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The influence of mesoscale climate drivers on hypoxia in a fjord-like deep coastal inlet and its potential implications regarding climate change: examining a decade of water quality data

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Abstract. Deep coastal inlets are sites of high sedimentation and organic carbon deposition that account for 11 % of the world's organic carbon burial. Australasia's mid- to high-latitude regions have many such systems. It is important to understand the role of climate forcings in influencing hypoxia and organic matter cycling in these systems, but many such systems, especially in Australasia, remain poorly described.

We analysed a decade of in situ water quality data from Macquarie Harbour, Tasmania, a deep coastal inlet with more than 180 000 t of organic carbon loading per annum. Monthly dissolved oxygen, total Kjeldahl nitrogen, dissolved organic carbon, and dissolved inorganic nitrogen concentrations were significantly affected by rainfall patterns. Increased rainfall was correlated to higher organic carbon and nitrogen loading, lower oxygen concentrations in deep basins, and greater oxygen concentrations in surface waters. Most notably, the Southern Annular Mode (SAM) significantly influenced oxygen distribution in the system. High river flow (associated with low SAM index values) impedes deep water renewal as the primary mechanism driving basin water hypoxia. Climate forecasting predicts increased winter rainfall and decreased summer rainfall, which may further exacerbate hypoxia in this system.

Currently, Macquarie Harbour's basins experience frequent (up to 36 % of the time) and prolonged (up to 2 years) oxygen-poor conditions that may promote greenhouse gas (CH_4, N_2O) production altering the processing of organic matter entering the system. The increased winter rainfall predicted for the area will likely promote the increased spread and duration of hypoxia in the basins. Further understanding of these systems and how they respond to climate change will improve our estimates of future organic matter cycling (burial vs. export).

1 Introduction

Fjords and fjord-like estuaries (also called deep coastal inlets – DCIs; Keith et al., 2020) are sites of high sedimentation and organic carbon (OC) burial. These systems account for approximately 11 % of the world's annual OC burial (Smith et al., 2015). Compared to other marine benthic environments (e.g. sediments along the continental shelf, deeper pelagic sediments, shallow-water carbonate sediments), they bury the most OC per unit area (Smith et al., 2015; Bianchi et al., 2018, 2020).

Their location within mid- to high-latitude coastal margins and disproportionate role in geochemical cycling make these systems especially vulnerable to anthropogenic pressure (Walinsky et al., 2009; Gilbert et al., 2010; Bianchi et al., 2018, 2020). Bianchi et al. (2018) have classified fjord and fjord-like DCIs as "aquatic critical zones" in need of further investigation, especially regarding how they might respond to changes in climatological drivers and anthropogenic pressure. One of the critical issues facing coastal environments is the expansion of oxygen-poor conditions due to increased anthropogenic organic matter loadings (Diaz and Rosenberg,

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2008; Oschlies et al., 2018; Breitburg et al., 2018; Pitcher et al., 2021).

Combined effects of environmental drivers or forcings drive the distribution of dissolved oxygen (DO) in any given system. In fjord and fjord-like DCIs, this includes wind, tidal exchange, river flow, organic loading, deep water renewal (DWR) (Edwards and Edelsten, 1977; Gade and Edwards, 1980; Geyer and Cannon, 1982), and microbial processing in the sediments and water column (Gilibrand et al., 2006; Maxey et al., 2020). Characteristics of these systems are shallow sills at their mouth and several sills or ridges that separate the estuary into various basins (Pickard and Stanton, 1980; Stanton and Pickard, 1980; Inall and Gillibrand, 2010). These morphological features restrict mixing and promote stratification of the water column by isolating basin waters from exchange mechanisms between the coastal ocean and surrounding catchment (Inall and Gillibrand, 2010). Hypoxia (defined as DO concentrations below $2\,\mathrm{mg\,L^{-1}}$) has been long recognised and can be a natural feature of these systems (Rosenberg, 1977; Rabalais et al., 2010; Inall and Gillibrand, 2010; Ji et al., 2020).

The availability of DO influences the eventual fate of OC processed by microbial communities as it enters either aerobic or anaerobic metabolic pathways (see del Giorgio and Williams, 2005). In addition, the cycling of organic matter and nutrients in oxygen-poor environments often leads to the production of potent greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) (Codispoti et al., 2005). The fate of carbon exported to marine systems from estuaries is tied to oxygen distribution. Estuarine morphology, physical oceanography, and anthropogenic impacts (e.g. hydroelectric dams, land-use modification, sewage outfalls) drive the oxygen distribution.

Understanding how DO distribution and availability in fjord-like systems respond to climate change requires understanding how they currently respond to changes in local and mesoscale environmental drivers. These drivers include rainfall, run-off, and associated nutrient and organic matter loading. Predicted climate change impacts include changes in air pressure, wind strength, rainfall patterns, and storm intensity (Grose et al., 2010; Priestley and Catto, 2021; Goyal et al., 2021), all of which have the potential to affect DO distribution in fjord-like estuaries (Austin and Inall, 2002; Gillibrand et al., 2005, 2006; Hartstein et al., 2019).

Understanding how broader environmental drivers affect localised DO distribution requires spatially extensive long-term datasets which are not readily available in many systems. Ideally, these datasets would provide enough statistical power to tease out relationships between external drivers (e.g. rainfall volume, rainfall accumulation, OC and organic nitrogen (ON) loading, river flow and climate oscillation indices) and DO distribution through the water column. A 10-year dataset is available for a relatively remote DCI on Tasmania's west coast, enabling analyses focusing on long-term trends in water quality, freshwater and organic matter loading, and their relationships with climate drivers.

The aims of this paper are to

1. understand the effects of rainfall or freshwater inputs on organic matter (OM) loading, nutrient loading, and DO distribution in a fjord-like deep coastal inlet;
2. describe the current effects that broader climate oscillations have on DO distribution and discuss implications that future climate predictions have on possible DO dynamics in these systems (example of a restricted sill system), especially regarding physical drivers of deep water renewal;
3. discuss implications for managing these systems regarding the regulation of freshwater input, OM loading, and the potential to promote oxygen-poor conditions.

2 Methods

2.1 Study area

Macquarie Harbour is a fjord-like DCI located on the west coast of Tasmania. Although the glacially carved status of the harbour itself is somewhat unclear (Baker and Ahmad, 1959; Kiernan, 1990, 1991, 1995), it has the morphology and resulting oceanographic dynamics shared by many fjords and fjord-like systems, including a propensity for oxygen-poor basins (Creswell et al., 1989; Hartstein et al., 2019). Descriptions of its DO drivers (Hartstein et al., 2019; Maxey et al., 2017, 2020) suggest disparate processes affecting surface water and basin DO distribution. Namely, DO in the basin waters is resupplied by DWR. Where or when the direct effects of these processes wane, diffusive mixing and water column oxygen demand become the key drivers of oxygen availability (Inall and Gillibrand, 2010; Hartstein et al., 2019; Maxey et al., 2020).

The harbour is oriented in an NW by SE direction, is approximately 33 km long and 9 km wide, and has a surface area of $276\,\mathrm{km^2}$. Compared to the rest of Australia, western Tasmania receives some of the highest rainfall (more than $2500\,\mathrm{mm\,yr^{-1}}$) and experiences high seasonal rainfall variability (Dey et al., 2018). As a result, broad-scale climate oscillations like the Southern Annual Mode (SAM) (Meneghini et al., 2007; Hill et al., 2009) affect westerly winds that generate orographic rainfall in Macquarie Harbour's catchment. Since the 1970s, both the SAM index (positive values associated with stronger westerlies) and winter rainfall in Macquarie Harbour's catchment have increased (Taschetto and England, 2009; Marshall et al., 2018; Fogt and Marshall, 2020).

The primary source of freshwater to the harbour is the Gordon River, which is responsible for up to 82 % of the system's freshwater input (Hartstein et al., 2019). The mouth of the Gordon River is located on the harbour's SE end and