Continental Shelf Research 166 (2018) 34–43

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

Enhanced mixing by patchy turbulence in the northern South China Sea

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ARTICLE INFO

Keywords:
Ocean mixing
Turbulent patch
Internal waves
Pycnocline
Mixing efficiency
South China Sea

ABSTRACT

Enhanced mixing induced by patchy turbulence in the pycnocline was investigated from the turbulent microstructure profiling in the northern South China Sea, where internal waves are active in the pycnocline. Totally 397 turbulence patches have been identified in March 2014 and August to September 2016 for the statistical analyses. The patch Thorpe scale L_{Tp} was found to be larger than the patch Ozmidov scales L_{Op}, i.e., $L_{Tp} = 5.56L_{Op}$, indicating that the patchy turbulence is mainly driven by the convection. The mean time scale of turbulent patches is 1.4×10^3 s for conversion from potential energy to turbulent dissipation. The mean mixing efficiency of $\Gamma = 0.23$ occurs in the patches, approximately twice as large as $\Gamma = 0.12$ in the pycnocline. Hence, the patchy turbulence in the pycnocline enhances the intensity of turbulent mixing and increases the mixing efficiency. Turbulent patches in the pycnocline occur mostly near the critical slope at the shelf break or over the sill in the northern SCS. The investigation of the Eulerian strain and available potential energy of turbulent patches indicates that convection induced by high frequency internal waves should be a major mechanism for the formation of turbulent patches.

1. Introduction

Small-scale turbulent processes have a fundamental role in the vertical transfers of momentum, heat and mass in the ocean, and thus they have great significance in ocean dynamics, particle and nutrient transports, and even global climate change (Gregg et al., 2003; Wunsch and Ferrari, 2004; Ivey et al., 2008). Decades of large number of turbulent microstructure observations have shown that turbulence in the ocean is intermittent in time and patchy in space, which significantly enhances our understanding of ocean turbulence (Gregg, 1980; Smyth et al., 2001; Lozovatsky and Fernando, 2002; Ivey et al., 2008). Patchy turbulence in the stably stratified pycnocline is one of the prominent oceanic processes (Garrett and Munk, 1979; Verso et al., 2016). However, the ubiquitous turbulent patches increase the difficulty of identifying the mixing processes and make it more difficult to parameterize turbulence mixing in the stratified ocean. Thus it is vital to describe the turbulent patches in the ocean thermocline, so that we can comprehensively understand and accurately predict the processes of turbulent mixing (Gregg, 1980; Arneborg, 2002; Ivey et al., 2008).

The turbulence patch can be considered as a localized, well mixed volume which arises from a linearly stratified fluid through a turbulent mixing event (Arneborg, 2002). The turbulent patches have been widely studied through theoretical analyses (Arneborg, 2002), laboratory experiments (Yakovenko et al., 2011; Verso et al., 2016) and field observations (Hebert et al., 1992; Planella et al., 2011). Arneborg (2002) found that the mixing efficiency in the stably stratified fluid with patchy turbulence may be 0.1, rather than the often used constant value of 0.2 in the ocean. Verso et al. (2016) carried out laboratory experiments to examine the growth of a localized turbulent patch under distinct stratified environments. Direct numerical simulations of the turbulent patch arising from the IW breaking indicated that there is an approximate balance in shear production, viscous dissipation and transport processes for turbulent kinetic energy (TKE) (Yakovenko et al., 2011). In spite of these studies, field observations of patchy turbulence in the stratified ocean are still few up to now. Therefore, more in-situ microstructural observations in the pycnocline are required to identify the main characteristics of turbulent patches and their impacts on the turbulent mixing.

Turbulent patches usually appear in the form of the overturns of density. The IW breaking and buoyancy convection may be the primary mechanism for turbulent mixing in the ocean pycnocline (Hebert et al., 1992; Smyth et al., 2001; Gregg et al., 2003; St. Laurent et al., 2011). Previous studies over a decade indicated that the IWs in the South China Sea (SCS) are the most energetic in the world ocean (Zhao et al., 2004; Klymak et al., 2011; Tang et al., 2014; Alford et al., 2015). The shelf ocean in the northern SCS is highly subject to strong IWs which are generated by the interaction between barotropic tides and topography at the Luzon Strait (Zhao et al., 2004). Some of IWs are locally

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https://doi.org/10.1016/j.csr.2018.06.013
Received 31 May 2017; Received in revised form 12 June 2018; Accepted 24 June 2018

broken at the Luzon Strait, resulting in the dissipation of nearly 40% IW energy, and other IWs propagate westwards from the Luzon Strait to the SCS ocean basin, and ultimately dissipate their remaining energy in the SCS shelf ocean (Alford et al., 2015). Microstructure observations in the northern SCS showed that turbulence is rather intense near the shelf-break region (St. Laurent, 2008). Recently, Tang et al. (2014) used a novel technique of seismic oceanography to detect oceanic fine-scale structures in the pycnocline on the continental slope in the northern SCS. The most pervasive features of the seismic images are coherent reflections from quasi-horizontal linear features of 5–10 km in length, which take on the undulations with a vertical extent of about 20 m and a horizontal extent of less than 1 km. These undulations may represent the oscillation of the high-frequency IWs with the IW period ranging from 8 min to 14 min (see Orr and Mignerey, 2003; Bai et al., 2013; Rudnick et al., 2013). Accordingly, the shelf ocean in the northern SCS is an ideal place to make detailed studies of turbulent patches in the pycnocline, which originate from the high-frequency IW breaking.

Based on in-situ observations by the turbulent microstructure profiler in the northern SCS, the objective of this study is to investigate the characteristics and spatial distribution of turbulent mixing enhanced by patchy turbulence in the pycnocline of the northern SCS. Three main questions about turbulent patches will be explored in details: (a) to characterize the temporal and spatial scales of turbulent patches, (b) to quantify mixing efficiency in turbulent patches, and (c) to explore the mechanism for the spatial distribution of turbulent patches. The paper is organized as follows: in Section 2 we describe field observations; in Section 3 we present the methodology for identifying turbulent patches and estimating the turbulence parameters; we show main results in Section 4 and discussion in Section 5; and finally, we provide a short summary in Section 6.

2. Field observations

In this study, two cruises of turbulence microstructural observations were performed in the northern SCS (Fig. 1). One cruise was conducted during 23–31 March 2014, in which all the observational sites were located on the west of the Dongsha coral atoll (Fig. 1). Field surveys included 25-hr continuous profiling at the site S and the vertical profiling at 41 sites along five cross-shelf sections (A, B, C, D and E) and 6 sites (from L1 to L6) across and along the shelf slope, respectively. The employed instruments contained one Seabird 911 conductivity-temperature-depth sensor (Seabird CTD) and one turbulence microstructure profiler (MSS-90L, hereinafter MSS). The second cruise was conducted from 26 August to 8 September 2016, in which all 35 sites were located on the east of the Dongsha coral atoll (Fig. 1). The MSS profiler was freely dropped at these 35 sites along three cross-shelf sections (F, G and H). The profiling measurements were spatially refined along the section G in the shelf-break waters.

The MSS is equipped with three standard CTD sensors, one fast thermistor sensor (FP07), two small-scale airfoil shear probes (PNS06), one microstructure conductivity sensor and one acceleration sensor. The sampling rate for all MSS sensors is 1024 Hz. Two or three consecutive casts of the microstructure profiler MSS each water column were launched with a freely falling speed of approximately $0.7\ m\ s^{-1}$ or equivalently a vertical size of 0.7 mm to measure the microstructure parameters from the surface to the seafloor in the shallow waters or to a maximum depth of 500 m in the deep waters. The Seabird CTD with a sampling rate of 24 Hz was launched from the sea surface down to 5 m above the seafloor. At the site S, the Seabird CTD was performed in a one-hour interval for 25 h from 25 to 26 March 2014, and the MSS profiler was launched between adjoining deployments of the Seabird CTD.

3. Methodology

3.1. Identification of the pycnocline and the turbulent patch

The water column below the surface mixed layer (SML) in the northern SCS is highly stratified in potential density. Herein we define the depth of SML using the optimal linear fit method (see Qiu et al., 2016). The pycnocline base is specified as the water depth where the potential density gradient decreases to $0.015\ kg\ m^{-4}$ below the SML. Fig. 2a shows a typical profile of potential density and density stratification during the survey in the northern SCS, where the upper and lower boundaries of the pycnocline are marked by z_u and z_l respectively. When the pycnocline base exceeded the maximum delivery depth of the microstructure profiler, we selected the maximum delivery depth immediately below the SML as pycnocline segments. In the shallow shelf sea, the water column is well mixed in both SML and the bottom mixed layer (BML). The BML top is specified as the depth where a potential density difference from the bottom waters amounts to $0.03\ kg\ m^{-3}$ (Perlin et al., 2005). At the shallow water stations, the

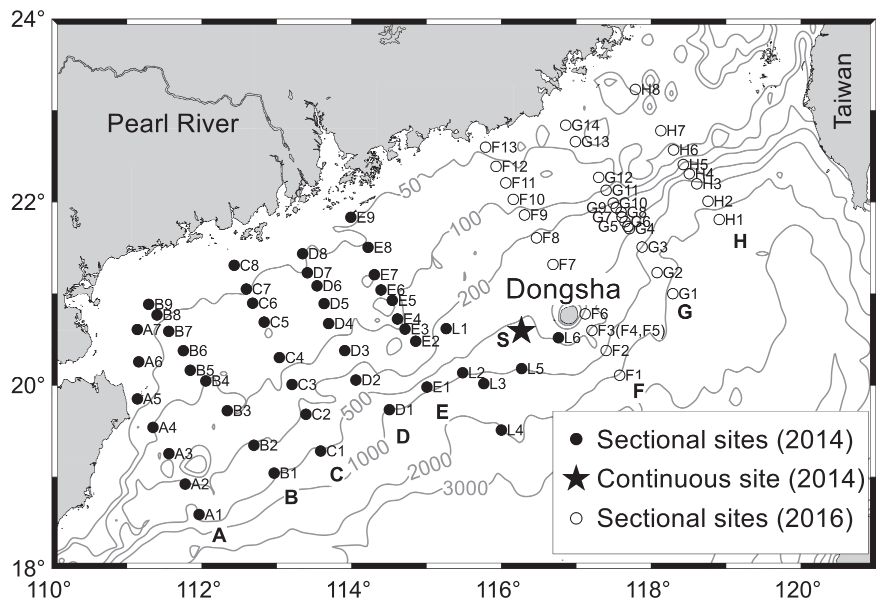

Fig. 1. Field observations in the northern SCS at the sectional sites (dots) and a 25-h continuous site S (star) in March 2014, and the sectional sites (circles) in August 2016. The isobaths are in meters.