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Development of a low-cost winch-controlled probe to generate temperature profiles of aquatic environments

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Abstract. Oceans and lakes represent aquatic habitats harbouring numerous scientific mysteries and crucial ecological data. Temperature profiles within these water bodies play fundamental roles in understanding their dynamic nature and environmental changes. This research focuses on the development of a winch-controlled temperature probe system integrated on an autonomous boat, with sensors, microcontrollers, safety mechanisms and navigation. Testing showcased the system's capability to acquire temperature profiles in relatively shallow waters while compensating for heaving motions. The results obtained from the experiments confirm overall system development, highlighting the dynamic thermal distribution within the lake environment and understanding the underlying factors driving these fluctuations.

1 Introduction

Temperature fluctuations, particularly with different depths, significantly impact the freshwater and marine ecosystems, climate patterns, and provide comprehensive environmental insights [1]. Current research tools like the Conductivity, Temperature, and Depth (CTD) probe [2] and satellite Sea Surface Temperature (SST) mapping [3], have yielded precise oceanic temperature profiles. However, these tools are either costly or impractical for shallow water deployment. This research focuses on leveraging cost-effective components to enhance marine temperature profiling in relatively shallow waters, addressing challenges such as heave adjustment [4], on-board Global Positioning System (GPS) navigation, data communication [5], waterproofing, as well as the temperature measurement. The main aim is offering a cost-effective solution while elevating the comprehension of marine temperature profiles to expand research opportunities in aquatic environments [6].

This research aims to address these challenges by developing a low-cost, winch-controlled temperature probe system, designed specifically for use in lakes and coastal waters. By leveraging affordable components, including sensors and microcontrollers, the system offers a solution for researchers and environmentalists who need precise temperature data without the high costs associated with conventional equipment. The proposed system

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integrates real-time heave compensation, autonomous navigation, and robust data collection capabilities to ensure accurate temperature profiling, even in dynamic conditions.

The primary objectives of this research are to design and validate a system that can reliably capture temperature profiles while compensating for environmental factors such as heave and wave motion. Additionally, the system aims to enhance the accessibility of aquatic temperature profiling by providing a scalable solution that can be deployed in a variety of settings, from small lakes to coastal regions. By demonstrating and validating the system's capabilities through field testing, this research seeks to contribute to the broader understanding of aquatic environments and to facilitate future research in this critical area.

2 Literature review

Several studies have investigated the development and utilization of winch-controlled probes for obtaining 3D temperature profiles in open sea environments. For example, it has been tested by Carrala [2] that the oceanographic rosette system was enhanced, in order to improve the effectiveness of CTD sampling studies. Their augmented system included adjustable control mechanisms, real-time surveillance, and a programmable logic controller (PLC) to minimize sensor maintenance and replacements. According to Tang [7], the broader implications of data assimilation were expanded, highlighting its influence on atmospheric conditions within coupled models. They demonstrated improved temperature and wind speed profiles globally, emphasizing the potential for data assimilation to enhance climate model performance. Furthermore, various tools were utilized and compared by Duraibabu [5], including CTD probes and optical fibre-based point sensors, to measure physical and chemical parameters of the water column. Their tests in marine and freshwater environments showed precise measurements comparable to commercial sensors, highlighting the reliability of their sensor system.

Low-cost heave correction can be achieved with a straightforward and efficient passive heave compensator [8], particularly in situations where excellent performance is not required. Based on the research conducted by Woodacre [4], a low-cost passive heave compensator has been developed, which was capable of withstanding high loads with minimal additional hardware. While effective for up to 80% heave decoupling, they suggested employing an active or hybrid passive-active system for situations requiring further motion decoupling. However, when compared to fully active systems, hybrid systems offer lower power consumption but may entail additional complexity. Then, Arkadiusz [9] designed a system featuring a hydraulic motor and a movable foundation with two degrees of mobility to counteract sea waves. Controlled by a Power Panel 500 PLC, the hydraulic motor simulates wave effects for testing control strategies. They utilized gyroscopes, magnetometers, and accelerometers to track wave contributions on the frame plate and experimented with various signals, including step reactions from the hydraulic motor, to refine the system's performance.

The preceding research endeavours [2-9] have laid the groundwork for the current research, highlighting the diverse capabilities and critical components of the winch-controlled probe, including data transfer and sensor integrations. Informed by these insights, the system aims to leverage the strengths and address the limitations of prior solutions to develop a low-cost and reliable winch-controlled probe system aligned with specific objectives. Emphasizing the importance of stability in open water environments, the research seeks to simplify and optimize previous designs to enhance signal tuning [10] as well as sample control [11], while incorporating contemporary approaches. Additionally, the research prioritizes passive heave compensation to ensure the accuracy of system outputs and feedback.

3 Methodology and design

The necessity for precise temperature profiling in aquatic environments resulted in the development of a winch-controlled temperature probe system, as shown in Figure 1. Challenges in obtaining accurate data across various water depths amidst dynamic aquatic conditions prompted a thorough analysis of system requirements [2]. The development of the winch-controlled temperature probe system was driven by the need for precise temperature profiling in both lake and oceanic environments. To address the challenges posed by dynamic aquatic conditions, such as varying water depths and movement, the design centred around high-accuracy sensors and efficient mechanical control. The vessel used for testing moved at an average speed of 1 m/s with a maximum speed of 2.5 m/s, allowing for stable navigation even in moderate currents.

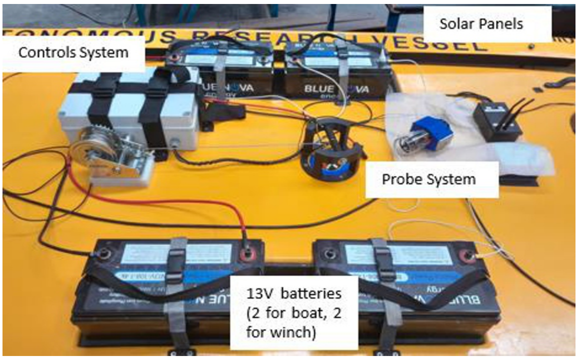

Fig. 1. Overview of the boat.

Key to the design was the selection of sensors that provided relatively high accuracy at a lower cost [10]. The Celsius temperature sensor and Bar30 pressure sensor were chosen for their ability to handle significant depths (up to 900 meters and 300 meters, respectively). These sensors allowed the system to control the probe's position with a precision of 5 cm and ensure that temperature and depth readings remained accurate within 0.1 °C and 2 cm, respectively. This level of precision was vital for capturing reliable temperature profiles, especially in shallow waters where variations in temperature can be subtle but still significant.

Additionally, features like a vent for watertight pressure management and a stainless-steel eye hook for efficient probe movement were incorporated. Waterproofing measures, including silicon sealant and O-rings, ensured durability in harsh aquatic conditions. These specifications were tailored to meet the demanding requirements of temperature profiling, establishing a solid foundation for the design and development.

3.1 Winch Operation and Heave Compensation

The design and development process aimed at reliable temperature profiling in oceanic or lake environments which prioritized heave compensation as a crucial aspect. The temperature probe and the electronics on the boat, shown in Figure 2, integrated a microcontroller with an Inertial Measurement Unit (IMU) module which played a central role in achieving this objective [12]. The system's winch, responsible for controlling the vertical movement of the temperature probe, operated at a speed of 0.5 m/s. However, due to the buoyancy of the probe in water, this speed reduced to 0.2 m/s during actual operations. Furthermore, the temperature sensor was programmed to pause for 2 seconds every 0.2 meters of descent till a maximum of 2 meters to ensure accurate data collection at each depth.

The temperature profiling system incorporates a stepper motor, controlled by a dedicated driver, to manage the probe's vertical movement for heave compensation. A microcontroller was used to analyse data from the Inertial Measurement Unit (IMU) with embedded software algorithms, which controls the stepper motor to maintain the probe's depth for consistent temperature measurements. The IMU integrated into the system provided critical feedback for heave compensation. As the boat encountered vertical movement due to waves or other disturbances, the IMU detected changes in position, and the winch adjusted the probe's movement accordingly. To compensate for the heave, the winch moved the probe in the opposite direction of the detected movement after a brief 0.5-second delay, which accounted for the computation time and initial motor torque. This design helped maintain accurate and consistent probe positioning despite environmental factors, although during lake testing, the

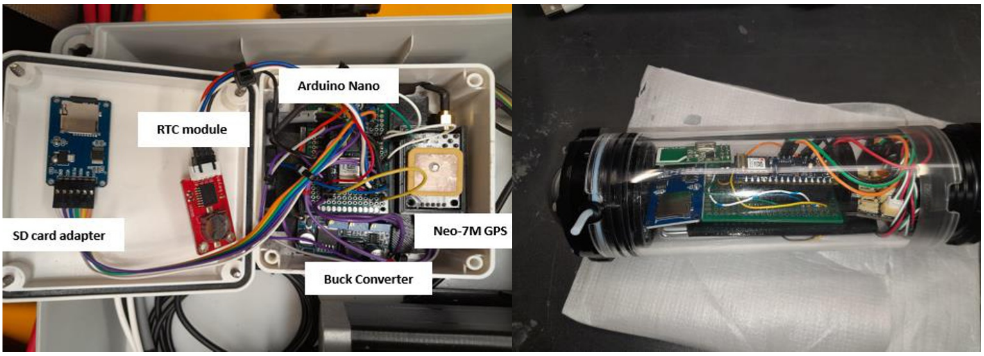

Fig. 2. Boat and temperature probe electronics.

vertical changes, or heaves, were minimal due to the relatively calm conditions. Acceptable heave changes were noted to be 0.1 meters or more.

Waterproofing measures such as silicon seals and lubricants protect sensor functionality. Other complementary components on the boat side facilitate synchronized data collection, safety monitor and autonomous operation, ensuring comprehensive temperature profiling in aquatic environments. This integrated system architecture aligns with research goals, and rigorous investigation in demanding aquatic settings.

3.2 Boat and probe integration

The IMU sensor detected vertical movements, posing a challenge for the mechanical design to manage. Attention to detail facilitated controlled lowering and raising of the temperature probe [13]. The mechanical design of the boat, depicted in Figure 3, allowed for smooth integration with the winch and sensor systems.

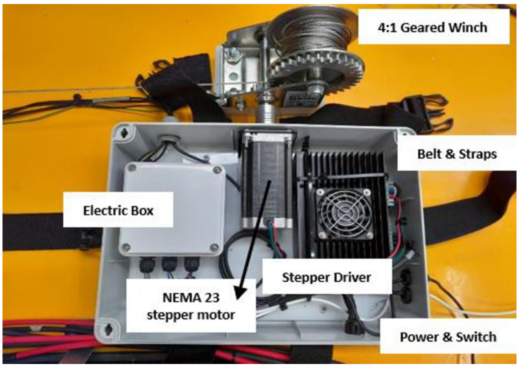

Fig. 3. Boat control system box.

A central hole was drilled in the deck of the boat for the probe's deployment. Placing the hole at the centre reduced the complexity of the IMU's calculations, as it minimized the need for adjusting for the boat's tilting angle during heave compensation. This strategic design choice streamlined the system's operation and improved the overall efficiency of the IMU-based compensations [14]. The selection of stainless-steel wire ropes showcased the system's resilience to maritime conditions, resisting corrosion in saltwater environments [5]. A sheave pulley above the opening improved winch performance, distributing load and reducing friction on the winch shaft. This mechanical advantage increased operational efficiency and prolonged winch lifespan by minimizing wear and tear.

The system layout on the boat was organized to ensure efficient operation in the water, with key components strategically positioned for optimal functionality. The winch and stepper motor were central to regulating the temperature probe's deployment and retrieval, with the stepper motor located nearby for precise control. The control box, housing critical electronics with a protection rating of IP67, was securely mounted on the boat.

3.3 GPS navigation

Incorporating GPS navigation capabilities further enhanced system precision and efficiency, allowing for precise deployment and retrieval of the probe based on predetermined coordinates. The system utilized data from two GPS sources for redundancy, with the boat's onboard GPS system serving as the primary source, and an additional GPS module attached to the microcontroller for added precision. Continuous comparison and alignment of data from both sources minimized errors, ensuring dependable spatial reference for operation [16]. Synchronized communication between the microcontroller and the boat's onboard computer facilitated automated deployment and recovery of the probe, as the boat navigated towards designated GPS points, improving productivity and reducing the risk of human error.

Initially, the system was intended to operate autonomously, guided by GPS coordinates for temperature sampling. However, during testing, the boat's GPS system encountered communication issues with the base station, requiring manual navigation. As a result, although the majority of GPS positions were within acceptable deviations, some errors in positioning were observed. These inaccuracies occasionally led to the probe not being lowered at the intended locations. Despite these issues, the overall design of the system proved effective for the purposes of the research, offering a low-cost solution that retained the temperature measurement accuracy necessary for small-scale aquatic testing.

3.4 Data collection

In addition to its functional components, the system was equipped with a comprehensive data management and retrieval strategy to ensure effective collection and analysis of critical data [15]. Designed to record both water temperature profiles and spatial information of the boat's movements, the system facilitated post-mission data processing. GPS coordinates of the boat's location were recorded at regular intervals by the boat's microcontroller and stored on an SD card, allowing for tracking of the boat's trajectory throughout its operation.

Similarly, temperature readings at specific depth intervals were recorded by sensors on the temperature probe and stored on the SD card, ensuring accurate data collection. The winch controlled the lowering of the probe, and each time the probe descended by 0.2 meters, the system paused for 2 seconds to allow the temperature sensor to adjust to the surrounding environment. These pauses mitigated errors caused by rapid movement through water layers of differing temperatures. After the probe had descended 10 times, it was retrieved back to the boat. This process was repeated at each predetermined GPS location.

Upon the boat's return to shore, the collected data could be easily retrieved from the SD cards for post-mission processing. This process allowed the team to visualize the boat's trajectory and generate detailed temperature profiles. The use of MATLAB for post-processing enabled the creation of 3D temperature profiles, providing valuable insights into temperature fluctuations and the environmental conditions of the lake.

3.5 System Synchronization and Safety

To ensure the integrity of the system during operation, the winch and sensors were synchronized with the boat's movements. As the boat moved, the probe's position was dynamically adjusted based on real-time data from the IMU and GPS. This coordination allowed for the continuous monitoring of the probe's depth, ensuring that temperature readings were taken at the correct intervals.

Safety was a critical aspect of the design, particularly in ensuring the probe's safe retrieval. In addition to the limit switch, which stopped the winch once the probe was lifted out of the water and hit the bottom of the boat, a proximity sensor acted as a backup. This sensor was positioned near the hole through which the probe was lowered and was triggered if the probe reached a certain height during retrieval. In the event of a limit switch failure, the proximity sensor would stop the winch to prevent damage to the probe or the boat. This redundancy ensured that the system could safely lift the probe without risking damage.

These safety features were tested rigorously during lake trials, where the system operated under real-world conditions. The lack of significant heaves during testing was beneficial for evaluating the system's ability to maintain steady operation without major disruptions. Although minimal vertical movement was detected, the IMU and winch system successfully compensated for any minor fluctuations in water level.

4 Results and discussion

The lake tests conducted using the winch-controlled probe system yielded valuable insights into the system's performance under real-world conditions. While some challenges arose, such as manual navigation due to GPS communication issues, the system still provided accurate temperature profiles, demonstrating its effectiveness for low-cost aquatic research.

4.1 System validation

Throughout the testing period, the system recorded over 300 reliable temperature readings at depths up to 2.5 meters. These readings were consistent with the anticipated temperature

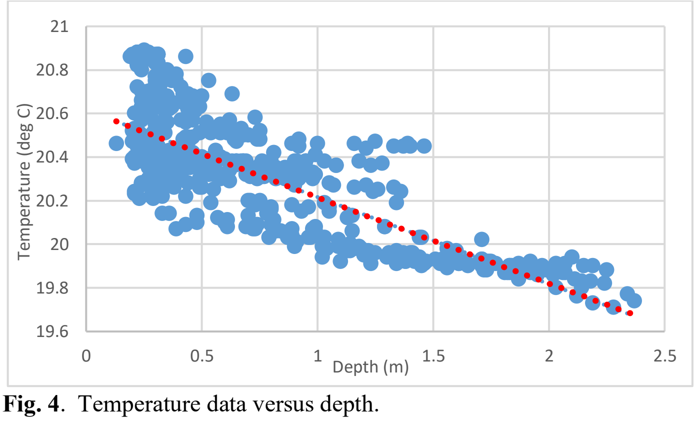

Fig. 4. Temperature data versus depth.

profile of the lake, reflecting the conditions on the day of testing. Figure 4 presents a plot of the temperature versus depth, demonstrating the general trend of temperature decreasing with depth, as the probe moved from the warmer surface layers into cooler subsurface layers.

The experiment results provide valuable insights into the durability of temperature profiles in controlled environments, particularly in relatively shallow waters. However, it's crucial to recognize that lake temperatures may be influenced by intricate interactions differing from controlled settings, potentially introducing variations not noticeable in steady waters. The data revealed a gradual cooling trend from the lake's shoreline to its centre, as illustrated by the temperature map in Figure 5. The map, which shows interpolated

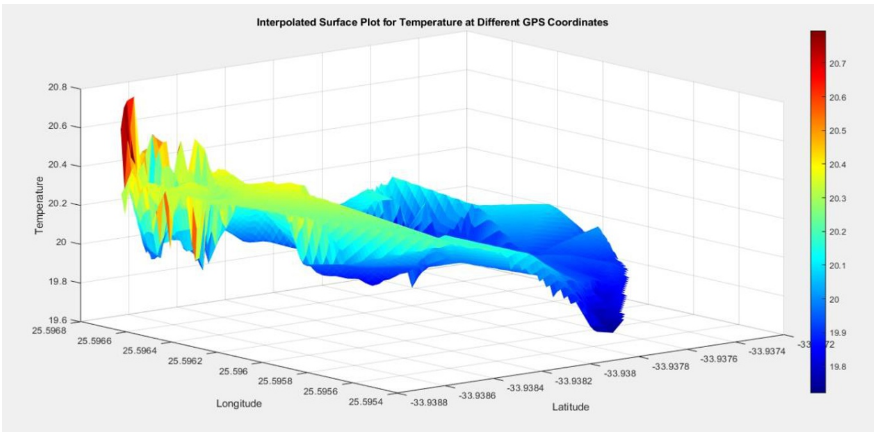

Fig. 5. 3D interpolated temperature plot at overall locations.

temperature data across different GPS positions, indicates cooler temperatures at the centre of the lake. This variation is likely influenced by several factors, including water depth, solar exposure, and water currents.

As previously noted, the GPS communication issue between the boat and the base station necessitated manual navigation, introducing some deviations from the intended course. In some instances, this led to the probe being lowered and lifted at unintended locations or not at all. Variations in the recorded and expected maximum depths were not only due to water drifts and drag forces acting on the probe, but also due to the misalignment between GPS positions. However, despite these setbacks, the system’s control algorithms worked well for most GPS positions. The temperature interpolation based on latitude and longitude provided meaningful results, but certain areas where the probe was not correctly positioned introduced minor anomalies. The manual control did affect the uniformity of data acquisition, and future iterations of the system should aim to improve GPS reliability to ensure accurate, autonomous probe deployment. Nonetheless, these deviations had a limited impact on the overall results, and the system was still able to capture the temperature variations throughout the lake.

The IMU-based heave compensation system performed effectively during the trials. Although there was minimal vertical movement due to the calm lake conditions, the system was able to compensate for minor vertical displacements as the boat moved. The winch adjusted the probe’s position accordingly, maintaining accurate depth control despite environmental disturbances. The 0.5-second delay in the winch operation, required for computing the heave adjustments and managing the motor’s torque, did not significantly affect the system's performance. During testing, no major heaves were detected, which reduced the need for active compensation. However, the system was designed to handle vertical displacements of 0.1 meters or larger, which would typically occur in more turbulent waters or oceanic environments. Further testing in rougher conditions is recommended to evaluate the full capabilities of the heave compensation system.

The safety features built into the system—particularly the limit switch and proximity sensor—were tested extensively during the lake trials. These mechanisms ensured that the probe was safely retrieved without any damage. The limit switch effectively detected when the probe was lifted out of the water, stopping the winch automatically. The proximity sensor acted as a backup, triggering when the probe reached a specific height near the boat's hull, ensuring an additional layer of safety.

4.2 Data analysis

Statistical evaluation and predictive analysis [15] of the temperature profiles generated by the system are feasible due to minimal variance in these environments. Visualization of scattered data and contour plots using MATLAB enhances understanding of recorded data, shown in Figure 6. Stratification allows detailed examination of temperature changes at

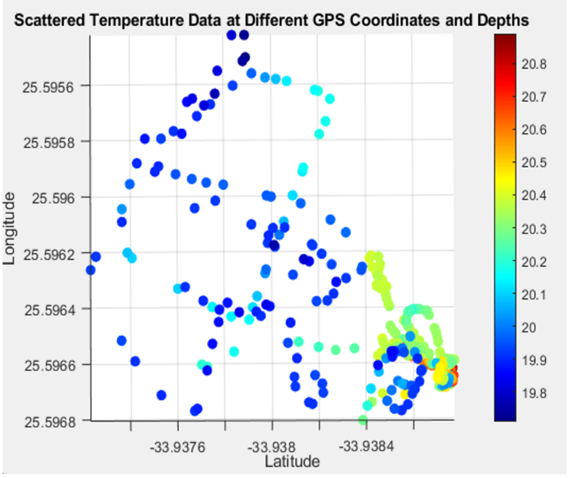

Fig. 6. Scatted data at different GPS and depth.

specific depths [17], maintaining data integrity and ensuring representation of temperature profiles [4,6]. Segmentation of depth measurements into five layers with consistent intervals facilitates precise data management and presentation, where multiple temperature readings are obtained at the same GPS points.

These layers facilitate a depiction of temperature profiles, ensuring that the accuracy and distinctiveness of temperatures remain intact. The first layer, between 0.1 and 0.6 meter depth, as shown in Figure 7, could provide insights into thermal dynamics within the lake, indicating cooler temperatures at greater depths and potential localized variations influenced by factors like water currents, underwater geography [6], and solar exposure [3].

5 Conclusion

In conclusion, the development and testing of the winch-controlled temperature probe system for aquatic temperature profiling has shown promising capabilities alongside areas for refinement. The integration of accurate sensors and real-time heave compensation contributed to the system's overall performance.

Despite challenges like GPS communication issues, which required manual navigation. The system proved its capability and successfully recorded over 300 temperature readings at depths of up to 2.5 meters, with an accuracy of ±0.1 °C for temperature and ±2 cm for depth. The data revealed distinct temperature gradients from the shore to the centre of the lake, reflecting the influence of various environmental factors such as depth and solar exposure. However, discrepancies observed in temperature data show the need for enhanced precision in probe movements and fine-tuning of navigation capabilities.

The IMU-based heave compensation system performed well under minor disturbances, maintaining accurate depth control. Safety features like the limit switch and proximity sensor ensured reliable probe retrieval without damage.

Utilization of contour plots and segmentation of depth layers provided detailed insights into temperature variations at specific depths and locations within the lake, revealing complex thermal distribution dynamics. These acquired testing results provide a proof of concept for the system in action, as well as a basis for understanding temperature profiles' implications on aquatic research. Addressing the differences in temperature readings during probe movements will require enhancements to navigation mechanisms, synchronization of winch operation with boat movement, and sensor response time calibration.

This research has demonstrated that a low-cost, lightweight system can deliver relatively accurate temperature data, making it a valuable tool for small-scale aquatic research. This research sets the foundation for more reliable aquatic temperature profiling devices, vital for advancing our understanding of aquatic ecosystems and their responses to changing climatic conditions. Future directions should explore deeper waters and diverse locations in the lake or oceanic environments.

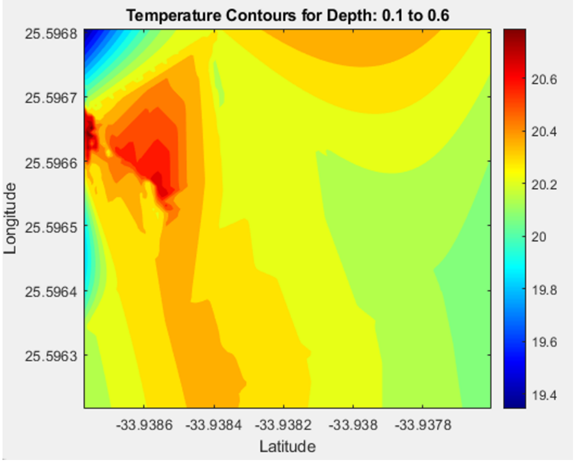

Fig. 7. Contour plots for layer 0.1~0.6 meters.

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