Ocean Cryosphere Exchanges in Antarctica:

Impacts on Climate and the Earth system

Temporal and spatial length scales in $\delta^{18}O$ observations

Deliverable D5.5

OCEAN:ICE is co-funded by the European Union, Horizon Europe Funding Programme for research and innovation under grant agreement Nr. 101060452 and by UK Research and Innovation

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About this document

Deliverable: D5.5 Temporal and spatial length scales in δ18O observations

Work Package: WP5 Ice sheet impacts on global ocean circulation

Delivery date: 30 April 2024

Type of document: Report

Dissemination level: Public

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1.Publishable summary

This deliverable is a report on analysis undertaken to determine the length scales and timescales of oxygen isotope ($\delta^{18}O$) variations in the surface ocean based on observations. We find that there are multiple length scales, up to three (depending on the length of the segment being analysed). We characterise these length scales as being eddy (typically 100-300km), an intermediate scale (500-700 km) and a gyre scale (1000-1500 km). The spatial distribution of the decorrelation length scales indicate the pervasiveness of eddies in the Southern Ocean, while longer length scales depict the zonal nature of the Antarctic Circumpolar Current as well as the structure of the Ross and Weddell gyres. The differences in the spatial patterns suggest that at the largest scales, the decorrelation length scales are anisotropic, with meridional length scales mostly featuring the circumpolar current, while northward scales indicating the northward spreading of the Subantarctic Mode Waters. Regarding the decorrelation timescales, unfortunately, the available time series in the Southern Ocean can only suggest some interannual variability, but the amount of observations is not enough to identify the structure or driver of such variability. Scales associated with oxygen isotopes are similar to those for salinity, whereas there are some differences with temperature.

2.Work performed and main achievements

2.1 Description of the work performed

Identifying the structure of the water masses, their distribution and their properties is essential for constructing an efficient observing system capable to detect the ongoing circulation changes due to enhanced melting of the Antarctica ice sheets. An efficient observing system would maximize the information gain from observational efforts while avoiding unnecessary information redundancy.

The structure the surface ocean can be assessed by the spatiotemporal variability of different water mass properties, -i.e., how a measured property varies in time and space with respect to the same property at another location or a different time. This can be estimated by diagnosing the decorrelation length and timescales. Decorrelation length scales indicate the lag or offset at which spatial changes in a property stop being correlated. The decorrelation length scale indicates the dominant length scale of spatial variability. Similarly, decorrelation time scales describe the lag or offset at which a timeseries stops being correlated with itself and thus the dominant timescale.

Decorrelation scales are estimated with the Autocorrelation function (E.P. Box et al., 2015), where the sample autocorrelation coefficient, r_k, for a given lag, k, is given by:

$$r_k = \frac{c_k}{c_0}$$

Where c_0 is the sample variance of the series and $c_k = \frac{1}{N}\sum_{t=1}^{N-k}(y_t - \bar{y})(y_{t+k} - \bar{y})$. Where y_t is the spatial- or time-series, and $\bar{y}$ is its mean. N is the number of points in the series. Figure 1 is an example of decorrelation length-scales. The point where the autocorrelation value intercepts with 0 gives the spatial lag at which the series is decorrelated and therefore points towards the size of the structure. Decorrelation scales were estimated for available observations of space- and time-series of temperature, salinity and $\delta^{18}O$ (the ratio of Oxygen-18 to Oxygen-16). For the spatial analysis, decorrelation length-scales were calculated for the northward, southward, eastward and westward directions.

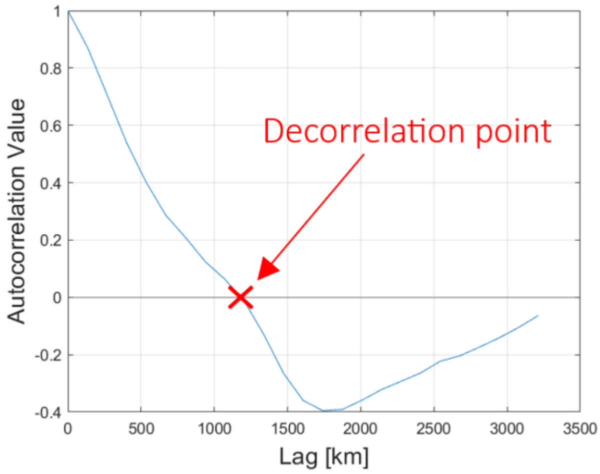

Fig.1: Spatial autocorrelation of a small section in the Southern Ocean.

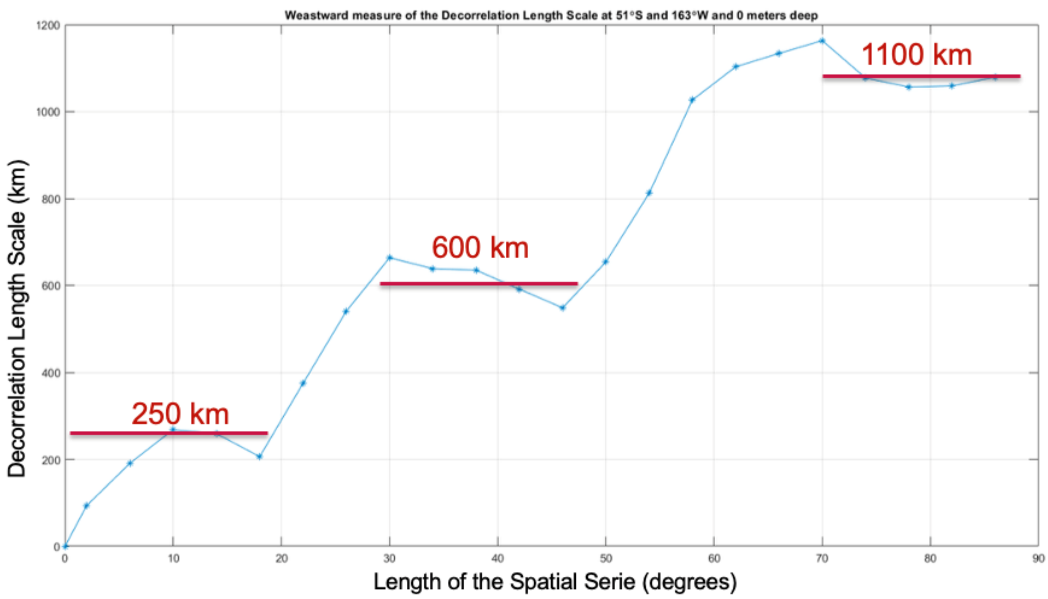

Fig.2: Dependency of westward decorrelation length scales and the chosen length of the spatial series for a spatial array starting at 51°S and 163°W.

3.1.1 Decorrelation length-scales

The decorrelation length-scales were calculated from state estimate fields of these properties from the Total Matrix Intercomparison (TMI) (Gebbie & Huybers, 2010). The TMI is a data-based transport matrix where a steady-state ocean circulation is constrained from climatological observation of different tracers (temperature, salinity and $\delta^{18}O$, among others). At the same time, the tracer fields

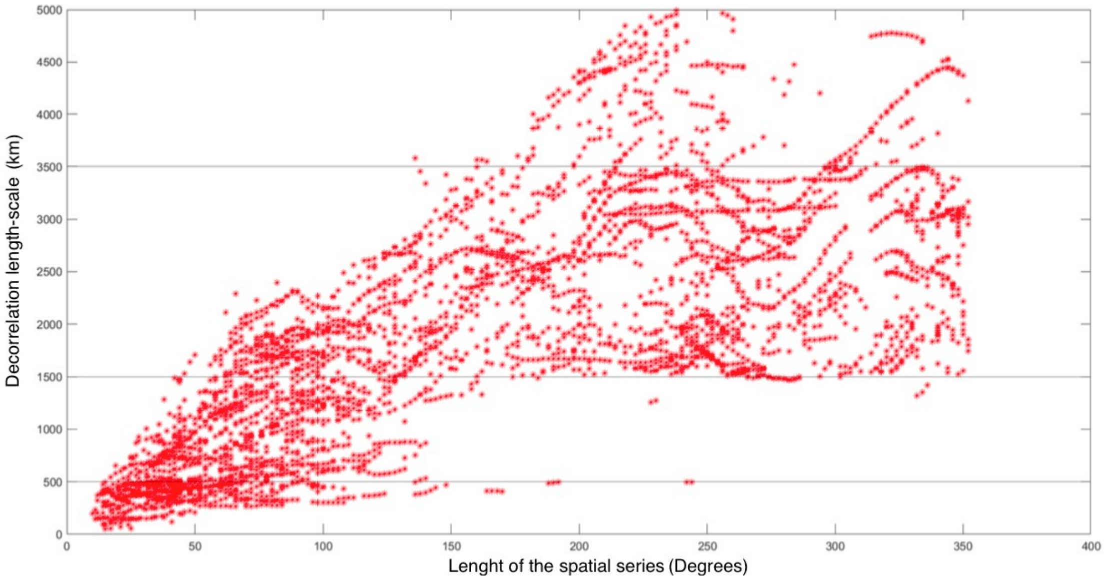

Fig.3: Eastward decorrelation lengthscales estimated from spatial series of different length in the Southern Ocean.

are adjusted within their uncertainty to produce the corresponding state tracer fields that are self-consistent with the TMI representation of ocean circulation. The state tracer fields have a resolution of 2° x 2° and are available at (Gebbie et al., 2023).

We found that there is a dependence between the decorrelation lengths calculated from the autocorrelation and the length of the spatial series (Figure 2 and 3). In general, the shorter the spatial series, the shorter the decorrelation length-scale, and thus, the smaller the structure that is represented. However, this relationship breaks at given length-scales for a few iterations where the length of the spatial series is increased but the decorrelation scale stays relatively constant (e.g., between 30 and 46° in Figure 2). From these "staircases", we infer four different categories which are representative of the size of the sampled structures: "small", "medium" and "large". At "small" spatial series of few degrees (few hundreds of kilometers), the decorrelation length-scales are of about 250

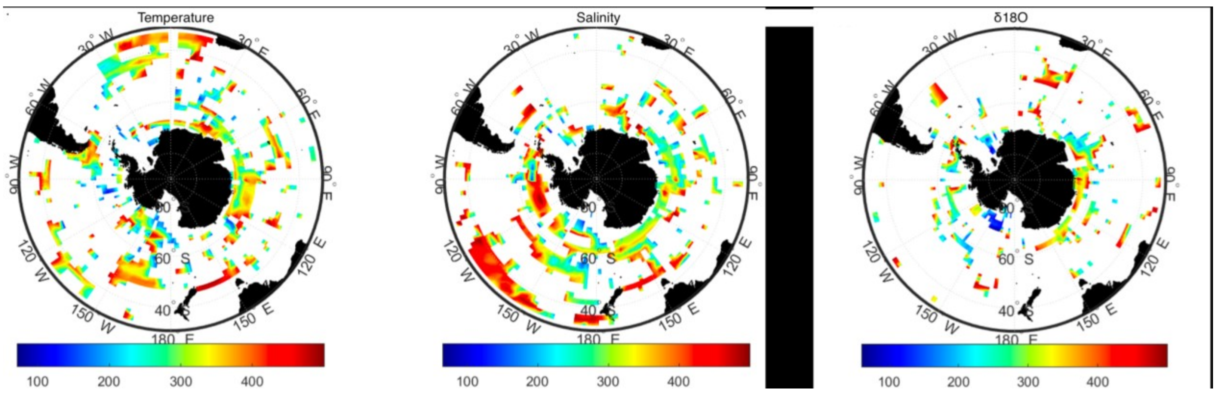

Fig.4: Westward "small" decorrelation length scales for surface temperature, salinity and $\delta^{18}O$ in kilometres. The colour-scale indicates the distance at which the spatial series is correlated with the meridional data series.

km. These decorrelation length-scales are in agreement with those estimated from Argo of <400 km (Ninove et al., 2016). At these length-scales, the structures are categorized as mesoscale eddies. For longer spatial series, 50-100°, decorrelation length scales typically increase to 500-2000 km, and feature the presence of small gyres. At even larger spatial series, the identified structures correspond to large scale gyres. The size of such coherent structures identified by the decorrelation length-scales offer guidance to future sampling efforts. As such, the spatial frequency of the sampling highly depends on the size of the water mass feature that is intended to be observed, the larger the water masses, the smaller the spatial frequency can be, and vice versa.

We attempted to make maps of decorrelation length scale using an automatic detection algorithm (Figure 4,5,6). The algorithm classifies the length scales according to changes in the decorrelation length scales tendency against changes in the length of the spatial series. Each step of the staircase in Figure 2 is defined as a water mass structure. Where the tendency changes with respect the "flatter" section, marks the characteristic decorrelation length scale or the size of the water mass structure. The algorithm worked but not everywhere, as in some cases, these staircases are not well captured automatically and thus this criterion is not always fulfilled, which is why there are white gaps in the decorrelation length scale maps. Further work would be required to refine the algorithm.

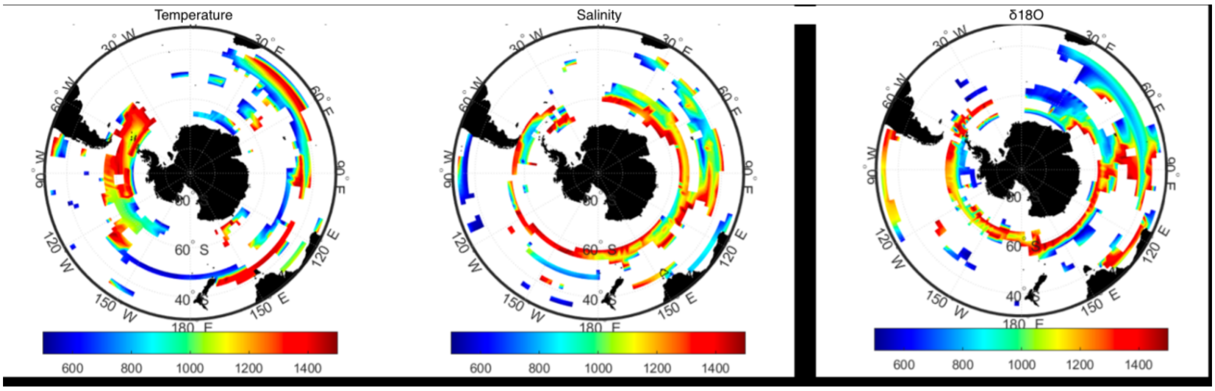

Fig.5: Same as Figure 4 but for the "medium" length scales.

The ubiquity of "small" decorrelation length scales when using short spatial series suggest the pervasiveness of eddies in the Southern Ocean (Figure 3 and 4). This agrees well with our knowledge of these structures in the Southern Ocean, although the length scales identified here are an order of magnitude larger than what previous observations suggest (Sallée et al., 2008). The eastward decorrelation length scales (not shown) are similar to the westwards length scales.

The larger the length scale, the larger are the water mass structures that are identified. Westward length scales are coherent with the meridional flow of the Antarctic Circumpolar Current, where decorrelation length scales reach up to 1400 km (Figure 5). The eastward length scales also depict the Circumpolar Current (not shown) similar to the westward length scales. At even at larger length scale ("large" length scales), we identify the Ross and Weddell gyre as covarying structures in terms of temperature, salinity and $\delta^{18}O$ (Figure 6). Decorrelation length-scales are greater in the Ross gyre than in the Weddell gyre. In general, the similarities among the decorrelation length-scales of highlight the tight relationship between $\delta^{18}O$ and salinity, which are equally impacted by the melting ice shelf, where temperature is typically correlated on longer length scales for both the Ross and Weddell gyre. It is worth noting that these length-scales are estimated from a state estimate, whereas in reality, temporal variability might alter how spatially correlated these regions are.

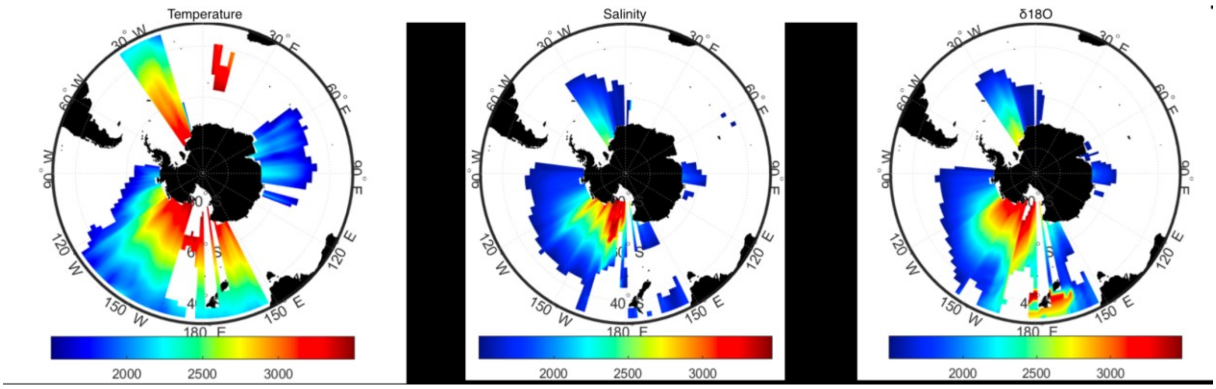

Fig.6: Same as Figure 4 but for “large” northward lengthscales.

At “medium” and “large” scales the decorrelation length scales are anisotropic – i.e., the northwards decorrelation length scales are typically larger and clearly depict the Ross and Weddell gyre structure than meridional length scales. Meridional length scales, leadingly feature the Antarctic Circumpolar Current.

3.1.2 Decorrelation time-scales

Water-mass properties and their distribution vary in a great range of timescales, from daily to interdecadal frequencies. Constraining this variability is essential to understand whether the ongoing change is a forced response (because of the ongoing warming) or is part of the inherent variability of the climate system, also known as internal variability. Long timeseries are needed to properly separate the internal climate variability from the forced response. Unfortunately, the available δ^{18}O measurements available in the Southern Ocean are not enough to provide an answer for the ongoing observed changes.

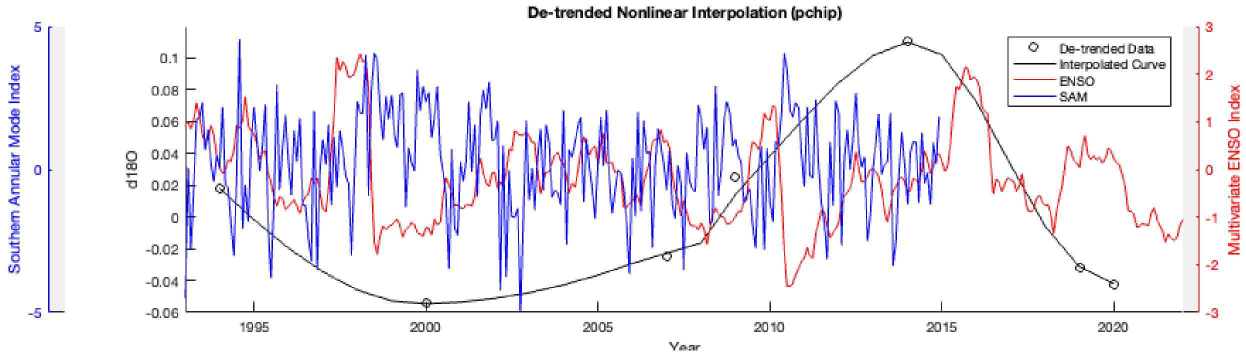

Fig.7: De-trended and interpolated δ^{18}O time series from the south-eastern Amundsen Sea (73.5°S – 75.5°S; 108°W - 100°W) (in black), overlapped with the El Niño-Southern Oscillation (ENSO; in red) and Southern Annular Mode (SAM; in blue) climatic indexes.

To the best of our knowledge, there is only one region in Antarctica which has been systematically sampled for δ^{18}O for years, the southeastern Amundsen Sea, which data has recently been made publicly available (Hennig et al., 2024). Because there is not enough data to resolve the seasonal cycle, here we estimate yearly averages from all the data available in the upper ocean (<400 m) in the south-eastern Amundsen Sea (73.5°S – 75.5°S; 108°W - 100°W) to some gain insights in the interannual variability. Measurements of δ^{18}O were carried out in 1994, 2000, 2007, 2009, 2014, 2019 and 2020, which shows an interannual variability with an amplitude of ~0.16‰ (Figure 5). Very similar variability is also identified for both temperature and salinity (not shown), pointing to the co-occurrence of warmer, saltier and δ^{18}O-enriched waters. Part of the variability is expected to result from large scale atmospheric patterns such as the Southern Annular Mode (SAM) and the El Niño-Southern Oscillation (ENSO). Atmospheric teleconnections impact the saltier and warmer Circumpolar Deep Water (CDW) inflow to the continental shelves by, -e.g., modifying the strength of the circumpolar westerly winds which induces meridional Ekman transport into the coastal regions (Dotto et al., 2018).

We performed an autocorrelation analysis on the detrended and interpolated time series of δ^{18}O data, which suggest a correlation timescale of about 5 years, and an anticorrelation peak after 10 years (Figure 6). This autocorrelation suggests some decadal variability, also seen in Figure 5. Unfortunately, the available observations are not enough to suggest any meaningful conclusions nor any correlations between δ^{18}O and SAM or ENSO climate indexes. The lack of available time-series in the Southern Ocean call for strengthening of the observing system to detect the ongoing and expected changes in the Antarctic ice-shelves and their effect in ocean circulation.

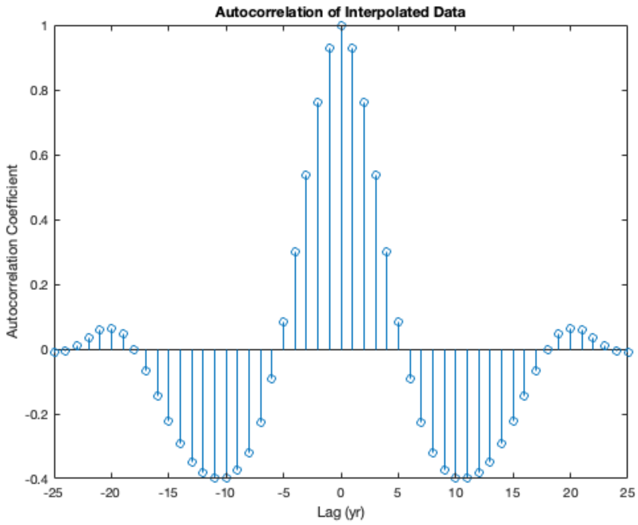

Fig.8: Decorrelation timescales of 5 years and anticorrelation timescales of 10 years computed from the interpolated times series in the south-eastern Amundsen Sea (73.5°S – 75.5°S; 108°W - 100°W).

2.3 Open Science

The data set used for the decorrelation length scales is available in https://doi.org/10.5281/zenodo.8226802 (Gebbie et al., 2023) and in GitHub https://github.com/ggebbie/TMI.jl

The time series data used for estimating the decorrelation timescales can be accessed at https://doi.org/10.25740/zf704jg7109 (Hennig et al., 2024). This report (also available) represents the methods and the results.

4. Impact

4.1 Contribution to the project objectives

This deliverable contributes to the achievement of the following objective (O) of the project indicated in the Description of the Action.

O1: Reduce the spatial and knowledge gaps in ocean observations around Antarctica

The results contained in this deliverable will inform the density of δ^{18}O observations required to observe the parameter completely. The shortest space scale is an eddy scale of 100-300 km. Thus, we recommend at least 100km sample spacing to resolve δ^{18}O variability. Time series exist that indicate significant δ^{18}O temporal variability on multi annual timescales, however there is insufficient temporal resolution to determine dominant timescales. Thus, we recommend collection of data sets of at least monthly resolution to determine temporal timescales in a similar way to what we have done for spatial scales.