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Physical and ecological processes of internal waves on an isolated reef ecosystem in the South China Sea

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[1] Field measurements at Dongsha Atoll in the northern South China Sea showed frequent drops in daily water temperature up to 8°C during intrusions of large nonlinear internal waves. The internal waves had a period of about 4 hours and velocity amplitude of 0.3 m s^{-1}. Large variations of dissolved oxygen were observed a week after cold-water intrusion, which was followed in another 2 days by a significant increase of chlorophyll content. The 7–8-day delay suggests that phytoplankton blooms occurred after the nutrients were released through microbial decomposition of organics brought up by the internal waves. This study highlights the effects of internal waves and the possible role of the microbial food web on nutrient regeneration in a tropical reef ecosystem. **Citation:** Wang, Y.-H., C.-F. Dai, and Y.-Y. Chen (2007), Physical and ecological processes of internal waves on an isolated reef ecosystem in the South China Sea, *Geophys. Res. Lett.*, *34*, L18609, doi:10.1029/2007GL030658.

1. Introduction

[2] Dongsha Atoll (Figure 1) is located at the edge of the continental shelf in the northern South China Sea (SCS). The atoll is exposed to nonlinear internal waves (NLIW) emanated almost daily from the Luzon Strait during spring tides [*Hsu and Liu*, 2000; *Liu et al.*, 2006]. These NLIWs with amplitudes reaching 140 m or more could energize the top 1500 m of the water column at timescales of 20 min to 2 hr. They are mostly single depression waves west of Luzon, but packets of multiple waves appear over the continental shelf [*Chao et al.*, 2007].

[3] The surface water of oceanic islands and atolls in the tropical ocean are oligotrophic, yet they support rich coral reefs and fisheries. This paradox may be explained, in part, by the dissipation of internal waves, which pumps nutrients up to the oligotrophic surface water of coral reefs. Physical forcing associated with internal waves is known to occur on the coral reefs [e.g., *Leichter et al.*, 2003, 2005; *Wolanski et al.*, 2004]. However, the ecological processes and mechanisms associated with nutrient enrichment by internal waves generally are unknown. *Da Silva et al.* [2002], based on SeaWiFS ocean color images in the central Bay of Biscay, reported that the internal waves could raise subsurface chlorophyll to near-surface. *Wolanski and Deleersnijder* [1998], based on model study of the response of tidal currents passing over a reef, suggested that the formation of huge, leaky internal waves at deep oceanic islands could bring nutrients up from below the pycnocline to within 40 m of the surface. Also, *Wolanski et al.* [2004] studied the influence of internal waves on coral reefs at Palau. They found that vertical thermocline displacement mainly occurred at 50–100-m depth and that the temperature changes in shallow waters were only 1°–1.5°C which would not be harmful to most reef organisms.

[4] Here, we report the mixing and dissipation of giant internal waves in shallow waters at Dongsha Atoll and the ecological responses following the intrusions of deep, nutrient-rich water. The possible mechanisms of the microbial food web and its role in a coral reef ecosystem are discussed.

2. Field Observations

[5] A moored instrument array was deployed at 20-m water depth northeast of Dongsha Atoll in July and August, 2006 (Figure 1). Sensors and data loggers were mounted 1 m above the bottom on a frame (non-magnetic stainless steel) anchored with a 3-ton concrete block. The measured parameters included bottom pressure, temperature, salinity, chlorophyll, dissolved oxygen and velocity profile (RDI WH300 and Hydrolab DS5X). The sampling rates were set from 1 to 15 min to track in detail the intrusions of internal waves and the subsequent property variations. Hydrographic (CTD) casts also were made around Dongsha Atoll to monitor the water column properties. Three casts, W1, W2 and W3 (locations marked in Figure 1), taken on 20 March 2007, 1 July 2004, and 29 November 2006, respectively, were selected to demonstrate the thermocline variation. At W3, additional water samples for nutrient concentration analysis were collected.

3. Internal Waves Pumping

[6] Sudden temperature decreases of up to 8°C were frequent at 20-m water depth (Figure 2). The fortnightly cycle indicated that the daily temperature decreases were associated with arrivals of internal waves. The onset of large temperature deceases lagged behind the neap-spring tidal cycle by 4 days. *Liu et al.* [2006] suggested that the giant internal waves in the South China Sea most likely are generated at Hengchun Ridge in Luzon Strait. *Chao et al.* [2007] showed that the ridges play a major role in exciting large isotherm depressions that travel far west into the SCS. The phase speed calculated by the model and verified by mooring data, was 3 m s^{-1} in the basin, 2 m s^{-1} on the

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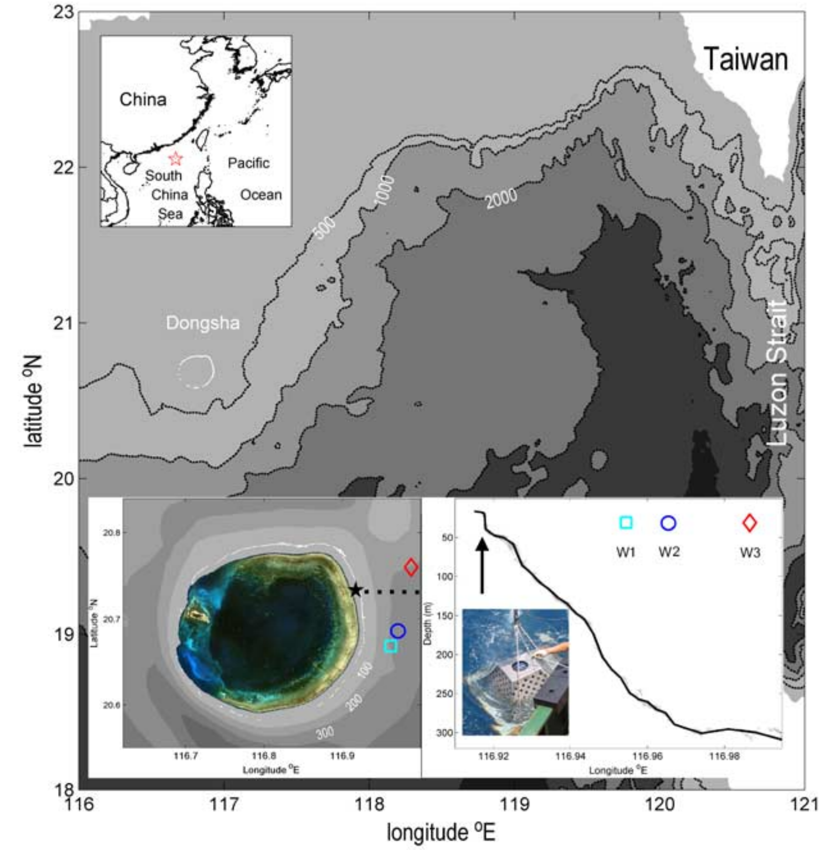

Figure 1. The Dongsha Atoll is located on the continental shelf in the northern South China Sea. The white dots indicate the 50-m depth contour based on vessel surveys. Lower-left insert: A Formosat2 image showing the atoll, depth contour, and the locations of the moored station (star), W1 (square), W2 (circle) and W3 (triangle) for hydrographic measurements. Lower-right insert: The water depth profile on the northeastern side of the atoll, and a photo showing the deployment of the instrument frame.

slope, and 0.6 m s^{-1} on the upper shelf; the decrease of internal wave speed is mainly due to the shoaling of the thermocline [*Liu et al.*, 2006; *Chang et al.*, 2006; *Chao et al.*, 2007]. Our observations of a 4-day lag from Luzon Strait to Dongsha plateau corresponds to an average speed of 2 m s^{-1}, which is consistent with the previous results.

[7] The tidal currents were aligned at NW–SE (337°–157°) direction following the local bathymetry. The harmonic analysis showed that the amplitudes of major tidal current constituents were 0.074, 0.153, 0.068, 0.042, and 0.078 m s^{-1} for S_2, M_2, N_2, K_1, and O_1, respectively. The tidal eccentricity averaged 0.05, and vertical variation was negligible. The velocity time series showed unusual 4-hr period oscillations during the intrusion of NLIW; the velocity amplitude associated with the internal waves was 0.3 m s^{-1} (Figure 3). The passage of NLIW initially generated a westward (onshore) flow against the ebb current, followed by an eastward flow 2 hr later. *Wolanski et al.* [2004] suggested that at the headland of Palau the internal waves run up the slope as a localized tongue of cold water. *Leichter et al.* [2005] reported cool water intrusions arriving as packets or sets of onshore pulses across the coral reefs in the Florida Keys. Our observations showed that the run up of cold water lasted for 2 hr with about equal time of the fall back.

[8] Most long internal waves appear to pass through continental slope and shelf to reach the shallow reef area; although significant amount of energy is lost during the propagation. *Chang et al.* [2006] estimated an average dissipation rate of 0.04 W m^{-2} based on the decrease of internal wave energy flux from 8.5 kW m^{-2} at the edge of the Dongsha plateau to 0.25 kW m^{-2} on the continental shelf 220 km westward. The vertical velocity shears are useful indication of mixing and dissipation of internal waves. We computed the rms vertical shears at 2-m vertical interval over a 4-hr period with 10-min increments. Results showed that large vertical shears occurred at the arrival of internal waves (Figure 3).

[9] Hydrographic profiles indicated that waters of <20°C typically were found below 100 m (Figure 4). We note that the three profiles were taken in different seasons under different weather conditions. W1 showed enhanced mixing at the upper 100 m due to northeast monsoon, W2 had a strong thermocline at 70 m, and W3 had lower salinity near the surface.

4. Ecological Effects

[10] Mixing and advection by internal waves could generate net upward fluxes of nutrients. In the northern SCS the nitrate is low with concentrations of 1–2 μM in the shallow

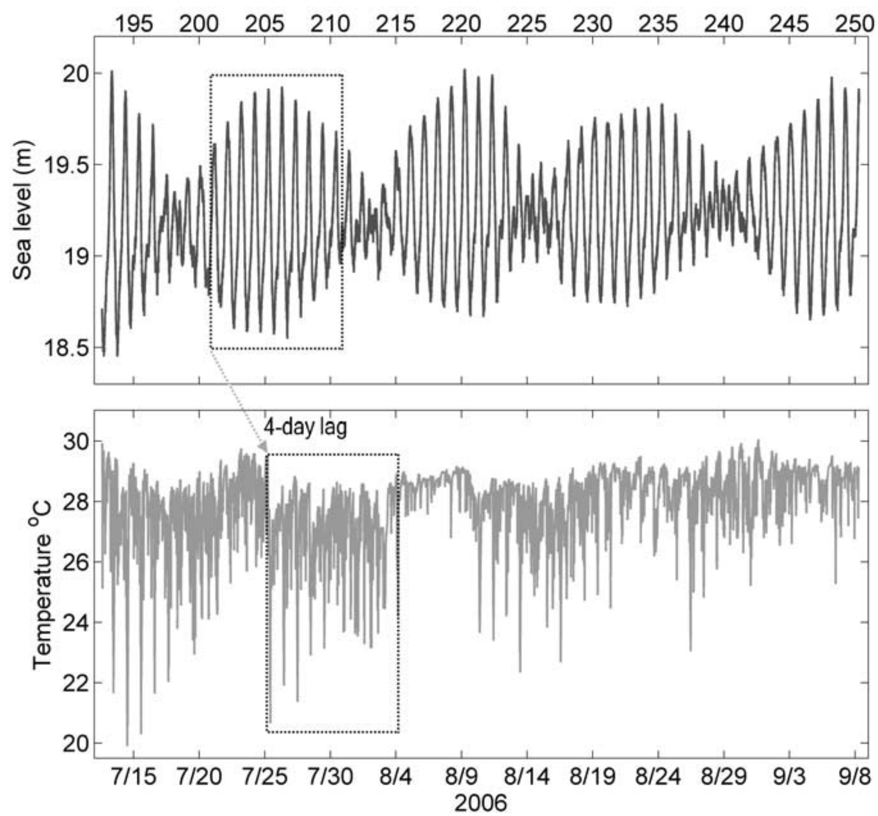

Figure 2. Sea level elevations and water temperature observed at the outer reef slope (20-m deep) of Dongsha Atoll. Temperature decreases of up to 8°C occurred daily over the period of more than a week. The cold water lagged behind the local neap-spring tidal cycle by 4 days.

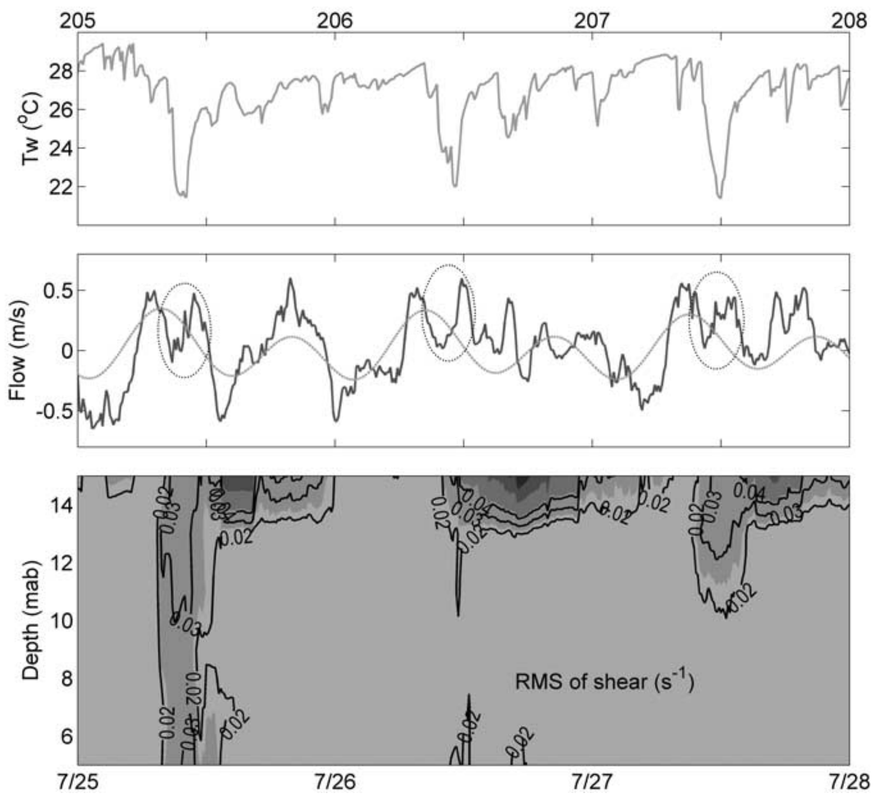

Figure 3. Time series plots at the moored station at Dongsha Atoll showing (top) water temperature (Tw) decreases of typical internal wave arrivals, (middle) principal axis flow (solid line) with cold water intrusions marked by ovals and tidal current (dotted line) at 10 mab, and (bottom) rms of vertical shear. The arrival of internal waves seems to be accompanied by large shear, which induces vertical mixing of water column.

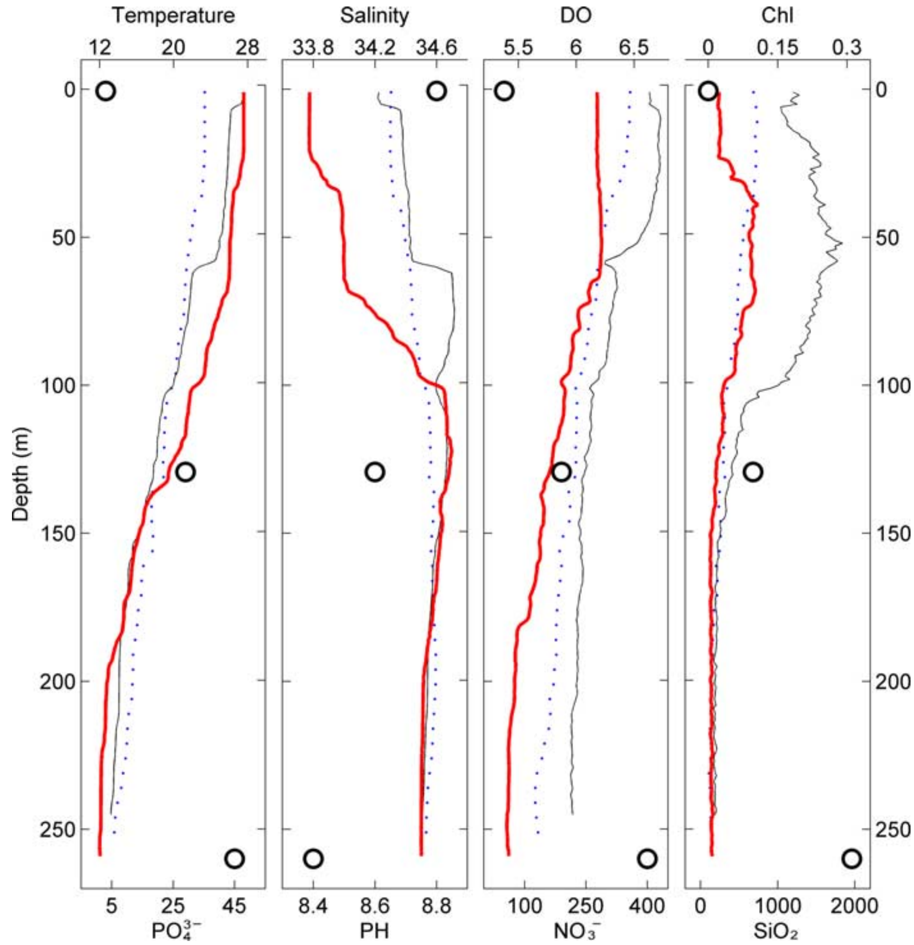

Figure 4. Profiles of (top axis) water temperature(°C), salinity(‰), dissolved oxygen(mg L^{-1}), and chlorophyll(μg L^{-1}) at stations W1 (dotted line), W2 (thin line), and W3 (thick line) at Dongsha Atoll as shown in Figure 1. The circles show the data (bottom axis) of PO_4^{3-} (μg L^{-1}), pH, NO_3^- (μg L^{-1}), and SiO_2 (μg L^{-1}) of water samples at station W3.

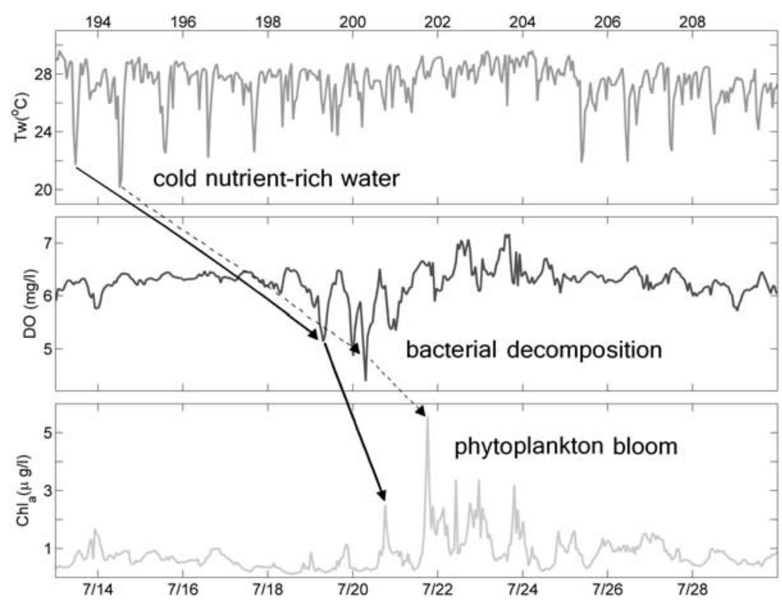

Figure 5. Observed variations of (top) water temperature, (middle) dissolved oxygen, and (bottom) chlorophyll at 20-m depth for 2 weeks following an internal wave incursion to Dongsha Atoll.

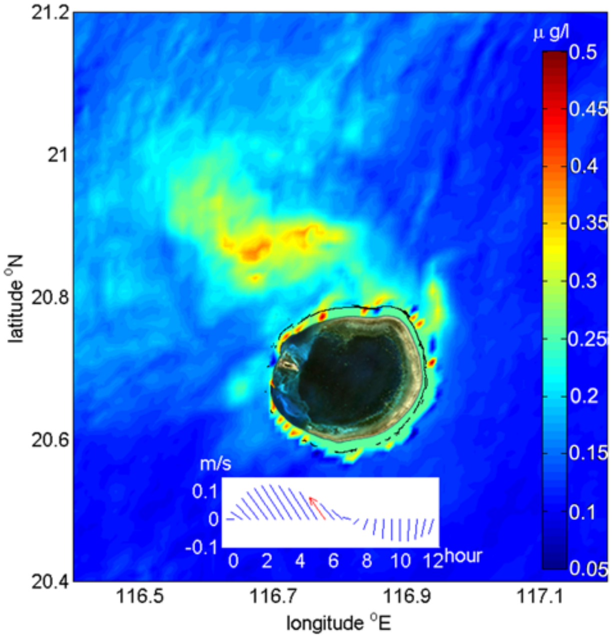

Figure 6. Chlorophyll concentrations based on a MODIS Aqua image of 2005.5.14.5:35 showing high concentrations fertilized by the internal wave pumping and dilution by advection by tidal currents. The insert shows the predicted tidal current based on harmonic analysis of flow measurements at the NE of the atoll. Chlorophyll data within the atoll are omitted due to the shallow water. The diffraction of NLIWs could be seen behind the atoll.

shelf water column, increasing to 4–12 μM at 100 to 200-m depth [*Chen*, 2006]. Higher concentrations of nutrients of deep, cold water were confirmed by water samples at 2-, 130-, and 260-m depth near Dongsha Atoll at station W3 (Figure 4). Water sample analysis showed concentrations of NO_3^-, PO_4^{3-} and silicates all increased with depth. The N:P ratio was 12:1, which was lower than the reference Redfield ratio of 16:1, indicating the area was nitrogen limited. *Wu et al.* [2003] found a similar pattern with limited nitrogen and relatively abundant phosphorus in the SCS where iron was possibly abundant due to high eolian iron flux from continental dust storms. Dissolved oxygen profiles showed higher concentrations near the surface, decreasing with depth. The chlorophyll profile showed a maximum at mid-depth, possibly due to light inhibition in shallow water and higher nutrients near the bottom of the mixed layer.

[11] Large variations of DO with a decreasing trend followed the intrusion of internal waves at the atoll by about 6 days, which was followed 2 days later by increases of chlorophyll (Figure 5). The long time lag of DO and chlorophyll following the intrusion of internal waves into shallow waters possibly indicated that the algal bloom was not directly due to vertical mixing or upwelling of nutrients.

[12] Internal tidal upwelling represents a significant, widespread, and episodic source of high nutrient fluxes for coral reefs [*Leichter et al.*, 2005; *Wolanski et al.*, 2004]. Additions of allochthonous nutrients in oligotrophic tropical waters are usually coupled with rapid and extensive increases of chlorophyll concentrations [e.g., *Friedrichs and Hofmann*, 2001; *da Silva et al.*, 2002], although a 1- to 2-day time lag may be observed due to dilution with deeper, low-chlorophyll waters. In our case, the maximum chlorophyll concentration occurred 7–8 days after the minimum temperature, suggesting that upwelling of nutrients was unlikely a linear factor for phytoplankton growth. *Kahru* [1983] showed that internal waves lifted the thermocline and increased primary production through nonlinear effects due to phytoplankton-nutrient dynamics. The large variations of DO that occurred between the dissipation of internal waves and the rapid increase of phytoplankton at Dongsha Atoll may be related to three possible processes: microbial decomposition of particulate organic matter (POM) brought up by the internal waves, vertical dispersion of the deep chlorophyll maximum and a subsurface oxygen minimum, and post-wave phytoplankton growth promoted by thermocline nutrients injected into the bottom of the surface mixed layer. The first process is more likely because the 7–8-day time lag was longer than necessary for the other two processes.

[13] The extensive seagrass beds, macroalgae, and corals in the atoll are the possible source of POM. The debris of seagrasses and macroalgae together with the mucus secreted by corals may be transported to the outer slope of the atoll and sink slowly in the water column. The impinging internal waves from deep water then lift the particle-laden cold water and facilitate recycling of nutrients to the reef ecosystem via the microbial food web [*Nielsen et al.*, 2004]. Furthermore, the sudden temperature drop of up to 8°C may cause temperature shock to zooplankton and reef organisms. Exposure to cold stress can alter membrane properties of organisms and cause severe damage or death [*Guschina and Harwood*, 2006]. Some organisms may be killed by such temperature shock and contribute to the POM pool. The decomposition of POM by aerobic bacteria in shallow waters may last for several days and induce large fluctuations of DO. Then the nutrients are regenerated, which induces rapid growth of phytoplankton. The phytoplankton bloom releases more oxygen and results in a surplus of DO. A MODIS chlorophyll image validates the high concentration fertilized by the internal wave pumping and dilution to the vicinity of the atoll by advection of tidal currents (Figure 6).

5. Conclusion

[14] The results of this study highlight the significance of the microbial food web on nutrient regeneration in oligotrophic shallow waters of Dongsha Atoll and have implications for the effects of oceanographic forcing and their variation in space and time on coral reefs. The microbial food web may perform a crucial role in transferring energy up the food chain since copepods are seldom able to directly capture the dominant primary producers in oligotrophic tropical systems [*Nielsen et al.*, 2004]. In addition, the episodic upwelling of deep water due to internal waves might account for the high coral cover on the northern and eastern shallow reef slopes of Dongsha Atoll, in contrast to the extreme high mortality of corals inside the lagoon that occurred during the 1997–98 El Niño warming event [*Dai*, 2005]. Further studies are needed to quantify the temporal and spatial variations of nutrients and microbial abundance

to demonstrate the ecological effects of internal waves in this coral reef ecosystem.

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