A comparative study of the Argo-era ocean heat content among four different types of datasets

Fanglou Liao* and Ibrahim Hoteit

Physical Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

*Corresponding author: Fanglou Liao (Fanglou.liao@unswalumni.com)

Abstract

We conducted a comparative study of ocean heat content (OHC) in the top 2000 m during the Argo-era using 12 latest and representative global ocean datasets. The differences in the global and basins-wide OHC trends were minor among the observation-based datasets, and remarkable among the ocean reanalyses (RAs). Some RAs might exhibit much higher or lower basins-wide warming rates than the observation-based datasets. In the top 700 m, RAs suggested similar large-scale warming and cooling patterns, in agreement with the observation-based datasets. Below 700 m, the major warming and cooling features were however significantly different between RAs and observation-based datasets. All datasets suffered from relatively larger uncertainties in the highly dynamic regions. Special caution is suggested when estimating the OHC using only a single dataset, especially a RA. Differences of RAs’ OHC from observation-based datasets were significantly reduced when considering their ensemble mean, to be further confirmed with a larger sample of datasets.

Key Points:

- Global and basins-wide OHC trends were largely similar among the observation-based datasets.
- RAs well captured the large-scale warming and cooling patterns indicated by observations in the top 700 m, but poorly below 700 m.
- The ensemble mean of multiple RAs has the potential to provide a more reliable estimate of OHC than a single RA.

1. Introduction

Studying the thermal state changes in the oceans is important to understand global climate change. Variations in the ocean thermal state are subject to internal climate variations such as El Niño-Southern Oscillation (ENSO) (Bjerknes, 1966, 1969); Cheng et al., 2018; Wang et al., 2018) and anthropogenic activities (Gleckler et al., 2012; Pierce et al., 2006). Recent warming of the Earth is largely attributed to increasing anthropogenic greenhouse gas (GHG) emissions (Cheng et al., 2021, 2022; Trenberth et al., 2016), modulated by distinctive climate events (Balmaseda et al., 2013). Over 90% of the excess heat (net radiative imbalance at the top-of-atmosphere) supplied to the earth system since the 1970s has been absorbed by the oceans (Riser et al., 2016); and it is manifested in ocean heat content (OHC) anomalies (Palmer et al., 2011; von Schuckmann et al., 2020), which is considered as a viable climate-change indicator (Cheng et al., 2017). Motivated by the increasing concerns regarding the adverse impacts of climate change and the essential role of the oceans in heat uptake, substantial efforts have been taken to study the OHC variations (Abraham et al., 2017).

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1029/2021EF002532.

This article is protected by copyright. All rights reserved.
Argo network emphasize the importance of integrating all observing systems of seawater temperature to increase our confidence in the OHC estimate. The most reliable datasets to examine OHC originate from observations. However, historical observations are spatiotemporally sparse (Abraham et al., 2013; Cheng & Zhu, 2016; Roemmich & Gilson, 2009), and are also subject to considerable geographic and seasonal biases (Roemmich & Gilson, 2009). For instance, significantly more data are available along the coastlines of the developed countries and many more records were collected in the summer than winter (Roemmich & Gilson, 2009). The advent of the global Argo (Array for Real-Time Geostrophic Oceanography, approximately at a resolution of 300 km) profiling floats in the 2000s significantly mitigated these biases. However, the higher latitudes, particularly the ice-covered regions, and the marginal seas are still poorly resolved by the Argo network. Additionally, Argo floats (except the Deep Argo) are confined to the top 2000 m, and many earlier Argo floats did not even reach this depth (von Schuckmann et al., 2020). These geographic and depth limitations of the Argo network emphasize the importance of integrating all observing systems of seawater temperature to increase our confidence in the OHC estimate.

Some gridded datasets of ocean temperature and salinity were constructed using only Argo or a synthesis of Argo and other observations (Cheng & Zhu, 2016; Good et al., 2013; Li et al., 2017; Roemmich & Gilson, 2009), mainly including measurements from Mechanical Bathythermograph (MBT, widely deployed from 1938 to the early 1960s), eXpendable BathyThermographs (XBTs, popular from 1970s to 2000s), mooring, gliders, conductivity-temperature-depth (CTD, since 1969), and bottles and instruments installed on marine mammals (Cheng et al., 2022; Garcia-Soto et al., 2021).

Numerical ocean modeling is another major source of oceanic temperature information. Many numerical ocean models are constrained by observations to generate RAs, which generally describe the ocean state much better than the unconstrained models (Hoteit et al., 2010; Stammer et al., 2016). In particular, Argo data were shown to significantly enhance the reliability of RAs (Chamberlain et al., 2021; Köhl, 2020; Zuo et al., 2019). However, large uncertainties remain in the RAs’ ocean state estimates, primarily in the regions of Antarctic Circumpolar Current (ACC) and the western boundary currents (WBCs), mainly due to complex spatiotemporal scales and strong nonlinearities (Carton et al., 2018; Chamberlain et al., 2021; Köhl, 2020; Zuo et al., 2019).

RAs differ from each other in various aspects such as the underlying model configuration and inputs, and the implemented data assimilation approach and setup. The following question then arises: how robust and reliable these RAs are for examining the global and basins-wide OHC and their variations? This can at least partially be answered by comparing representative RAs with observation-based datasets. Identifying the differences between these datasets allows to quantify the accuracies and weaknesses of RAs in estimating the OHC, eventually providing clues towards improving them. Likewise, this comparison may also improve the evaluation of the OHC with the observation-based datasets, particularly those using zero anomalies as the background field in the absence of observations (Good et al., 2013).
Liang et al. (2021) recently compared the OHC variability and changes using eight observation-based datasets over the period 2005–2019. An earlier study by Palmer et al. (2017) analyzed the OHC variability and changes from a total of 19 RAs. Our study built on these works by examining four different types of representative ocean datasets in the estimation of global and basins-wide OHC variations. This was motivated by the lack of a direct and comprehensive comparison of state-of-the-art RAs with observation-based datasets in estimating the OHC over the Argo-era, notwithstanding the recent study of Stammer et al. (2021) that compared the salinity estimate between observation-based datasets and RAs.

A total of 12 state-of-the-art ocean datasets (Tab. 1) are examined here to evaluate their performances in estimating the global and basins-wide OHC. These datasets can be grouped into four different types: three datasets based on Argo (BOA, IPRC, and SIO); three datasets merging Argo and other ocean measurements (EN4.2.2, IAP and Ishii); five RAs (BRAN2020, ECCOv4r4, GECCO3, ORAS5, and SODA3.12.2); and one free-running (without data assimilation) model simulation (SODA3.12.2.0).

The goal of this study is twofold: 1) evaluate the performances of the state-of-the-art global ocean datasets in estimating the OHC; and 2) present comprehensive global and basins-wide OHC estimates from the latest data sources during the Argo-era. The remainder of this paper is organized as follows. Section 2 provides a brief description of the datasets and methodologies. Section 3 presents and interprets the results. Section 4 offers a summary of the main findings along with a discussion on potential future extensions.

2. Data and Methods

2.1 Datasets

The used datasets can be classified into four types. They are outlined in Tab. 1 and briefly described in this section. Readers are referred to the corresponding references for full details.

(1) Gridded datasets based on Argo data only

This group of datasets was constructed from the Argo data only or at least the temperature information was only taken from the Argo. Here, three of such gridded datasets were used: Barnes objective analysis (BOA) global gridded Argo dataset (Li et al., 2017; Lu et al., 2020), the International Pacific Research Center (IPRC) dataset (http://apdrc.soest.hawaii.edu/projects/argo/), and the Scripps Institution of Oceanography (SIO) dataset (Roemmich & Gilson, 2009). All the three datasets have a horizontal resolution of ~0.1° and are confined to the top 2000 m, due to the depth limit of the Argo profiling floats. The vertical depth unit is dbar (decabar) in all three datasets. For simplicity, this study approximately considered the original depth unit dbar to be 1 m, with a depth error of less than 2% at 2000 m depth. We refer to these three datasets as the Argo group, which was used to identify the consensuses and discrepancies in the OHC estimate among the Argo-based-only datasets.

(2) Gridded datasets based on Argo and other measurements

This group of datasets merges both Argo and other historical observations. We included three of these datasets: the EN4.2.2 (hereinafter EN4) from the Met Office Hadley Centre (Good et al., 2013), the Institute of Atmospheric Physics (IAP) (Cheng & Zhu, 2016) dataset, and Ishii et al. (2017) dataset. Similarly to the Argo datasets, the
The five RAs used in this study, namely BRAN2020 (Chamberlain et al., 2021), ECCOv4r4 (Forget et al., 2015), GECCO3 (Köhl, 2020), ORAS5 (Zuo et al., 2019) and SODA3.12.2 (Carton et al., 2018), differ significantly between each other. First, the horizontal resolution increases from ~1° (ECCOv4r4) to 0.1° (BRAN2020). Second, the atmospheric forcing and therefore the temporal coverage are also different. Third, BRAN2020, ORAS5, and SODA3122 were derived using the sequential data assimilation techniques and are thus not dynamically-consistent. ECCOv4r4 and GECCO3 were generated using the MIT General Circulation Model (MITgcm) and its adjoint and are dynamically-consistent ocean state estimates (Hoteit et al., 2018; Stammer et al., 2016), which means that the ECCOv4r4 (GECCO3) state estimate satisfies known equations of motion and conservation laws (Wunsch, 2011). Other differences among these RAs include numerical mixing schemes and assimilated datasets, to name but a few. Overall, these RAs represent the latest global or quasi-global reanalyzes, and almost all outperformed their predecessors in the estimation of the ocean state. We refer to these datasets as the RA group. Comparisons between this group and the first two observation-based groups (Argo and AllObs) will showcase the capabilities and weaknesses of state-of-the-art RAs.

Additionally, we combine all the three above-mentioned groups into one group and refer to it as the All group. The consensuses and discrepancies in the All group indicates the robustness and uncertainties of OHC estimate in the current representative datasets.

(4). **Free-running model dataset**

The last used dataset is SODA3.12.2.0 (hereinafter SODA31220), which was simulated by an unconstrained model, with the only difference from SODA3122 being that SODA31220 did not assimilate observations. The comparison between SODA3122 and SODA31220 is conducted to assess the effects of data assimilation on improving the simulations of the spatiotemporal characteristics of OHC.

**2.2 Methods**

We focused our study on the Argo-era between 2005–2017, an overlapping period of all the used datasets. We confined our investigation domain between 63°S and 63°N, similar to Liao et al. (2022) because of the spareness of the observations in the polar areas. The domains of the different basins are taken from Fig. 1 in Liao et al. (2022).
OHC is calculated as the product of potential temperature, seawater density, specific heat capacity, and grid volume (Eq. 1) (Hakkinen et al., 2016; Liao et al., 2022). Following Hakkinen et al. (2015), the first year (2005) was chosen as the baseline to calculate the OHC anomalies.

\[
\text{OHC} = \rho \delta v C_p (\theta - \theta_{2005}) = \rho \delta v C_p \Delta \theta, \quad (1)
\]

where \( \rho \) (kg m\(^{-3}\)) corresponds to the seawater density, \( \delta v \) (m\(^3\)) is the grid volume, \( C_p \) (J kg\(^{-1}\)°C\(^{-1}\)) is the specific heat of seawater at constant pressure, \( \theta \) (°C) represents the annual mean potential temperature, and \( \theta_{2005} \) denotes the annual mean potential temperature in 2005.

The potential temperature change is decomposed into two components considering that similar OHC variations may be associated with different processes (Liao et al., 2022). The first component is attributed to the vertical movement of neutral density surfaces (a continuous analog of discretely referenced potential density surfaces (Jackett and McDougall, 1997)), the so-called heave (hereinafter called HV). The second component occurs along the neutral density surfaces, the so-called spiciness (hereinafter called SP). The HV component generally dominates the potential temperature change (Hakkinen et al., 2015, 2016); however, the SP component can be of regional importance, e.g., in the subpolar North Atlantic (SPNA). We followed Bindoff and Mcdougall (1994) to decompose the potential temperature as:

\[
\frac{d\theta}{dt} \bigg|_z = \frac{\text{HV}}{d\theta/dz|_n} d\theta/dz + \frac{\text{SP}}{d\theta/dt|_n}, \quad (2)
\]

where \( t \) (year) denotes the time, \( z \) (m) is the depth, and \( |n| \) means along a neutral density surface.

The ensemble mean (ESM) and spread (ESD) of each group are calculated to quantify the consensuses and discrepancies among the different datasets (Liang et al., 2021; Liu et al., 2020; Wang et al., 2018):

\[
\text{ESM}(x, y, t) = \frac{1}{N} \sum_{k=1}^{N} X_k(x, y, t), \quad (3)
\]

\[
\text{ESD}(x, y, t) = \left( \frac{1}{N-1} \sum_{k=1}^{N} (X_k(x, y, t) - \text{ESM}(x, y, t))^2 \right)^{1/2}, \quad (4)
\]

where \( N \) is the number of datasets; \( X \) represents each dataset; and \( x \) and \( y \) denote the longitude and latitude, respectively.

The spatial distributions of the ESM and ESD in section 3.3 were calculated using the data from each dataset interpolated onto the horizontal grid of IPRC. The IPRC land/sea mask was chosen as a common mask owing to having the smallest ocean area among all the selected datasets. The top 2000 m was divided into the upper ocean (0–700 m) and the intermediate ocean (700–2000 m). Based on a multiple linear regression using the least squares method, we calculated the trends in the global and basins-wide OHC, HV, and SP in these two ocean layers. Additionally, the meridional distributions of trends in the zonally-integrated OHC, HV and SP were calculated.

Detailed geographic patterns of trends in the OHC, HV, and SP were obtained by calculating the vertically-integrated values at each geographic location for both upper and intermediate oceans. Additionally, the trends in the zonal
averages of the vertical displacements of neutral density surface and SP-associated potential-temperature change along the neutral density surfaces were calculated.

It is worthwhile to note that we also calculated the OHC from 2005 to the latest year for each product. Additionally, considering the marginal seas (e.g., Gulf of Mexico) are not well resolved by the observation-based datasets, we used the land/sea mask of the IPRC dataset to calculate the OHC. This excluded the influences of the different spatial coverages in the comparison of the OHC estimates among all the datasets. These supplementary results are archived in Zenodo (https://doi.org/10.5281/zenodo.6393654).

3. Results

3.1 Estimate of trends in the global and basins-wide OHC

a. The upper ocean (0–700 m)

All the datasets suggested a warming trend in the upper Pacific, Atlantic and Indian Oceans (Fig. 2 and Tabs. 2–5), with the Argo group indicating a corresponding ESM of the warming rate at 1.92, 0.64 and 2.13 ZJ·yr⁻¹ (ZJ means Zettajoule and equals 10²¹ joules; yr means year), respectively. The differences in the upper-ocean OHC trends were minor among both the Argo datasets and the AllObs datasets. Almost all the observation-based datasets showed that the upper Indian and Atlantic Oceans exhibited the highest and lowest warming rates, respectively. The intense warming in the upper Indian Ocean is consistent with the rapid Indian Ocean warming during 2003–2012, resulting from an increased Indonesian Throughflow (ITF) transporting more heat from the Pacific Ocean (Lee et al., 2015).

Additionally, the AllObs group suggested a much stronger warming in the upper Atlantic Ocean than the Argo group. The estimated global warming rate in the AllObs group was found to be consistently higher (15.11–18.44%) than the Argo group. The primary reason is that the coastal areas and marginal seas are better resolved with the introduction of other historical measurements. We further calculated the OHC rate after applying the IPRC land/sea mask to all the datasets to validate this hypothesis. A decrease in the global warming rate was evident in the AllObs group, but not notable in the Argo group (Tab. 2).

The RA group showed a much larger spread compared to the two observation-based groups (Fig. 2 and Tabs. 2–5). Some RAs exhibited a much higher warming rate than the observation-based datasets in the upper Pacific, Atlantic and Indian Oceans. For example, GECCO3 (BRAN2020) exhibited a warming rate 65.40% (83.80%) and 291.12% (138.89%) higher than the ESM of the Argo group in the upper Pacific and Atlantic Oceans, respectively. This large upper-ocean warming rate in GECCO3 is consistent with Köhl (2020), which showed that the heat uptake was almost exclusive in the top 700 m in GECCO3. The warming rates calculated based on SODA31220 were generally even higher, whilst SODA3122 had a much better agreement with the observation-based datasets. Overall, RAs exhibited smallest discrepancies with observation-based datasets in the upper Indian Ocean.

The calculated warming rates in the upper Pacific and Atlantic Oceans were generally higher over the extended period (2005– column, Tabs. 3 and 4) than over 2005–2017. The warming rate, was however lower over the extended period in the upper Indian Ocean (2005– column, Tab. 5).
Fig. 2 shows that the HV dominated the OHC variations, indicating that the examined OHC variations mainly resulted from the vertical movements of neutral density surfaces (or approximated as isopycnals). The SP was largely associated with cooling and it could partially dampen the HV-associated warming. Opposing HV variations by SP is typical in the subtropical regions (Hakkinen et al., 2016). As for the global HV and SP variations, observation-based datasets were relatively in good agreement, but noticeable differences existed in each basin. Significantly larger differences in the HV and SP variations were observed among RAs. For instance, BRAN2020, GECCO3 and ORAS5 showed much stronger HV-associated warming in the upper Pacific Ocean (Fig. 2f). The large spread in the HV-associated warming among these RAs may be related to the atmospheric forcing or the simulations of vertical diffusion of heat (Liao et al., 2022). Among all the datasets, GECCO3 (ECCOv4r4) revealed the strongest SP-associated warming (cooling) in the upper Atlantic (Indian) Ocean. A possible reason for the large SP spreads in the Atlantic and Indian Oceans may be due to the suboptimal representations of the highly salty Mediterranean overflow water (MOW) and the Red Sea overflow water (RSOW), respectively. A proper simulation of outflows of these highly salty waters from the marginal seas remains a challenge for current ocean models (Sasaki et al., 2020; Zuo et al., 2019). Furthermore, SODA31220 generally showed the largest HV-associated warming rates for each basin (the second largest in the Indian Ocean).

Table 2

In summary, all the datasets suggested warming in the upper ocean, but much better agreements in terms of OHC changing rates of the upper ocean were observed in the observation-based datasets in comparison to the RAs. Special caution is clearly needed when estimating global or basins-wide OHC using only one single RA or a free-running model simulation.

b. The intermediate ocean (700–2000 m)

Almost all the datasets suggested warming in the intermediate Pacific, Atlantic and Indian Oceans (Fig. 3 and Tabs. 3–5). The corresponding ESM of the warming rate is 1.59, 1.45 and 0.65 ZJ·yr⁻¹ in the Argo group, respectively. The global OHC trend in the intermediate ocean was similar among the observation-based datasets, which also exhibited a warming rate in the intermediate Pacific Ocean comparable to that in the intermediate Atlantic Ocean, and was approximately twice (or even thrice) as high as that in the intermediate Indian Ocean. All the observation-based datasets presented a total global warming rate between 8.28–9.41 ZJ·yr⁻¹ in the top 2000 m, similar to the reported global warming rate of 9.1 ± 0.3 ZJ·yr⁻¹ from 1986 to 2020 (Cheng et al., 2021). The time period considered in this study is much shorter; however, this consistency with the literature on the top 2000 m warming indicates that the global warming rate of the top 2000 m has been relatively stable since around 1986.

Similar to the upper ocean, the calculated warming rates based on RAs could be significantly different from those calculated using the observation-based datasets, especially in the intermediate Indian Ocean. BRAN2020 likely overestimated the warming rates in the Pacific, Atlantic and Indian Oceans. In contrast, the warming might be
underestimated in ECCOv4r4 and GECCO3, especially in the intermediate Pacific and Indian Oceans. In fact, both ECCOv4r4 and GECCO3 exhibited a cooling in the intermediate Indian Ocean, whilst all the other datasets suggested warming. Compared to the ESM of the Argo group, SODA31220 showed a much higher warming rate in the intermediate Atlantic and Indian Oceans, but it agreed well with the observations in the intermediate Pacific Ocean.

According to the observation-based datasets, the ratio of the global warming rate in the intermediate ocean to that in the upper ocean ranged from 56% to 87%. Although a similar ratio was observed in ORAS5 (88%) and SODA3122 (69%), ECCOv4r4 and GECCO3 presented an exclusive heat uptake in the top 700 m. BRAN2020 suggested that the global warming rate between 700–2000 m was even greater than the top 700 m.

The SP was largely associated with warming in the intermediate ocean (Fig. 3). Some datasets (e.g., IPRC) even indicated that the SP plays a greater role than HV. Certain differences in the HV and SP components could be identified among the observation-based datasets despite the high agreement in estimating the OHC. For instance, IPRC and Ishii showed significantly stronger SP-associated warming in the intermediate Pacific Ocean (Fig. 3j). The large differences in the SP from other observation-based datasets may be indicative of large differences in the salinity anomalies in IPRC and Ishii. BRAN2020 presented the largest HV-associated warming in all major intermediate basins (Fig. 3f–h) and second strongest SP-associated cooling of a marginal statistical significance in the intermediate Indian Ocean (Fig. 3l). The much weaker warming by ECCOv4r4 was primarily attributed to the strongest SP-associated cooling in the Pacific (Fig. 3j) and Indian (Fig. 3l) Oceans, as its HV estimates were similar to those of the observation-based datasets.

In summary, almost all the datasets suggested warming in the intermediate Pacific (Tab. 3), Atlantic (Tab. 4) and Indian (Tab. 5) Oceans. The observation-based datasets showed that warming in the intermediate Atlantic Ocean was significantly stronger than in the upper Atlantic Ocean, whilst warming in the intermediate Pacific and Indian Oceans were slightly and significantly weaker than in the upper oceans, respectively. Marked differences were observed between the RAs in the intermediate ocean.

### 3.2 Meridional distributions of the warming trend

#### a. The upper Ocean (0–700 m)

The meridional distributions of the zonally-integrated warming trend of the upper ocean were mostly similar among the different datasets. Extensive warming was observed in the subtropical South Pacific (Fig. 4b) and North Atlantic Oceans (Fig. 4c). Additionally, warming was seen throughout the upper Indian Ocean, except for some zonal bands in the South Indian Ocean (Fig. 4d). Major cooling patterns appeared mainly in the tropical North Pacific Ocean and SPNA.

Certain differences were still noticeable. Among the observation-based datasets, IPRC exhibited a significant cooling in the tropical North Atlantic Ocean (Fig. 4c). The warming peak around 30° N in the North Atlantic Ocean was much weaker in SIO than in IAP (Fig. 4c). RAs were able to capture similar large-scale warming and cooling patterns; however, the spread between the RAs and from observation-based datasets were evident. For instance, GECCO3
approximately exhibited the largest warming trend along most of the latitudes in terms of the global upper-ocean OHC (Fig. 4a). SODA31220 clearly overestimated the warming trend, especially in the Pacific Ocean (Fig. 4b).

Overall agreements in terms of the HV among the different datasets were approximately better than those in SP. The HV and SP showed an approximately out-of-phase relationship in the low-middle latitudes. The most significant and extensive deviations of the SP relative to the observation-based datasets appeared in GECCO3, especially in the Pacific (Fig. 4j) and Atlantic (Fig. 4k) Oceans. For instance, GECCO3 presented approximately the strongest SP-associated cooling equatorward of 30°N in the North Pacific Ocean, whereas the other datasets mostly indicated SP-associated warming in this region. Strong SP-associated cooling was suggested by ORAS5 in the South Pacific (Fig. 4j), Indian Oceans (Fig. 4l), and in some zonal bands of the North Atlantic Ocean (Fig. 4k). Additionally, BRAN2020 exhibited a significantly stronger SP-associated cooling and warming in the equatorial Pacific ocean and the Pacific sector of the Southern Ocean (Fig. 4j), respectively.

Fig. 3.

The ESM of the RA group was in good agreement with the observational ESMs in the upper ocean (Fig. 5). This is largely an offset between the different RAs, as shown in Fig. 2. The ESM of multiple RAs may be a better choice to reduce uncertainty and increase our confidence in the OHC estimate. However, a larger sample of RAs is required to further confirm the advantages of the ESM.

Despite the high agreement, some differences remain in the ESM of the different groups. Approximately between 20–30° N, the Argo group exhibited a notably weaker warming than the AllObs and RA groups (Fig. 5a). This was mainly attributed to the differences in the HV-associated warming in the upper Atlantic Ocean (Fig. 5g). The corresponding SP-associated warming (cooling) was the strongest (weakest) from the Argo group (Fig. 5k), which could partially compensate for the weaker HV-associated warming. In contrast, the SP-associated warming between 20–30° S was significantly weaker in the Argo group than the other datasets (Fig. 5k). Moreover, the Argo group suggested weaker SP-associated cooling or warming between around 20–50° S in the Indian Ocean (Fig. 5l). Compared to the SP component, the overall differences in HV variations were generally smaller among the different datasets, especially poleward of approximately 40°.

Fig. 5.

In the tropical South Pacific Ocean (Fig. 6b), tropical North Atlantic Ocean and around 40° N in the Atlantic Ocean (Fig. 6c) and midlatitudes of the South Indian Oceans (Fig. 6d), large ESDs appeared in the Argo group. The ESDs in the RA group were generally larger than those in the observational groups over most latitudes. The larger sample in the RA group (five datasets) than the Argo and AllObs groups (each having three datasets) could at least partially account for the larger ESD. Large ESDs primarily appeared in the low-middle latitudes of each basin. These consistently large uncertainties will be demonstrated to be mostly associated with boundary currents and their extensions, such as intense WBCs, suggestive of relatively poorer performance of both RAs and observation-based
datasets in the highly dynamic regions. Moreover, large ESDs in the HV component generally correspond to large ESDs in the SP component, indicating that the large uncertainties of subsurface temperature and salinity may co-exist.

In summary, compared to observation-based datasets, RAs exhibited similar meridional patterns of zonal-integrated warming trends, but remarkable differences were observed in some regions. Despite some regional discrepancies, the agreement between the observation-based datasets and RAs significantly improved when considering their ESMs.

*b. The intermediate Ocean (700–2000 m)*

Significantly larger differences were observed between these datasets in the intermediate ocean than in the upper ocean (Fig. 7). More specifically, BRAN2020 suggested a much stronger warming rate (Fig. 7a), primarily equatorward of 30° and in the Southern Ocean. Both HV and SP contributed to these differences. For instance, BRAN2020 exhibited the strongest HV-associated (Fig. 7f) and SP-associated (Fig. 7j) warming in the tropical South Pacific Ocean. In sharp contrast, GECCO3 largely exhibited a cooling trend equatorward of 30° (Fig. 7a). However, between around 35°–45°N in the Atlantic Ocean, the strongest warming trend was shown by GECCO3 (Fig. 7c), mainly associated with SP (Fig. 7k). Furthermore, ORAS5 also presented remarkably different HV and SP variations. It for instance, exhibited the strongest HV-associated cooling (Fig. 7f) and significantly larger SP-associated warming than most other datasets (Fig. 7j) approximately equatorward of 30° in the Pacific Ocean.

Similar to the upper ocean, the ESM of each group agreed well with each other in the intermediate ocean. Warming was noticeable in most of the latitudes of the Pacific and Atlantic Oceans, particularly strong at approximately 50° S in the South Pacific Ocean (Fig. 8b) and around 35° N in the North Atlantic Ocean (Fig. 8c). A dipole pattern appeared in the South Indian Ocean (Fig. 8d), with a pair of strong warming and cooling patches located south of and north of 30° S, respectively.

Despite these similar large-scale patterns, marked differences were observed among different groups. Compared to the *AllObs* and *RA* groups, the *Argo* group exhibited significantly weaker HV-associated warming (Fig. 8e) and stronger SP-associated (Fig. 8i) warming in the low-middle latitudes of the Northern Hemisphere, primarily in the Atlantic and Indian Oceans (Fig. 8g, h, k, l). In the South Pacific Ocean, the *RA* group showed much stronger SP-associated warming approximately between 10–20° S and much stronger SP-associated cooling approximately between 30–50° S (Fig. 8j). Additionally, the *RA* group exhibited HV-associated warming in the North Indian Ocean, whilst the *Argo* and *AllObs* groups showed cooling associated with the HV (Fig. 8h). Moreover, the *RA* group suffered from remarkable discrepancies with the observational groups in the SP variations in the Indian Ocean. More specifically, observational groups suggested SP-associated warming in the bulk of Indian Ocean, whilst the *RA* group showed SP-associated cooling in the North Indian Ocean and middle latitudes of the South Indian Ocean (Fig. 8l).
Different groups reached a high agreement in terms of SP variations approximately at 10° S in the South Indian Ocean (Fig. 8l).

Fig. 8.

Fig. 9 clearly indicated that the ESDs in the RA group were significantly larger than those from the observation-based datasets. The Argo and AllObs groups did not present significant differences, except in the low-middle latitudes of the North Atlantic Ocean, where the ESDs of the AllObs group were notably larger than the Argo group (Fig. 9c), mainly due to the HV component (Fig. 9g). The ESDs in the HV and SP components calculated from observation-based datasets in the low and middle latitudes of the Pacific Ocean were large (Fig. 9f, j); however, an offset between these two yielded small ESDs in the total OHC variations (Fig. 9b). In the RA group, the ESDs were primarily concentrated in the Pacific sector of the Southern Ocean (Fig. 9b), associated with SP (Fig. 9j); in the tropical North Pacific Ocean (Fig. 9b), associated with both the HV (Fig. 9f) and SP (Fig. 9j); in the tropical South Pacific Ocean (Fig. 9b), mainly associated with the SP (Fig. 9j); in the subtropical North Atlantic Ocean (Fig. 9c), associated with both the HV (Fig. 9g) and SP (Fig. 9k); and in the subtropical South Indian Ocean (Fig. 9d), with a comparable contribution from HV and SP (Fig. 9h, l).

Fig. 9.

In summary, significantly larger differences were observed among these datasets in the intermediate ocean than in the upper ocean. Although large-scale patterns of OHC variations were similar among the ESMs of different groups, certain differences in terms of HV and SP variations were observed between the observation-based datasets and RAs. In general, RAs presented notably larger ESDs than the observational groups.

3.3 Geographic distribution of warming trends

a. The upper Ocean (0–700 m)

The spatial patterns of the OHC trends in the upper ocean were largely similar among the examined datasets (Fig. 10). Large-scale warmings appeared in the eastern and southwest Pacific Oceans, northwest Atlantic Ocean, and North and southeast Indian Oceans. Intense cooling mainly appeared in the northwest Pacific Ocean, a cooling tongue in the South Pacific Ocean, and northeast Atlantic Ocean. The cooling-warming pair in the western and eastern Pacific Oceans had an El Niño-like feature, which was previously reported by Liang et al. (2021). The profound cooling in the northeast Atlantic Ocean, known as North Atlantic warming hole (NAWH) in the literature, was a striking feature in the context of the global ocean warming. Some studies linked the NAWH to a weakening Atlantic meridional overturning circulation (AMOC; Caesar et al., 2018). Cheng et al. (2022) demonstrated that this NAWH is a result of GHG and industrial aerosols, with these two effects reinforcing each other in the SPNA. The intense warming associated with the Gulf Stream and North Atlantic Current was largely manifested in the deepening of midthermocline isopycnals (Häkkinen et al., 2015) as a result of a shift from a negative North Atlantic Oscillation (NAO) index in the 1950s–60s (Williams et al., 2014) to a positive NAO index since 1990s. Previous observations linked a poleward shift of the Gulf Stream to a positive NAO phase (Taylor & Stephens, 1998). The North Indian Ocean warming could be traced back to a negative IPO phase (Lee et al., 2015).

This article is protected by copyright. All rights reserved.
Some products (e.g., BOA and BRAN2020) exhibited more small-scale features than others (e.g., IAP and ECCOv4r4). The fine structures in BOA were attributed to a flexible response function used in BOA, which permits more mesoscale properties (Li et al., 2017). BRAN2020, as the only eddy-resolving dataset used in this study, is able to resolve the mesoscale eddies approximately; instead, mesoscale eddies are parametrized in the coarser resolution datasets (e.g., ECCOv4r4). The large influencing radius of 20° leads to a smoother pattern in IAP (Cheng & Zhu, 2016; Cheng et al., 2022). The smooth patterns in both ECCOv4r4 and GECCO3 are likely due to their smoothen formulation as least-squares solutions fitting the data over long time periods.

Some differences in terms of the warming or cooling strength were observed between the observational datasets. Most observation-based datasets exhibited a zonal cooling feature in the tropical North Atlantic Ocean, especially in IPRC (Fig. 10b), but was almost absent in IAP (Fig. 10e). IPRC (Fig. 10b) also showed more intense warming in the northwest Atlantic Ocean than IAP (Fig. 10e). Large deviations among the observation-based datasets also existed in the WBC systems. For instance, intense warming associated with the Agulhas Current was present in IPRC (Fig. 10b), but it was not observed in SIO (Fig. 10c). Among the observation-based datasets, SIO (Fig. 10c) approximately indicated the weakest warming trend in the Arabian Sea and the southeast Indian Ocean.

The RA group showed notable discrepancies from observation-based datasets. The warming associated with the Gulf Stream and the North Atlantic Current was weaker in the RA group compared to the observation-based datasets, except GECCO3, which also showed stronger warming north of 10° S in the Indian Ocean than most other RAs (Fig. 10i). In contrast, GECCO3 presented a much weaker NAWH. BRAN2020 (Fig. 10g) and GECCO3 (Fig. 10i) indicated stronger warming between 15–30° S in the Atlantic Ocean than other datasets. The large-scale cooling patterns in the southwest and subtropical South Indian Oceans were more notable in ECCOv4r4 (Fig. 10h) than in most other datasets.

Compared to SODA3122, SODA31220 presented stronger cooling in the northwest Pacific and significantly stronger warming in the eastern Pacific Ocean (Fig. 10l). The warming in the northwest and southwest Atlantic, and southeast Indian Oceans was also generally stronger in SODA31220 than in SODA3122. However, the NAWH was notably weaker in SODA31220 than most other datasets.

The spatial patterns of HV (Fig. 11) were similar to those of OHC (Fig. 10), with a major difference in the SPNA. More specifically, the intense SPNA cooling was dominated by SP, which was consistent to some extent with the freshening in the SPNA during 2005–2015 (Li et al., 2019). Additionally, the major HV-associated warming patterns were generally stronger than the corresponding OHC warming patterns, meaning that SP variations generally opposed HV variations (Fig. 12). The zonal band of cooling in the tropical North Atlantic in IPRC (Fig. 10b) was due to both HV (Fig. 11b) and SP-associated cooling (Fig. 12b). Additionally, IPRC exhibited localized SP-associated warming in the northeast Atlantic Ocean (Fig. 12b), which was likely an outlier. Among the RAs, BRAN2020 was notably different from the observation-based datasets. It showed much stronger HV-associated warming in the California Current system but much weaker HV-associated warming in the southeast Indian Ocean (Fig. 11g). GECCO3 showed a large-scale pattern of SP-associated cooling approximately equatorward of 33° N in the Pacific Ocean (Fig. 12i),
which was not observed in all other datasets. On the contrary, the moderate SP-associated cooling north of 30° N in
the Pacific Oceans indicated by the observation-based datasets was poorly resolved by GECCO3. Most importantly,
the intense SP-associated cooling exhibited by GECCO3 in the SPNA was much weaker than in the other datasets
(Fig. 12i). A salient difference between ORAS5 and observation-based datasets was an intense SP-associated cooling
feature along the southern coast of Australia and in the Tasman Sea (Fig. 12j).

Fig. 11.

In terms of ESM, there were no large-scale marked discrepancies in the spatial distributions of the different groups
(Fig. 13). It could be seen that the large ESDs were primarily in the highly dynamic regions. More specifically, the
large ESDs in the Argo group were associated with the Gulf Stream, Agulhas Current and its retroflection, and Brazil–
Malvinas Confluence zone. This suggests that the current ocean observing system (primarily the Argo floats) needs
to be expanded to better resolve these energetic flows to narrow the uncertainties (Cheng & Zhu, 2016; Good et al.,
2013; Köhl, 2020; Li et al., 2017; Liang et al., 2021; Zuo et al., 2019). The abovementioned ESDs were generally
smaller in the AllObs group. However, the AllObs group showed a much larger spread in the Gulf of Mexico (Fig.
13f). In the RA group, the largest ESDs were also associated with WBCs, especially in the Gulf Stream and its
associated extensions, Kuroshio and Agulhas Current retroflection regions (Fig. 13g). These marked ESDs among
RAs were indicative of the inadequacies of the current RAs in the highly dynamic regions, resulting from a set of
factors, such as inadequate observations and imperfect representation of the underlying physical processes, among
others. The ESDs of OHC variations largely originate from the HV component. However, even in the Argo group,
large SP-associated ESD appeared along the ACC path in the Indian sector, and in the Gulf Stream region (Fig. 13u).
ESDs were generally more extensive and larger in the RA group, especially in the Atlantic and Southern Oceans.

Fig. 12.

In summary, the large-scale patterns of warming and cooling were similar among the datasets, but their strength was
product-dependent. Most significant spread was generally observed in the highly dynamic regions, as indicated by
both observation-based datasets and RAs.

b. Intermediate ocean (700–2000 m)

In the intermediate ocean, most datasets showed widespread and moderate warming trends (Fig. 14). In the northwest
Atlantic Ocean, intense warming was observed. Additionally, strong warming was also seen in part of the Southern
Ocean. Large-scale cooling mainly appeared in the subtropical South Indian Ocean and part of the Southern Ocean.

Remarkable differences were found despite these consensuses. One of the most salient differences was the moderate
cooling trend indicated by IAP in the tropical North Atlantic Ocean (Fig. 14e). Additionally, there were discernable
differences among the observational datasets in the Southern Ocean, and comparatively, the differences among RAs
were much more notable. Both warming and cooling in BRAN2020 were generally much stronger. The profound
warming exhibited by BRAN2020 in the northwest Indian Ocean was almost not visible in other datasets. ECCOv4r4
(Fig. 14h) and GECCO3 (Fig. 14i) suggested cooling in the eastern Pacific Ocean and intense cooling southeast of South Africa. Additionally, the cooling in the northwest Pacific Ocean was stronger and more extensive in ECCOv4r4 (Fig. 14h) and GECCO3 (Fig. 14i). Given several differences between ECCOv4r4 and GECCO3 (e.g., horizontal resolution, surface forcing), it would be interesting to explore whether their common cooling patterns that are absent in the other datasets are related to their dynamically-consistent formulation. Except for these common differences shared by ECCOv4r4, GECCO3 also exhibited other differences. The warming in the subtropical South Pacific Ocean was for instance much stronger in GECCO3 (except compared to SODA31220). Additionally, GECCO3 was the only data showing intense basin cooling in the North and tropical South Indian Oceans. The remarkable cooling feature exhibited by GECCO3 in the northwest Atlantic Ocean was also an outlier. Furthermore, the intense warming in the northeast North Atlantic Ocean shifted eastward in GECCO3. A comparison of the two SODA3 datasets showed that the SODA31220 (Fig. 14l) indicated warming and cooling at higher rates, especially in the Atlantic and Southern Oceans.

Fig. 14.

Like the upper ocean, the HV dominated the OHC variations in the intermediate ocean in most datasets (Fig. 15), but the SP could be regionally important (Fig. 16). Overall, the differences in the HV and SP spatial distributions among the datasets were much larger in the intermediate ocean than in the upper ocean. This may be attributed to the relatively sparser observations and poorer modelling ability of RAs at greater depths.

The intense warming north of 30° N in the North Atlantic Ocean was mainly attributed to the HV component. SIO exhibited much weaker HV-associated warming in this region (Fig. 15c). The observed tropical North Atlantic cooling in IAP (Fig.13e) was mainly related to the HV (Fig. 15e). Equatorward of approximately 30° in the Pacific Ocean, IPRC and Ishii differed from others by presenting a large-scale pattern of HV-associated cooling (Fig. 15b, f) and SP-associated warming (Fig. 16b, f).

Although almost all RAs exhibited intense HV-associated warming in the North Atlantic and South Pacific Oceans, remarkable differences can still be observed. BRAN2020 overestimated the HV-associated warming in the Atlantic Ocean, the South Pacific Ocean, the South Indian Ocean, and the Arabian Sea (Fig. 15g). ECCOv4r4 showed the second largest HV-associated warming rate north of approximately 20° S in the Indian Ocean (Fig. 15h), where GECCO3 presented moderate HV-associated cooling (Fig. 15i). HV-associated cooling in the tropical Pacific Ocean was present in GECCO3 (Fig. 15i) and ORAS5 (Fig. 15j), which was similar to IPRC (Fig. 15b) and Ishii (Fig. 15f), to some degree.

The SP-associated cooling in the South Pacific and Indian Oceans, and in the North Pacific and Atlantic Ocean was also overestimated by BRAN2020 (Fig. 16g). ECCOv4r4 (Fig. 16h) and GECCO3 (Fig. 16i) exhibited SP-associated cooling in the tropical North Pacific and the North Indian Oceans that were not present in most other datasets. The zonal patterns of SP-associated cooling in the subtropical South Indian Ocean and the Pacific sector of the Southern Ocean might outliers in GECCO3. The above-mentioned strong cooling suggested by GECCO3 in the North Atlantic Ocean (Fig. 14i) was associated with SP (Fig. 16i). ORAS5 (Fig. 16j) presented a similar spatial distribution of SP

14

This article is protected by copyright. All rights reserved.
477 variations to IPRC (Fig. 16b) and Ishii (Fig. 16f). Compared to SODA3122, SODA31220 exhibited much stronger
478 SP-associated warming in the South Pacific, Atlantic and the Southern Oceans, and much stronger SP-associated
479 cooling in the North Atlantic Ocean.
480
481 The ESM of OHC variations in the intermediate ocean indicated warming over the bulk of the global ocean, with
482 intense warming in the North Atlantic Ocean and along the northern flank of ACC (Fig. 17). Cooling mainly occurred
483 in the subtropical South Indian Ocean, which could also be seen in the northeast Atlantic Ocean and on the southern
484 flank of ACC in the Pacific sector. The RA group exhibited stronger warming in the Atlantic Ocean than the
485 observation-based datasets and moderate cooling in the low-middle latitudes of the eastern Pacific Ocean (Fig. 17c).
486 In the two observational groups, the large-scale ESDs of OHC variations were primarily associated with the Agulhas
487 and North Atlantic Currents (Fig. 17e, f). Additionally, moderate ESDs were seen in approximately all WBCs and
488 along the ACC path. The RA group showed more widespread and larger ESDs (Fig. 17g), which was particularly
489 significant in the North Atlantic Ocean, the northwest Indian ocean, and Agulhas Current and its retroflexion region.
490 Large ESDs in the observational groups primarily originated from the HV component, especially in the Agulhas
491 Current retroflexion region and in the Gulf Stream system (Fig. 17m). Large ESDs related to SP appeared in the North
492 Atlantic Ocean (Fig. 17u). The ESDs in both HV and SP were generally larger in the RA group and a large ESD in
493 HV generally corresponded to a large ESD in SP. The largest ESDs in SP appeared west of the Iberian Peninsula. It
494 was likely related to the misrepresentation of MOW, which is a hot issue in RAs. Similarly, significant ESDs related
495 to SP in this region also appeared in the observational group, especially in the Argo group (Fig. 17u), suggesting that
denser observations are required.
498 In summary, observation-based datasets agreed well in terms of the large-scale patterns of OHC variations in the
499 intermediate ocean, but exhibited noticeable differences in the HV and SP variations. RAs showed much larger
500 differences among each other and from the observation-based datasets. However, the ESM of RAs captured the major
501 large-scale patterns indicated by the observation-based datasets. Both observation-based datasets and RAs suffered
503 from large ESD in the highly dynamic regions.

504 3.4 Isopycnal displacements and SP variations in the potential density domain

505 We calculated the trends in the zonal-averaged vertical displacements of the neutral density surfaces (Fig. 18) and
506 zonal-averaged SP-associated potential temperature change (Fig. 20) in the Pacific, Atlantic, and Indian Oceans to
507 analyze the warming or cooling contributions from different water-masses. This is similar to the method used in prior
508 studies (Hakkinen et al., 2016; Liao et al., 2022).

This article is protected by copyright. All rights reserved.
The latitude-potential density distributions of trend in the isopycnal deepening were largely similar in all the datasets, especially among the observation-based datasets (Fig. 18). In the Pacific Ocean, BRAN2020 overestimated the deepening of water-mass with a density of over 27 kg·m⁻³ in the South Pacific Ocean (Fig. 18g). This density range covers the Antarctic Intermediate Water (AAIW, $\sigma_\theta = 27.0$–27.4 kg·m⁻³) and Upper Circumpolar Deep Water (UCDW, $\sigma_\theta = 27.8$–28.0 kg·m⁻³). GECCO3 (and also ORAS5 and SODA31220) suggested shifting in this intense deepening to lighter water (Fig. 18i), which may extend to the South Pacific Subtropical Mode Water (SPSTMW, $\sigma_\theta \approx 26$ kg·m⁻³).

In the Atlantic Ocean, SIO (Fig. 18o) approximately exhibited the lowest deepening rate associated with the North Atlantic Subtropical Mode Water (NASTMW, also known as the Eighteen Degree Water (EDW), $\sigma_\theta = 26$–27 kg·m⁻³). RAs generally presented a slightly higher rate, especially BRAN2020 (Fig. 18s). The Atlantic Subpolar Mode Waters (SPMW, $\sigma_\theta = 27$–27.6 kg·m⁻³) were shown to be associated with a large shoaling in approximately all datasets; however, this shoaling was significantly weaker in ORAS5 (Fig. 18v) and in the two SODA3 datasets (Fig. 18w,x). Additionally, the AAIW and UCDW in the Atlantic Ocean were deepened in most datasets, but at a much lower rate in SIO (Fig. 18o) and ECCOv4r4 (Fig. 18t), and was almost absent in GECCO3 (Fig. 18u). Almost all waters denser than 27 kg·m⁻³ (except the SPMW) significantly deepened in BRAN2020 (Fig. 18s).

In the Indian Ocean, isopycnal deepening mainly occurred in the southern hemisphere. North of 30° S, moderate isopycnal shoaling was associated with water denser than 27 kg·m⁻³, corresponding to the northern branch of the AAIW in the South Indian Ocean. This appeared in most datasets, especially in GECCO3 (Fig. 18G); however, it was almost absent in BRAN2020 (Fig. 18E). Additionally, ECCOv4r4 did not exhibit the deepening associated with the southern branch of AAIW in the South Indian Ocean (Fig. 18F).

The ESMs of isopycnal deepening of the different groups were similar in terms of the major deepening or shoaling patterns (Fig. 19). Larger ESDs appeared in the South Pacific (Fig. 19g) and North Atlantic Oceans (Fig. 19o) in the RA group. Additionally, larger ESDs were also observed in the South Atlantic Ocean in the AllObs group (Fig. 19n).

The distribution of the SP-associated warming or cooling in the density domain was largely similar among the different datasets in the Pacific Ocean (Fig. 20). In both the South and North Pacific Oceans, an SP-associated warming pattern in the lighter water and an SP-associated cooling pattern in the denser water were observed. These patterns of water-mass variations were robust in most datasets except SODA31220 (Fig. 20l). Furthermore, most of the datasets exhibited SP-associated warming in the high latitudes of the North Pacific Ocean, which was associated with the North Pacific Intermediate Water (NPIW, $\sigma_\theta = 26.2$–26.8 kg·m⁻³). SP variations in the Pacific Ocean were generally minor for water denser than 27 kg·m⁻³, but BRAN2020 showed strong SP-associated cooling of water denser than 27 kg·m⁻³ in the South Pacific Ocean (Fig. 20g).
All datasets commonly showed the significant SP-associated cooling corresponding to the SPMW, the most salient characteristics in the SP variations of the Atlantic Ocean, though weakest in GECCO3 (Fig. 20u) and SODA3122 (Fig. 20w). Almost all datasets showed SP-associated warming approximately between 25–26.5 kg·m\(^{-3}\) equatorward of 30°S in the South Atlantic Ocean, which was remarkable in BRAN2020 (Fig. 20s) and GECCO3 (Fig. 20u) but very weak in Ishii (Fig. 20r).

SP variations were weak in the North Indian Ocean. In the South Indian Ocean, the most salient feature was the significant SP-associated cooling approximately from the sea surface to the water of a density of 27 kg·m\(^{-3}\), which mainly covers the Indian Ocean Subtropical Mode Water (IOSTMW, \(\sigma_\theta = 25.8–26.7\) kg·m\(^{-3}\)). ECCOv4r4 (Fig. 20F) and SODA31220 (Fig. 20J) approximately showed the strongest SP-associated cooling of the IOSTMW, whilst Ishii might significantly underestimate it.

The distributions of the ESM of SP variations in the density coordinate were similar among the different groups (Fig. 21). The intense SP-associated warming in the North Pacific Ocean was slightly stronger in the RA group (Fig. 21c), compared to the observation-based datasets, especially the Argo group (Fig. 21a). Additionally, the ESM of SP-associated warming in the South Atlantic Ocean was notably stronger in the AllObs and RA groups (Fig. 21j, k). Furthermore, the SP-associated cooling in the South Indian Ocean was also slightly stronger in the RA group (Fig. 21s). Larger ESDs of SP variations appeared in the North Atlantic Ocean and the Pacific Ocean, even in the Argo group.

4. Summary and Discussions

The spatiotemporal characteristics of global and basins-wide OHC from 2005 to 2017 were compared among 12 extensively used datasets. Moreover, a potential temperature decomposition and water-mass analysis were performed to further analyze the consensuses and discrepancies among these datasets. The main findings can be summarized as follows:

1. The total global OHC trends estimated by the observation-based datasets were generally similar. Over 2005–2017, the average OHC rate in the Argo group was 4.7 ZJ • yr\(^{-1}\) and 3.7 ZJ • yr\(^{-1}\) in the upper and intermediate oceans, respectively. RAs exhibited significant deviations from the average of the Argo group, with a maximum difference of 84.4% and 116.65%, respectively. The largest differences in the OHC changing rate were observed in the upper Atlantic and intermediate Indian Oceans, with some RAs exhibiting an OHC changing rate more than twice as high as those in observations.

2. Overall, observation-based datasets were in good agreement, despite some regional differences. In the upper ocean, RAs exhibited similar large-scale patterns indicated by observation-based datasets. In the intermediate ocean, RAs showed remarkable differences from the observation-based datasets, especially in the Atlantic and Indian Oceans. HV dominated the OHC variations in most of the global ocean, but SP could be regionally important.
3. Although an individual RA might differ significantly from the observation-based datasets, the ESM of the RAs showed a high agreement with that of the observation-based datasets. Almost all the datasets exhibited larger ESDs in the highly dynamic regions.

Although we reported marked reductions in the differences between RAs and observation-based datasets when considering the ESM, our small sample of five RAs cannot support a strong statement regarding the advantages of ESM. With that said, consideration of the ESM of multiple datasets rather than an individual dataset has the potential to increase our confidence in the OHC estimate.

This is more of a descriptive study. It primarily presented the consensuses and discrepancies in OHC variations and their components estimated using the latest datasets. Studies have been conducted to compare Argo datasets; however, comparing the observation-based datasets and RAs in the Argo-era makes this study worthy. It reveals the performance of the state-of-the-art RAs at estimating the OHC by comparing them with the current available observation-based datasets. It provides references for investigating of ocean state changes and clues to model developers for potential improvements in modeling and data assimilation. Additionally, the comprehensive OHC estimation over the Argo-era offers the community improved knowledge of global and regional warming in recent years.

This study only examined a set of global ocean temperature datasets. The inclusion of other datasets may reveal additional details. However, major conclusions are believed to hold because the datasets are representative and cover the four major sources of ocean temperature information for climate investigations.

We focus on the top 2000 m, over which OHC estimate based on observation-based datasets is believed to have a relatively small uncertainty. The pilot Deep Argo floats have been deployed. Once these reach their target density, it will be interesting to conduct a similar intercomparison study for the deep and abyssal oceans. This is particularly necessary because the lower ocean is more challenging to resolve and much less of it has been examined compared to the upper ocean. Typical reasons include a coarser vertical resolution, poor knowledge of physics (e.g., mixing) in the lower ocean, fewer observations, and a much longer memory time. An extension of this study to the deep and abyssal oceans is needed to understand the changes of the heat storage in the global ocean (Palmer et al., 2011).

Acknowledgments: We thank the two reviewers for providing their helpful comments and suggestions. The Argo-related data were collected and made freely available by the International Argo Program and the national programs that contribute to it (https://argo.ucsd.edu, https://www.ocean-ops.org). The Argo Program is part of the Global Ocean Observing System. Efforts taken to collect, process and deliver other observations (such as XBT) are also greatly appreciated. We are also grateful for the publicly available datasets used in this work.

Data and code availability: The public data and codes used in this study can be accessed as follows.

BOA: ftp://data.argo.org.cn/pub/ARGO/BOA_Argo/;


SIO: http://sio-argu.ucsd.edu/RG_Climatology.html;

This article is protected by copyright. All rights reserved.
EN4.2.2: https://www.metoffice.gov.uk/hadobs/en4/download-en4-2-2.html;

IAP: http://www.ocean.iap.ac.cn/;

Ishii: https://climate.mri-jma.go.jp/pub/ocean/ts/v7.3/;


ECCOv4r4: https://ecco-group.org/datasets-ECCO-V4r4.htm;

GECCO3: https://www.cen.uni-hamburg.de/en/icdc/data/ocean/docs-ocean/wget-gecco3-all.txt;

ORAS5: https://www.cen.uni-hamburg.de/en/icdc/data/ocean/easy-init-ocean/ecmwf-oras5.html;

SODA3.12.2: https://dsrs.atmos.umd.edu/DATA/;

SODA3.12.2.0: https://dsrs.atmos.umd.edu/DATA/.

The calculated annual-mean data can be accessed through https://doi.org/10.5281/zenodo.6393654.

The code for potential temperature decomposition: http://www.teos-10.org/preteos10_software/neutral_density.html;

The code for converting the in-situ temperature to potential temperature:

http://sam.ucsd.edu/sio210/propseawater/ppsw_matlab/.
5. References


This article is protected by copyright. All rights reserved.


This article is protected by copyright. All rights reserved.


This article is protected by copyright. All rights reserved.


This article is protected by copyright. All rights reserved.
Table 1. Summary of 12 datasets used in this paper. The number in the *Grids* column stands for the grids in the longitude, latitude, and vertical directions, respectively. $H_{\text{max}}$ denotes the maximum depth in dbar or m. / stands for not applicable. **WOD**: World Ocean Database. **ASBO**: Arctic Synoptic Basin Wide Oceanography. **GTSSPP**: Global Temperature and Salinity Profile Program. **CORA**: Coriolis data set for ReAnalysis. **NRT**: Near-real-time. **IFREMER**: Institut français de recherche pour l’exploitation de la mer. **NODC**: the U.S. National Oceanographic Data Center. **ICOADS2.1**: International Comprehensive Ocean-Atmosphere Data Set, release 2.1. 1* indicates the period 1979–2015; 2* indicates the period 2015–present. Note that the latitudinal coverage only reflects the latitude range of each product grid, but not necessarily the meridional domain where temperature information is available.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Years</th>
<th>Latitudes</th>
<th>Grids</th>
<th>$H_{\text{max}}$</th>
<th>Forcing</th>
<th>Data assimilated</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOA</td>
<td>2004–2020</td>
<td>80°S–80°N</td>
<td>360x160x58</td>
<td>1975</td>
<td>/</td>
<td>Argo</td>
</tr>
<tr>
<td>IPRC</td>
<td>2005–2019</td>
<td>90°S–90°N</td>
<td>360x180x27</td>
<td>2000</td>
<td>/</td>
<td>Argo</td>
</tr>
<tr>
<td>SIO</td>
<td>2004–2021</td>
<td>65°S–80°N</td>
<td>360x145x58</td>
<td>1975</td>
<td>/</td>
<td>Argo</td>
</tr>
<tr>
<td>EN4.2.2</td>
<td>1900–2021</td>
<td>83°S–89°N</td>
<td>360x173x42</td>
<td>5350</td>
<td>/</td>
<td>WOD19, ASBO, GTSSPP, Argo</td>
</tr>
<tr>
<td>IAP</td>
<td>1940–2021</td>
<td>90°S–90°N</td>
<td>360x180x41</td>
<td>2000</td>
<td>/</td>
<td>WOD13</td>
</tr>
<tr>
<td>Ishii</td>
<td>1955–2019</td>
<td>90°S–90°N</td>
<td>360x180x28</td>
<td>3000</td>
<td>/</td>
<td>WOD13, GTSSPP, Argo</td>
</tr>
<tr>
<td>BRAN2020</td>
<td>1993–2020</td>
<td>75°S–75°N</td>
<td>360x1500x51</td>
<td>4509</td>
<td>JRA-55</td>
<td>CORA+NRT</td>
</tr>
<tr>
<td>ECCOv4r4</td>
<td>1992–2017</td>
<td>90°S–90°N</td>
<td>360x360x50</td>
<td>5906</td>
<td>ERA-Interim</td>
<td>IFREMER, NODC, WOA09</td>
</tr>
<tr>
<td>GECCO3</td>
<td>1948–2018</td>
<td>90°S–90°N</td>
<td>800x400x40</td>
<td>5720</td>
<td>NCEP RA1</td>
<td>EN4.2.1</td>
</tr>
<tr>
<td>ORAS5</td>
<td>1979–2018</td>
<td>90°S–90°N</td>
<td>144x1021x75</td>
<td>5902</td>
<td>ERA-Interim*</td>
<td>EN4.2.1+NRT</td>
</tr>
<tr>
<td>SODA3.12.2</td>
<td>1980–2017</td>
<td>75°S–90°N</td>
<td>1440x1070x50</td>
<td>5395</td>
<td>JRA-55</td>
<td>WOD13+ICOADS2.1</td>
</tr>
<tr>
<td>SODA3.12.2.0</td>
<td>1980–2017</td>
<td>75°S–90°N</td>
<td>1440x1070x50</td>
<td>5395</td>
<td>JRA-55</td>
<td>/</td>
</tr>
</tbody>
</table>
Table 2. Summary of OHC rate (ZJ·yr⁻¹) of the global ocean. The number in the brackets are the differences (in percentage) between each product and the ensemble mean of Argo group. The first two columns of numbers (italic) are analyzed in this paper. The IPRC in the bracket after the time period means that the IPRC land/sea mask applies.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–700</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOA</td>
<td>42(1.42)</td>
<td>3.65(-1.31)</td>
<td>5.82(3.43)</td>
<td>3.46(-0.69)</td>
<td>4.47(-2.44)</td>
<td>3.66(-0.71)</td>
<td>5.62(2.99)</td>
<td>3.45(-0.35)</td>
</tr>
<tr>
<td>IPRC</td>
<td>457(-2.74)</td>
<td>3.96(7.05)</td>
<td>5.16(-8.38)</td>
<td>3.50(0.38)</td>
<td>4.64(1.26)</td>
<td>3.96(7.34)</td>
<td>5.19(-4.83)</td>
<td>3.50(1.19)</td>
</tr>
<tr>
<td>SIO</td>
<td>4.89(4.16)</td>
<td>3.48(-5.75)</td>
<td>5.91(4.95)</td>
<td>3.50(0.31)</td>
<td>4.64(1.18)</td>
<td>3.44(-6.63)</td>
<td>5.56(1.84)</td>
<td>3.43(-0.84)</td>
</tr>
<tr>
<td>EN4</td>
<td>5.41(15.11)</td>
<td>3.93(6.21)</td>
<td>6.49(15.23)</td>
<td>3.73(6.87)</td>
<td>4.14(-9.67)</td>
<td>3.75(1.70)</td>
<td>5.27(-3.47)</td>
<td>3.49(0.86)</td>
</tr>
<tr>
<td>IAP</td>
<td>5.56(18.44)</td>
<td>3.11(-15.78)</td>
<td>6.00(6.64)</td>
<td>2.64(-24.33)</td>
<td>4.71(7.22)</td>
<td>3.13(-15.02)</td>
<td>5.21(-4.58)</td>
<td>2.64(-23.66)</td>
</tr>
<tr>
<td>Ishii</td>
<td>5.41(15.17)</td>
<td>4.00(8.23)</td>
<td>6.01(6.69)</td>
<td>3.83(9.85)</td>
<td>4.91(7.24)</td>
<td>3.89(5.54)</td>
<td>5.57(2.16)</td>
<td>3.69(6.62)</td>
</tr>
<tr>
<td>BRAN2020</td>
<td>7.58(61.49)</td>
<td>8.01(116.65)</td>
<td>7.48(32.84)</td>
<td>6.24(78.87)</td>
<td>6.69(45.94)</td>
<td>7.39(100.47)</td>
<td>6.78(24.20)</td>
<td>5.87(69.60)</td>
</tr>
<tr>
<td>ECCOv4r4</td>
<td>4.28(-8.96)</td>
<td>1.49(-59.58)</td>
<td>4.28(-24.05)</td>
<td>1.49(-57.19)</td>
<td>3.35(-27.01)</td>
<td>1.48(-59.97)</td>
<td>3.35(-38.69)</td>
<td>1.48(-57.37)</td>
</tr>
<tr>
<td>GECCO3</td>
<td>8.66(84.40)</td>
<td>1.68(-54.63)</td>
<td>10.07(78.87)</td>
<td>1.59(-54.39)</td>
<td>7.89(72.22)</td>
<td>1.73(-53.08)</td>
<td>9.22(69.07)</td>
<td>1.64(-52.67)</td>
</tr>
<tr>
<td>ORAS5</td>
<td>5.75(22.47)</td>
<td>5.07(37.10)</td>
<td>5.75(2.17)</td>
<td>5.07(45.22)</td>
<td>5.38(17.48)</td>
<td>4.62(25.20)</td>
<td>5.38(-1.32)</td>
<td>4.62(33.34)</td>
</tr>
<tr>
<td>SODA3122</td>
<td>4.56(-2.90)</td>
<td>3.15(-14.88)</td>
<td>4.56(-18.99)</td>
<td>3.15(-9.84)</td>
<td>3.72(-18.77)</td>
<td>3.22(-12.57)</td>
<td>3.72(-31.77)</td>
<td>3.22(-6.88)</td>
</tr>
<tr>
<td>SODA31220</td>
<td>11.55(145.85)</td>
<td>6.34(71.46)</td>
<td>11.55(105.10)</td>
<td>6.34(81.62)</td>
<td>9.85(114.98)</td>
<td>5.83(58.20)</td>
<td>9.85(80.57)</td>
<td>5.83(68.48)</td>
</tr>
<tr>
<td>Argo</td>
<td>4.70(0.00)</td>
<td>3.70</td>
<td>5.63</td>
<td>3.49</td>
<td>4.58</td>
<td>3.69</td>
<td>5.46</td>
<td>3.46</td>
</tr>
</tbody>
</table>
Table 3. As for Tab.2 but of the Pacific Ocean.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>0–700</td>
<td>700–2000</td>
<td>0–700</td>
<td>700–2000</td>
<td>0–700</td>
<td>700–2000</td>
</tr>
<tr>
<td>BOA</td>
<td>1.61(-16.22)</td>
<td>1.43(-10.01)</td>
<td>2.48(-2.96)</td>
<td>1.32(-8.20)</td>
<td>1.61(-15.34)</td>
<td>1.43(-9.79)</td>
</tr>
<tr>
<td>IPRC</td>
<td>1.78(-7.13)</td>
<td>1.63(2.30)</td>
<td>2.34(-8.17)</td>
<td>1.42(-0.88)</td>
<td>1.78(-6.19)</td>
<td>1.63(2.61)</td>
</tr>
<tr>
<td>SIO</td>
<td>2.37(23.34)</td>
<td>1.71(7.71)</td>
<td>2.84(11.13)</td>
<td>1.57(9.08)</td>
<td>2.31(21.53)</td>
<td>1.70(7.18)</td>
</tr>
<tr>
<td>EN4</td>
<td>1.68(-12.53)</td>
<td>1.48(-6.97)</td>
<td>2.50(-2.06)</td>
<td>1.31(-8.99)</td>
<td>1.43(-24.93)</td>
<td>1.44(-9.19)</td>
</tr>
<tr>
<td>IAP</td>
<td>1.80(-6.13)</td>
<td>1.38(-13.43)</td>
<td>2.39(-6.49)</td>
<td>1.06(-25.90)</td>
<td>1.63(-14.07)</td>
<td>1.34(-15.41)</td>
</tr>
<tr>
<td>Ishii</td>
<td>2.10(9.56)</td>
<td>1.59(0.22)</td>
<td>2.57(0.89)</td>
<td>1.47(2.44)</td>
<td>1.99(4.67)</td>
<td>1.57(-0.76)</td>
</tr>
<tr>
<td>BRAN2020</td>
<td>3.53(83.80)</td>
<td>3.26(104.86)</td>
<td>3.53(38.41)</td>
<td>2.64(83.71)</td>
<td>3.16(66.32)</td>
<td>3.14(98.50)</td>
</tr>
<tr>
<td>ECCOv4r4</td>
<td>2.46(28.42)</td>
<td>0.46(-71.00)</td>
<td>2.46(-3.40)</td>
<td>0.46(-67.92)</td>
<td>2.21(16.51)</td>
<td>0.45(-71.46)</td>
</tr>
<tr>
<td>GECCO3</td>
<td>3.17(65.40)</td>
<td>0.54(-65.96)</td>
<td>4.04(58.51)</td>
<td>0.49(-65.92)</td>
<td>2.99(57.48)</td>
<td>0.53(-66.63)</td>
</tr>
<tr>
<td>ORAS5</td>
<td>2.35(22.69)</td>
<td>1.60(0.70)</td>
<td>2.35(-7.72)</td>
<td>1.60(11.39)</td>
<td>2.28(20.22)</td>
<td>1.55(-2.33)</td>
</tr>
<tr>
<td>SODA3122</td>
<td>1.44(-24.94)</td>
<td>1.19(-25.21)</td>
<td>1.44(-43.54)</td>
<td>1.19(-17.27)</td>
<td>1.18(-37.91)</td>
<td>1.23(-22.65)</td>
</tr>
<tr>
<td>SODA31220</td>
<td>5.57(190.34)</td>
<td>1.54(-2.80)</td>
<td>5.57(118.39)</td>
<td>1.54(7.52)</td>
<td>5.02(164.33)</td>
<td>1.52(-4.31)</td>
</tr>
<tr>
<td>Argo</td>
<td>1.92</td>
<td>1.59</td>
<td>2.55</td>
<td>1.44</td>
<td>1.90</td>
<td>1.58</td>
</tr>
</tbody>
</table>
Table 4. As for Tab.2 but of the Atlantic Ocean.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>0–700</td>
<td>700–2000</td>
<td>0–700</td>
<td>700–2000</td>
<td>0–700</td>
<td>700–2000</td>
</tr>
<tr>
<td>BOA</td>
<td>0.79(23.45)</td>
<td>1.50(2.83)</td>
<td>1.84(11.51)</td>
<td>1.45(2.55)</td>
<td>0.58(14.53)</td>
<td>1.51(3.93)</td>
</tr>
<tr>
<td>IPRC</td>
<td>0.51(-20.85)</td>
<td>1.53(5.33)</td>
<td>1.14(-30.65)</td>
<td>1.38(-2.51)</td>
<td>0.51(-0.39)</td>
<td>1.53(5.71)</td>
</tr>
<tr>
<td>SIO</td>
<td>0.62(-2.61)</td>
<td>1.34(-8.16)</td>
<td>1.96(19.15)</td>
<td>1.42(-0.03)</td>
<td>0.44(-14.14)</td>
<td>1.31(-9.63)</td>
</tr>
<tr>
<td>EN4</td>
<td>1.17(81.97)</td>
<td>1.87(28.50)</td>
<td>2.49(51.15)</td>
<td>1.80(27.12)</td>
<td>0.29(-43.46)</td>
<td>1.61(11.20)</td>
</tr>
<tr>
<td>IAP</td>
<td>1.15(79.17)</td>
<td>1.14(-21.62)</td>
<td>1.98(20.12)</td>
<td>0.97(-31.23)</td>
<td>0.79(54.44)</td>
<td>1.22(-16.08)</td>
</tr>
<tr>
<td>Ishii</td>
<td>1.12(75.53)</td>
<td>1.81(24.49)</td>
<td>1.89(14.43)</td>
<td>1.75(23.35)</td>
<td>0.70(37.00)</td>
<td>1.71(18.08)</td>
</tr>
<tr>
<td>BRAN2020</td>
<td>1.53(138.89)</td>
<td>3.60(147.82)</td>
<td>2.24(35.75)</td>
<td>2.63(85.82)</td>
<td>1.21(137.84)</td>
<td>3.27(125.60)</td>
</tr>
<tr>
<td>ECCOv4r4</td>
<td>0.54(-15.00)</td>
<td>1.22(-16.16)</td>
<td>0.54(-66.96)</td>
<td>1.22(-13.93)</td>
<td>-0.15(-130.18)</td>
<td>1.14(-21.58)</td>
</tr>
<tr>
<td>GECCO3</td>
<td>2.51(291.12)</td>
<td>1.61(10.49)</td>
<td>3.17(92.12)</td>
<td>1.70(19.69)</td>
<td>2.15(322.87)</td>
<td>1.61(11.11)</td>
</tr>
<tr>
<td>ORAS5</td>
<td>1.02(59.72)</td>
<td>2.25(55.02)</td>
<td>1.02(-37.92)</td>
<td>2.25(59.15)</td>
<td>0.77(52.18)</td>
<td>1.99(37.34)</td>
</tr>
<tr>
<td>SODA3122</td>
<td>0.89(38.47)</td>
<td>1.71(17.52)</td>
<td>0.89(-46.18)</td>
<td>1.71(20.66)</td>
<td>0.27(-46.65)</td>
<td>1.65(14.11)</td>
</tr>
<tr>
<td>SODA31220</td>
<td>2.91(355.01)</td>
<td>3.49(139.81)</td>
<td>2.91(76.86)</td>
<td>3.49(146.20)</td>
<td>2.31(353.72)</td>
<td>3.10(113.82)</td>
</tr>
<tr>
<td>Argo</td>
<td>0.64</td>
<td>1.45</td>
<td>1.65</td>
<td>1.42</td>
<td>0.51</td>
<td>1.45</td>
</tr>
<tr>
<td>Time period</td>
<td>Depth (m)</td>
<td>BOA</td>
<td>IPRC</td>
<td>SIO</td>
<td>EN4</td>
<td>IAP</td>
</tr>
<tr>
<td>-------------</td>
<td>----------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>2005–2017</td>
<td>700–2000</td>
<td>0.72/0.44</td>
<td>0.80/2.67</td>
<td>0.44/3.31</td>
<td>0.56/13.64</td>
<td>0.59/9.64</td>
</tr>
<tr>
<td>2005–2017</td>
<td>0–700</td>
<td>2.28/4.73</td>
<td>0.80/2.67</td>
<td>1.11/22.27</td>
<td>1.61/12.74</td>
<td>1.54/7.53</td>
</tr>
<tr>
<td>2005–2007</td>
<td>700–2000</td>
<td>0.70/0.32</td>
<td>0.70/0.39</td>
<td>0.52/18.69</td>
<td>0.54/33.38</td>
<td>0.59/10.49</td>
</tr>
</tbody>
</table>

As for Tab.2 but for the Indian Ocean.
FIGURE 1. The spatial domains of the Pacific (PAC, red), Atlantic (ATL, blue) and Indian (IND, yellow) Oceans defined in this study.
FIGURE 2. Global and basins-wide warming trend in the upper ocean (0–700 m). **Left to right:** The global ocean (GLO), Pacific Ocean (PAC), Atlantic Ocean (ATL), and Indian Ocean (IND). **Top to bottom:** OHC, HV, and SP. The unit is ZJ·yr⁻¹, as shown in the title. *Argo* (grey square) denotes the ensemble mean of the *Argo* group (BOA, IPRC, and SIO); *AllObs* means the ensemble mean of the *AllObs* group (EN4, IAP, and Ishii); *RA* means the ensemble mean of the *RA* group (BRAN2020, ECCOv4r4, GECCO3, ORAS5, and SODA3122); *All* means the ensemble mean of all datasets except SODA31220. The error bar for each dataset shows the 95% confidence interval of the trend estimate, but stands for the two times of the ensemble spread for each ensemble group. Note that the left column (for the global ocean) has a different vertical axis from the 2nd–4th columns (for each major basin).
FIGURE 3. Similar to Fig. 2 but for the intermediate ocean (700–2000 m).
FIGURE 4. Zonal-integrated warming trend as a function of the latitude in the upper ocean (0–700 m). **Left to right**: global ocean (GLO), Pacific Ocean (PAC), Atlantic Ocean (ATL), and Indian Ocean (IND). **Top to bottom**: OHC, HV, and SP. The unit is PJ m$^{-1}$ yr$^{-1}$ (PJ means petajoule, equals $10^{15}$ J), as shown in the title.
**FIGURE 5.** The ESM of the warming trend as a function of the latitude in the upper ocean (0–700 m). **Left to right:** global ocean (GLO), Pacific Ocean (PAC), Atlantic Ocean (ATL), and Indian Ocean (IND). **Top to bottom:** OHC, HV, and SP. The unit is PJ·m⁻¹·yr⁻¹ (PJ means petajoule, equals 10¹⁵ J), as shown in the title. The black line represents the ESM of the Argo group, the red line represents the ESM of the AllObs group, the blue line represents the ESM of the RA group and the magenta line represents the ESM of the All group.
FIGURE 6. The ESD of the warming trend as a function of the latitude in the upper ocean (0–700 m). **Left to right:** global ocean (GLO), Pacific Ocean (PAC), Atlantic Ocean (ATL), and Indian Ocean (IND). **Top to bottom:** OHC, HV, and SP. The unit is PJ·m⁻¹·yr⁻¹, as shown in the title. The black line represents the ESD of the Argo group, the red line represents the ESD of the AllObs group, the blue line represents the ESD of the RA group, and the magenta line represents the ESD of the All group.
FIGURE 7. Similar to Fig. 4 but for the intermediate ocean (700–2000 m).
FIGURE 8. Similar to Fig. 5 but for the intermediate ocean (700–2000 m).
FIGURE 9. Similar to Fig. 6 but for the intermediate ocean (700–2000 m).
FIGURE 10. Geographic distribution of vertically-integrated OHC trend per meter squared in the upper ocean (0–700 m). The unit is GJ·m⁻²·yr⁻¹ (GJ means gigajoules and equals 10⁹ J). The horizontal and vertical axes stand for the longitude and latitude, respectively.
FIGURE 11. Similar to Fig. 10 but for the HV component.
FIGURE 12. Similar to Fig. 10 but for the SP component.
FIGURE 13. Geographic distribution of the ESM and ESD of OHC, HV, and SP trends in the upper ocean (0–700 m) in different groups. **Left to right:** Argo group, AllObs group, RA group, and all datasets except SODA31220. The top two rows stand for OHC, the central two rows for HV, and the bottom two rows for SP. Note that different color bars were used for the ESM and ESD to improve the visualization.
FIGURE 14. Similar to Fig. 10 but for the intermediate ocean (700–2000m).
FIGURE 15. Similar to Fig. 11 but for the intermediate ocean (700–2000m).
FIGURE 16. Similar to Fig. 12 but for the intermediate ocean (700–2000m).
FIGURE 17. Similar to Fig. 13 but for the intermediate ocean (700-2000m).
FIGURE 18. Trend of the zonal-averaged sinking of the neutral density surfaces. Positive values (m-yr$^{-1}$) indicate deepening of the neutral density surface; therefore HV-related warming. **Left to right: BOA, IPRC, SIO, EN4, IAP, Ishii, BRAN2020, ECCOv4r4, GECCO3, ORAS5, SODA3122, and SODA31220. **Top to bottom: Pacific Ocean, Atlantic Ocean, and the Indian Ocean. The horizontal axis is the latitude ($^\circ$), with ticks at 60°S, 30°S, the Equator, 30°N and 60°N, respectively. Due to the space limit, 60° S and 60° N are not labeled. The vertical axis is the neutral density (kg·m$^{-3}$).
FIGURE 19. ESM and ESD of the trend of the zonal-averaged sinking of the neutral density surfaces. Left to right: Argo group, AllObs group, RA group, and All group. The top two rows stand for the Pacific Ocean, the central two rows for the Atlantic Ocean, and the bottom two rows for the Indian Ocean. Note that different color bars are used for the ESM and ESD to improve the visualization.
FIGURE 20. Trend of the zonal-averaged SP-related potential temperature change. Positive (°C yr⁻¹) means SP warming. **Left to right:** BOA, IPRC, SIO, EN4, IAP, Ishii, BRAN2020, ECCOv4-r4, GECCO3, ORAS5, SODA3122, and SODA31220. **Top to bottom:** Pacific Ocean, Atlantic Ocean, and the Indian Ocean. The horizontal axis is the latitude (°), with ticks at 60°S, 30°S, the Equator, 30°N and 60°N, respectively. The vertical axis is the neutral density (kg·m⁻³).
FIGURE 21. Similar to Fig. 20 but for the SP-associated potential temperature change.