Satellite Synthetic Aperture Radar Detection of Ocean Internal Waves in the South China Sea

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LONG-TERM GOALS

The long-term goal of the project is to meet the goal of ONR DRI NLIW, which is to achieve the basic science understanding that leads to a predictive capability that will be able to tell when and where non-linear internal waves will occur and what effects they will have on the hydrodynamic and acoustic environment. This project focuses on the use of remotely sensed variables, together with models and in situ observation that can reproduce and predict the generation and structure of these waves, their evolution during propagation, and the processes controlling dissipation.

OBJECTIVES

1). To determine the statistical features of ocean internal waves in SCS. Interpreting ten years of satellite synthetic aperture radar (SAR) images, the statistical features of ocean internal waves in SCS will be determined.

2). To understand the effects of topography/thermocline on the evolution of solitary internal waves in SCS.

3). To explore the SAR imaging conversion mechanisms of internal waves.

APPROACH

In this research, the PI's use both *in situ* and remotely sensed data. For the remotely sensed data, the main source is the synthetic aperture radar (SAR) carried by various satellites, i.e., ERS-1/2, Radarsat-1/2 and Envisat. High resolution NOAA AVHRR data and SeaWifs, as well as data from Terra and Aqua satellites will also be used. Historical XBT/AXBT data will be used to determine the vertical thermal structure in the study area. The data will be obtained from NOAA archives, which are in the public domain.

For the analysis, for different features the PI plans to apply different data analysis methods, which best match the nature of these features. Two-dimensional Fourier transform is used to study wave number

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characteristics of internal waves. The HHT method developed by Huang et al. (1998) will be used to determine the variation of spatial phase of internal waves and to trace back to their generation locations.

The objectives of theoretical analysis are to understand the nature, physics, mechanism, and laws of variation of the studied process, to derive unknown geophysical parameters using parameters and information derived from SAR image interpretation as inputs, to analyze the relation between the studied process and the surrounding environment, and to predict the future development of the studied process.

Dr. Quanan Zheng serves as a lead PI and coordinates the project. Zheng will focus on data collection, satellite image interpretation, and the theoretical analysis. Dr. R. Dwi Susanto from LDEO, Columbia University, serves as a Co-PI. Susanto focuses on image processing, statistical analysis, and takes part in data collection and the theoretical analysis.

WORK COMPLETED

1). Statistical analysis. The statistical analysis of IW occurrence in the northern South China Sea (NSCS) has been completed using seven years of satellite SAR images from 1995 to 2001. The statistical analysis of sea surface boundary conditions has been completed using long-term field measurements of sea surface wind and sea state in NSCS [Editorial Group, 1982]. The statistical analysis of IW generation boundary conditions in the Luzon Strait has been completed using 20 years of vertical temperature profiles from 1980 to 1999 [Boyer and Levitus, 1994].

2). Dynamical analysis. Nonlinear analysis of effects of shoaling thermocline on the IW generation has been completed. The role of Kuroshio playing in IW generation in the Luzon Strait has been analyzed using linear wave models and the Fourier transform methods. Dynamical analysis of bottom-topography-induced stationary IW in NSCS has been completed.

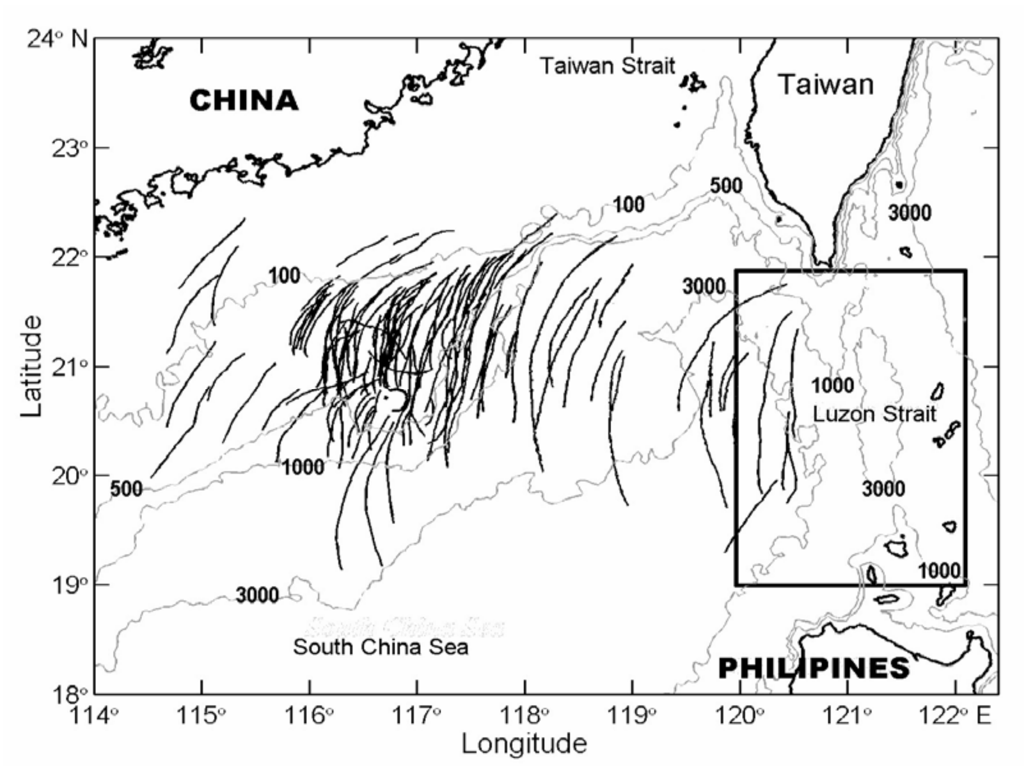
RESULTS

1). Statistics of IW occurrence in NSCS. Using seven years of satellite SAR images from 1995 to 2001, statistics of IW occurrence in NSCS generate the following results.

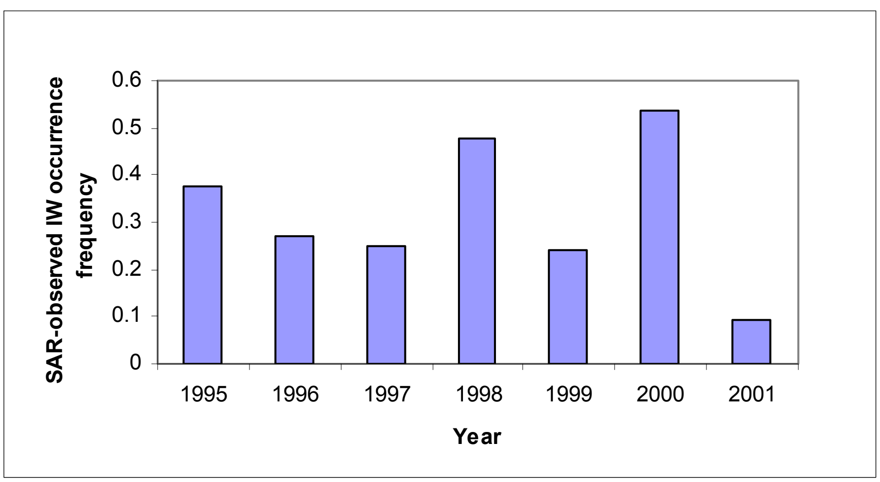
Latitudinal distribution of IW packets in NSCS is shown in Figure 1 (partially from Zhao et al., 2004). Statistics indicate that 22% of IW packets distributed in the east of 118ºE obviously originate from the Luzon Strait, and 78% of IW packets west of 118ºE may propagate from the east or evolve from the solitons originating from the east boundary owing to the fission effect of shoaling thermocline.

Yearly distribution of IW occurrence frequencies is shown in Figure 2. One can see an interannual variability, the frequencies in 1995, 1998, and 2000 are 2 to 5 times higher than that in other years. This interannual variability implies that there are long-term and large scale processes modifying the SAR-observed IW occurrence.

M**onthly SAR-observed IW occurrence frequencies** show that the high frequencies are distributed from April to July and reach a peak in June with a maximum frequency of 20%. The low occurrence frequencies are distributed in winter from December to February of next year with a minimum frequency of 1.5% in February (Figure 3).

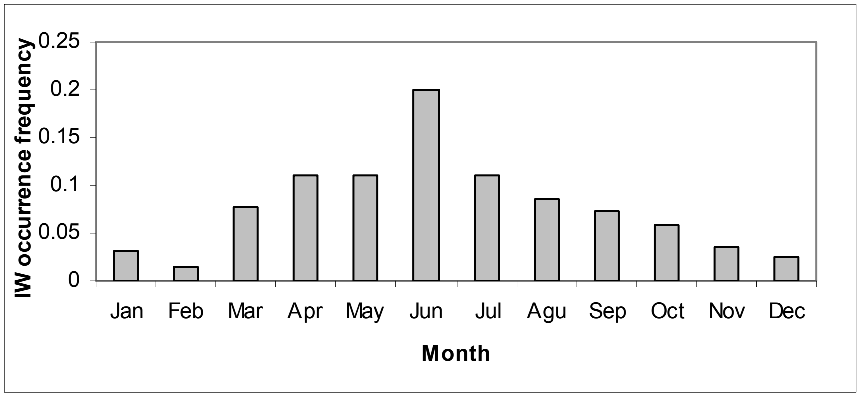


[Figure 1. A map of latitudinal distribution of IW packets in NSCS. Bold lines represent crest lines of leading waves in IW packets interpreted from SAR images. The rectangular box on the right defines an IW generation source region for the dynamical analysis.]



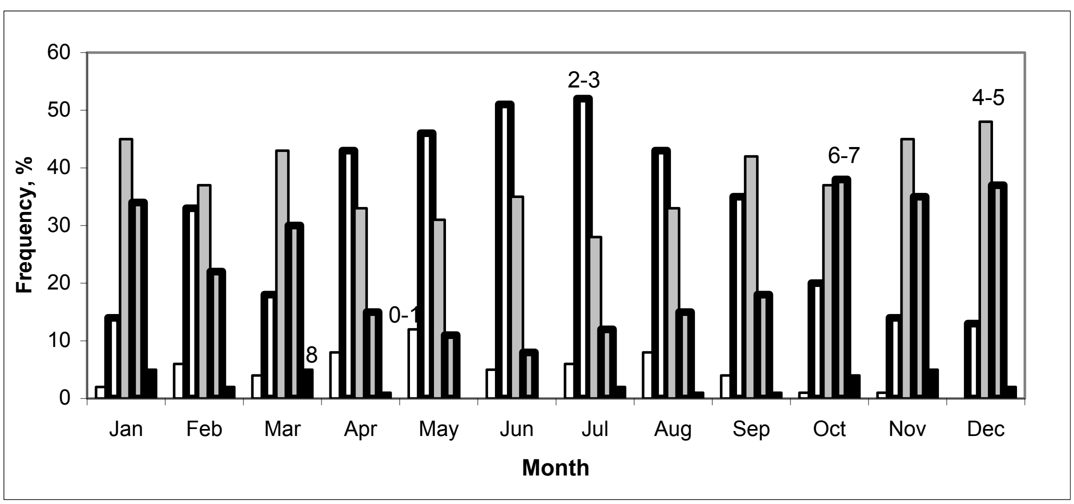
[Figure 2. Yearly distribution of SAR-observed IW occurrence frequencies in NSCS.]

2). Statistics of sea surface boundary conditions. Statistics indicate that high frequencies of low wind conditions (scales 0-1 and 2-3) are distributed from April to September and reach a peak phase from May to July with a maximum frequency of 58% in July. The low frequencies are distributed from November to March of next year. The frequency distributions of high wind conditions (scales 4-5, 6-7, and 8) are just anti-phase with low wind conditions. High frequencies are distributed from October to March of next year and reach a peak phase from November to January with a maximum frequency of 87% in December (Figure 4).

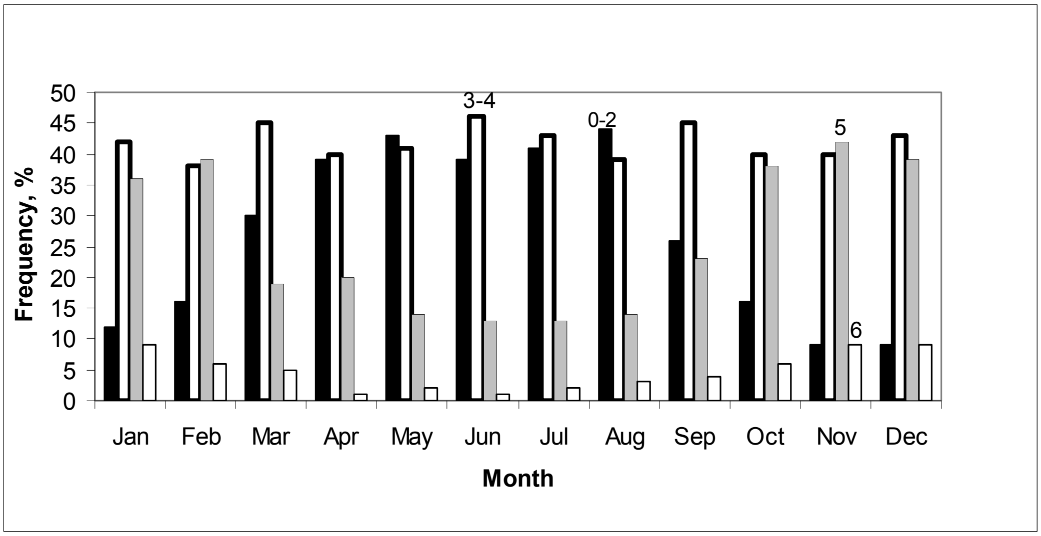


[Figure 3. Monthly distribution of SAR-observed IW occurrence frequencies in NSCS.]

The statistical distribution of monthly sea state frequencies is shown in Figure 5. One can see that high frequencies of Wind Wave Scales 0-2 (for the wave height less than 0.7 m) are distributed from April to August and reach a peak value of 44% in August. The low frequencies are distributed from October to February of next year with frequencies lower than 16%. March and September appear as transit phases. The frequencies of Scales 3-4 (for the wave height from 0.8 to 1.9 m) have an almost even distribution with a mean of 41.8% and a standard deviation of 2.5%. The distributions of Scales 5 (for the wave height from 2.0 to 3.4 m) and 6 (for the wave height from 3.5 to 6.0 m) are anti-phase with Scales 0-2.



[Figure 4. Statistical distributions of monthly mean wind frequencies at statistical cells centered at 22ºN 118ºE in NSCS. The numerals marked at peak bars represent wind scale ranges.]



[Figure 5. Same as Figure 4, but for monthly mean sea state.]

3). Nonlinear analysis of effects of shoaling thermocline on the IW generation. The study proposes that the IW generation needs the necessary and sufficient conditions: initial disturbance formation, and wave amplitude growth. Due to dissipation effect on the disturbance energy, only fully grown waves have a chance to radiate out of the source region. A physical model and PKdV equation are applied to the analysis of the sufficient conditions for solitary IW amplitude growth. The results indicate that the thermocline shoaling provides the forcing to soliton amplitude growth, so that the soliton amplitude growth ratio (SAGR) serves as a decisive factor for the IW occurrence frequency.

4). The role of Kuroshio playing in IW generation in the Luzon Strait. A linear model describing western boundary current instability generation mechanism for the ocean internal waves is developed. Analytical solutions are derived from a zero-order complex frequency – wave number relation. The theoretical results are used in the case of the Kuroshio east of the Luzon Strait. Based on the analysis, it is found that for the western propagating disturbance, the Kuroshio west wing is unstable and the east wing is stable; while the reverse is true for the eastern propagating disturbance. The results are used to interpret satellite SAR images of the ocean internal waves, which are generated in the Luzon Strait and propagated westward.

5). Dynamical analysis of bottom-topography-induced stationary IW in NSCS. The satellite SAR images display wave-like patterns of the ocean bottom topographic features at the south outlet of Taiwan Strait (TS). Field measurements indicate that the most TS water body is vertically stratified. In order to explore the mechanisms and to determine the relations between the SAR imagery and the bottom features, a two-dimensional, three-layer ocean model with sinusoidal bottom topographic features is developed.

IMPACT/APPLICATIONS

The results of this project will provide the users a statistical outline of internal wave behavior and boundary conditions in SCS, and will benefit the broader oceanographic community, ocean engineering industries, underwater navigation and operational users. The results may also serve as a basis for empirical, theoretical, and numerical prediction models of internal wave behavior in SCS, and contribute to creation of a predictive system. The results will further reveal SAR imaging mechanisms and be used for SAR image interpretation.

RELATED PROJECTS

Quanan Zheng serves as a CO-PI for an ongoing ONR PO project titled "Analysis of Fine Structures of Flows, Hydrography, and Fronts in Taiwan Strait". The study areas of two projects are immediately adjacent. Therefore, two projects sometimes share the same data resources of field observations.

Because the southern end of the South China Sea is connected to the Indonesian Seas via Karimata Strait. The monsoon effect on the water exchange between the South China Sea and the Indonesian Seas may affect the seasonal characteristics of the South China Sea as well as the Indonesian Seas. Hence, it might have an affect the sub-mesoscale features in the Indonesian Seas (project supported by the ONR: N00014-04-1-0698; PI: Dwi Susanto). There is also an ongoing international [Indonesia, United States, Australia, France, and the Netherlands] collaborative research called INSTANT. Susanto also serves as INSTANT's PIs. The US part supported by NSF. The primary objective of INSTANT is to measure the variability of the ITF and its associated heat and freshwater flux exported into the Indian Ocean.

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