# Peer-Reviewed Technical Communication

# Using an Autonomous Underwater Vehicle to Track the Thermocline Based on Peak-Gradient Detection

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***Abstract*—The thermocline plays a key role in underwater acoustics and marine ecology. In oceanographic surveys, it is often desirable to detect the thermocline and track its spatio–temporal variation. Mobility of an autonomous underwater vehicle (AUV) makes it an efficient platform for thermocline tracking. In this paper, we present an autonomous algorithm for detecting and tracking the thermocline by an AUV. The key is detection and close tracking of the maximum vertical gradient of temperature. On August 31 and September 1, 2010, the Tethys AUV ran the algorithm to closely track the thermocline across a sharp temperature front in Monterey Bay, CA.**

***Index Terms*—Autonomous underwater vehicle (AUV), peak-gradient detection, thermocline.**

## I. Introduction

THE depth at which the vertical temperature gradient is maximum is called the thermocline [1]. The thermocline is of great significance to the physical, chemical, and biological functioning of marine environments. Temperature is a dominant determinant of underwater sound speed. The direction of sound propagation depends on the sound-speed profile. Hence, the thermocline depth and the shape of the temperature profile determine the bending of the sound rays, which affects the sonar performance [2]. The thermocline also plays a key role in marine ecology. The common coincidence of the thermocline (for temperature) and the nutricline (for nutrient concentration) defines a physical–chemical structure that regulates the ocean carbon cycle [3]. In oceanographic surveys, it is often desirable to detect the thermocline and track its spatio–temporal variation. Cazenave *et al.* (including the first and second coauthors of this paper) have previously developed a method of using an autonomous underwater vehicle (AUV) to closely track the vertical displacement of the thermocline, which was successfully applied in investigating internal tidal waves in Monterey Bay, CA, in 2007 [4]. We first deployed the vehicle on a short mission to measure the vertical temperature profile, and then recovered the AUV to quickly review the measured profile and visually identify the thermocline. Then, we set a narrow temperature envelope (i.e., lower and upper temperature bounds) around the thermocline, and commanded the vehicle to run within the temperature envelope, thereby closely tracking the thermocline. This method was not fully autonomous because it required human intervention (i.e., data analysis) in a preliminary survey to set temperature bounds for thermocline tracking. In some other experiments that used AUVs for thermocline tracking [5], [6], human intervention was required to define a preset threshold of the vertical temperature gradient.

Petillo *et al.* presented an autonomous thermocline-tracking algorithm for an AUV [7]. The vehicle first conducts a deep dive and calculates the average vertical gradient of temperature over the full depth. Then, the layer where the temperature gradient exceeds the full-depth average temperature gradient is defined as the thermocline layer. The AUV subsequently confines its sawtooth trajectory in the vertical dimension (i.e., a yo-yo trajectory) within this layer in an attempt to track the thermocline.

In [8] and [9], Cruz and Matos took a major step forward in using an AUV to autonomously track the thermocline. The temperature profile was properly modeled as being composed of three layers (from shallow to deep): the upper mixed layer with a low vertical temperature gradient, the thermocline layer with a high vertical temperature gradient, and the deep-water layer with a low vertical temperature gradient. Suppose the AUV runs on a yo-yo trajectory in the vertical dimension and is currently on an ascent leg. The vehicle records the maximum temperature gradient $|\mathrm{TempGrad}|_{\max}$ on this ascent leg. Three thresholds of temperature gradient are accordingly defined: $\mathrm{Thr}_{tc} = 1/2|\mathrm{TempGrad}|_{\max}, \mathrm{Thr}_{\mathrm{top}} = 1/4|\mathrm{TempGrad}|_{\max}$, $\mathrm{Thr}_{\mathrm{bottom}} = 1/8|\mathrm{TempGrad}|_{\max}$ (the coefficients can be set to different values depending on the water column's properties). On the succeeding descent leg, when the measured temperature gradient exceeds $\mathrm{Thr}_{tc}$, the AUV will assume it has exited the upper mixed layer and entered the thermocline layer. The vehicle continues to dive, and when the temperature gradient drops below $\mathrm{Thr}_{\mathrm{bottom}}$, the AUV will assume it has exited the thermocline layer and entered the deep-water layer. At this point, the vehicle flips attitude to ascent. Also at this point, the vehicle records the maximum temperature gradient $|\mathrm{TempGrad}|_{\max}$ on the just completed descent leg, and accordingly set the three thresholds of temperature gradient $\mathrm{Thr}_{tc}$, $\mathrm{Thr}_{\mathrm{top}}$, and $\mathrm{Thr}_{\mathrm{bottom}}$ for the upcoming ascent leg. On the ascent leg, when the measured temperature gradient exceeds $\mathrm{Thr}_{tc}$, the AUV will assume it has exited the deep-water layer and entered the thermocline layer. The vehicle continues to

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climb, and when the temperature gradient drops below $\mathrm{Thr}_{\mathrm{top}}$, the AUV will assume it has exited the thermocline layer and entered the upper mixed layer. At this point, the vehicle flips attitude to descent. The AUV tracks the thermocline by alternating the descent and ascent behaviors. Depth limits are set for vehicle safety.

We have independently developed an autonomous algorithm for an AUV to detect and track the thermocline [10]. We present our method in Section II, and also compare it with Petillo's and Cruz's methods. On August 31 and September 1, 2010, the Tethys AUV [11] ran the presented algorithm to closely track the thermocline across a sharp temperature front in Monterey Bay, CA, as described in Section III. We propose future work in Section IV.

## II. A Method for Detecting and Tracking the Thermocline Based on Peak-Gradient Detection

The mechanism of our method is as follows.

1) The AUV detects the maximum vertical gradient of temperature on each descent or ascent leg on a yo-yo trajectory. The corresponding depth $DEP_{\mathrm{TempGradmax}}$ is regarded as the thermocline depth.
2) The AUV sets the target depth for the upcoming ascent or descent leg to $DEP_{\mathrm{target}} = DEP_{\mathrm{TempGradmax}} \pm DEP_{\mathrm{extension}}$ where $DEP_{\mathrm{extension}}$ is an extension depth to ensure that the AUV crosses the thermocline with some extra depth range. When the vehicle reaches the target depth on an ascent (or descent) leg, it flips attitude to descent (or ascent).
3) The AUV repeats the above descent and ascent behaviors so as to closely track the thermocline.

The key components of the algorithm are given as follows.

### A. Averaging Temperature in Depth Bins

The vertical gradient of temperature $\partial T/\partial z$ is the partial derivative of temperature $T$ as a function of depth $z$ (a positive number increasing with depth). This differentiation amplifies temperature measurement noise as well as temperature's fine-scale variation over depth. To mitigate this effect, we divide the water column into a number of depth bins, and average the AUV's temperature measurements in each bin. The averaged temperature $\bar{T}$ in each bin is used for calculating the vertical gradient of temperature

$$\mathrm{TempGrad}(m) = \frac{\bar{T}(m) - \bar{T}(m-1)}{\Delta z} \quad (1)$$

where $\Delta z$ is the depth bin size, and $m$ is the depth bin index. The value of $\Delta z$ is set for a balance between noise rejection and depth resolution in calculating the temperature gradient. If $\Delta z$ is set too small, temperature noise may cause a large error in the calculated temperature gradient which will lead to a wrong thermocline depth. If it is set too large, depth resolution will be too coarse. Setting of this parameter is affected by the temperature sensor's specification (measurement noise) and also the environment (temperature's fine-scale variation over depth). There will be more discussions on the setting of $\Delta z$ in Section IV.

### B. Detecting the Peak Vertical Gradient of Temperature

We run the AUV on a yo-yo trajectory (in the vertical dimension) that is defined by successive target depths (as will be described in Section II-D). On each descent or ascent leg, the AUV seeks the maximum vertical gradient of temperature $|\mathrm{TempGrad}|_{\max}$ and the corresponding depth $DEP_{\mathrm{TempGradmax}}$ (regarded as the thermocline depth) as follows (both variables are initialized to zero):

$$\begin{aligned} &\text{If } |\mathrm{TempGrad}(m)| > |\mathrm{TempGrad}|_{\max}, \\ &\quad \text{set } |\mathrm{TempGrad}|_{\max} \text{ to } |\mathrm{TempGrad}(m)|, \\ &\quad \text{and set } DEP_{\mathrm{TempGradmax}} \text{ to } DEP_{\mathrm{BinEnd}}(m-1). \end{aligned} \quad (2)$$

Since the differentiation in (1) is conducted on the $m$th and $(m-1)$th depth bins, we take $DEP_{\mathrm{BinEnd}}(m-1)$ [i.e., the depth of the last sample in the $(m-1)$th bin] as the thermocline depth. When the AUV turns from descent to ascent (or from ascent to descent), it reports $|\mathrm{TempGrad}|_{\max}$ of the entire descent (or ascent) leg it has just completed and the corresponding $DEP_{\mathrm{TempGradmax}}$. At the start of the next ascent (or descent) leg, peak-gradient detection starts anew.

### C. Tracking the AUV's Descent and Ascent

On each descent or ascent leg, the AUV seeks the peak vertical temperature gradient along the entire leg, and reports $|\mathrm{TempGrad}|_{\max}$ and the corresponding $DEP_{\mathrm{TempGradmax}}$ on completion of the leg. Hence, it is a key task to keep track of the start and end of a descent or ascent leg. Following our previously developed algorithm for capturing peaks in a biological thin layer [12], we define a state variable $S_{DEP}$ ($S_{DEP} = 1$: descending; $S_{DEP} = 0$: ascending), and two accompanying variables: the maximum depth $DEP_{\max}$ (for descent) and the minimum depth $DEP_{\min}$ (for ascent), as expressed in (3), shown at the top of the next page. $DEP(n)$ is the AUV's depth at the current time [note that $DEP(n)$ is a positive number increasing with depth]. $DEP_{\max}$ is initialized to zero; at the attitude flip from descent to ascent, $DEP_{\min}$ will be set to the flipping-point depth. When the AUV turns from descent to ascent, $S_{DEP}$ flips from 1 to 0. Conversely, when the AUV turns from ascent to descent, $S_{DEP}$ flips from 0 to 1. To prevent false state changes due to the depth sensor's measurement noise, we set a threshold $\delta_{dep} = 0.5$ m. At the end of a descent leg, only when the depth has decreased four times in a row and also has decreased from $DEP_{\max}$ by more than $\delta_{dep}$, does $S_{DEP}$ flip from 1 to 0. The requirement of four consecutive depth decrements will cause some delay in detecting the AUV's attitude change, which means that a short starting segment (near the attitude flip point) of the ensuing ascent leg will be included for finding $|\mathrm{TempGrad}|_{\max}$ on the just completed descent leg. In effect, when setting the target depth on the ascent leg using $|\mathrm{TempGrad}|_{\max}$, the temperature profile on the short starting segment of the ascent leg (which contains more recent temperature profile information than that contained in the ending segment of the descent leg) is also taken into account. Therefore, this extra inclusion does not pose a problem for setting the vehicle's target depth on the ascent leg. Likewise, for robust detection of attitude change from ascent to descent, at the end of an ascent leg, only when the depth

If $S_{DEP}(n-1)=1$ (descending)
  If $DEP(n) > DEP_{\max}$,
    set $S_{DEP}(n)$ to $1,$ and set $DEP_{\max}$ to $DEP(n)$.
  Else
    If $DEP(n) - DEP_{\max} < -\delta_{dep}$ AND [depth has decreased four times in a row],
      set $S_{DEP}(n)$ to 0 (ascending), and set $DEP_{\min}$ to $DEP(n)$.
    Else
      set $S_{DEP}(n)$ to 1.
Else
  If $DEP(n) < DEP_{\min}$,
    set $S_{DEP}(n)$ to $0,$ and set $DEP_{\min}$ to $DEP(n)$.
  Else
    If $DEP(n) - DEP_{\min} > \delta_{dep}$ AND [depth has increased four times in a row],
      set $S_{DEP}(n)$ to 1 (descending), and set $DEP_{\max}$ to $DEP(n)$.
    Else
      set $S_{DEP}(n)$ to 0. (3)

has increased four times in a row and also has increased from $DEP_{\min}$ by more than $\delta_{dep}$, does $S_{DEP}$ flip from 0 to 1.

### D. Setting the Target Depth of the Upcoming Leg

On each descent or ascent leg, the vehicle detects the peak vertical gradient of temperature $|\mathrm{TempGrad}|_{\max}$ and saves the corresponding thermocline depth $DEP_{\mathrm{TempGradmax}}$. At the end of the leg, the vehicle sets the target depth for the upcoming leg based on the latest thermocline depth as follows:

$$DEP_{\mathrm{target}} = \begin{cases} DEP_{\mathrm{TempGradmax}} + DEP_{\mathrm{extension}}, & \text{for descent} \\ DEP_{\mathrm{TempGradmax}} - DEP_{\mathrm{extension}}, & \text{for ascent} \end{cases} \quad (4)$$

where $DEP_{\mathrm{extension}}$ is an extension depth. For an upcoming descent leg, the vehicle targets a depth that is deeper than $DEP_{\mathrm{TempGradmax}}$ by $DEP_{\mathrm{extension}}$; for an upcoming ascent leg, the vehicle targets a depth that is shallower than $DEP_{\mathrm{TempGradmax}}$ by $DEP_{\mathrm{extension}}$. We set this extension depth to let the AUV cover a larger depth range, for two reasons: 1) to capture the true peak (rather than a local maximum) of temperature gradient; and 2) to allow for variation of the thermocline depth over distance. Once the vehicle reaches the target depth, it starts to flip attitude (to change from descent to ascent or conversely). Since it takes a short moment for the AUV to change attitude, the vehicle will overshoot by some distance before making the turn. This will further enlarge the AUV's depth envelope.

In Petillo's method (see Section I), the AUV only calculates the average vertical gradient of temperature over a full-depth dive, but not the peak vertical gradient of temperature $|\mathrm{TempGrad}|_{\max}$. The layer where the temperature gradient exceeds the full-depth average temperature gradient is defined as the thermocline layer. This is a fine method for the AUV to safely cover the thermocline layer, but when the thermocline is mild (i.e., the maximum temperature gradient is not much higher than the full-depth average temperature gradient), the thermocline layer defined by the above criterion (temperature gradient merely exceeding the full-depth average temperature gradient) can have a large thickness. As a consequence, the AUV's vertical undulation range can be large, leading to low horizontal resolution of the thermocline.

A commonality of Cruz's method and our method is that the peak vertical gradient of temperature $|\mathrm{TempGrad}|_{\max}$ on the just completed descent/ascent leg is used to define the AUV's depth range on the upcoming ascent/descent leg. The major difference between the two methods and their respective advantages and disadvantages are suggested as follows.

- In Cruz's method, the AUV's vertical undulation range depends on the temperature profile's shape and the setting of the three threshold coefficients $\alpha_{tc}$, $\alpha_{\mathrm{top}}$, and $\alpha_{\mathrm{bottom}}$ (for defining $\mathrm{Thr}_{tc} = \alpha_{tc}|\mathrm{TempGrad}|_{\max}$, $\mathrm{Thr}_{\mathrm{top}} = \alpha_{\mathrm{top}}|\mathrm{TempGrad}|_{\max}$, and $\mathrm{Thr}_{\mathrm{bottom}} = \alpha_{\mathrm{bottom}}|\mathrm{TempGrad}|_{\max}$, respectively; see Section I). Suppose the vehicle is on descent and has entered the thermocline layer. On its way exiting the thermocline layer, the vehicle looks for the point where the measured temperature gradient drops below $\mathrm{Thr}_{\mathrm{bottom}} = \alpha_{\mathrm{bottom}}|\mathrm{TempGrad}|_{\max}$ (note that $|\mathrm{TempGrad}|_{\max}$ is from the preceding ascent leg). If the temperature gradient drops sharply below the thermocline, the AUV will find that exit point quickly and flip attitude to ascent; but if the temperature gradient drops slowly below the thermocline, the AUV will continue diving for a large depth before reaching the exit point. Considering the strong spatial and temporal variability in water column thermal gradients that is typical of many coastal environments, it may be relatively difficult to define one set of $\alpha$ factors that will work consistently well. Cruz's method is beneficial for keeping the AUV crossing

TABLE I
SPECIFICATIONS OF THE TETHYS AUV'S TEMPERATURE, CONDUCTIVITY, AND DEPTH SENSORS

| Measurement | Sensor model | Range | Accuracy | RMS noise |
|---|---|---|---|---|
| Temperature | NBOSI | -5 ~ 45ºC | 0.0005ºC | 0.0003ºC (at 10 Hz sampling rate) |
| Conductivity | NBOSI | 0 ~ 9 S/m | 0.0001 S/m | 0.00002 S/m (at 10 Hz sampling rate) |
| Pressure | Keller PA-6ST/50BAR | 50 bar (500 m in water) | 0.5% Full Scale | Not provided by manufacturer. |

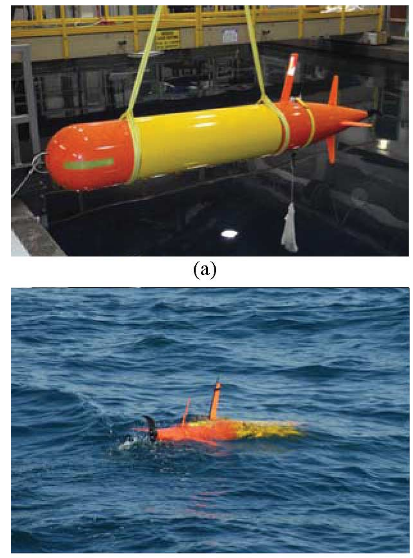
the thermocline, but maybe at a price of a large vertical undulation range which compromises the horizontal resolution of thermocline tracking.

- In our method, the target depth for the upcoming leg is set to $DEP_{\mathrm{TempGradmax}} \pm DEP_{\mathrm{extension}}$. So for temperature profiles of different shapes, the AUV's vertical undulation range around $DEP_{\mathrm{TempGradmax}}$ remains the same: $\pm DEP_{\mathrm{extension}}$. Thus, the AUV tracks the maximum vertical gradient of temperature within a known vertical range (note that $DEP_{\mathrm{TempGradmax}}$ may vary from profile to profile). At a properly small $DEP_{\mathrm{extension}}$, the AUV can track the thermocline with a small vertical undulation (and thus a dense sampling of the thermocline). Hence, our method is particularly useful for tracking a strong thermocline at high horizontal resolution, whereas Cruz's method is very useful for covering a relatively thick thermocline layer where the vertical temperature gradient is mild. In water columns with strong thermoclines, there are physical processes that result from buoyancy forcing of the thermocline itself, such as internal waves [4]. Adequately resolving high spatial frequency internal wave structures (not aliasing their structures) requires enhanced horizontal resolution, which tighter yo-yo vertical envelopes provide. Compared with Cruz's method which requires setting of three threshold coefficients, our method is also simpler to implement.

  However, in our method, if $DEP_{\mathrm{extension}}$ is set too small, the detection algorithm may be fooled by a local maximum of temperature gradient and miss the true peak gradient, or the vehicle may not catch up with a steep rise or fall of the thermocline depth. To prevent this potential problem, we propose approaches of adaptively adjusting $DEP_{\mathrm{extension}}$ and the depth bin size $\Delta z$ in Section IV.

## III. FIELD TESTS

The Tethys AUV [11], developed at the Monterey Bay Aquarium Research Institute (MBARI), Moss Landing, CA, as shown in Fig. 1, has a length of 2.3 m and a diameter of 0.3 m (i.e., 12 in) at the midsection. The propeller-driven vehicle can run effectively from 0.5 to 1 m/s. Propulsion power consumption is minimized through a careful design of a low-drag body and a high-efficiency propulsion system [13]. In addition, by using a buoyancy engine, the vehicle is capable of trimming to neutral buoyancy and drifting in a lower power mode. The Tethys AUV combines the merits of propeller-driven and buoyancy-driven vehicles. In the August/September 2010 field tests, the vehicle's sensor suite included Neil Brown Ocean Sensors, Inc. (NBOSI) temperature and conductivity sensors, a Keller depth sensor, a WET Labs ECO-Triplet Puck fluorescence/backscatter sensor, an Aanderaa dissolved oxygen sensor, and a LinkQuest Doppler velocity log (DVL). The conductivity–temperature–depth (CTD) sensors' specifications are given in Table I.



(a)

(b)

Fig. 1. The Tethys AUV (a) suspended over MBARI's test tank and (b) deployed in Monterey Bay, CA. The orange tail section of the vehicle is the propulsion and control section, which also includes antennas for Iridium and Argos satellites, GPS, and line-of-sight radio-frequency communications. The yellow center section is the main pressure vessel housing vehicle electronics and batteries. The orange head section is a wet volume housing a suite of science sensors.

The AUV's underwater navigation is by DVL-aided dead reckoning. The DVL provides the earth-referenced velocity of the AUV when the ocean bottom is within range. The vehicle's estimated speed is combined with measured heading and attitude and then accumulated to provide the estimated location of the AUV. The vehicle periodically ascends to the surface for a Global Positioning System (GPS) fix to correct the AUV's underwater navigation error [11].

On August 31 and September 1, 2010, we tested the presented thermocline tracking algorithm on the Tethys AUV in Monterey Bay, CA. The algorithm was coded in C++ and ran in real time on the AUV's computer. The AUV's horizontal tracks in the two missions are shown in Fig. 2. The AUV's vertical trajectories (autonomously defined by real-time thermocline detection and tracking) are shown in Fig. 3. The AUV's average horizontal speed was about 0.8 m/s. Its average vertical speed was about 0.13 m/s on descent legs and 0.17 m/s on ascent legs, respectively. Thus, the flight-path angle of the yo-yo trajectory (the angle between the trajectory and the horizontal) was $\beta_{\mathrm{flight\_path}} = \mathrm{atan}(0.13/0.8) = 9^\circ$ on descent legs and $\beta_{\mathrm{flight\_path}} = \mathrm{atan}(0.17/0.8) = 12^\circ$ on ascent legs. In both missions, we set the depth bin size $\Delta z$ to 1 m. The CTD sensors' sampling rate was about 2 Hz. Therefore, on average,

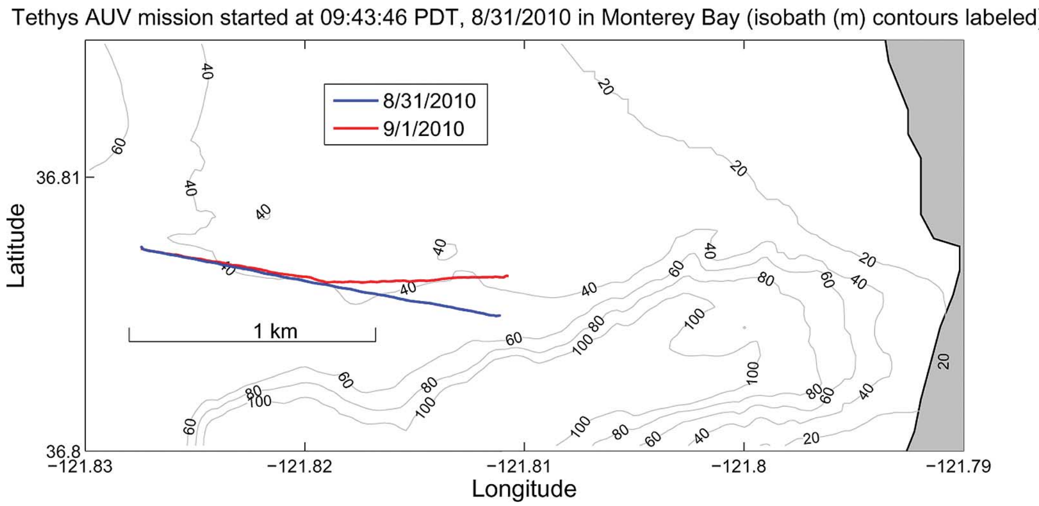



Fig. 2. Horizontal tracks of the Tethys AUV in missions on August 31, 2010 (mission log 20100831T152204, in blue) and on September 1, 2010 (mission log 20100901T173034, in red).

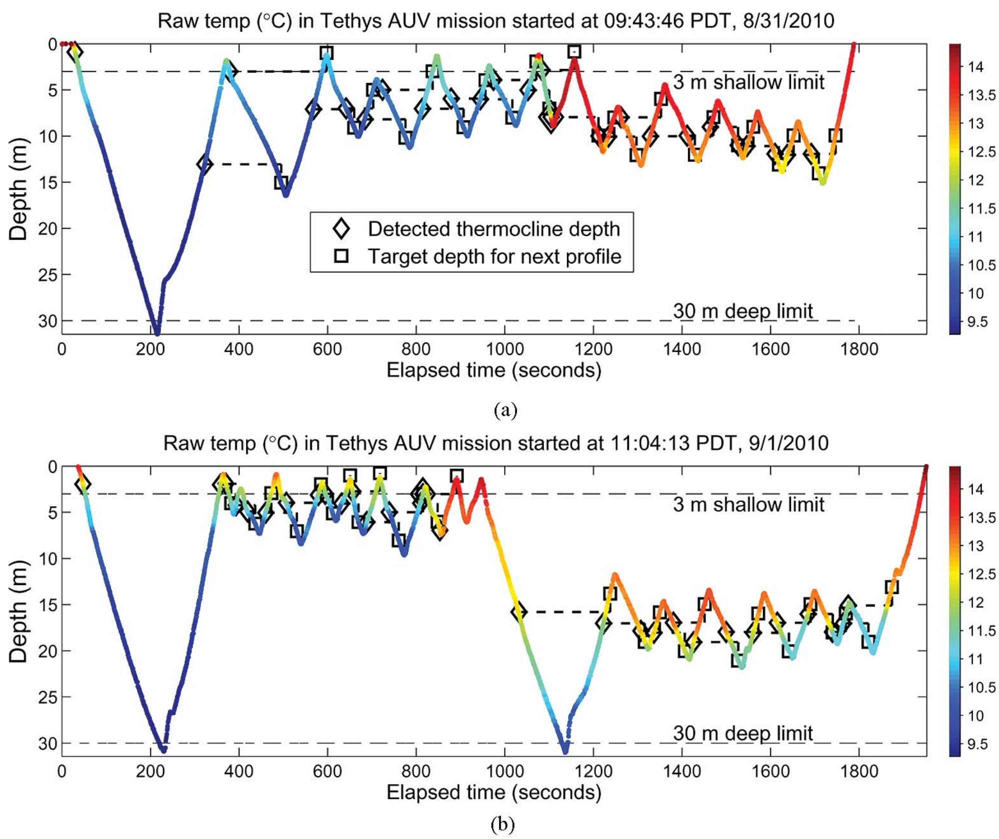



Fig. 3. Vertical trajectories of the Tethys AUV on (a) August 31, 2010 and (b) September 1, 2010. On each descent or ascent leg, the Tethys AUV detected the thermocline (marked by the diamond), and accordingly set the target depth for the upcoming leg (marked by the square).

each depth bin contained about 13 temperature data samples [(1 m/0.15 m/s) $\times$ 2 samples/s $\approx$ 13 samples]. Note that the smaller $\beta_{\rm flight\_path}$, the denser is the data samples in each bin (thus the more accurate the calculated temperature gradient), but the coarser is the horizontal resolution of thermocline tracking. We considered the above setting providing a reasonable balance between the two conflicting requirements.

### *A. Tethys AUV Mission on August 31, 2010*

In the AUV mission on August 31, 2010 (mission log 20100831T152204), the vehicle started with a dive from surface to 30 m, and then began thermocline tracking. For the AUV's operational safety, we set the vehicle's shallow and deep limits to 3 and 30 m, respectively, for the entire mission. A closeup view of ten yo-yo legs is given in Fig. 4. Bin-averaged temperature profiles (calculated offline) on those ten yo-yo legs are shown in Fig. 5. In Fig. 5, on each descent or ascent leg, the depth bin corresponding to the maximum $|\mathrm{TempGrad}|$ [by (1)] is marked by the triangle (pointing downward to denote a descent leg; pointing upward to denote an ascent leg).

On each descent or ascent leg, the Tethys AUV detected the thermocline (marked by the diamond in Fig. 4), and accordingly

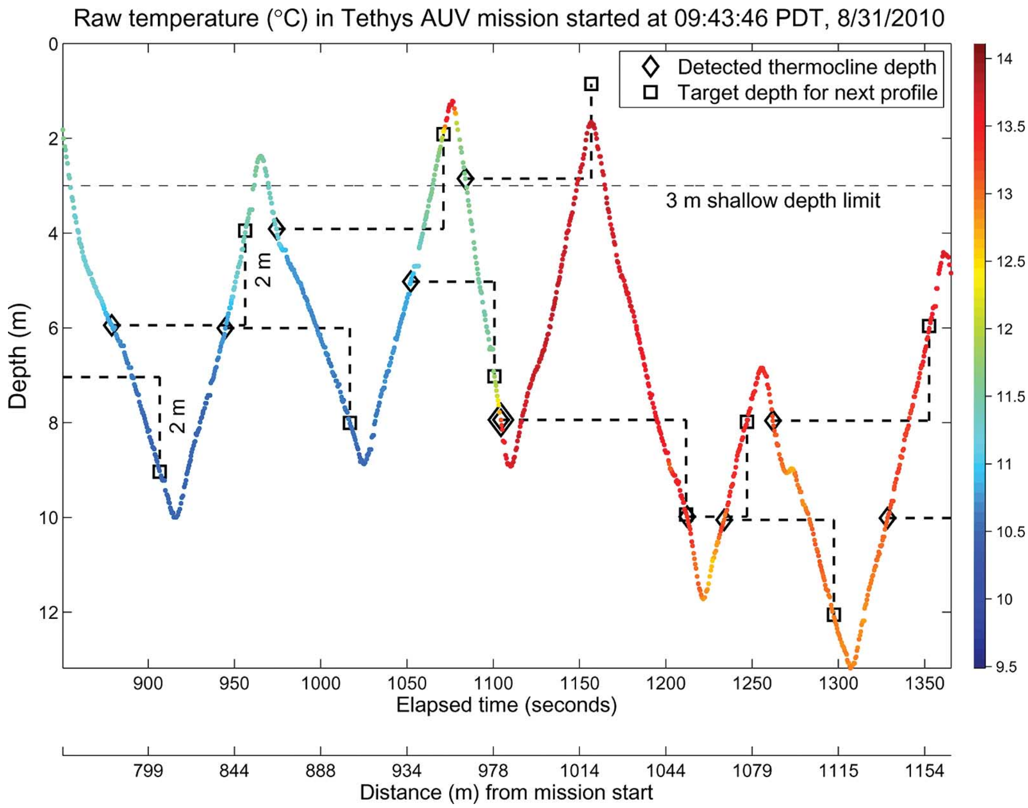



Fig. 4. Ten yo-yo legs of the Tethys AUV before and after the temperature front in the mission on August 31, 2010.

set the target depth for the upcoming leg (marked by the square in Fig. 4). For example, the first diamond marks the detected thermocline depth ($DEP_{\mathrm{TempGradmax}}$) at 5.9 m on the descent leg. By (4), the target depth ($DEP_{\mathrm{target}}$) of the upcoming ascent leg was set to 5.9 m $-$ 2 m $=$ 3.9 m, where 2 m was the extension depth $DEP_{\mathrm{extension}}$. On the ascent leg, when the AUV reached the 3.9-m target depth, it started to flip attitude to descent. Due to an 8-s lag of the AUV elevator's response (from the instant when the attitude flip command was issued to the instant when the elevator angle turned from positive to negative), the vehicle overshot by about 1.6 m. On that ascent leg, on the way toward the 3.9-m target depth, the vehicle detected the thermocline at 6.0-m depth, and accordingly set the target depth for the next descent leg to 6.0 m $+$ 2 m $=$ 8.0 m. Note that whenever the AUV ascended to the 3-m shallow limit (set for the entire mission), it flipped attitude to descent. The Tethys AUV's mission level software employs the state configured layered control architecture [14], [15]. Maintaining the 3-m shallow limit was a higher priority behavior than the behavior of reaching the target depth on a yo-yo profile. Therefore, if the target depth was shallower than 3 m, the 3-m shallow limit would override that target depth and the AUV would start flipping attitude at 3-m depth. It should be noted that in present Tethys missions, attitude control is executed jointly by turning the elevator and moving the mass (the battery pack). Consequently, the vehicle's response to the attitude-flip command is faster and the overshoot is accordingly reduced.

A note on the thermocline depth at 1104 s (marked by the double diamonds on the descent leg): it was actually detected at the very start of the succeeding ascent leg and was taken as the depth corresponding to $|\mathrm{TempGrad}|_{\max}$ on the ascent leg. This detection point was unusual in that it lay right at the AUV's turn from descent to ascent: the $(m-1)$th depth bin was on the descent leg and the $m$th depth bin was on the succeeding ascent leg [see (1)]. As explained following (2), the depth of the last sample in the $(m-1)$th depth bin was taken as the thermocline depth. Thus, the thermocline depth is marked (by the double diamonds) on the descent leg whereas the actual detection occurred at the very start of the succeeding ascent leg. This thermocline depth was used to set the target depth of the ensuing descent leg from 1160 to 1220 s.

The AUV crossed a sharp temperature front at about 1100 s into the mission. From 900 to 1300 s (over a distance of 316 m), the water temperature (averaged over depth) rose sharply from 10.8 °C to 13.1 °C. Near the front, the thermocline depth fell from approximately 6 m on the colder water side to approximately 10 m on the warmer water side [see Fig. 3(a)]. When crossing the sharp temperature front, it was likely that the 2-m extension depth ($DEP_{\mathrm{extension}}$) was not sufficient for the AUV to swiftly catch up with the steep fall of the thermocline depth. One indication was that the detected thermocline depth appeared to continue to fall when the AUV flew farther into the warmer water. To prepare the AUV for a precipitating thermocline across the front, we modified the tracking strategy in the second AUV mission described in Section III-B.

### B. Tethys AUV Mission on September 1, 2010

The Tethys AUV mission on September 1, 2010 (mission log 20100901T173034) is shown in Fig. 3(b). The vehicle's

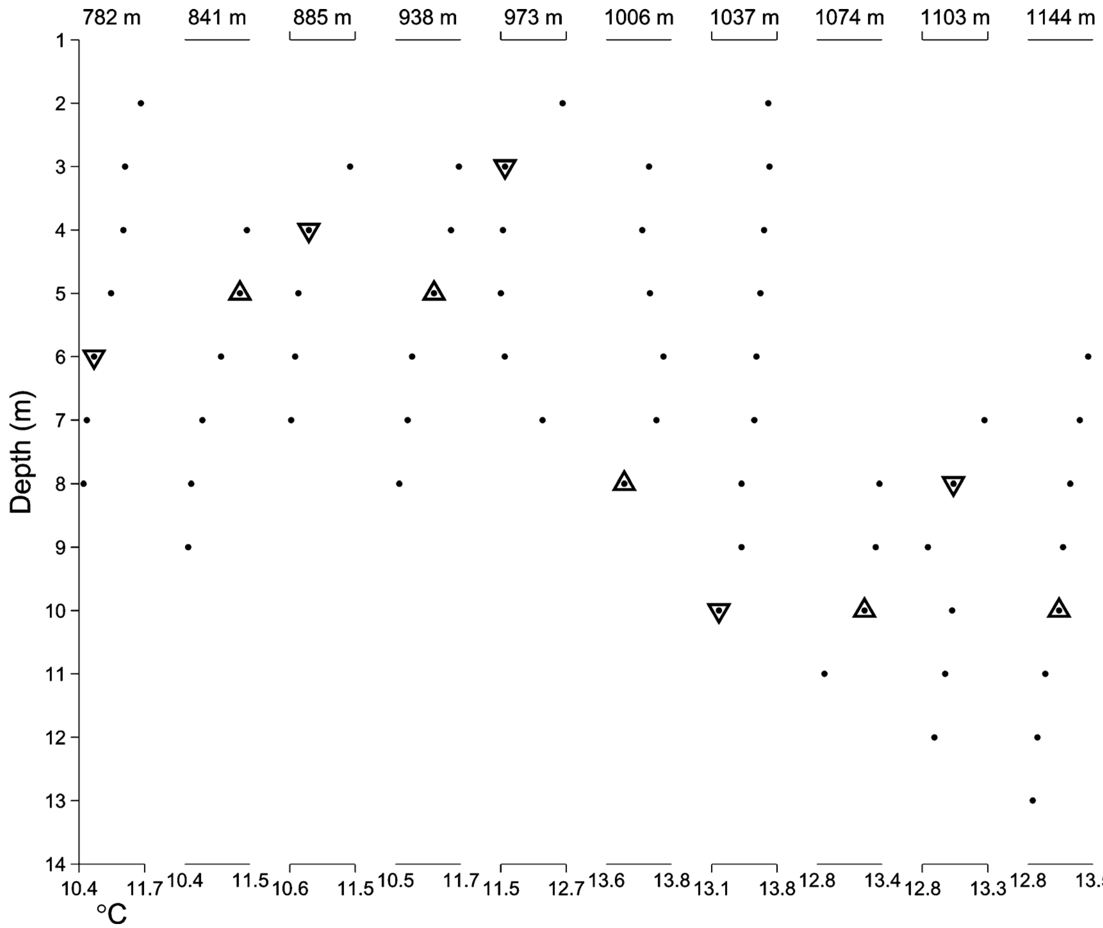



Fig. 5. Bin-averaged temperature profile (calculated offline) of each of the ten yo-yo legs in Fig. 4. The depth bin corresponding to the maximum $|\mathrm{TempGrad}|$ is marked by the triangle (pointing downward to denote a descent leg; pointing upward to denote an ascent leg). For each leg, the measured temperature range is shown at the bottom, and the distance from the mission start to the center of the leg is noted at the top.

operational safety limits were still set to 3 and 30 m. The vehicle started with a dive from surface to 30-m depth, and then began thermocline tracking. In the first half of the mission, the AUV tracked the thermocline at around 5-m depth. The vehicle again encountered a sharp temperature front about halfway into the mission. Based on the experience on the preceding day that the 2-m extension depth might not be sufficient for the AUV to swiftly catch up with a steep fall of the thermocline depth, we programmed the AUV to carry out a full-depth dive (from surface to 30-m depth) at the midway point in this mission. Adopting this strategy, the AUV successfully caught and tracked the deeper thermocline at approximately 17-m depth on the warmer water side.

## IV. Conclusion and Future Work

We have developed an autonomous method for detecting and tracking the thermocline by an AUV. On August 31 and September 1, 2010, the Tethys AUV ran the presented algorithm to closely track the thermocline across a sharp temperature front in Monterey Bay, CA. An AUV can also use the presented algorithm to autonomously detect and track the maximum vertical gradient of other seawater properties, e.g., nitrate-cline for nitrate. It is known that phytoplankton thin layers often form near the nitrate-cline [16]. Improvements of the algorithm are proposed as follows.

### A. Autonomous Adjustment of the Extension Depth $DEP_{\mathrm{extension}}$

The purpose of $DEP_{\mathrm{extension}}$ [in (4)] is to let the AUV cover some extra depth range to catch the true peak gradient of temperature. If it is set too small, the detection algorithm may be fooled by a local maximum of temperature gradient and miss the true peak gradient, or the vehicle may not catch up with a steep rise or a fall of the thermocline depth. If it is set too large, the vehicle's vertical undulation range will be unnecessarily enlarged, resulting in lower horizontal resolution in tracking the thermocline. When $DEP_{\mathrm{extension}}$ is less than sufficient, can the AUV autonomously recognize the problem and accordingly increase it? From the Tethys AUV's performance in the August 31 and September 1, 2010, missions, we observe the following two warning signs that signify that $DEP_{\mathrm{extension}}$ is not sufficient.

- The vertical distance between $DEP_{\mathrm{TempGradmax}}$ and the preceding or ensuing attitude-flip point is small.
  In Fig. 4, on the descent leg between 966 and 1025 s, the AUV detected the peak vertical gradient of temperature at a depth of 3.9 m (i.e., $DEP_{\mathrm{TempGradmax}} = 3.9$ m). Actually, the target depth of the preceding ascent leg was only 3.9 m.

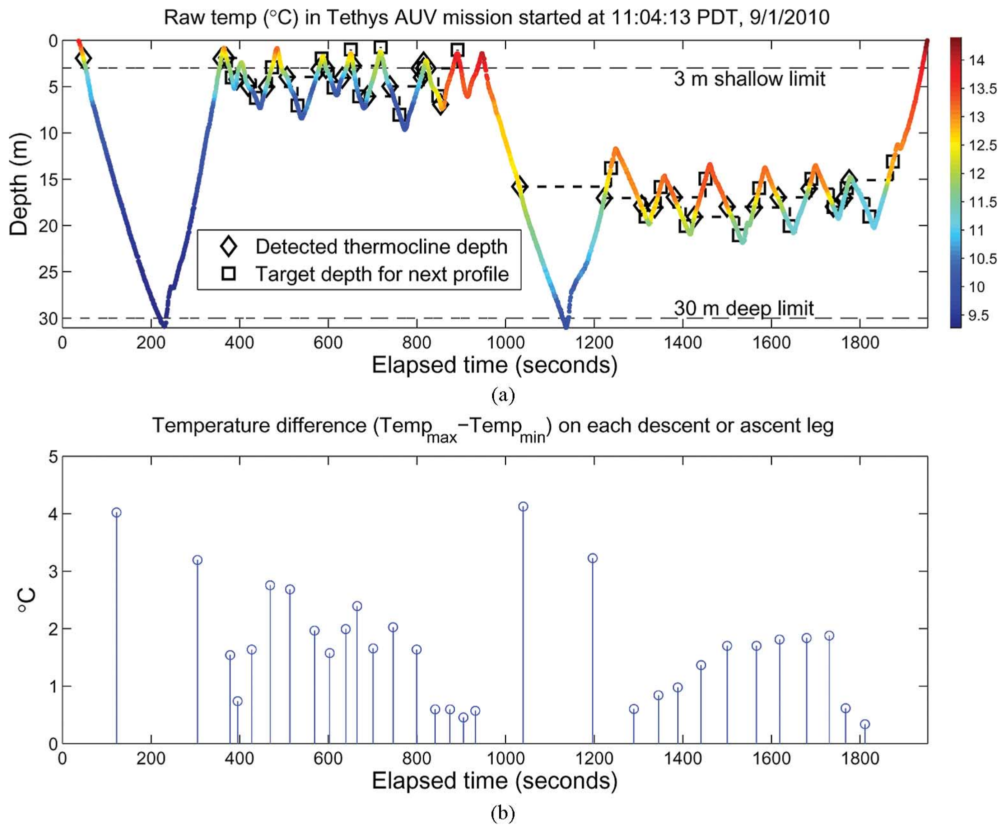



Fig. 6. (a) Temperature measured by the Tethys AUV in the September 1, 2010, mission, and (b) the temperature range ($\Delta\bar{T} = \bar{T}_{\max} - \bar{T}_{\min}$) on each descent or ascent leg.

It was the vehicle's overshoot that allowed it to continue to climb to the 2.4-m depth attitude-flip point. If not for the overshoot (i.e., if the AUV had flipped to descent at 3.9-m depth), the vehicle would likely have narrowly missed the peak temperature gradient point at 3.9-m depth on that descent leg. This manifests that the 2-m $DEP_{\text{extension}}$ was not sufficient to ensure the AUV's tracking of the thermocline. The insufficient $DEP_{\text{extension}}$ was again manifested on the descent leg between 1077 and 1110 s: the AUV detected the peak vertical gradient of temperature at a depth of 7.9 m (i.e., $DEP_{\text{TempGradmax}} = 7.9$ m), even deeper than the 7-m target depth for this leg. If not for the AUV's overshoot, the vehicle would surely have missed this peak temperature gradient point. In both instances, the vertical distance between $DEP_{\text{TempGradmax}}$ and the preceding or ensuing attitude-flip point was very small (even smaller than the vehicle's overshoot distance). The lesson is that when this distance falls below some threshold, the AUV should adaptively increase $DEP_{\text{extension}}$.

- The temperature range on a yo-yo profile drops significantly from preceding profiles.

  In both missions, the Tethys AUV crossed a sharp temperature front halfway into the mission. Based on the experience on August 31 that the 2-m extension depth might not be sufficient for the AUV to swiftly catch up with a steep fall of the thermocline depth, on September 1, we programmed the AUV to carry out a full-depth dive (from surface to 30-m depth) at the midway point to ensure that the vehicle could catch up with the thermocline even if its depth fell steeply. It is generally difficult to predict when and where the AUV will encounter sharp changes in thermocline depth in rapidly changing coastal waters. Can the AUV autonomously adjust $DEP_{\text{extension}}$ to catch up with a steep rise or fall of the thermocline depth? We propose an adaptive strategy that makes use of the temperature range measured on each yo-yo profile: $\Delta\bar{T} = \bar{T}_{\max} - \bar{T}_{\min}$ where $\bar{T}_{\max}$ and $\bar{T}_{\min}$ are respectively the maximum and minimum bin-averaged temperature on this profile. $\Delta\bar{T}$ on each descent or ascent leg in the September 1, 2010, mission is shown in Fig. 6(b). We note that on four legs at the front (around 900 s into the mission), $\Delta\bar{T}$ was very small (compared with the preceding profiles), indicating that the AUV was restricted to a flat segment of the temperature profile and "lost sight of the big picture." Hence, the peak temperature gradients found on those four legs were local rather than global maxima. Consequently, the AUV could not have caught up with the thermocline had it not carried out the full-depth dive. This observation points out that the AUV can utilize $\Delta\bar{T}$ to adaptively adjust $DEP_{\text{extension}}$: when $\Delta\bar{T}$ drops significantly, $DEP_{\text{extension}}$ should be increased so that the AUV can keep track of the global peak gradient of temperature.

### B. *Autonomous Adjustment of Depth Bin Size* $\Delta z$

Depth bin size $\Delta z$ [in (1)] is selected for a balance between noise rejection and depth resolution in calculating the vertical

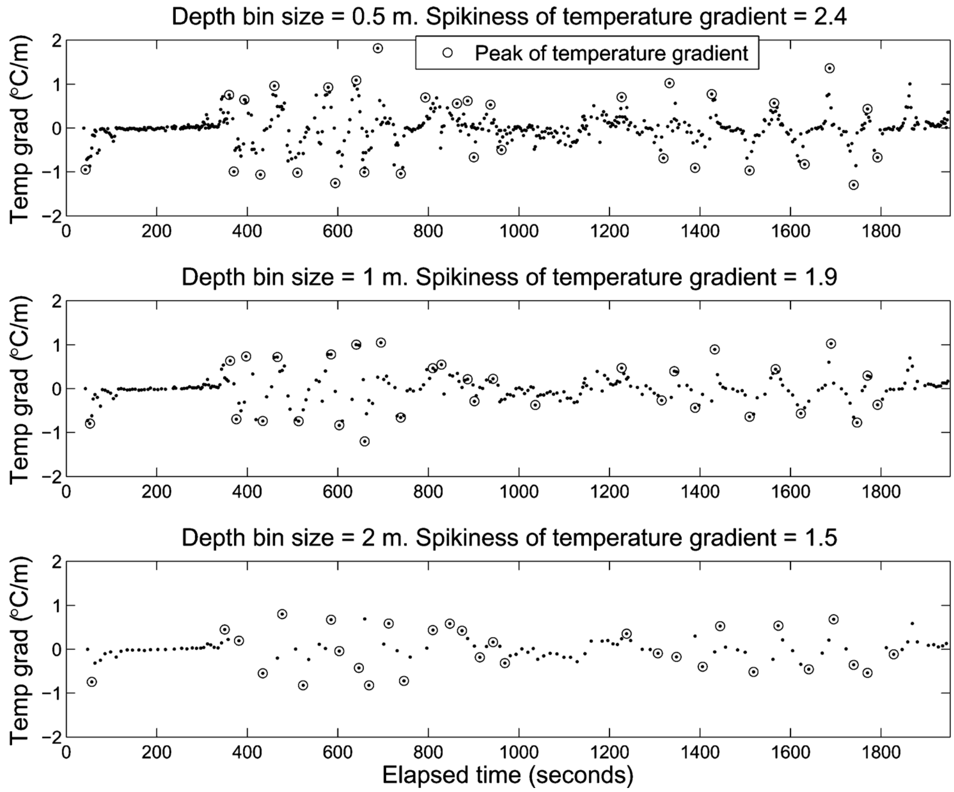



Fig. 7. Calculated vertical gradient of temperature using different values of depth bin size, for the September 1, 2010, Tethys AUV mission.

temperature gradient. If $\Delta z$ is set too small, temperature noise may cause a large error in the calculated temperature gradient which will lead to a wrong thermocline depth. If it is set too large, depth resolution will be too coarse. In Fig. 7, we compare the calculated temperature gradients using three different values of $\Delta z$: 0.5, 1, and 2 m for the September 1, 2010, Tethys AUV mission ($\Delta z$ was set to 1 m in the actual mission). We define a dimensionless "spikiness" of temperature gradient by

$$SP_{\mathrm{TempGrad}} = \frac{E\left[\mathrm{abs}(\mathrm{TempGradPeaks})\right]}{\mathrm{std}(\mathrm{TempGrad})} \qquad (5)$$

where $E\left[\mathrm{abs}(\mathrm{TempGradPeaks})\right]$ is the average height (absolute value) of the temperature gradient peaks, and $\mathrm{std}(\mathrm{TempGrad})$ is the standard deviation of all the gradients.

$SP_{\mathrm{TempGrad}}$ is a measure of the abruptness of the gradient peaks against the background gradient. A high $SP_{\mathrm{TempGrad}}$ is an indication of erroneous gradient due to noise in temperature measurements. In Fig. 7, $SP_{\mathrm{TempGrad}} = 2.4$, 1.9, and 1.5 for depth bin size of 0.5, 1, and 2 m, respectively. We consider 1-m bin size as providing a good balance between robustness and resolution of temperature gradient. In future improvement of the algorithm, we desire to let the AUV possess the capability of adaptively setting $\Delta z$ based on temperature measurements in the field.

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## References

[1] G. L. Pickard and W. J. Emery, *Descriptive Physical Oceanography: An Introduction*, 5th ed. New York: Pergamon Press, 1990, ch. 4, pp. 40–41.

[2] R. J. Urick, *Principles of Underwater Sound*, 3rd ed. Los Altos, CA: Peninsula, 1983, ch. 5, pp. 117–121.

[3] P. Cermeño, S. Dutkiewicz, R. P. Harris, M. Follows, O. Schofield, and P. G. Falkowski, "The role of nutricline depth in regulating the ocean carbon cycle," *Proc. Nat. Acad. Sci.*, vol. 105, no. 51, pp. 20344–20349, Dec. 2008.

[4] F. Cazenave, Y. Zhang, E. McPhee-Shaw, J. G. Bellingham, and T. Stanton, "High-resolution surveys of internal tidal waves in Monterey Bay, California, using an autonomous underwater vehicle," *Limnol. Oceanogr.: Methods*, vol. 9, pp. 571–581, 2011.

[5] H. C. Woithe and U. Kremer, "A programming architecture for smart autonomous underwater vehicles," in *Proc. IEEE Int. Conf. Intell. Robots Syst.*, St. Louis, MO, Oct. 2009, pp. 4433–4438.

[6] D. Wang, P. F. J. Lermusiaux, P. J. Haley, D. Eickstedt, W. G. Leslie, and H. Schmidt, "Acoustically focused adaptive sampling and on-board routing for marine rapid environmental assessment," *J. Mar. Syst.*, vol. 78, pp. S393–S407, 2009.

[7] S. Petillo, A. Balasuriya, and H. Schmidt, "Autonomous adaptive environmental assessment and feature tracking via autonomous underwater vehicles," in *Proc. IEEE OCEANS Conf.*, Sydney, Australia, May 2010, DOI: 10.1109/OCEANSSYD.2010.5603513.

[8] N. Cruz and A. C. Matos, "Reactive AUV motion for thermocline tracking," in *Proc. IEEE OCEANS Conf.*, Sydney, Australia, May 2010, DOI: 10.1109/OCEANSSYD.2010.5603883.

[9] N. Cruz and A. C. Matos, "Adaptive sampling of thermoclines with autonomous underwater vehicles," in *Proc. MTS/IEEE OCEANS Conf.*, Seattle, WA, Sep. 2010, DOI: 10.1109/OCEANS.2010.5663903.

[10] Y. Zhang, J. G. Bellingham, M. Godin, J. P. Ryan, R. S. McEwen, B. Kieft, B. Hobson, and T. Hoover, "Thermocline tracking based on peak-gradient detection by an autonomous underwater vehicle," in *Proc. MTS/IEEE OCEANS Conf.*, Seattle, WA, Sep. 2010, DOI: 10.1109/OCEANS.2010.5664545.

[11] J. G. Bellingham, B. Hobson, M. A. Godin, B. Kieft, J. Erikson, R. McEwen, C. Kecy, Y. Zhang, T. Hoover, and E. Mellinger, "A small, long-range AUV with flexible speed and payload," presented at the Ocean Sci. Meeting, Portland, OR, Feb. 2010, Abstract MT15A-14.

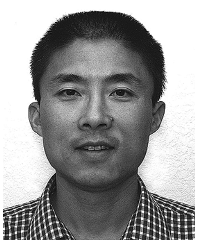
[12] Y. Zhang, R. S. McEwen, J. P. Ryan, and J. G. Bellingham, "Design and tests of an adaptive triggering method for capturing peak samples in a thin phytoplankton layer by an autonomous underwater vehicle," *IEEE J. Ocean. Eng.*, vol. 35, no. 4, pp. 785–796, Oct. 2010.

[13] J. G. Bellingham, Y. Zhang, J. E. Kerwin, J. Erikson, B. Hobson, B. Kieft, M. Godin, R. McEwen, T. Hoover, J. Paul, A. Hamilton, J. Franklin, and A. Banka, "Efficient propulsion for the Tethys long-range autonomous underwater vehicle," in *Proc. IEEE/OES Autonom. Underwater Veh.*, Monterey, CA, Sep. 2010, DOI: 10.1109/AUV.2010.5779645.

[14] M. A. Godin, J. G. Bellingham, B. Kieft, and R. McEwen, "Scripting language for state configured layered control of the Tethys long range autonomous underwater vehicle," in *Proc. MTS/IEEE OCEANS Conf.*, Seattle, WA, Sep. 2010, DOI: 10.1109/OCEANS.2010.5664515.

[15] J. G. Bellingham and T. R. Consi, "State configured layered control," in *Proc. IARP 1st Workshop Mobile Robots Subsea Environ.*, Monterey, CA, Oct. 1990, pp. 75–80.

[16] J. P. Ryan, M. A. McManus, and J. M. Sullivan, "Interacting physical, chemical and biological forcing of phytoplankton thin-layer variability in Monterey Bay, California," *Continental Shelf Res.*, vol. 30, no. 1, pp. 7–16, 2010.

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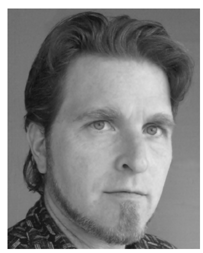

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Dr. Ryan was awarded a fellowship by the Office of Naval Research in support of his M.S., and a NASA New Investigator Research grant in support of his postdoctoral research.