

200-year Durability Assessment

Technical review on deepwater ocean re-exposure of
MCFS deployment offshore New Zealand

December 2025

Part 1. Technical review on deepwater ocean re-exposure

1. Introduction

This section provides an overview of the scientific literature characterizing the re-exposure of deepwater to the surface. An area of particular interest are deepwaters (greater than 1000 meters), generally located south of 45°S and north of 45°N in the Pacific.

The document introduces key concepts and outlines the results of the most relevant papers found during the literature review.

2. General concepts

Ocean ventilation describes how mixed layer properties such as temperature, salinity, and dissolved gas concentrations (i.e. from interaction with atmosphere) are translated from the ocean surface (mixing layer depth) into the deeper interior ocean (Styles et al., 2024).

The ocean mixing layer depth (MLD) defines the upper layer of the ocean where properties like temperature and salinity are relatively uniform due to turbulent mixing driven by wind, buoyancy fluxes, and waves. It is essentially the surface layer that interacts directly with the atmosphere.

Ocean ventilation is important because a) it governs the absorption of heat and anthropogenic carbon dioxide from the atmosphere, which affects the climate and ii) It supports marine life by replenishing the water column and deep ocean with oxygen and distributes nutrients essential for biological productivity.

Ocean ventilation has received a lot of attention as it is a key process in developing the understanding of the global ocean conveyor concept (Figure 1) (see Marshall and Speer, 2012; Talley, 2013).

Here, we are instead interested in the complementary concept of deepwater re-exposure to the surface, which describes how waters from the deep ocean are then recirculated to the mixing layer depth and exposed to the atmosphere. This has received less attention.

Another concept that is employed in the literature is the residence time, which is the time that the ventilated fluid spends in the interior between next surface contact, the rate of ventilation of surface water into and out of the ocean interior (e.g. Primeau and Hollzer, 2006).

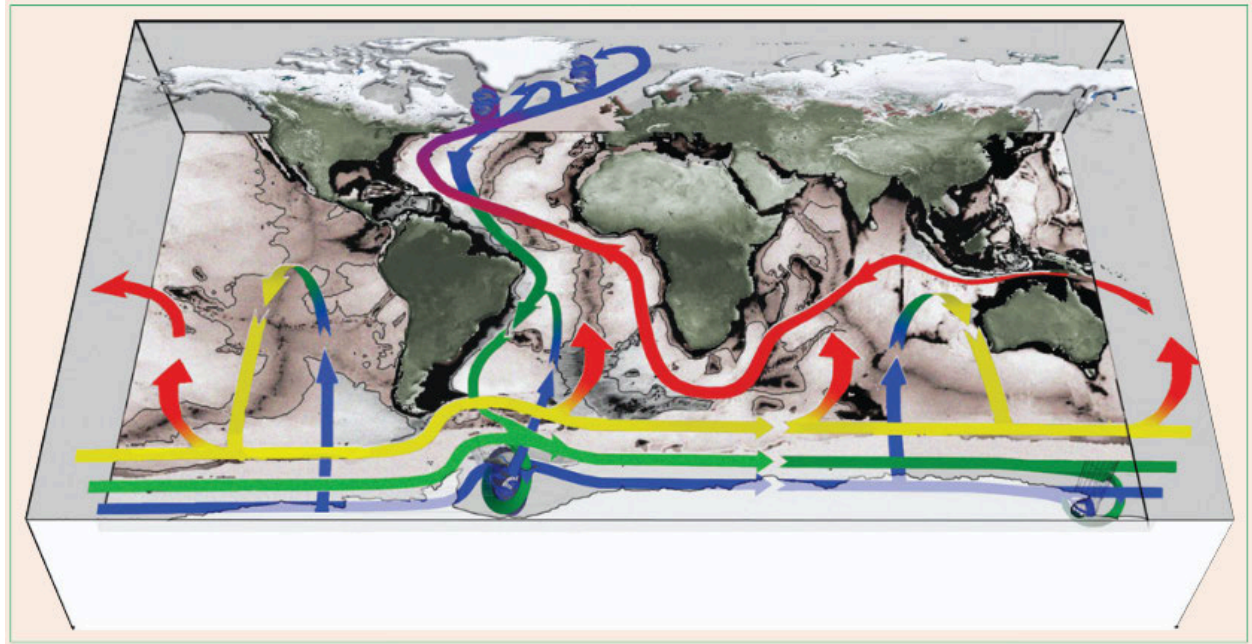


Figure 1. Conceptual model of the Global Ocean Conveyor (GOC). Colder(warmer) arrow colors indicate deeper(shallower) waters. (reproduced from Marshall and Speer, 2012).

3. Mechanisms of surface ocean ventilation and deep ocean re-exposure

The primary processes responsible for ocean ventilation and the subsequent re-exposure of deep water to the atmosphere are outlined below:

1. **Baroclinic effects:** seawater density gradients (i.e. buoyancy gradient) due to changes in temperature and salinity.
 - a. **Deep Water Formation (high latitude):** Occurs at high latitudes where surface waters become very dense due to cooling and/or brine rejection during sea ice formation, causing them to sink to the deep ocean (e.g., in the North Atlantic and around Antarctica).
 - b. **Subduction (mid latitude):** The sinking of surface water into the ocean's interior along density gradients (isopycnals), often occurring in mid-latitudes.
 - c. **Surface water heating (equatorial latitudes):** A high amount of solar radiation received in this region leads to warmer surface waters (more buoyant) and increased stratification.
2. **Wind effects** - Wind pushing stratified surface waters equilibrated with vertical motions leads to vertical motions depending on the seabed and landmass configuration.

- a. **Downwelling:** The rising or sinking of surface waters, which can be driven by wind patterns, converging surface currents or where Ekman transport pushes water towards a coast.
- b. **Upwelling:** The rising of deep, nutrient-rich (and often CO₂-rich, oxygen-poor) water towards the surface, driven by wind patterns (e.g., coastal upwelling due to Ekman transport away from the coast, equatorial upwelling) or where currents diverge (Kämpf and Chapman, 2016).
3. **Overturning Circulation (Advective transport):** The global-scale circulation brings deep waters towards the surface in certain regions, notably the Southern Ocean. (e.g Talley)
4. **Vertical Mixing (Diffusive Transport):** Vertical mixing (due to winds, tides, and internal waves) helps to transport surface properties downwards, or upwards (Ferrari et al, 2016; Holtzer and Primeau, 2006; Talley, 2013)

4. Methods to study ocean ventilation and re-exposure processes and timescales

There are several methods used to study ocean ventilation and the re-exposure of deep water:

4.1 Tracer studies

Natural tracers such as Carbon14 (Matsumoto et al., 2007): Once in the ocean interior and isolated from the atmosphere, it will have no source of carbon 14 (C14) and decay at a known rate. Therefore, the amount of (C14) that has decayed within the ocean is a measure of time since losing contact with the atmosphere. Transient or anthropogenic tracers such as CFC gases (chlorofluorocarbons). These gases were historically introduced in the atmosphere at known rates and are known to equilibrate rapidly with seawater. Levels of dissolved CFC can then be used to infer ages, though they have not been in existence long enough to have penetrated the deep Indian and Pacific oceans (Gebbie and Huybers, 2012).

4.2 Hydrographic surveys

Ship-based measurements of temperature, salinity, oxygen, nutrients, and other properties at various depths provide snapshots of the ocean's vertical structure and can identify water masses that have been recently ventilated or are old deep waters being upwelled. Repeat hydrographic sections over time can also reveal changes in ventilation. (e.g. WOCE, 2002, and a large number of subsequent studies analyzing the collected data). These studies have been essential to develop and validate a robust conceptual model of the global circulation “great ocean conveyor” (GOC) (see Figure 2).

4.3 Numerical modeling of oceanic water mass transport

Ocean general circulation models (OGCMs) simulate ocean currents and the transport of heat, salt, and tracers, on timescales ranging from decades to centuries. These models can be used to study the mechanisms of ocean ventilation into and out of the ocean interior and associated water mass pathways and timescales involved, notably through the derivation of Total Transport Matrix (TMM) which provides a more computationally efficient framework Pasquier et al. (2025) . The ‘age’ of ocean water, or the time taken for water to transit between defined regions, is a metric that can be easily and intuitively derived from Lagrangian calculations (van Sebille et al., 2018) and this is an approach that has been widely used though the focus is often on ocean ventilation to ocean interior rather than pathways from interior to surface.

We note that in the studies, the “age” of an ocean water parcel is actually described as a probability function of many particles, or transit-time distribution (TTD), which describes the distribution of travel time between two regions (van Sebille et al., 2018). Although the approach is quite intuitive, it is obviously highly sensitive to the quality and assumptions and spatial scales of the numerical model(s) from which Lagrangian trajectories are determined (e.g. emission scenarios). Another difficulty is that ventilation and re-exposure time scale of the deep ocean (possibly in the order of 1000s of years) usually exceeds the timescale over which model outputs are available, hence the need to “loop” them.

The following section focuses on a subset of studies that address both ocean ventilation and re-exposure, the latter being particularly relevant to the present scope.

5. Deep water re-exposure to the ocean surface

5.1 Overview of key studies

Here we focus on studies by Holzer et al. (2020), Chamberlain (2020), that builds upon previous work by Chamberlain et al. (2019). General techniques described in Holzer and Primeau (2006), Haine et al. (2008), and Holzer and Primeau (2008). We also consider a paper by Kawasaki et al. (2022) that applied Lagrangian tracking techniques to explore the deep water pathways in the North Pacific Ocean.

Using a coupled climate model for the decades 1990-2000 and 2090-2100 (RCP8.5 “high-emissions” scenario) (CMPI5), Holzer et al. (2020) quantify transport into the ocean interior and from the interior back to the surface over the globe for both periods.

The ocean transport mapping is undertaken by discretizing the entire 3D ocean into grid points and computing corresponding connectivity matrices between them. Simulations use decadal mean circulations and assume they are “frozen in time”, or in other word flow is considered to be statics of thousands of years. The resolution of their model is roughly 1° in longitude and latitude, with a refinement to about 0.3° latitude around the equator and in the Southern Ocean,

with 50 vertical layers in the vertical with thickness ranging from 10m (surface) to 300m (bottom).

Specific transport metrics derived include :

- mean time for which water at (x,y,z) traces back to the last ventilation anywhere (i.e., motion from surface to interior). This is also known as the ideal mean age.
- mean time for which water at (x,y,z) traces forward to re-exposure to the atmosphere (anywhere) (i.e., motion from interior to surface).
- The sum of these two parameters is the mean residence time of water currently at (x,y,z) between successive exposure to surface and atmosphere.

These are computed globally, and for a range of relevant subset regions of the ocean.

In their Figure 1 (Figure 2), they provide maps of ideal mean age and time to next surface re-exposure for the Atlantic and Pacific. Values are averaged along longitudes and presented from the southern (90S) to northern (90N) poles, so that “age” or time to re-exposure is shown as 2D matrices with latitude shown on the x-axis and depth in the y-axis. The panels relevant for time until re-exposure are the second and fourth panels.

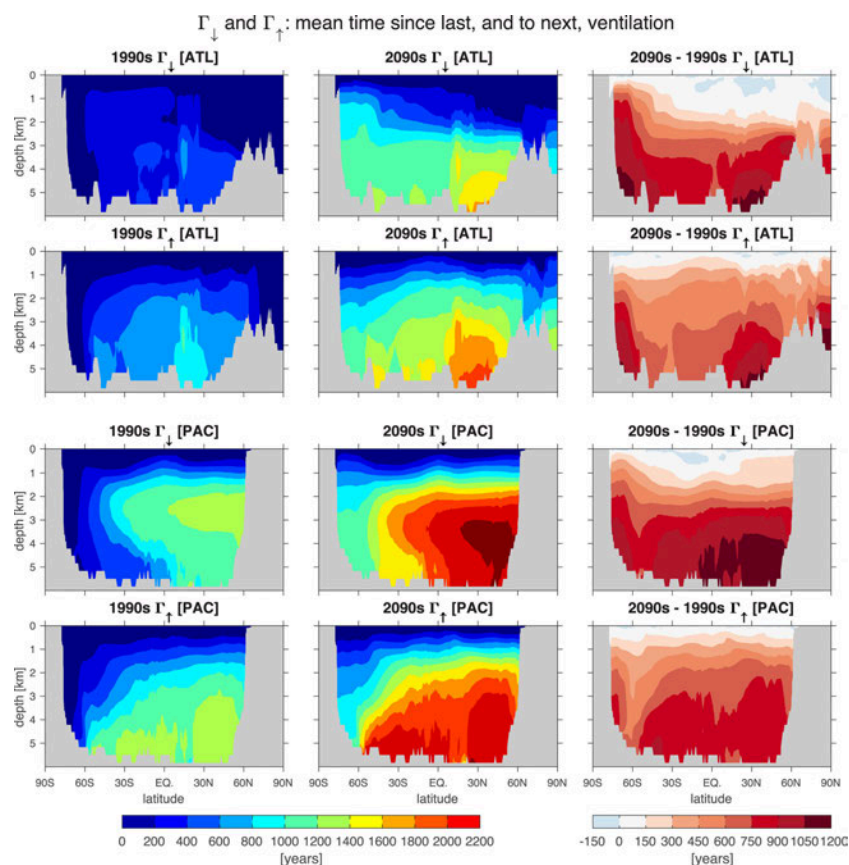


Figure 2. The top two rows of plots show Atlantic zonal averages of the ideal mean age Γ_d and the mean reexposure time Γ_r for the 1990s, 2090s, and the 2090–1990 differences. The bottom two rows show the corresponding Pacific zonal averages (reproduced from Holzer et al., 2020).

Key aspects are outlined below.

- Time to surface re-exposure of ocean deepwaters (2nd and 4th panels) is generally smaller in the Atlantic Ocean (600-1000 years) than in the Pacific Ocean (1000-1400 years). Time to surface re-exposure appears to increase northwards (i.e., longer time in the North Pacific vs South Pacific). A similar pattern is visible in the mean ideal age plots (1st and third panels).
- These patterns can be attributed to more vigorous overturning circulation in the Atlantic, with relatively young water masses sinking in the North Atlantic and traveling southward. This process ventilates the deep Atlantic, resulting in younger deep waters; the subsequent upwellings in the Southern/Indian and Pacific oceans will more quickly re-expose deepwater to the surface. In contrast, the Pacific, particularly its northern region, is thought to be the terminus of the GOC's deep branch and therefore experiences weaker overturning circulation. Holzer and Primeau 2006 note that diffusive effects could also act to transport and stabilize deeper in the North Pacific ocean.
- Comparison of results obtained for the 1990 and 2090 decades shows significant increases in ventilation age and time to re-exposure, attributed to a “more sluggish deep and overturning 2090s circulation”. The significant slowdown of the GOC in the high-emission scenario is due to increased ocean stratification (due to surface water warming) that perturbs deep water formation processes (cooling) and vertical exchanges with the ocean interior, which currently power the GOC.
- We note the timescales for re-exposure of Pacific deepwaters are generally larger than found in Kawasaki et al. (2022), which focused on a central Pacific area (30S to 30N), with a re-exposure time of 500 to 800 years. They remain in the same order of magnitude.

The fraction of the global ocean volume ventilated per unit area and reexposed per unit area is mapped in their Figure 2 (Figure 3). This shows:

- The process of ventilation, which involves bringing deep water to the surface, occurs most intensely in the Weddell and Ross Seas (Southern Hemisphere) and the Labrador, Irminger, and Greenland Seas (Northern Hemisphere). Ventilation also occurs to a lesser extent at the poleward edges of the subtropical gyres, resulting in the formation of mode and intermediate waters.
- Deep ocean water is re-exposed to the atmosphere in large volumes in the Ross Sea, the Antarctic seas east of the Weddell Sea, and a broad area of the Southern Ocean where deep waters rise and diverge. Deep ocean water exposure is also visible in western boundary currents and in the equator (equatorial upwelling).

fraction of ocean ventilated or re-exposed per unit area

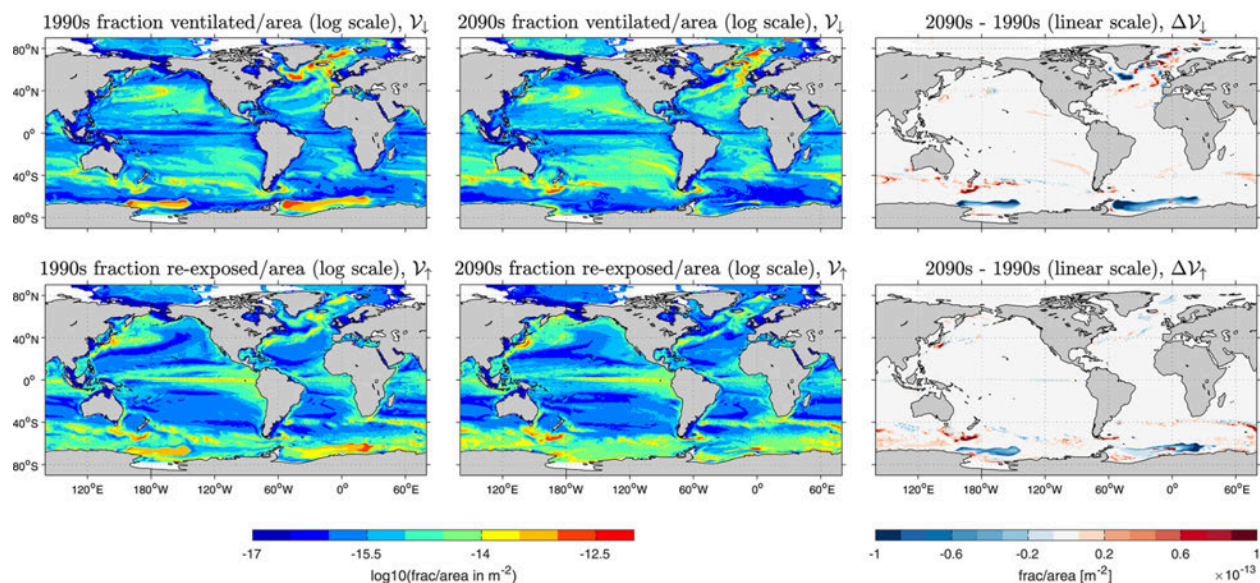


Figure 3 - The fraction of the global ocean volume ventilated per unit area (top) and reexposed per unit area (bottom). The fields are plotted for the 1990s and 2090s together with their 2090–1990 difference. Note that the fields for each decadal-mean circulation are plotted with a logarithmic color scale, while the 2090–1990 difference is plotted with a linear color scale (reproduced from Holzer et al., 2020).

Holzer et al. (2020) paper provides more detailed information on connectivity between different regions of the global ocean surface (see Figure 4). On the global scale, authors note that “*the Southern Ocean (SO) is the world's major gateway both into and out of the ocean interior, with 38% of the ocean last ventilated in the SO, 47% of the ocean destined for next ventilation (reexposure) in the SO, and 22% of the ocean in transit between successive SO ventilations (SO→SO). The North Atlantic (NA) stands out as the other key ventilation region, with 20% of the ocean last ventilated in the NA and 11% in NA →SO transit. The NA region is primarily a conduit into the interior, with only 2.3% of the ocean destined for reexposure in the NA.*”

With respect to pathways for ocean deepwater originating for the North Pacific (30S to 30N), Kawasaki et al. (2022) note that “*half of the North Pacific deep water returns to the Southern Ocean, and its principal pathway is along the western boundary current in the Southwest Pacific Basin in the deep layer. About 30% is exported to the Indian Ocean after upwelling to the shallow layer in the western North Pacific Ocean. The rest is transported to the Arctic Ocean through the Bering Strait or evaporates within the Pacific Ocean.*”

Connectivity information from Holzer et al. (2020) paper (and Holzer and Primeau (2008)) could be used for a more in-depth assessment on deepwater pathways between specific regions if necessary.

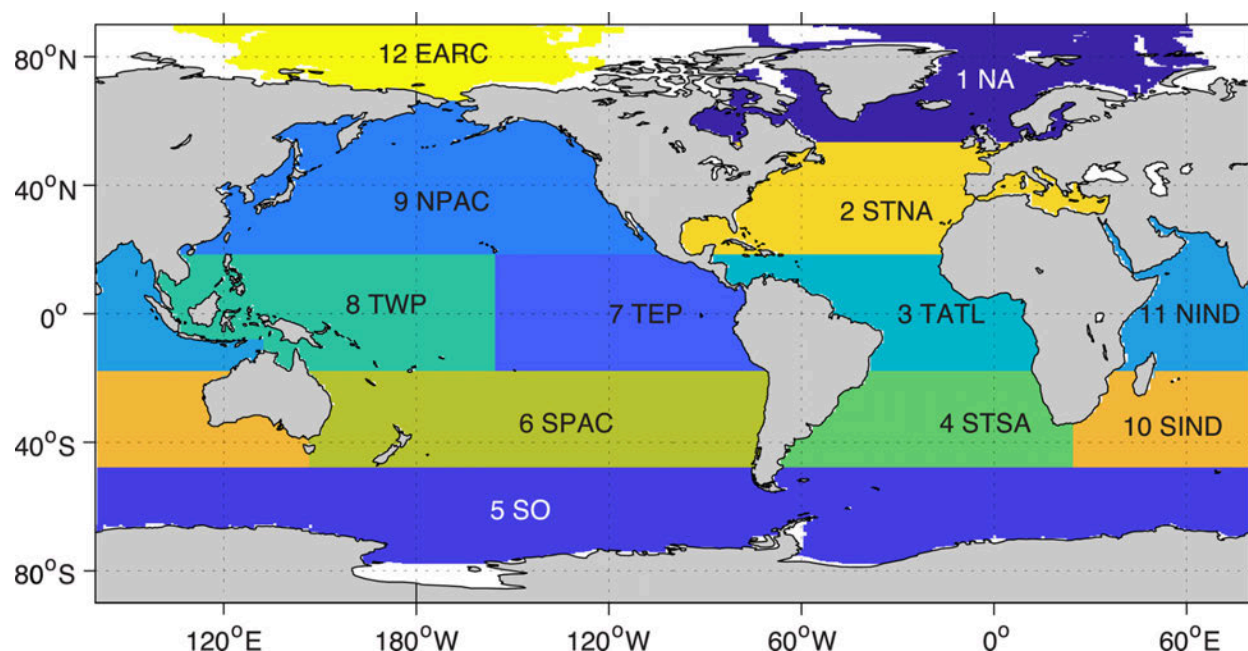


Figure 4. Tiling of the global ocean surface with 12 regions, used for connectivity assessment. We name the 12 regions as follows: North Atlantic (NA), SubTropical North Atlantic (STNA), Tropical Atlantic (TATL), SubTropical South Atlantic (STSA), Southern Ocean (SO), South Pacific (SPAC), Tropical Eastern Pacific (TEP), Tropical Western Pacific (TWP), North Pacific (NPAC), Southern Indian Ocean (SIND), Northern Indian Ocean (NIND), and Eastern Arctic (EARC) (reproduced from Holzer et al., 2020).

5.2 Recent literature on global carbon sequestration assessment

This paragraph briefly outlines recent literature published in the last two years, including Nowicki et al. (2022, 2024), which is referenced in Puro.Earth (2025), and Pasquier et al. (2025), which is applied further in Part 2. These two key studies evaluate and characterize global carbon sequestration efficiency, though with slightly different focal points.

Pasquier et al. (2025) introduce an idealized, yet computationally efficient, method to estimate transit time distributions (TTDs) from climate-model archives of virtual water parcels, enabling inference of carbon sequestration at the global scale. The approach builds on the Transit Time Matrix (TTM) framework developed by Primeau (2005) and applies it to the 1° resolution ACCESS-ESM1.5 dataset (Ziehn et al., 2020). The method achieves computational savings of over 150× relative to standard climate-model simulations, enabling analysis over extended timescales of 1,000-3,000 years. Critically, the model can be rapidly interrogated to evaluate potential seafloor injection locations and derive corresponding pathways and timescales from deep-ocean storage to surface re-exposure. Accordingly, it is therefore a robust and effective tool in the context of Gigablue operations, which focus on sequestering carbon-rich material on the seabed.

Nowicki et al. (2022, 2024) share a similar objective of assessing carbon sequestration at the global scale, with a focus on sea surface exchanges and water column processes (i.e. biological pump) . Their approach employs a similar Transit Time Matrix (TTM) framework developed from the Ocean Circulation Inverse Model (OCIM, 2° resolution) (DeVries and Primeau, 2011). While incorporating more sophisticated biogeochemical physics relative to Pasquier et al. 2025, Nowicki's work focuses primarily on the sea surface and water column processes (e.g. a realistic air-sea CO₂ disequilibrium and the effects of primary production) as they capture carbon from the surface and transport it to the seabed, rather than the inverse pathway from seabed back to surface that is relevant to simulate Gigablue operations. Accordingly, this method is less suitable for estimating the re-exposure pathways and timescales associated with the ventilation of deep water, which is the focus of the present work. Note too, the Nowicki method has a coarser resolution (2°) relative to Pasquier underlying hydrodynamic dataset (1°).

Part 2. Nearbed Drainage Hydrodynamics in Bounty Trough Region, New Zealand

1 Introduction

1.1 Background

The carbon capture process involves the release of engineered particles that stimulate phytoplankton growth and organic matter production in surface waters. As these particles and associated organic matter sink through the water column, they transport carbon from the surface to deeper ocean layers, effectively sequestering atmospheric CO₂.

The enhanced biological activity results in local depletion of essential macronutrients (nitrogen, phosphorus, and silicon) in the surface mixed layer, as these nutrients are incorporated into the sinking organic matter. Puro.Earth methodology therefore requires a thorough assessment of nutrient depletion to ensure carbon capture does not remove all available nutrients from the water, which would harm natural algae growth. This is critical for environmental risk assessment and regulatory compliance. A characterization of the spatial and temporal extents of nutrient depletion in the upper part of the ocean is outlined in the technical note (Oceanum, 2025b).

Once the engineered material that fixed carbon has settled on the seabed, carbon remineralization will begin within the bottom water masses in its vicinity, effectively transferring captured carbon back into seawater. It is therefore essential to understand bottom water mass dynamics, particularly residence and resurfacing times, as these will control carbon sequestration timescales and the effectiveness of long-term storage. This assessment is required in Puro Methodology (section 3.7.4).

1.2 Scope

An overview of the scientific literature characterizing the re-exposure of deepwater to the surface is provided in Part 1. Recently, Pasquier et al. (2025) mapped the deep ocean carbon sequestration efficiency at the global scale through numerical modelling. Although this provides a valuable base to estimate resurfacing timescales of deep ocean water masses for open-ocean regions, the methodology relies on the relatively coarse climate models (1x1° resolution), which do not resolve the bathymetry and water mass dynamics within the continental shelf and how it is connected to the deeper open-ocean.

This is particularly relevant for the area of interest that is in close vicinity of the Bounty Trough which is a major submerged canyon-like feature with steep slopes and is expected to have a strong influence on the local hydrodynamic regime.

To bridge this gap, this technical note aims to assess the bottom water mass connectivity from the New Zealand shelf to the deeper open ocean regions, in order to “connect” the continental shelf dynamics with results available for the deep ocean, as per Pasquier et al. (2025) and their subsequent analyses (see Part 1; section 5.2 for justification on the use of the Pasquier et al., 2025 model over the Nowicki et al., 2024 model).

The analysis was conducted in two stages. In the first stage, we characterized the near-bed flow regime across the broader region of interest using data from the global GLORYS ocean reanalysis product. The analysis focused on the deepest model layer, representing the near-bed water mass, over a 10-year period.

In the second stage, we employed a Lagrangian particle tracking framework to simulate the dispersion of bottom water masses and to characterize connectivity with deeper ocean regions over both 10- and 20-year periods.

1.3 Structure

Further details on the numerical modelling methodology are provided in Section 2. Results are provided in Section 3 and include maps of the near-bed current connectivity for the Bounty Trough region. Conclusions are provided in Section 4, and the references cited are listed in the final Section 5.

2 Modeling methodology

2.1 Information provided by GB

GB tracked the plume from 809(2)(b)(ii) of GB particles. These results have been presented in detail in the “Lagrangian particle tracking” report. Each event represents a December simulation, selected to capture the range of oceanographic variability that could occur during the planned deployment period. The detailed deployment parameters are summarized in Table 2.1. As mentioned in the previous technical note (Oceanum, 2025b), the modelling undertaken by Gigablue includes the following assumptions.

- The modelling is based on a hypothetical release of 9(2)(b)(ii) of Gigablue particles 9(2)(b)(ii).

- The modelling also assumed an instantaneous release of substrate, which is not operationally feasible. In practice, the release would be distributed progressively throughout the day.

Given the fast settling velocity expected for the settling phase 9(2)(b)(ii), the last time step prior to the particle sinking was used as a proxy for the final positions on the seabed. These final positions were combined into a single footprint and used as initial positions for the near-bed transport simulations (Figure 2.1).

Table 2.1 Deployment parameters for the supplied GB runs.

9(2)(b)(ii)



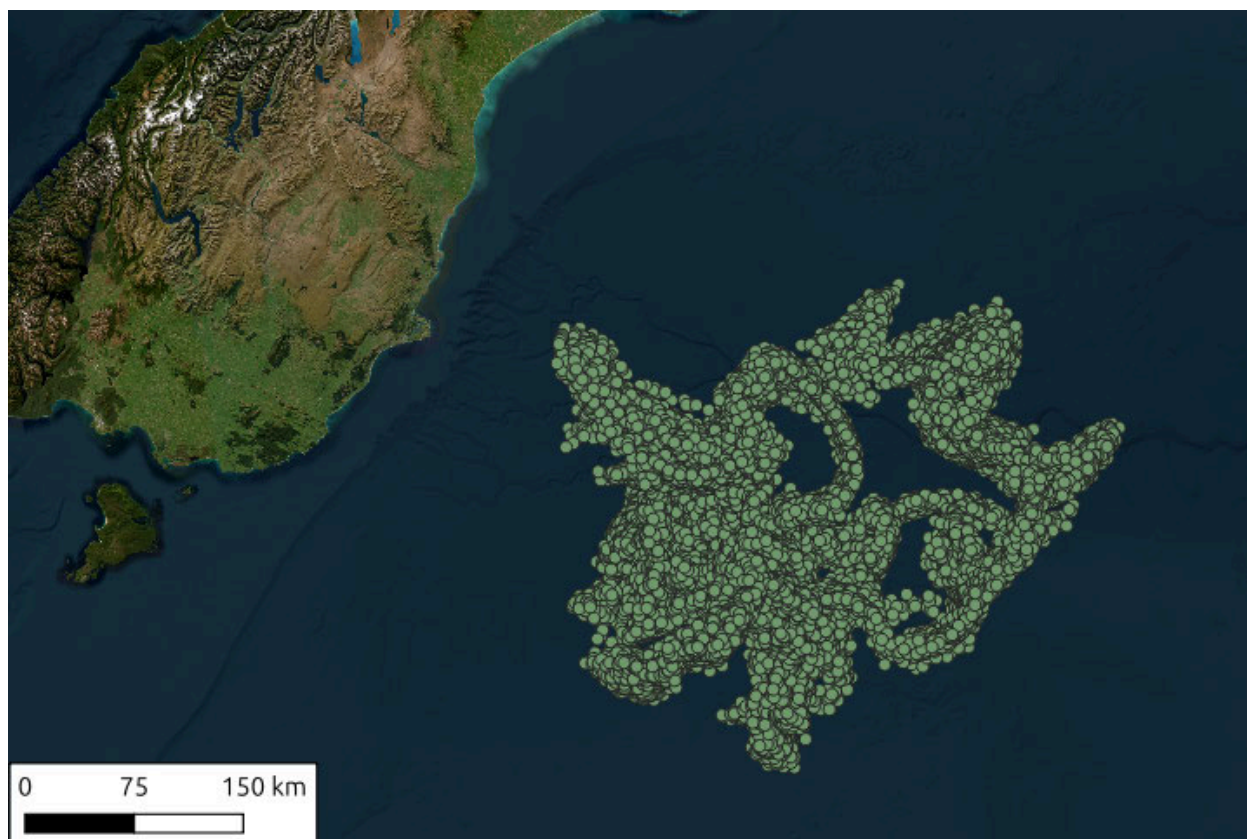


Figure 2.1 Particle cloud from all of the December releases 9(2)(b)(ii)

2.2 Nearbed water mass transport modelling approach

The spatial and temporal dynamics of bottom water masses within the New Zealand continental shelf and its connectivity with the deeper open-ocean are characterized using a Lagrangian particle tracking framework similar to that applied in previous reports Oceanum (2025a, 2025b).

We use the combined footprint of final particle positions on the seabed (see Figure 2.1) as initial positions and track their dispersion over both 10-year and 20-year periods throughout the region of interest or until connection with the deeper open-ocean (see Figure 3.3. for model domain extents). The simulation uses hydrodynamic flow fields from [1/12° resolution GLORYS Reanalysis](#) subset for the deepest model layer at each grid point in order to capture near-bed water mass transport pathways. Note the 20-year simulations use the same 10-year period twice. This approach is similar to that of Pasquier et al. (2025).

The analysis employed a two-dimensional Lagrangian dispersion simulation using velocity fields from the deepest model layer of the GLORYS reanalysis product (1/12° horizontal resolution). The simulations focused exclusively on horizontal advective transport pathways, assuming that water mass parcels follow the seabed topography. The model did not include horizontal diffusion or vertical processes such as upwelling, turbulence, and mixing.

In order to simulate long time periods while retaining manageable computational time, particles were tracked with a daily timestep over the 10 and 20-year periods. Particle densities are reconstructed on the 50x50km horizontal grid to inform on particles' distribution within and along the boundary of the model domain and provide inputs for subsequent open-ocean deepwater resurfacing modelling methodology (as per Pasquier et al., 2025).

2.3 Deep ocean recirculation to surface timescales

The estimation of timescales associated with the recirculation of near-bottom water masses back to the surface is based on the methodology and results presented in Pasquier et al. (2025). His modelling is based on hydrodynamic fields from the ACCESS-ESM1.5 dataset (Ziehn et al., 2020). Its ocean component is the Modular Ocean Model version 5 (MOM5, Griffies (2012)), which has a horizontal resolution of $1^\circ \times 1^\circ$ and 50 vertical levels.

The resurfacing timescales are characterized through the derivation of transit time distributions (TTDs). In the context of ocean carbon sequestration, TTD refers to the statistical distribution of time required for water parcels to travel between regions. This typically describes either transport from the ocean surface (where water parcels last contacted the atmosphere) to an interior ocean location, usually the seabed, or transport from the seafloor back to the surface. In this study, we focus on the latter case to determine the timescales for near-seafloor water parcels to travel from their exit points on the New Zealand continental shelf to the broader open ocean and eventual re-exposure at the surface. The goal is to evaluate ocean carbon sequestration timescales and, consequently, sequestration efficiency.

The concepts of Transit-Time Distribution and sequestration efficiency are further described below for reference:

- **Transit-Time Distribution (TTD), $\mathcal{T}$**

The TTD considered here is the distribution of all the possible times that water can take to travel from the seafloor injection location to the ocean surface. It was efficiently computed at all seafloor locations in a single simulation through what is called the adjoint boundary propagator (denoted $\mathcal{T}$ in Pasquier et al., 2025). Efficient computation of ocean TTDs is often necessary as ocean TTDs typically skew to the right and exhibit very long tails. That means that some pathways are extremely slow. This is particularly true here because the pathways considered start from the seafloor.

- **Sequestration efficiency, $\mathcal{E}(\tau)$**

The sequestration efficiency, denoted $\mathcal{E}(\tau)$ for a given time horizon τ , quantifies the fraction of water that has not reached the surface after τ . That is, if $\mathcal{E} = 70\%$ for $\tau = 100$ years, then 70 % of the water released at the seafloor location is still below the surface after 100 years (and so is the DIC a fortiori).

3 Results

3.1 Regional settings

Simulations undertaken by GB and Oceanum (2025a) indicate the GB material is likely to settle on the New Zealand continental shelf in the vicinity of the Bounty Trough (i.e. for the release locations being considered). The Bounty Trough is bounded by the Chatham Rise to the north and the Bounty Plateau and Campbell Plateau to the south. The depth here ranges from 1300 - 3000 m (Figure 3.1).

The regional flow regime includes the Southland Current (SC) flowing from southwest to northeast along the continental shelf, veering eastward as it follows the Chatham Rise. To the south, a branch of the Subantarctic Front (SAF) passes through the Pukaki Saddle, veering westward to interact with the SC (Stevens et al., 2021).

The mean nearbed flow dynamics are illustrated in Figure 3.2 that shows the mean flows in the deepest model layer at each grid cell. The main transport pathways consists in:

- Dominant west-directed flow feature in the Southern Trough
- Southland Current's north to northeast-directed flow feature in the Northern Trough
- Weaker and more variable currents with temporal fluctuations over the last decade in the Central Trough.

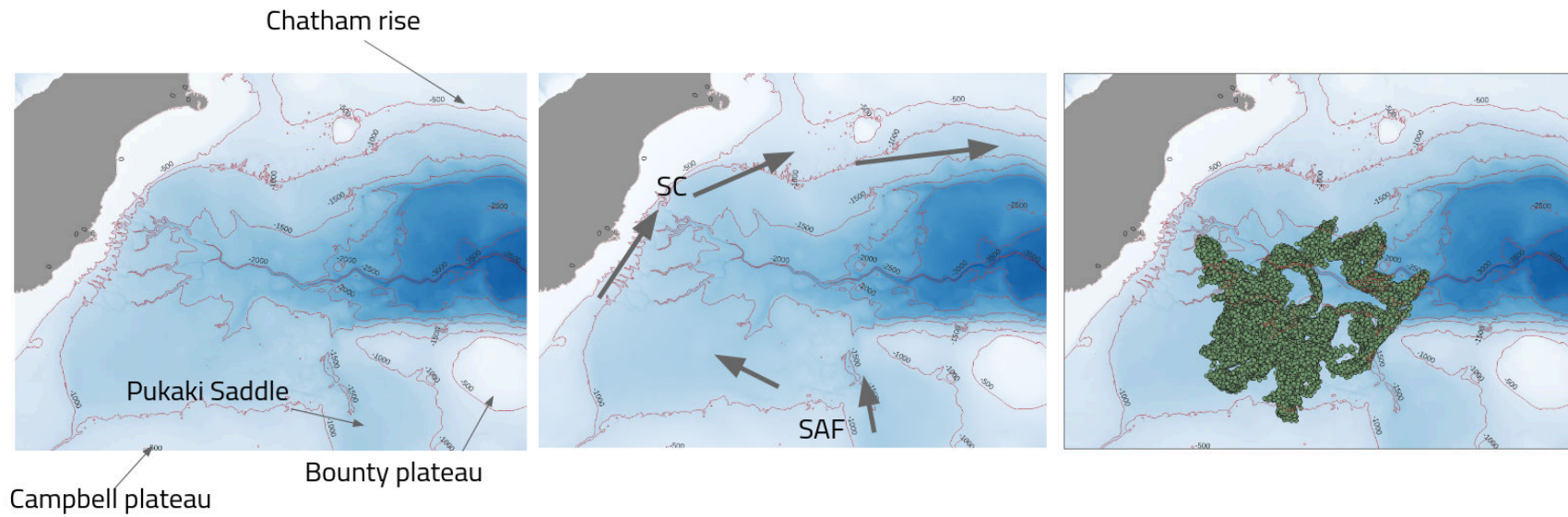


Figure 3.1. Main bathymetric features in the region of interest (left), regional flow features in the region of interest (middle), and the combined footprint of final positions prior to settling of all December releases.

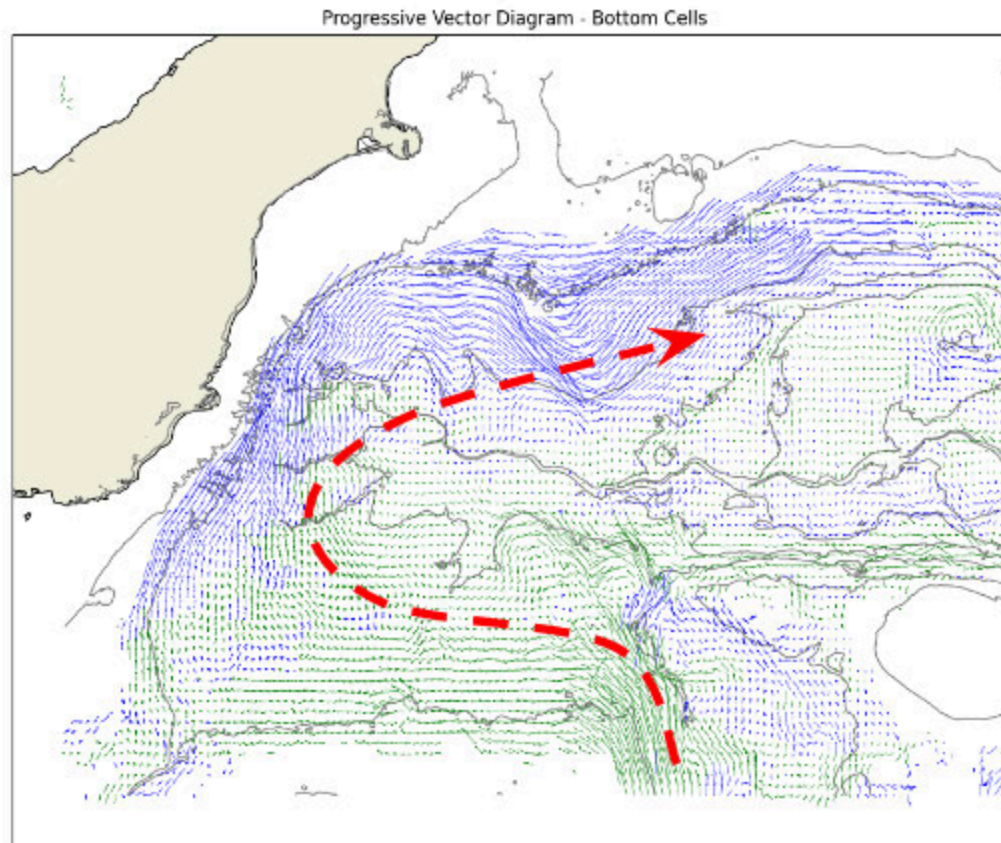


Figure 3.2 Mean flows in the deepest model layer at each grid cell (blue arrows=east-directed flow, green arrows=west-directed flow). The red arrow shows the main transport pathways.

3.2 Nearbed water mass connectivity

The final particle positions and density fields after 10 and 20 years are provided in Figure 3.3 and 3.4. The primary exit points to deeper ocean regions correspond to high-density yellow pixels around the edges of the model domain.

Two dominant regions are visible to the northeast, past the Chatham Rise eastern end and south-southeast areas of the domain, past the Bounty Trough Plateau. Particle cloud animations indicate a distinct east-directed transport within the Bounty Trough, bounded by the Chatham Rise to the north and Bounty Trough Plateau to the south, splitting northward and southward to eventually exit the model domain (see Figure 3.5).

The fraction of particles still within the domain is 9(2)(b)(ii). Final particle positions were provided for subsequent analysis as per Pasquier et al. (2025)'s methodology to estimate expected deep ocean water resurfacing times for positions corresponding to exit positions from the present modelling of the continental shelf dynamics.

9(2)(b)(ii)



Figure 3.3. Particle density distribution in the region of interest, after 10 years of advection using currents from the deepest model layer at each grid point. Final positions of particles exiting the domain are shown as black dots. Particles that are still within the domain at the end of the simulation 9(2)(b)(ii) are shown in red. Note the particle density color scale is logarithmic.

9(2)(b)(ii)



Figure 3.4. Particle density distribution in the region of interest, after 20 years of advection using currents from the deepest model layer at each grid point. Final positions of particles exiting the domain are shown as black dots. Particles that are still within the domain at the end of the simulation 9(2)(b) are shown in red. Note the particle density color scale is logarithmic.

9(2)(b)(ii)



Figure 3.5. Inferred main transport pathways.

3.3. Deep ocean recirculation to surface timescales

Following methodology in Pasquier et al. (2025), the focus of this modelling component was to determine the timescales for near-bottom water parcels to travel from their exit points on the New Zealand continental shelf (as characterized in Section 3.2) to the broader open ocean and eventual re-exposure at the surface. The objective is to evaluate the temporal scales of ocean carbon sequestration and thereby assess sequestration efficiency.

Here, we assume that the substrates reach the seafloor before releasing DIC (Figure 1). The DIC released by the substrates is then transported by currents and eddies and will take many different pathways returning to the ocean surface. Some of the DIC may be swept by fast upwelling currents and reach the surface in a few years, but some of the DIC may remain in the deep ocean for millennia before reaching the surface. To quantify the time taken by DIC to resurface through all these possible pathways, we compute the Transit-Time Distribution (TTD; e.g., Haine et al., 2008).

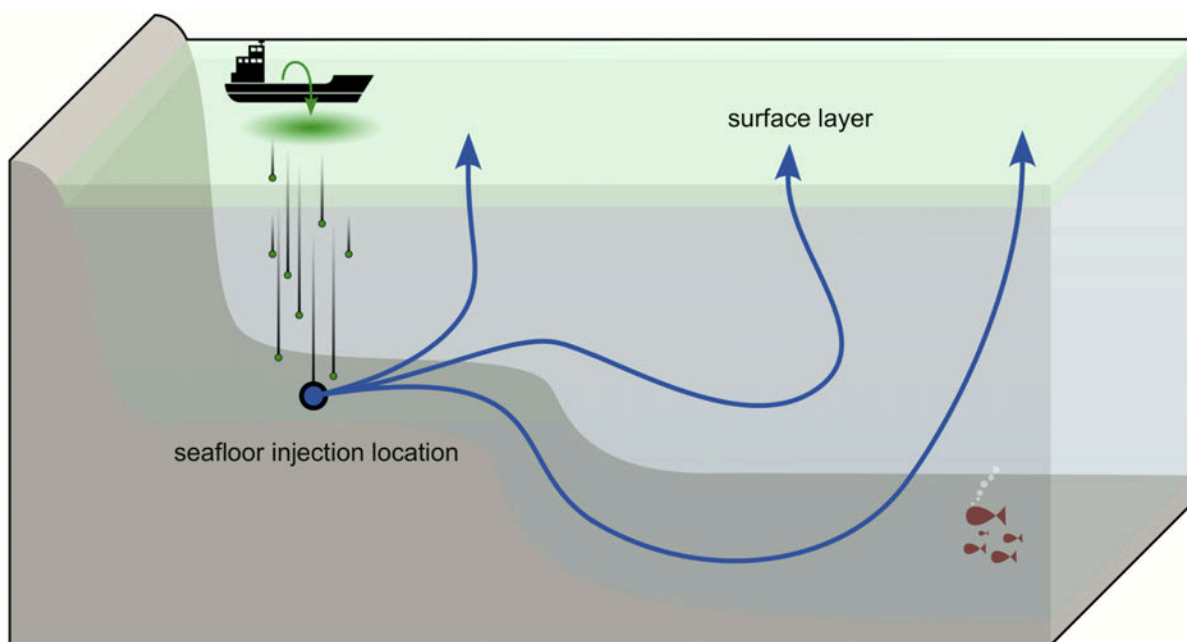


Figure 3.6: Gigablue substrates, loaded with carbon taken up from the surface, sink to the seafloor, where DIC is returned to the water. This carbon is then transported by currents and eddies until it eventually reaches the surface of the ocean, where it may then return to the atmosphere. But this transit, from the seafloor to the ocean surface, is indirect and inherently complex. Water takes many water pathways to reach the surface, which can be fast (a few years) or slow (millennia). To take all these pathways into account, we must quantify the Transit-Time Distribution (TTD).

Results are summarized in Figure 3.7. The top left panel shows the initial positions input to the model. These correspond to the final positions of the 20-year simulation described in Section 3.2 that characterizes the connectivity from the NZ continental shelf to the deep ocean region (Figure 3.4). The top right panel shows the Transit Time Distribution (TTD) of all individual water parcels injected in the model at the seafloor. 9(2)(b)(ii)

9(2)(b)(ii) These indicate 9(2)(b)(ii) 9(2)(b)(ii) The two bottom plots inform on the “sequestration efficiency”, that is the fraction of water parcels that remain sequestered (not yet returned to the surface) after a specified time period. The bottom left panel is a zoomed-in view of the bottom right panel.

The bottom left panel indicates a sequestration efficiency of 9(2)(b)(ii) 9(2)(b)(ii) at the 200-year mark. This means that 9(2)(b)(ii) of water parcels injected at the seafloor remain sequestered after 200 years. Sequestration efficiency becomes 9(2)(b)(ii) at about the 300-year mark. Quantitative sequestration efficiency distribution statistics are provided in Table 3.1 at the 200, 300, 400 and 500-year horizons. The median sequestration efficiencies (P50) are respectively 9(2)(b)(ii) and 9(2)(b)(ii), with 9(2)(b)(ii) being the relevant MCFS durability value for a 200 year horizon according to the MCFS methodology. Corresponding sequestration efficiencies exceeded by 9(2)(b)(ii) of all simulated water parcels (P25) are 9(2)(b)(ii) and 9(2)(b)(ii)

9(2)(b)(ii)



Figure 3.7. Transit Time Distribution (TTD) from seafloor to ocean surface. Seafloor injection positions (top left); seafloor depth plotted now is that of the coarse model. TTD of all individual water parcels injected in the model at the seafloor (top right). Sequestration “efficiency” after a specified time period (bottom panels; the bottom left panel is a zoomed-in view of the bottom right panel)

Table 3.1. Sequestration efficiency statistics after 200, 300, 400, and 500 years (mean, 25, 50, and 75th percentiles). Sequestration efficiency", that is the fraction of water parcels that remain sequestered (not yet returned to the surface) after a specified time period.

9(2)(b)(ii)



Conclusions

This technical note examined the connectivity of bottom water masses on the New Zealand continental shelf in the Bounty Trough region with the deeper open ocean. The near-bed flow regime across the broader region of interest was characterized using the deepest model layer from the GLORYS reanalysis over the most recent 10-year period. A Lagrangian particle tracking framework was employed to simulate the dispersion of bottom water masses and their connectivity with deeper ocean regions over 10- and 20-year time periods.

The principal finding indicates relatively short timescales for connectivity between the continental shelf and the deeper ocean, of the order 10 to 20 years. Approximately 9(2)(b)(ii) of initially deployed particles were observed to exit the model domain within 10 years. Near-complete flushing of near-bed water parcels from the Trough and into the deep ocean occurred within 20 years, with 9(2)(b)(ii) of particles remaining in the model domain.

Once in the open-ocean region, the Transit Time Distribution (TTD) modelling indicates a near-bottom water mass's sequestration efficiency of 9(2)(b)(ii) at the 200-year mark, becoming 9(2)(b)(ii) and 9(2)(b)(ii) at the 300, 400 and 500-year horizons, respectively (median values).

Several limitations and assumptions should be considered when interpreting the results of the near-bed Lagrangian simulations:

- The initial footprint used for the Lagrangian modelling is based on a limited run which focuses on a specific release transect and which uses a limited number of particles 9(2)(b)(ii). The outcomes of the study are therefore valid for these final seabed locations.
- The simulations assumed that bottom water parcels above settled material remain in contact with the seabed topography throughout their transport, focusing exclusively on horizontal transport pathways. Vertical advection (e.g., associated with upwelling) and vertical mixing were not incorporated in the model framework. In practice, vertical advection and mixing processes could promote the upward transfer of bottom water masses into the upper water column before exiting the model domain. However, the timescales associated with vertical motion in the deep ocean are expected to be considerably longer (on the order of 100–1,000 years) compared to the horizontal transport timescales of 9(2)(b)(ii) that resulted in near-complete particle flushing to the open ocean.
- The validity of GLORYS reanalysis data in the complex, steep-sloped bathymetry of the Bounty Trough region remains uncertain due to limited in-situ measurements to allow validation in this area.

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