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Spatio-temporal patterns in coastal turbidity — Long-term trends and drivers of variation across an estuarine-open coast gradient

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ABSTRACT

Turbidity in the coastal environment is greatly affected by human activities on the land and this is likely to be exacerbated with expanding urbanisation and climate change. Investigating the temporal and spatial drivers of variation in turbidity is key to understanding processes influencing turbidity and for developing management strategies to mitigate future increases in turbidity. We analyse 22 years of monthly turbidity data from 1992 to 2013 in New Zealand's Hauraki Gulf to determine whether turbidity has changed in response to implementation of land management regulations. We also investigate how spatial and temporal patterns in turbidity relate to meteorological and oceanographic variables along an estuarine to open-coast gradient.

Turbidity, total suspended solids and chlorophyll *a* declined along the estuarine to open-coast gradient. Correlation analysis suggested that suspended sediment was the major determinant of turbidity along this gradient. Improvements in turbidity were evident at some harbour sites, but overall there were no consistent trends across the sites. Some cyclical patterns in turbidity were evident, but these were only weakly related to ENSO. The greatest component of temporal variation at all sites was between samples (months). The primary correlates of this variation in turbidity differed across the estuarine-open coast gradient; recent wave conditions explained the greatest variation in turbidity at open coast sites, whereas tidal currents and daily rainfall were the primary correlates at harbour channel and estuarine sites. The strong coupling found between meteorological factors and coastal turbidity highlight a number of mechanisms whereby turbidity will likely increase as a result of climate change along this coastal gradient. Improvements in land management practices, particularly in rural areas, as well as coastal protection are therefore essential to offset the likely effects of climate change on coastal turbidity.

1. Introduction

Turbidity in coastal environments can be greatly enhanced by anthropogenic activities on the land such as farming, deforestation and urban development that increase erosion, surface runoff and sediment contamination in coastal ecosystems (Davies-Colley et al., 2004; Thrush et al., 2004; Drewry et al., 2006; Hayward et al., 2006; Klein, 2012; Fabricius et al., 2014; van Maren, 2014). By reducing light levels in the coastal environment, increased turbidity can threaten the ecosystem services provided by marine organisms, such as reducing the extent, abundance and productivity of benthic macroalgae (Pehlke and Bartsch, 2008; Shepherd et al., 2009; Derrien-Courtel et al., 2013). Higher concentrations of suspended sediments associated with high turbidity can also reduce the quality of food to suspension feeders by introducing more sediment-associated pollutants, nutrients and contaminants (Schoellhamer et al., 2007; Smith and Schindler, 2009), as well as compromising visibility for predation (e.g. Henkel, 2006; Thompson and Price, 2006), impairing habitat choice and chemosensory discrimination (Wenger et al., 2011, 2012) and foraging, breeding, growth and condition for selected fish species (e.g. Sigler et al., 1984; Bruton, 1985; Wenger et al., 2012). Due to the ecological importance of turbidity and water clarity, the Australian and New Zealand Environment and Conservation Council include turbidity as a measure of the condition of overall coastal and estuarine water quality used for environmental reporting (ANZECC, 2000), akin to many other local government bodies and organisations globally.

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Turbidity is the cloudiness of a fluid and results from the intense scattering of light by fine particles (Kirk, 1985). In the coastal environment, the primary scattering particles are fine suspended sediments and phytoplankton, along with other light-attenuating materials such as the water itself and dissolved organic matter (Davies-Colley and Smith, 2001). High turbidity in coastal waters can therefore be due to intense phytoplankton blooms, runoff of sediments from the land associated with rainfall events, resuspension of sediments already in the system by wind, waves and currents, and also as a result of various combinations or interactions between these primary determinants. Consequently, coastal turbidity is governed by complex interactions between meteorological, oceanographic, geological, biological and anthropogenic processes. Wave height, tidal forcing and rainfall have been shown to be important drivers of variation in turbidity in the coastal environment (Larcombe et al., 1995; Piniak and Storlazzi, 2008; Devlin and Schaffelke, 2009; Storlazzi et al., 2009; Fabricius et al., 2013, 2014). Large-scale climate cycles such as the El Niño Southern Oscillation (ENSO) are therefore likely to influence long-term trends in coastal turbidity in many regions due to their indirect influence on local weather conditions. ENSO is the most prominent year-to-year climate variation on Earth and gives rise to the El Niño and La Niña events that recur every 2–7 years (McPhaden et al., 2006). The Southern Oscillation is an atmospheric pressure gradient spanning the Tropical Indian and Pacific Oceans, intimately linked to the strength of tropical trade winds that has been shown to affect patterns of weather variability worldwide (McPhaden et al., 2006). Previous studies have found significant relationships between ENSO and various environmental attributes that were hypothesised to influence coastal turbidity including river flow (Mosely, 2000), riverine nutrient loading and water quality (Scarsbrook et al., 2003; Zeldis et al., 2008) and coastal algal blooms (Rhodes et al., 1993).

Most studies have focussed on turbidity within estuaries and embayments reporting that local river runoff associated with rainfall events, the spring-neap tidal cycle and wind patterns may affect turbidity within these areas from semidiurnal to interannual time scales (e.g. Cloern and Nichols, 1985; Schoellhamer, 1996, 2002; Morrison et al., 2006; Brodie et al., 2010). However, a comprehensive understanding of how such processes influence turbidity outside of these sheltered estuaries and embayments is lacking, in part due to the rarity of long-term monitoring data. It has been noted that the drivers responsible for resuspending bottom sediments differ on open coasts than those driving resuspension within harbours, embayments and estuaries, even though these two water bodies may be adjacent (Chen et al., 2010). Investigating how the primary drivers of turbidity vary across an estuarine-open coast gradient using long-term monitoring data is therefore important to further understand the complex temporal and spatial relationships that influence turbidity in coastal waters.

New Zealand has been subjected to extensive land-use change following human settlement and sedimentation in the coastal environment has increased as a result of catchment modification through farming, deforestation and urbanisation (Goff, 1997; Hayward, 2006; Grenfell et al., 2007). Increased sediment runoff from the land caused by anthropogenic processes and associated eutrophication is considered one of the key threats, both globally (Smith, 2009), and for the Hauraki Gulf (SoE, 2011), the large body of water adjacent to New Zealand's largest city, Auckland. Awareness of the impact of development on coastal waters and the environment in general resulted in the introduction of the Resource Management Act in New Zealand in 1991. This legislation included the implementation of sediment controls and greater point source discharge management as well as a statutory requirement to monitor the state of the environment and policy effectiveness. In the region surrounding Auckland, this statutory declaration gave rise to the Auckland Council Regional Plan on sediment control (ARC, 1999) that became operative in 2001. Under this plan sediment retention ponds, silt fences, contour drains and runoff diversion channels have all been implemented to reduce runoff of sediments from new land and roading developments into the surrounding estuarine and coastal environments. However, minimal sediment controls were implemented to reduce sediment inputs from existing uses in rural areas such as farming and forestry. It remains unknown whether the implementation of these land management regulations have resulted in declines in sediment runoff and improvements in coastal water quality or "trend reversal" as reported in previous studies and reviews (e.g. Cloern, 2001; Nixon, 2009 and references within). In general, relatively few long-term data sets exist on coastal turbidity that would allow a robust investigation into this question.

Monitoring of coastal water quality parameters, including turbidity, total suspended solids and chlorophyll *a* have been carried out at stations located throughout the Hauraki Gulf by the Auckland Council since 1991 (Scarsbrook, 2008), roughly the same time as the Resource Management Act was implemented in New Zealand. This provides a unique dataset to investigate long-term trends in turbidity and assess whether turbidity has changed in relation to changes in land-management practices. This study first investigates the spatial patterns in turbidity across an estuarine to open-coast gradient and examines the relative contributions of suspended sediment and phytoplankton to the turbidity measurements. We then focus on investigating temporal patterns in turbidity, and relating long-term, seasonal and month-to-month variability in turbidity to potential meteorological and oceanic drivers, as well as ENSO. This novel analysis of a long-term turbidity dataset is therefore important from a management perspective in terms of understanding how previously implemented strategies have affected coastal water clarity, understanding how the primary drivers of variation in turbidity vary across an estuarine to open coast gradient, and in predicting how turbidity will be affected by climate change.

2. Methods

2.1. Study area

The Hauraki Gulf, located on the northeast coast of the North Island, New Zealand (Fig. 1), is a large island-studded embayment. It is protected from the prevailing southwesterly winds, but is exposed to ocean swells from the northeast. The Hauraki Gulf includes a number of estuaries, including the 18 km long Waitemata Harbour that is surrounded by New Zealand's largest and most populated city, Auckland. The Hauraki Gulf provides an extremely important setting for recreational, cultural, societal and economic demands due to the typical gradient from shallow, riverine dominated estuaries, sheltered harbour entrances, urban areas surrounded by coastal beaches and rural, open-coast shores exposed to northeasterly conditions. Auckland's population is rapidly growing and coastal land around the Hauraki Gulf continues to be developed, albeit at a slower rate and under much stricter land management regulations than in the past.

2.2. Water quality monitoring programme

The Auckland Council's Saline Water Quality monitoring programme involves monthly collection of water samples by helicopter or boat from a range of coastal marine and estuarine sites throughout the Hauraki Gulf (Scarsbrook, 2008; Walker and Vaughan, 2014). Surface water samples (depth ~ 0.5 m) are