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Hydrographic field investigations in the Northern South China Sea by open cruises during 2004–2013

Lili Zeng · Qiang Wang · Qiang Xie · Ping Shi · Lei Yang · Yeqiang Shu · Ju Chen · Dandan Sui · Yunkai He · Rongyu Chen · Dongxiao Wang

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Abstract In the past 10 years (2004–2013), annual open cruise during late summer provided new opportunities for comprehensive studies in the Northern South China Sea (NSCS). The 10-year field investigation program was carried out by the South China Sea Institute of Oceanology, Chinese Academy of Sciences (SCSIO, CAS). Measurements included water mass property, ocean circulation, atmospheric structure, and chemical and biological elements. The observation data collected during these open cruises have been intensively used in the studies of marine oceanographic, meteorological, chemical, and biological processes in the NSCS. In this study, comprehensive assessment of data application in oceanographic and meteorological studies is provided: (1) the property and variability of water masses in different layers; (2) the distribution of main currents and three-dimensional structure of mesoscale eddies; and (3) atmospheric structure and its feedback to the ocean. With the continuance of open cruises, it is feasible to construct high-quality, gridded climatological marine meteorological datasets in the NSCS in the near future.

SPECIAL TOPIC: Land-ocean integrated research and development of carbon sink

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L. Zeng · Q. Wang · Q. Xie · P. Shi · L. Yang · Y. Shu · J. Chen · D. Sui · Y. He · R. Chen · D. Wang (✉)
State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China
e-mail: dxwang@scsio.ac.cn

Q. Xie
Sanya Institute of Deep-Sea Science and Engineering, Chinese Academy of Sciences, Sanya 572000, China

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1 Introduction

The South China Sea (SCS) is a large tropical marginal sea experiencing a dominant seasonal reversal in the surface wind field associated with summer and winter monsoons [1]. It connects the western Pacific (WP) and the eastern Indian Ocean. Much work has been done on the Kuroshio intrusion into the SCS through the Luzon Strait [2–5]. In the SCS, the Pearl River, the Red River, and the Mekong River are the three largest rivers, transporting abundant fresh water with large seasonal variation [6].

To understand the physical, chemical, and biological aspects of the northern SCS (NSCS), we need continuous observations with higher resolution. The Argo Project started in 2000 [7] was expected to improve data coverage in the NSCS. However, the temporal and spatial resolution of the data is still insufficient due to limited floats in the NSCS, which mainly distributed along the western boundary current. More routine observations in the SCS are required for scientific research in the SCS, such as upper-ocean stratification, water mass property, ocean circulation, and atmospheric boundary layer (ABL) structure, etc.

The NSCS open cruises (research vessel: Shiyan 3) began in 2004. Since the first NSCS open cruise in 2004, the number of oceanic and atmospheric observations increased gradually. Open cruise allows researchers from other research institutions on board to carry out their own experiments. In this way, the observations during each cruise could cover more marine research fields, such as hydrology, biology, geology, marine ecology, marine chemistry, algal ecology,

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marine optics, marine acoustics, and ocean color science [5]. The 10-year field investigation program was carried out by the South China Sea Institute of Oceanology, Chinese Academy of Sciences (SCSIO, CAS). Following that, a much more aggressive field investigation program was promoted by the National Natural Science Foundation of China (NSFC) since 2010.

Hydrological observation instruments carried onboard mainly included conductivity–temperature–depth (CTD), underway conductivity and temperature sensor (CT), expendable bathythermograph (XBT), shipboard acoustic doppler current profiler (ADCP), lowered ADCP (LADCP), moorings, moving vessel profiler (MVP), turbulence ocean microstructure acquisition profiler (TurboMAP), and automated flowing pCO_2 measuring system. All oceanographic and meteorological instruments on board and related information of open cruises in the NSCS from 2004 to 2013 are given in Table S1.

For example, shipboard CTD profiles were recorded by SBE 911plus with an accuracy of 0.02 psu (Fig. 1a). Beginning in 2009, underway CT was carried on board. Surface profiling was recorded by the SBE 21 SEACAT thermosalinograph conductivity and temperature recorder. The unique free-fall profiler offers researchers near-surface observations (within 10 m depth) even as the ship moves away from the deployment location. The open cruise carried

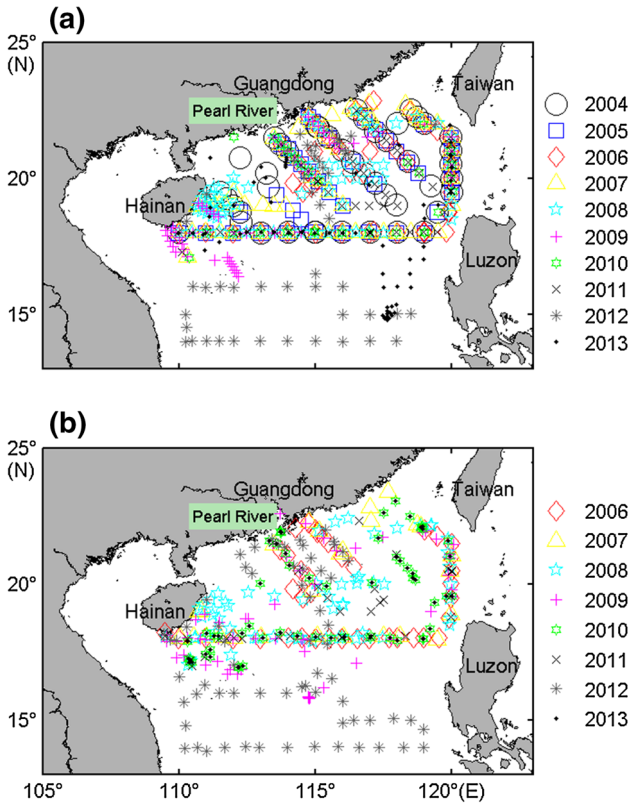

Fig. 1 Stations of **a** conductivity–temperature–depth (CTD) and **b** high-resolution global positioning system (GPS) soundings during the open cruises in the Northern South China Sea

automatic weather stations (AWS) and air-sea flux observation system. Since 2006, launched high-resolution global positioning system (GPS) soundings four times per day (Fig. 1b). GPS sounding is an excellent way to obtain the vertical temperature and humidity structure of the atmosphere over the ocean [8]. Observations obtained have been widely used in the studies of heat flux, vertical structures of the atmosphere and tropical weather systems, and marine ABL [9].

2 Data quality control and methods

All datasets obtained from the open cruises in the NSCS have been archived. Quality control has been applied to the data. For example, duplicate profiles and those with obviously errors are removed. In addition, the profiles that do not pass the monthly, seasonal, and annual standard deviation checks are excluded. Hourly average is usually made for those data with high sampling frequency, such as surface temperature and salinity, and air-sea flux observation system, which is measured every five seconds by underway CT and thirty minutes, respectively.

The isothermal layer depth (ILD) is defined as the depth where the temperature decreases by 0.8 °C from the temperature at 10 m depth [10]. The mixed layer depth (MLD) is calculated as the depth where the density is equal to the sea surface density plus the increment in density equivalent to 0.8 °C [6, 10]. The ABL is defined as the first level from the surface where virtual potential temperature increases by 1 °C [11]. Gridded data were obtained by taking the median of the MLDs and ABLs in each 0.25° bin, followed by a slight smoothing and Kriging interpolation.

In addition to the observations from the NSCS open cruises, three satellite datasets are used in this study. One is daily-mean precipitation estimates from the Microwave Imager and Precipitation Radar onboard the Tropical Rainfall Measuring Mission satellite (TRMM 3B42), which is available at 0.25° resolution. The second is the weekly-mean sea surface temperature (SST) with 0.25° resolution derived from the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) product. The third one is gridded surface level anomaly (SLA) at 7-day interval and 0.25° resolution distributed from the Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO).

3 Results

3.1 Water mass property

The datasets of SST in 2010 open cruise and sea surface salinity (SSS) during 2011 open cruise are plotted in Fig. 2.