

# Watermass co-ordinates isolate the historical ocean warming signal

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## Abstract

Persistent warming and water cycle change due to anthropogenic climate change modifies the temperature and salinity distribution of the ocean over time. This ‘forced’ signal of temperature and salinity change is often masked by the background internal variability of the climate system. Analysing temperature and salinity change in watermass-based coordinate systems has been proposed as an alternative to traditional Eulerian (e.g., fixed-depth, zonally-averaged) co-ordinate systems. The impact of internal variability is thought to be reduced in watermass co-ordinates, enabling a cleaner separation of the forced signal from background variability - or a higher ‘signal-to-noise’ ratio. Building on previous analyses comparing Eulerian and water-mass-based one-dimensional coordinates, here we recast two-dimensional co-ordinate systems - temperature-salinity (? - ?), latitude-longitude and latitude-depth - onto a directly comparable equal-volume framework. We compare the internal variability, or ‘noise’ in temperature and salinity between these remapped two-dimensional co-ordinate systems in a 500 year pre-industrial control run from a CMIP6 climate model. We find that the median internal variability is lowest (and roughly equivalent) in ? - ? and latitude-depth space, compared with latitude-longitude co-ordinates. A large proportion of variability in ? - ? and latitude-depth space can be attributed to processes which operate over a timescale greater than 10 years. Overall, the signal-to-noise ratio in ? - ? co-ordinates is roughly comparable to latitude-depth co-ordinates, but is greater in regions of high historical temperature change. Conversely, latitude-depth co-ordinates have greater signal-to-noise ratio in regions of historical salinity change. Thus, we conclude that the climatic temperature change signal can be more robustly identified in watermass-co-ordinates.

# **Watermass co-ordinates isolate the historical ocean warming signal**

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29 SIGNIFICANCE STATEMENT: Changes in ocean temperature and salinity are driven both by  
30 human-induced climate change and by modes of natural variability in the climate system, such as  
31 the El-Niño Southern Oscillation. It can be difficult to isolate the human-induced ‘signal’ of climate  
32 change from the natural fluctuations or ‘noise’ in the climate system. Watermass-based methods,  
33 which ‘follow’ a parcel of water around the ocean, have been thought to improve on ‘Eulerian’  
34 (i.e., analyses performed at fixed latitude, longitude and depth) frames of reference as they are  
35 less impacted by the ‘noise’. However, it is difficult to cleanly compare between watermass-based  
36 methods and Eulerian methods. Here, we aim to quantify the extent to which watermass-based  
37 frameworks improve on Eulerian frameworks in isolating the climate signal from the noise. We  
38 recast watermass and Eulerian methods onto an equivalent grid, enabling a clean comparison  
39 between them, and find that doing so increases the signal-to-noise ratio in watermass-based co-  
40 ordinates in regions of ocean warming. These results emphasise the utility of watermass-based  
41 methods in analysing long-term climatic temperature change in the ocean.

## 42 **1. Introduction**

43 Anthropogenic climate change is characterised by the persistent build-up of heat in the climate  
44 system (Stocker et al. 2013) and long-term changes to the hydrological cycle (Durack et al. 2012;  
45 Sohail et al. 2022). A vast proportion of excess heat in the climate system is absorbed by the  
46 ocean (Schuckmann et al. 2020), and changes to the water cycle manifest as ocean salinity changes  
47 (Pierce et al. 2012). These human-induced changes to ocean heat and salinity occur alongside  
48 natural variability in the climate system, driven in part by physical modes of climate variability  
49 like the El-Niño Southern Oscillation (ENSO) (Trenberth 2020) and the North Atlantic Oscillation  
50 (Visbeck et al. 2001). Natural variability in the climate system can obscure forced anthropogenic  
51 trends in the ocean, adding ‘noise’ to the signal.

52 Numerous studies have aimed to tackle the problem of detecting the anthropogenic signal of  
53 climate change in observations and climate models. A conventional approach to detecting changes  
54 in ocean temperature and/or salinity involves detecting changes to ocean properties at fixed loca-  
55 tions on the ocean surface (that is, in latitude-longitude co-ordinates, Hawkins and Sutton 2012;  
56 Hamlington et al. 2011) or by zonally-averaging (that is, in latitude-depth co-ordinates, Pierce et al.  
57 2012; Boyer et al. 2005; Swart et al. 2018; Hobbs et al. 2021). In these traditional Eulerian frames

58 of reference, the ‘noise’, natural variability in the climate system, can be reduced by coarsening  
59 the grid, filtering out the relevant time-scales, taking large ensemble means, and/or by focusing  
60 on specific ocean regions that may not be impacted by dominant modes of variability (Hamling-  
61 ton et al. 2011; Penland and Matrosova 2006; Maher et al. 2021; Pierce et al. 2012). In doing  
62 so, past research has effectively increased the ‘signal-to-noise’ ratio - allowing for a more robust  
63 identification of the long-term climate change-induced trend.

64 Watermass-based frameworks have been proposed as an alternative to traditional Eulerian-based  
65 methods for tracking ocean change. Tracking changes in ocean properties following iso-surfaces  
66 of conservative tracers, such as density, temperature and/or salinity, is thought to filter out short-  
67 timescale, highly variable adiabatic motions, potentially reducing internal variability and noise  
68 in the system (Silvy et al. (2020); Palmer et al. (2007); Zika et al. (2015, 2021)). In addition,  
69 watermass-based methods can enable a direct attribution of heat or salt content tendencies to  
70 surface fluxes and diabatic mixing, as only diabatic flux terms are present in the budget (Walin  
71 1982; Groeskamp et al. 2019; Holmes et al. 2019; Bladwell et al. 2021; Hieronymus et al. 2014).

72 However, a clean comparison of the internal variability, and thus signal-to-noise ratio, in  
73 watermass-based and Eulerian methods is challenging because the volume bounded by watermass-  
74 based coordinate surfaces can change with time. Thus, a given temperature or salinity surface could  
75 expand to fill a large portion of the ocean, while volumes bounded by latitude, longitude and depth  
76 surfaces are (by construction) fixed in time. For instance, Palmer et al. (2007); Palmer and Haines  
77 (2009) compared ocean temperature variability above the 14°C isotherm, and the 220m depth  
78 level, which are approximately geographically collocated. While the use of a temperature-based  
79 co-ordinate reduces internal variability, the 14°C isotherm expands over time to accommodate an  
80 increasingly warm ocean, while the 220m depth level remains fixed. Following work by Sohail  
81 et al. (2021), Holmes et al. (2022) avoided this problem by using a percentile-based co-ordinate  
82 system that enables a constant-volume comparison between one-dimensional temperature, depth  
83 and latitude co-ordinate systems. Holmes et al. (2022) showed that internal variability is indeed  
84 reduced in one-dimensional temperature co-ordinates (aligning with findings from Palmer and  
85 Haines (2009)), but only for specific timescales and regions of the ocean.

86 While one-dimensional fixed-depth and fixed-temperature frameworks remain popular choices  
87 in assessing ocean heat and salt content (Wolfe et al. 2008; Morrison and Hogg 2013; Sohail et al.

2021, 2022), two-dimensional co-ordinate systems retain more information and are often used to assess ocean heat and salt content change (e.g., Roemmich et al. (2015); Silvy et al. (2020); Rathore et al. (2020)). For instance, in one dimension, ‘cold’ temperature surfaces conflate the ocean interior with surface polar regions, but introducing a second dimension (e.g. salinity) isolates the interior ocean from the polar surface effectively. Variability in two-dimensional watermass coordinates has been compared to variability in Eulerian coordinates by ‘re-projecting’ diabatic tendencies inferred in water mass coordinates back onto the geographical coordinates. Evans et al. (2014) inferred seasonal diabatic tendencies in Temperature versus Salinity (hereafter  $T - S$ ) co-ordinates within the Drake Passage and then remapped these onto the average locations of the corresponding  $T - S$  classes along a repeat hydrographic section. Similarly, Zika et al. (2021) inferred the diabatic tendencies necessary to explain changes in the global inventories of sea water in  $T - S$  coordinates and mapped these onto the 3D geographical distribution of those water masses. In each case, Eulerian changes were larger than the inferred diabatic tendencies. However, these methods have relied on inferring the diabatic tendency from either a numerical model or an inverse model, and the derived solution is not necessarily unique. Thus, a clean, objective comparison assessing whether the projection of internal variability into two-dimensional watermass frameworks (e.g.  $T - S$  co-ordinates) is reduced compared to Eulerian counterparts (e.g., latitude-longitude, latitude-depth) has not been conducted.

In this paper, we recast two dimensional co-ordinate systems, namely,  $T - S$  space, latitude-longitude space, and latitude-depth space, onto a constant-volume-based two-dimensional framework using a statistical method called *Binary Space Partitioning* (BSP). We then track changes to the ocean’s temperature and salinity properties to quantify the internal variability (the ‘noise’) with the aim of establishing whether the signal-to-noise ratio of the climate signal increases in watermass-based frameworks. The coupled climate model data used in this study is described in section 2. We provide details of BSP and its two-dimensional remapping in section 3. Our findings, detailed in section 4, confirm that the median internal variability (the ‘noise’) is lowest in  $T - S$  and latitude-depth space, and is described by longer timescale processes. We explore the historical ‘signal’ in section 5, and show that signal-to-noise ratio is larger in  $T - S$  space in regions of high temperature change compared to its Eulerian counterparts. Conclusions are summarised in section 6.

## 2. Model data: ACCESS-CM2

In this work, we focus on a number of simulations performed using the ACCESS-CM2 climate model (Bi et al. 2020) as part of the Australian submission to the 6th generation Climate Model Intercomparison Project (CMIP6) (Eyring et al. 2016). The ocean model component of ACCESS-CM2 is the Modular Ocean Model version 5.1 (Griffies and Greatbatch 2012) and uses Conservative Temperature and Practical Salinity as its standard temperature and salinity variables (McDougall 2003; McDougall and Barker 2011). More details on ACCESS-CM2, the ACCESS-CM2 submission to CMIP6, and in particular, the forcing and spin-up of the piControl and historical runs, are provided by Bi et al. (2020); Mackallah et al. (2022).

We analyse a 500 year pre-industrial control (piControl) simulation, as well as a 165 year historical simulation (Eyring et al. 2016). In this work, we analyse the model Potential Temperature, Practical Salinity and grid cell volume variables in temperature-salinity, latitude-longitude, and latitude-depth coordinates over the entire pre-industrial control period, and the entire historical period, covering 1850 to 2014. A single ensemble member (*r1i1p1f1*) is used in this analysis.

The monthly-averaged temperature and salinity in the piControl and historical runs are first binned into 2D  $T - S$ , latitude-longitude and latitude-depth percentile coordinates using BSP as described in section 3. As in Irving et al. (2020), we find that the pre-industrial control simulation has a persistent drift in both temperature and salinity. The globally-integrated heat content grows significantly (by  $O(10^{24})$  J) over the 500-year period of the control run, while the ocean freshwater flux drops by  $O(10^{16})$  kg. In order to remove these long-term drifts in the pre-industrial control run, we de-drift and de-season binned outputs. De-drifting is accomplished by removing a cubic fit of the piControl time series over the relevant overlapping time period, following Irving et al. (2020). The seasonal cycle is removed by subtracting the time-mean seasonal cycle over the entire time period of interest from the monthly time series.

Note that de-drifting and de-seasoning is conducted *after* aggregating or reorganising data into its relevant diagnostic. This is primarily because removing the drift from every grid point in the native grid does not guarantee there will be no drift in the aggregated or reorganised data. De-drifting after binning ensures that any drift in the system is removed in the final diagnostic, and thus does not contaminate calculations of variance in this diagnostic.

### 3. Theory

Typically, watermass-based analyses involve tracking ocean properties at constant temperature or salinity (Worthington 1981; Walin 1982; Zika et al. 2015, 2018; Holmes et al. 2019). By following constant tracer isosurfaces, the heat and salt budgets contain contributions from diabatic processes only. However, there are still diasurface volume fluxes in these coordinates which must be accounted for and whose associated tracer flux may be ill-defined (see Holmes et al. (2019) and Bladwell et al. (2021) for details). In addition, as the surface outcrop location of temperature and salinity surfaces may shift over time, it is difficult to link changes at a given tracer isosurface to a specific geographical region in strongly forced ocean models. Thus, cleanly comparing between pure watermass-based coordinate systems and Eulerian coordinate systems (which track ocean changes at fixed latitude, longitude or depth) can be difficult, in part because Eulerian coordinate systems are fixed-volume by construction, while the volume of water bounded by temperature or salinity surfaces can change with time.

#### *a. Binary Space Partitioning*

In order to overcome this issue, we recast all 2D co-ordinate systems using a statistical method called Binary Space Partitioning (BSP). Originating from computer graphics and image processing fields (e.g. Radha et al. (1996); Thibault and Naylor (1987)), BSP is a method for recursively, hierarchically subdividing a distribution using arbitrarily oriented lines. We can use BSP to effectively partition the ocean’s two-dimensional volume distribution into equal weight bins in watermass and Eulerian space.

To illustrate how BSP works, consider a two-dimensional volume distribution  $v(x, y)$  which is the volume of sea-water per unit  $x$  and  $y$ .  $x$  and  $y$  can be coordinates defined by Eulerian space or coordinates defined by time variable scalars such as  $T$ ,  $S$ , density, etc. To form a BSP tree, we recursively subdivide the distribution with alternating axis-oriented lines  $n$  times, such that the volume of the ocean in each subdivision is  $1/2^n$  of the total ocean volume  $\iint v(x, y) dx dy$ . This procedure is shown graphically in Figure 1.

The initial slice (figure 1a) divides the volume in half along some  $y$ -value  $y_1$ , such that each subdivision contains half of the ocean volume  $\frac{1}{2} \iint v(x, y) dx dy$ . The subsequent slice (figure 1b) divides each subdivided section further in half along two  $x$ -values  $x_1$  and  $x_2$ , such that each



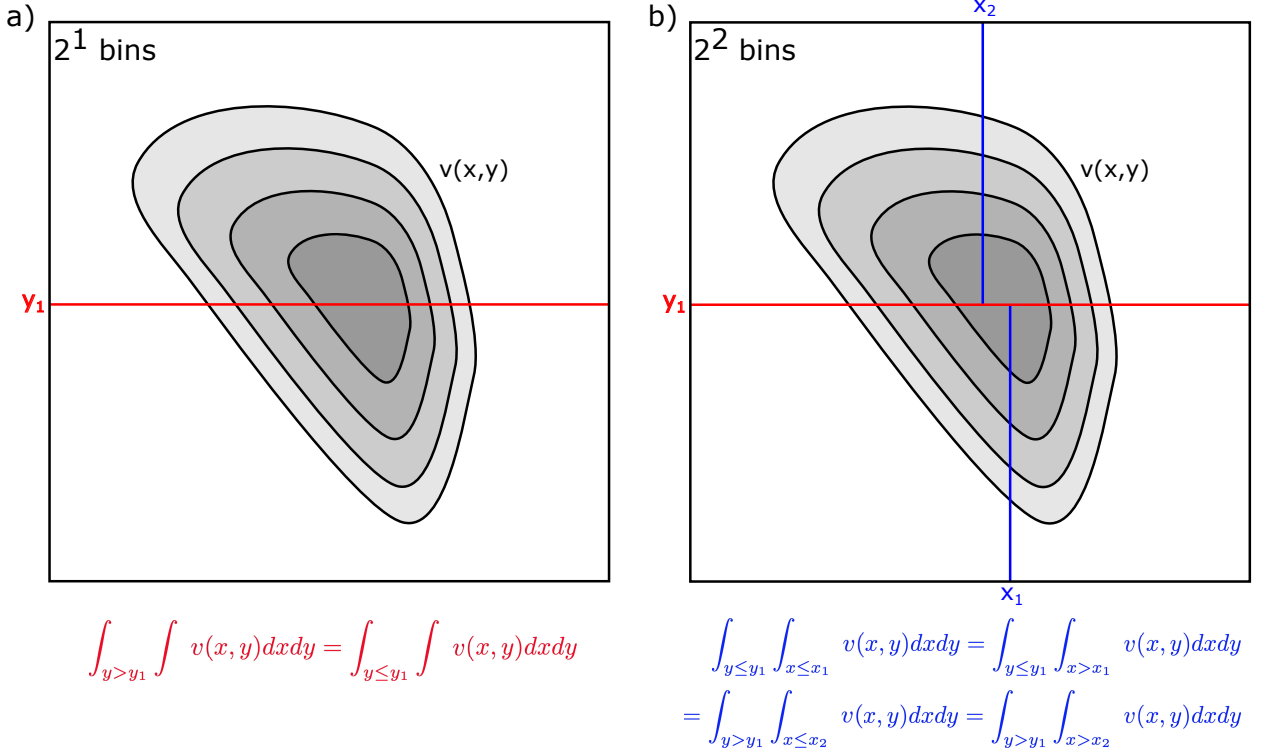


FIG. 1. A simple demonstration of Binary Space Partitioning applied to a generic two-dimensional volume distribution. a) One slice orthogonal to the  $y$ -axis at  $y_1$  (in red) yields  $2^1$  equal-volume bins of  $v(x,y)$ . b) Two additional slices orthogonal to the  $x$ -axis at  $x_1, x_2$  (in blue) yield  $2^2$  equal-volume bins of  $v(x,y)$ .

subdivision now contains a quarter of the ocean volume,  $\frac{1}{4} \iint v(x,y) dx dy$ . This process of recursive subdivision is repeated  $n$  times along alternating axes such that each time a volume constraint of  $\frac{1}{2^n} \iint v(x,y) dx dy$  is met. The resulting BSP tree structure thus compresses any general distribution into equal-volume bins.

Once the BSP has been performed for a given choice of  $x$  and  $y$  coordinates, we can track changes to the mean temperature,  $T$  and salinity,  $S$  in each bin over time. This allows us to quantify how variability (‘noise’) behaves in each co-ordinate system regardless of whether it is Eulerian or water-mass based.

In this work, we use BSP to partition the ocean’s volume into  $2^n$  equal-volume bins in three 2D coordinate systems:  $T - S$ , latitude-longitude and latitude-depth space. We first illustrate the partitioning of the ocean’s  $T - S$  volume distribution in the ACCESS-CM2 piControl run in figure 2 for  $n = 1, 2, 5$ , and 8.

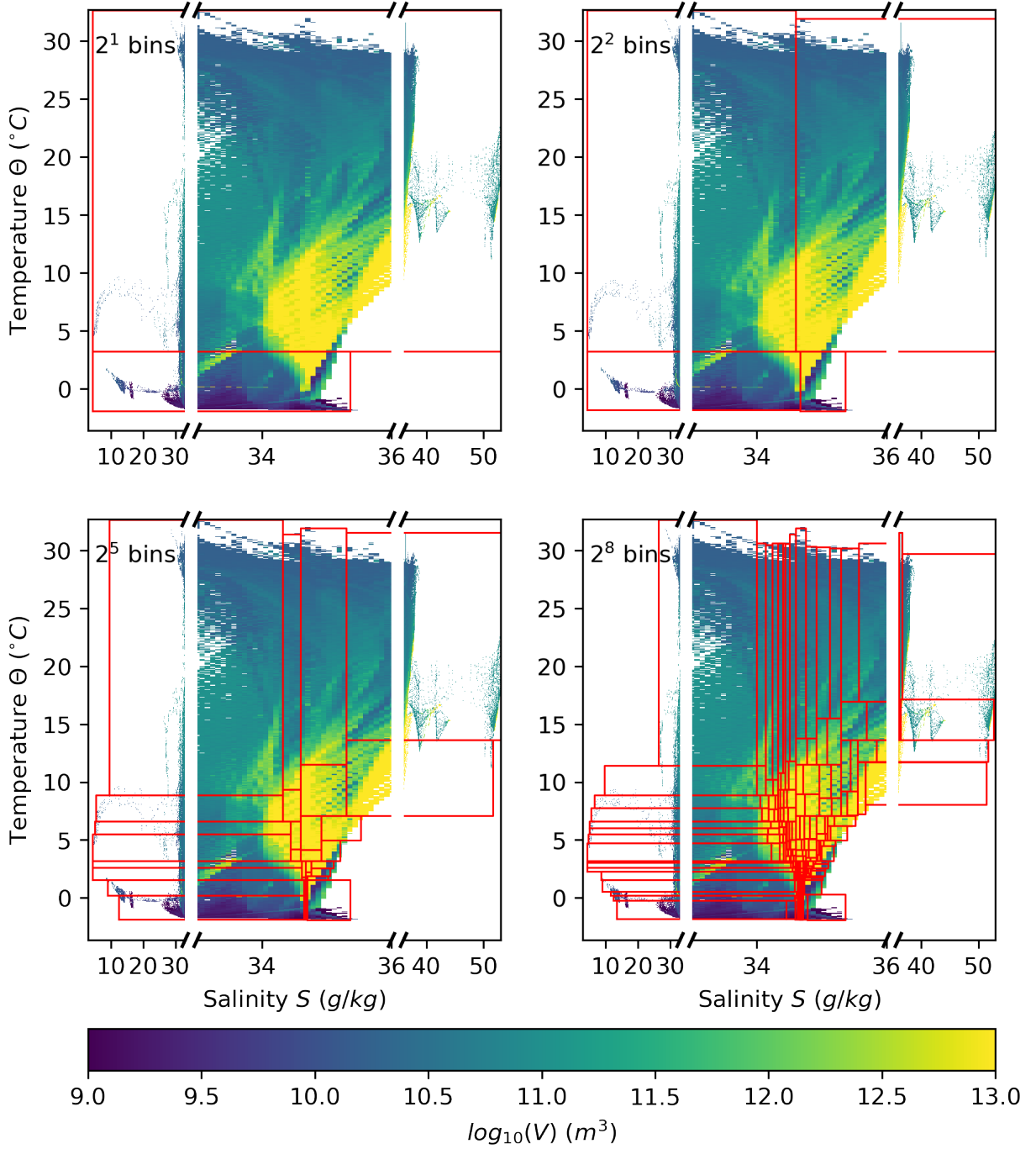


FIG. 2. BSP splitting on alternating axes, applied to the time-mean ACCESS-CM2 piControl volumetric distribution in  $T-S$  space, with  $2^n$  bins, where a)  $n=1$ , b)  $n=2$ , c)  $n=5$ , and d)  $n=8$ . Note that the salinity axis has three linear scales, delineated by the two horizontal breaks.

194 In latitude-longitude and latitude-depth co-ordinates, we perform BSP on the depth-integrated  
195 and zonally-integrated time-mean volume distribution, respectively. Figure 3 shows the resulting  
196 BSP bins in both Eulerian co-ordinate systems for  $n = 8$ , coloured by their mean temperature and  
197 salinity. The BSP binning algorithm only ‘sees’ the (depth- or zonally-integrated) ocean volume,  
198 ignoring any land masses. The BSP algorithm will thus not abide by continental boundaries and it  
199 will form bins that stretch across continents and between ocean basins to meet the equal volume  
200 constraint. To limit such inter-basin BSP bins, and to account for the periodicity of longitude, we  
201 choose to ensure that the Americas and Drake Passage form both the far western and far eastern  
202 boundary of the ocean. This is done by slicing the ocean at  $70^\circ\text{W}$  longitude from  $90^\circ\text{S}$  to  $3^\circ\text{N}$   
203 latitude. Then, a diagonal slice is made from  $70^\circ\text{W}$  longitude to  $100^\circ\text{W}$  between  $3^\circ\text{N}$  latitude and  
204  $20^\circ\text{N}$ , and the slice continues north from  $20^\circ\text{N}$  to  $90^\circ\text{N}$  along the  $100^\circ\text{W}$  longitude. Data points  
205 between this line and the Greenwich Meridian, moving east, are labelled with negative longitudes  
206 (i.e. are measured west of Greenwich) while the remaining data points to the east of Greenwich are  
207 labeled with positive longitudes (i.e. are measured east of Greenwich). This ensures, for example,  
208 that data points either side of the Isthmus of Panama do not combine into the same BSP bin (hence  
209 the grey, empty cells in figure 3a and b)

210 The BSP algorithm dynamically adjusts its bin limits to capture equal volumes at all times.  
211 In a time-varying vertical grid modeling system (as in ACCESS-CM2 which uses a  $z^*$  vertical  
212 coordinate), this dynamic adjustment, combined with grid cell volume changes in coarse-resolution  
213 regions, can lead to an unphysical representation of model properties. Specifically, in the coarsely-  
214 resolved deep ocean, infinitesimal fluctuations in the grid cell volume due to the movements of  
215 the coordinate system surfaces can trigger large changes in BSP bin limits. This means that the  
216 deep ocean variability can appear to be quite large within a given BSP bin, driven primarily by  
217 changing bin limits as they accommodate small volumetric changes in sparsely resolved regions of  
218 the ocean. The impact of the coarse vertical resolution on the BSP binning algorithm is clear in  
219 figure 3c and d, where empty regions are scattered through depth amongst the BSP bins. This is  
220 because, as the model grid coarsens vertically, the volume, T and S information becomes aligned  
221 along increasingly distant grid cell centers. Hence, the BSP algorithm needs to make a decision  
222 about which grid cells to cover to ensure a set of equal-volume bins. This leads to some regions  
223 not being covered by any BSP bins, as they do not contain any model information (grey cells in

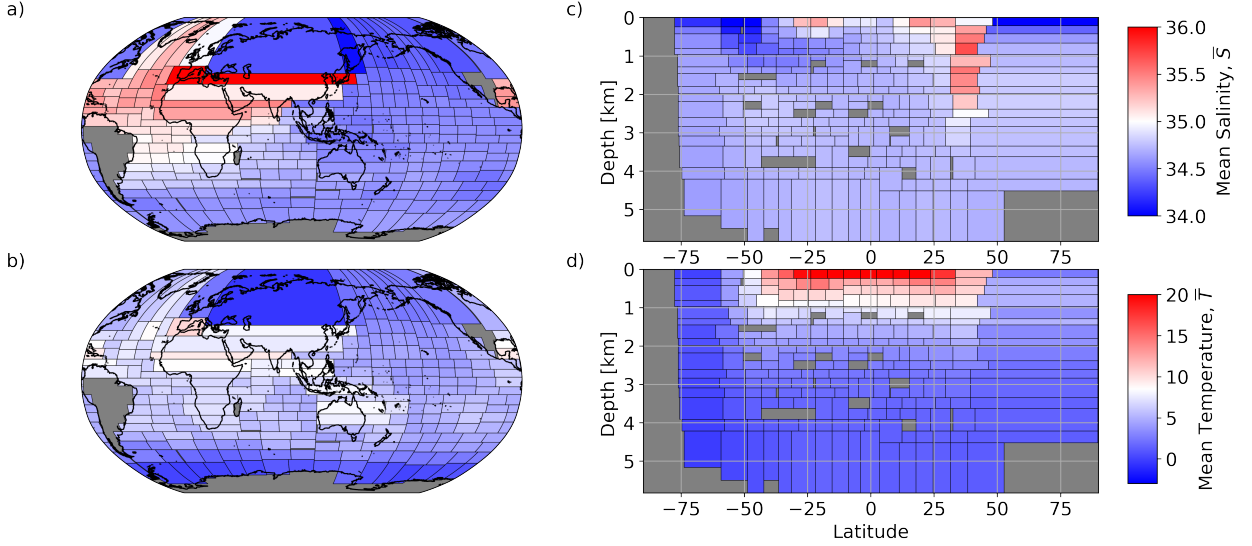


FIG. 3. BSP splitting on alternating axes with  $2^8$  bins, applied to the ACCESS-CM2 piControl (a and c) depth-integrated volumetric distribution in latitude-longitude co-ordinates, and (b and d) zonally-integrated volumetric distribution in latitude-depth co-ordinates. BSP bins are coloured by the time-mean (top row) salinity and (bottom row) temperature in each bin. Empty cells (where there is no BSP bin) are coloured in grey.

figure 3c and d). In order to minimise the shifting of BSP bin limits in response to minute grid-cell volume changes in the deep ocean, we first take the time-mean of the grid cell volumes and then use this static field, along with the time varying  $T - S$  properties of the grid-cells, to define the BSP bins and the  $T - S$  variability within them.

The coarse vertical resolution also impacts the results in  $T - S$  space, as regions that are strongly stratified (but coarsely resolved vertically) will have significant gaps in temperature and salinity when re-projected onto  $T - S$  space. The impact of coarse vertical resolution in the model can be reduced by linearly interpolating the vertical model grid. In section 5, we show how our results change when the vertical model grid resolution is doubled and quadrupled via linear interpolation.

Note that in BSP, the choice of which axis to cut along, or indeed the angle of the line that makes the cut, is entirely arbitrary. If choosing to cut orthogonal to the distribution axes, there exist  $2^n$  combinations of the order of subdivision that are valid. More generally, the choice to slice orthogonally to an axis is also arbitrary, and the BSP algorithm could, for instance, be directed to modify its angle until the volume constraint  $\frac{1}{2^n} \iint v(x, y) dx dy$  is met. However, not all combinations are physically plausible when subdividing the ocean in  $T - S$  or Eulerian space, and

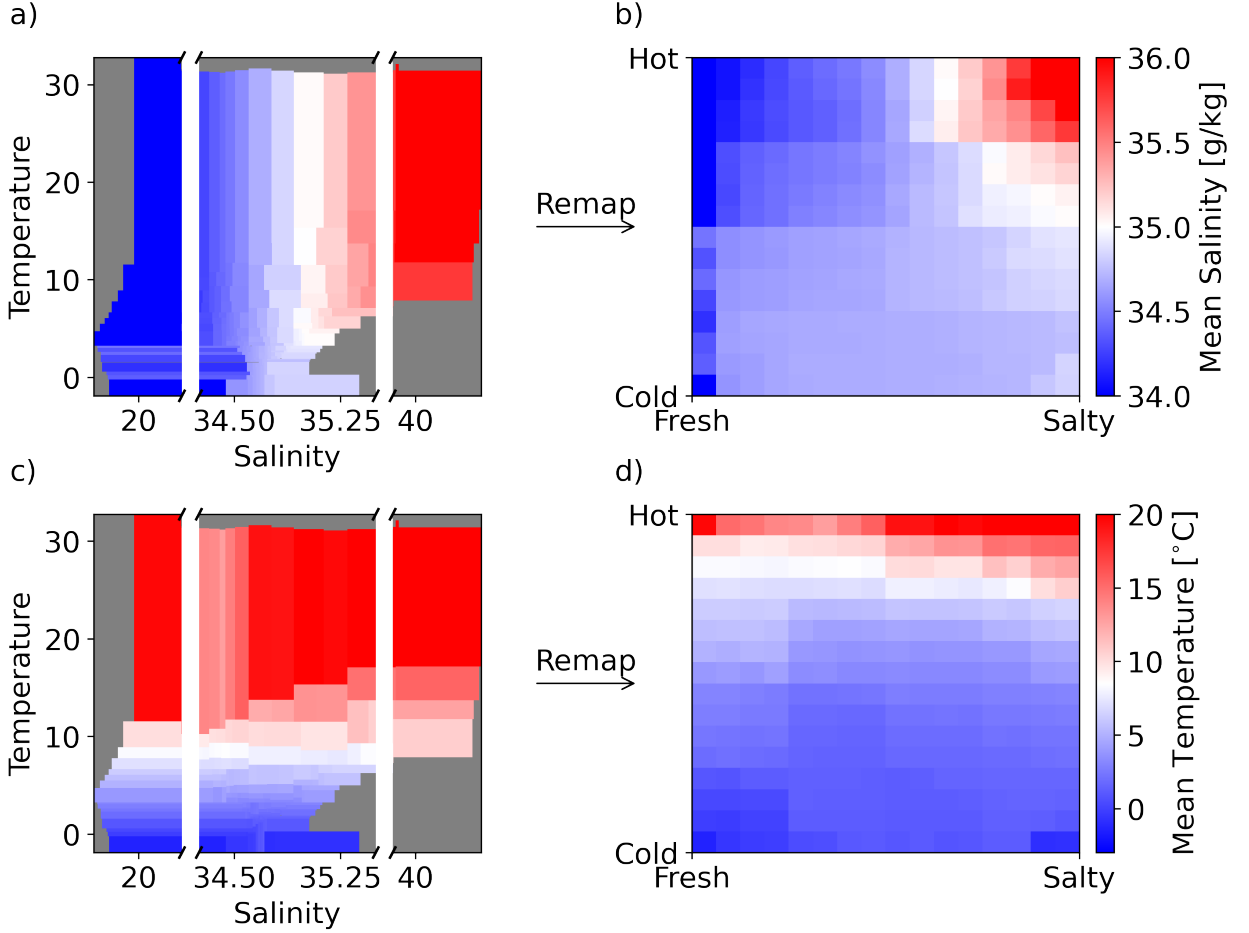


FIG. 4. Remapping BSP bins from (a and c) real  $T-S$  space, to (b and d) relative  $T-S$  space based on a binary tree structure. BSP bins are coloured by (a and b) time-mean salinity, and (c and d), time-mean temperature in the ACCESS-CM2 piControl run. Empty cells (where there is no BSP bin) are coloured in grey.

we opt to focus hereafter on the specific case of orthogonal slices alternating between the  $y$ - and  $x$ - axes (xyxyxyxy for 8 cuts). This order of BSP split combinations preserves the aspect ratio of BSP bins, ensuring a more equivalent representation of  $x$ - and  $y$ - variability. We explore this aspect ratio argument, and impact of choosing to slice along other orders of subdivision, in the Appendix, and reserve exploration of non-orthogonal slices in BSP for future work.

#### *b. Visualising 2D BSP framework*

In Eulerian space, the BSP bins generally align with the regular latitude-longitude (and latitude-depth) grid, as demonstrated by the general uniformity in BSP bin size in figure 3. However, in

$T - S$  space, the ocean's volume is concentrated over a relatively narrow range of temperatures and salinities (figures 2). Thus, the equal-volume binning using BSP leads to a large difference in the temperature and salinity ranges spanned by a given bin in  $T - S$  space. Surface waters (which occupy a large range of temperatures and salinities but represent minimal volume) are over-represented in the visualisation, as exhibited in figure 4a. Instead, it is advantageous to visualise each bin with an equal area in order to more clearly convey the equal-volume nature of the BSP framework. In order to achieve this, we make use of the binary tree structure obtained from the BSP. By construction, the corner bins obtained from the BSP (i.e, the top-right, top-left, bottom-right and bottom-left bins) represent the extrema in  $T - S$  space. All other bins are situated relative to these extrema in the BSP tree, and can be remapped relative to these corner bins. Hence, we remap the bins obtained from BSP onto a plot relative to the ocean's extrema.

In figure 4, we plot the output of this remapping in  $T - S$  space. We plot the mean salinity (figure 4a and b) and the mean temperature (figure 4c and d) within each BSP bin in  $T - S$  and in remapped  $T - S$  space. The remapping effectively preserves the fresh-to-salty and hot-to-cold gradient of temperature and salinity in each bin (figure 4b and d). The use of the BSP tree structure in the remapping ensures that each bin (representing a single unit of volume) is saltier (fresher) and hotter (colder) than the bin to its left (right) and below (above) it. The fact that we 'tag' each BSP bin in this relative space also means that in time series where the overall volume distribution of the ocean changes (for instance, in the historical run), the BSP bins will remain positioned relative to one another, and thus will stay comparable as the  $x^{th}$  percentile warmest (coldest), saltiest (freshest) bin in the model run.

The characteristic salinity and temperature of the global ocean can be seen in the remapped BSP plots in all coordinate systems (figure 5). The salty North Atlantic is visible in the top left of figure 5b and right side of figure 5c, while the relatively fresher Pacific and Southern Oceans are evident in the bottom and right hand side of figure 5b and top left of figure 5c, respectively. The clear thermal stratification of the global ocean through depth is also retained in the remapped latitude-depth plots, as shown in figure 5f. Overall, the latitude-depth BSP diagnostic aligns well with traditional zonally-averaged plots (not shown). However, there are some clear differences between the two diagnostics. Low volume regions are naturally collapsed in the BSP framework and combined with other, adjacent water masses to reach the equal-volume constraint. This is

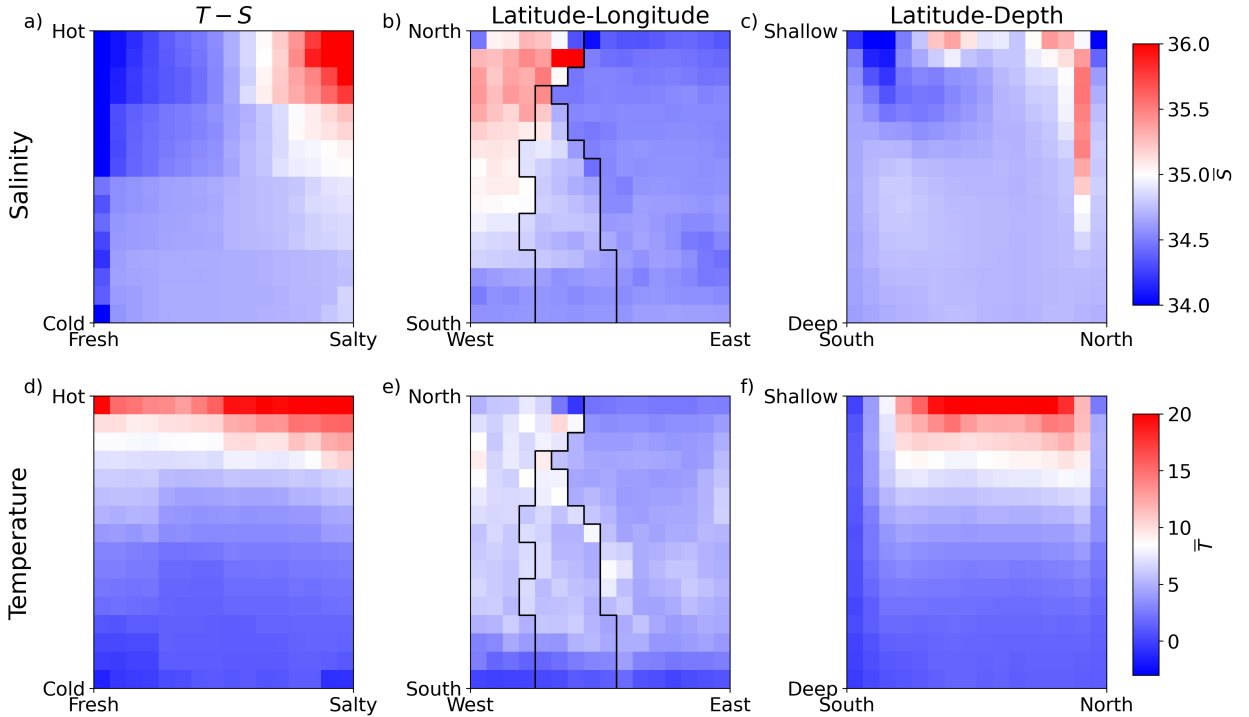


FIG. 5. Time-mean (a - c) salinity and (d - f) temperature in remapped equal-volume BSP bins, in (a and d)  $T - S$ , (b and e) latitude-longitude, and (c and f) latitude-depth co-ordinates, from the ACCESS-CM2 piControl simulation. The vertical black lines in panels b and e roughly delineate the Atlantic (left), Indian (center) and Pacific (right) basins.

particularly true for the Arctic, which occupies the northern high latitudes but has a low overall volume and thus is collapsed to the rightmost BSP bins in figures 5c and f. The (fresh) tropical and (salty) sub-tropical surface waters are also collapsed to a handful of bins near the surface of the ocean in figure 5c.

In this work, we present all results in the form of this remapped BSP visualisation, as it provides equal visual weight to each volume of ocean regardless of the space occupied by each bin in its original coordinate system. This remapping also retains the salient features of the different coordinate systems while presenting the data on an equivalent constant-volume metric, enabling a cleaner comparison between different coordinate systems. For ease of interpretation of the BSP remapping and further results in  $T - S$  space, we show the broad geographic distribution of the warmest (coldest), freshest (saltiest) 25% volume of the ocean in the Appendix (figure B1).

### 299 *c. Signal-to-Noise Ratio*

300 The signal-to-noise ratio is commonly employed to determine the relative impact of internal  
301 variability in the climate system (e.g., Hawkins and Sutton (2012)). Here, we define signal-  
302 to-noise ratio ( $F/N$ ) as the change in temperature (or salinity) in a given bin over the historical  
303 period (1850 to 2014), divided by the standard deviation of the temperature (or salinity) over the  
304 pre-industrial control period:

$$F/N = \Delta C / \sigma_{control}, \quad (1)$$

305 where  $C$  is any generic tracer. The signal ( $F$ ) is calculated as the linear trend from 1850 to 2014,  
306 multiplied by the number of years in the entire period (165 years). In this work, we calculate  $F/N$   
307 for the mean  $T$  and  $S$  in all BSP bins in  $T - S$ , latitude-longitude, and latitude-depth co-ordinates  
308 (section 5).

## 309 **4. Results**

310 The BSP framework enables an equal-volume comparison between three popular two-  
311 dimensional coordinate systems used to assess ocean and climatic changes - the temperature-  
312 salinity, latitude-longitude, and latitude-depth coordinate systems. In this section, we explore the  
313 internal variability, or ‘noise’, in these three co-ordinate systems.

### 314 *a. Internal Variability*

315 We begin by assessing the internal variability in the mean temperature and salinity of each BSP  
316 bin in the three coordinate systems in question. Overall, the  $T - S$  coordinate system exhibits  
317 a broad range in variance, from low variability in BSP bins corresponding to the ocean interior  
318 (bottom-middle bins in figure 6a and d), to high variability in BSP bins corresponding to the  
319 ocean’s surface (edge and corner bins in figure 6a and d). The range in variability between surface  
320 and interior BSP bins is also reflected in the latitude-depth plots (figure 6c and f), where deep  
321 bins have much lower variability than surface bins. Latitude-longitude co-ordinates (which are  
322 depth-integrated) tend to have a smaller range in variability overall (figure 6b and e).

323 The difference in variability between different BSP bins, and between co-ordinate systems, can  
324 be traced to two possible sources. First, the process of integrating over the ocean volume in



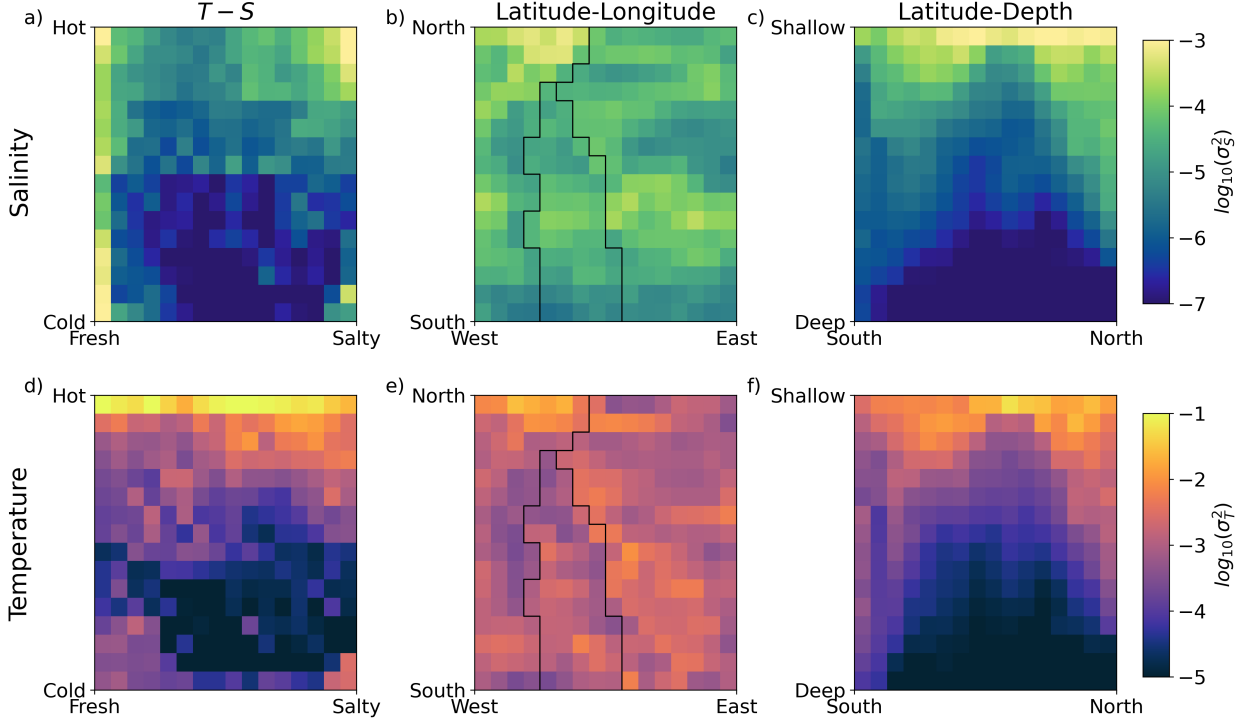


FIG. 6. (a - c) Variance in salinity,  $\log_{10}(\sigma_S^2)$  and (d - f) temperature,  $\log_{10}(\sigma_T^2)$  in equal-volume BSP bins, in (a and d)  $T - S$ , (b and e) latitude-longitude, and (c and f) latitude-depth co-ordinates.

different co-ordinate systems may lead to differing phase-cancellation characteristics of variability that varies in space. For example, any modes of variability that result in warming at one longitude and cooling at another longitude at the same latitude and depth will compensate each other in that given latitude-depth bin, leading to reduced variability in latitude-depth compared to the longitude-latitude coordinate where the two phases of the variability are separated.

Second, watermass-based co-ordinates exclude by construction adiabatic processes (associated with, for example, wind-driven circulation changes), which may have a higher amplitude variability. Thus, the difference between variability in  $T - S$  space and its Eulerian counterparts may be due to the fact that variability in  $T - S$  space is due to diabatic processes, while variability in Eulerian co-ordinates may be due to *both* diabatic and adiabatic processes.

The histogram of salinity and temperature variance in each co-ordinate system (figure 7) provides further insight into differences between watermass-based and Eulerian co-ordinate systems.  $T - S$  co-ordinates and latitude-depth co-ordinates have similar median variability, likely for different reasons -  $T - S$  co-ordinates filter out adiabatic processes, resulting in a lower median variability,

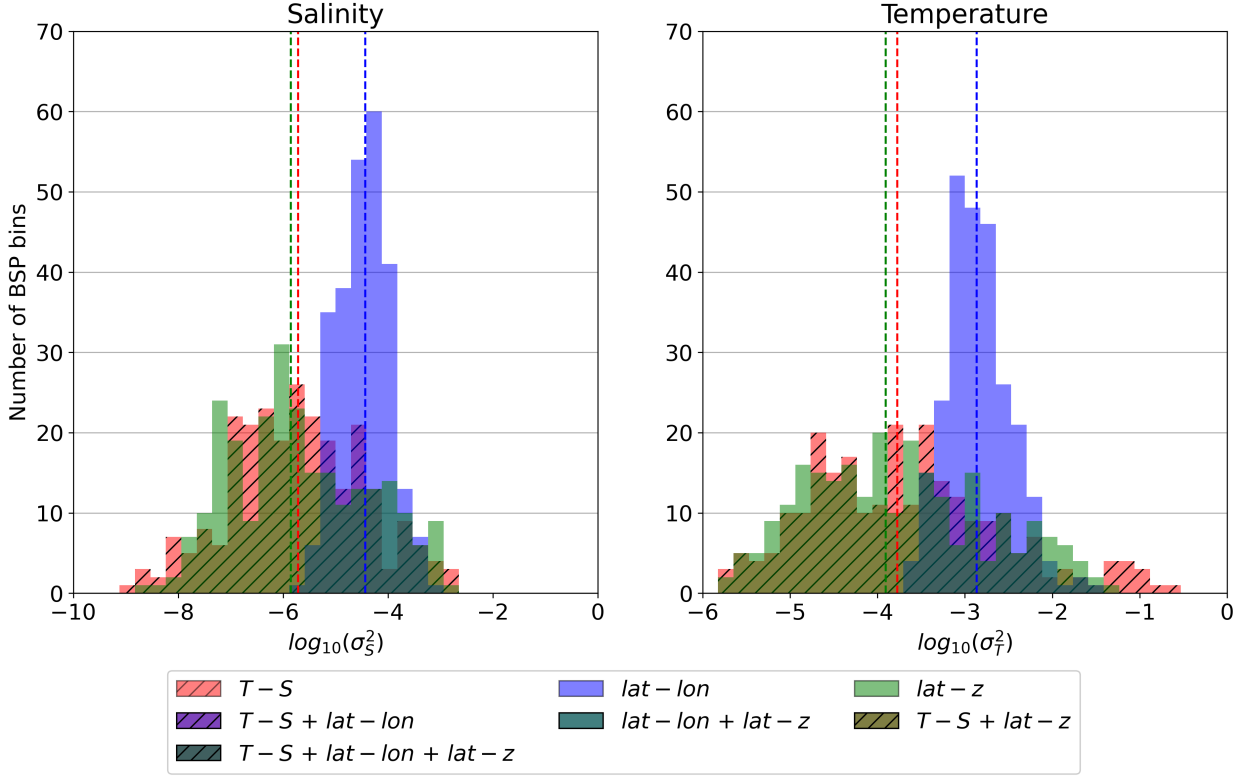


FIG. 7. Distribution of a) salinity variance,  $\log_{10}(\sigma_S^2)$  and b) temperature variance,  $\log_{10}(\sigma_T^2)$  across all BSP bins in  $T-S$  (red), latitude-longitude (blue) and latitude-depth (green) co-ordinates. Dashed lines show the median variance for each co-ordinate system.

while latitude-depth co-ordinates naturally highlight deep ocean processes separate from the surface ocean, leading to a lower median variance. Latitude-longitude co-ordinates, on the other hand, have a higher median variance.

In order to assess how statistically different these histograms are, we apply the Kolmogorov-Smirnoff (K-S) test of ‘goodness of fit’ between histogram pairs. The K-S test assesses the probability that a given pair of distributions were randomly sampled from the same data. The  $T-S$  and latitude-depth histograms are identified as the only statistically similar pair of histograms, implying that the medians (red and green lines) may not be statistically different. No other distributions in this analysis pass the K-S test for statistical similarity.

As discussed in section 1, moving from one-dimensional temperature co-ordinates to two-dimensional  $T-S$  co-ordinates can enable a cleaner separation of surface and ocean interior watermasses due to the addition of the salinity co-ordinate. The histograms in figure 7 indicate

that this separation leads to a more skewed distribution of variance, with a large number of weakly varying interior bins and a small handful of surface ocean bins (note the logarithmic x-axis). Due to this skewness, the mean variance across the entire distribution (as calculated in the 1D case in Holmes et al. (2022)) for our 2D case is strongly impacted by surface bins (which have higher variance). On the other hand, the median variance (vertical lines in Fig. 7) is lower, reflecting the much more numerous interior BSP bins. Moving forward, we opt to compare the median terms of interest, though we do explore the difference between mean and median variance in our spectral analysis below.

The internal variability in figure 6 is a consequence of inter-annual and sub-decadal ocean processes, ( $<10$  year periods, such as the El-Niño Southern Oscillation and North Atlantic Oscillation), and multi-decadal and centennial processes ( $>10$  year periods, such as Atlantic Meridional Overturning Circulation variability). In order to parse the relative influence of sub-decadal processes on internal variability, we present the variability of the 10-year high-pass filtered temperature and salinity signal relative to the total temperature and salinity variability, in figure 8. A fraction of 1 in figure 8 indicates that all of the variability in the given bin may be attributed to sub-decadal processes, while a fraction of 0 indicates that all of the variability in the given bin may be attributed to multi-decadal processes. Overall, variability in latitude-depth coordinates is influenced most by multi-decadal processes (figure 8c and f), likely due to the emphasis on deep ocean processes which change minimally over time in this co-ordinate system. The bulk of variability in  $T - S$  co-ordinates is also due to multi-decadal processes. Surface waters in  $T - S$  and latitude-depth space (edge bins in figure 8a, c, d and f) have a high proportion of sub-decadal variability. Latitude-longitude co-ordinates have a higher fraction of sub-decadal variability overall, particularly in the North Atlantic and Equatorial Pacific (possibly due to the influence of ENSO; figure 8b and e).

The difference between different co-ordinate systems is highlighted by plotting the distribution of proportion of sub-decadal variance (see figure 9). In latitude-depth space, approximately 80 – 85% of the total variability comes from  $> 10$  year processes (green dashed lines in figure 9), again due to the over-representation of deep ocean volumes in this co-ordinate system.  $T - S$  co-ordinates also host a high proportion of multi-decadal processes, with the overall multi-decadal variability representing 77 – 80% of the total, suggesting that diabatic processes tend to occur, on average, at multi-decadal timescales (red dashed lines in figure 9). In contrast, around 50% of the total

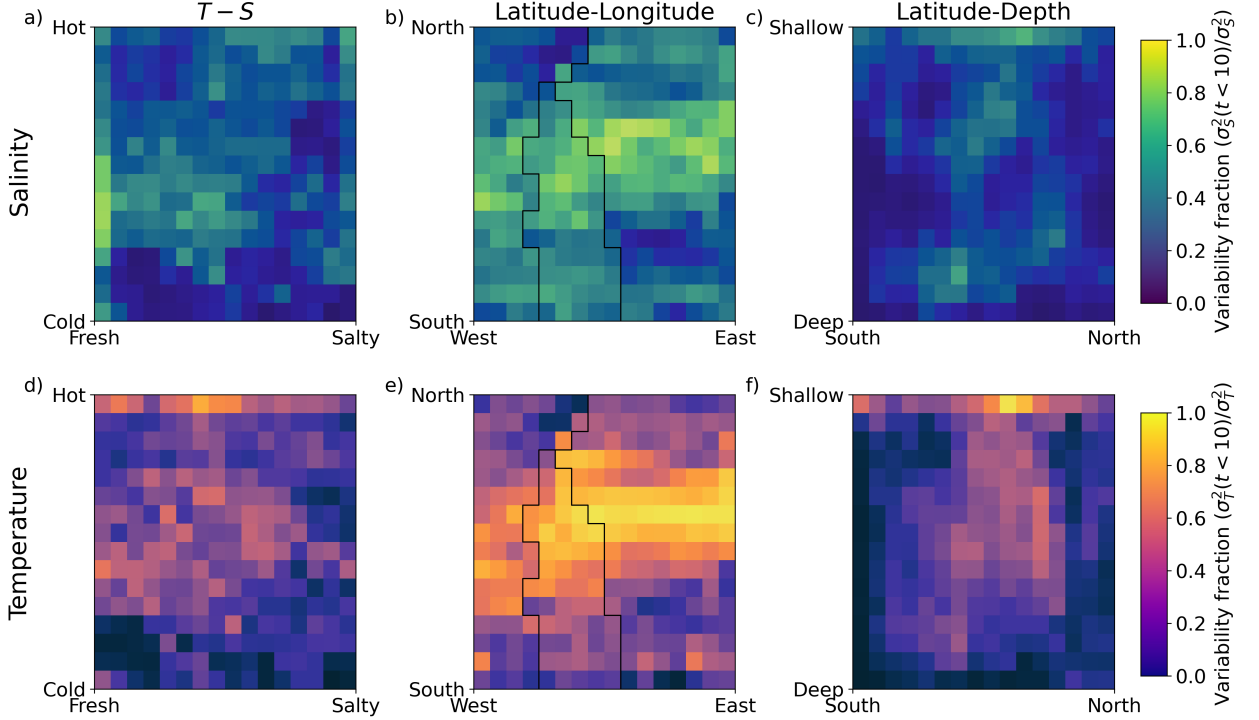


FIG. 8. Proportion of variance due to sub-decadal processes, (a - c) in salinity  $\sigma_S^2(t < 10)/\sigma_S^2$  and (d - f) in temperature  $\sigma_T^2(t < 10)/\sigma_T^2$ , in (a and d)  $T - S$ , (b and e) latitude-longitude, and (c and f) latitude-depth co-ordinates.

salinity and temperature variability in latitude-longitude space comes from  $> 10$  year processes (blue dashed lines in figure 9). These results are consistent with the one-dimensional analysis of Holmes et al. (2022) who showed that the mean temperature variance in a 1D temperature-based coordinate became comparable to variability in one-dimensional depth and latitude co-ordinates at decadal to multi-decadal time-scales, where diabatic processes dominate.

The variability fractions presented here are stable across all feasible BSP split combinations (figure A1). For all split combinations, a lower fraction of variability comes from sub-decadal processes in latitude-depth and  $T - S$  co-ordinates compared with latitude-longitude co-ordinates.

The variability in all three co-ordinate systems may be further broken down into characteristic timescales using spectral analysis, as shown in figure 10. As highlighted earlier, mean variance is more sensitive to outlier values in the skewed distributions presented. As a consequence, mean power spectra (figure 10a and c) are more impacted by outlier (often surface) sources of variability. Our mean results in figure 10c compare with the prior one-dimensional analysis of Holmes et al.

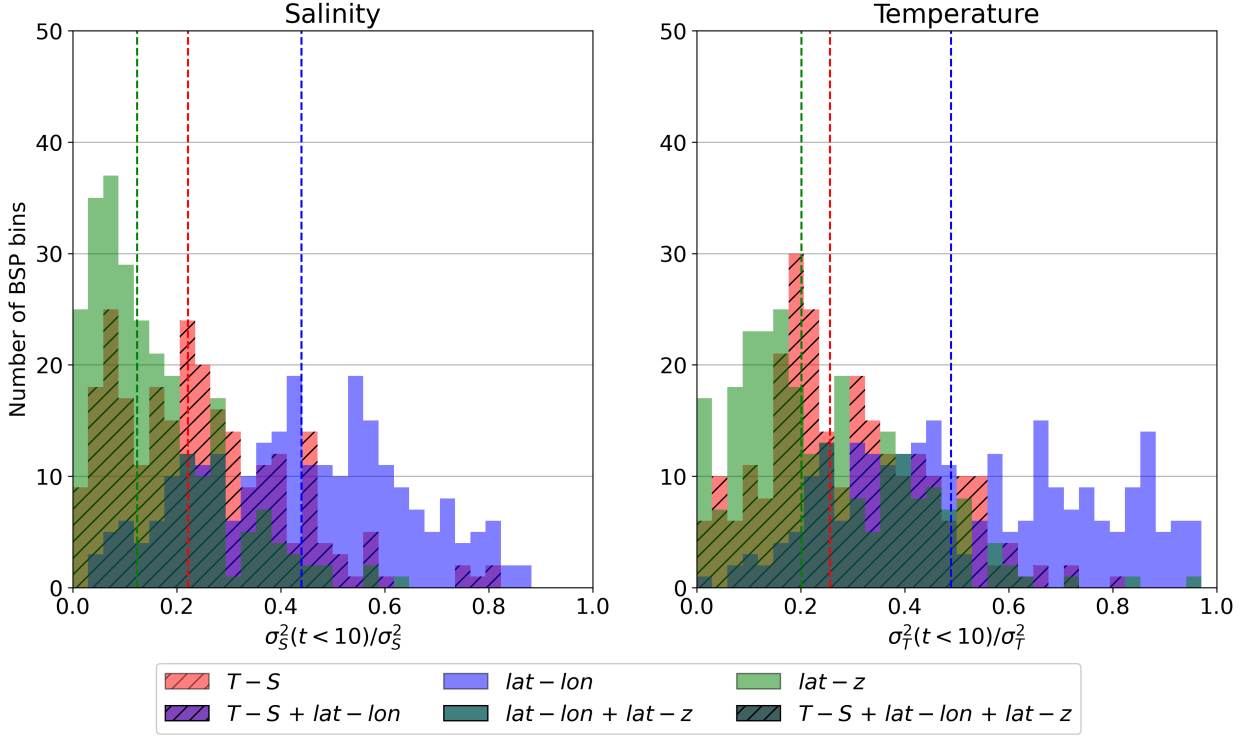


FIG. 9. Distribution of proportion of variance due to sub-decadal processes a) in salinity  $\sigma_S^2(t < 10)/\sigma_S^2$  and b) in temperature  $\sigma_T^2(t < 10)/\sigma_T^2$  across all BSP bins in  $T-S$  (red), latitude-longitude (blue) and latitude-depth (green) co-ordinates. Dashed lines show the median variance proportion for each co-ordinate system.

(2022) (specifically, figure 11a in Holmes et al. (2022)). The mean power spectra of temperature shows a clear peak in the 2 - 3 year time period in temperature in all coordinate systems (figure 10c), aligning with findings by Holmes et al. (2022), who concluded that this peak is likely due to ENSO. Holmes et al. (2022) found that the mean temperature variability in  $T$  space exceeds that in depth space at  $t > 10$  years.

The median power spectra, that is, the median of all power spectra at each timescale, is a means of comparison between co-ordinate systems which is more reflective of the more numerous ocean interior bins. The median power spectra highlight the similarity between latitude-depth and  $T-S$  co-ordinates (figures 10b and d). Across all time periods, median variance in  $T-S$  space is similar (but slightly higher) than that in latitude-depth space. Overall, latitude-longitude co-ordinates have the highest median variance across most time periods.

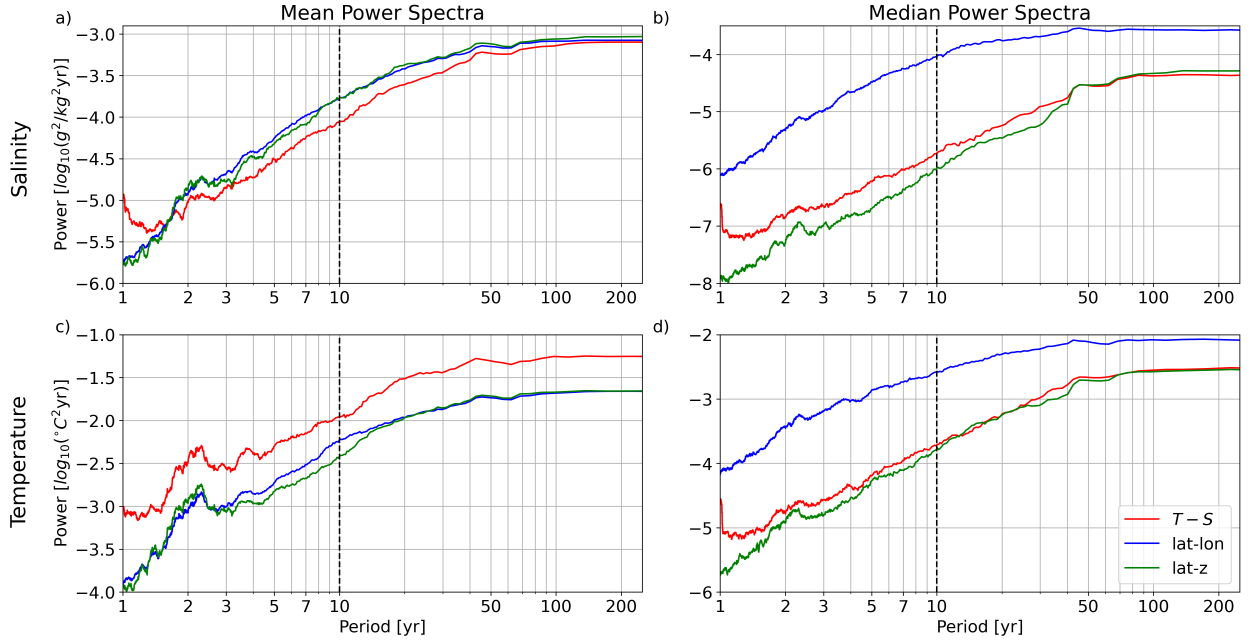


FIG. 10. Power spectra of (a and b) salinity variability and (c and d) temperature variability in  $T-S$  co-ordinates (red), latitude-longitude co-ordinates (blue) and latitude-depth co-ordinates (green). Spectra are presented both as the mean of all BSP bins (a and c) and the median of all BSP bins (b and d). The vertical dashed line shows a period of 10 years, the cutoff used in figure 8. Power spectra are calculated from monthly data, using Thompson’s multitaper method with 19 Slepian tapers.

### b. Modes of Variability

The primary modes of variability that drive internal variability in the three coordinate systems may be explored via Principal Component Analysis (PCA), where a principal component (PC) is the eigenvector of the covariance matrix of the distribution. The correlation coefficients obtained from PCA can indicate dominant modes of variability in the time series. PCA yields several PCs which collectively explain the total variance in a time series. We can thus find the number of PCs needed to adequately explain a high proportion of variance in a time series – the lower the number of PCs, the ‘simpler’ the time series can be considered to be. Figure 11 shows the cumulative proportion of variance explained by the PCs obtained from PCA.

$T-S$  and latitude-depth co-ordinates capture total salinity variance with the fewest PCs, while  $T-S$  co-ordinates are superior in capturing temperature variance with the fewest PCs (compare green and red lines in figure PCAs). In  $T-S$  space, 95% of the total temperature variance is

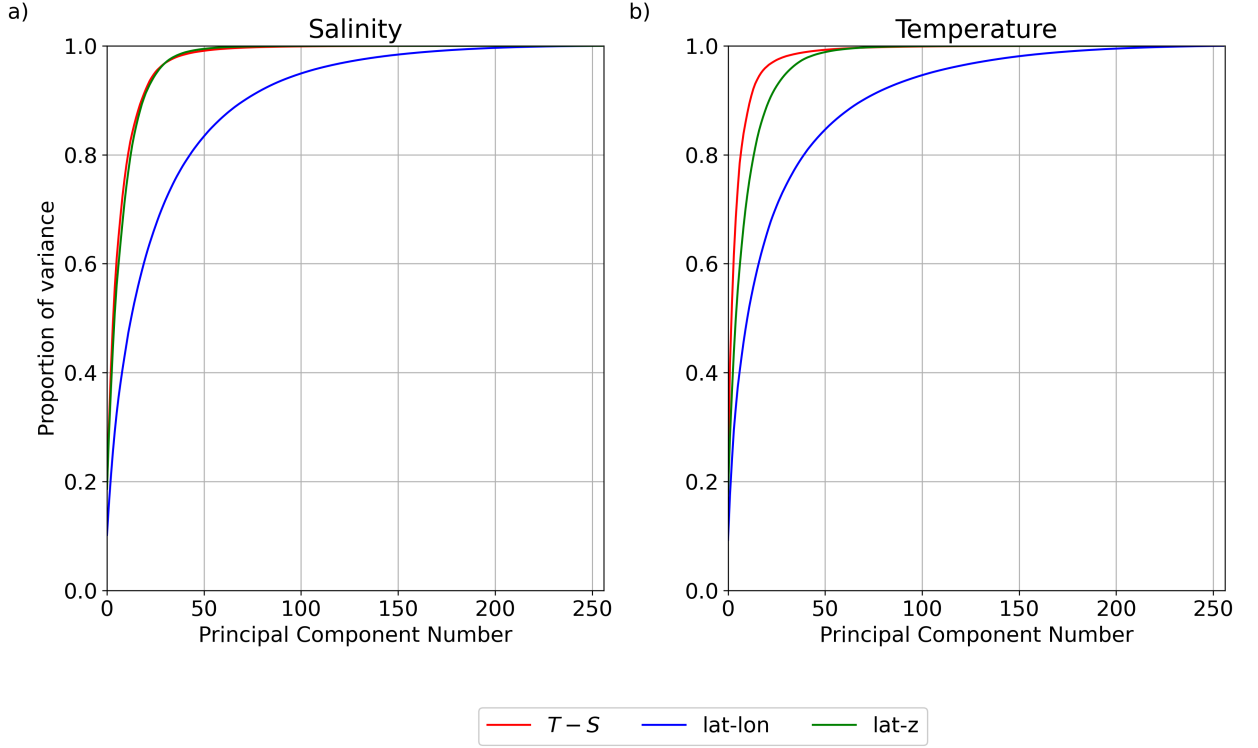


FIG. 11. Cumulative proportion of total variance captured by principal components in the Principal Component Analysis, for monthly a) salinity, and b) temperature, in  $T-S$  co-ordinates (red), latitude-longitude co-ordinates (blue) and latitude-depth co-ordinates (green).

captured in 17 principal components, while in latitude-depth and latitude-longitude co-ordinates 31 and 104 PCs respectively are required to capture 95% of temperature variance.

In the salinity time series (figure 11b), 95% of variance can be captured by 26, 25, and 101 PCs in  $T-S$  space, latitude-depth space and latitude-longitude space, respectively. Thus, while  $T-S$  co-ordinates remain the preferred choice to express temperature variability most simply, latitude-depth presents an equivalent alternative for salinity variability.

## 5. Discussion: Implications for signal-to-noise ratio

Overall, our results so far show that the projection of internal variability, or ‘noise’ in the global ocean, into latitude-depth and  $T-S$  co-ordinates is roughly equivalent, and is lower than latitude-longitude co-ordinates. Here we assess the ‘signal’, that is, the historical temperature and salinity tendency, in  $T-S$ , latitude-depth space and latitude-longitude space. Figure 12 shows the

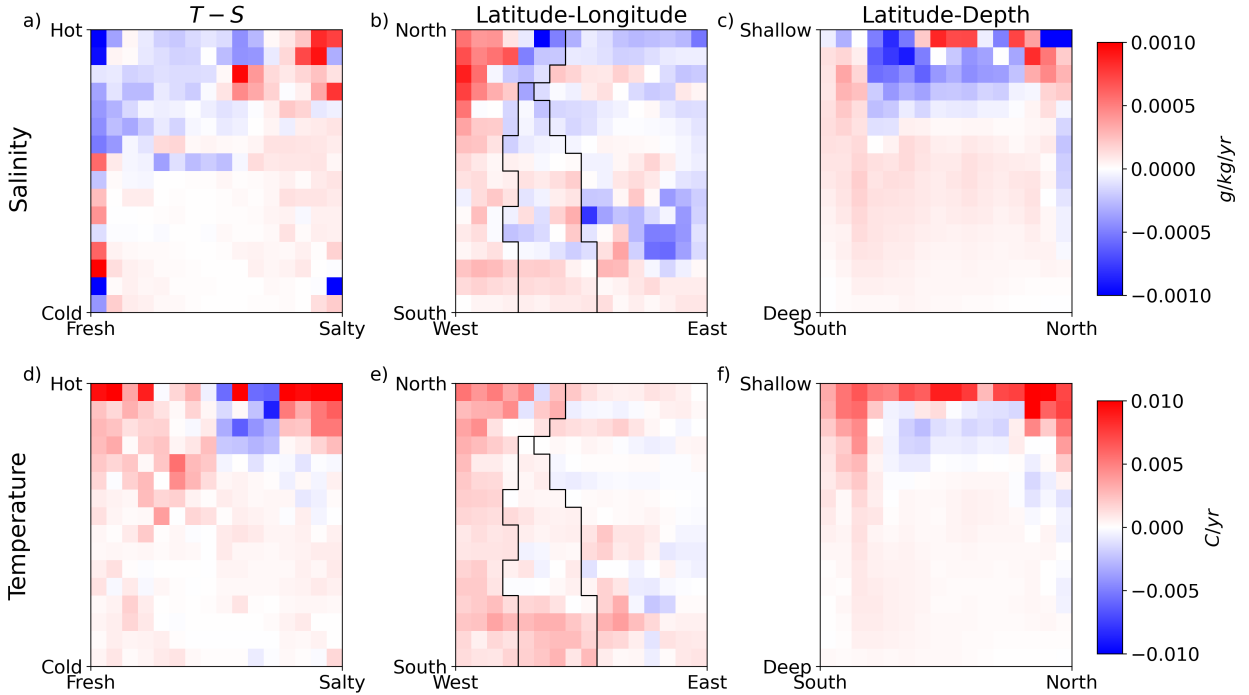


FIG. 12. Linear trend in historical (a - c) salinity (in g/kg/year) and (d - f) temperature (in °C/year), in (a and d)  $T - S$ , (b and e) latitude-longitude, and (c and f) latitude-depth co-ordinates, from 1970-2014. The linear trend is calculated by finding the slope of the linear regression on monthly data from January 1970 to December 2014.

temperature and salinity tendencies from 1970 to 2014 in the ACCESS-CM2 historical simulation. The salinity tendency (figure 12a, b and c) aligns with previous model and historical estimates of salt content change. In  $T - S$  space, salty regions get saltier, and fresh regions get fresher, following a ‘wet-gets-wetter-dry-gets-drier’ pattern (Allan et al. 2020). This is most pronounced in the warmest 50% of the ocean in  $T - S$  space, corresponding with the surface ocean that experiences widening salinity contrasts first. The Antarctic Intermediate Water is freshening and sub-tropical waters are becoming more saline, aligning well with observations of salinity change (see figure 12c). Tropical salinity changes are not as obvious in this framework as the tropics constitute a relatively small proportion of the global ocean volume. Overall, the changes in salinity in  $T - S$  space and latitude-depth space align with findings by Sohail et al. (2022); Silvy et al. (2020).

Temperature tendency in a fixed-volume framework is proportional to heat content change, so the temperature tendencies presented in figure 12d, e and f may be thought of as equivalent to the ocean heat content change. In  $T - S$  space, there is broad warming over almost all water masses



463 in the 50% warmest BSP bins, save a small water mass in a warm, salty quadrant of the global  
464 ocean. Further exploration (not shown) suggested this cooling patch may have originated in the  
465 tropical and sub-tropical Pacific, though the watermasses corresponding to the cooling also exist  
466 in the Indian and Atlantic sectors. This warming profile is consistent, at least in temperature space  
467 and depth space, with findings by Sohail et al. (2021). Thus, the BSP remapping captures well  
468 previously observed trends in ocean heat and salt content, lending credence to the method as a  
469 means to assess changes in historical temperature and salinity, or the climate change ‘signal’.

470 Having quantified both the temperature and salinity signal and noise in the climate system, we  
471 proceed to test the signal-to-noise ratio across the three co-ordinate systems of interest. We focus  
472 on the entire historical signal, from 1850 to 2014, as our climate ‘signal’ (note that this is in contrast  
473 to other detection and attribution studies which look at the recent past since 1950, e.g. Pierce et al.  
474 (2012)). We follow equation (1) to calculate signal-to-noise ratio, and use the linear trend over  
475 the historical period (i.e.,  $C$  in 2014 minus  $C$  in 1850), multiplied by the number of years (165)  
476 as  $\Delta C$  in the signal-to-noise ratio calculation. The signal-to-noise ratio in  $T - S$ , latitude-depth  
477 and latitude-longitude space is shown for each BSP bin in figure 13, for salinity (panels a-c), and  
478 temperature (panels d-f).

482 Latitude-depth co-ordinates broadly show the highest signal-to-noise ratio, with a  
483 large proportion of bins having a signal which exceeds twice the standard deviation of the pre-  
484 industrial control simulations  $F/N > 2$ , particularly in the deep ocean. Latitude-depth  $F/N$  is  
485 especially high for salinity (figure 13c), particularly in the deep ocean. This is in contrast to  
486 previous studies that have found the anthropogenic signal to be most pronounced in the surface  
487 ocean relative to noise (e.g. Pierce et al. (2012)). This is likely because we choose to assess our  
488 signal,  $F$ , as the linear trend over the entire historical period (1850-2014), rather than the recent  
489 past since 1950 considered by other detection and attribution studies. Thus, the long-term changes  
490 to deep ocean salinity and temperature are more readily picked up, and at the same time surface  
491 temperature and salinity changes are lower in a relative sense. Given the sharp contrast in variance  
492 between the surface and deep bins, this leads to a relatively large  $F/N$  in the deep ocean compared  
493 to the surface. Our analysis also shows a high temperature  $F/N$  in water masses corresponding  
494 to Subantarctic Mode Waters (figure 13f), consistent with past research (Banks et al. 2000, 2002;  
495 Swart et al. 2018; Hobbs et al. 2021).

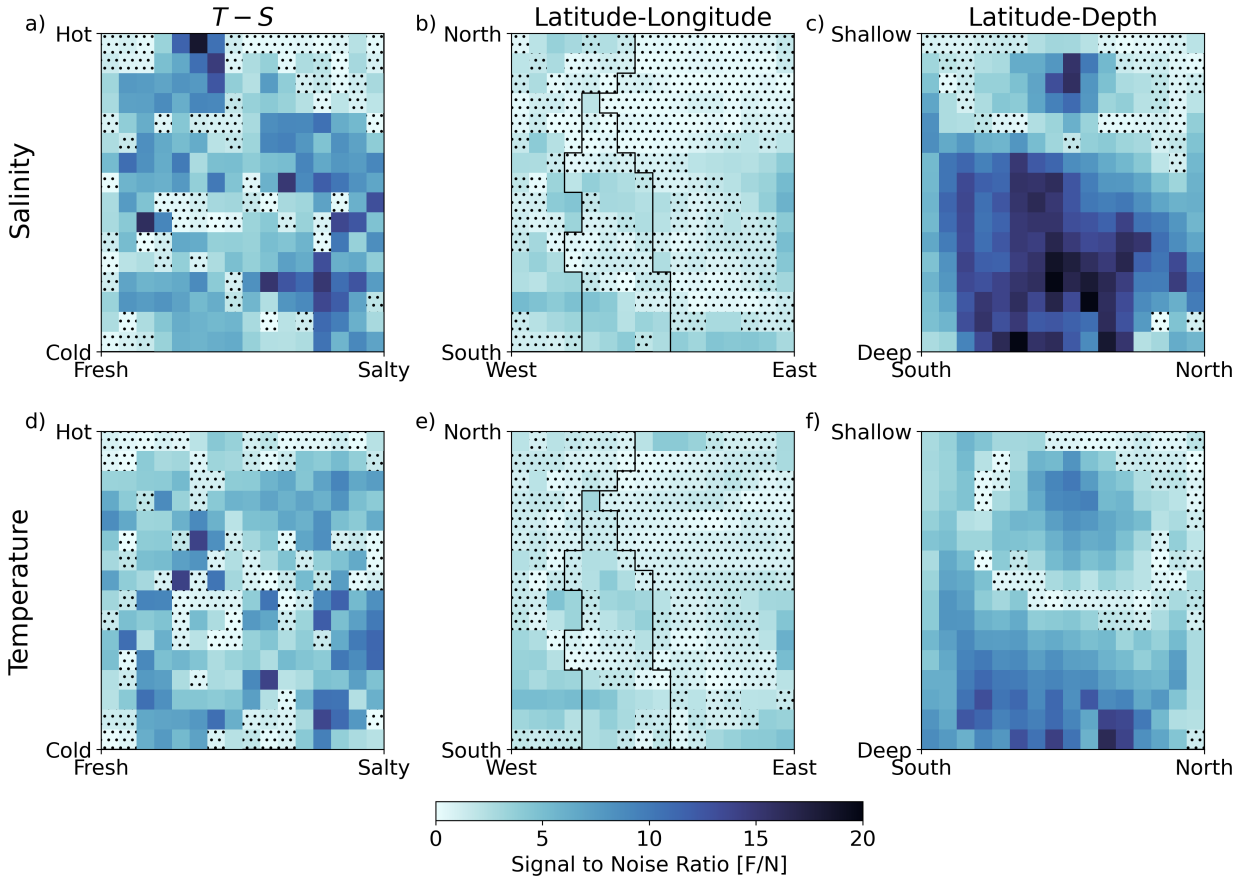


FIG. 13. Signal-to-noise ratio of (a - c) salinity and (d - f) temperature, in (a and d)  $T - S$ , (b and e) latitude-longitude, and (c and f) latitude-depth co-ordinates. Stippling shows BSP bins with a signal-to-noise ratio,  $F/N < 2$ .

$T - S$  coordinates also perform relatively well in isolating the forced signal, with the hot-spots of  $F/N$  broadly distributed across the  $T - S$  co-ordinates in both salinity and temperature. Latitude-longitude coordinates perform the worst in isolating the historical forced signal from internal variability, with the majority of bins having a relatively low signal-to-noise ratio, in both salinity and temperature.

While latitude-depth co-ordinates clearly show the greatest  $F/N$  across the different co-ordinate systems assessed here, these bins appear to be isolated to the deep ocean, which does not exhibit a particularly strong climate change signal (as shown in figure 12c and f). A co-ordinate system which has enhanced  $F/N$  in regions of high  $T$  and  $S$  change is of particular utility, as these are the regions of most interest for future studies. In order to investigate this, we plot the cumulative

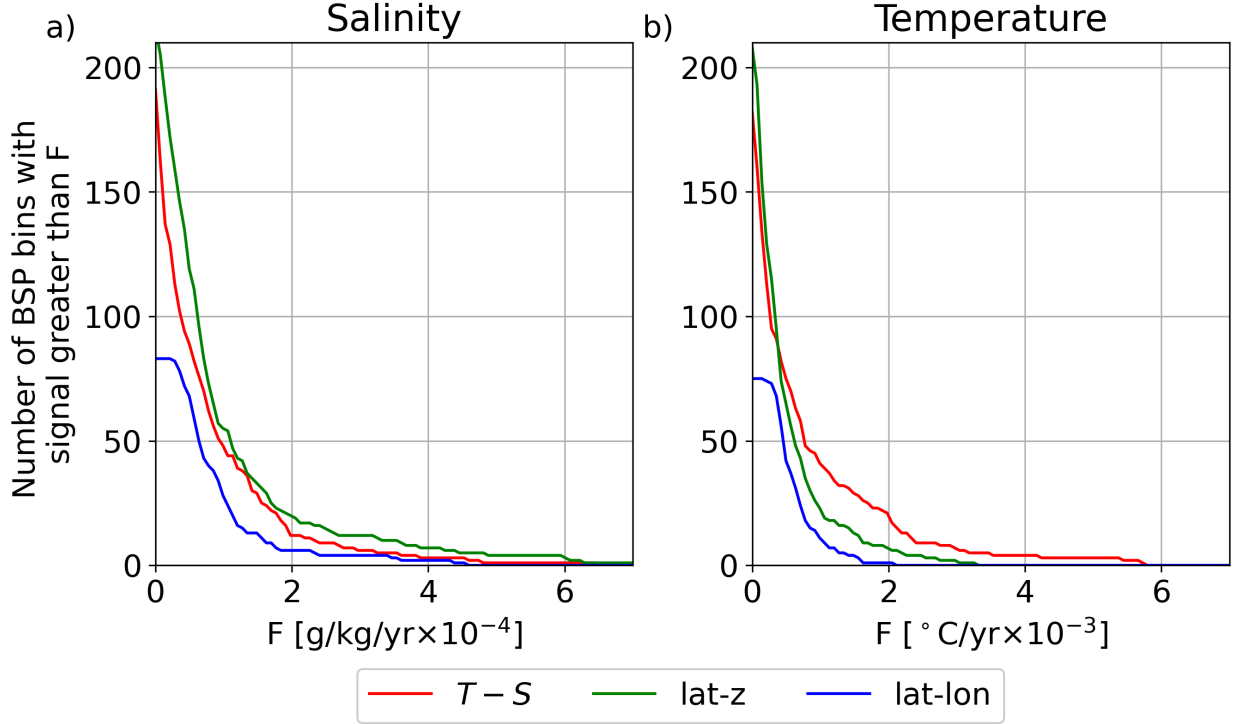


FIG. 14. Number of BSP bins with signal greater than  $F$  for each co-ordinate system,  $T - S$  (red), latitude-longitude (blue) and latitude-depth (green), in (a) salinity and (b) temperature. Only bins with a signal-to-noise ratio of  $F/N > 2$  are accumulated.

number of bins with a signal greater than  $F$  and an  $F/N > 2$  in each co-ordinate system in figure 14. For salinity (figure 14a), latitude-depth co-ordinates clearly have more BSP bins with  $F/N > 2$  across all signal strengths (but particularly in the high  $F$  regime). However,  $T - S$  co-ordinates prove to be superior in isolating high  $F/N$  in high temperature change regions. While latitude-depth overall has more BSP bins across all signal strengths for temperature, this advantage is isolated to lower signal regions, and thus may not be as useful. Hence,  $T - S$  co-ordinates are superior to their Eulerian counterparts in capturing the climate change signal in temperature, due to a high  $F/N$  in regions of high temperature change,  $F$ .

The results and discussion have so far focussed on analysis of the native ACCESS-CM2 model grid. However, as flagged in section 3, increasing the vertical resolution of the model grid may change the representation of variability in  $T - S$  and latitude-depth space, altering the conclusions of this study. In figure 15, we show how the median noise and signal-to-noise ratio in  $T - S$

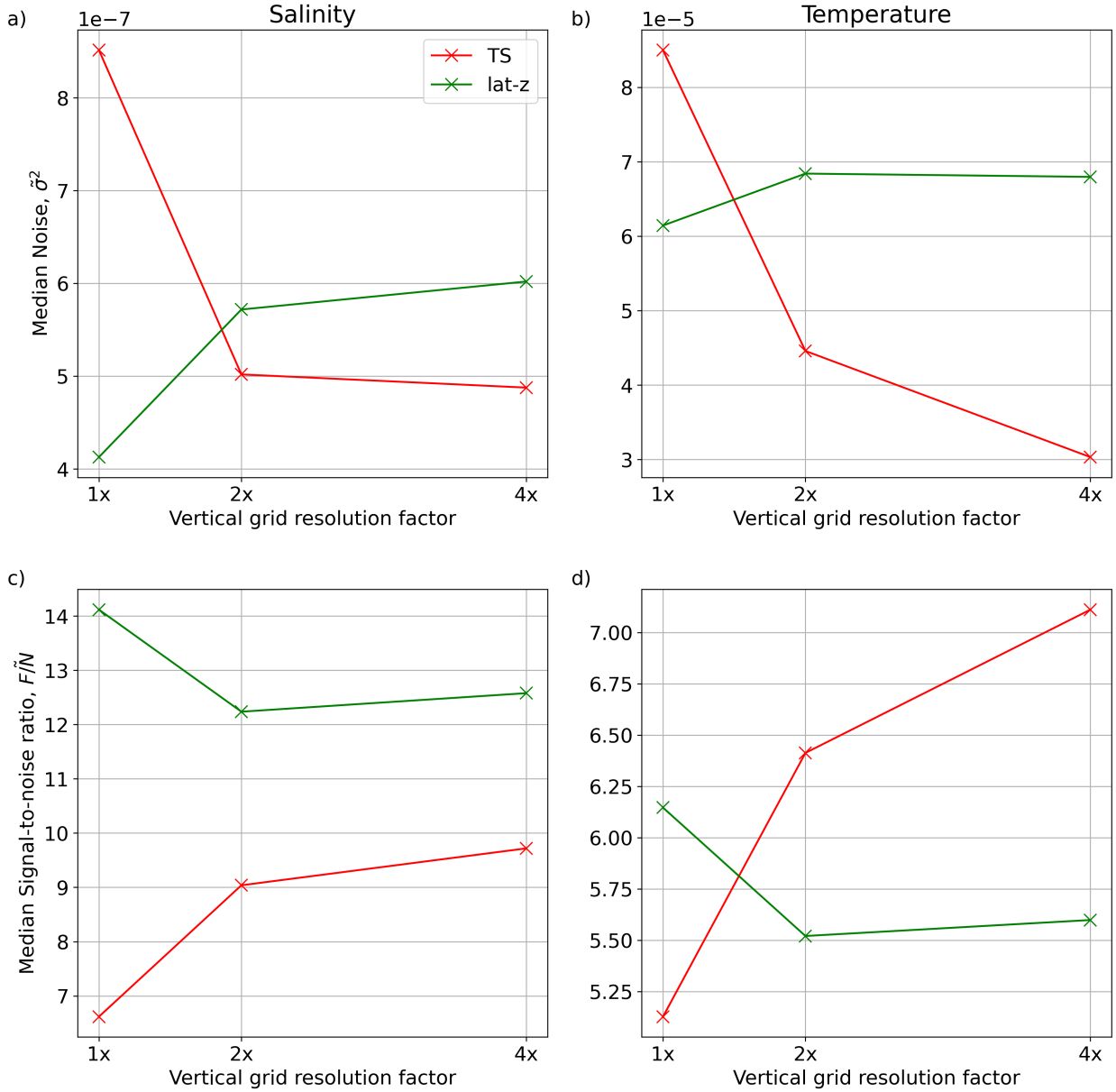


FIG. 15. The median (a and b) noise and (c and d) signal-to-noise ratio of (a and c) salinity and (b and d) temperature, given a doubling (2x) and quadrupling (4x) of the native model vertical grid via linear interpolation. The first 100 years of the ACCESS-CM2 control simulation are analysed here. Only  $T - S$  (red) and latitude-depth (green) co-ordinates are compared.

and latitude-depth co-ordinates changes with a doubling and quadrupling of the model vertical resolution. As vertical resolution increases, the median noise in  $T - S$  space decreases for both temperature and salinity (figure 15a and b). In latitude-depth space, the median variance increases,

though not by as much as variance decreases in  $T - S$  space, implying that  $T - S$  co-ordinates are more sensitive to vertical model resolution. Therefore, models with a native Eulerian grid will naturally be better represented in Eulerian co-ordinate systems, but as the vertical grid resolution increases, the representation of  $T$  and  $S$  is improved, enhancing the utility of  $T - S$  co-ordinates as a diagnostic tool.

The gap in median signal-to-noise ratio between latitude-depth and  $T - S$  narrows for salinity as vertical resolution increases (figure 15c). For temperature, the median signal-to-noise ratio in  $T - S$  becomes larger than that in latitude-depth upon doubling of the vertical grid resolution (figure 15c). Hence, it is essential to use a model which adequately resolves vertical structures of temperature and salinity to unlock the key benefits of water mass co-ordinates. The F/N in regions of high  $T$  and  $S$  change (as shown in figure 14) does not change significantly with different vertical resolutions (not shown). Therefore, one of the the main conclusions of this study, that is, that watermass co-ordinates isolate the historical temperature change signal, is robust regardless of the model vertical resolution.

There are several questions open for further exploration, particularly in terms of the BSP algorithm presented here. In the past, watermass-based frameworks have been used to develop simple ocean heat and salt content budgets, wherein salt and heat content tendencies can be related solely to diabatic air-sea flux and mixing processes (Holmes et al. 2019; Sohail et al. 2021; Bladwell et al. 2021). In the two-dimensional BSP framework, such a budget is more difficult to formulate, as changes to the properties of a bin can potentially change the BSP bins in adjacent  $T - S$  regions. That said, the formulation of a budget in the BSP framework would yield a more process-based understanding of some of the trends and variability seen in this analysis, and is reserved for future work. In addition, while the two-dimensional frameworks assessed here retain regional information, the diagnostics are calculated over the entire global data set. An analysis which is confined only to certain regions may provide further guidance towards the driving processes in different regions of the ocean. Such a process-based, regional approach may also aid in understanding the tendency results in figure 12, including the cooling patch in  $T - S$  space. In addition, one-dimensional analyses in temperature space have highlighted the potential benefits of using watermass-based co-ordinates to reduce sampling bias arising from adiabatic heave in observations (Palmer et al. 2007; Palmer and Haines 2009). BSP presents an opportunity to extract synthetic profiles from

climate model data, following Allison et al. (2019), and assess the influence of two-dimensional co-ordinate systems on observational sampling biases and observed heat and salt content.

## 6. Conclusions

Watermass-based frameworks are becoming popular for capturing changes in ocean heat and salt content, in part because they are believed to reduce internal variability, thus more effectively isolating the historical ‘signal’ of climate change. However, a rigorous comparison between watermass-based frameworks and Eulerian (latitude-longitude, latitude-depth, etc.) co-ordinate systems has been difficult due to fundamental differences in the way these co-ordinate systems are formulated. In this work, we introduce a statistical method, called *Binary Space Partitioning* (BSP) to recast  $T - S$ , latitude-longitude and latitude-depth co-ordinate systems onto an equivalent, equal-volume co-ordinate. Applied to pre-industrial control and historical simulations of a state-of-the-art climate model, ACCESS-CM2, BSP enables an apples-to-apples comparison of internal variability between watermass-based and Eulerian co-ordinates. We find that  $T - S$  and latitude-depth co-ordinates have equally low global variability, and the majority of this variability can be attributed to multi-decadal processes in both co-ordinate systems. Overall, we find that the historical temperature signal is more effectively isolated in  $T - S$  space, with a signal-to-noise ratio that is greater than its Eulerian counterparts in regions of high temperature change. Latitude-depth co-ordinates, on the other hand, present the best option for isolating the historical salinity change signal, with a signal-to-noise ratio that is greater than  $T - S$  and latitude-longitude co-ordinates in regions of high salinity change. These results present the lower bound of variance and signal-to-noise ratio in  $T - S$  co-ordinates, and are dependent on the model’s vertical grid resolution. Our findings provide a road-map for choosing the best two-dimensional co-ordinate system when analysing global data sets, suggesting that  $T - S$  co-ordinates are most appropriate for temperature change studies, and latitude-depth co-ordinates are preferred for salinity change analyses.

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594 *Data availability statement.* All data used in this work is publicly available via ESGF: [https://esgf-](https://esgf-node.llnl.gov/search/cmip6/)  
595 [node.llnl.gov/search/cmip6/](https://esgf-node.llnl.gov/search/cmip6/).

## 596 APPENDIX A

### 597 **Variability across $2^n$ combinations of axis subdivisions**

598 In this study, we opt to subdivide alternating axes (starting with the  $y$ -axis) 8 times, to yield  
599  $2^8 = 256$  bins. However, as mentioned in section 3, there are 256 possible combinations of  
600 axis subdivisions that may have been chosen, including  $xxxxxxx$ ,  $xxxxxxy$ ,  $yyyyyyx$ , etc. In  
601 this appendix, we explore the influence of choosing some of these other combinations of axis  
602 subdivisions on our results.

603 When assessing internal variability in two-dimensional tracer space, an ideal coordinate system  
604 would equally represent changes in both the  $x$ - and  $y$ -axes. For instance, in some climate model  
605 grids latitude and longitude have roughly equivalent resolutions as variability in the latitudinal  
606 and longitudinal directions is roughly similar. Of course, for the sake of reducing computational  
607 complexity, dimensions which are known apriori to exhibit characteristically lower variability may  
608 have reduced resolution - for instance, ocean model grids typically have lower depth resolution  
609 than latitude or longitude. Without such apriori knowledge of variability in a given dimension, and  
610 in an attempt to create a like-for-like co-ordinate system, we argue that the most appropriate BSP  
611 split combinations would be ones that preserve the aspect ratio of bins. Thus, we propose that the  
612 most physically plausible BSP split combinations are combinations of  $xy$  and  $yx$ . Always splitting  
613 in axis pairs ensures that no long, thin bins are created which span a large range in one dimension  
614 but a small range in another dimension.

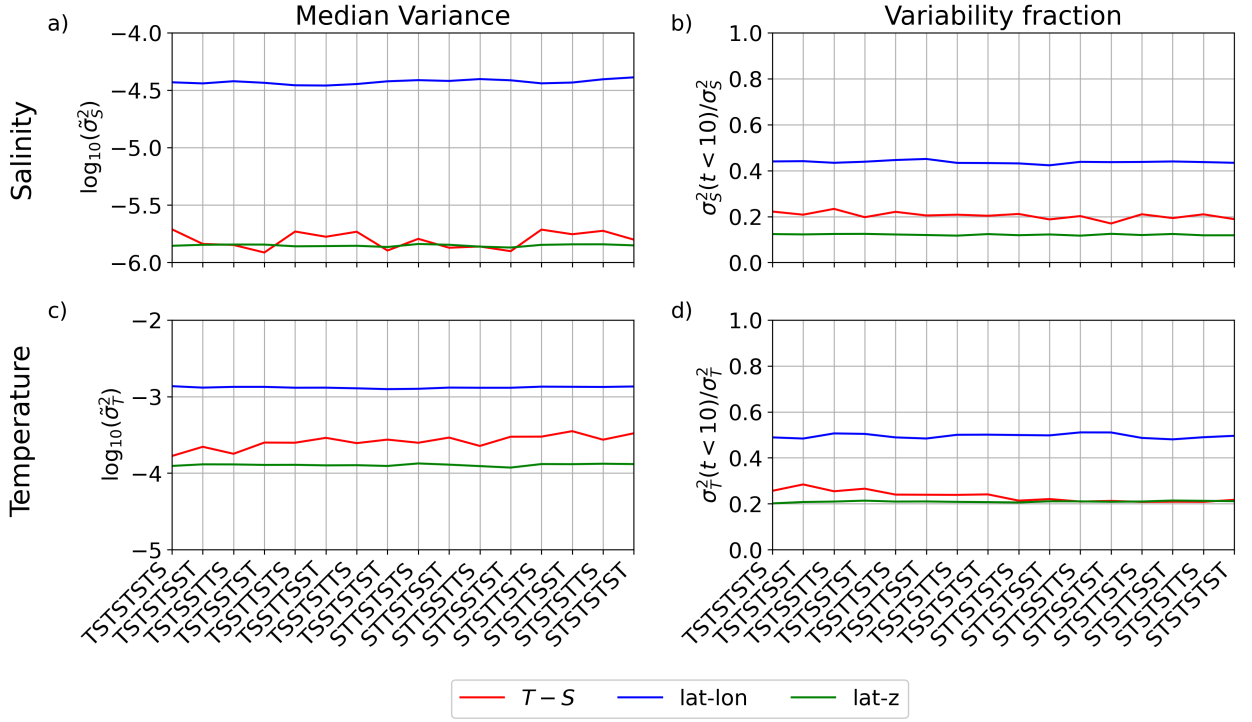


FIG. A1. (a and c) Median variance and (b and d) median fraction of sub-decadal variance in  $T-S$  (red), latitude-longitude (blue) and latitude-depth (green) co-ordinates across 16 plausible BSP split combinations.



For  $n = 8$ , there are 16  $yx$  and  $xy$  combinations that preserve the BSP bin aspect ratio. As the variance distributions (figure 7) are highly skewed, we examine how the median (rather than mean) variance changes across the 16 BSP split combinations in figure A1 a and c. For salinity,  $T - S$  and latitude-depth co-ordinates have extremely similar median variances across all split combinations. For temperature on the other hand, latitude-depth co-ordinates have consistently lower median variance than  $T - S$ , and this gap changes based on the specific split combination used. That said, the median variance of  $T - S$  and latitude-depth remains quite close relative to the latitude-longitude co-ordinate system, which has a median variance that is approximately one order of magnitude larger. Across all BSP split combinations,  $T - S$  and latitude-depth co-ordinates are dominated by multi-decadal processes, while latitude-longitude co-ordinates have a roughly equal split between sub-decadal and multi-decadal processes (see figure A1 b and d). Our exploration of alternative BSP split combinations further solidifies our findings, showing that our results are insensitive to the order of (physically constrained) BSP splitting used.

## APPENDIX B

### **Geographic location of watermasses in $T - S$ space**

It is difficult to conceptualise changes in watermass space in terms of the geographic location of said water masses. In an attempt to aid in interpretation of the results we show the volume fraction in each latitude-longitude and latitude-depth grid cell that corresponds to the warmest (coldest) and freshest (saltiest) 25% volume of the ocean, in figure B1. The 25% coldest and freshest ocean by volume is predominantly located in the Southern Ocean and surface Arctic ocean (figure B1a, b and c). Antarctic Bottom Water and Pacific subsurface waters are captured in this quadrant. The 25% coldest and saltiest ocean is much more broadly distributed - and largely corresponds to the deepest ocean water (figure B1d, e and f). The North Atlantic Deep Water and North Atlantic overturning are captured in this quadrant.

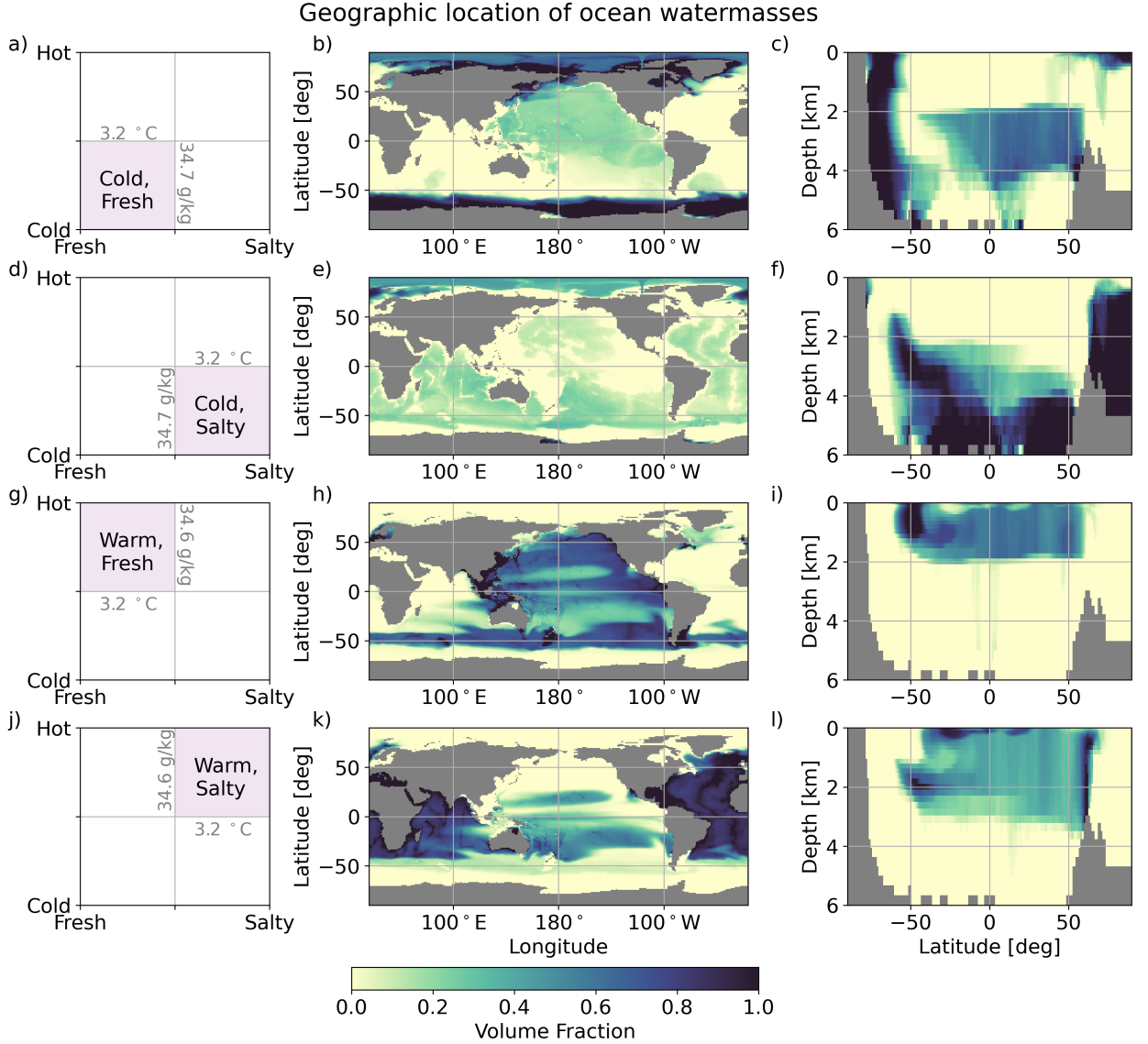


FIG. B1. The volume fraction, in latitude-longitude and latitude-depth co-ordinates, occupied by four water masses in  $T - S$  space: (a, b and c) The coldest, freshest 25% of the ocean, (d, e and f) the coldest, saltiest 25% of the ocean, (g, h and i) the warmest, freshest 25% of the ocean and (j, k and l) the warmest, saltiest 25% of the ocean. Note that these quadrants are the same as those presented in Figure 2 for  $2^2$  bins, and their temperature and salinity limits are denoted in grey. Land masses are coloured in dark grey.

The 25% warmest and freshest ocean is largely isolated to the surface Pacific ocean, as well as the Antarctic Intermediate Water, but excludes the Pacific subpolar gyres (figure B1g, h and i). The 25% warmest and saltiest ocean, on the other hand, is almost exclusively isolated to the Indian and Atlantic oceans (excluding the Indo-Pacific warm pool), and includes the Pacific subpolar gyres (figure B1j, k and l).

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