12-8-2023

Computational Fluid Dynamics Modeling of Internal Wave Interactions on Conch Reef, Florida Keys

Megan Miller

Thesis of
Megan Miller

Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science
Marine Science

Nova Southeastern University
Halmos College of Arts and Sciences

December 2023

Approved:
Thesis Committee

Committee Chair: Alexander Soloviev, Ph.D.

Committee Member: Steven Miller, Ph.D.

Committee Member: Bernhard Riegl, Ph.D.

NOVA SOUTHEASTERN UNIVERSITY

HALMOS COLLEGE OF ARTS AND SCIENCES

Computational Fluid Dynamics Modeling of Internal Wave Interactions on Conch Reef, Florida Keys

By

Megan Miller

Submitted to the Faculty of
Halmos College of Arts and Sciences
in partial fulfillment of the requirements for
the degree of Master of Science with a specialty in:

Marine Science

Nova Southeastern University

January 2024

Abstract

Internal waves breaking on continental shelves play a significant role in mixing and nutrient delivery to coral reef ecosystems. As internal solitary waves, or solitons, propagate shoreward onto continental slopes, they can become unstable and break into turbulent bores that bring cool, nutrient-rich sub-thermocline water shoreward onto coral reefs. The propagation of turbulent bores generated by internal waves interacting with a complex surface creates high-frequency variabilities in the thermal and nutrient environment of Conch Reef in the Florida Keys, which has been studied previously. Here, I have created a three-dimensional model using ANSYS Fluent Computational Fluid Dynamics (CFD) software to simulate the interaction of breaking internal waves and the complex bottom topography of a well-studied spur and groove reef. Modeling the dispersion and retention of cold, nutrient-rich water on three-dimensional reef topography can increase our understanding of bathymetrically induced mixing from internal waves and how this plays a role in benthic community structure and a reef's resilience to heat stress.

Keywords: Florida Keys, internal waves, internal solitons, internal bores, CFD, ANSYS Fluent, physical oceanography, coral reef dynamics

Acknowledgements

This work has been supported by the ONR Awards N00014-18-1-2835, N00014-21-1-4007, N00014-22-1-2008, N00014-23-1-2270, and N00014-23-1-2746. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the U.S. Navy. The views expressed in this article are those of the author and do not necessarily reflect the official policy or position of the Department of the Navy, Department of Defense, nor the U.S. Government.

I would like to express my deepest gratitude to my parents, whose unwavering support and encouragement have been the driving force behind my academic journey. Your belief in my abilities has given me the confidence to pursue my dreams and I would not be where I am without you.

I must mention the best boy in the whole wide world, my Rango, the light of my life and my best friend. Thank you for all the walks, smiles, hugs and kisses and for being the cutest distraction ever.

I thank my boyfriend Kelly whose unwavering support and understanding have been a constant source of comfort during the challenges of graduate school. I am forever grateful for your love, encouragement, and keeping me fed throughout graduate school.

Breanna Vanderplow and Alfredo Quezada, your friendship, insightful conversations, and the countless moments of shared laughter has made this journey more enjoyable and meaningful, and I am forever grateful for having you two in my life.

I thank Dr. Breanna Vanderplow for her guidance and support in my modeling journey. Your mentorship made this work possible, and I thank you endlessly for all your help.

Special thanks are due to my advisor, Dr. Alex Soloviev, whose expertise, guidance, and mentorship have been invaluable throughout the process of researching and writing this thesis.

I am endlessly grateful for my committee members, Dr. Steven Miller and Dr. Bernhard Riegl for their expertise and guidance throughout this project. Thank you to Dr. Miller for giving me an opportunity to see my study site firsthand and organizing a special trip for me.

I would also like to thank Brian Ettinger for scouting me to join the Physical Oceanography Lab and for all the exciting dives.

I thank AJ Kluge, Stephanie Ball, Terry Thompson and Geoffrey Morrison for their valuable insights, fun conversations and support throughout my graduate school experience.

To each of you, I am grateful not only for your contributions to my academic success but also for the personal impact you've had on my life. This achievement would not have been possible without your support, and I am truly thankful to have shared this experience with all of you.

Table of Contents

List of Figures

Figure 16. Model 2 temperature contours of bottom surface (left) and ZX planes spaced 100 m apart along the Y axis (right). Sequential images every 50 timesteps from internal bore propagation, run-up, breaking and receding along the reef slope.

Figure 17. Model 2 contours of X-Component of velocity (cm/s) shown on ZX plane in middle of domain for timesteps 1300-2400.

Figure 18. Adapted from Leichter et al (2005). Vertical structure of temperature and cross-shore, vertical, and alongshore components of currents above the reef for a 24-hour period in July 2003.

Figure 19. Adapted from Leichter et al (2005). Sequential images (reading down columns) of water temperature interpolated onto the reef bathymetry. 20 frames at approximately 5-min intervals spanning approximately 2 hours in July 2003.

Figure 20. Adapted from Leichter et al. (2005). Instantaneous horizontal temperature anomaly interpolated onto the reef bathymetry for same time-period as Figure 19.

1. Introduction

1.1 Internal Waves

Internal waves are known to occur in all ocean basins and their existence has been documented since the 1950s (Ewing, 1950). Internal waves are gravity waves that oscillate beneath the surface of the ocean where the density stratification is focused along a primary pycnocline. They are often observed over continental shelves during the summer months whenever a distinct warm and light surface layer is present (Garrett & Munk, 1979). When the water column is strongly stratified with respect to temperature and density, internal waves tend to travel along the density interface towards the continental shelf. Internal waves are one of a variety of mechanisms by which deep, sub-thermocline water gets mixed with the water above. Breaking internal waves account for a significant amount of diapycnal mixing and turbulence in coastal oceans caused by shoaling internal waves interacting with sloping topography and transporting sediments near the bed (Cacchione et al., 2002).

Internal waves are ubiquitous features where strong tides occur in highly stratified waters over irregular topography and can often be detected in optical satellite imagery of coastal waters (Figure 1). Numerous generating mechanisms have been discussed previously, including surface generation by variable wind stress, traveling pressure fields, variable buoyancy flux, and surface waves (Garrett & Munk, 1979), see Figure 2 (MacKinnon, 2013). Here we discuss internal waves whereby the generating mechanism is tidal forcing. Specifically, internal tides are generated by the advection of a stratified water column across the topography of the seafloor, herein the continental slope and shelf, by a barotropic tide. Observations and theoretical models (Niiler, 1968; Stommel, 1965) show that the internal wave activity in the Straits of Florida is driven by the interaction between the barotropic tide and a resonant internal seiche between Florida and the Bahamas. Internal wave activity is greatest during summer months due to the coupling of the internal seiche and barotropic tide. The seasonal variability of the energy oscillations within the Florida Straits can be attributed to multiple factors acting together such as changes in stratification depth, spin-off eddies, and meandering of the Gulf Stream (Soloviev et al., 2003).

Figure 1. Internal waves off Northern Trinidad in southeastern Caribbean Sea. Astronaut photograph provided by Johnson Space Center (2013).

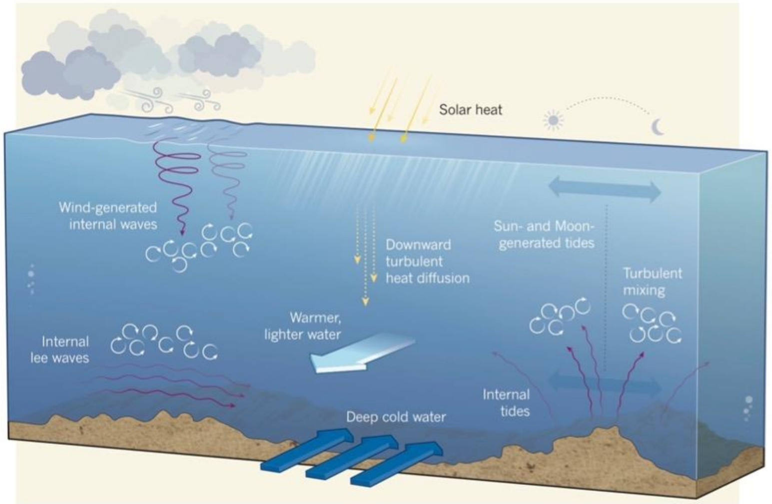


Figure 2. Internal waves are generated by three main mechanisms: Moon- and Sun-generated tidal flow over steep or rough topography (lower right); fluctuating wind stress on the ocean surface (upper left); and quasi-steady flow over rough topography (lower left). MacKinnon, J. (2013).

As internal waves propagate inshore on a gradually sloping continental shelf, they can become unstable and break into turbulent surges, *internal bores*, that continue traveling up the reef slope. (Helfrich, 1992; Wallace & Wilkinson, 1988). Cooper (1947) postulated that large amplitude internal waves running up the continental slope in the same way a surface wave runs up the beach could be possible mechanism by which nutrient-rich water from mid-depths could be brought up higher onto the shelf. As internal waves interact with gentle slopes of coastal oceans, they can become nonlinear and break into internal bores, or internal tidal bores if they are of tidal frequencies. For steep internal waves or internal waves occurring over gentle slopes (low Iribarren number, $\xi < 1$), canonical bores are formed as the wave gradually shoals over a shallow slope. This type of breaking results in a steep leading wave front followed by drop in temperature as the wave progresses. Canonical bores cause mixing on the bottom as well as vertically throughout the water column due to the turbulent interactions between receding currents and incoming bores. See Figure 3, adapted from Masunaga et al. (2019).

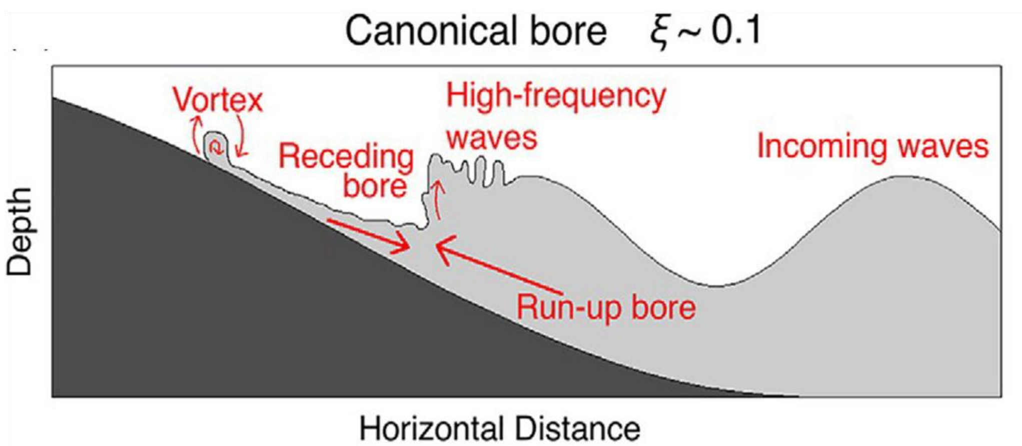


Figure 3. Vertical cross-section of the wave structure of a canonical bore as the onshore propagating bore interacts with the receding currents. (Masunaga et al., 2019)

1.2 Impacts on Coral Reefs

Coral reefs are some of the most biologically productive ecosystems on Earth and their importance to humankind has been demonstrated through a wide range of ecosystem goods and services provided to millions of people. Since the 1980's, coral reefs have been threatened worldwide by anthropogenic stressors, including increased sea surface temperatures (SST), disease spread, overfishing, pollution, ocean acidification, to name a few. Persistent, elevated ocean temperatures cause disruption between corals and their photosynthetic algal symbionts, *Symbiodinium*, in which heat-stressed corals dispel their symbionts, leading to coral bleaching and potential mortality. Coral reef ecosystems typically thrive within a narrow thermal and

nutrient range, and the optimum temperature for most scleractinian (stony) corals is very close to their upper thermal limit, so even a moderate increase in SST of 1–2° C can impose stress on a coral colony and lead to bleaching. Catastrophic mass bleaching events have increased in both severity and frequency in the last 30 years, and the Florida Keys have experienced eight mass bleaching events since 1987. It has been proposed that coral reefs in areas exposed to small-scale localized upwelling act as refuges for coral populations by counteracting prolonged SST heating (Riegl & Piller, 2003). Shoaling internal waves are one mechanism by which cold, nutrient-enhanced water gets lifted from below the thermocline and dispelled onto the reef, altering the thermal and nutrient environment. Frequent, step-like changes in temperature due to breaking internal waves creates a heterogeneous thermal structure on the forereef and reef flat from the cold, dense water settling in the "pockets" of the high rugosity surface of a coral reef.
Shoaling and breaking internal waves are a known mode of transport of ecologically important features in coastal oceans such as sediment, inorganic nutrients, plankton, larvae and dissolved oxygen. This method of transient upwelling is thought to play a significant role in the nutrient dynamics of nearshore ecosystems.

1.3 Conch Reef, Florida Keys

Conch Reef is used as in this study because of the well-documented evidence of internal wave activity and their effects on a Florida coral reef. Internal waves have been documented further north, offshore of Fort Lauderdale beach, however it is unknown whether internal waves reach far enough inshore to affect the reefs here. Depending on the steepness of the continental slope, internal waves traveling shoreward can either run up the slope unbroken or begin to shoal and break into turbulent bores that continue up the slope as front-like surges (Helfrich, 1992; Wallace & Wilkinson, 1988). The reef slope of Conch Reef has a prominent step around the 15-m contour with coral spur and groove formations lining the reef crest from 12 to ~ 30 m. At approximately 35 m, the reef ends as the slope becomes more gradual, extending into a continuous sand plain for 8-10 km into the Straits of Florida. The reef here primarily consists of plating and mound scleractinian corals, soft corals, sponges, and coralline algae encrusting the Plio-Pleistocene carbonate reef platform (Leichter et al., 2005).

Turbulent bores from internal waves are a consistent feature of Conch Reef, a spur and groove patch reef located just offshore of Key Largo. Leichter et al. (1996) conducted a study of the internal wave activity here and documented rapid increases in onshore flow speeds corresponding to the tidal cycle. Evidence for internal bores arriving on reef slopes in the Florida Keys has been documented by frequent, sudden drops in temperature above the reef predominantly occurring at semidiurnal frequencies (Leichter et al., 1998; Leichter et al., 2003). The increased flows were associated with sudden drops in temperature near the seabed and dramatic increases in salinity. Internal tidal bores have been identified as a mechanism of larval transport and plankton delivery from below the thermocline to Conch Reef, thereby influencing the composition of benthic reef biota, settlement rates, and availability of suspended food particles (Leichter et al., 1998).

An important feature of internal wave events on Conch Reef are increased concentrations of nutrients nitrate (NO_3^{-1}) and soluble reactive phosphate (SRP). Quantifying the background levels and marked increases in nutrient concentrations on the Florida Keys reef tract led to the working hypothesis that significant nutrient inputs could be linked to upwelling events caused by internal tidal bores (Boyer & Jones, 2002; Lapointe & Smith, 1987; Leichter et al., 2003; Szmant & Forrester, 1996;). Periods of increased nutrient concentrations were associated with decreased temperatures on the reef slope caused by the upslope flow of individual internal bores, indicating that this mechanism of upwelling is responsible for 10-40-fold increases in nutrient concentrations on Conch Reef (Leichter et al., 2003). Background levels of NO_3^- and SRP are typically 0.1–0.2 and 0.01–0.02 μmol L^{-1}, respectively, but for a period in June 2000 and 2001, concentrations were elevated to 1.0–4.0 μmol L^{-1} NO_3^- and 0.1–0.3 μmol L^{-1} SRP. The estimated inputs of nitrogen and phosphorus by internal bores are said to be 20–40 times higher than sources from wastewater and storm water runoff to nearshore waters, making it difficult to discern naturally occurring fluctuations of nutrient inputs from potential anthropogenic sources. It is therefore thought that rapid macroalgal growth and blooms of *C. isthmocladum* on Florida's coral reefs can be linked to periods of strong internal tidal upwelling rather than directly from anthropogenic runoff as previously thought. The highly episodic nature of large nutrient inputs and cold-water pulses by internal bores are thought to be contributing to the suboptimal conditions for stony corals in the Florida Keys Reef Tract, making it critical to understand both the long- and short-term effects of upwelling by internal bores.

Leichter et al. (2005) conduced the first in-situ, high frequency three-dimensional analysis of the runup of internal waves on a coral reef for the purpose of investigating the time-varying thermal structure across the reef due to internal wave interactions. For the study, a large array of temperature sensors (Benthic Oceanographic Array) was deployed in a dense rectangular configuration to record temperature in intervals across the reef. A vertical string of temperature sensors as well as an acoustic Doppler current profiler were deployed in 35 m depth just southeast of the BOA (Figure 4).

Figure 4. Satellite image of Upper Florida Keys (Nasa) with approximate location of Conch Reef highlighted.

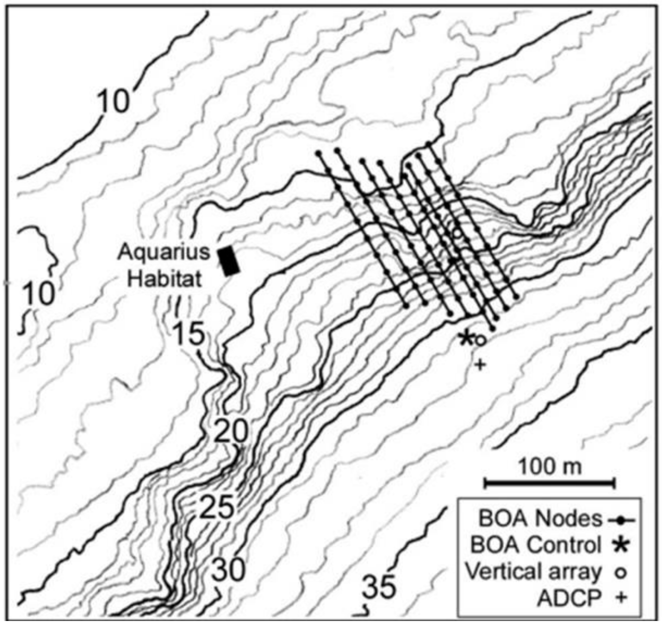


Figure 5. Array of instruments deployed at study site in Leichter et al. (2005) study.

The goal of this thesis work is to create a 3-dimensional computational fluid dynamics model of internal waves interacting with the continental slope and coral reef at a well-studied reef off the coast of the Florida Keys using observed temperature and salinity values and the bottom topography of Conch Reef. Using a computational fluid dynamics modeling approach to study the physics of this sub-surface phenomenon can increase our knowledge of bathymetrically induced mixing due to internal waves and how they can impact coral reef environments. Understanding the dynamics of internal wave-induced upwelling is an important element in understanding the drivers of reef community structure and incorporating physical models into this research can help us to better understand these interactions This is the first study, to my knowledge, that simulates internal wave formation, propagation and breaking under conditions specific to documented events while using real bottom topography data.

2. Methodology

2.1 ANSYS Fluent Methods/Equations

ANSYS Fluent is a computational fluid dynamics (CFD) simulation software that calculates fluid flow, turbulence, and heat transfer on discrete cell volumes. We utilize a CFD modeling approach to simulate sub-surface phenomena in an idealized situation in order to observe the small-scale dynamics of turbulent bores interacting with the complex topography of a coral reef. ANSYS Fluent uses a pressure-based Navier Stokes solution with a transient time calculation to solve conservation of momentum, mass and energy. Gravity was set to -9.81 m s^{-1} in the Z direction and the energy model was on. The density variation is caused by temperature (and salinity), so the flow is buoyancy-driven and therefore acts as a natural convection flow. We apply Fluent's Large Eddy Simulation (LES) to model turbulence, which resolves large turbulent eddies in space and time as they incorporate momentum, mass and energy. In conjunction with the LES model, we use the Wall Adapting Local Eddy Viscosity Model (WALE) to model eddy viscosity. Turbulence was calculated by filtering the time-dependent Navier-Stokes equations (Equations 1-4). The boundary conditions for all the walls excluding the bottom were set to 0 Pa specified shear; the bottom boundary was set to the default no-slip conditions, in which Ansys Fluent uses the properties of the flow adjacent to the wall boundary to predict the shear stress on the fluid at the wall.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho \bar{u}_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \bar{u}_i) + \frac{\partial}{\partial x_j}(\rho \bar{u}_i \bar{u}_j) = \frac{\partial}{\partial x_j}(\sigma_{ij}) - \frac{\partial \bar{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

where σ_{ij} is the stress tensor due to molecular viscosity defined by

$$\sigma_{ij} = \left[\mu\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\right] - \frac{2}{3}\mu \frac{\partial u_i}{\partial x_i}\delta_{ij} \tag{3}$$

and τ_{ij} is the subgrid-scale stress defined by

$$\tau_{ij} = \rho \overline{u_i u_j} - \rho \bar{u}_i \bar{u}_j \tag{4}$$

Eddy viscosity was calculated using the WALE model (Equations 5-7).

$$\mu_t = \rho L_s^2 \frac{(S_{ij}^d S_{ij}^d)^{3/2}}{(\bar{S}_{ij}\bar{S}_{ij})^{5/2} + (S_{ij}^d S_{ij}^d)^{5/4}} \tag{5}$$

where L_s and S^d_{ij} in the WALE model are defined, respectively as:

$$L_s = \min\left(xd, C_w V^{1/3}\right) \quad (6)$$

$$S^d_{ij} = \frac{1}{2}\left(\bar{g}^2_{ij} + \bar{g}^2_{ji}\right) - \frac{1}{3}\zeta_{ij}\bar{g}^2_{kk}, \bar{g}_{ij} = \frac{\delta \bar{u}_i}{\delta x_j} \quad (7)$$

The default value of the WALE constant C_W is 0.325 (Fluent Theory Guide).

2.2 Model 1 Setup

The first simulation consisted of a simplified domain with a generalized outline of the continental slope at Conch Reef. This initial model, "Model 1" from here on, was created to verify that Ansys Fluent could successfully simulate internal wave run-up using temperature and salinity conditions documented from Conch Reef. The domain's geometry was sketched in Ansys Spaceclaim, using Figure 6 (Leichter et al., 1996), as well as Google Earth as a reference to sketch the continental shelf and slope seaward of Conch Reef. A cylindrical object was sketched in the shallow end of the domain in order to represent a basic outline of a reef structure. The domain, shown in Figure 7, was 3500 m long on the X axis, 1000 m wide on the Y axis, and 166 m deep on the Z axis. The mesh was generated in ANSYS Meshing and consisted of 5 m cells for the volume mesh everywhere except the bottom. The inflation method in ANSYS Meshing was utilized with the 'First Layer Thickness' option in order to generate thin cells adjacent to the bottom boundary. The first layer of cells on the bottom boundary were 0.5 m vertically and growth rate was set to 0.25 m for a total of 10 layers extending into the fluid domain (see Figure 8). The fluid domain consisted of two distinct layers of water, an upper warmer layer of 29.5° C and a deeper cooler layer of 26° C (Figure 7). Salinity values were 36.5‰ for the lower layer and 35.0‰ for the upper layer. These values were put into a User Defined Function (UDF) and compiled into ANSYS Fluent in order to calculate the density of the two layers. The wave is generated by leaving a gap between the stratification layer and the back wall, and a buoyancy-driven flow is induced by the force of gravity acting on the density variations of the two water layers. The model is initialized with the cold, dense body of water 100 m away from the back wall (offshore), so that the water mass "falls" back on the wall and generates the flow. Model 1 was run for 7070 timesteps.

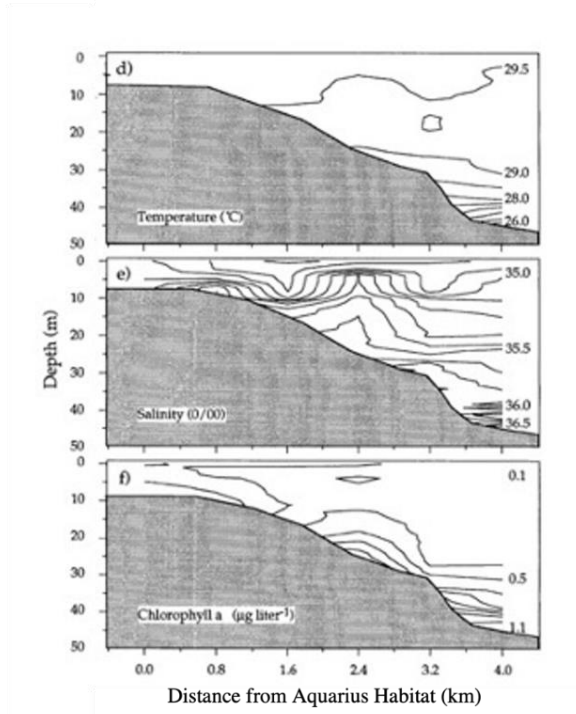


Figure 6. Adapted from Leichter et al. (1996). Water column sections of temperature, salinity and Chl *a* concentration on 23 July 1994. Source of temperature, salinity, and continental slope outline for Model 1.

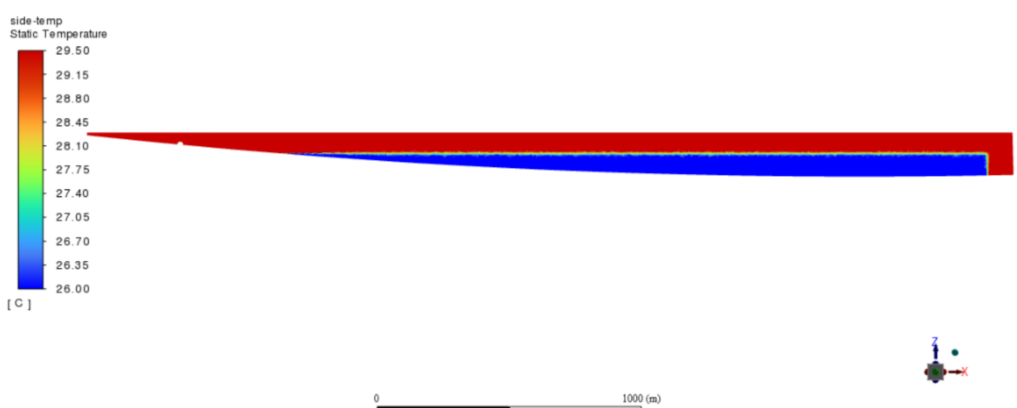


Figure 7. Initialization of Model 1 with temperature and salinity values in Ansys Fluent. Temperature contour of ZX axis in middle of domain at y=500.

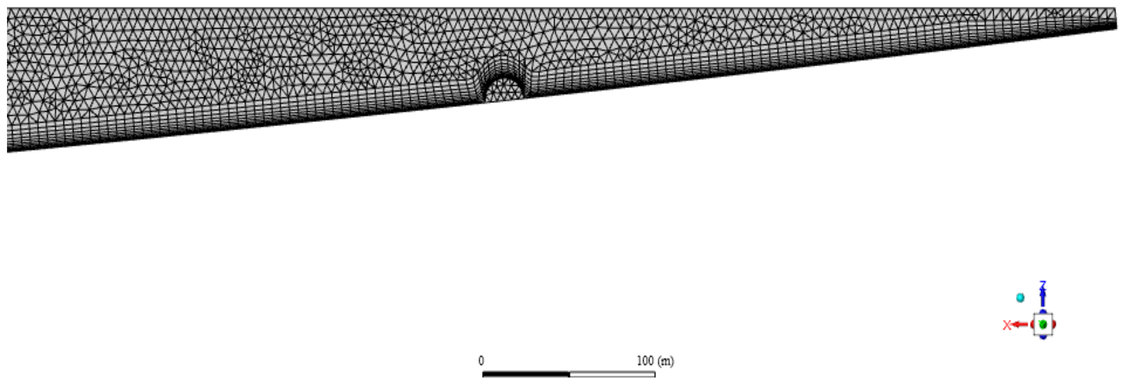


Figure 8. Model 1 mesh display, zoomed in to inflation layers on bottom boundary.

2.3 Model 2 Setup

After confirming the successful calculation of internal waves using this method on simple geometry in Model 1, the next step in this study was to run the internal wave simulation using real bottom topography of the study site in the domain. The bottom topography of Conch Reef was implemented into the model as the domain's bottom boundary using a continuously updated digital elevation model (CUDEM) Ninth Arc-Second and Third Arc-Second Resolution Bathymetric-Topographic Tiles from NOAA National Centers for Environmental Information. The DEM file was converted to STL in QGIS using the DEM to 3D function. In Ansys Spaceclaim, the imported STL (Standard Triangle Language) file of the seafloor consisted of faceted data and had to be transformed into a solid body by reverse-engineering the facets. The domain extents for Model 2 were 1,753 m long on the X axis, 540 m wide on the Y axis, 85 m deep on the Z axis for the deepest part of the domain (offshore), and ~12-15 m deep above the reef crest. Meshing in Ansys Workbench was then used to generate the body mesh, which consisted of 4 m mesh cells everywhere in the domain except near the bottom. Face sizing method was used to create 1 m mesh cells on the bottom surface and extending up to 5 m off the bottom. Mesh resolution everywhere else in the fluid domain 5 m above the bottom was 4 m cell size. Model 2 was initialized with the thermocline at -40 m, with temperatures 293.45 K (20.3 C) for the bottom layer, and 302.65 K (29.5 C) for the top layer, and salinities 36.5 and 35 ppt, respectively (Figure 9). The mesh resolution in Model 2 allows for a more detailed visualization of the small-scale dynamics of the cold-water intrusions on the reef. Figure 10 shows a close-up snapshot of the mesh structure, which increases in resolution closer to the bottom for the purpose of greater accuracy of flow behavior as it interacts with a non-uniform surface. This simulation was run for 6000 timesteps with time step size of 1 second, so for a total of 100 minutes.

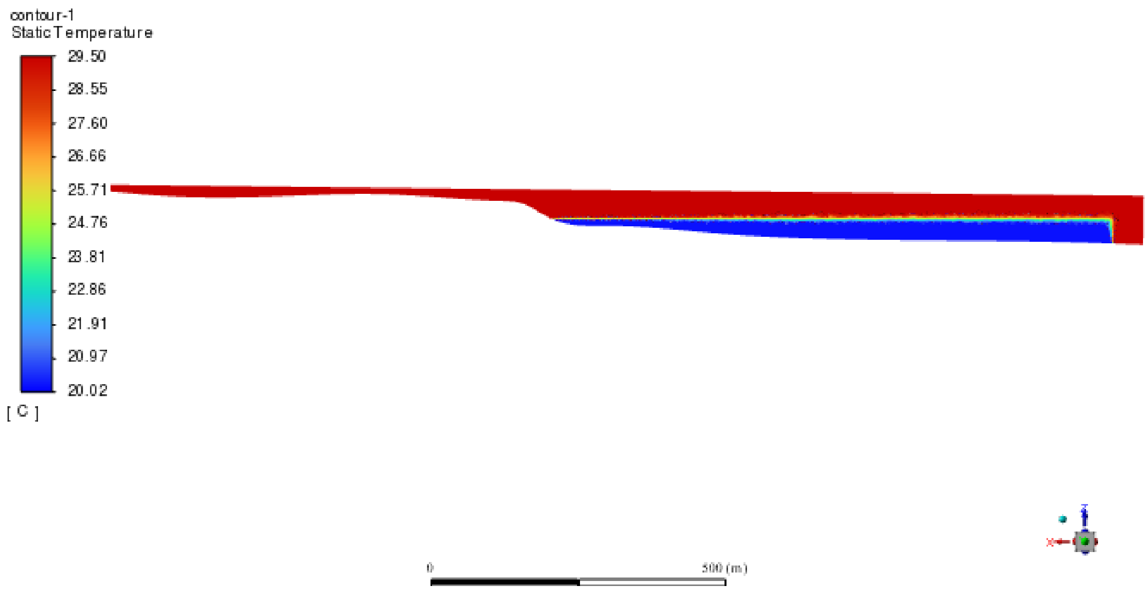


Figure 9. Model 2 temperature contour of initialized stratification.

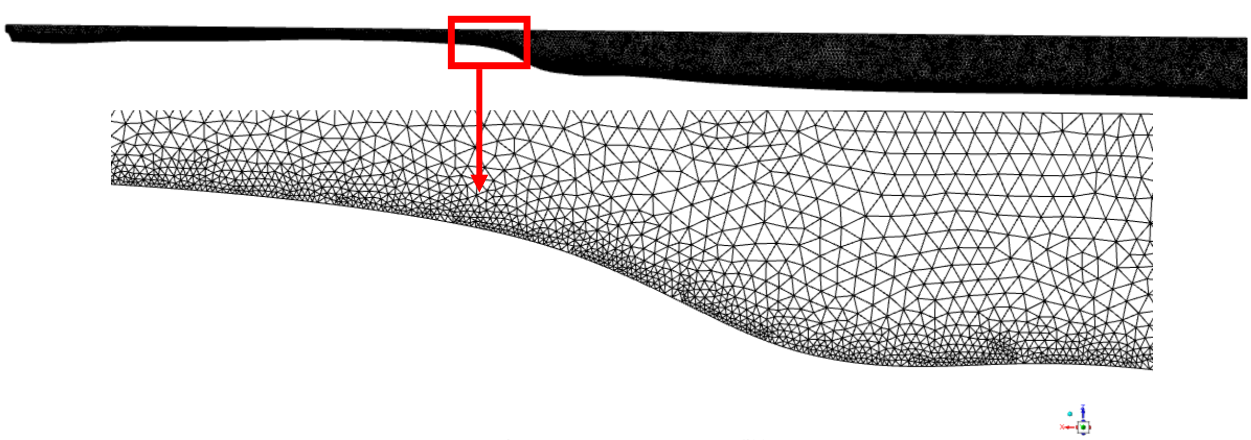


Figure 10. Model 2 Mesh display, zoomed in on reef slope to show smaller mesh on bottom boundary.

3. Results and Discussion

3.1 Model 1 Results

Using ANSYS Fluent, we have created a 3D non-hydrostatic CFD model to simulate internal solitary waves forming and breaking on the continental slope and topography of a coral reef. ANSYS Fluent possesses a wide range of post-processing tools that allow for visualization of simulation results. In order to visualize the internal wave, we can create contours of temperature, salinity, density and velocity at different locations in the domain. Figure 11 shows Model 1 at timestep 900, where the internal waves are formed after the colder water mass (blue) has collapsed on the back wall and begins propagating towards shore (towards the left in figure). In Figure 12 at timestep 4000, the formation of multiple distinct internal solitary waves is visible. As the leading wave reaches the steepening slope, it begins to resemble a plunging internal solitary wave breaker (Masunaga et al., 2019). Figure 13 shows the simulation at timestep 5530 where the wave has broken into a small bore-like form or front of cold water that hits the cylindrical reef structure. Temperature contours are on a plane in the middle of the domain along the Y axis, as well as on the bottom and reef structure (Figure 14). Since this simulation did not include the bottom topography and was used as a “test run” of the internal wave calculation, we will focus the discussion on Model 2, which included the reef topography and gives a more realistic, detailed view of the internal wave interactions.

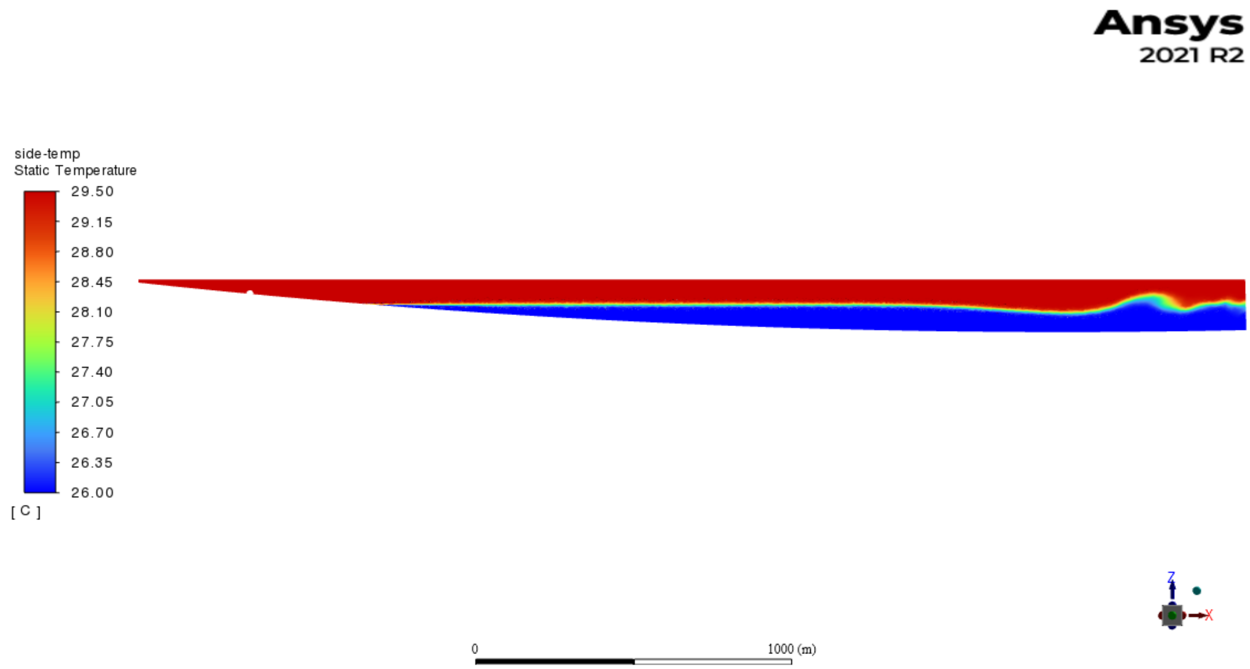


Figure 11. Model 1 temperature contour on ZX plane at timestep 0900.

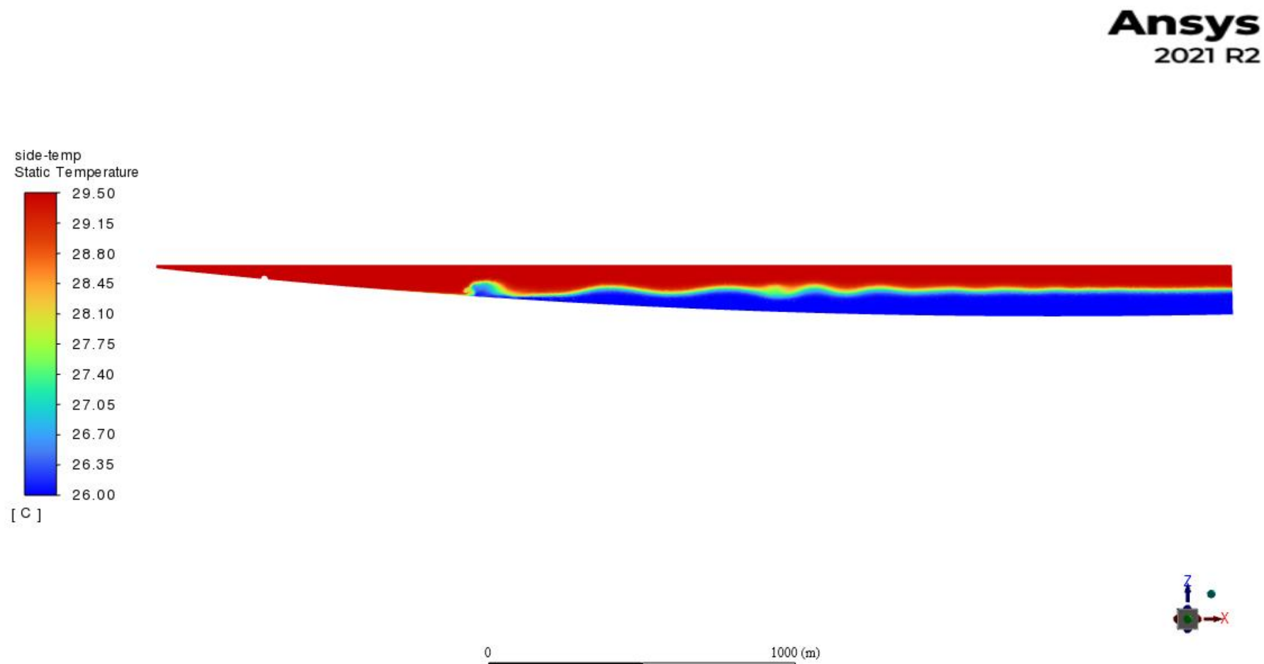


Figure 12. Model 1 temperature contour on ZX plane at timestep 4000. Leading wave begins to overturn and break on steepening slope.

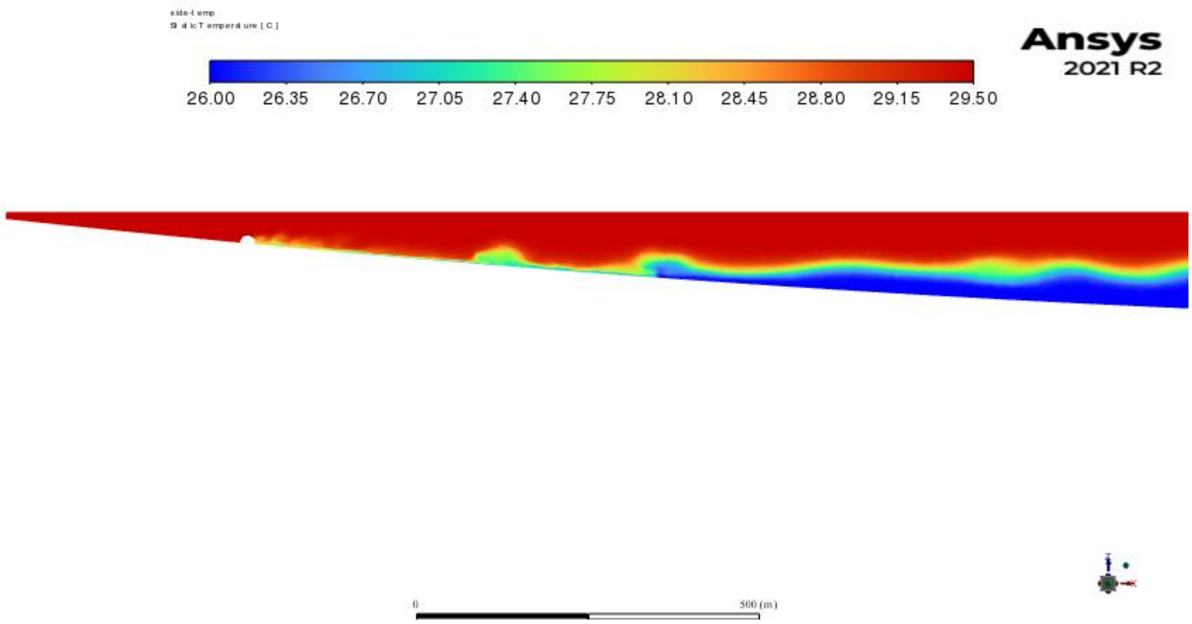


Figure 13. Model 1 temperature contour on ZX plane at timestep 5530. Bore run-up to hypothetical reef structure.

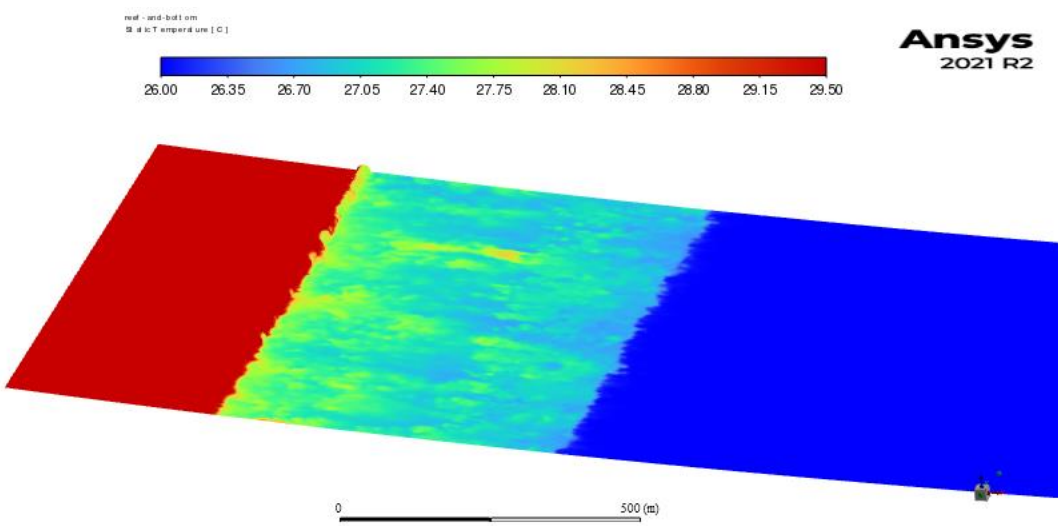


Figure 14. Model 1 temperature contour on bottom boundary and reef structure at timestep 5530. Bore run-up to hypothetical reef structure.

3.2 Model 2 Results

ANSYS Fluent has a graphical interface that allows the user to easily visualize what's happening during the calculation. We use temperature contours to visualize the internal wave interactions with the bottom topography to directly see if and how the cold, deep water reaches the reef slope and interacts with features of the reef. Model 2 showed similar generation and propagation of internal waves using the same temperature and salinity values from the previous studies like that of Model 1 but using the bottom topography of Conch Reef as the domain's bottom boundary. Figure 15 shows temperature contours on a ZX plane directly in the middle of the domain (Y = 270 m) for 12 timesteps spaced 100 seconds apart during the simulation. In this figure, a set of internal waves can be seen propagating (from right to left), becoming unstable and shoaling as they reach the steepening slope, breaking into an internal bore of cool water (~22-23° C) that continues up the reef slope. As the leading internal bore recedes back down the slope, it interacts with the incoming waves, generating turbulence as the cool water is mixed vertically in the water column. The temperature contours in timesteps 2100–2400 show resemblance to the previously discussed phenomenon of canonical bore formation and the associated mixing caused by the interaction between the receding current and incoming waves. Because the bottom topography was not uniform in features such as slope, sand grooves and coral spurs across the y-axis, the shoaling and breaking of the solitary waves varied at different locations in the y-direction. To visualize this, four ZX planes spaced 100 m apart along the y-axis were created to view the temperature contours at the same times during the calculation but at different locations in the domain. Figure 16 shows temperature contours on the bottom topography (left) and the corresponding temperature contours on ZX planes at different locations along the y-axis, spaced 100 m apart. Figure 17 shows contours of the X component of velocity (cm/s) on a ZX plane in the middle of the domain for timesteps 1300–2400. During the early stages of the simulation (Timestep 1300), a group of solitary internal waves propagated along the thermocline at speeds up to 45 cm s^{-1}. During internal bore run-up onto the reef slope (Timestep 1900), velocity in the positive X direction (right to left) reached speeds up to 83 cm s^{-1}.

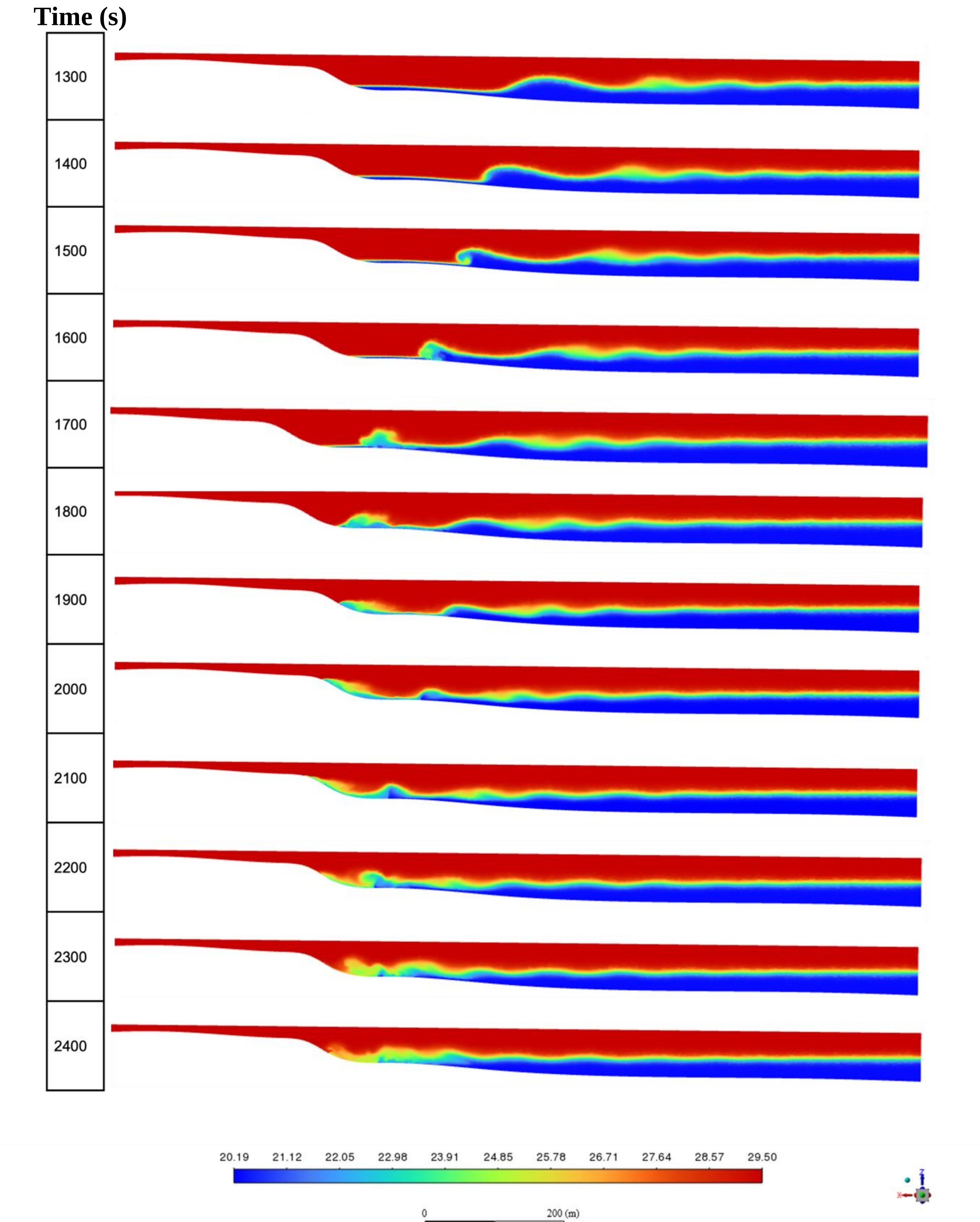


Figure 15. Model 2 temperature contours on ZX plane in middle of Y-axis of the domain. Internal waves traveling along the thermocline can be seen propagating (from the right) towards the slope, breaking, and receding throughout the simulation. Images taken every 100 timesteps (100 s) throughout the calculation.

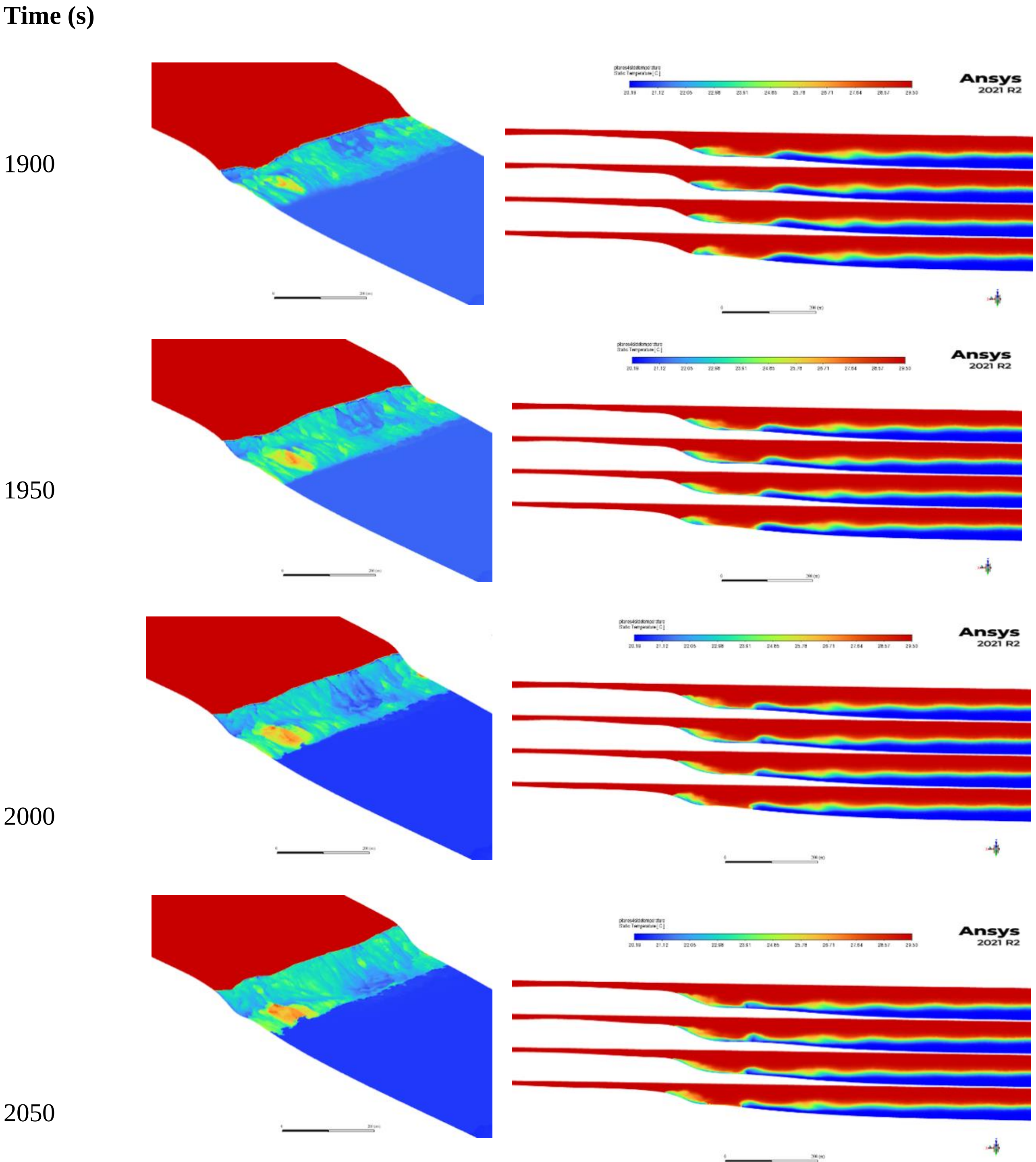


Figure 16. Temperature contours of bottom surface (left) and ZX planes spaced 100 m apart along the Y axis (right). Sequential images every 50 timesteps from internal bore propagation, run-up, breaking and receding along the reef slope.

Time (s)

2100

2150

2200

2250

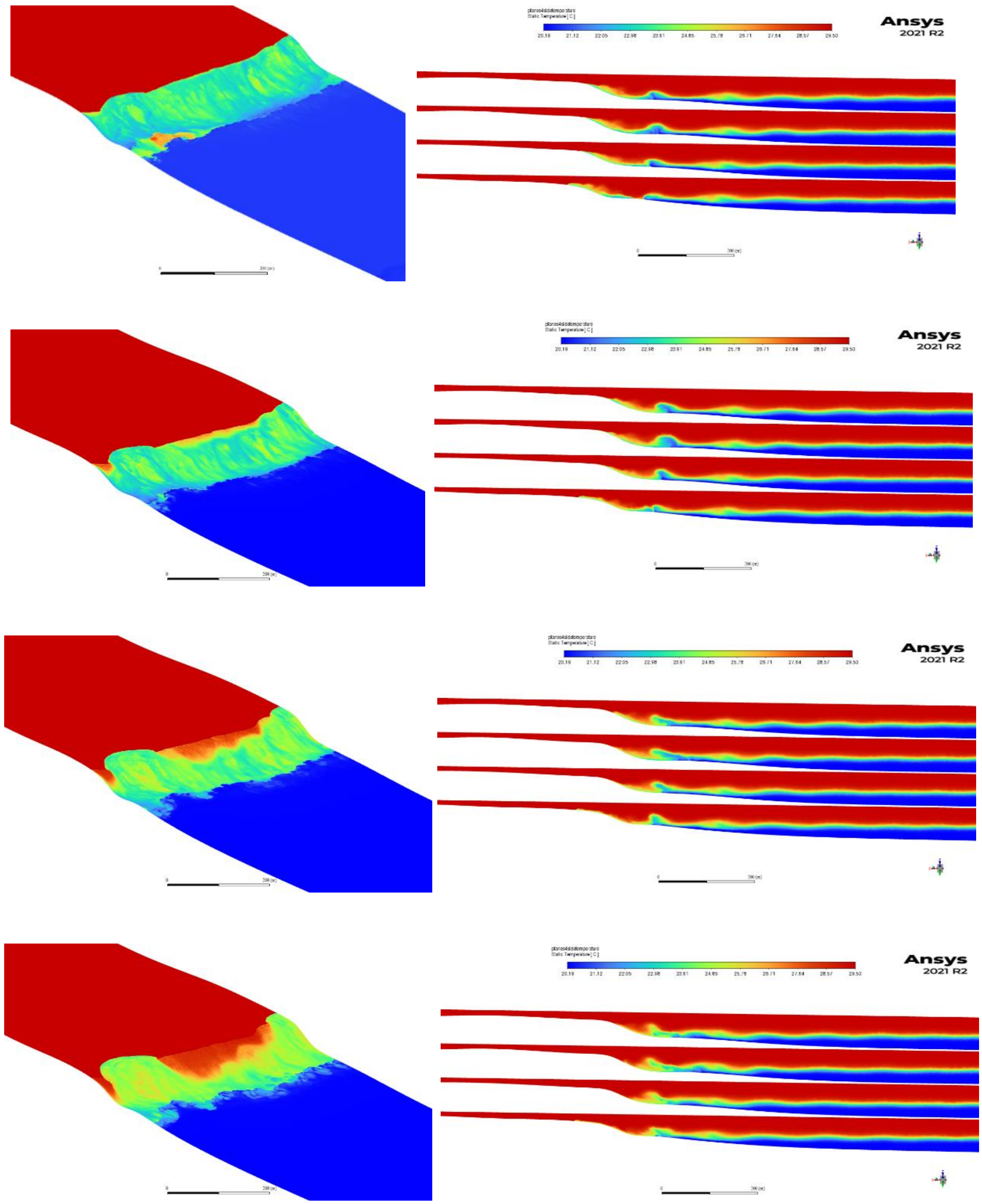
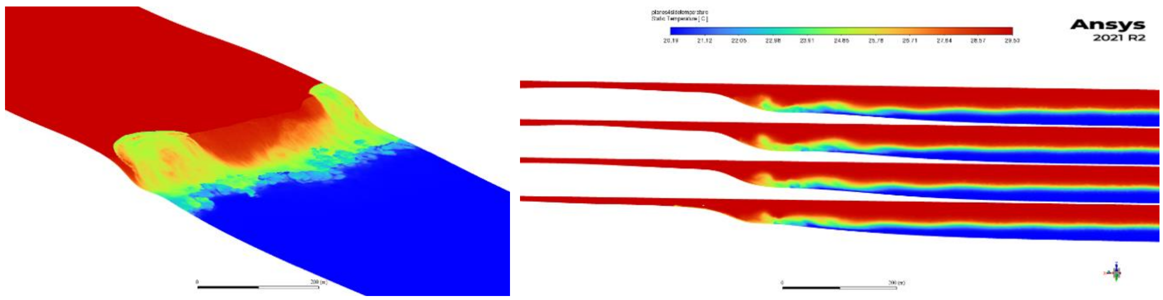


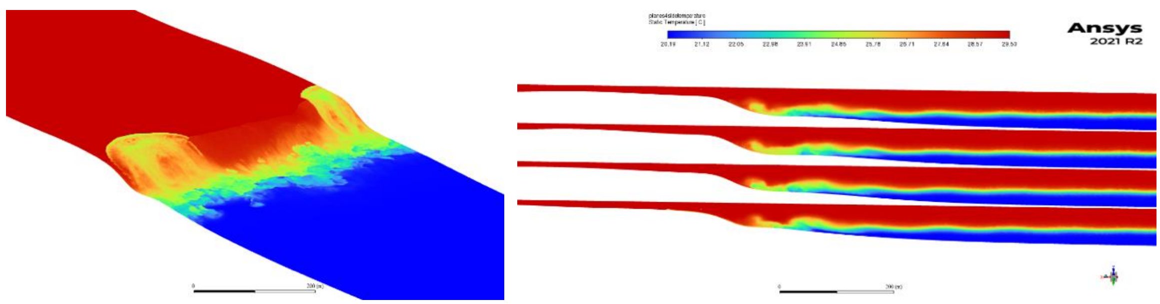
Figure 16 (*continued*).

Time (s)

2300



2350



2400

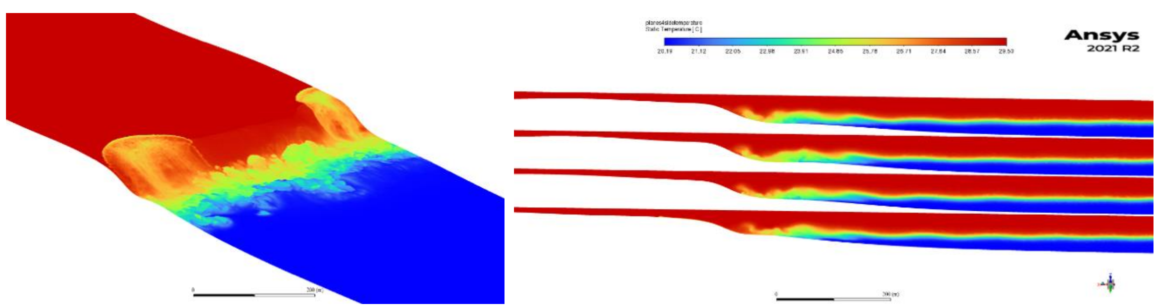


Figure 16 (*continued*).

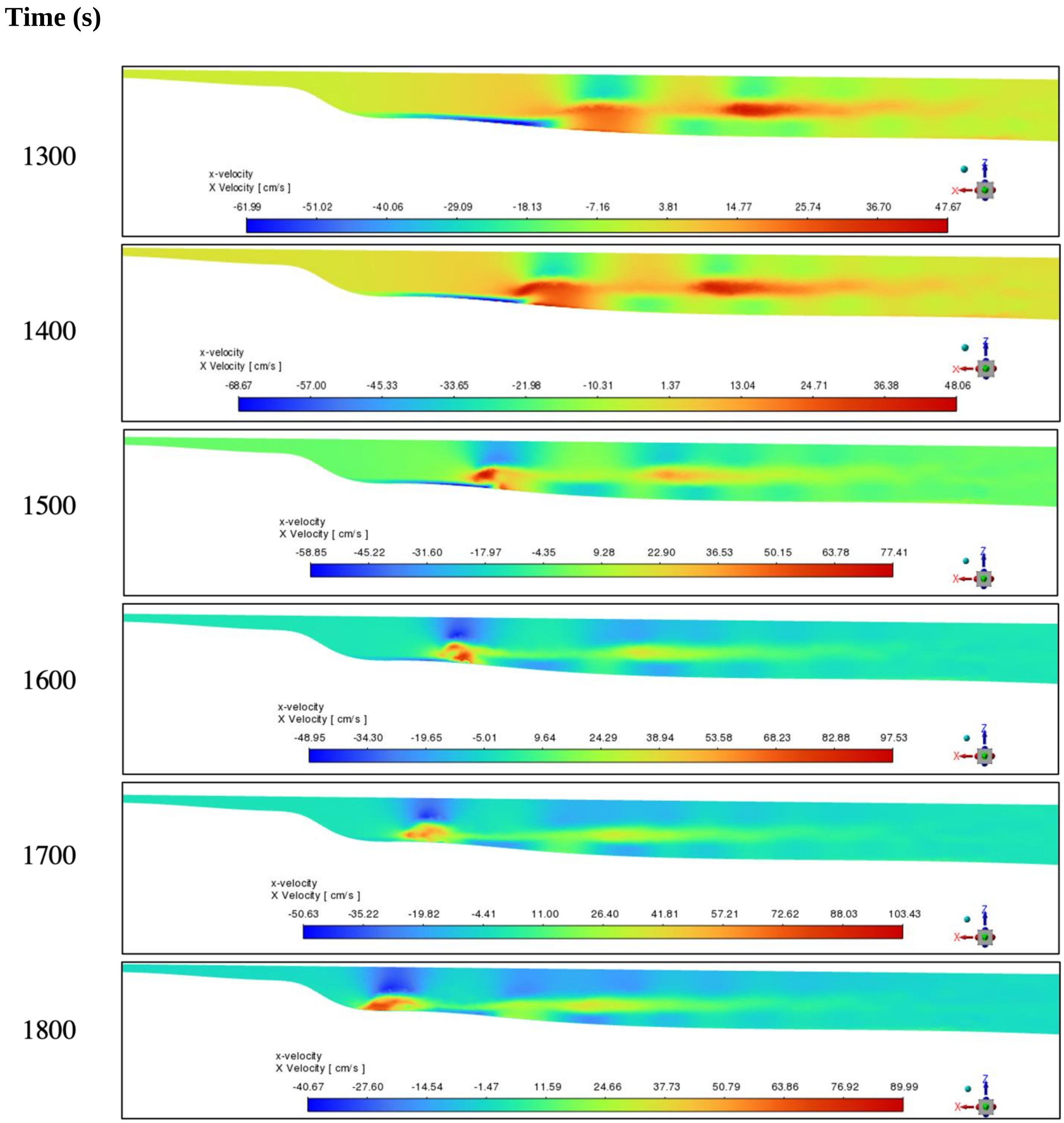


Figure 17. Model 2 contours of X-Component of velocity (cm/s) shown on ZX plane in middle of domain for timesteps 1300-2400.

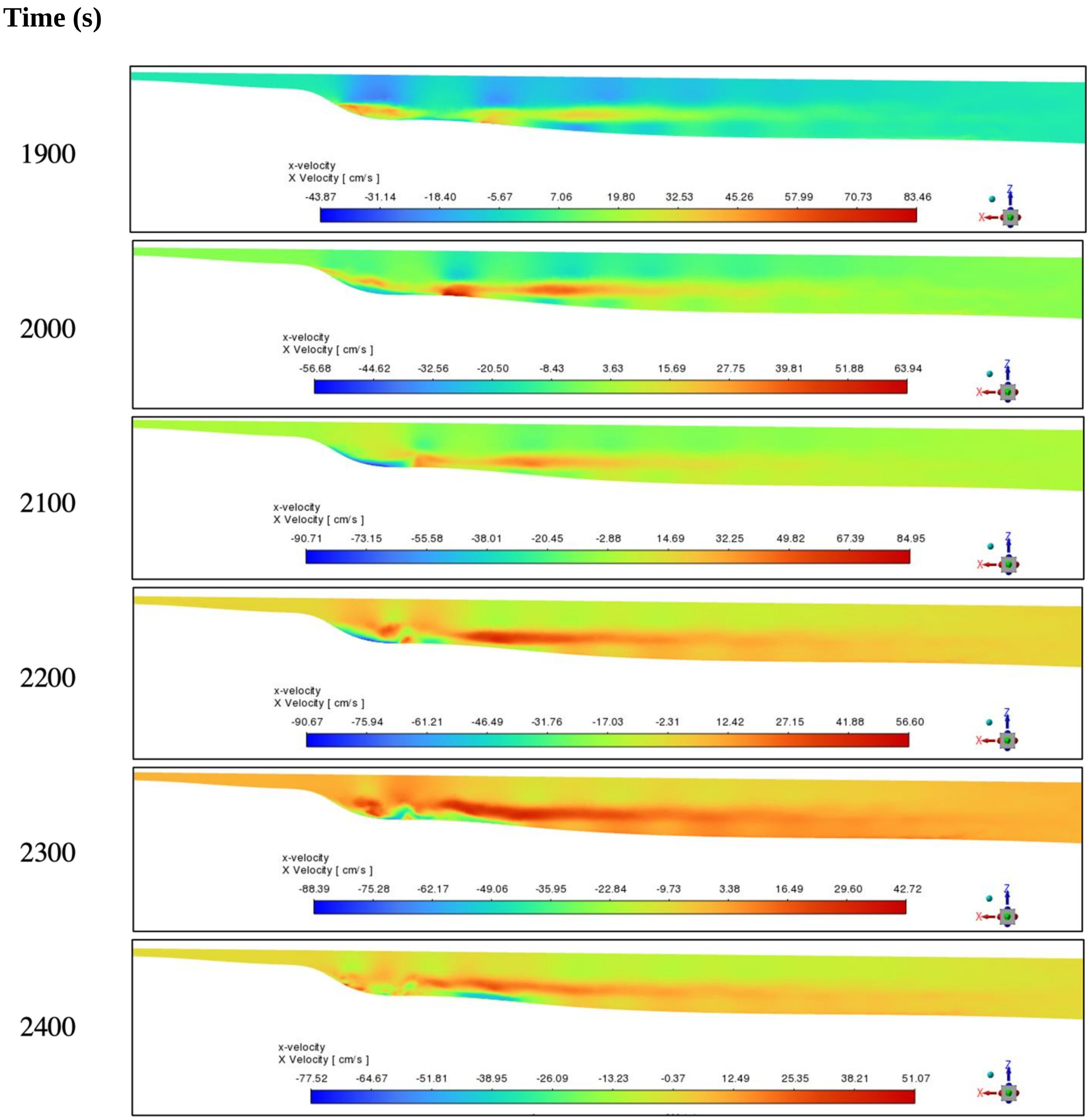


Figure 17 (*continued*).

3.3 Qualitative Comparison to Observations

Using models to simulate and understand complex ocean processes has become a powerful tool in science and research since the 1960's. When using models to simulate real physical phenomena occurring naturally in the ocean, model validation is a crucial step in the research process. Model validation is the process of determining the accuracy of model outputs in comparison to observed data. Although models are only a representation of real occurrences and no model can be considered "correct," model validation can attest to the plausibility and reliability of model performance. Quantitative, numerical validation would be preferential here in determining the accuracy of the internal wave model presented, however due to time constraints a quantitative analysis was not feasible for the model validation. Instead, a qualitative comparison of the model results to the findings of the study Leichter et al. (2005) can be done by comparing the spatial patterns of bottom temperature from the model and in-situ observations.

Based on the temperature contours on the bottom domain at times of internal bore runup and receding, the model showed broad qualitative agreement with the observed temperature data that was interpolated onto the reef bathymetry during an internal wave event. Temperature and velocity data were collected from May to August 2003 to construct a detailed, high-frequency, three-dimensional view of the runup of internal waves on a coral reef (Figure 18). On July 24, 2003, the documented cooling events were characterized by rapid movement of cool water bores onto the reef followed by internal vertical mixing. The internal bores arrived in the form of energetic pulses with cross shore velocities ranging from 25 to 30 cm s^{-1}. Data from the vertical temperature array showed synchronized drops in temperature within the bottom 2-10 m of the water column indicating that the cool water bores were being mixed vertically in the water column. Temperature data from the across-shore temperature array were interpolated onto the reef bathymetry, constructing a three-dimensional image of the spatial patterns of temperature produced by internal wave arrival (Figure 19). In the July period examined, the cool water fronts from the arrival and breaking of internal waves generated high spatial heterogeneity of temperature across the reef, indicated by positive and negative thermal anomalies that were associated with specific bathymetric features. Warm anomalies were found on the protruding edges of the coral spur formations and cool anomalies were found to occur within the sand grooves or depressions in the reef (Figure 20).

We see qualitative agreement in these temperature patterns when comparing the bottom temperature contours from Model 2 in Figure 16 to the interpolations of temperature from the study in Figure 19. The pattern of warm pools on the protruding edge of the reef described in Leichter et al. (2005) can be seen in timesteps 2000-2050, as well as cool water remaining in areas with grooves after the water recedes back down in timesteps 2300-2400. The patchiness of temperature heterogeneity shown in the model and in-situ observations can potentially be used a proxy for determining areas where dissolved nutrients, suspended particles, plankton, zooplankton and larvae are being upwelled and possibly concentrated in depressions or grooves of the reef. Understanding this 'pooling' effect can therefore increase our understanding of how larval settlement, thermal variability, and increased nutrient uptake by benthic algae affect coral reef communities on small temporal and spatial scales.

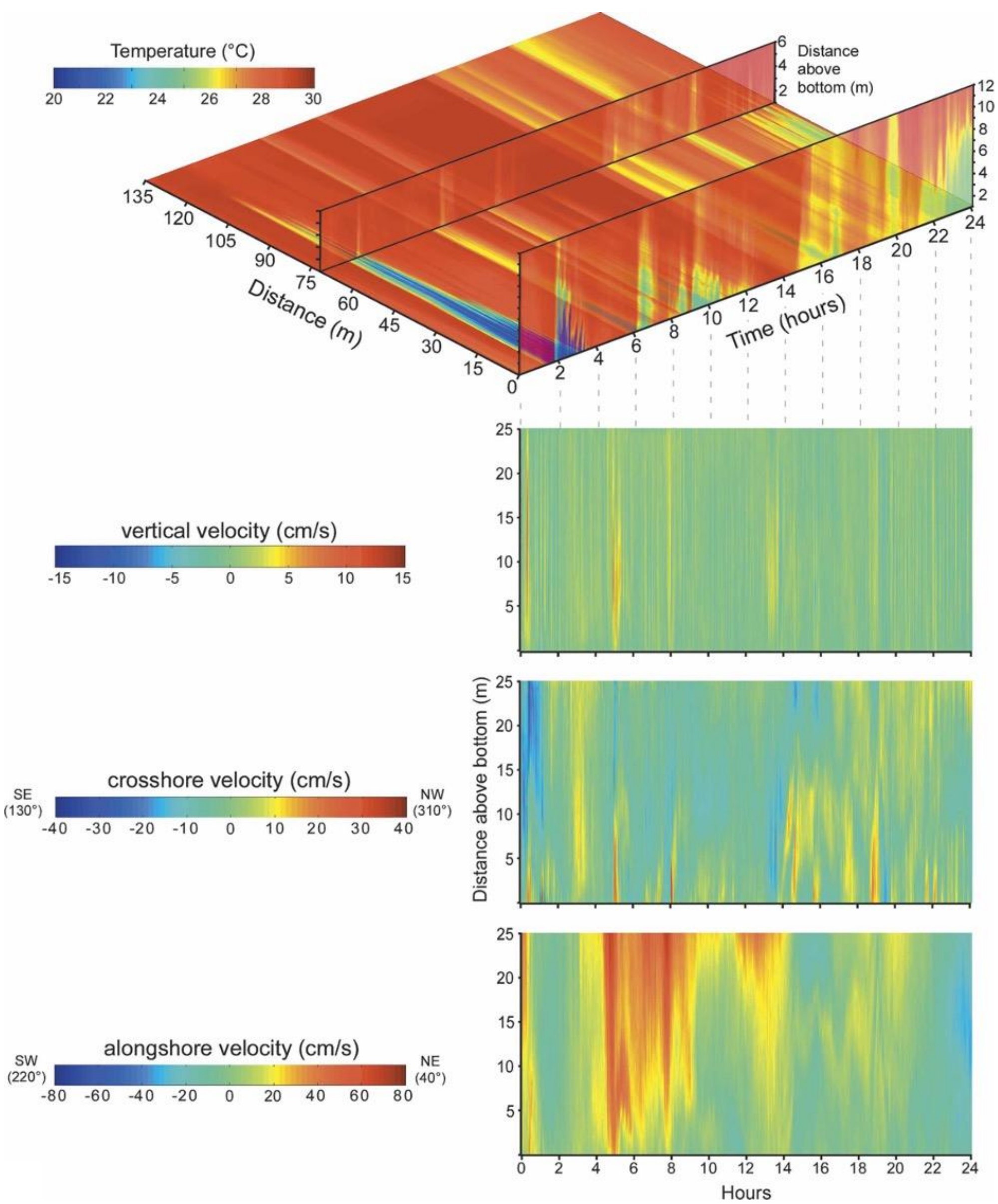


Figure 18. Vertical structure of temperature and cross-shore, vertical, and alongshore components of currents above the reef for a 24-hour period in July 2003, Leichter et al., (2005).

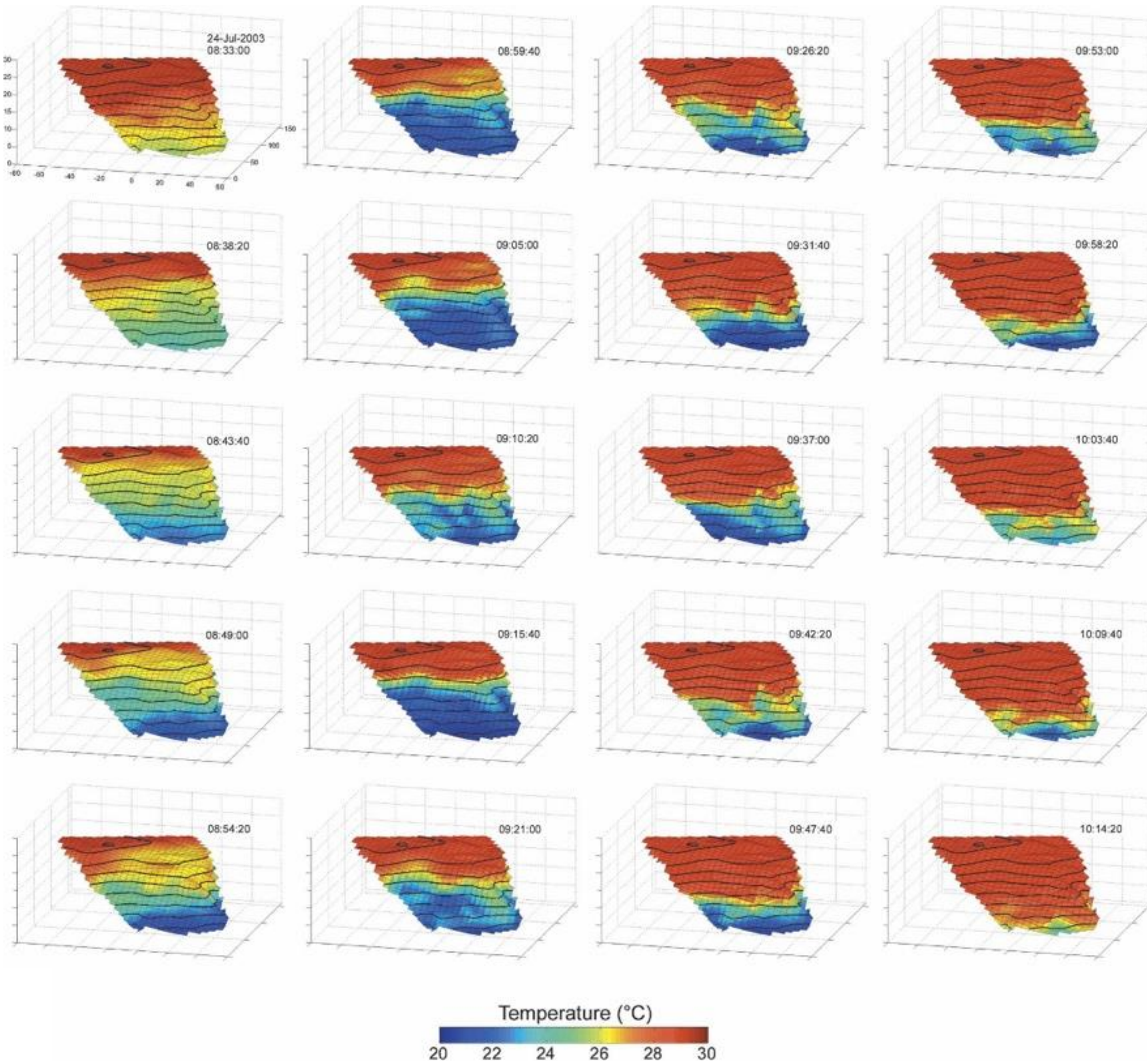


Figure 19. Sequential images (reading down columns) of water temperature interpolated onto the reef bathymetry. 20 frames at approximately 5-min intervals spanning approximately 2 hours in July 2003. Adapted from Leichter et al., (2005).

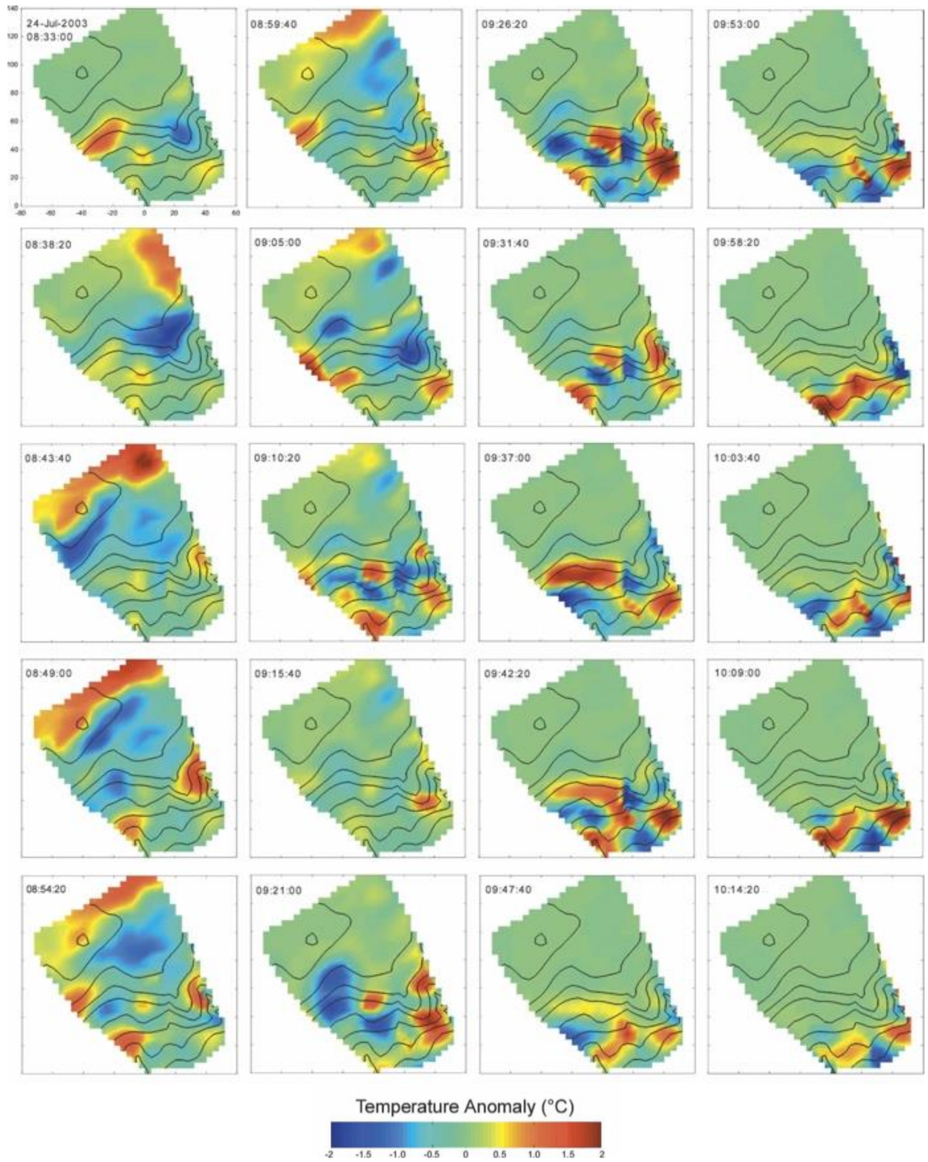


Figure 20. Instantaneous horizontal temperature anomaly interpolated onto the reef bathymetry for same time-period as Figure 19. Adapted from Leichter et al., (2005).

4. Limitations and Future Work

Although this model serves as a good qualitative approximation for the fluid dynamics of internal wave activity at Conch Reef, further improvements to the model would be beneficial in further improving the accuracy of the model. Specifically, implementing a continuous stratification profile taken from in-situ temperature data in the initialization of the model would allow for greater accuracy in the output of temperature and velocity components than the two-layered system described in this study. Because the fluid domain was an idealized two-layered system of water with temperatures differing by almost 10°, the density gradient is much higher than reality. The two-layered fluid and confining boundaries of the domain causes the buoyancy-driven flow from the simulation to have greater velocities than what was documented from ADCP measurements in the discussed study. Introducing a continuously stratified water column would be beneficial in improving the model's accuracy of velocity as well as temperature distribution. A higher resolution topography file with vertical accuracy small enough to capture the rugosity of the coral reef structures would expand the model's efficacy in reproducing small-scale dynamics on the scale of 10's of cm's. Lastly, introducing a passive scalar representing nutrients Nitrate and Phosphate to simulate concentration diffusion and distribution would provide insight into dynamics and fate of biologically important nutrients that are being upwelled during these events.

5. Conclusions

The CFD model generated in this study serves as a valuable tool in the visualization of internal solitary waves and internal bore dynamics on the complex, three-dimensional surface of a coral reef. Understanding the dynamics of internal wave-induced upwelling is an important element in understanding the drivers of reef community structure and incorporating models into this research can help us to better understand these interactions. This model serves as a good basis for potential future work on relating biological and chemical factors with physical models in the pursuit of attempting to describe the complex dynamics shaping coral reef communities. With threats of increased ocean temperatures and more frequent and severe coral bleaching events, internal waves are thought to potentially mitigate heat stress on coral reefs in some areas. Because of this, it is thought that coral reefs could become restricted to refugial and marginal habitats in the future and the influences of internal waves could be an important determinant of the distribution of reefs in the future, therefore it is critical to understand the frequency and magnitude of internal wave effects on coral reefs, especially those with high risk of bleaching and mortality due to heat stress like that of the Florida Keys Reef Tract. Combining physical models like the one presented here with in-situ data and knowledge of large-scale oceanographic drivers of internal waves can increase our understanding of how these events will impact coral reefs in the face of a changing climate.

References

Bachman, S. D., Kleypas, J. A., Erdmann, M., & Setyawan, E. (2022). A global atlas of potential thermal refugia for coral reefs generated by internal gravity waves. *Frontiers in Marine Science, 9,* 921879. https://doi.org/10.3389/fmars.2022.921879

Boyer, J. N., & Jones, R. D. (2002). A view from the bridge: External and internal forces affecting the ambient water quality of the Florida Keys National Marine Sanctuary (FKNMS). *The Everglades, Florida Bay, and Coral Reefs of the Florida Keys: An Ecosystem Sourcebook. CRC Press, Boca Raton, FL*, 609-628.

Cacchione, D. A., Pratson, L. F., & Ogston, A. S. (2002). The shaping of continental slopes by internal tides. *Science*, *296*(5568), 724-727. DOI: 10.1126/science.1069803

Cooper, L. H. N. (1947). Internal waves and upwelling of oceanic water from mid-depths on to a continental shelf. *Nature*, *159*(4043), 579-580. https://doi.org/10.1038/159579c0

Ewing, G. C. (1950). Relation between band slicks at the surface and internal waves in the sea. *Science*, *111*(2874), 91-94. DOI: 10.1126/science.111.2874.91.b

Garrett, C., & Munk, W. (1979). Internal waves in the ocean. *Annual Review of Fluid Mechanics*, *11*(1), 339-369. https://doi.org/10.1146/annurev.fl.11.010179.002011

Helfrich, K. R. (1992). Internal solitary wave breaking and run-up on a uniform slope. *Journal of Fluid Mechanics*, *243*, 133-154. https://doi.org/10.1017/S0022112092002660[Opens in a new window]

Lamb, K. G. (2014). Internal wave breaking and dissipation mechanisms on the continental slope/shelf. *Annual Review of Fluid Mechanics*, *46*, 231-254. https://doi.org/10.1146/annurev-fluid-011212-140701

Lapointe, B. E., & Smith, N. P. (1987). A preliminary investigation of upwelling as a source of nutrients to Looe Key National Marine Sanctuary. https://repository.library.noaa.gov/view/noaa/1627/noaa_1627_DS1.pdf

Leichter, J. J., Wing, S. R., Miller, S. L., & Denny, M. W. (1996). Pulsed delivery of subthermocline water to Conch Reef (Florida Keys) by internal tidal bores. *Limnology and Oceanography*, *41*(7), 1490-1501. https://doi.org/10.4319/lo.1996.41.7.1490

Leichter, J. J., Shellenbarger, G., Genovese, S. J., & Wing, S. R. (1998). Breaking internal waves on a Florida (USA) coral reef: A plankton pump at work? *Marine Ecology Progress Series, 166,* 83-97. doi:10.3354/meps166083

Leichter, J. J., Stewart, H. L., & Miller, S. L. (2003). Episodic nutrient transport to Florida coral reefs. *Limnology and Oceanography*, *48*(4), 1394-1407. https://doi.org/10.4319/lo.2003.48.4.1394

Leichter, J. J., Deane, G. B., & Stokes, M. D. (2005). Spatial and temporal variability of internal wave forcing on a coral reef. *Journal of Physical Oceanography, 35*(11), 1945-1962. https://doi.org/10.1175/JPO2808.1

Leichter, J. J., Stokes, M. D., Vilchis, L. I., & Fiechter, J. (2014). Regional synchrony of temperature variation and internal wave forcing along the Florida Keys reef tract. *Journal of Geophysical Research: Oceans*, *119*(1), 548-558. https://doi.org/10.1002/2013JC009371

MacKinnon, J. (2013). Mountain waves in the deep ocean. *Nature*, *501*(7467), 321-322. https://doi.org/10.1038/501321a

Masunaga, E., Arthur, R. S., & Fringer, O. B. (2019). Internal wave breaking dynamics and associated mixing in the coastal ocean. *Encyclopedia of Ocean Sciences*, 548-554. https://web.stanford.edu/~fringer/publications/masunaga-etal-eos-2019.pdf

Niiler, P. P. (1968, February). On the internal tidal motions in the Florida Straits. In *Deep Sea Research and Oceanographic Abstracts* (Vol. 15, No. 1, pp. 113-123). Elsevier. https://doi.org/10.1016/0011-7471(68)90031-4

Soloviev, A. V., Luther, M. E., & Weisberg, R. H. (2003). Energetic baroclinic super-tidal oscillations on the southeast Florida shelf. *Geophysical Research Letters*, *30*(9). https://doi.org/10.1029/2002GL016603

Stommel, H. (2022). *The Gulf Stream: A physical and dynamical description*. Univ of California Press. DOI: 10.1126/science.129.3362.1544.c

Szmant, A. M., & Forrester, A. (1996). Water column and sediment nitrogen and phosphorus distribution patterns in the Florida Keys, USA. *Coral Reefs*, *15*, 21-41. https://doi.org/10.1007/BF01626075

Riegl, B., & Piller, W. E. (2003). Possible refugia for reefs in times of environmental stress. *International Journal of Earth Sciences*, *92*, 520-531. https://doi.org/10.1007/s00531-003-0328-9

Taylor, J. R. (1992). The energetics of breaking events in a resonantly forced internal wave field. *Journal of Fluid Mechanics*, *239*, 309-340. doi:10.1017/S0022112092004427

Wallace, B. C., & Wilkinson, D. L. (1988). Run-up of internal waves on a gentle slope in a two-layered system. *Journal of Fluid Mechanics*, *191*, 419-442. doi:10.1017/S0022112088001636