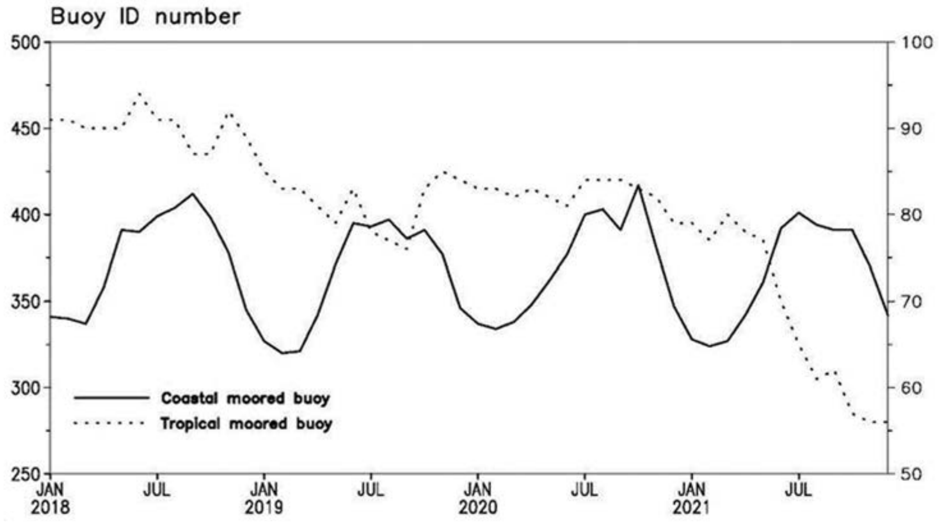
Ocean surface currents (trajectory), atmospheric pressure, sea surface temperature

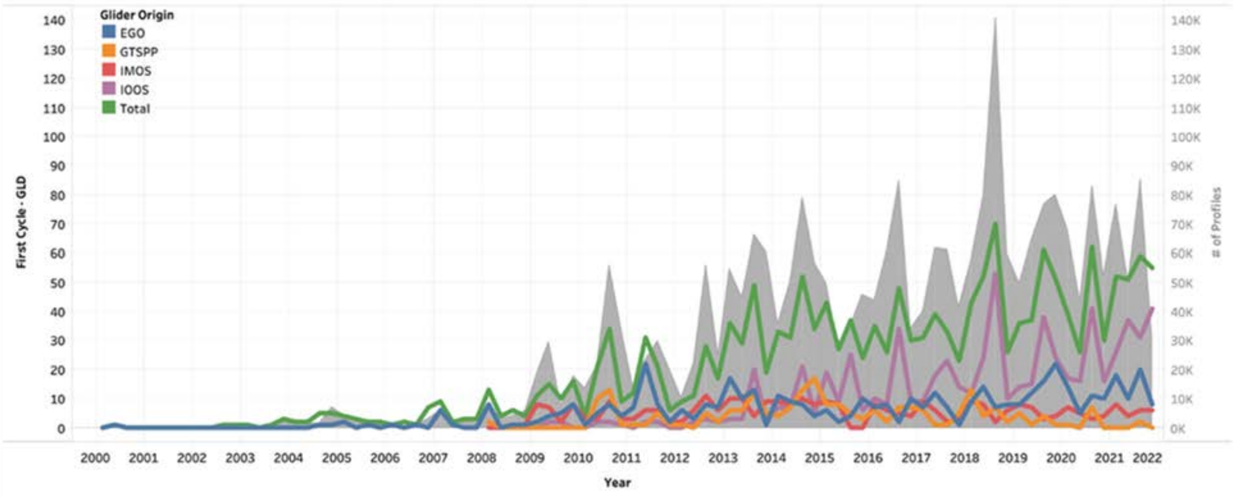
Drifter life about 18 months

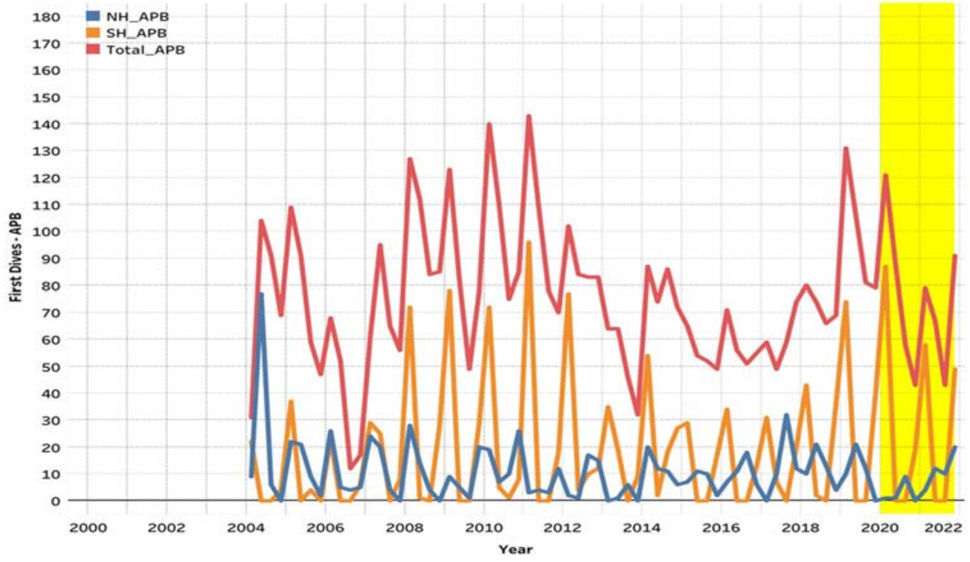
Similar deployment logistics to Argo

Drop in total number of reporting drifters through mid-2022, particularly in the Indian Ocean

Drop in percent coverage in each basin, ‘hole’ opened up in the Northern Indian Ocean.

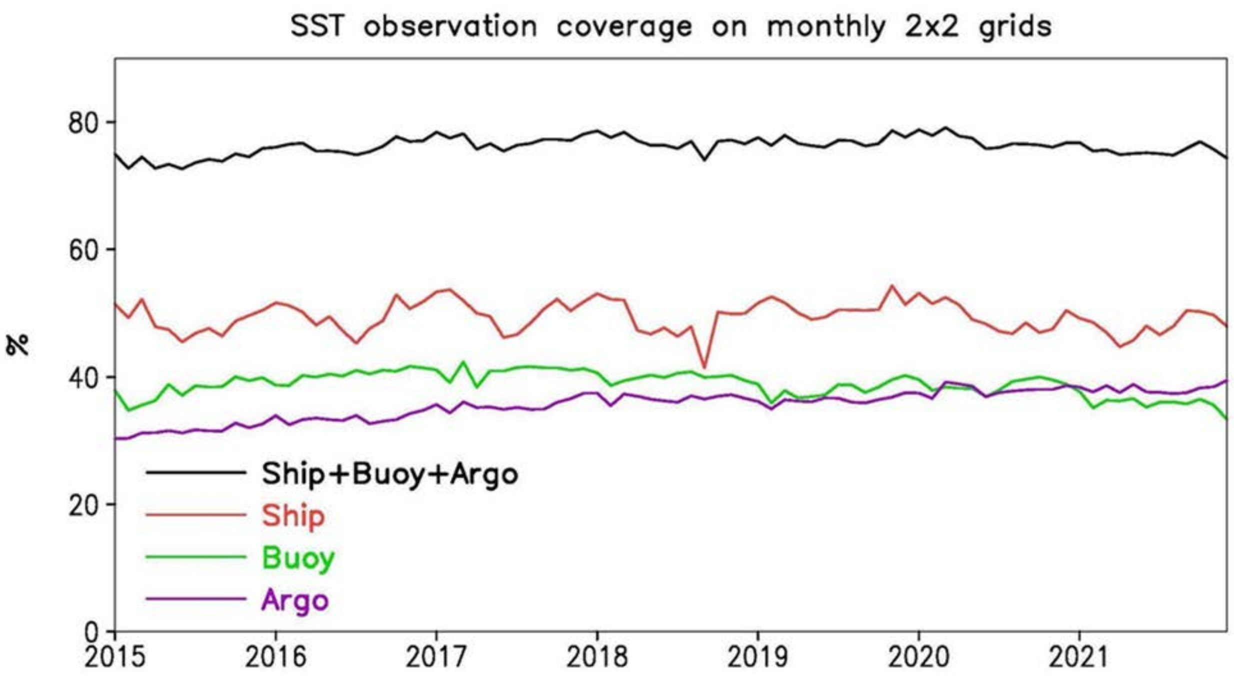




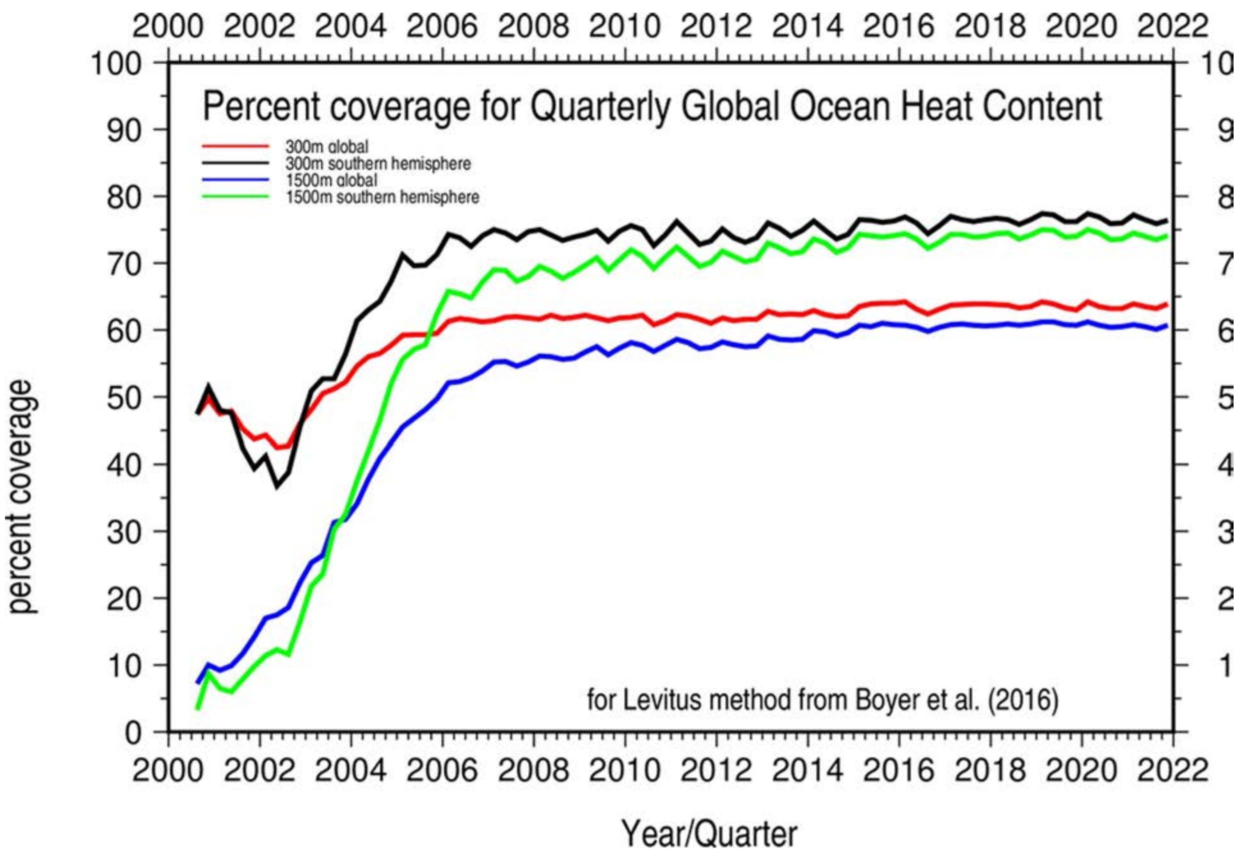


Top Left: Moored buoys coastal and tropical array 2018-2021
Top Right: Gliders deployments reported from the from the main data assembly centers 2000 - 2022
Bottom: Instrumented pinnipeds total animals reporting 2004-2021 mid-year.

Effects of the pandemic on ocean temperature monitoring



Percent coverage for monthly sea surface temperature (2°x2° lat/lonboxes 2015-2022 midyear based on International Comprehensive Ocean and Atmosphere Data Set (ICOADS)



Percent coverage of subsurface ocean temperature measurements for the calculation of ocean heat congtent (4° radius around each 1° grid box midpoint) based on the World Ocean Database

Effects of the pandemic on other essential ocean variables

- **Salinity**: Nearly same coverage as for subsurface ocean temperature, seasonal salinity anomalies not affected, but float lifetime is a much more important factor for salinity. At surface, effect on sea surface salinity not analyzed.
- **Oxygen/nutrients**: Irreplaceable loss of time series data from repeat hydrography, other research cruises. Diminished capacity on cruises that did go out led to concentration of efforts on physical variables. Biogeochemical Argo not yet to level to handle oxygen monitoring, nor nutrients (nitrate only nutrient now measured by Argo)
- **Ocean carbon/acidification**: As with oxygen/nutrients, irreplaceable loss of subsurface time series from repeat hydrography and other research cruises. Argo not ready to handle carbon monitoring (pH sensor). For surface, SOCAT diminished number of ships of opportunity, but annual carbon budgets still calculated.
- **Ocean currents**: monitoring mainly at surface through global drifter program – number of drifters dropped but system still maintained.
- **Ocean biology**: not yet robust monitoring, but loss of data due to research cruise limitations. Sensor data (e.g. fluorescence) not yet a functioning monitoring system.

Recommendations for resiliency of the ocean observing system

1. Research cruises are an irreplaceable component of the ocean observing system for the collection of high quality reference data, for some essential ocean variables the only reliable data. Research cruises are also integral to deploying autonomous platforms. Efforts need to be made to maintain supply lines, expert crews, and available ship time.

1. Autonomous platforms are key to the resiliency of the ocean observing system – efforts need to be made to find alternate means of deployment and to improve sensor accuracy and reliability.

1. Developing and maintaining independent new components of the ocean observing system is important to allow for more overlap among components and fall back capability from one component to another if one particular component is stressed.