Numerical modelling of the upwelling and associated hydrodynamics at various scales along the coral reefs at Sodwana Bay, South Africa

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Abstract

This study investigates hydrodynamics and short-term temperature fluctuations at high-latitude coral reefs, focusing on Sodwana Bay in South Africa. A refined hydrodynamic model nested within a global ocean model was developed to investigate temperature anomalies. On-reef hydrodynamics were also measured using Tilt Current Meters over eight months between 25/08/2021 and 16/05/2022 to describe the on-reef hydrodynamics at Sodwana during temperature anomaly events. During temperature anomaly events, the predominant current direction is south-southwestward, occasionally reversing to the north with cold water temperature anomalies. Current speeds range from 0.1 to 0.2m/s, peaking at 0.35m/s at the shallow low rugosity site. The nested model, developed using the Delft 3D Flexible Mesh hydrodynamic modelling suite, successfully replicates the observed temperature anomalies in 2004. The nested modelled better replicates the temperature anomaly amplitudes compared to the reanalysed NEMO global ocean model due to the high model resolution around Sodwana. A nested hydrodynamic model is necessary for accurate analysis of short-term temperature fluctuations. A representative anomaly in February 2004 was investigated using the nested model. The anomaly was associated with remote upwelling of cold water near the Delagoa Peninsula, followed by advection towards Sodwana. As it reaches the region, the entire Sodwana region is engulfed by the cold upwelled water. The model revealed that local upwelling occurs within the Sodwana canyons during this event, making the water in the canyons 1 °C colder than the surrounding water. When the locally upwelled water spreads over the reef system, the anomaly amplitude is enhanced by approximately 20%.

Numerical modelling of the upwelling and associated hydrodynamics at various scales along the coral reefs at Sodwana Bay, South Africa

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Key Points:

- Currents and temperature were measured on the Sodwana reef system using low cost Tilt Curret Meters.
- A hydrodynamic model was developed and nested within a global ocean model to investigate upwelling and cold water temperature anomalies at Sodwana.
- The nested model successfully replicated the cold water temperature anomalies observed at Sodwana.

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Abstract

This study investigates hydrodynamics and short term temperature fluctuations at high latitude coral reefs, focusing on Sodwana Bay in South Africa. A refined hydrodynamic model nested within a global ocean model was developed to investigate short term temperature anomalies. On-reef hydrodynamics were also measured using Tilt Current Meters over eight months between 25/08/2021 and 16/05/2022 to describe the on-reef hydrodynamics at Sodwana during temperature anomaly events. During temperature anomaly events, the predominant current direction is south-southwestward, occasionally reversing to the north with cold water temperature anomalies. Current speeds range from 0.1 to 0.2 m/s, peaking at 0.35 m/s at the shallow low rugosity site. The nested model, developed using the Delft 3D Flexible Mesh hydrodynamic modelling suite, successfully replicates the observed temperature anomalies in 2004. The nested modelled better replicates the temperature anomaly amplitudes compared to the reanalysed NEMO global ocean model due to the high model resolution around Sodwana. A nested hydrodynamic model is necessary for accurate analysis of short-term temperature fluctuations. A representative anomaly in February 2004 was investigated using the nested model. The anomaly was associated with remote upwelling of cold water near the Delagoa Peninsula, followed by advection towards Sodwana. As it reaches the region, the entire Sodwana region is engulfed by the cold upwelled water. The model revealed that local upwelling occurs within the Sodwana canyons during this event, making the water in the canyons 1 °C colder than the surrounding water. When the locally upwelled water spreads over the reef system, the anomaly amplitude is enhanced by approximately 20 %.

Plain Language Summary

This study investigated upwelling and cold water temperature anomalies along the Sodwana Bay coral reef system using a combination of field measurements and numerical hydrodynamic modelling. The temperature anomalies are important for the sustainability and survival of high latitude reef systems such as Sodwana as they provide potential refuge to coral bleaching events. The study found that the temperature anomalies are associated with upwelling of cold water around the Delagoa Bight region near Maputo, Mozambique, after which the cold water is transported by ocean currents southward to the Sodwana region. When the cold water interacts with the submarine canyons located offshore of Sodwana, the cold water is channelled up the canyons and onto the reefs enhancing the magnitude of the temperature anomalies.

1 Introduction

Coral reefs are complex ecosystems influenced by hydrodynamics and physical processes on various length and time scales (Monismith, 2007). Investigating and understanding coral reef systems are crucial for the maintenance and survival of the reefs, especially in light of current changes to the global climate and ocean temperatures. They are indicators of the health and state of the oceans as they respond quickly to changes in the ambient state of the ocean, be it temperature, contaminants or any other physical or biological processes (Pandolfi et al., 2003; Hughes et al., 2005; Mumby & Steneck, 2008; Hoegh-Guldberg & Bruno, 2010).

A diverse array of biological and physical processes influences the ecological functioning and sustainability of coral reefs. The specific physical processes that govern the health and functionality of reefs can vary depending on the type of reef system and its geographical location. Coral reefs typically found in tropical regions, including atolls, are particularly susceptible to their immediate environmental conditions, which include factors such as tidal water levels and local hydrodynamics (Koweek et al., 2014; Safaie et al., 2018; Matěcká et al., 2022). However, prominent coral reefs in high-latitude areas exhibit a reduced sensitivity to local physical processes like tides and winds. Instead,
larger-scale processes such as regional upwelling, coastline geometries, and global ocean patterns influence the functioning of these reefs. These mesoscale processes ultimately impact the reef-scale processes and subsequently affect the overall functioning of these reef systems (Frys et al., 2020; Wells et al., 2021). Less is known about the physical processes governing these reefs because an understanding of the hydrodynamics, starting from a regional mesoscale down to the local reef scale, is required to understand the functioning of these reef systems. Research has begun investigating the effect of these larger scale processes governing high latitude reefs, such as ocean transport and upwelling associated with the Ningaloo reef in Western Australia (Xu et al., 2013, 2016). However, there is still little known regarding coral reefs situated in other high-latitude regions of the world and how the hydrodynamics at various scales influence their functioning.

Numerical hydrodynamic models are effective tools for investigating ocean processes at various time and length scales. These models have been a crucial part of investigating and understanding both the physical and biological functioning of coral reefs around the world (Black et al., 1991; Storlazzi et al., 2011; Rogers et al., 2013, 2017; Yao et al., 2022). Wells et al. (2023) recently used regional hydrodynamic and temperature data from the reanalysed NEMO global ocean model to investigate cold water temperature anomalies on the Sodwana reefs on the northeastern coast of South Africa. Previous research suggests that these temperature anomalies provide refuge to the reefs during potential bleaching events along the Sodwana coral reef system (Lutjeharms & de Ruijter, 1996; Celliers & Schleyer, 2002; Riegl & Piller, 2003; Rautenbach et al., 2023). The temperature anomalies are characterised by a rapid temperature drop of a few degrees on the Sodwana reefs and occur over a time scale of days (Wells et al., 2021).

The coarse resolution of global ocean models, such as reanalysed NEMO global ocean model used by Wells et al. (2023), is adequate for investigating regional hydrodynamic processes offshore of coral reef systems but cannot replicate the reef scale hydrodynamics or physical processes accurately. The course resolution of these models does not resolve the complex nearshore bathymetric features around reef systems, such as the continental shelf and submarine canyons. The question arises, what effect does complex nearshore bathymetry have on the local reef scale hydrodynamics, and what is the role of mixing at spatial scales between 100 m and 1000 m? A refined hydrodynamic model with high spatial and temporal resolutions around the reef systems should better represent sub-mesoscale hydrodynamics and complex nearshore bathymetric features. The refinement also reduces local truncation errors of discrete numerical schemes (Le et al., 2014).

This paper focuses on the setup and validation of a refined hydrodynamic model one-way nested within a global ocean model. The nested model was set up using the Delft 3D Flexible Mesh hydrodynamic modelling suite and validated using measured on-reef hydrodynamics and long-term temperature data recorded on Nine-Mile Reef. This study also presents a temperature and salinity nudging technique within the nested model to ensure the regional nested model’s hydrodynamics adequately replicates the global ocean model regional hydrodynamics offshore of the Sodwana region. The nested model was then used to investigate the cold water temperature anomalies observed at Sodwana and their associated hydrodynamics.

Field data measurements are another powerful tool for investigating and describing the hydrodynamics around coral reefs. Measurements of the local on-reef hydrodynamics are required to validate numerical hydrodynamic models and provide insight into the on-reef flow and temperature. Coral reefs are often located in less economically developed third-world regions (Moberg & Folke, 1999; Spalding et al., 2001). Therefore, researchers investigating coral reefs in these regions do not always have access to traditional hydrodynamic measuring instruments, such as Acoustic Doppler Current Profilers, due to the high cost or availability of these instruments. This study presents on-reef hydrodynamic measurements from an alternative low-cost and robust instrument called a Tilt Current Meter (TCM). Multiple TCMs were designed and developed in-house and
deployed along the Sodwana reefs. The TCM measurements were used to describe the on-reef hydrodynamics at Sodwana during temperature anomaly events.

2 Method

2.1 Case Study Site

The Sodwana reef system is one of the most southerly coral reefs in the world and is located in the Delagoa Bioregion of South Africa, which begins just north of Richards Bay and extends Northwards into Mozambique (Ramsay, 1994). Figure 1 shows the location of Sodwana Bay and the surrounding GEBCO bathymetry (GEBCO Bathymetric Compilation Group, 2021). Many coral reef systems located at higher latitudes have already begun to experience the effects of warming events associated with climate change, such as coral bleaching (Riegl & Piller, 2003). Sodwana has shown resilience to these warming and bleaching events, which has been attributed to strong ocean mixing and short-term cold water temperature anomalies (Celliers & Schleyer, 2002; Riegl & Piller, 2003). The temperature anomalies observed at Sodwana make the region an ideal case study site to investigate the driving mechanisms of these events and can potentially describe similar temperature anomaly events in other regions of strong ocean mixing and complex shelf topography. Similar prominent coral reef systems located along coastlines within boundary currents that experience upwelling events include the Ningaloo Reef, on the west coast of Australia in the path of the Leeuwin Current (Xu et al., 2013, 2016), the Florida Reef Tract, located along the coast of Florida in the Gulf Stream (Walker & Gilliam, 2013; Frys et al., 2020). These reefs are also located at similar latitudes to Sodwana in subtropical regions around the Tropic of Capricorn or Cancer.

Figure 1. GEBCO bathymetry of region surrounding Sodwana Bay. Vertical datum is mean sea level.

The region is characterised by high mesoscale eddy kinetic energy that interacts with the complex shelf topography driving complex flow fields (M. Roberts et al., 2014). Sodwana is situated near the origin of the warm Agulhas Current where the continental shelf is narrow and characterised by steep gradients and submarine canyons on the continental slope (Ramsay, 1994). The Delagoa bight is also located approximately 200 km north of the Sodwana region at the southern end of the Mozambique Channel. The Delagoa Bight is one of the largest coastline indentations along the east coast of Africa, and the local widening of the continental shelf is associated with complex regional flow structures (Lutjeharms & Da Silva, 1988; Lamont et al., 2010).
2.2 Available data

2.2.1 Long term temperature data

Hourly temperature data measured at Sodwana between 1994 and 2015 were used to compare with the numerically modelled temperature data. The temperature measurements were obtained using an individual (self-contained) Star-Oddi mini underwater temperature recorder with an accuracy of ±0.05 °C, deployed at a depth of 18 m on Nine-Mile Reef (see Figure 3). This data was made available by the Oceanographic Research Institute and SAAMBR.

2.3 Field data collection

The reef currents were measured using TCMs deployed along the Sodwana reef system. The TCMs measure current speed and direction at a fixed point approximately 0.5 m above the reef. The instrument is positively buoyant and tethered to an anchor fixed to the sea bed and tilts in the ambient current due to the drag forces exerted on the instrument (Hansen et al., 2017; Anarde & Figlus, 2017; Marchant et al., 2014; Kjeldorff et al., 2020). Figure 2 shows a TCM deployed on Two-Mile Reef (see Figure 3) at Sodwana.

Figure 2. TCM tilting on Two-Mile Reef.

The relationship between the TCM’s tilt and current speed was measured and calibrated in a flume for steady and oscillatory currents similar to those on the Sodwana reefs. This relationship was used to convert the angle and direction of tilt recorded by the TCMs to current speed and direction. The TCMs sample and record the tilt at a 1 Hz frequency for five minutes every hour. The tilt was frequency filtered to remove the wave-induced oscillatory currents and inherent instrument noise from the tilt signal. The frequency-filtered 1 Hz current speed and direction measured by the TCMs were time-averaged over the five-minute sampling intervals to give the five-minute mean currents measured on the reefs.

The TCM does not resolve 3-dimensional flow. It resolves the horizontal flow in the x and y plane, which is averaged over the surface area of the instrument. Due to the sampling frequency, the instrument does not capture small-scale turbulent flows with time scales shorter than one second. Additionally, the instrument cannot resolve vertical length scales less than 50 cm due to the housing size.
A total of ten TCMs were deployed over the Sodwana reef system between 25/08/2021 and 16/05/2022, with varying deployment lengths. Eight TCMs were located around Two-Mile Reef. A TCM was also located on Five-Mile Reef and on Seven-Mile Reef (see Figure 3). This study presents the data from three TCMs deployed on Two-Mile Reef. The three chosen TCMs had the most temporal data coverage over the eight months of deployment between 25/08/2021 and 16/05/2022. They were also the most representative locations for different conditions found along the reef system. TCM 1 was located in the middle of Two-Mile Reef with high rugosity at a depth of 15 m. TCM 2 was deployed at the southern extent of Two-Mile Reef with low rugosity at a depth of 18 m. TCM 3 was deployed at the offshore extent of Two-Mile Reef on the outer reef shelf at a depth of 30 m. Figure 3 shows the locations of the TCMs deployed along the Sodwana reefs with an enhanced view of Two-Mile Reef. The instruments were retrieved every three months for data collection, marine defouling and battery replacement.

Figure 3. Locality map of the study area showing the locations of major reefs and locations at Sodwana Bay and a detailed map showing the locations of the TCMs around Two-Mile Reef. TCM locations are shown with triangles. Solid-filled triangles denote the TCMs used in this study and the dashed hollow triangles denote the additional TCMs deployed but not presented in this study.

2.3.1 Numerically modelled ocean reanalysis data

Modelled daily mean current velocities, temperature and salinity were used as boundary-forcing conditions for the nested hydrodynamic model. This data comes from the GLORYS12V1 product provided by Copernicus Marine Service (CMEMS). The model component of GLORYS12V1 is from the ocean NEMO model version 3.1. The model has a horizontal resolution of 1/12° and 50 vertical levels. The GLORYS12V1 product covers 27 years between 1993 and 2020 on a daily time step (Jean-Michel et al., 2021). ECMWF ERA-Interim, and ERA5 reanalyses data at the surface force the NEMO model. This model does not include tidal forcing. Along track altimetry data and in situ vertical temperature and salinity profiles from the sea mammals database (Roquet et al., 2011) and moorings from TAO/RAMA/PIRATA programs (Cabanes et al., 2012) are assimilated using a reduced-order Kalman filter (Jean-Michel et al., 2021; Lellouche et al., 2021). Modelled daily mean Sea Surface Height (SSH) from the GLORYS12V1 product was also used.
as boundary forcing conditions for the nested hydrodynamic model. The NEMO model includes a horizontal diffusive length of 200 km and a horizontal diffusive velocity of 0.01 m/s (Madec & the NEMO Team, 2016). This equates to a horizontal eddy diffusivity of 2000 m$^2$/s used to account for the sub-grid scale unresolved physics in the NEMO model.

### 2.3.2 Tide data

Tidal constituents from the global ocean tide model DTU10 were used as boundary-forcing conditions for the nested hydrodynamic model. The DTU10 model provides the following 10 constituents: Semidiurnal: M2, S2, K2, N2 - Diurnal: S1, K1, O1, P1, Q1 - Shallow water: M4 at a horizontal resolution of 0.125$^\circ$. (Lyard et al., 2020).

### 2.3.3 Wind data

The nested hydrodynamic model used modelled wind data as a surface boundary forcing condition. This data comes from the Climate Forecast System Reanalisys (CFSR) product provided by the National Centers for Environmental Prediction (NCEP). The product provides time and space varying wind speed and direction 10 m above the ocean and land surface. The CFSR wind data is available over 31 years between 1979 and 2009 on an hourly time step with a spatial resolution of 0.5$^\circ$ (Saha et al., 2010).

### 2.4 Hydrodynamic numerical modelling

A three-dimensional (3D) hydrodynamic numerical model was set up and nested within the global reanalysed NEMO model. The nested model has varying degrees of spatial resolution, starting around the resolution of the reanalysed NEMO model at the offshore boundaries and increasing in resolution towards the Sodwana region. The nested model was used to downscale the regional hydrodynamics and investigate the temperature anomalies around the Sodwana reefs at a local sub-mesoscale. This section describes the setup of the nested hydrodynamic model.

#### 2.4.1 Model description

The Delft 3D Flexible Mesh (FM) hydrodynamic model simulates 3D unsteady flow and scalar transport and was used to set up the refined nested model. The numerical hydrodynamic modelling system D-Flow FM solves the unsteady shallow water equations in three dimensions and consists of the horizontal equations of motion and the continuity equation (Kernkamp et al., 2022). Delft 3D FM solves the unsteady Navier Stokes equations for an incompressible fluid under shallow water and the Boussinesq assumptions. The partial differential equations, in combination with an appropriate set of initial and boundary conditions, are solved on an unstructured finite volume grid (Kernkamp et al., 2022). The model includes tidal forcing, Coriolis forcing, space-varying wind shear stresses, bottom friction shear stresses and a turbulence model to account for the vertical turbulent viscosity and diffusivity.

Wells et al. (2021) suggested that non-hydrostatic processes, such as breaking of internal waves along the shelf slope, could be a potential driving mechanism of the temperature anomalies at Sodwana. Breaking of internal waves occurs when the slope of the internal wave beam is equal to the topographic slope of the shelf (Lamb, 2014; Alberty et al., 2017; Wang et al., 2019). The length of an internal wave is dependent on the vertical density gradient and Brunt-Väisälä frequency (Lamb, 2014). An analysis of the shelf slope near Sodwana and the potential slope of internal waves in the region based on the vertical density profiles shows that the region is not conducive to internal wave breaking. Therefore, since the model was not used to investigate non-hydrostatic processes, such as internal wave breaking, a hydrostatic model was deemed appropriate. Under the
shallow water assumption, the vertical momentum equation is reduced to a hydrostatic pressure equation (Kernkamp et al., 2022).

### 2.4.2 Grid and bathymetry

A combination of surveyed data (Ramsay, 1994) and GEBCO bathymetry data (GEBCO Bathymetric Compilation Group, 2021) was used to generate the bathymetry used in the nested model. The survey provides bathymetry data around the nearshore region along the reefs and shelf around Sodwana. The GEBCO data provides the regional bathymetry offshore of the Sodwana region at a 0.004° resolution. Mean Sea Level (MSL) was used as the vertical datum for the model.

The spatial extent of the model was selected to be large enough to allow for regional hydrodynamic features to develop. These regional flows include mesoscale eddy structures and western boundary currents along the East African coastline. The model domain extends approximately 1000 km offshore of Sodwana, coinciding with the 44°E line of longitude. The northern boundary is located approximately 1400 km north of Sodwana, coinciding with the 16°S line of latitude. The southern boundary is located approximately 1700 km from Sodwana, coinciding with the 43°S line of latitude. The horizontal mesh resolution varies from approximately 10 000 m at the offshore boundaries to 100 m around the shelf canyons and reef system. Figure 4 presents the nested model grid and bathymetry showing the increasing mesh resolution around the Sodwana region.

![Figure 4. Nested hydrodynamic model bathymetry and mesh.](image)

### 2.4.3 Boundary forcing conditions

The modelled tidal constituents from the DTU10 global tide model were applied as space and time-varying water level conditions along the lateral boundaries. Modelled Sea Surface Heights from the reanalysed NEMO model was applied as time and space-varying water levels along the lateral offshore boundaries. Current velocities, temperature and salinity from the reanalysed NEMO model were applied as space, time and depth-varying conditions along the offshore lateral boundaries.

A nudging technique was used on the temperature and salinity in the deep offshore region of the nested model. Nudging is a technique used to help ensure that the modelled temperature and salinity in the nested model replicate specified boundary conditions or observations (Paniconi et al., 2003). The nudging includes an extra term in the nested model’s scalar tracer equations (temperature and salinity) that pulls the nested model temperature and salinity towards the specified temperature conditions. The nudging of the scalar tracers can be described by:
$$\frac{DS}{Dt} = \frac{S_{\text{nudge}} - S}{T_{\text{nudge}}}$$  \hspace{1cm} (1)$$

where $S$ is the scalar tracer quantity in the nested model, $S_{\text{nudge}}$ is the scalar quantity from the reanalysed NEMO model that the nested model is being nudged towards, and $T_{\text{nudge}}$ is the nudging time scale.

The nested model was nudged using the reanalysed NEMO modelled temperature and salinity fields at a nudging time scale of a day. The nested model was nudged offshore of the Sodwana region to ensure the nested model regional temperature, salinity, and flow patterns replicate the reanalysed NEMO model. Nudging was excluded within a 0.5° radius around Sodwana. Therefore, the nudging terms will not influence the local hydrodynamics and complex flow interaction with the shelf and canyons within the nested model.

2.4.4 Mixing and turbulence

Vertical turbulent mixing is computed by a $k-\epsilon$ closure model. The horizontal turbulent mixing is represented by a constant eddy viscosity and eddy diffusivity values of 1 m$^2$/s. Therefore, the diffusion and mixing in the offshore regions will be governed by the grid’s numerical diffusion and resolution, which will be larger than the specified eddy diffusivity. In the highly resolved nearshore regions, the mixing will still be dominated by the numerical resolution, however, to a much smaller extent than in the reanalysed NEMO model. This will provide a more accurate representation of the mixing in the nearshore regions even though the nested model mixing is still numerically dominated.

2.4.5 Simulation period and timestep

The nested model was run over the year 2004 using the reanalysed NEMO model and CFSR wind data as boundary conditions. This year was chosen due to identifiable temperature anomalies observed during this year and the availability of measured temperature data on Nine-Mile Reef during this period (Roberts et al., 2006; Wells et al., 2021). Due to computational time limitations, the model was not run for longer than a year, even though 21 years of measured temperature data is available. The nested model was spun up for a month before 2004 to ensure the model’s boundary conditions and flow fields were fully developed before the modelled year began. The nested model had an automated internal time step that adjusted based on the cell size and hydrodynamic conditions to satisfy a CFL number of 0.7.

3 Results

3.1 Measured reef currents and temperature

The three TCMs deployed around Two-Mile Reef recorded current speed and direction over an eight-month period between 25/08/2021 and 16/05/2022. Figure 5 shows rose plots of the five-minute mean currents recorded by the TCMs.

At TCM 1 and 2, the predominant current direction is south-southwestwards. The current flows in the predominant direction for 53% of the time at TCM 1 and 60% at TCM 2. Both TCMs were located on Two-Mile Reef. TCM 1 was located in an area of high rugosity, and TCM 2 was in an area of low rugosity. There is a higher variability in the current direction at TCM 1 compared to TCM 2. This is likely due to the higher reef rugosity at TCM 1 enhancing reef scale turbulence. The current speeds at TCM 1 were also lower than at TCM 2. This is also likely due to the higher reef rugosity enhancing the bottom friction around TCM 1. The maximum current speed observed at TCM 1 was 0.20 m/s and 0.35 m/s at TCM 2.
TCM 3 was located along the offshore slope of Two-Mile Reef at a deeper depth of 30 m in an area of low rugosity. The predominant current direction was west-southwest at TCM 3. The current direction aligns with the contours of the offshore reef slope. The current speeds measured at TCM 3 were smaller than at the other TCMs, with a maximum current speed of 0.18 m/s.

Northerly current directions, often referred to as northerly current reversals, were also observed at all three TCM locations. These reversals occurred between 10% and 20% of the deployment period. Each reversal lasts, on average, for a few days before switching back to the predominant southerly or southwesterly direction.

Figure 6 presents the temperature time series and current velocity stick vectors measured by TCM 2. The measurements from TCM 2 were presented because the depth and low rugosity are representative of the entire Sodwana reef system.

The deployment began towards the end of winter, and the average temperatures on the reef were around 22 °C. The average temperature increased to approximately 24 °C by the beginning of summer in December. The average temperature increased as summer progressed, rising above 26 °C over January and February. Short-term fluctuations in temperature were observed during December 2021 and March 2022. These temperature fluctuations were of a similar magnitude and time scale as the temperature anomalies defined in Wells et al. (2021).

The current stick vector time series shows that the predominant flow direction is south-southwestward over the deployment period, with typical current speeds between 0.1 and 0.2 m/s. It also shows that the short-term drops in temperature are associated with northerly current reversals and variations from the predominant current direction. Figure 6 presents the measured temperature time series and current velocity stick vectors over the short-term temperature fluctuations during December 2021.

Two temperature anomalies occurred in quick succession during December 2021. The first anomaly peaked on 23/12/2021, and the second peaked on 28/12/2021. Both
anomalies lasted for approximately five days each. A current reversal occurred four days before the first anomaly when the current direction changed from southward to northward. The northerly current reversal then changed back to a southward direction at the start of the first anomaly. The current direction fluctuated between northerly and southerly directions for the duration of both anomalies. After the temperature anomalies, the current direction returned to a predominant southerly direction. This shows that the short-term temperature fluctuations over this period are associated with northerly current reversals or changes in the current direction from the predominant southward direction. Similar northerly current reversals were observed during the short-term temperature fluctuations observed during March 2002 and at the other two TCM locations.

Figure 6. a) Temperature time series and b) stick vector time series of current speed and directions measured by TCM 2. Zoomed in view of the c) temperature time series and d) stick vector time series of current speed and directions measured by TCM 2 from 09/12/2021 to 09/01/2023.
3.2 Nested model validation: Nesting process

The first step in validating the nested model is to check whether the regional modelled flow fields agree with the reanalysed NEMO-modelled flow fields, especially during the anomaly periods. The nested model performed well in replicating the regional hydrodynamic features modelled by the reanalysed NEMO model. Figure 7 presents an example comparison of the regional near-surface flow fields from the reanalysed NEMO and the nested model during the February 2004 temperature anomaly.

![Figure 7](image)

Figure 7. Spatial surface current fields from the reanalysed NEMO model (left) and the nested model (right) on 14/02/2004 at the peak of the anomaly.

The regional structure of the NEMO and nested model current fields are similar and compare well at the peak of the anomaly. It is evident from Figure 7 that the current speed of the strong southward jet that detaches from the Delagoa Peninsula is stronger and more focused in the nested model. This is likely due to the nested model’s increased resolution around the Delagoa Bight and Peninsula. The model resolution around the Delagoa Bight in the nested model is approximately double the resolution of the reanalysed NEMO model.

3.3 Nested model validation: Reef temperature

The nested model temperature at Nine-Mile Reef was compared to the measured temperature to investigate how well the nested model replicates the temperature on Nine-Mile Reef, including the temperature anomalies during 2004. Wells et al. (2023) showed that the reanalysed NEMO model replicated the temperature anomalies near Sodwana on a regional scale. However, the temperature anomalies had lower amplitudes than the measured anomaly amplitudes. This section investigates if a higher resolution hydrodynamic model better replicates the temperature anomalies on the reefs.

Figure 8 presents a time series comparison of the measured and nested model temperature at Nine-Mile Reef during 2004. The comparison shows that the nested model replicates the seasonal temperature and short-term temperature fluctuations well dur-
ing 2004. The nested model replicated the peak amplitudes of the temperature anomalies in February and the beginning of December well. The nested model also replicates the temperature anomalies during April and the end of December; however, the amplitudes of these anomalies are underpredicted, but less so than in the reanalysed NEMO model.

The modelled currents on Nine-Mile Reef show similar characteristics to the TCM-measured currents. The predominant current direction during the year is south-southwestwards. Throughout the year, occasional northerly current reversals occur. These reversals occur for 15% of the year. All temperature anomalies observed during 2004 are associated with northerly current reversals around the time of the anomaly. This does not necessarily imply that current reversals are driving the temperature anomalies. However, it shows a link between the occurrence of northerly current reversals on the reef and the temperature anomalies. Figure 8 presents a time series comparison of the measured and modelled temperature over February 2004 when the most significant temperature anomalies occurred. This comparison includes the reanalysed NEMO model temperature extracted at 20 m near Sodwana and the modelled temperature from the nested model with an increased horizontal diffusivity of 2000 m²/s, which is comparable to the eddy diffusivity used in the reanalysed NEMO model. This gives an indication of how the eddy diffusivity used in the reanalysed NEMO model affects the temperature anomaly amplitudes even when the nested model revolves the complex nearshore bathymetry.

The nested model replicates both anomalies well during February 2004. However, the measured temperature shows a larger temperature fluctuation associated with the tidal signal. The Pearson’s correlation coefficient between the nested model and measured temperature over this period was 0.84. The reanalysed NEMO model replicates the temperature anomalies; however, the amplitude of both anomalies is lower than the measured anomaly amplitudes. The correlation coefficient between the reanalysed NEMO model and the measured temperature over this period was 0.76. The nested model rerun with an eddy diffusivity of 2000 m²/s shows a reduction of the temperature anomaly amplitudes. The nested model temperature with increased eddy diffusivity closely follows the reanalysed NEMO model temperature over the anomaly period. The temperature correlation coefficient between the nested model with increased eddy diffusivity and the measured temperature was 0.74 and the reanalysed NEMO temperature was 0.85. This indicates that the reason for the lower amplitudes of the anomalies modelled by the reanalysed NEMO model is a result of an overestimation of the mixing in the reanalysed NEMO model in the nearshore regions. The increased mixing in the nested model smooths out the temperature fields resulting in lower anomaly amplitudes. The increased resolution of the nested model reduces the numerical mixing in the nearshore regions resulting in less smoothing of the temperature fields near Sodwana with more accurate anomaly amplitudes.

3.4 Cold water temperature anomaly hydrodynamics

The Delft 3D model was set up to investigate the nearshore hydrodynamics during a cold water temperature anomaly event. Wells et al. (2023, under review) used the reanalysed NEMO temperature and flow fields to identify the predominant regional flow patterns associated with the anomalies. They linked the temperature anomalies to regional upwelling and advection of cold water to the Sodwana region. Wells et al. (2023, under review) found that most anomalies were associated with remote upwelling of cold water near the Delagoa Peninsula, followed by advection from the Delagoa Bight towards the Sodwana region. The remote upwelling occurs at a regional scale which the reanalysed NEMO model replicates. The course resolution of the reanalysed NEMO model does not replicate what happens at a local scale when the cold water interacts with the local complex bathymetry, such as the shelf and canyons. The nested model allows for an
Figure 8. a) Comparison of the measured and modelled temperature at Nine-Mile Reef at a depth of 20 m during 2004. The grey line represents the measured temperature and the black line represents the nested model temperature. b) Stick vector time series of modelled currents on Nine-Mile Reef. c) Comparison of the measured and modelled temperature at Nine-Mile Reef near the seabed over the February 2004 anomaly period. The solid grey line represents the measured temperature, the dashed grey line represents the reanalysed NEMO model temperature, the solid black line represents the nested model temperature and the dashed black line represents the nested model temperature with a diffusivity of 2000 m²/s.

investigation into the local hydrodynamics when the advected pocket of cold upwelled water interacts with the Sodwana region.

Wells et al. (2023, under review) showed that the temperature anomaly in February 2004 is associated with remote upwelling of a pocket of cold water near the Delagoa Peninsula. The upwelling is linked to the intermittent separation of a strong southward stream from the Delagoa Peninsula. Figure 9 presents a six-day time evolution of the nested model temperature and flow fields at a depth of 30 m, from 06/02/2004 to 12/02/2004. The time evolution shows the interaction between the complex bathymetry and the pocket of cold upwelled water as it advects towards Sodwana.

The anomaly during February 2004 is a typical anomaly associated with upwelling around the Delagoa Peninsula and advection towards Sodwana (Wells et al. 2023, under review). The spatial extent of the upwelled cold water pocket is significantly larger than the Sodwana reef system. Therefore, when the pocket of cold upwelled water reaches the Sodwana region, it engulfs the reefs, resulting in a cold water temperature anomaly.
Figure 9. Time evolution of the regional temperature fields (top) and a zoomed-in view of the temperature fields around Sodwana (bottom) at a depth of 30 m leading up to the peak of the temperature anomaly on 14/02/2004. This is a typical example anomaly associated with remote upwelling near the Delagioa Peninsula followed by advection to the Sodwana region along the Delagoa shelf. The current velocity vectors have been overlaid as a quiver plot and scaled by speed. The location of Sodwana has been denoted by a pink dot on the coastline.

This shows that the temperature anomalies are linked to large mesoscale flow patterns; however, the interaction between the hydrodynamics and complex bathymetry around Sodwana, such as the canyons, may still affect the magnitude of the anomalies. The nested model allows for a detailed description of the hydrodynamics and temperature around the complex bathymetry and canyons near Sodwana to investigate the effect of the local hydrodynamics on the temperature anomalies. Figure 10 presents the temperature inside and around the canyons and shelf at various depths at the peak of the temperature anomaly in February 2004.

The temperature fields at the 60 m and 90 m depth layers show colder water inside both Wright Canyon and White Sands Canyon along the Sodwana shelf (see Figure 3), indicative of local upwelling in the canyons. The temperature is approximately 1 °C colder inside the canyons than offshore of the canyons. The cold water associated with the local canyon upwelling is spread over the reefs between the canyon heads as it upwells out of the canyons at the 30 m depth layer. The cold water associated with the local canyon upwelling at the 30 m depth layer is also approximately 1 °C colder than the surrounding water. A 6 °C drop in temperature was recorded at Nine-Mile Reef during the February 2004 anomaly (see Figure 8). Therefore the local canyon upwelling enhances the temperature anomaly amplitude by 20 % during the February 2004 temperature anomaly.
4 Discussion

Hydrodynamic data from the two TCMs deployed in the shallower region around Two-Mile Reef showed that the predominant current direction along the reef is south-southwestwards, with occasional current reversals to a northward direction. This agrees with previously ADCP measurements taken offshore of Nine-Mile Reef at Sodwana Bay during March 2001 (Roberts et al., 2006; Morris, 2009) and TCM measurements from a previous deployment by Deoraj et al. (2022). TCM 1, located in an area of high rugosity on Two-Mile Reef, had on average lower current speeds and a higher directional spread around the predominant southward direction when compared to TCM 2, which was located in an area of low rugosity. TCM 3 on the deeper offshore slope of Two-Mile Reef measured lower current speeds than at the shallower sites. The predominant south-westerly current direction at TCM 3 lined up more parallel with the slope contours.

Cold water temperature anomalies were observed in the TCM temperature measurements during December 2021 and March 2022. The temperature anomalies were associated with current direction variations from the predominant southward current direction during the anomaly periods on Two-Mile Reef. For some anomalies, northward current reversals occurred slightly before or after the actual drop in temperature measured on the reef. This suggests that the northerly current reversals are not driving the temperature anomalies but are associated with the anomalies. Roberts et al. (2006) and Wells et al. (2021) linked the temperature anomalies to large mesoscale hydrodynamic patterns, such as mesoscale cyclonic eddy structures. The northerly current reversals observed on the reefs are likely linked to these mesoscale features propagating past the Sodwana region. During the anomaly periods, the current direction at TCM 2 becomes variable and switches between northward and southward throughout the anomaly period. Deoraj et al. (2022) showed through a large eddy simulation of the Sodwana Bay that high directional variability occurred around the southern extent of Two-Mile Reef during northerly current reversal events. The high directional variability was shown to be associated with the formation and migration of a separated eddy in the lee of Jesser Point. The current directional variability may increase the time the cold water stays on the reef system. By retaining the cold water for a longer period, the heat loading on the reefs that leads to coral bleaching will be broken and reduces the bleaching potential during the summer months. This study does not investigate the biological impacts of the reef cooling or time scales associated with bleaching and cooling needed to effectively reduce the heat loading. However, this investigation provides insight into the key physical fac-

Figure 10. Temperature fields at a) 30 m, b) 60 m and c) 90 m depth layers around the Sodwana shelf and canyons at the peak of the temperature anomaly in February 2004 (12/02/2004).
tors that affect these biological processes and can be used as a guide for future research. Additionally, the nutrient-rich water associated with upwelling can help to support the growth of phytoplankton, which in turn can provide food for the corals and other organisms in the ecosystem (Anderson et al., 2002; Jacobs et al., 2020).

A Delft 3D FM hydrodynamic model was set up and nested within the reanalysed global ocean NEMO model. The nested model had a similar resolution to the reanalysed NEMO model offshore of the Sodwana region but was refined around the Sodwana region to better resolve the local nearshore hydrodynamics and replicate the observed temperature anomalies at Sodwana. The nested model replicated the reanalysed NEMO hydrodynamics well at a regional scale, aided by the temperature and salinity nudging offshore of the Sodwana region. The nudging ensured that the temperature and salinity in the nested model were similar to the reanalysed NEMO temperature and salinity fields and reduced potential boundary errors within the nesting process.

The nested model was run over 2004 due to notable temperature anomalies that occurred during this year. The nested model was shown to replicate the temperature signal and anomalies measured at Sodwana over this period. Wells et al. (2023) showed that the reanalysed NEMO model also replicated the temperature anomalies to some degree and linked the anomalies to regional hydrodynamic patterns. However, the amplitude of the anomalies replicated by the NEMO model was lower than the measured anomalies. An eddy diffusivity of 2000 m²/s characterises the reanalysed NEMO model’s mixing, which smooths the temperature fields and, subsequently, the temperature anomaly peaks at Sodwana. This smoothing results in the peaks of the temperature anomalies being, on average, lower than those of the measured anomalies. The higher resolution of the nested model meant the numerical mixing within the nested model was significantly reduced in the nearshore region around Sodwana. Therefore there was less smoothing of the temperature fields within the nested model resulting in a better replication of the temperature anomaly amplitudes. The temperature smoothing due to mixing was shown by rerunning the nested model over the February anomaly period with an increased eddy diffusivity of 2000 m²/s. The nested model temperature with an increased eddy diffusivity showed smoothing of the temperature fields and lower anomaly amplitudes similar to the reanalysed NEMO model.

This shows that the global ocean models, such as the reanalysed NEMO model, over-predict mixing in the nearshore regions. Highly resolved nested hydrodynamic models are capable of better representing mixing in the ocean than low-resolution global ocean models because nested models can more accurately resolve the complex processes that drive mixing, such as turbulence, eddies, and other forms of flow (Masuda & Osafune, 2021; Holmes et al., 2021). Nested models can therefore provide a more accurate description of how water masses of different temperatures, salinities, and nutrient levels interact in the ocean (Masuda & Osafune, 2021). In particular, the higher resolution model is required to better replicate the short-term nearshore temperature fluctuations and anomalies around the shelf and reef systems.

The anomaly investigated during February 2004 is associated with remote upwelling of cold water near the Delagoa Peninsula, followed by advection from the Delagoa Bight towards the Sodwana region. The cold upwelled water advects directly to Sodwana. The spatial extent of the upwelled cold water pocket is significantly larger than the Sodwana reef system. As a result, when the pocket of cold water reached the Sodwana region, the entire Sodwana reef system was immersed in colder water. The nested model’s increased resolution surrounding the Sodwana region was used to investigate the interaction between the complex nearshore bathymetry and local hydrodynamics during an anomaly event. The nested model showed cooler water inside the canyons at depths below 30 m, which is indicative of local canyon upwelling, which spreads out over the reef system when it reaches the heads of the canyons. This shows that the local hydrodynamics do not drive the temperature anomaly during February 2004; however, it does show that the inter-
action between the local hydrodynamics and complex bathymetry and canyons can enhance the temperature anomaly amplitude at Sodwana. This study only looks at a single representative anomaly, high resolution hydrodynamic modelling of more anomalies of a larger number of anomalies would be required to statistically quantify the influence of the local canyon upwelling.

5 Conclusion

We measured the on-reef hydrodynamics during temperature anomaly events using three TCMs deployed around Two-Mile Reef on Sodwana for eight months between 25/08/2021 and 16/05/2022. The measured current direction was predominantly south-southwestward, with occasional intermittent northerly direction reversals often associated with cold water temperature anomalies. The current speeds on Two-Mile Reef were between 0.1 and 0.2 m/s with a maximum current speed of 0.35 m/s at the shallow rugosity site.

To investigate Sodwana’s cold water temperature anomalies, a Delft 3D FM hydrodynamic model was set up and nested within the reanalysed global ocean NEMO model. This study focussed on downscaling the reanalysed NEMO model hydrodynamics around Sodwana and validating the nested model by assessing the model’s ability to replicate the cold water temperature anomalies at Sodwana. The nested model was run over the year 2004 when notable temperature anomalies occurred. The nested model successfully replicated the temperature anomalies during this period, and the modelled temperature on Nine-Mile Reef compared well to the measured temperature.

The nested model replicated the amplitudes of the temperature anomalies better than the reanalysed NEMO model, which tended to underpredict the anomaly amplitudes. Two temperature anomaly amplitudes were still underpredicted in the nested model, but it is an improvement over using the reanalysed NEMO model, which underpredicts the amplitude of all the temperature anomalies near Sodwana. The nested model better replicated the temperature anomalies due to the increased model resolution around the Sodwana region. The higher grid resolution around Sodwana resulted in less mixing and smoothing of the temperature fields in the nearshore region when compared to the reanalysed NEMO model. This suggests that the mixing in regional global ocean models over-predicts the smoothing of temperature fields in the nearshore regions, and a nested hydrodynamic model is required to investigate short-term temperature fluctuations in these regions accurately.

The representative anomaly investigated in February 2004 using the nested model was associated with remote upwelling of cold water near the Delagoa Peninsula, followed by its advection towards the Sodwana region. The extent of the upwelled cold water pocket was significantly larger than the Sodwana reef system, resulting in the immersion of the entire reef system by the cold upwelled water. The nested model with increased resolution revealed that local upwelling occurs within the Sodwana canyons during the upwelling event, resulting in the water in the canyons being 1 °C colder than the surrounding water. When the locally canyon upwelled water reaches the head of the canyons, it spreads out over the reef system, enhancing the anomaly amplitude by approximately 20 % in the case of the example selected.

This study provides insight into the key physical processes linked to temperature anomalies at regional and local scales. It also presents a method of setting up a hydrodynamic model nested within a global ocean model to specifically focus on short-term temperature fluctuations around coral reefs. The methodology laid out in this research can also be adapted to investigate other coral reefs located in strong boundary currents that interact with complex coastlines. However, this study does not include the biological impacts associated with the local hydrodynamics and changes to the hydrodynam-
ics during the temperature anomaly events. It is recommended that this nested model
be used in a focused biological study to investigate how the local hydrodynamics affects
cold water and nutrient retention times on the reefs and, subsequently the effect on the
biological functioning of the reefs. The nested model was only run for a year, during which
five prominent anomalies were observed. It is recommended that the nested model is run
for a longer period to statistically quantify the influence of local canyon upwelling on the
temperature anomalies.

Open Research Section

Modelled current and temperature fields from the reanalysed NEMO global ocean
model were downloaded from the Copernicus Marine Environment Monitoring Service

The Delft3D FM modelling suite used for the nested model development is licensed
software available from https://www.deltares.nl/en/software-and-data. Access to licens-
ing for this software can be requested through software@deltares.nl.

Oceanographic Research Institute and SAAMBR are the custodians of the long-
term temperature data measured at Nine-Mile Reef used in this study. The data was made
available for this study through a direct request to the Oceanographic Research Insti-
tute and SAAMBR. They can be contacted at info@seaworld.org.za.

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References

tide in a submarine canyon. *Journal of Geophysical Research: Oceans, 122*(8),
6872–6882. doi: 10.1002/2016JC012583

Anarde, K., & Figlus, J. (2017, jul). Tilt Current Meters in the Surf Zone: Ben-
chmarking Utility in High-Frequency Oscillatory Flow. In *Coastal dynamics*
(pp. 923–932).

and eutrophication: Nutrient sources, composition, and consequences. *Estuar-

reefs can be self-seeding. *Marine Ecology Progress Series, 74* (1), 1–11. doi: 10
.3354/meps074001

Cabanes, C., Grouazel, A., Schuckmann, K., Hamon, M., Turpin, V., Coatanoan,
C., . . . Tracq, P.-Y. (2012, 03). The cora dataset: Validation and diagnostics of ocean

doi: 10.1016/S0025-326X(02)00302-8

drodynamics at Sodwana Bay, South Africa. *Environmental Fluid Mechan-


Numerical modelling of the upwelling and associated hydrodynamics at various scales along the coral reefs at Sodwana Bay, South Africa

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**Key Points:**

- Currents and temperature were measured on the Sodwana reef system using low cost Tilt Curret Meters.
- A hydrodynamic model was developed and nested within a global ocean model to investigate upwelling and cold water temperature anomalies at Sodwana.
- The nested model successfully replicated the cold water temperature anomalies observed at Sodwana.

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Abstract
This study investigates hydrodynamics and short term temperature fluctuations at high latitude coral reefs, focusing on Sodwana Bay in South Africa. A refined hydrodynamic model nested within a global ocean model was developed to investigate short term temperature anomalies. Off-reef hydrodynamics were also measured using Tilt Current Meters over eight months between 25/08/2021 and 16/05/2022 to describe the on-reef hydrodynamics at Sodwana during temperature anomaly events. During temperature anomaly events, the predominant current direction is south-southwestward, occasionally reversing to the north with cold water temperature anomalies. Current speeds range from 0.1 to 0.2 m/s, peaking at 0.35 m/s at the shallow low rugosity site. The nested model, developed using the Delft 3D Flexible Mesh hydrodynamic modelling suite, successfully replicates the observed temperature anomalies in 2004. The nested modelled better replicates the temperature anomaly amplitudes compared to the reanalysed NEMO global ocean model due to the high model resolution around Sodwana. A nested hydrodynamic model is necessary for accurate analysis of short-term temperature fluctuations. A representative anomaly in February 2004 was investigated using the nested model. The anomaly was associated with remote upwelling of cold water near the Delagoa Peninsula, followed by advection towards Sodwana. As it reaches the region, the entire Sodwana region is engulfed by the cold upwelled water. The model revealed that local upwelling occurs within the Sodwana canyons during this event, making the water in the canyons 1 °C colder than the surrounding water. When the locally upwelled water spreads over the reef system, the anomaly amplitude is enhanced by approximately 20%.

Plain Language Summary
This study investigated upwelling and cold water temperature anomalies along the Sodwana Bay coral reef system using a combination of field measurements and numerical hydrodynamic modelling. The temperature anomalies are important for the sustainability and survival of high latitude reef systems such as Sodwana as they provide potential refuge to coral bleaching events. The study found that the temperature anomalies are associated with upwelling of cold water around the Delagoa Bight region near Maputo, Mozambique, after which the cold water is transported by ocean currents southward to the Sodwana region. When the cold water interacts with the submarine canyons located offshore of Sodwana, the cold water is channelled up the canyons and onto the reefs enhancing the magnitude of the temperature anomalies.

1 Introduction
Coral reefs are complex ecosystems influenced by hydrodynamics and physical processes on various length and time scales (Monismith, 2007). Investigating and understanding coral reef systems are crucial for the maintenance and survival of the reefs, especially in light of current changes to the global climate and ocean temperatures. They are indicators of the health and state of the oceans as they respond quickly to changes in the ambient state of the ocean, be it temperature, contaminants or any other physical or biological processes (Pandolfi et al., 2003; Hughes et al., 2005; Mumby & Steneck, 2008; Hoegh-Guldberg & Bruno, 2010).

A diverse array of biological and physical processes influences the ecological functioning and sustainability of coral reefs. The specific physical processes that govern the health and functionality of reefs can vary depending on the type of reef system and its geographical location. Coral reefs typically found in tropical regions, including atolls, are particularly susceptible to their immediate environmental conditions, which include factors such as tidal water levels and local hydrodynamics (Kwee et al., 2014; Safaie et al., 2018; Maticka et al., 2022). However, prominent coral reefs in high-latitude areas exhibit a reduced sensitivity to local physical processes like tides and winds. Instead,
larger-scale processes such as regional upwelling, coastline geometries, and global ocean patterns influence the functioning of these reefs. These mesoscale processes ultimately impact the reef-scale processes and subsequently affect the overall functioning of these reef systems (Frys et al., 2020; Wells et al., 2021). Less is known about the physical processes governing these reefs because an understanding of the hydrodynamics, starting from a regional mesoscale down to the local reef scale, is required to understand the functioning of these reef systems. Research has begun investigating the effect of these larger scale processes governing high latitude reefs, such as ocean transport and upwelling associated with the Ningaloo reef in Western Australia (Xu et al., 2013, 2016). However, there is still little known regarding coral reefs situated in other high-latitude regions of the world and how the hydrodynamics at various scales influence their functioning.

Numerical hydrodynamic models are effective tools for investigating ocean processes at various time and length scales. These models have been a crucial part of investigating and understanding both the physical and biological functioning of coral reefs around the world (Black et al., 1991; Storlazzi et al., 2011; Rogers et al., 2013, 2017; Yao et al., 2022). Wells et al. (2023) recently used regional hydrodynamic and temperature data from the reanalysed NEMO global ocean model to investigate cold water temperature anomalies on the Sodwana reefs on the northeastern coast of South Africa. Previous research suggests that these temperature anomalies provide refuge to the reefs during potential bleaching events along the Sodwana coral reef system (Lutjeharms & de Ruijter, 1996; Celliers & Schleyer, 2002; Rieg & Pillar, 2003; Rautenbach et al., 2023). The temperature anomalies are characterised by a rapid temperature drop of a few degrees on the Sodwana reefs and occur over a time scale of days (Wells et al., 2021).

The coarse resolution of global ocean models, such as reanalysed NEMO global ocean model used by Wells et al. (2023), is adequate for investigating regional hydrodynamic processes offshore of coral reef systems but cannot replicate the reef scale hydrodynamics or physical processes accurately. The course resolution of these models does not resolve the complex nearshore bathymetric features around reef systems, such as the continental shelf and submarine canyons. The question arises, what effect does complex nearshore bathymetry have on the local reef scale hydrodynamics, and what is the role of mixing at spatial scales between 100 m and 1000 m? A refined hydrodynamic model with high spatial and temporal resolutions around the reef systems should better represent sub-mesoscale hydrodynamics and complex nearshore bathymetric features. The refinement also reduces local truncation errors of discrete numerical schemes (Le et al., 2014).

This paper focuses on the setup and validation of a refined hydrodynamic model one-way nested within a global ocean model. The nested model was set up using the Delft 3D Flexible Mesh hydrodynamic modelling suite and validated using measured on-reef hydrodynamics and long-term temperature data recorded on Nine-Mile Reef. This study also presents a temperature and salinity nudging technique within the nested model to ensure the regional nested model’s hydrodynamics adequately replicates the global ocean model regional hydrodynamics offshore of the Sodwana region. The nested model was then used to investigate the cold water temperature anomalies observed at Sodwana and their associated hydrodynamics.

Field data measurements are another powerful tool for investigating and describing the hydrodynamics around coral reefs. Measurements of the local on-reef hydrodynamics are required to validate numerical hydrodynamic models and provide insight into the on-reef flow and temperature. Coral reefs are often located in less economically developed third-world regions (Moberg & Folke, 1999; Spalding et al., 2001). Therefore, researchers investigating coral reefs in these regions do not always have access to traditional hydrodynamic measuring instruments, such as Acoustic Doppler Current Profilers, due to the high cost or availability of these instruments. This study presents on-reef hydrodynamic measurements from an alternative low-cost and robust instrument called a Tilt Current Meter (TCM). Multiple TCMs were designed and developed in-house and
deployed along the Sodwana reefs. The TCM measurements were used to describe the on-reef hydrodynamics at Sodwana during temperature anomaly events.

2 Method

2.1 Case Study Site

The Sodwana reef system is one of the most southerly coral reefs in the world and is located in the Delagoa Bioregion of South Africa, which begins just north of Richards Bay and extends Northwards into Mozambique (Ramsay, 1994). Figure 1 shows the location of Sodwana Bay and the surrounding GEBCO bathymetry (GEBCO Bathymetric Compilation Group, 2021). Many coral reef systems located at higher latitudes have already begun to experience the effects of warming events associated with climate change, such as coral bleaching (Riegl & Piller, 2003). Sodwana has shown resilience to these warming and bleaching events, which has been attributed to strong ocean mixing and short-term cold water temperature anomalies (Celliers & Schleyer, 2002; Riegl & Piller, 2003).

The temperature anomalies observed at Sodwana make the region an ideal case study site to investigate the driving mechanisms of these events and can potentially describe similar temperature anomaly events in other regions of strong ocean mixing and complex shelf topography. Similar prominent coral reef systems located along coastlines within boundary currents that experience upwelling events include the Ningaloo Reef, on the west coast of Australia in the path of the Leeuwin Current (Xu et al., 2013, 2016), the Florida Reef Tract, located along the coast of Florida in the Gulf Stream (Walker & Gilliam, 2013; Frys et al., 2020). These reefs are also located at similar latitudes to Sodwana in subtropical regions around the Tropic of Capricorn or Cancer.

Figure 1. GEBCO bathymetry of region surrounding Sodwana Bay. Vertical datum is mean sea level.

The region is characterised by high mesoscale eddy kinetic energy that interacts with the complex shelf topography driving complex flow fields (M. Roberts et al., 2014). Sodwana is situated near the origin of the warm Agulhas Current where the continental shelf is narrow and characterised by steep gradients and submarine canyons on the continental slope (Ramsay, 1994). The Delagoa bight is also located approximately 200 km north of the Sodwana region at the southern end of the Mozambique Channel. The Delagoa Bight is one of the largest coastline indentations along the east coast of Africa, and the local widening of the continental shelf is associated with complex regional flow structures (Lutjeharms & Da Silva, 1988; Lamont et al., 2010).
2.2 Available data

2.2.1 Long term temperature data

Hourly temperature data measured at Sodwana between 1994 and 2015 were used to compare with the numerically modelled temperature data. The temperature measurements were obtained using an individual (self-contained) Star-Oddi mini underwater temperature recorder with an accuracy of ±0.05 °C, deployed at a depth of 18 m on Nine-Mile Reef (see Figure 3). This data was made available by the Oceanographic Research Institute and SAAMBR.

2.3 Field data collection

The reef currents were measured using TCMs deployed along the Sodwana reef system. The TCMs measure current speed and direction at a fixed point approximately 0.5 m above the reef. The instrument is positively buoyant and tethered to an anchor fixed to the sea bed and tilts in the ambient current due to the drag forces exerted on the instrument (Hansen et al., 2017; Anarde & Figlus, 2017; Marchant et al., 2014; Kjeldorff et al., 2020). Figure 2 shows a TCM deployed on Two-Mile Reef (see Figure 3) at Sodwana.

Figure 2. TCM tilting on Two-Mile Reef.

The relationship between the TCM’s tilt and current speed was measured and calibrated in a flume for steady and oscillatory currents similar to those on the Sodwana reefs. This relationship was used to convert the angle and direction of tilt recorded by the TCMs to current speed and direction. The TCMs sample and record the tilt at a 1 Hz frequency for five minutes every hour. The tilt was frequency filtered to remove the wave-induced oscillatory currents and inherent instrument noise from the tilt signal. The frequency-filtered 1 Hz current speed and direction measured by the TCMs were time-averaged over the five-minute sampling intervals to give the five-minute mean currents measured on the reefs.

The TCM does not resolve 3-dimensional flow. It resolves the horizontal flow in the x and y plane, which is averaged over the surface area of the instrument. Due to the sampling frequency, the instrument does not capture small-scale turbulent flows with time scales shorter than one second. Additionally, the instrument cannot resolve vertical length scales less than 50 cm due to the housing size.
A total of ten TCMs were deployed over the Sodwana reef system between 25/08/2021 and 16/05/2022, with varying deployment lengths. Eight TCMs were located around Two-Mile Reef. A TCM was also located on Five-Mile Reef and on Seven-Mile Reef (see Figure 3). This study presents the data from three TCMs deployed on Two-Mile Reef. The three chosen TCMs had the most temporal data coverage over the eight months of deployment between 25/08/2021 and 16/05/2022. They were also the most representative locations for different conditions found along the reef system. TCM 1 was located in the middle of Two-Mile Reef with high rugosity at a depth of 15 m. TCM 2 was deployed at the southern extent of Two-Mile Reef with low rugosity at a depth of 18 m. TCM 3 was deployed at the offshore extent of Two-Mile Reef on the outer reef shelf at a depth of 30 m. Figure 3 shows the locations of the TCMs deployed along the Sodwana reefs with an enhanced view of Two-Mile Reef. The instruments were retrieved every three months for data collection, marine defouling and battery replacement.

Figure 3. Locality map of the study area showing the locations of major reefs and locations at Sodwana Bay and a detailed map showing the locations of the TCMs around Two-Mile Reef. TCM locations are shown with triangles. Solid-filled triangles denote the TCMs used in this study and the dashed hollow triangles denote the additional TCMs deployed but not presented in this study.

### 2.3.1 Numerically modelled ocean reanalysis data

Modelled daily mean current velocities, temperature and salinity were used as boundary-forcing conditions for the nested hydrodynamic model. This data comes from the GLORYS12V1 product provided by Copernicus Marine Service (CMEMS). The model component of GLORYS12V1 is from the ocean NEMO model version 3.1. The model has a horizontal resolution of 1/12° and 50 vertical levels. The GLORYS12V1 product covers 27 years between 1993 and 2020 on a daily time step (Jean-Michel et al., 2021). ECMWF ERA-Interim, and ERA5 reanalyses data at the surface force the NEMO model. This model does not include tidal forcing. Along track altimetry data and in situ vertical temperature and salinity profiles from the sea mammals database (Roquet et al., 2011) and moorings from TAO/ARAMA/PIRATA programs (Cabanes et al., 2012) are assimilated using a reduced-order Kalman filter (Jean-Michel et al., 2021; Lellouche et al., 2021). Modelled daily mean Sea Surface Height (SSH) from the GLORYS12V1 product was also used.
as boundary forcing conditions for the nested hydrodynamic model. The NEMO model includes a horizontal diffusive length of 200 km and a horizontal diffusive velocity of 0.01 m/s (Madec & the NEMO Team, 2016). This equates to a horizontal eddy diffusivity of $2000 \text{ m}^2/\text{s}$ used to account for the sub-grid scale unresolved physics in the NEMO model.

### 2.3.2 Tide data

Tidal constituents from the global ocean tide model DTU10 were used as boundary-forcing conditions for the nested hydrodynamic model. The DTU10 model provides the following 10 constituents: Semidiurnal: M2, S2, K2, N2 - Diurnal: S1, K1, O1, P1, Q1 - Shallow water: M4 at a horizontal resolution of 0.125°. (Lyard et al., 2020).

### 2.3.3 Wind data

The nested hydrodynamic model used modelled wind data as a surface boundary forcing condition. This data comes from the Climate Forecast System Reanalyses (CFSR) product provided by the National Centers for Environmental Prediction (NCEP). The product provides time and space varying wind speed and direction 10 m above the ocean and land surface. The CFSR wind data is available over 31 years between 1979 and 2009 on an hourly time step with a spatial resolution of 0.5° (Saha et al., 2010).

### 2.4 Hydrodynamic numerical modelling

A three-dimensional (3D) hydrodynamic numerical model was set up and nested within the global reanalysed NEMO model. The nested model has varying degrees of spatial resolution, starting around the resolution of the reanalysed NEMO model at the offshore boundaries and increasing in resolution towards the Sodwana region. The nested model was used to downscale the regional hydrodynamics and investigate the temperature anomalies around the Sodwana reefs at a local sub-mesoscale. This section describes the setup of the nested hydrodynamic model.

#### 2.4.1 Model description

The Delft 3D Flexible Mesh (FM) hydrodynamic model simulates 3D unsteady flow and scalar transport and was used to set up the refined nested model. The numerical hydrodynamic modelling system D-Flow FM solves the unsteady shallow water equations in three dimensions and consists of the horizontal equations of motion and the continuity equation (Kernkamp et al., 2022). Delft 3D FM solves the unsteady Navier Stokes equations for an incompressible fluid under shallow water and the Boussinesq assumptions. The partial differential equations, in combination with an appropriate set of initial and boundary conditions, are solved on an unstructured finite volume grid (Kernkamp et al., 2022). The model includes tidal forcing, Coriolis forcing, space-varying wind shear stresses, bottom friction shear stresses and a turbulence model to account for the vertical turbulent viscosity and diffusivity.

Wells et al. (2021) suggested that non-hydrostatic processes, such as breaking of internal waves along the shelf slope, could be a potential driving mechanism of the temperature anomalies at Sodwana. Breaking of internal waves occurs when the slope of the internal wave beam is equal to the topographic slope of the shelf (Lamb, 2014; Alberty et al., 2017; Wang et al., 2019). The length of an internal wave is dependent on the vertical density gradient and Brünt-Väisälä frequency (Lamb, 2014). An analysis of the shelf slope near Sodwana and the potential slope of internal waves in the region based on the vertical density profiles shows that the region is not conducive to internal wave breaking. Therefore, since the model was not used to investigate non-hydrostatic processes, such as internal wave breaking, a hydrostatic model was deemed appropriate. Under the
shallow water assumption, the vertical momentum equation is reduced to a hydrostatic pressure equation (Kernkamp et al., 2022).

2.4.2 Grid and bathymetry

A combination of surveyed data (Ramsay, 1994) and GEBCO bathymetry data (GEBCO Bathymetric Compilation Group, 2021) was used to generate the bathymetry used in the nested model. The survey provides bathymetry data around the nearshore region along the reefs and shelf around Sodwana. The GEBCO data provides the regional bathymetry offshore of the Sodwana region at a 0.004° resolution. Mean Sea Level (MSL) was used as the vertical datum for the model.

The spatial extent of the model was selected to be large enough to allow for regional hydrodynamic features to develop. These regional flows include mesoscale eddy structures and western boundary currents along the East African coastline. The model domain extends approximately 1000 km offshore of Sodwana, coinciding with the 44°E line of longitude. The northern boundary is located approximately 1400 km north of Sodwana, coinciding with the 16°S line of latitude. The southern boundary is located approximately 1700 km from Sodwana, coinciding with the 43°S line of latitude. The horizontal mesh resolution varies from approximately 10 000 m at the offshore boundaries to 100 m around the shelf canyons and reef system. Figure 4 presents the nested model grid and bathymetry showing the increasing mesh resolution around the Sodwana region.

Figure 4. Nested hydrodynamic model bathymetry and mesh.

2.4.3 Boundary forcing conditions

The modelled tidal constituents from the DTU10 global tide model were applied as space and time-varying water level conditions along the lateral boundaries. Modelled Sea Surface Heights from the reanalysed NEMO model was applied as time and space-varying water levels along the lateral offshore boundaries. Current velocities, temperature and salinity from the reanalysed NEMO model were applied as space, time and depth-varying conditions along the offshore lateral boundaries.

A nudging technique was used on the temperature and salinity in the deep offshore region of the nested model. Nudging is a technique used to help ensure that the modelled temperature and salinity in the nested model replicate specified boundary conditions or observations (Paniconi et al., 2003). The nudging includes an extra term in the nested model’s scalar tracer equations (temperature and salinity) that pulls the nested model temperature and salinity towards the specified temperature conditions. The nudging of the scalar tracers can be described by:
\[ \frac{DS}{Dt} = \frac{S_{nudge} - S}{T_{nudge}} \]  

where \( S \) is the scalar tracer quantity in the nested model, \( S_{nudge} \) is the scalar quantity from the reanalysed NEMO model that the nested model is being nudged towards, and \( T_{nudge} \) is the nudging time scale.

The nested model was nudged using the reanalysed NEMO modelled temperature and salinity fields at a nudging time scale of a day. The nested model was nudged offshore of the Sodwana region to ensure the nested model regional temperature, salinity, and flow patterns replicate the reanalysed NEMO model. Nudging was excluded within a 0.5° radius around Sodwana. Therefore, the nudging terms will not influence the local hydrodynamics and complex flow interaction with the shelf and canyons within the nested model.

2.4.4 Mixing and turbulence

Vertical turbulent mixing is computed by a \( k-\epsilon \) closure model. The horizontal turbulent mixing is represented by a constant eddy viscosity and eddy diffusivity values of 1 \( m^2/s \). Therefore, the diffusion and mixing in the offshore regions will be governed by the grid’s numerical diffusion and resolution, which will be larger than the specified eddy diffusivity. In the highly resolved nearshore regions, the mixing will still be dominated by the numerical resolution, however, to a much smaller extent than in the reanalysed NEMO model. This will provide a more accurate representation of the mixing in the nearshore regions even though the nested model mixing is still numerically dominated.

2.4.5 Simulation period and timestep

The nested model was run over the year 2004 using the reanalysed NEMO model and CFSR wind data as boundary conditions. This year was chosen due to identifiable temperature anomalies observed during this year and the availability of measured temperature data on Nine-Mile Reef during this period (Roberts et al., 2006; Wells et al., 2021). Due to computational time limitations, the model was not run for longer than a year, even though 21 years of measured temperature data is available. The nested model was spun up for a month before 2004 to ensure the model’s boundary conditions and flow fields were fully developed before the modelled year began. The nested model had an automated internal time step that adjusted based on the cell size and hydrodynamic conditions to satisfy a CFL number of 0.7.

3 Results

3.1 Measured reef currents and temperature

The three TCMs deployed around Two-Mile Reef recorded current speed and direction over an eight-month period between 25/08/2021 and 16/05/2022. Figure 5 shows rose plots of the five-minute mean currents recorded by the TCMs.

At TCM 1 and 2, the predominant current direction is south-southwestwards. The current flows in the predominant direction for 53% of the time at TCM 1 and 60% at TCM 2. Both TCMs were located on Two-Mile Reef. TCM 1 was located in an area of high rugosity, and TCM 2 was in an area of low rugosity. There is a higher variability in the current direction at TCM 1 compared to TCM 2. This is likely due to the higher reef rugosity at TCM 1 enhancing reef scale turbulence. The current speeds at TCM 1 were also lower than at TCM 2. This is also likely due to the higher reef rugosity enhancing the bottom friction around TCM 1. The maximum current speed observed at TCM 1 was 0.20 m/s and 0.35 m/s at TCM 2.
TCM 3 was located along the offshore slope of Two-Mile Reef at a deeper depth of 30 m in an area of low rugosity. The predominant current direction was west-southwest at TCM 3. The current direction aligns with the contours of the offshore reef slope. The current speeds measured at TCM 3 were smaller than at the other TCMs, with a maximum current speed of 0.18 m/s.

Northerly current directions, often referred to as northerly current reversals, were also observed at all three TCM locations. These reversals occurred between 10% and 20% of the deployment period. Each reversal lasts, on average, for a few days before switching back to the predominant southerly or southwesterly direction.

Figure 6 presents the temperature time series and current velocity stick vectors measured by TCM 2. The measurements from TCM 2 were presented because the depth and low rugosity are representative of the entire Sodwana reef system.

The deployment began towards the end of winter, and the average temperatures on the reef were around 22 °C. The average temperature increased to approximately 24 °C by the beginning of summer in December. The average temperature increased as summer progressed, rising above 26 °C over January and February. Short-term fluctuations in temperature were observed during December 2021 and March 2022. These temperature fluctuations were of a similar magnitude and time scale as the temperature anomalies defined in Wells et al. (2021).

The current stick vector time series shows that the predominant flow direction is south-southwestward over the deployment period, with typical current speeds between 0.1 and 0.2 m/s. It also shows that the short-term drops in temperature are associated with northerly current reversals and variations from the predominant current direction. Figure 6 presents the measured temperature time series and current velocity stick vectors over the short-term temperature fluctuations during December 2021.

Two temperature anomalies occurred in quick succession during December 2021. The first anomaly peaked on 23/12/2021, and the second peaked on 28/12/2021. Both
anomalies lasted for approximately five days each. A current reversal occurred four days before the first anomaly when the current direction changed from southward to northward. The northerly current reversal then changed back to a southward direction at the start of the first anomaly. The current direction fluctuated between northerly and southerly directions for the duration of both anomalies. After the temperature anomalies, the current direction returned to a predominant southerly direction. This shows that the short-term temperature fluctuations over this period are associated with northerly current reversals or changes in the current direction from the predominant southward direction. Similar northerly current reversals were observed during the short-term temperature fluctuations observed during March 2002 and at the other two TCM locations.
3.2 Nested model validation: Nesting process

The first step in validating the nested model is to check whether the regional modelled flow fields agree with the reanalysed NEMO-modelled flow fields, especially during the anomaly periods. The nested model performed well in replicating the regional hydrodynamic features modelled by the reanalysed NEMO model. Figure 7 presents an example comparison of the regional near-surface flow fields from the reanalysed NEMO and the nested model during the February 2004 temperature anomaly.

![Figure 7: Spatial surface current fields from the reanalysed NEMO model (left) and the nested model (right) on 14/02/2004 at the peak of the anomaly.](image)

The regional structure of the NEMO and nested model current fields are similar and compare well at the peak of the anomaly. It is evident from Figure 7 that the current speed of the strong southward jet that detaches from the Delagoa Peninsula is stronger and more focused in the nested model. This is likely due to the nested model’s increased resolution around the Delagoa Bight and Peninsula. The model resolution around the Delagoa Bight in the nested model is approximately double the resolution of the reanalysed NEMO model.

3.3 Nested model validation: Reef temperature

The nested model temperature at Nine-Mile Reef was compared to the measured temperature to investigate how well the nested model replicates the temperature on Nine-Mile Reef, including the temperature anomalies during 2004. Wells et al. (2023) showed that the reanalysed NEMO model replicated the temperature anomalies near Sodwana on a regional scale. However, the temperature anomalies had lower amplitudes than the measured anomaly amplitudes. This section investigates if a higher resolution hydrodynamic model better replicates the temperature anomalies on the reefs.

![Figure 8: Time series comparison of the measured and nested model temperature at Nine-Mile Reef during 2004.](image)
ing 2004. The nested model replicated the peak amplitudes of the temperature anomalies in February and the beginning of December well. The nested model also replicates the temperature anomalies during April and the end of December; however, the amplitudes of these anomalies are underpredicted, but less so than in the reanalysed NEMO model.

The modelled currents on Nine-Mile Reef show similar characteristics to the TCM-measured currents. The predominant current direction during the year is south-southwestwards. Throughout the year, occasional northerly current reversals occur. These reversals occur for 15% of the year. All temperature anomalies observed during 2004 are associated with northerly current reversals around the time of the anomaly. This does not necessarily imply that current reversals are driving the temperature anomalies. However, it shows a link between the occurrence of northerly current reversals on the reef and the temperature anomalies. Figure 8 presents a time series comparison of the measured and modelled temperature over February 2004 when the most significant temperature anomalies occurred. This comparison includes the reanalysed NEMO model temperature extracted at 20 m near Sodwana and the modelled temperature from the nested model with an increased horizontal diffusivity of 2000 m$^2$/s, which is comparable to the eddy diffusivity used in the reanalysed NEMO model. This gives an indication of how the eddy diffusivity used in the reanalysed NEMO model affects the temperature anomaly amplitudes even when the nested model resolves the complex nearshore bathymetry.

The nested model replicates both anomalies well during February 2004. However, the measured temperature shows a larger temperature fluctuation associated with the tidal signal. The Pearson’s correlation coefficient between the nested model and measured temperature over this period was 0.84. The reanalysed NEMO model replicates the temperature anomalies; however, the amplitude of both anomalies is lower than the measured anomaly amplitudes. The correlation coefficient between the reanalysed NEMO model and the measured temperature over this period was 0.76. The nested model re-run with an eddy diffusivity of 2000 m$^2$/s shows a reduction of the temperature anomaly amplitudes. The nested model temperature with increased eddy diffusivity closely follows the reanalysed NEMO model temperature over the anomaly period. The temperature correlation coefficient between the nested model with increased eddy diffusivity and the measured temperature was 0.74 and the reanalysed NEMO temperature was 0.85. This indicates that the reason for the lower amplitudes of the anomalies modelled by the reanalysed NEMO model is a result of an overestimation of the mixing in the reanalysed NEMO model in the nearshore regions. The increased mixing in the nested model smooths out the temperature fields resulting in lower anomaly amplitudes. The increased resolution of the nested model reduces the numerical mixing in the nearshore regions resulting in less smoothing of the temperature fields near Sodwana with more accurate anomaly amplitudes.

### 3.4 Cold water temperature anomaly hydrodynamics

The Delft 3D model was set up to investigate the nearshore hydrodynamics during a cold water temperature anomaly event. Wells et al. (2023, under review) used the reanalysed NEMO temperature and flow fields to identify the predominant regional flow patterns associated with the anomalies. They linked the temperature anomalies to regional upwelling and advection of cold water to the Sodwana region. Wells et al. (2023, under review) found that most anomalies were associated with remote upwelling of cold water near the Delagoa Peninsula, followed by advection from the Delagoa Bight towards the Sodwana region. The remote upwelling occurs at a regional scale which the reanalysed NEMO model replicates. The course resolution of the reanalysed NEMO model does not replicate what happens at a local scale when the cold water interacts with the local complex bathymetry, such as the shelf and canyons. The nested model allows for an
Figure 8. a) Comparison of the measured and modelled temperature at Nine-Mile Reef at a depth of 20 m during 2004. The grey line represents the measured temperature and the black line represents the nested model temperature. b) Stick vector time series of modelled currents on Nine-Mile Reef. c) Comparison of the measured and modelled temperature at Nine-Mile Reef near the seabed over the February 2004 anomaly period. The solid grey line represents the measured temperature, the dashed grey line represents the reanalysed NEMO model temperature, the solid black line represents the nested model temperature and the dashed black line represents the nested model temperature with a diffusivity of 2000 $m^2/s$.

investigation into the local hydrodynamics when the advected pocket of cold upwelled water interacts with the Sodwana region.

Wells et al. (2023, under review) showed that the temperature anomaly in February 2004 is associated with remote upwelling of a pocket of cold water near the Delagoa Peninsula. The upwelling is linked to the intermittent separation of a strong southward stream from the Delagoa Peninsula. Figure 9 presents a six-day time evolution of the nested model temperature and flow fields at a depth of 30 m, from 06/02/2004 to 12/02/2004. The time evolution shows the interaction between the complex bathymetry and the pocket of cold upwelled water as it advects towards Sodwana.

The anomaly during February 2004 is a typical anomaly associated with upwelling around the Delagoa Peninsula and advection towards Sodwana (Wells et al. 2023, under review). The spatial extent of the upwelled cold water pocket is significantly larger than the Sodwana reef system. Therefore, when the pocket of cold upwelled water reaches the Sodwana region, it engulfs the reefs, resulting in a cold water temperature anomaly.
Figure 9. Time evolution of the regional temperature fields (top) and a zoomed-in view of the temperature fields around Sodwana (bottom) at a depth of 30 m leading up to the peak of the temperature anomaly on 14/02/2004. This is a typical example anomaly associated with remote upwelling near the Delagio Peninsula followed by advection to the Sodwana region along the Delagoa shelf. The current velocity vectors have been overlaid as a quiver plot and scaled by speed. The location of Sodwana has been denoted by a pink dot on the coastline.

This shows that the temperature anomalies are linked to large mesoscale flow patterns; however, the interaction between the hydrodynamics and complex bathymetry around Sodwana, such as the canyons, may still affect the magnitude of the anomalies. The nested model allows for a detailed description of the hydrodynamics and temperature around the complex bathymetry and canyons near Sodwana to investigate the effect of the local hydrodynamics on the temperature anomalies. Figure 10 presents the temperature inside and around the canyons and shelf at various depths at the peak of the temperature anomaly in February 2004.

The temperature fields at the 60 m and 90 m depth layers show colder water inside both Wright Canyon and White Sands Canyon along the Sodwana shelf (see Figure 3), indicative of local upwelling in the canyons. The temperature is approximately 1 °C colder inside the canyons than offshore of the canyons. The cold water associated with the local canyon upwelling is spread over the reefs between the canyon heads as it upwells out of the canyons at the 30 m depth layer. The cold water associated with the local canyon upwelling at the 30 m depth layer is also approximately 1 °C colder than the surrounding water. A 6 °C drop in temperature was recorded at Nine-Mile Reef during the February 2004 anomaly (see Figure 8). Therefore the local canyon upwelling enhances the temperature anomaly amplitude by 20 % during the February 2004 temperature anomaly.
Figure 10. Temperature fields at a) 30 m, b) 60 m and c) 90 m depth layers around the Sodwana shelf and canyons at the peak of the temperature anomaly in February 2004 (12/02/2004).

4 Discussion

Hydrodynamic data from the two TCMs deployed in the shallower region around Two-Mile Reef showed that the predominant current direction along the reef is south-southwestwards, with occasional current reversals to a northward direction. This agrees with previously ADCP measurements taken offshore of Nine-Mile Reef at Sodwana Bay during March 2001 (Roberts et al., 2006; Morris, 2009) and TCM measurements from a previous deployment by Deoraj et al. (2022). TCM 1, located in an area of high rugosity on Two-Mile Reef, had on average lower current speeds and a higher directional spread around the predominant southward direction when compared to TCM 2, which was located in an area of low rugosity. TCM 3 on the deeper offshore slope of Two-Mile Reef measured lower current speeds than at the shallower sites. The predominant southwesterly current direction at TCM 3 lined up more parallel with the slope contours.

Cold water temperature anomalies were observed in the TCM temperature measurements during December 2021 and March 2022. The temperature anomalies were associated with current direction variations from the predominant southward current direction during the anomaly periods on Two-Mile Reef. For some anomalies, northward current reversals occurred slightly before or after the actual drop in temperature measured on the reef. This suggests that the northerly current reversals are not driving the temperature anomalies but are associated with the anomalies. Roberts et al. (2006) and Wells et al. (2021) linked the temperature anomalies to large mesoscale hydrodynamic patterns, such as mesoscale cyclonic eddy structures. The northerly current reversals observed on the reefs are likely linked to these mesoscale features propagating past the Sodwana region. During the anomaly periods, the current direction at TCM 2 becomes variable and switches between northward and southward throughout the anomaly period. Deoraj et al. (2022) showed through a large eddy simulation of the Sodwana Bay that high directional variability occurred around the southern extent of Two-Mile Reef during northerly current reversal events. The high directional variability was shown to be associated with the formation and migration of a separated eddy in the lee of Jesser Point. The current directional variability may increase the time the cold water stays on the reef system. By retaining the cold water for a longer period, the heat loading on the reefs that leads to coral bleaching will be broken and reduces the bleaching potential during the summer months. This study does not investigate the biological impacts of the reef cooling or time scales associated with bleaching and cooling needed to effectively reduce the heat loading. However, this investigation provides insight into the key physical fac-
tors that affect these biological processes and can be used as a guide for future research. Additionally, the nutrient-rich water associated with upwelling can help to support the growth of phytoplankton, which in turn can provide food for the corals and other organisms in the ecosystem (Anderson et al., 2002; Jacobs et al., 2020).

A Delft 3D FM hydrodynamic model was set up and nested within the reanalysed global ocean NEMO model. The nested model had a similar resolution to the reanalysed NEMO model offshore of the Sodwana region but was refined around the Sodwana region to better resolve the local nearshore hydrodynamics and replicate the observed temperature anomalies at Sodwana. The nested model replicated the reanalysed NEMO hydrodynamics well at a regional scale, aided by the temperature and salinity nudging offshore of the Sodwana region. The nudging ensured that the temperature and salinity in the nested model were similar to the reanalysed NEMO temperature and salinity fields and reduced potential boundary errors within the nesting process.

The nested model was run over 2004 due to notable temperature anomalies that occurred during this year. The nested model was shown to replicate the temperature signal and anomalies measured at Sodwana over this period. Wells et al. (2023) showed that the reanalysed NEMO model also replicated the temperature anomalies to some degree and linked the anomalies to regional hydrodynamic patterns. However, the amplitude of the anomalies replicated by the NEMO model was lower than the measured anomalies. An eddy diffusivity of 2000 m²/s characterises the reanalysed NEMO model’s mixing, which smooths the temperature fields and, subsequently, the temperature anomaly peaks at Sodwana. This smoothing results in the peaks of the temperature anomalies being, on average, lower than those of the measured anomalies. The higher resolution of the nested model meant the numerical mixing within the nested model was significantly reduced in the nearshore region around Sodwana. Therefore there was less smoothing of the temperature fields within the nested model resulting in a better replication of the temperature anomaly amplitudes. The temperature smoothing due to mixing was shown by rerunning the nested model over the February anomaly period with an increased eddy diffusivity of 2000 m²/s. The nested model temperature with an increased eddy diffusivity showed smoothing of the temperature fields and lower anomaly amplitudes similar to the reanalysed NEMO model.

This shows that the global ocean models, such as the reanalysed NEMO model, over-predict mixing in the nearshore regions. Highly resolved nested hydrodynamic models are capable of better representing mixing in the ocean than low-resolution global ocean models because nested models can more accurately resolve the complex processes that drive mixing, such as turbulence, eddies, and other forms of flow (Masuda & Osafune, 2021; Holmes et al., 2021). Nested models can therefore provide a more accurate description of how water masses of different temperatures, salinities, and nutrient levels interact in the ocean (Masuda & Osafune, 2021). In particular, the higher resolution model is required to better replicate the short-term nearshore temperature fluctuations and anomalies around the shelf and reef systems.

The anomaly investigated during February 2004 is associated with remote upwelling of cold water near the Delagoa Peninsula, followed by advection from the Delagoa Bight towards the Sodwana region. The cold upwelled water advects directly to Sodwana. The spatial extent of the upwelled cold water pocket is significantly larger than the Sodwana reef system. As a result, when the pocket of cold water reached the Sodwana region, the entire Sodwana reef system was immersed in colder water. The nested model’s increased resolution surrounding the Sodwana region was used to investigate the interaction between the complex nearshore bathymetry and local hydrodynamics during an anomaly event. The nested model showed cooler water inside the canyons at depths below 30 m, which is indicative of local canyon upwelling, which spreads out over the reef system when it reaches the heads of the canyons. This shows that the local hydrodynamics do not drive the temperature anomaly during February 2004; however, it does show that the inter-
action between the local hydrodynamics and complex bathymetry and canyons can enhance the temperature anomaly amplitude at Sodwana. This study only looks at a single representative anomaly, high resolution hydrodynamic modelling of more anomalies of a larger number of anomalies would be required to statistically quantify the influence of the local canyon upwelling.

5 Conclusion

We measured the on-reef hydrodynamics during temperature anomaly events using three TCMs deployed around Two-Mile Reef on Sodwana for eight months between 25/08/2021 and 16/05/2022. The measured current direction was predominantly south-southwestward, with occasional intermittent northerly direction reversals often associated with cold water temperature anomalies. The current speeds on Two-Mile Reef were between 0.1 and 0.2 m/s with a maximum current speed of 0.35 m/s at the shallow rugosity site.

To investigate Sodwana’s cold water temperature anomalies, a Delft 3D FM hydrodynamic model was set up and nested within the reanalysed global ocean NEMO model. This study focussed on downscaling the reanalysed NEMO model hydrodynamics around Sodwana and validating the nested model by assessing the model’s ability to replicate the cold water temperature anomalies at Sodwana. The nested model was run over the year 2004 when notable temperature anomalies occurred. The nested model successfully replicated the temperature anomalies during this period, and the modelled temperature on Nine-Mile Reef compared well to the measured temperature.

The nested model replicated the amplitudes of the temperature anomalies better than the reanalysed NEMO model, which tended to underpredict the anomaly amplitudes. Two temperature anomaly amplitudes were still underpredicted in the nested model, but it is an improvement over using the reanalysed NEMO model, which underpredicts the amplitude of all the temperature anomalies near Sodwana. The nested model better replicated the temperature anomalies due to the increased model resolution around the Sodwana region. The higher grid resolution around Sodwana resulted in less mixing and smoothing of the temperature fields in the nearshore region when compared to the reanalysed NEMO model. This suggests that the mixing in regional global ocean models over-predicts the smoothing of temperature fields in the nearshore regions, and a nested hydrodynamic model is required to investigate short-term temperature fluctuations in these regions accurately.

The representative anomaly investigated in February 2004 using the nested model was associated with remote upwelling of cold water near the Delagoa Peninsula, followed by its advection towards the Sodwana region. The extent of the upwelled cold water pocket was significantly larger than the Sodwana reef system, resulting in the immersion of the entire reef system by the cold upwelled water. The nested model with increased resolution revealed that local upwelling occurs within the Sodwana canyons during the upwelling event, resulting in the water in the canyons being 1°C colder than the surrounding water. When the locally canyon upwelled water reaches the head of the canyons, it spreads out over the reef system, enhancing the anomaly amplitude by approximately 20% in the case of the example selected.

This study provides insight into the key physical processes linked to temperature anomalies at regional and local scales. It also presents a method of setting up a hydrodynamic model nested within a global ocean model to specifically focus on short-term temperature fluctuations around coral reefs. The methodology laid out in this research can also be adapted to investigate other coral reefs located in strong boundary currents that interact with complex coastlines. However, this study does not include the biological impacts associated with the local hydrodynamics and changes to the hydrodynamic-
ics during the temperature anomaly events. It is recommended that this nested model be used in a focused biological study to investigate how the local hydrodynamics affects cold water and nutrient retention times on the reefs and, subsequently the effect on the biological functioning of the reefs. The nested model was only run for a year, during which five prominent anomalies were observed. It is recommended that the nested model is run for a longer period to statistically quantify the influence of local canyon upwelling on the temperature anomalies.

Open Research Section

Modelled current and temperature fields from the reanalysed NEMO global ocean model were downloaded from the Copernicus Marine Environment Monitoring Service data access portal (https://data.marine.copernicus.eu/product).

The Delft3D FM modelling suite used for the nested model development is licensed software available from https://www.deltares.nl/en/software-and-data. Access to licensing for this software can be requested through software@deltares.nl.

Oceanographic Research Institute and SAAMBR are the custodians of the long-term temperature data measured at Nine-Mile Reef used in this study. The data was made available for this study through a direct request to the Oceanographic Research Institute and SAAMBR. They can be contacted at info@seaworld.org.za.

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References


