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## RESEARCH LETTER

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## Climate-Driven Stratification Intensifies Internal Wave Cooling on a Shallow Island Reef

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### Key Points:

- Internal waves create cooling effect up to 2.3°C compared to background with no waves
- Increased stratification in a warmer ocean enhances nonlinear wave cooling effect by up to 0.5°C
- Overall trend points to continued warming, emphasizing the critical need mitigate climate change

### Supporting Information:

Supporting Information may be found in the online version of this article.

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**Abstract** As ocean temperatures rise, understanding the cooling role of internal waves is crucial for reef preservation. Climate-induced surface warming increases stratification, altering internal wave propagation. We use high-resolution, nonhydrostatic simulations at Dongsha Atoll in the South China Sea to explore seasonal bottom temperature changes affecting benthic ecosystems for climate scenario SSP5-8.5 for 2020 and 2100. Our findings show internal waves transport cooler, deeper waters into shallow areas, reducing warming by up to 2.3°C relative to conditions without waves. Enhanced stratification and internal tide forcing in a warmer, more strongly stratified ocean increases wave-driven cooling by up to 0.5°C in shallow zones. Variability in bottom temperature are also enhanced by up to 4.5°C. However, net warming by 2100 is projected at up to 2.8°C in shallow areas and 0.9°C in deeper regions. Areas with strong internal wave activity could serve as thermal refugia, despite overall trends pointing to continued ocean warming.

**Plain Language Summary** Coral reefs are some of the most vulnerable ecosystems to ocean warming, which is driven by climate change. In this study, we explore how underwater waves, called internal waves, affect water temperatures around Dongsha Atoll in the South China Sea. Using a model of the ocean, we looked at how internal waves and climate warming might impact water temperatures near the reef in 2020 and 2100. Internal waves bring cooler, deeper waters to the surface, which helps cool the shallows of the reef by up to 2.3°C compared to conditions without these waves. In a warmer future, stronger layering in the ocean enhances this cooling effect, adding another 0.5°C of cooling in shallow areas. We also found that future ocean warming will increase temperature fluctuations near the bottom, making them more variable by up to 4.5°C. Despite the cooling effects of internal waves, overall temperatures are expected to rise—up to 2.8°C in shallow areas and 0.9°C in deeper ones by 2100. While internal waves may create cool areas that help some reefs survive, the long-term trend of ocean warming highlights the urgent need to address climate change.

## 1. Introduction

Internal waves are pivotal in redistributing heat and momentum across the global ocean (Alford et al., 2015) and play essential ecological roles through upwelling and mixing in nearshore environments (Davis et al., 2020; Suanda et al., 2017; Walter et al., 2012). When internal tides (internal waves at tidal frequency) encounter topographic features, they propagate shoreward and transform into nonlinear internal waves, often resulting in the formation of bore fronts (Chao et al., 2006; McSweeney et al., 2019; Scotti et al., 2007). As these waves move into shallower depths, they steepen and break, creating dissipative bores and contributing to a complex internal wave field characterized by a spectrum of frequencies and wavelengths propagating from multiple distant sources (Arthur & Fringer, 2016; Lamb, 2014; Nash et al., 2004; Walter et al., 2012). Internal waves facilitate the cooling of shallow reefs by upwelling cooler, deeper waters (Davis et al., 2020; Reid et al., 2019; Rogers et al., 2022), making regions with strong internal wave activity potential thermal refugia for benthic organisms (Bachman et al., 2022; Storlazzi et al., 2020).

In a future warmer climate, the ocean surface warms more rapidly than at depth intensifying vertical stratification (Intergovernmental Panel on Climate Change (IPCC), 2023). Prior studies have shown increasing stratification in various regions of the world for both historical time periods and future climate projections (Decarlo et al., 2015;

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Li et al., 2020; Yadidya & Rao, 2022). This enhanced stratification varies seasonally and regionally but is anticipated to impact internal tides and wave-driven upwelling processes.

Previous studies have demonstrated that stronger stratification can amplify internal tide generation in the Luzon Strait through increased tidal velocity magnitude (Decarlo et al., 2015). In a future warmer ocean, particularly at local scales where internal waves interact with shallow coastlines, we anticipate stronger wave motions, enhanced upwelling, and warmer background ocean temperatures. While prior work has assumed a linear relationship between barotropic tidal amplitude and upwelling (Storlazzi et al., 2020), the concurrent increase in stratification and increased internal tide velocity suggests an important nonlinear interaction which impacts nearshore temperatures and has yet to be thoroughly evaluated. This study addresses the question: in a warming and increasingly stratified ocean, how will upwelling from shoaling internal waves change bottom temperatures near the coast?

To address this question, we conduct high-resolution simulations of Dongsha Atoll in the South China Sea using the SUNTANS model (Fringer et al., 2006), assessing internal wave upwelling under various seasonal and climate conditions. We focus on time-averaged bottom temperature and bottom temperature variability which are critical to benthic organisms, and we decompose temperature changes due to climate warming and internal waves.

## 2. Methods

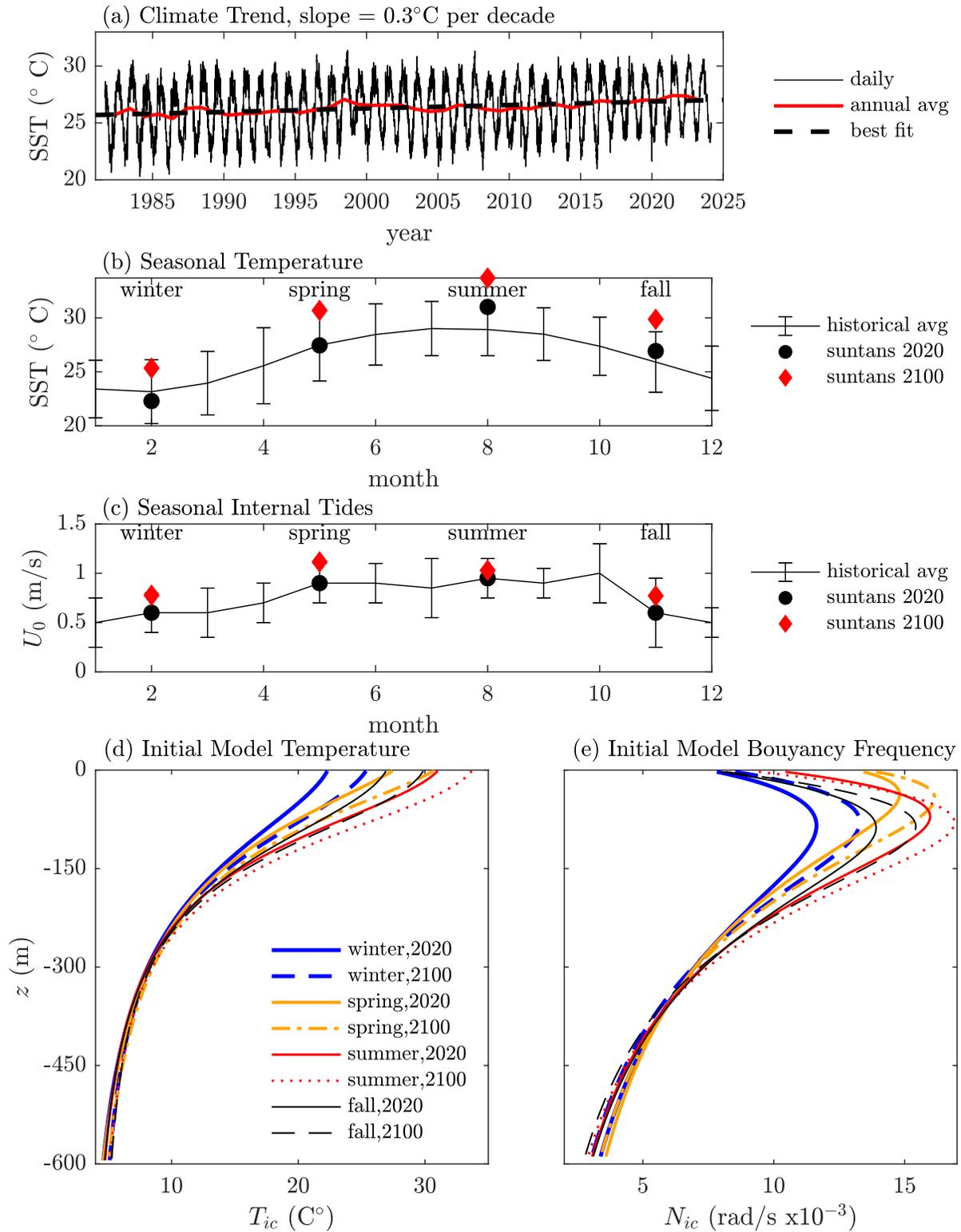
### 2.1. Constructing Temperature Profiles

We construct representative temperature profiles consistent with season and projected climate changes, using historical seasonal stratification from the Luzon Strait based on hindcast model results. Specifically, we take the historical average buoyancy frequency  $N_H(m, z)$ , which is a function of month  $m$  and depth  $z$ , and the change in stratification (Decarlo et al., 2015). Assuming future changes in stratification will have a similar spatial distribution for each season but different magnitude, we approximate a future background buoyancy frequency  $N_{ic}$  (see Text S1 in Supporting Information S1). The result is the initial temperature profile  $T_{ic}$  that is consistent with the desired bottom and surface temperatures for a given year, season, and climate scenario; and is consistent with historical trends of  $N_{ic}$  (Figures 1d and 1e).

The model is forced with the velocity field derived from a first-mode semidiurnal ( $M_2$ ) internal tide that is consistent with  $N_{ic}(z)$  (Rogers et al., 2019, 2022). We assume one tidal mode ( $M_2$ ) for simplicity and because it is the dominant tidal constituent in the South China Sea. For the magnitude of the internal tidal motions  $U_0$ , we rely on seasonal observations of internal tidal velocity magnitude from the South China Sea (Huang et al., 2022) (Figure 1c). For future conditions, we assume the generation of internal tides from vertical density perturbations is linearly proportional to  $N^2$  (Baines, 1982; Decarlo et al., 2015), and changes in  $U_0$  scale proportionally to changes in  $N_{ic,max}^2$  (Figure 1c) (see Text S1 in Supporting Information S1). While the  $M_2$  barotropic tidal amplitude may change due to sea level rise and other anthropomorphic effects (Haigh et al., 2020), we assume these effects on the internal tide are negligible. This is consistent with models of internal tide generation which show that the strength of the internal tides in the South China Sea increases with increasing stratification (Chuang & Wang, 1981; Shaw et al., 2009; Zhang et al., 2011; Zheng et al., 2007).

### 2.2. Model Setup

To simulate internal wave motions and their impact on temperature fields, we utilized the SUNTANS model, which solves the three-dimensional, Reynolds-averaged Navier-Stokes equations under the Boussinesq approximation, alongside the depth-averaged continuity equation for the free surface and transport equations for salinity and temperature (Fringer et al., 2006). SUNTANS has been applied to a wide-range of field-scale internal wave problems in the South China Sea and Dongsha Atoll, with model results matching observations with little model tuning (Dai et al., 2023; Davis et al., 2020; Jeon et al., 2023; Ramp et al., 2019; Rogers et al., 2019; Simmons et al., 2011; Zhang et al., 2011) (see Text S6 in Supporting Information S1). Internal wave motions at the eastern boundary were forced using a mode-1 internal tide consistent with the initial stratification and  $M_2$  tidal period, while wave motions at the outgoing boundaries were absorbed (Rogers et al., 2019, 2022). The model domain covers a 213 by 341 km area of the South China Sea. See Text S2 in Supporting Information S1 for additional model setup details.



**Figure 1.** Climate and seasonal temperature and internal tide trends in the South China Sea. (a) Daily, annual average, and long-term historical trends in sea surface temperature (SST), (b) seasonal historical trends in SST and assumed SST for model runs, and (c) seasonal velocity trends of internal tides and assumed offshore velocity scale  $U_0$  for suntans model runs, (d) initial temperature  $T_{ic}$  and (e) initial buoyancy frequency  $N_{ic}$ . Error bars in (b) and (c) represent one standard deviation of time variability. Winter, spring, summer, fall notation for 2020 and 2100 in (b) and (c) correspond to initial conditions for SUNTANS model runs in (d) and (e).

Eight model runs were conducted to explore different seasonal conditions and climate scenarios for the present (2020) and future (SSP5-8.8, 2100) (Table S1 in Supporting Information S1).  $T_{ic}$ ,  $N_{ic}$  and  $U_0$  varied by season and climate year (Figures 1b–1e).

### 2.3. Averaging and Statistics

We are focused on areas near the bottom of the water column ( $b$ ) where benthic organisms live. Thus, the time average ( $\bar{\cdot}$ ) bottom temperature  $\bar{T}_b$  and bottom temperature variability  $T_{b,range}$  taken as the difference between maximum and minimum  $T_b$  in time, are the primary quantities of interest. The time averaging period is the last two  $M_2$  periods of each simulation.

To understand why  $\bar{T}_b$  is changing in a future climate we consider the components of temperature change ( $\Delta\bar{T}_b$ ) due to climate ( $\Delta\bar{T}_c$ ), and complex internal wave processes ( $\Delta\bar{T}_{iw}$ ),

$$\Delta\bar{T}_b \equiv \bar{T}_{b,2100} - \bar{T}_{b,2020} = \Delta\bar{T}_c + \Delta\bar{T}_{iw}. \quad (1)$$

$\Delta\bar{T}_c$  is a linear effect imposed by the initial climate conditions (Figure 1d),

$$\Delta\bar{T}_c = T_{ic,2100} - T_{ic,2020}. \quad (2)$$

### 2.4. Climate and Seasonal Trends

Sea surface temperature (SST) in the South China Sea follows distinct seasonal trends and has been rising at a rate of 0.3°C per decade (Figures 1a and 1b) based on SST taken from AVHRR OI v2.1 satellite from 1981 to 2024 (<https://coastwatch.pfeg.noaa.gov>). Climate projections indicate that by 2020, the South China Sea had warmed by 0.5°C at the surface and 0.1°C at 600 m depth (the depth of the model domain for this study) compared to the historical baseline from 1982 to 2023 (Intergovernmental Panel on Climate Change (IPCC), 2023). By 2100 for climate scenario SSP5-8.5, the region is expected to warm by 2.8°C at the surface and 0.4°C at 600 m depth relative to the same baseline.

## 3. Results

### 3.1. Instantaneous Temperature Field

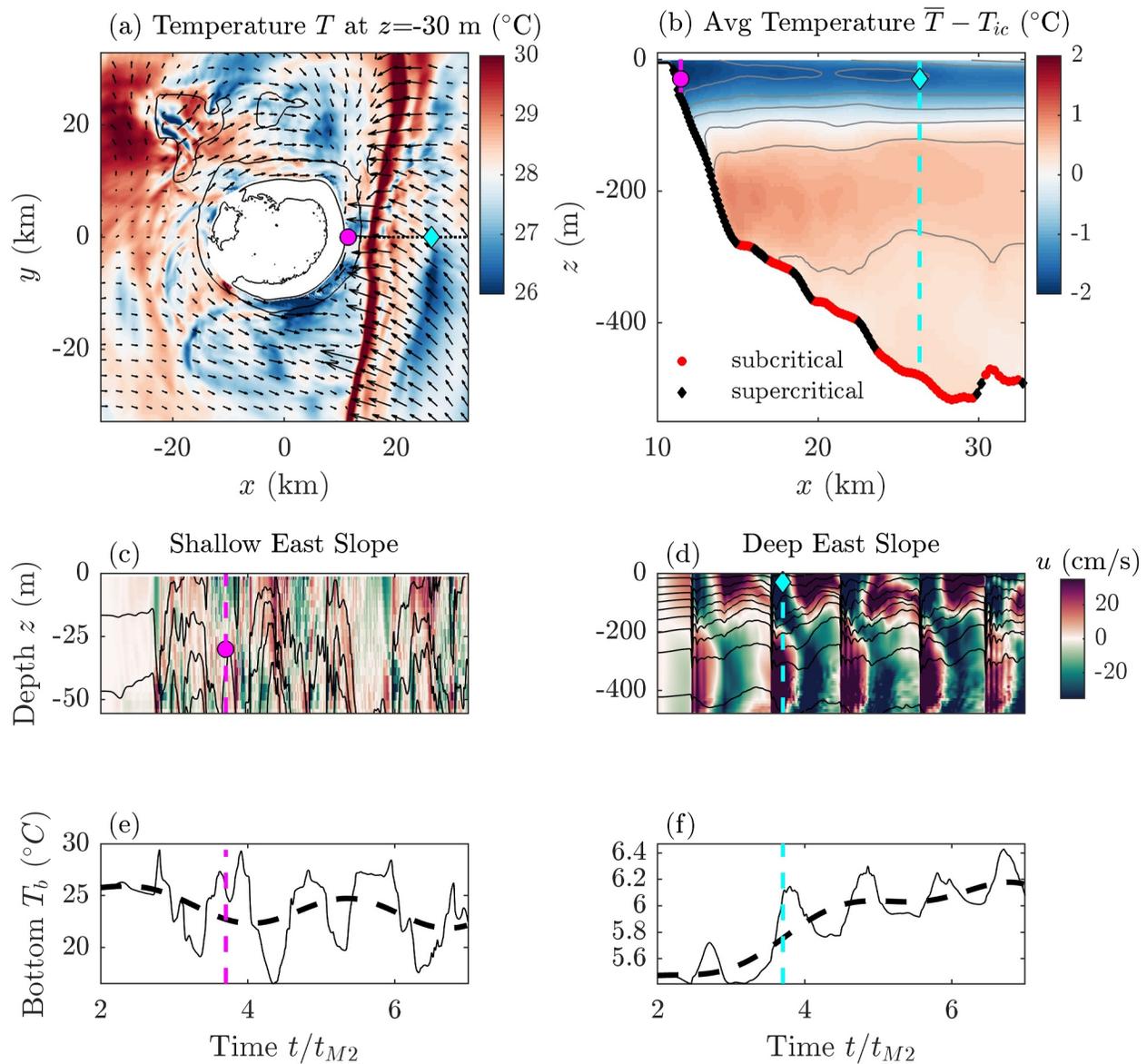
The internal tide steepens into nonlinear internal waves, wrapping around the island and modifying temperature field around the atoll (Figure 2a), consistent with previous modeling studies of Dongsha Atoll (Davis et al., 2020; Rogers et al., 2019, 2022; Zhang et al., 2011).

At the offshore eastern slope (478 m depth), the incoming internal tide is accompanied by an elevated free surface signature and a warm wave front at 30 m depth (Figures 2a and 2b). Near the bottom, internal tide fronts bring warmer pulses ( $\sim 0.5^\circ\text{C}$ ) and offshore flow (Figure 2d), contributing to an overall warming trend (Figure 2f). In contrast, at the shallow eastern slope (55 m depth), the internal tide creates a more complex pattern with cooler pulses ( $\sim 8^\circ\text{C}$ ) and onshore flow at the bottom (Figure 2c), resulting in a cooling trend (Figure 2e).

### 3.2. Time-Averaged Temperature

The departure of the time-averaged bottom temperature from the initial conditions ( $\bar{T}_b - T_{ic}$ ) reflects the cumulative impact of internal waves on bottom temperature (Figures 2b and 3). We use the 100 m depth boundary as the transition between “deep” and “shallow” areas as it is the approximate transition between shallow depths where sunlight influences benthic organisms in the meso-photic zone, and deeper areas where light does not penetrate.

There is a cooling effect in shallow areas (less than 100 m) on the exterior slopes of the atoll, while deeper areas (greater than 100 m) generally experience a warming effect (Figures 2b and 3a). The change in average bottom temperature ( $\bar{T}_b$ ) between 2020 and 2100 illustrates the anticipated climate impact over time, with temperature increases across the model domain (Figure 3b).

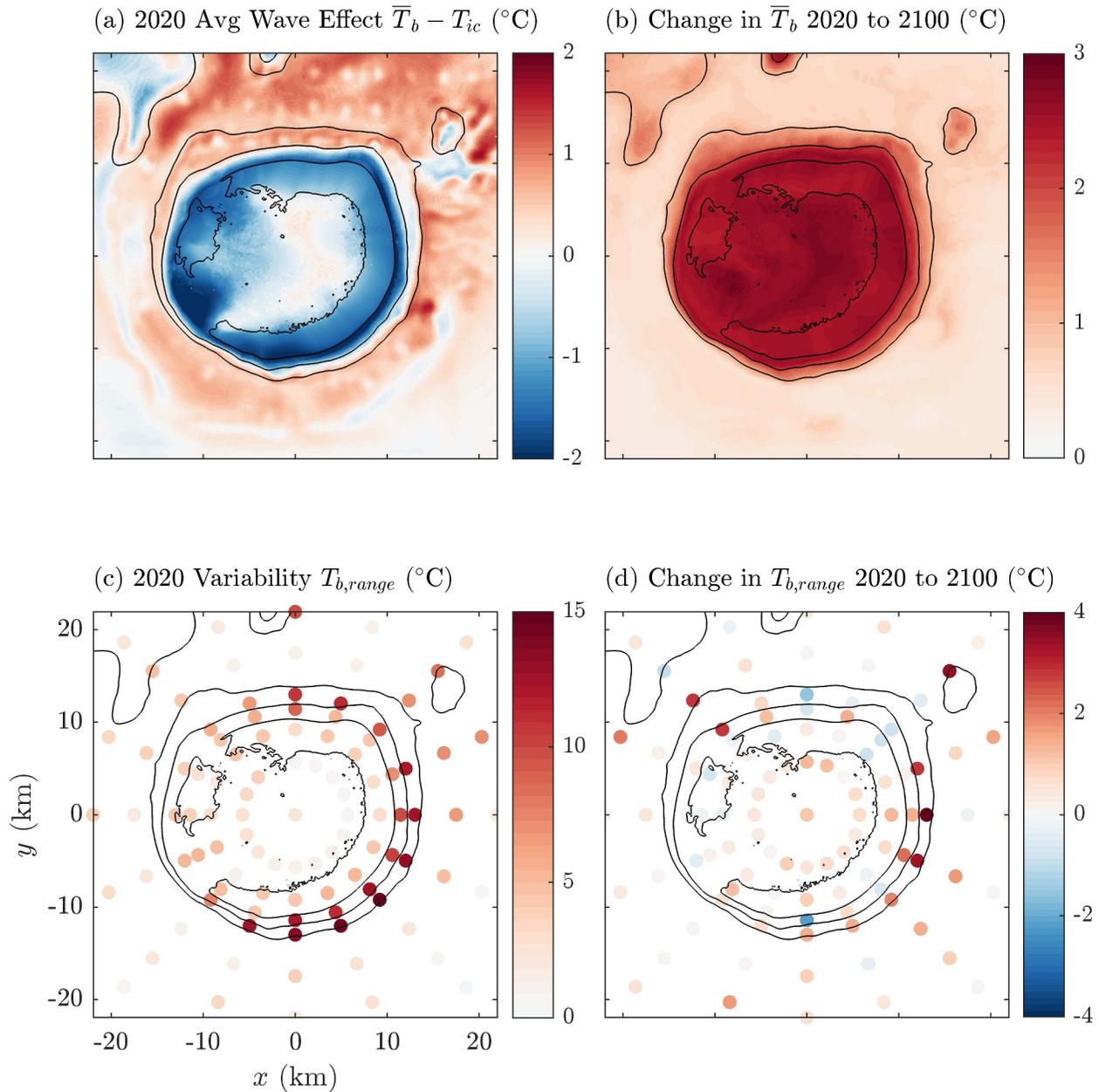


**Figure 2.** Temperature fields for run R3b (baseline 2020 summer) showing (a) top-down view of instantaneous temperature and velocity field at 30 m depth at time/  $t_{M2} = 3.7$ . (b) Time averaged temperature  $x$ - $z$  profile showing subcritical and supercritical slope areas along eastern facing slope. Velocity (colors) and temperature (-)  $3^{\circ}\text{C}$  contours at (c) shallow east slope and (d) deep east slope. Bottom temperature  $T_b$ , instantaneous (-) and low-pass filtered (-) at (e) shallow east slope and (f) deep east slope. Note markers in (a) ( $\bullet$ ,  $\blacklozenge$ ) are collocated in space and time in (b-f). Solid lines in (a) are the 5 and 200 m depth contours, vectors have a maximum magnitude of 1.5 m/s.

To understand the wave effect ( $\bar{T}_b - T_{ic}$ ) on average, we averaged regions 10–20 km from the atoll center, differentiating between deep (100–600 m) and shallow (5–100 m) areas (Figures 4a and 4b). In deep areas, the internal waves result in a temperature increase of up to  $1.0^{\circ}\text{C}$ , varying by season and location on the atoll and showing higher temperatures in 2100 compared to 2020 (Figure 4a). In contrast, in shallow areas, the wave effect leads to a temperature decrease of up to  $2.3^{\circ}\text{C}$ , also varying by season and showing cooler temperatures in 2100 compared to 2020 (Figure 4b).

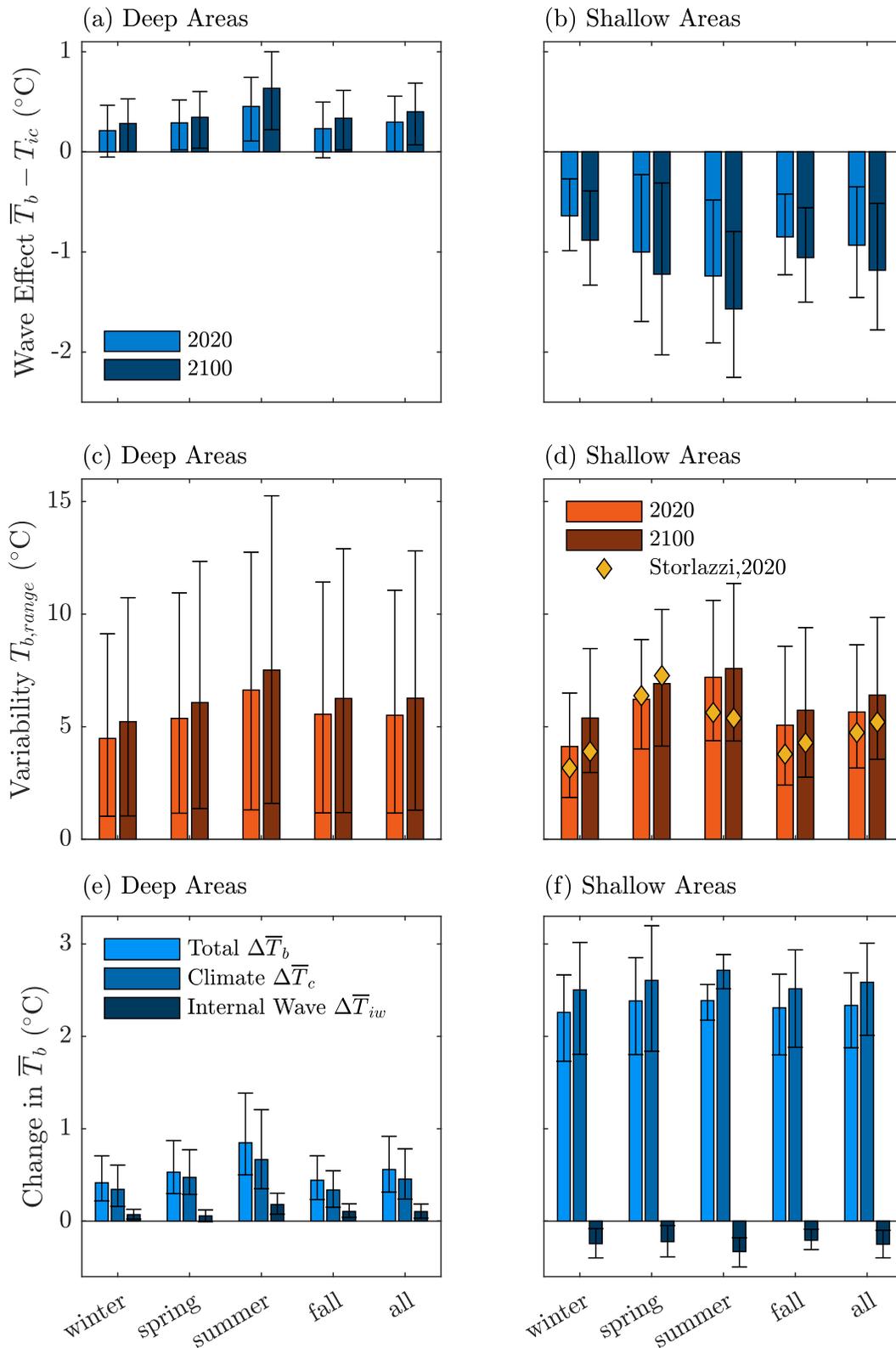
### 3.3. Temperature Variability

Bottom temperature variability, calculated as the range of bottom temperature, shows the greatest fluctuations in deep areas along the eastern and southern slopes of the atoll (Figure 3c), and magnitude similar to previous



**Figure 3.** Wave effects and long-term changes to time-averaged temperature (top) and temperature variability (bottom) for summer conditions showing (a) difference between average bottom temperature with internal waves and the initial condition with no internal waves in 2020 (run R3b), (b) change in average temperature between future 2100 condition with internal waves (run R3f) and 2020 baseline with internal waves (run R3b), (c) range of bottom temperature in 2020 (run R3b), and (d) change in bottom temperature range between future 2100 condition (run R3f) and 2020 baseline (run R3b). Solid lines (-) represent the 5, 100, and 200 m depth contours.

observations on Dongsha (Davis et al., 2020; Sinnett et al., 2022). These areas of high variability align with regions of intense internal wave energy, with north-south asymmetry primarily caused by rotational effects, a pattern observed in previous studies (Rogers et al., 2022). The change in variability between 2020 and 2100 reveals an increase of up to 4.5°C along the southern and eastern slopes (Figure 3d). We average the temperature variability for deep and shallow areas, and in both, the magnitude and trends in temperature variability are quite similar (Figures 4c and 4d) and are consistent with a linear estimate (Storlazzi et al., 2020; Zhao et al., 2016) (see Text S4 in Supporting Information S1).



**Figure 4.** Seasonal variation in wave effect (top) and temperature variability (middle) and climate and wave effects (bottom) for years 2020 and 2100 as a function of spatially-averaged deep (left) and shallow (right) areas. Here, shallow represents depths between 5 and 100 m, deep represents depths between 100 and 600 m, and both exclude areas within the interior lagoon and distances greater than 20 km from the atoll center. Error bars represent the spatial variability of the 16th and 84th percentiles. Markers in (d) are a linear estimate (Storlazzi et al., 2020).

### 3.4. Climate and Wave Effects

To assess the relative contributions of climate change and internal waves to changes in average bottom temperature from 2020 to 2100, we decompose the total temperature change ( $\Delta\bar{T}_b$ ) into components driven by climate ( $\Delta\bar{T}_c$ ) and internal waves ( $\Delta\bar{T}_{iw}$ ) (Equation 1). In deep areas (100–600 m depth), average temperatures increase by up to 1.4°C (Figure 4e). Seasonal variability is primarily influenced by the climate component  $\Delta\bar{T}_c$ , while internal waves add up to 0.3°C of additional warming. In shallow areas (5–100 m depth), average temperatures rise by up to 2.8°C (Figure 4f), with climate-induced variability driving the changes, and internal waves contributing a cooling effect of up to 0.5°C. We separate the impact of the density stratification and boundary forcing on the wave-induced temperature change ( $\Delta\bar{T}_{iw}$ ) in Figures 4e and 4f, and find that both effects are important (See Text S5 in Supporting Information S1). Thus, due to the non-linear effects of stratification, internal waves result in future average temperatures that are 0.5°C cooler in shallow areas (and 0.3°C warmer in deep areas) than the same internal wave field with present day stratification.

## 4. Discussion

### 4.1. Physical Implications

This study examines various internal tide forcing and stratification scenarios for the present day (2020) and the year 2100 under the SSP5-8.5 emissions scenario. Rather than predicting specific outcomes, our goal is to explore a range of potential impacts in a future climate. The primary model forcing comes from changes in stratification, derived from a combination of observations, hindcast model data, and scaled climate projections. Additionally, internal tide magnitude is based on observations and scaled according to the buoyancy frequency for future scenarios.

The total temperature change on Dongsha Atoll over the simulated 80 years results from a combination of climate-driven warming—more pronounced at the surface than at depth—and internal wave-driven upwelling, a nonlinear process. In shallow areas wave-driven processes create upwelling and cooler bottom waters on average, while in deeper areas they create downwelling and warmer bottom waters on average (Figure 3a). Superimposed on these long-term trends are seasonal variations, which we sampled to capture a range of variability. In our model, climate trends are imposed as initial temperature conditions, with surface layers warming more than deeper ones and showing seasonal variations consistent with sea-surface temperature (SST) observations (Figure 1). The SUNTANS model computes the internal wave effects.

As internal tides approach the atoll, they evolve into nonlinear internal waves, steepening, breaking, and wrapping around the atoll in complex patterns (Figure 2), consistent with other modeling and observational studies (Davis et al., 2020; Rogers et al., 2019, 2022; Zhang et al., 2011). The waves become more nonlinear with onshore propagation because the effective depth of the pycnocline  $H_e$  (Vitousek & Fringer, 2014) (see Text S3 in Supporting Information S1) decreases for roughly the same wave amplitude  $a$ , increasing the Froude number (i.e.,  $Fr = \frac{U_0}{C_0} \sim \frac{a}{H_e}$ , assuming  $U_0 \sim aC_0/H_e$ ).

For Dongsha Atoll, the transition between regions that are cooled and those that are warmed is at approximately 100 m, corresponding to the location of maximum buoyancy frequency  $N_{ic}$  (Figure 1e). This trend in average temperatures arises from the upwelling of cool pulses in shallow waters and downwelling of warm pulses in deeper areas with some three-dimensional effects also playing a role (Figure 2), and has been noted in previous studies of Dongsha (Davis et al., 2020; Rogers et al., 2022). This is most likely linked to the expected maximum interface descent of a shoaling solitary internal waves, and the effective thickness of the upper layer (Sutherland et al., 2013), which changes depending on season and year (Figures 1c and 1d). The steady Lagrangian flow induced by internal waves, or Stokes drift, is onshore at surface and bottom and offshore at mid-depth, which is the source of nepheloid layers, and is generally centered on the pycnocline (Arthur & Fringer, 2016). The nonlinear effect of multiple internal waves is to displace the return region because the internal waves are transporting cold water onshore, although complex three-dimensional effects are also likely important here. Thus, pulsing of cooler deep waters upslope is the primary cooling mechanism in the shallow regions, while downwelling of warmer pulses is the primary warming mechanism in deep areas.

On average, the wave-induced cooling in shallow areas is up to 2.3°C, with a stronger effect in the future (2100) scenario and high spatial variability. In contrast, deeper areas see a temperature increase of 1.0°C due to internal waves.

Despite the cooling effect of internal waves, the overall trend is one of net warming across the atoll by 2100. Shallow regions are expected to warm by up to 2.8°C, while deeper areas will warm by up to 1.4°C (Figure 4). This disparity is primarily driven by climate-induced warming, which is more pronounced near the surface. However, internal waves provide an additional cooling effect in shallow areas (reducing ocean warming temperatures by up to 0.5°C) and a warming effect in deeper regions due to nonlinear wave dynamics. Due to the enhanced stratification, internal waves in the 2100 scenario result in future average temperatures that are 0.5°C cooler in shallow areas (and 0.3°C warmer in deep areas) than they would be with the same internal wave field in present day stratification conditions.

Bottom temperature variability is another key variable examined in this study. Predictions from the SUNTANS model in shallow regions show generally higher variability compared to results from an approximate linear model (Storlazzi et al., 2020) (Figure 4d). This suggests that the nonlinear wave effects enhance bottom temperature variability compared to a linear internal wave. We found that temperature variability is highest on the eastern and southern sides of the atoll, where internal wave activity is most intense (Figure 3). This variability increases in a future climate by up to 4.5°C relative to variability in 2020, with the most significant changes in temperature variability are observed along the southern and eastern slopes of the atoll (Figure 3).

This study focuses on one atoll under a limited range of conditions and different islands may exhibit varying physical behaviors depending on internal tide forcing, stratification (Froude number), latitude (Rossby number), slope (slope criticality), and size (excursion number), among other factors (Equation S6 in Supporting Information S1) (Rogers et al., 2022). In terms of generalizability, while the South China Sea exhibits exceptionally large amplitude internal tides, climate trends of increasing surface stratification on internal tides and their interaction with supercritical slopes at mid-latitudes are expected to be quite common globally. To isolate the effects of internal tides and stratification, we excluded influences such as barotropic tides, large-scale ocean currents, and other potential drivers, and sampled limited seasonal variability under one future climate scenario. Additionally, our model does not account for surface gravity waves, which are important in very shallow regions and drive circulation in the interior lagoon. These factors warrant further investigation in future studies.

## 4.2. Ecological Implications

This study's primary contribution lies in quantifying the nonlinear interaction between climate warming and internal wave effects on bottom temperatures, which have important ecological implications. Previous studies have assumed a linear response of internal waves to future climate conditions, ignoring the impact of changing density profiles on internal wave dynamics (Storlazzi et al., 2020). Our findings show that, in shallow regions, internal waves provide an additional cooling effect in future scenarios, driven by the nonlinear interaction between enhanced stratification and upwelling.

Deeper, upwelled waters are cooler and generally rich in nutrients, which can be beneficial for benthic organisms. Despite some exceptions from low oxygen waters (Williams et al., 2018), cooler average temperatures are generally favorable for coral reefs. Reduced bottom temperatures compared to surrounding waters can alleviate thermal stress, potentially creating thermal refugia that offer some protection against ocean warming (Reid et al., 2019; Storlazzi et al., 2020; Wyatt et al., 2020). Thus, upwelled waters in shallow regions, along with lower temperatures, can be beneficial for benthic organisms under many conditions.

Additionally, our study shows that temperature fluctuations driven by internal waves increases in some regions. Thermal variability is often considered beneficial for benthic organisms, as corals in naturally variable environments can develop enhanced resistance to bleaching at high temperatures, up to certain thresholds (Safaie et al., 2018).

The creation of cooler regions by internal waves introduces the potential for thermal refugia, where areas with strong internal wave activity could be partially shielded from the effects of ocean warming. However, despite the cooling effects of internal waves in shallow regions, the overall trend remains one of increasing temperatures over time. Climate change is the primary driver of ocean temperature increases, with internal waves acting as a secondary, mitigating influence. Consequently, while some localized refugia may persist, the broader expectation

is continued warming, leading to increased bleaching and widespread declines in coral reefs (Carpenter et al., 2008; Hoegh-Guldberg et al., 2007). This underscores the urgent need to address the root causes of climate change and reduce carbon emissions to protect these vital ecosystems.

## 5. Conclusions

We conducted a series of high-resolution simulations at Dongsha Atoll using the SUNTANS model to quantify changes in bottom temperature under several seasonal and climate scenarios in the year 2020 and 2100. The climate affects the ocean temperatures by warming surface waters more than those at depth, which is reflected in our model through the initial temperature stratification. We focus on two primary factors influencing bottom temperature: climate-induced warming and internal wave effects.

Our findings for the 2020 scenario indicate that internal waves cool the shallow regions of the atoll by up to 2.3°C compared to background conditions without internal waves, while deeper regions are warmer. With increased stratification in a future climate, internal tidal forcing is intensified, and the nonlinear wave effects further cool the shallow regions by up to 0.5°C. We also find increased bottom temperature fluctuations of up to 4.5°C relative to 2020 in regions of the atoll exposed to internal tidal energy. Despite the enhanced cooling from internal waves, the shallow regions are expected to experience net warming by up to 2.8°C by 2100 under the SSP5-8.5 climate scenario.

The nonlinear interaction between climate warming and internal waves affects the bottom temperature, which carries significant ecological implications. Notably, the presence of regions that are cooler than previously predicted opens the possibility of thermal refugia, where areas with strong internal wave activity are partially shielded from the effects of ocean warming. However, the overall trend remains one of increased temperature, underscoring the urgent need to address the root causes of ocean warming.

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Data Availability Statement

SUNTANS model run output and model code is available in Rogers and Fringer (2025).

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