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Partnering with the commercial fishing sector and Aotearoa New Zealand's ocean community to develop a nationwide subsurface temperature monitoring program

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ABSTRACT

Coastal regions of the world's oceans are critical to supporting the fishing sector, recreation, tourism, and the global blue economy. However, there is a paucity of subsurface, *in situ* ocean measurements in coastal and shelf regions worldwide that corresponds to the region where a majority of commercial fishing occurs. In Aotearoa New Zealand, the Moana Project and technology partner ZebraTech, Ltd. have co-designed a fully automatic system that measures, transmits, processes, and disseminates temperature observations in near real-time with a goal of providing broad-scale coverage of New Zealand's coastal and shelf seas. In the first two years, more than 300 sensors were deployed by over 250 vessels with the cooperation and support of the commercial fishing sector, providing more than one million temperature measurements per month throughout New Zealand's exclusive economic zone. Participation by the fishing sector is critical to program success with continuous improvement based on fishing sector feedback. Here we introduce the fishing-vessel-based temperature and pressure data collection on a national scale and present initial results showcasing a step change in research quality ocean temperature data collection. Next, we highlight the full-circle data pathway including improved ocean forecasts and near real-time return of the data to the vessels that obtained them. Finally, a discussion of key partnerships, use cases, and lessons learned in Aotearoa New Zealand provides a potential framework for deploying similar systems in data-poor regions worldwide with the support of the commercial fishing fleet and citizen scientists.

1. Introduction

In Aotearoa New Zealand and globally, coastal and shelf seas are critical for fisheries, aquaculture, tourism, recreation, and guardians of the natural environment, or *kaitiaki* (Wheaton et al., 2021). Such regions are often highly variable, yet a paucity of *in situ* observations limits understanding of their dynamics (O'Callaghan et al., 2019). Near real-time subsurface ocean observations are vital for understanding ocean processes and changes on global, regional, and local scales. Examples include monitoring ocean health and well-being (e.g., Liu et al., 2014; Lavin et al., 2022), fishing and aquaculture operations and management (Fisheries New Zealand, 2021), understanding and predicting extreme marine events such as marine heatwaves (e.g., Kerry et al., 2022; Stevens et al., 2022; McAdam et al., 2023; Schaeffer et al., 2023), the impact of marine heatwaves on commercial fishing catch and pelagic marine ecosystem health (Scannell et al., 2020; Amaya et al., 2023; Fragkopoulou et al., 2023), and informing data-driven sustainable fishing (Fisheries New Zealand, 2021; OPMCSA, 2021).

Real-time ocean observations help inform atmospheric weather and climate forecasts. Accurate representation of the upper ocean heat content can support improved numerical weather prediction (Sanabia

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et al., 2013; Varlas et al., 2019) and seasonal forecasting (McAdam et al., 2023). This is particularly important for extreme events such as tropical cyclones (e.g., Domingues et al., 2021), which can rapidly intensify when traveling over anomalously warm coastal waters (Dzwonkowski et al., 2020). Operational oceanography relies on the integration of *in situ* and remote sensing observation networks to deliver accurate forecasts and alert systems (e.g., Fujii et al., 2019). In addition, correctly simulating the top of the thermocline, one of the most difficult regions to predict, improves data assimilating ocean forecasts (Santana et al., 2023).

Traditionally, large-scale subsurface ocean observing initiatives have relied on instruments deployed either from research vessels or via autonomous platforms like floats, moorings, or drifters to capture measurements of the physical ocean state. Global observing programs such as Argo Wong et al. (2020) and the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP; Sloyan et al., 2019) aim to improve the availability of near real-time subsurface ocean observations. While these programs provide global spatial and temporal coverage of *in situ* ocean temperature and salinity (Davis et al., 2019), gaps persist in the subsurface observation of coastal and shelf regions worldwide (Vranken et al., 2020). Fishing activity, a critical component of the global Blue Economy (Rout et al., 2019; United Nations Department of Economic and Social Affairs, 2014), is concentrated in those same coastal and shelf regions (Vranken et al., 2020).

A similar pattern emerges in Aotearoa New Zealand's oceans: few near real-time, subsurface observations of physical ocean parameters are available in waters shallower than 1000 m, where fishing and other economic activities are most prevalent (Fig. 1). Currently, observational data are sparse and there is no coordinated national ocean observing program (O'Callaghan et al., 2019). In 2021, New Zealand's Ministry for Primary Industry identified that the "major gap" in knowledge of subsurface temperature at fishing depths is an emerging issue (Fisheries New Zealand, 2021). The fishing sector is a significant contributor to the national economy (Dixon and McIndoe, 2022) with more than 1500 commercial fishing vessels registered in 2021. These vessels fish throughout New Zealand's coastal waters and beyond at a range of depths depending on the target species. More than 40% of Aotearoa New Zealand's fisheries quota is held by Māori, who have had fisheries and aquaculture quota returned as part of Treaty of Waitangi settlements (Inns, 2013; Castle, 2015; Fisheries Industry Transformation Plan Leadership Group, 2023) and are the *kaitiaki* of the nation's Exclusive Economic Zone (EEZ). Subsurface ocean temperature is a key parameter for dynamic and ecosystem-based management strategies and for understanding fish stock health and distribution, including for species such as hoki, snapper, and others both in Aotearoa New Zealand and globally (Fisheries New Zealand, 2021). As Aotearoa New Zealand prioritizes sustainable, data-driven fishing, closing these data knowledge gaps is vital to understanding the subsurface ocean in these regions, informing fishing and broader ocean management decisions, and supporting sustainable fishing practices (The Aotearoa Circle, 2021; OPMCSA, 2021; Fisheries New Zealand, 2021).

Fishing gear-based observing systems can provide high-resolution information below the ocean surface in regions that are dynamic and often difficult to observe, including western boundary currents, shelf regions, and ocean fronts. Most fishing gear, such as nets or traps, can inherently serve as a profiling mechanism for sensors since fishing activities send gear from the surface to some ocean depth, followed by retrieving it from depth back to the vessel to catch fish. In recent years, several programs have deployed sensor systems at regional and local scales by partnering with fishing vessels using a variety of approaches (Gawarkiewicz and Malek Mercer, 2019). The Environmental Monitors on Lobster Traps (eMOLT) team, a cooperative effort between the National Oceanic and Atmospheric Administration's Northeast Fisheries Science Center, the Gulf of Maine Lobster Foundation, and the commercial fishing industry in the northeastern United States, has been deploying sensors via fishing vessel since 1993 (Manning and Pelletier, 2009). Worldwide, systems based on fishing vessels as observing platforms use sensor systems to obtain ocean observations for a range of scientific goals (e.g., Patti et al., 2016; Ito et al., 2021; Penna et al., 2023; Olsen et al., 2023; Vranken et al., 2023). However, each program entails different levels of human intervention for hardware maintenance, data transfer, and overall data management.

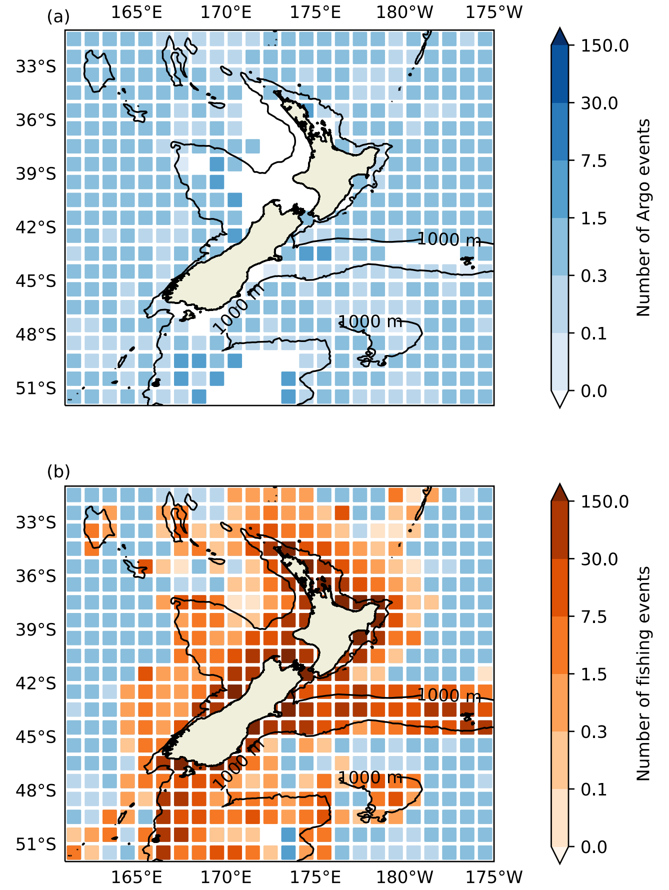


Fig. 1. (a) Average number of Argo profiles per month within each $1^\circ \times 1^\circ$ horizontal grid cell across the Aotearoa New Zealand region during 2007–2017 and the (b) average number of fishing events per month overlaid on the average number of Argo events per month for the same time period. An event refers to any deployment of commercial fishing gear at any depth. Color scales are nonlinear. Argo data were sourced from the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) and Aotearoa New Zealand fisheries data were provided by the Ministry for Primary Industries (MPI).

More than 65% of the population of Aotearoa New Zealand lives within 5 km of the ocean (OECD, 2019). Many ocean communities, including indigenous communities with long-standing connections to their local ocean, value sustainable fishing, are invested in commercial fishing, and have long-term knowledge of their local and regional oceans through culture, ancestry, occupation, and recreation (Wheaton et al., 2020). Crowdsourcing ocean observations facilitates knowledge transfer between the fishing sector, local communities, researchers, and the technology sector, shaping the program together to maximize mutual benefits (Peters et al., 2015; Carson et al., 2021; Ito et al., 2021; Vranken et al., 2023). This crowdsourcing model also empowers participants to observe the ocean in regions that are important to them while engaging with researchers to gain insights into changes in subsurface temperature that directly influence their daily lives.

To address the existing gap in subsurface ocean observations in coastal and shelf regions surrounding Aotearoa New Zealand, as well as the challenges in deploying sensors from fishing vessels, the Moana Project (www.moanaproject.org, Souza et al., 2023a) and technology partner ZebraTech, Ltd (Nelson, New Zealand) have developed a

Table 1
Key Mangōpare temperature and depth sensor program requirements and specifications, as determined via co-design with program participants and sensor/data users.

Target sensor requirements
Fully automatic after install
Temperature range of -2 °C – 35 °C
Temperature accuracy of 0.05 °C
Temperature Response rate of 1 s
Pressure accuracy of 0.5% of rated pressure range
Withstands daily commercial fishing operating environment
Battery life and calibration last for two years
Lightweight (100 g with protective "tough jacket")
Mounting options designed for fishing gear
Variable subsurface sampling regime
Deck unit requirements
Solar-powered, stand-alone
Near real-time data transmission from sensor to cloud
Withstands vessel environment
Flexible and easy to install on a range of vessels
Firmware updates available over-the-air
Data compression for minimal data transmission costs
Position Accuracy: see Appendix A
Data pathway
Data reliably provided in near real-time
Data available via API
Fully automatic (no human intervention)
Data quality control in accordance with international standards
Fishing specific processing quality control and position processing

purpose-built, cost-efficient, fully automatic temperature and pressure sensor. The sensor was specifically designed to be mounted on a wide range of commercial fishing gear, as well as other types of equipment, requiring minimal human intervention for operation. The Moana Project provides a framework to motivate and inform the sensor program across multidisciplinary and multicultural research themes (Souza et al., 2023a) with a project-wide aim "to improve understanding of coastal ocean circulation, connectivity and marine heatwaves to provide information that supports New Zealand's seafood industry" (Moana Project, 2018).

In this paper, we provide an overview of the system, encompassing the design of the observing system, its hardware components, and the data pathway. We present a description of an *in situ* ocean temperature dataset that results from the nation-wide deployment of the Mangōpare sensor system. Finally, we briefly summarize the key partnerships that the observing system depends on, data applications, and benefits for a broad range of ocean interest groups.

2. Methods

2.1. System requirements and specifications

System requirements were collaboratively developed with the Aotearoa New Zealand commercial fishing sector, including vessel owner/operators, skippers, crew, company representatives, sector representatives, as well as Moana Project research teams, project partner Whakatōhea (the Moana Project *iwi* - or Māori tribe - partner), external researchers, government agencies, industry organizations, and citizen scientists. The Moana Project aimed to establish an observing system that provides measurements for use by participating vessels, for operational ocean forecasting, and to improve ocean data products that feed back to the broader ocean community. Discussions with and input from the fishing sector covered a wide range of topics, such as the need for an automated system, anticipated operating environments, suggestions for requirements, and data accessibility. Based on this co-design process, a critical requirement for the sensor system development was ease of use, requiring minimal-to-no intervention and ensuring that the sensor would be included with each fishing gear deployment. The design process identified additional key design factors, including the forces the sensor would be subject to in operational vessel settings, avoiding damage to fishing gear, rapid thermal response when profiling, the need for a solar-powered, vessel-mounted transmission box (deck unit), returning the measurements to the vessel that obtains them, and the establishment of a robust end-to-end system (Table 1).

Data management focuses on ensuring data quality, reliability, and availability, to provide measurable benefit to the broader ocean community. Key principles include:

- Adhere to international data sharing standards: FAIR (Wilkinson et al., 2016), CARE (Carroll et al., 2020), and CF-compliant (Eaton et al., 2021) data formatting and metadata.
- Apply robust quality control in accordance with international best practices (U.S. Integrated Ocean Observing System, 2020; Wong et al., 2021).
- Develop fishing-specific data processing (e.g., correlating sensor position with vessel position).
- Provide measurements and relevant metadata for use in Moana Project hydrodynamic models and to the collecting vessels in near real-time.
- Disseminate measurements via the Global Telecommunications System (GTS) and work with existing data portals (when permission is granted by data owner) to ensure measurements are available to users through tools that maximize benefit.

2.2. System description

The Moana Project and ZebraTech have deployed a fully automatic data pathway that requires no human intervention after the initial sensor and deck unit installation (Fig. 2). This pathway starts with the Mangōpare temperature and pressure sensor (Fig. 3) installed on commercial fishing gear or similar. The sensor is pressure-triggered to begin measuring upon submersion, continues measuring while underwater and stops when it exists the water. Sensor measurements are subsequently offloaded automatically via Bluetooth to the solar-powered deck unit located on the vessel within Bluetooth range of the sensor retrieval location. The deck unit transmits the data to cloud servers in near real-time via internal cellular capabilities or through a connection to the vessel's Wi-Fi system. If the deck unit cannot connect (due to lack of cellular coverage or vessel Wi-Fi outage), it stores all measurements until a connection is made and stored measurements can be automatically transmitted.

The sensor was named "Mangōpare" (meaning hammerhead shark) by a representative of Whakatōhea. The 200 m (called "Moana TD200") and 1000 m ("Moana TD1000") depth-rated sensor models operate with different sampling regimes that reflect their operating depths (Table 1). Both models begin recording temperature and depth when the sensor is submerged in the water where it is activated by a specified pressure change ("activation pressure threshold") of 2–3 dbar, depending on sensor model. Once submerged, a variable sampling rate ensures well-sampled water column profiles while minimizing file size for data transmission. During sensor ascent or descent within the water column, the sensor measures every 1 dbar in the upper 200 dbar (TD200 and TD1000), and 1 sample per 4 dbar deeper than 200 dbar (TD1000 only). If the sensor does not measure 1 dbar or greater pressure change for five minutes, e.g., when resting on the ocean floor, it switches to a static sampling mode and records a measurement every five minutes until 1 dbar pressure occurs. Static sampling mode incorporates wave effects to prevent the sensor from entering profiling mode due to wave-induced pressure changes (Zebra-Tech, Ltd., 2024).

The sensor, deck unit, and data pathway return one file, containing a metadata header and the sensor measurements, per sensor deployment. A deployment refers to submersion of the sensor through exit of the gear from the water and return to the vessel. Upon transmission to the cloud, observations are automatically quality-controlled in

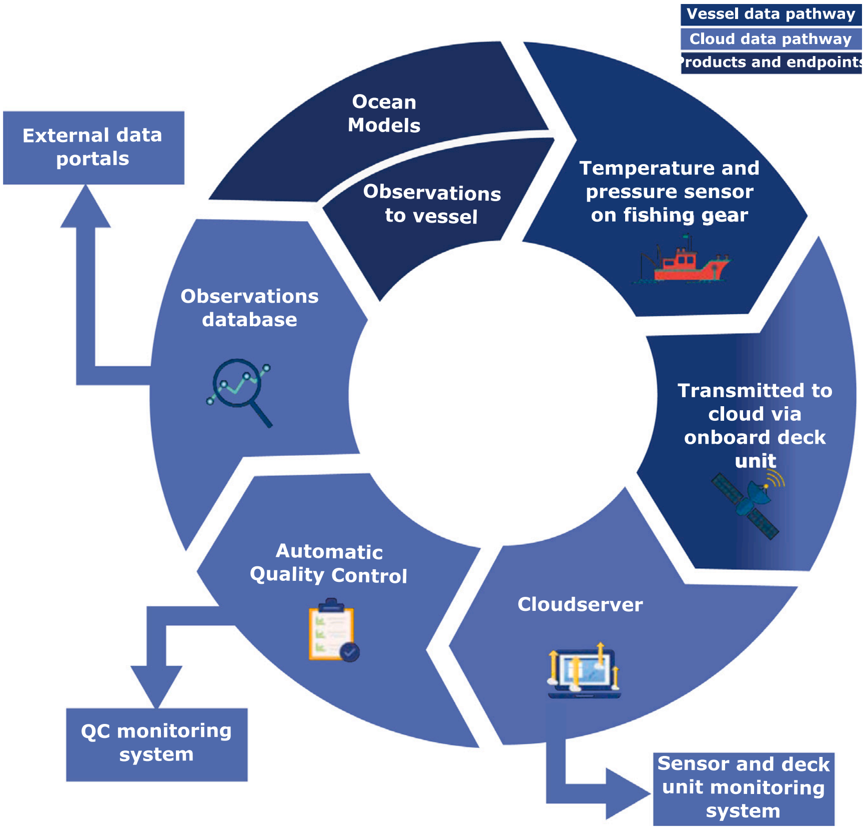


Fig. 2. Overview of the data pathway used by the Moana Project, including: installation of a sensor on commercial fishing gear or similar and a deck unit on-board the vessel, deployment of the gear-mounted sensor during normal operations, data transmission via the onboard deck unit to a cloudserver in near real-time, automated quality control and data processing, and development of observational and model data products which are then returned to the vessel that obtained the measurements.

Fig. 3. The ZebraTech Moana TD1000 temperature and pressure sensor (left) and solar-powered deck unit (right).

near real-time to provide high-quality, reliable data suitable for scientific and operational use. Standard temperature and pressure quality-control tests were developed in collaboration with the Fishing Vessel Ocean Observing Network (FVON, https://fvon.org/), based primarily on IOOS Quality Assurance of Real Time Ocean Data best practices (U.S. Integrated Ocean Observing System, 2020) and Argo quality-control procedures (Wong et al., 2021), and informed by previous work in other regions such as that described by Penna et al. (2023). Additional fishing- and sensor-specific quality-control processes flag measurements that do not pass quality checks and assign positions to individual measurements. Quality control tests are applied to temperature, pressure, time, and position, and are based on factors such as ocean processes and dynamics, sensor specifications, and fishing method (see Jakoboski et al., 2023, for a full list of tests and descriptions). Test outcomes are integrated into Quality Control Flags associated with each variable and included in the resulting data files according to World Meteorological Organization (2000) standards. The highest quality data is represented by a quality flag value of 1, “likely good” data by a value of 2, “likely bad” by a value of 3, and “bad” data by a quality flag value of 4 in accordance with standard oceanographic tests (World Meteorological Organization, 2000; U.S. Integrated Ocean Observing System, 2020; Wong et al., 2021).

Sensor geospatial position measurements derive from the GPS position of the vessel-mounted deck unit. Deployments are classified as “towed” or “passive”. A “towed” classification indicates the sensor is mounted on fishing gear that is towed behind a vessel (e.g., trawling), while sensor deployments obtained by fishing gear left behind by the vessel (e.g., potting) or when fishing occurs in approximately the same location (e.g., seining) are classified as “passive”. In the towed case, we assume the sensor and vessel have the same position. In the passive case, the deployment is associated with a single position, calculated as the average between the first and last positions of the deployment that were assigned a position quality flag of “good” (i.e. the positions where the gear was deployed and retrieved). In the future, the passive case could include distinct positions for the approximate initial sensor descent (downcast) and final ascent (upcast).

Additional processing includes ensuring the measurements are associated with the correct vessel, managing fishing data privacy to ensure data are only shared publicly when permission is given by the data owner (e.g., vessel owner), and monitoring the quality of sensor deployments over time (Jakoboski et al., 2023). Quality-control routines are regularly updated and delayed-mode quality control processes are planned for future deployment, similar to those implemented by Penna et al. (2023).

Processed measurements are returned to the vessel that obtained them within three hours of transmission from the vessel via email and online portal options. The data pathway is operational 24 h a day, 7 days a week to support 7-day Moana Project hydrodynamic forecasts and timely return of individual vessel measurements for use by vessel operators. The vessel and/or designated email recipient(s) receive a graphical visualization of the measurements, a geographic map and summary statistics for each deployment, and a CSV file containing the quality-controlled measurements. The email system was developed with close feedback from the fishing sector and other program participants to ensure that the provided formats are useful to those collecting the data. Measurements and associated metadata are made available for assimilation into the Moana Project hydrodynamic model suite (Souza, 2022; Souza et al., 2023b; Kerry et al., 2023) via API (Application Programming Interface).

Measurements obtained by Mangōpare sensors for the Moana Project are owned by the vessels that obtain them. Initially, measurements were only provided to the public on an aggregated, 1° × 1° horizontal grid in accordance with New Zealand guidelines on the release of fishing position information (Ministry for Primary Industries Manatū Ahu Matua, 2019). After the completion of the sensor rollout in September 2022, commercial fishing sector representatives and program participants (fishing vessels and citizen scientists) discussed the benefits of moving toward an open data policy. As a result, vessels owners now volunteer to share their anonymized data publicly (Jakoboski et al., 2024) in CF-compliant netCDF format (Eaton et al., 2021) via a Thematic Real-time Environmental Distributed Data Services (THREDDS) data server (Unidata, 2023). The data are provided to the global operational community via the Global Telecommunications System (GTS). GTS insertion is coordinated through OceanOPS (https://www.ocean-ops.org/) and the Meteorological Service of New Zealand.

2.3. Mounting hardware, installation, and operation of the Mangōpare sensor

ZebraTech, Ltd. provides a range of mounting hardware (e.g., Fig. 4) designed specifically for commercial fishing applications (Zebra-Tech, Ltd. and Moana Project, 2022). Mounting hardware is designed for the simplest install possible while providing a robust platform to attach the sensor to commercial fishing gear or similar. An attachment loop can be fitted to the sensor for manual deployment, such as a line or fishing rod (Fig. 4c), and sensor mounting options exist for recreational, research, industry, and *waka* (Māori traditional voyaging) vessels. Mounting options are continually developed as new applications are identified. Each new mounting method is deployed on a trial vessel with crew providing essential feedback.

The Mangōpare sensor program team identifies the appropriate sensor, mounting hardware, and deck unit for each participating vessel through communication with vessel owners and skippers. These are securely packaged with simple installation instructions, shipped to the vessel, and installed by vessel crew, technical team, or researcher, depending on vessel and application. The sensor is attached to fishing gear via the selected mounting hardware and the deck unit is attached to the vessel deck (e.g., railing or similar) using provided u-bolts. All hardware can be installed using standard tools that are found on most vessels. In the case of a deck unit that is connected to the vessel’s Wi-Fi system for data transmission to the cloud, vessel Wi-Fi credentials are programmed into the deck unit prior to shipping.

On board the vessel, system maintenance is limited to ensuring that the sensor is attached to any new or swapped fishing gear and the deck unit solar panel is clean and maintains a clear view to the sky. If the sensor or deck unit is damaged during operations, it is shipped back to ZebraTech for replacement. Each sensor is returned to ZebraTech after two years for battery replacement and calibration, following which the sensor is returned to the vessel for reinstall and redeployment.

2.4. Mangōpare sensor program rollout

Sensor deployment occurred in three phases, beginning in September 2019 with prototype trials that consisted of testing in the laboratory and on potting and trawling vessels local to Nelson, NZ. During the trial phase (June 2020 through March 2021), an initial batch of Moana TD200 and TD1000 sensors were deployed on a fleet of trial commercial fishing vessels with the aim of testing the sensor system on a range of fishing gear types and in a variety of locations with the Aotearoa New Zealand EEZ. The Moana Project finished the rollout phase and provided 300 sensors (counting individual sensor-vessel pairs) free-of-charge to more than 250 vessels by the end of September 2022. Some vessels deploy multiple sensors, e.g., on more than one pot or more than one sensor per longline. Currently, sensor deployments include 14 different commercial fishing gear types and four deployment types not associated with commercial fishing (e.g., manual cast from non-fishing vessel, research vessel and hydrographic survey deployments). A wide range of commercial fishers participate in the program — from single, independent fishers to large commercial fishing companies with extensive fleets. Participating vessels include inshore and deepwater vessels fishing for a variety of fish species during different months of the year and regions across Aotearoa New Zealand.

The Moana Project focused on deploying sensors on commercial fishing vessels; in addition, sensors were provided to research and a range of citizen science vessels that expressed interest in joining the program. Commercial fishing vessels provided the majority of sensor deployments throughout the program (96.4% of deployments). Broader ocean community (education, recreation, *waka ama*, and personal commuting, 1.2%) and research (2.4%) vessels provided additional observations in key regions, demonstrating the viability of the sensor for both commercial fishing and citizen science applications. Researchers utilize the sensor during trawl surveys, reef dives, manta ray surveys, hydrographic surveys, and other research activities. *Waka ama* teams deploy the sensor during training sessions. Students on board education and private commuter vessels measure ocean temperature daily, providing an opportunity for hands-on ocean observation and direct interaction with scientists for the next generation of oceanographers.

2.5. Partnerships and communication

The program is a result of connecting with more than 400 individual contacts representing a majority of Aotearoa New Zealand’s active commercial fishing vessels. Support from Aotearoa New Zealand’s commercial fishing sector is essential to program design, rollout, and continued operation. Sensor rollout on this scale was made possible by the contributed expertise and resources of key commercial fishing sector representatives. Representatives from the Mangōpare sensor program presented at fishing sector conferences and workshops and contacted individuals directly through their own networks to reach as many commercial fishers as possible. As more vessels joined the program, fishers heard about the program through word of mouth and requested to participate directly.

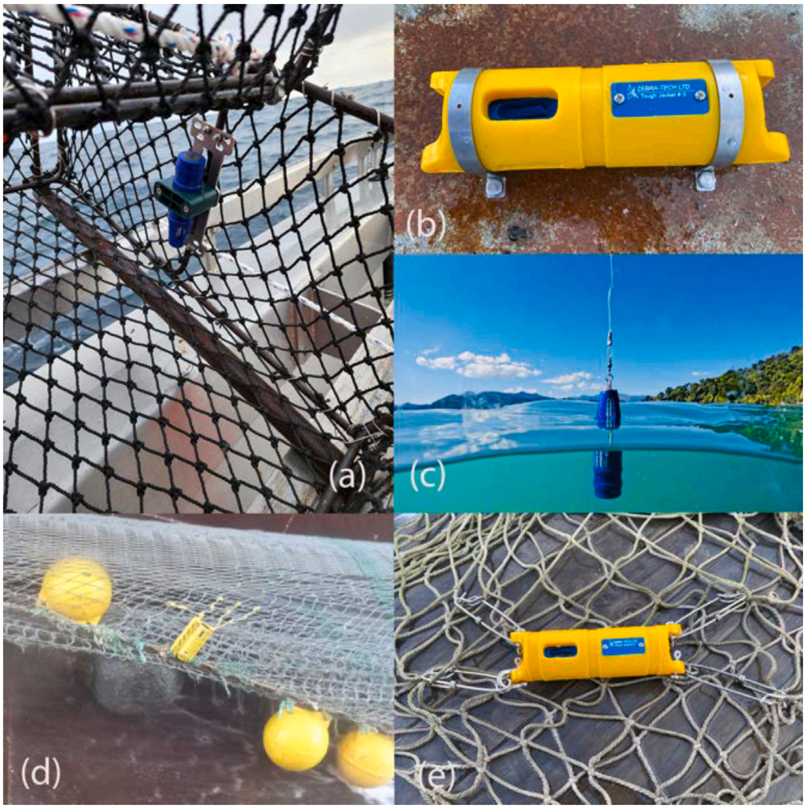


Fig. 4. Sample Mangōpare sensor (blue), or sensor within a protective "tough jacket" (yellow), installation on a (a) lobster pot, (b) trawl door, (c) fishing line, (d) mounting plate on net, and (e) shark clips on net. Additional mounting options, not shown here, are currently in use by the commercial fishing fleet. Photos are courtesy of: (a) William Maclardy, (b) John Radford - ZebraTech, (c) Amanda Rudkin, (d) Talleys Group Ltd., (e) John Radford - ZebraTech.

Worldwide, traditional stewards of the land and sea can have long-established connections with the local natural environment. Co-design with Māori stakeholders is critical to considering indigenous values and to working toward CARE principles (Carroll et al., 2020). Feedback and input from Māori partners occurred during *hui* (meetings) and interactions with Māori fishers.

These partnerships create a unique opportunity for collaboration, ensuring that participants find value in the ocean observations they collect. After the sensor rollout phase, communication with the fishing sector and program partners remains a key priority through updating participants and requesting feedback via meetings, sensor program information papers (Moana Project, 2021), newsletters, media releases featuring participants, and direct communication with individuals. Early collaboration with commercial fishing representatives was essential for fisher engagement and program success.

3. Results

3.1. Sample data

The variable sampling rate of the Moana TD200 and TD1000 sensors results in measurements with varying temporal resolution based on changes in sensor pressure. Some fishing gear types (e.g., potting) include a downcast profile, a bottom temperature timeseries, and an upcast profile. Fishing methods such as seining, trawling, trolling, and diving produce a range of trajectory shapes at differing depths throughout the water column (Fig. 5). We format data as general trajectories, with a latitude, longitude, timestamp, and pressure associated with each individual temperature measurement due to the variable nature of the sensor movement after deployment. For use cases that require oceanographic profile rather than trajectories, the downcast and upcast can be segmented from the deployment, approximated as profiles during post-processing, and assigned a single latitude, longitude, and timestamp per profile.

Each participating vessel is able to obtain a historical picture of the ocean temperature that corresponds to the exact locations it has been fishing. An example from a single fishing vessel shows widespread sensor deployment over a six-month period (Fig. 6a). The sensor captures the vertical ocean temperature structure and temperature changes from austral spring through fall (Fig. 6b).

3.2. Temporal coverage

Results cover the initial three years of the sensor program from June 2020, prior to the completion of the sensor rollout in September 2022, to December 2023, fifteen months after the end of the rollout. The number of sensor measurements per month and the number of sensors installed on a vessel during a given month increased between June 2020 and September 2022 as the program moved through the prototype, trial, and rollout phases (Fig. 7a). The number of measurements per month remained approximately stable after the end of the rollout with some expected month-to-month variability due to seasonal factors and extreme weather events.

Various environmental, regulatory, market, and societal factors impact ocean measurements obtained by fishing vessels and the broader ocean community. Some fishing methods are more seasonal than others, which introduces a seasonal cycle to the spatial and temporal coverage of the sensor data. Dividing the number of measurements by the number of installed sensors gives an estimate of the seasonality of measurements per vessel from 2020 through 2023 (Fig. 7b). Based on the 42-month study period, the number of measurements per vessel reach maxima during the summer season (December–February) and minima during winter (June–August). This is likely a reflection of commercial fishing seasons and of meteorological seasons (weather).

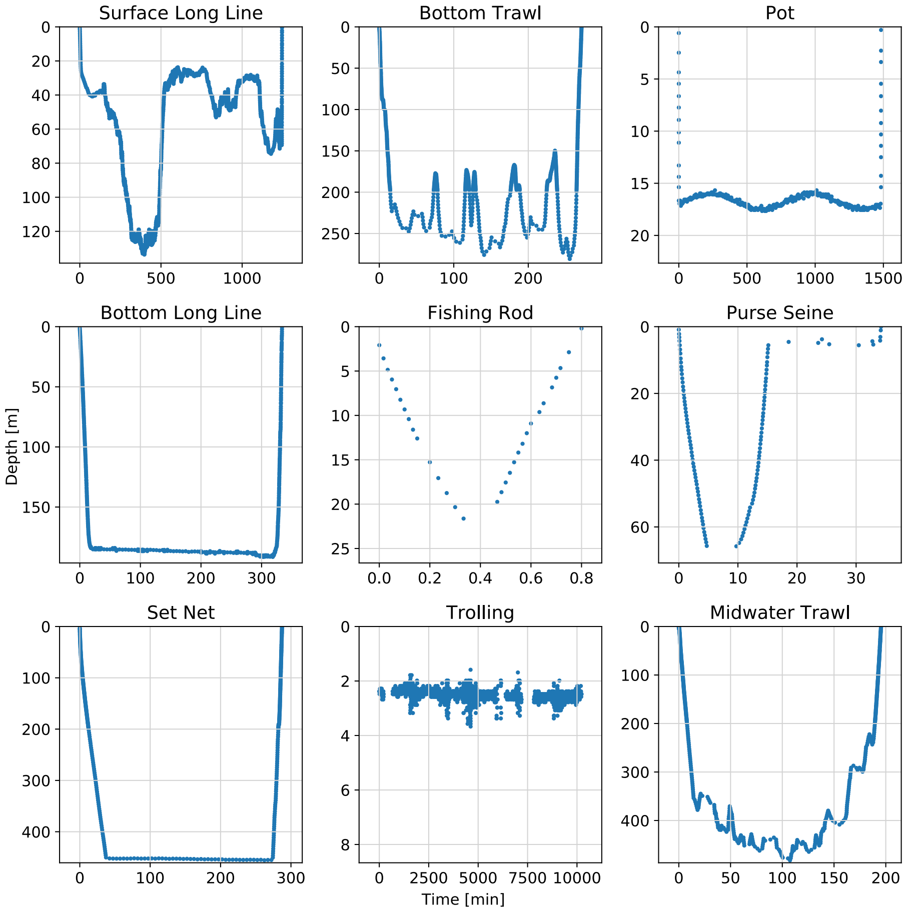


Fig. 5. Sample Moana TD200 or TD1000 deployments on a subset of fishing gear types within Aotearoa New Zealand's EEZ. Time is in minutes since deployment start.

Patterns in temporal coverage were also impacted by Covid-19 through restrictions on movement and business operations, operational fishing costs, and reduced international export associated with changes in the global fishing market (Delpeuch and Symes, 2020). For example, commercial rock lobster fishing paused for periods when exporting to key markets was not feasible (Bolger and Stuart Nash, 2020). Despite global challenges, the network of sensors continued to return measurements during all months since the beginning of the program (Fig. 7a) and maintained coastal coverage through seasonal storms and the Covid-19 shut down period.

Most sensor deployments occurred over a period of less than 10 h with a secondary peak near 25 h (Fig. 8a), likely associated with pots left at sea overnight. A corresponding isolated peak does not appear in the number of samples per deployment (Fig. 8b) because the sample rate decreases when the sensor is at a constant pressure to reduce transmission file size. This approach effectively reduces the number of very large files, with nearly all files containing less than 1200 measurements, despite deployments ranging from 0–30 h. Fig. 8 excludes the top 2% of outliers that include exceptional cases, e.g., where a pot with a sensor mounted on it was lost and retrieved months later.

Initially, a higher percentage of measurements were obtained by towed gear than passive gear, reflecting early program participants (Fig. 7a). The percentage of measurements from passive gear increased by the end of the sensor roll-out. This is increase was in part due to an effort to observe Moana Project research focus areas located in shallower waters.

3.3. Spatial coverage

The Moana Project aimed to achieve coverage of Aotearoa New Zealand's EEZ using multiple fishing gear types and to trial the sensor in a wide range of ocean and fishing environments. Sensors were deployed in both nearshore and open-ocean regions throughout the Moana Project modeling suite domain and regions suggested or requested by the fishing sector. This includes the coastal regions of Aotearoa New Zealand's North and South Islands, as well as the Chatham Rise and Motu Maha (Auckland Island)/western Campbell Plateau (Fig. 9). The resulting spatial coverage effectively complements Argo observations in the Aotearoa New Zealand region by filling much of the gap in subsurface observations that occurs in waters shallower than 1000 m and providing measurements in regions critical to the fishing sector. Additional observations outside of the domain of the Moana Project modeling suite (not shown here) include vessels traveling to Australia, toward the southern Indian Ocean, and to Antarctica.

Maximum deployment depth depends on ocean depth, fishing method and target species, and sensor model depth rating (Fig. 8c). A majority of deployments occur in the upper 100 m, which reflects the coastal nature of many fishing areas and the depth range of a subset of fishing methods. A second peak in Fig. 8c occurs near 500 m due to the fishing of specific species (i.e., hoki trawling) at those depths.

The remaining unobserved regions (shown in white, Fig. 9b) are due to a lack of fishing activity or a prevalence of fishing vessels that do not have an existing satellite connected on-board that can be accessed via Wi-Fi and are active outside of cellular coverage for long periods. Vessels unable to return data in near real-time were not eligible participation in the initial sensor roll out. Additional deck unit development is under consideration, along with the use of increasing communication satellite networks, to address telemetry requirements in remote areas. In the future, sensor coverage in these areas is also expected to improve with planned cellular network expansion.

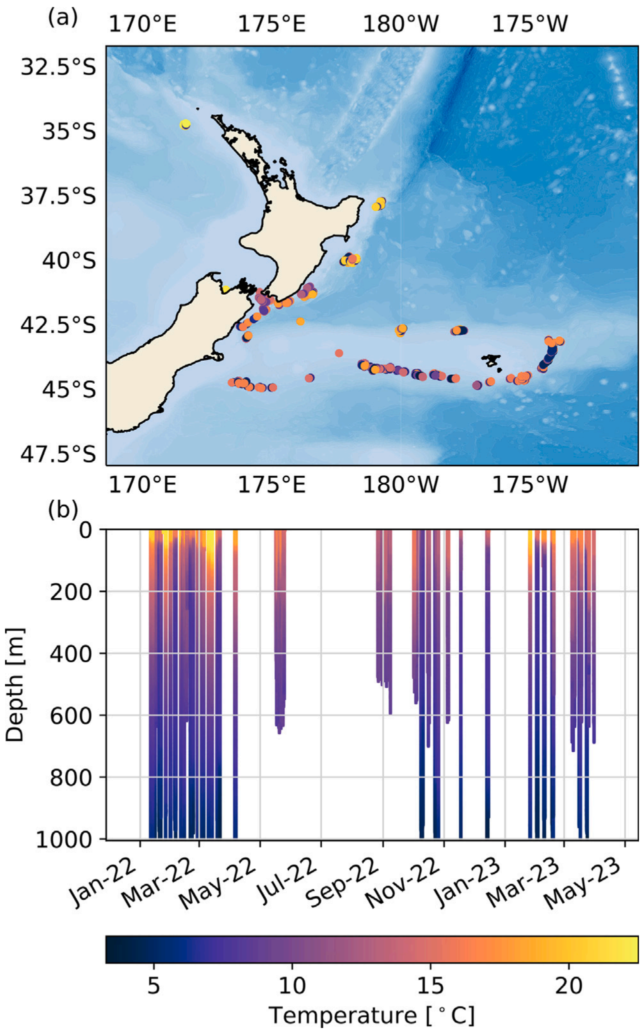


Fig. 6. (a) Horizontal sensor coverage obtained by a single vessel, Sealord's Otakou, over the six-month period from 1 October 2022 through 31 March 2023 and (b) the resulting temperature over the same time period as a function of depth, as an example of a vessel tracking their fishing temperature over time.

3.4. Sensor accuracy

Temperature and pressure accuracy are determined in the laboratory and through ocean deployment comparisons against a reference sensor. An initial ocean deployment comparison in Appendix B shows close agreement between a Moana TD200 and reference sensor and that initial pressure and temperature drift after two years remain within the target specifications. Further testing has been conducted and is the subject of future comparisons studies.

4. Discussion and conclusions

The Moana Project's Mangōpare sensor program demonstrates that partnering with the commercial fishing sector and citizen scientists to deploy new, purpose-built, *in situ* sensing technology can lead to a near real-time, scientific-quality, widespread view of subsurface, coastal ocean temperature on a national scale. This approach utilizes existing resources to complement established subsurface ocean observing systems, such as Argo, and reduce the gap in available coastal temperature measurements where commercial fishing often needs them most (Fisheries New Zealand, 2021) and other economic activities are often concentrated. This framework is readily applicable in data poor regions globally where fishing (or similar) activity occurs.

4.1. Observing system co-design

As the program is dependent on close communication with volunteer vessels, it provided a unique opportunity for system co-design and user feedback. The Mangōpare sensor program demonstrates a "nation of oceanographers", including commercial fishers, citizen scientists, and researchers, observing their ocean in the regions they live and work. The resulting *in situ* sensor measurements can be used for a wide range of applications that benefit ocean stakeholders nation-wide. Opportunities exist to continue to incorporate feedback from program participants and stakeholders and to shape the program in a *mātauranga Māori* (Māori traditional knowledge) context.

Returning the data directly to the fishers who collected it in near real-time empowers the ocean-going community to better understand their subsurface ocean. Close relationships with fishers allows us to share knowledge of ocean changes, facilitating two-way and mutually beneficial data flow (Olsen et al., 2023). Participants expressed great interest in their data and anecdotal evidence suggests that fishers can use their own data to improve fishing quality by correlating near real-time data and historical subsurface temperature with catch in the exact locations where fishing occurs. Research is ongoing in this space. Similar feedback has been received in a fishing-vessel-based observing program in Japan (Ito et al., 2021) that involves close relationships with participating fishers.

4.2. Observing system evolution

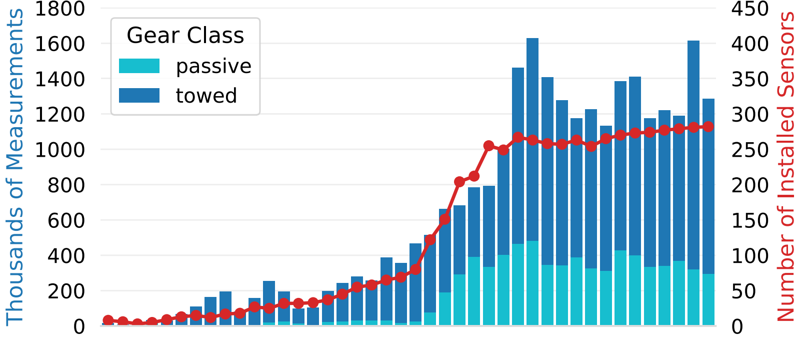
Differing characteristics of various fishing methods (e.g., position accuracy, seasonality, frequency and duration of deployments) allow observing programs to tailor the choice of fishing gear types to target particular objectives or regions of the ocean. For example, some vessels fish continuously by changing gear type and target fishery during seasonal fishery closures. The portable nature of the sensor system allows us to leverage hard working vessels or to shift vessels easily and, therefore, ensures the sensors are working continuously.

While fishing techniques and associated characteristics vary widely, we can identify potential vessels by working closely with fishing sector representatives, fishers, and local communities, and provide sensors to vessels most appropriate for target applications. For example, the identification of data sparse regions where fishing occurs allows us to seek willing fishers in the region to help fill the gaps. Beyond Aotearoa New Zealand, this has been demonstrated in Northern Australia, where virtually no data existed prior to the instrumentation of fishing vessels, by the Fish-SOOP program. The next step is to identify the minimum number of observations (and hence vessels and gear types) required to characterize particular regions, as well as the data requirements to constrain ocean models. In this way, programs such as this can ensure that the observing system can evolve efficiently with good geographic spread, without over-observing some regions at the potential expense of others. The Mangōpare Sensor Program aims to deploy additional sensors to new participants in undersampled regions, increase the availability of the resulting data, and develop new tools and analyses to support sustainable, data-driven fisheries management (OPMCSA, 2021) and to facilitate the use of sensor measurements both within Aotearoa New Zealand and beyond.

4.3. Improving ocean forecasts and dynamical insight

The near real-time temperature observations have been assimilated into publicly-available hydrodynamic ocean models to enhance the accuracy of ocean forecasts in previously under-sampled regions. This leads to forecast improvement in regions critical to stakeholders, particularly in coastal areas where many economic activities take place. A suite of observing system simulation experiments (OSSEs) have been conducted by Kerry et al. (2024) that indicate the value of the program's subsurface temperature data to model improvement. The

(a) Number of Mangōpare Measurements by Month



(b) Average Number of Monthly Mangōpare Deployments per Installed Sen

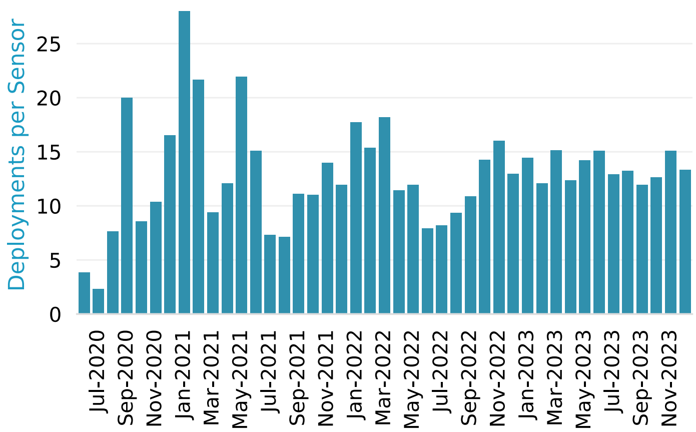


Fig. 7. (a) Number of Mangōpare measurements per month, in thousands of measurements, from June 2020 through December 2023 by gear class (towed or passive, different shades of blue) and the number of sensors of either gear class registered as "installed" during that month (red). "Installed" means the sensor is registered as currently installed on a vessel and does not indicate whether the vessel is necessarily fishing that month. (b) The average number of Mangōpare deployments per installed sensor obtained by dividing the total monthly number of Mangōpare measurements (a) by the total number of installed sensors for each month. Only measurements with a "good" or "probably good" quality flag are included.

results show a reduction in subsurface temperature root-mean-squared-error when compared to state estimates from models that only include satellite and Argo observations (Kerry et al., 2024). Error reduction is more prominent in shelf seas and shows a substantial improvement for bottom temperatures. These results are in agreement with those of Aydoğdu et al. (2016) who show that assimilating fishing vessel-based temperature observations improves model results in the Adriatic Sea. However, more research is needed into how best to assimilate subsurface data (as identified by Gwyther et al., 2022, 2023) and subsurface fishing vessel observations will be useful for assessing model improvement.

Sensor measurements and ocean forecasts have been used in oceanographic research to provide dynamical insight; for example, to identify the subsurface structure of marine heatwaves. During a 2022 marine heatwave that impacted Aotearoa New Zealand (Salinger et al., 2024), peak positive temperature anomalies in Te Moana-a-Toi (the Bay of Plenty) often occurred and persisted below the surface (Fig. 10). This marine heatwave had a weaker and shorter-lived signature at the surface (similar to the subsurface intensified marine heatwaves identified by Schaeffer and Roughan, 2017; Schaeffer et al., 2023; Elzahaby et al., 2021), highlighting the value of *in situ* measurements for resolving the depth-structure of marine heatwaves in coastal waters. We presented figures similar to and including Fig. 10 to local fishers, providing another parameter that they can use to make commercial fishing decisions on individual and sector levels.

4.4. International collaboration

The Mangōpare program is part of the Fishing Vessel Ocean Observing Network that aims to coordinate and foster the development of a global network of fishing vessel-based ocean observing programs (Vranken et al., 2023). The network includes collaborations with multiple research organizations, the private-sector, universities and operational agencies across five continents with a footprint in Europe, the United States, Asia and Australia. In addition, pilot programs have been run in Africa and the Southern Ocean. Collectively, we are working to develop international best practices for data quality assurance and quality control, real time data delivery, and sensor inter-comparison studies and improvements.

Partnering with the vast network of several million fishing vessels already operating globally and instrumenting them with purpose-built sensors to monitor critical ocean variables represents a highly scalable and efficient approach to ocean observation. The co-designed nature of the system lends itself to strong industry partnerships and collaboration, ensuring system improvement through continual feedback and data uptake and impact. Equally, the program lends itself to partnership and collaboration with First Nations people and ocean custodians. We have shown that this type of observing system has untapped potential to provide a step change in ocean data acquisition over large and remote areas. As new resources become available, these near real-time sensor observations can be further incorporated into international operational ocean forecasting efforts, early alert systems for marine heatwaves, shelf seas monitoring, fisheries science, coastal management, indigenous knowledge, and oceanographic research programs, providing a view into the subsurface ocean state in regions critical to the broader ocean community.

In summary, we have demonstrated an accessible and inclusive approach to collecting extensive numbers of research quality observations on a national scale in ocean regions that are critical to marine

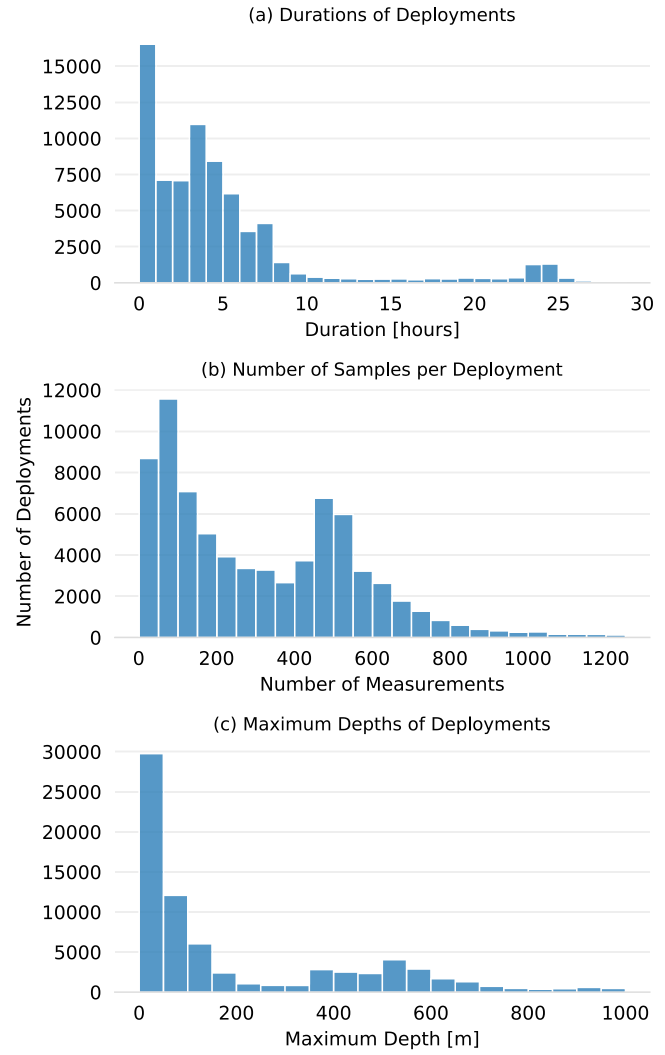


Fig. 8. Histograms of (a) the duration of each Mangōpare sensor deployment in 1 h bins, (b) the number of samples in each deployment in bins of 50 measurements, and (c) the maximum depth reached by each deployment in 50 m bins. (a) and (b) exclude durations and number of samples, respectively, that represent the highest 2% of values. Only measurements with a "good" or "probably good" quality flag are included.

ecosystems, society, and the blue economy. This program complements existing ocean observing strategies and provides a fit-for-purpose, cost-efficient, crowdsourced solution to broad-scale ocean observing in partnership with the seafood sector and the broader ocean community that aligns with the requirements of 21st-century data users.

CRediT authorship contribution statement

Julie Jakoboski: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Moninya Roughan:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **John Radford:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **João Marcos Azevedo Correia de Souza:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology. **Malene Felsing:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition, Conceptualization. **Robert Smith:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Naomi Puketapu-Waite:** Project administration, Investigation, Data curation. **Mireya Montaño Orozco:** Writing – review & editing, Writing – original draft, Software, Data curation. **Kimberley H. Maxwell:** Writing – review & editing, Writing – original draft, Methodology. **Cooper Van Vranken:** Writing – review & editing, Writing – original draft, Methodology.

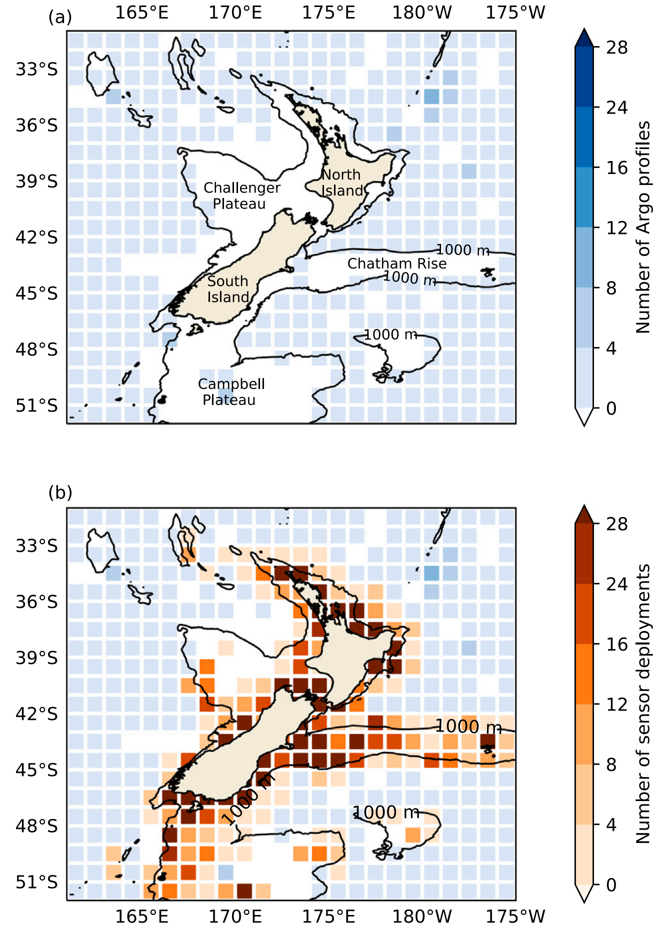


Fig. 9. (a) Average number of Argo profiles per month within each 1° × 1° horizontal grid cell across the Aotearoa New Zealand region during the fifteen-month period from 1 October 2022 through 31 December 2023 and the (b) average number of Mangōpare deployments per month overlaid on the average number of Argo events per month for the same time period, adapted from Figure 5 of Vranken et al. (2023). An event refers to any deployment of commercial fishing gear at any depth.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Publicly available Mangōpare sensor data can be found at the following DOI: 10.5281/zenodo.10420342. Please contact the authors to discuss the availability of the full (restricted) dataset.

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We wish to thank the fishing sector representatives who have contributed their time and effort to ensuring this program is successful, including Richard Wells, Oliver Wilson, Carol Scott, Rosa Edwards,

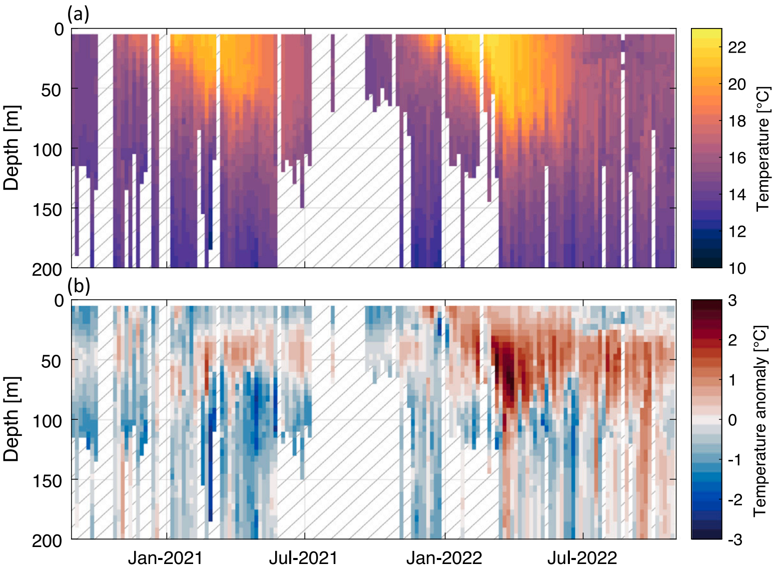

Fig. 10. Five-day mean (a) temperature and (b) temperature anomaly in the Te Moana-a-Toi (Bay of Plenty) region as a function of depth between September 2020 and October 2022, as measured by the Mangōpare sensor program. Temperature anomalies in (b) are computed relative to the 2013 CARS Aus8 climatology (Ridgway et al., 2002). Hatched areas in (a) and (b) correspond to periods where no sensor data are available.

James Robertson, Dr. Tom McCowan, Jules Hills, Ben Steele-Mortimer, and Tim Pankhurst, the fishing company representatives who have championed this program to their teams, the hundreds of vessel owners, skippers, and crew who volunteer their time to deploy the sensors, and members of the broader ocean community who reached out to join the program. We received invaluable input from project partner Whakatōhea and each of the Moana Project research teams. We would like to acknowledge the gifting of the sensor name “Mangōpare” by Danny Paruru of Whakatōhea. The international Fishing Vessel Ocean Observing Network (FVON) team contributed overall best practices discussions and coordinated international efforts of similar programs to share lessons learned. We would like to thank Carles Castro Muniain of the Ocean Data Network for his collaboration on data pathway and quality control best practices, Rebecca Cowley from the Australian Integrated Marine Observing System for contributing her quality control expertise, Dr. Emma Jones at New Zealand’s National Institute of Water and Atmospheric Science (NIWA) for coordinating sensor deployment alongside a reference sensor during trawl survey activity, Steve Knowles for his work on the data pathway, Jack Fenaughty for facilitating Southern Ocean deployments, and Dr. Peter McComb for his ongoing support of the program.

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Appendix A. Position accuracy

Sensor position is derived from the deck unit (vessel) position. As a result, sensor position accuracy depends on fishing gear type, fishing method, and the specifications of the on-board GPS sensor. The Moana Project utilizes the ZebraTech solar-powered deck unit GPS sensor that reports position every 15 s, with an average GPS sensor error of 6.3 m and a 95% confidence interval of 13.8 m.

We assume the sensor position of towed gear is the same as the vessel position. In this case, position accuracy is a function of the GPS sensor accuracy plus the distance between the vessel and the sensor. For bottom and midwater trawling, the sensor is generally mounted on the trawl doors, which can be approximately 50–2000 m behind the vessel, depending on vessel, gear type, and fishing depth (per communication with vessel operators, Fig. A.1). For towed gear, distances between the sensor and deck unit generally increase with fishing depth.

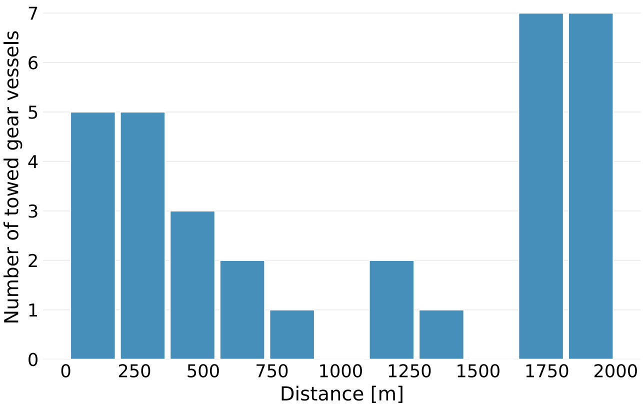

Fig. A.1. Histogram (fraction of vessels) of approximate maximum distance between sensor and deck unit during fishing/deployment operations for towed gear (i.e. trawling), based on survey responses from 33 vessels participating in the Moana Project sensor program. Distances change during deployment and are estimates of maximum distance only.

We calculate the position of passive gear, which includes gear that is detached from the vessel, by considering the fishing gear deployment and retrieval locations. In the passive gear case, the position accuracy depends on how much the gear drifts between deployment and retrieval, approximated by the distance between the deployment and retrieval positions (“deployment–retrieval” distance). In the simplest case, all measurements in each passive gear deployment are assigned a single position, which is the average of the position of the first and last measurements in each deployment with a standard position quality flag of “1” (“good”, U.S. Integrated Ocean Observing System, 2020). Some fishing gear types, such as surface long lining, can drift as much as 10–20 km or more, depending on ocean conditions (per communication with vessel operators, Fig. A.2). During June 2020–January 2023, 96.3% of passive gear deployments had a deployment–retrieval distance of less than 5 km. The remaining $< 4\%$ of deployments either drifted long distances (in some cases, due to the loss of gear that was

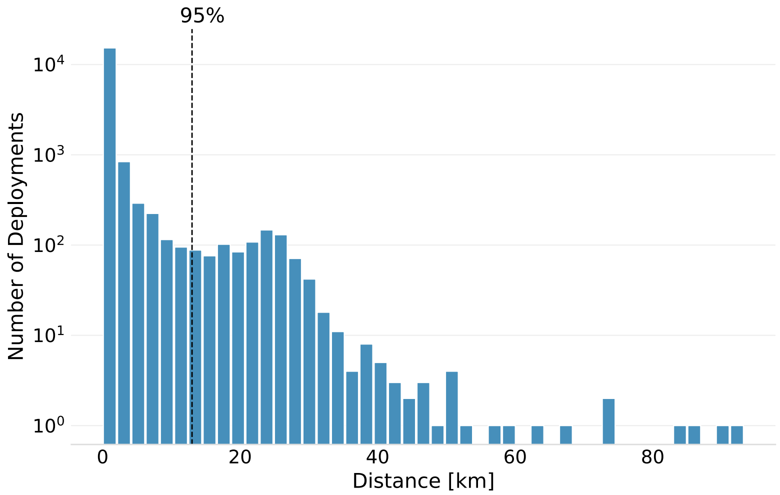

Fig. A.2. Histogram of number of passive deployments by approximate distance between the deployment and retrieval locations. 95% of passive deployments have a deployment–retrieval distance of less than 13.2 km (dashed black line), and 91.3% less than 5 km. Vertical axis is logarithmic.

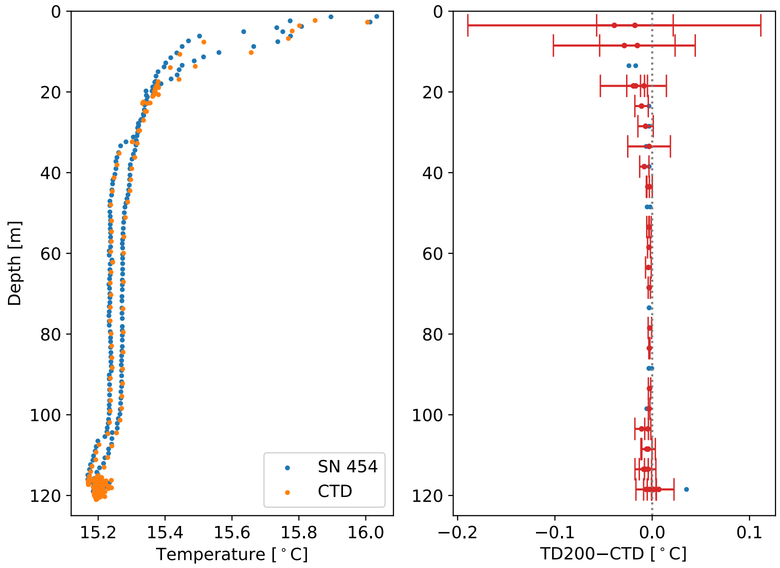

Fig. B.1. (left) A representative temperature-depth profile of the Seabird CTD and a Moana TD200 sensor deployed concurrently (Seabird CTD in orange, Moana TD200 serial number 454 in blue) and (right) the difference between the Moana TD200 and Seabird CTD. Error bars (red) show the standard error of the difference for each bin, for bins with more than one sample per sensor. Blue points indicate the difference between the Moana TD200 and Seabird CTD for depth bins that do not have more than one sample per sensor.

later retrieved) or data failed to offload in between deployments for a variety of reasons. In the latter case, deployment–retrieval distance reflects the distance over multiple deployments. Passive gear deployments with large deployment–retrieval distances are flagged during the quality control process, depending on chosen distance thresholds (5 – 20 km as “probably good” and > 20 km as “probably bad” in the Mangōpare sensor program quality control routines).

Appendix B. Initial comparisons with a reference sensor

While the sensor is tested and calibrated in a laboratory setting, we compare to a calibrated reference Seabird SBE37-SM during an October 2022 NIWA (National Institute of Water and Atmospheric Research, New Zealand) trawl survey. The reference Seabird SBE37-SM temperature sensor has an initial accuracy of 0.002 °C and a typical stability of 0.0002 °C, last calibrated 85 months before deployment. During the survey, a Moana TD200 sensor was mounted alongside a CTD assembly deployed on the trawl net, approximately 100 m behind the trawl doors. The trawl survey completed simultaneous deployments of the Moana TD200 and CTD units in the coastal ocean west of New Zealand’s North Island.

To compare sensors with different sampling rates, temperature measurements for individual sensors were averaged into 5 m depth bins. Given the different sampling rates between instruments, we cannot determine whether the source of any difference might be due to variable ocean state, impacts from slightly different instrument locations, or are a reflection of the temperature or pressure accuracy. However, the difference between 5 m bin-averaged Moana TD200 and Seabird CTD temperature measurements during a single coastal ocean deployment are within the Moana TD200 specified accuracy at nearly all depths (Fig. B.1). Depth ranges with relatively high differences between Moana TD200 and the Seabird CTD correspond to depths where the vertical temperature gradient is high, indicating large differences are likely due to a highly variable ocean state rather than sensor error. An in-depth analysis of all comparison deployments is in progress.

During the two-year specified calibration interval, it is possible that sensors may drift over time. After two-years of deployment on a vessel at sea, sensors are returned to the laboratory for a comparison with reference temperature (Fluke 5610-6) and pressure (Sensor CPT 6020) sensors in a calibration tank. Initial results show very little evidence of drift when deployed in a commercial fishing setting. A Moana TD200 deployed 253 times over two years returned maximum temperature and pressure errors that remain within sensor specifications. Five additional sensors returned after two years of vessel deployment remain within sensor specifications. Further drift comparisons will be done as sensors reach the two-year re-calibration due date.

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