Detecting Surface Kuroshio Front in the Luzon Strait From Multichannel Satellite Data Using Neural Networks

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***Abstract*—An objective classification method is developed to distinguish the water masses of Kuroshio and South China Sea (SCS) by using an artificial neural network (ANN). Sea surface temperature (SST) and ocean-color data obtained from the Moderate Resolution Imaging Spectroradiometer in two specified areas to the east and west of Luzon, representing the Kuroshio and SCS waters, respectively, are used to train, validate, and test the ANN model. The water masses of Kuroshio and SCS can be distinguished correctly with a high success rate of over 99%. The model is then applied to the Luzon Strait, and the result of water mass classification agrees well with the temperature-salinity characteristics derived from a cruise in May and June of 2006. The performance is good in summertime when the SST or ocean color has a rather uniform spatial distribution and the traditional method of front detection by using a threshold value is inappropriate.**

***Index Terms*—Kuroshio intrusion, neural network, remote sensing, water mass.**

I. Introduction

THE SOUTH China Sea (SCS) is a large marginal sea surrounded by the Philippines, Taiwan, Borneo, Southeast Asia, and the southern portion of China. As a major channel for the water exchange between the SCS and the North Pacific, Luzon Strait is located between Taiwan and the Luzon islands with a width of over 300 km and a sill depth of over 2000 m at the center. The Kuroshio, which is the western boundary current of the North Pacific subtropical gyre, flows northward along the east coasts of Philippines and Taiwan. It has been known for several decades that there is an intrusion of waters from the Pacific into the SCS through the Luzon Strait. Nitani [1] reported that the Kuroshio may either leap across the Luzon Strait (in summer) or penetrate well into the SCS (in winter) as a loop current, in response to the seasonally reversing monsoon. As a result, the hydrographic properties of the Luzon Strait are affected markedly by both the west Philippine Sea and SCS waters, which have different characteristic properties of the water masses. Originating from the equatorial Pacific, the Kuroshio water is relatively warmer and saltier with lower chlorophyll-a concentration (Chl-a) than the SCS water, as evidenced from hydrographic observations [2]. The seasonal variation of the intrusion of the Philippine Sea Water into the SCS has been studied in many earlier studies by analyzing the temperature-salinity (T-S) characteristics of historical hydrographic data [3]–[5]. The Kuroshio intrusion into the SCS through the Luzon Strait was found to be an all-year-round event with greater strength in winter and summer than in spring and autumn [5]. Centurioni *et al.* [6] analyzed satellite-tracked drifter data of the surface mixed layer between 1989 and 2002 and confirmed that the inflow of the Philippine Sea water through the Luzon Strait mostly occurs during winters.

Previous studies based on analysis of hydrographic stations and surface drifter data provide both indirect and direct evidences of the Kuroshio intrusion into the SCS through the Luzon Strait. However, these studies only give statistical and climatic pictures of the intrusion. Furthermore, the spatial and temporal distributions of hydrographic stations and drifter data also affect the reliability and accuracy of the intrusion results. Satellite remote sensing, on the other hand, provides useful information of the ocean surface due to its large spatial and temporal coverages. From analyzing satellite-derived sea surface temperature (SST) images and wind data, Farris and Wimbush [7] concluded that the Kuroshio intrusion into the SCS may be induced by the local wind stress. Ho *et al.* [8] studied the long-term variation of SST from the Advanced Very High Resolution Radiometer and found that the Kuroshio intrusion into the SCS has an obvious response to the El Niño–Southern Oscillation events. Yuan *et al.* [9] used satellite ocean color, SST, and sea surface height data to investigate the Kuroshio intrusion and its path in the Luzon Strait. Penaflor *et al.* [10] examined the monsoonal phytoplankton blooms of the Luzon Strait from Moderate Resolution Imaging Spectroradiometer (MODIS) Chl-a and SST data and found some likely causes such as upwelling and Kuroshio intrusion.

At the western edge of the Kuroshio around the Luzon Strait, a Kuroshio front separating two water masses of SCS and Kuroshio with different physical and biological parameters (e.g., temperature, salinity, and Chl-a) will be formed. Generally, satellite remote sensing has been used to detect and monitor the oceanic front based on threshold values of SST

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or Chl-a [11], [12]. Nevertheless, the SST front will disappear in summer because the surface heating effect makes the water temperature of the whole region more uniform. To overcome this difficulty, Takahashi and Kawamura [13] proposed a method using satellite-derived Chl-a images to detect the Kuroshio front in the ocean south of Japan in summer. However, in the Luzon Strait where the SST and Chl-a concentration on both sides of the Kuroshio front are not significantly different particularly in summer, the aforementioned front-detection method based on the threshold value will not be applicable.

In this letter, a novel method is proposed to detect the Kuroshio intrusion in the Luzon Strait. This method is based on the fundamental difference of the radiance spectra of the SST and ocean-color channels in the Kuroshio and SCS waters. An artificial neural network (ANN) approach is used to classify water masses in the Luzon Strait into the Kuroshio and SCS types, and the Kuroshio boundary or front can be defined objectively.

II. Data and Methods

A. *In Situ Data Set*

The Joint Hydrographic Survey of 2006 (JHS2006), organized by the National Center for Ocean Research in Taiwan, was conducted simultaneously by four research vessels from May 20 to June 3, 2006. This survey covers a large area of the adjacent seas surrounding Taiwan within a short span of two weeks. The stations of JHS2006 were occupied every half-degree in the zonal and meridional directions in the Luzon Strait. Hydrographic observations of conductivity, temperature, and depth (CTD) as well as other biogeochemical parameters and water samplings were carried out from JHS2006. Forty-one stations in the Luzon Strait covering the area of 20–22° N and 119–123° E (Fig. 1) are selected from all the JHS2006 stations to study the classification of the water mass in this region. It is noted that station 4 lacks T-S data. This region is generally known as the intrusion area of the North Pacific waters into the SCS. Therefore, the characteristics of water mass are complex in this region and the boundary or front between the two water masses may vary spatially and seasonally. The T-S diagram in each station is used as a basis to classify the water mass of the Luzon Strait into the Kuroshio and SCS types.

B. *Satellite Data and ANN*

Ocean-color sensors measure radiance spectra of seawater which are sensitive to variances in composition of nature admixtures in seawater [14]. Therefore, the radiance spectra can be used as tracers of water exchange among different water masses. In this study, various radiance spectra measured by the SST and ocean-color channels combining with the ANN were utilized to differentiate water masses in the Luzon Strait and the adjacent seas. The satellite data used in this study for the classification of water masses and detection of the Kuroshio front were acquired from the MODIS. In order to compare the satellite data with the ground truth, which is taken from the JHS2006 observations, MODIS data at 05:35 UTC on June 1, 2006 with a coverage area of 16–24° N, 117–127° E (Fig. 2) were obtained.

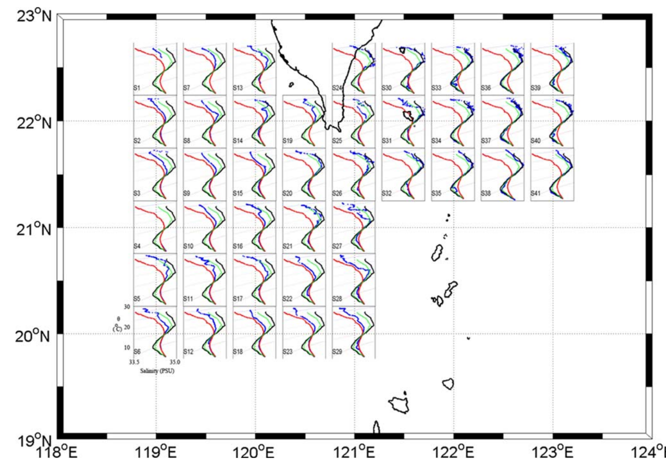

Fig. 1. T-S diagrams for all stations of the cruise JHS2006 are shown in blue lines. Typical Kuroshio and SCS T-S curves, shown in black and red lines, respectively, are based on measurements made by Chen and Huang [2]. T-S curves for the mixture of 25% SCS waters and 75% Kuroshio waters are shown as the green lines.

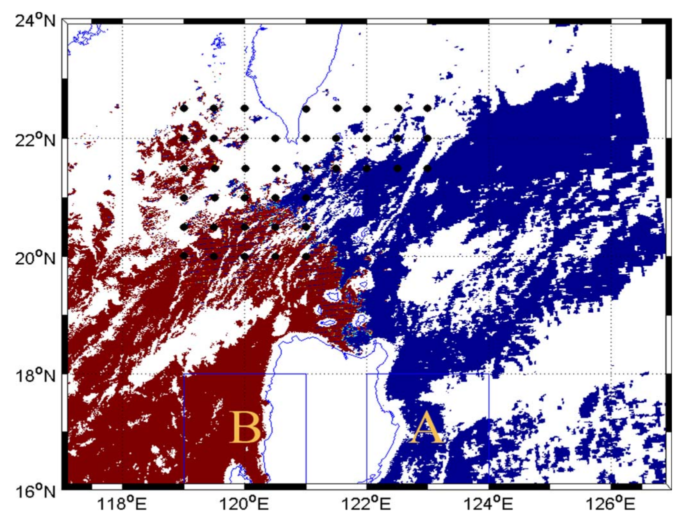

Fig. 2. Study area around the Luzon Strait. Solid circles represent the CTD stations for the cruise of JHS2006 during May–June of 2006. The boxes A and B are chosen to represent typical Kuroshio and SCS water types, respectively. Water-type classifications derived from ANN for the satellite MODIS image taken at 05:35 UTC on June 1, 2006. The blue and red areas indicate the Kuroshio and SCS types, respectively, whereas white areas indicate bad retrievals, cloud coverage, or land.

MODIS revisits the same Earth's surface every one to two days with 36 spectral channels ranging in wavelength from 0.4 to 14.4 μm, which corresponds to temperature-sensible and ocean-color bands. The spatial resolution of MODIS is varying, with 1.1 km of spatial resolution at nadir.

ANN is a powerful method for inversion problems. The most popular algorithm for ANN is the backpropagation technique [15]. In this study, the ANN used consists of a three-layered multiperceptron architecture, which utilizes a Levenberg–Marquardt backpropagation learning algorithm [16]. A gradient-based algorithm is used to calculate the network weights in this study, and the computing process is iterated until the weights have converged. Standard execution procedures of ANN require three independent data sets for the processes of training, validation, and test. First, the training process is used to develop the neural network. Second,

TABLE I
SUMMARY TABLE CHARACTERIZING THE TYPICAL DIFFERENCES (*IN SITU* MEASUREMENTS) BETWEEN SCS AND KUROSHIO WATERS

	Kuroshio	*SCS*
SST	Low	High
Chl-a	Low	High
Salinity	High	Low

validation process is used to validate the training process for preventing overfitting. Finally, the developed ANN is utilized to predict and evaluate the outputs using test data sets. In this study, a multilayered perceptron ANN, which consists of one hidden layer with eight hidden units, is used to classify the water mass into the Kuroshio and SCS types based on satellite imagery. The number of hidden layers and units are chosen by trial and error, depending on MODIS data set. Data of SST and ocean-color channels from MODIS imagery serve as the input for the network analysis. The data of SST channels in MODIS are the brightness temperatures at middle thermal bands (3.9/4.1 μm split window) and at thermal bands (11/12 μm split window), while the data of ocean-color channels are remote sensing reflectance centered at 412, 443, 488, 531, 551, and 667 μm. All samples are masked with cloud and negative remote sensing reflectance.

The survey area of JHS2006 is focused on the Luzon Strait (Fig. 1). The area encompasses the water masses of the Kuroshio and SCS types. It is known that the Kuroshio flows along the eastern Luzon island (area A in Fig. 2), while on the western side of the Luzon Strait is the SCS waters (area B in Fig. 2). SCS waters should be characterized by higher temperature, higher Chl-a, higher sea floor, more suspended sediment contents, lower salinity, etc. Kuroshio waters should show somehow opposite characteristics (Table I). The characteristics of SST and ocean-color channels from MODIS imagery at the areas A and B should be representative of typical Kuroshio and SCS waters. All samples in areas A and B were separated randomly into three equal parts for training, validation, and test purposes. About one-third of the samples were used for training, another one-third of the samples for validating, and the remaining samples for testing. The prediction accuracy for classification is used to evaluate the result. When the ANN is developed successfully, the ANN is applied to predict the water type of each pixel in the whole satellite imagery around the Luzon Strait. Ground-truth results of water types at the JHS2006 stations from T-S characteristics were then compared with the ANN predictions.

III. RESULTS AND DISCUSSION

The T-S diagrams for all 41 stations of JHS2006 are shown in Fig. 1 (in blue) together with typical SCS (in red) and Kuroshio (in black) T-S curves based on measurements reported by Chen and Huang [2]. The SCS waters near the Luzon Strait, which is a few hundred kilometers away from the sampling locations along the western Luzon island [2] for typical SCS waters, should have a somewhat different T-S curve due to the mixing process. Similar results were reported by Chen *et al.* [17] near the Luzon Strait between 115° E and 121° E from hydrographic measurements, and their T-S plots indicate that the SCS waters just on the west side of 121° E is the result of the mixing of approximately 50% of Kuroshio waters and 50% of SCS waters in the upper column. In order to distinguish the water types more clearly in the Luzon Strait, a criterion of the T-S curves from the mixing of 75% of Kuroshio waters and 25% of SCS waters is adopted in this study (green lines in Fig. 1). If the T-S curves of a certain station are to the left of this criterion T-S curve, it is categorized as SCS water type and vice versa. Fig. 1 shows that water properties in the Luzon Strait differ between the east side and west side of 121.5° E. Those on the east side (stations 30–41) have almost identical T-S curves as the Kuroshio waters, while those on the west side (stations 1–29) show mixed characteristics of Kuroshio and SCS waters in the upper column and characteristics of SCS waters in the lower part. As the station location is further westward, the water properties tend to more resemble the SCS waters (Fig. 1). For stations to the west of 120° E (stations 1–18), the waters can be categorized solely as SCS waters based on our criteria. Between 120° E and 121° E, water properties showed mixed characteristics of SCS and Kuroshio waters. The water types categorized based on the criterion T-S plots for all stations are listed in Table II. The Kuroshio intrusion appears to reach 120.5° E at about 21° N during the period of the JHS2006 experiment.

TABLE II
WATER TYPES DERIVED FROM THE ANN CLASSIFIER AND THE T-S CHARACTERISTICS OF JHS2006 FOR EACH STATION ARE ABBREVIATED RESPECTIVELY AS THE LETTERS IN THE LOWER AND UPPER PARTS OF EACH BOX. THE LETTERS S AND K REPRESENT THE SCS AND KUROSHIO WATER TYPES, RESPECTIVELY, WHEREAS THE LETTER X INDICATES BAD RETRIEVALS OR CLOUD COVERAGE, AS SHOWN IN FIG. 2. NOTE THAT STATION S4 LACKS T-S DATA, AND THUS, ITS UPPER PART IS LEFT BLANK

S1 S S	S7 S S	S13 S X		S24 K X	S30 K X	S33 K X	S36 K X	S39 K X
S2 S S	S8 S X	S14 S S	S19 S X	S25 S X	S31 K X	S34 K X	S37 K K	S40 K K
S3 S S	S9 S S	S15 S X	S20 K X	S26 K K	S32 K K	S35 K K	S38 K K	S41 K K
S4 S	S10 S S	S16 S S	S21 K K	S27 S K				
S5 S S	S11 S S	S17 S S	S22 S S	S28 S S				
S6 S S	S12 S S	S18 S S	S23 S S	S29 S S				

The satellite image of MODIS at 05:35 UTC on June 1, 2006, which was the most cloud-free image around the Luzon Strait during the observational period of JHS2006, was acquired and processed. All samples in areas A and B are randomly divided into three data sets of the same size, i.e., training, validation, and test. The prediction accuracies are found to be over 99% for the test data set, and the results indicate that the ANN can classify correctly the samples of areas A and B into the typical Kuroshio and SCS types. The developed ANN was then applied to the whole satellite image including the Luzon Strait and the JHS2006 study area, and the classification results are shown in Fig. 2. Pseudocolors are used in Fig. 2, with blue and red representing the Kuroshio and SCS waters, respectively, and white areas indicating bad retrievals or cloud coverage. A front separating the Kuroshio and SCS waters can be clearly observed, extending from the northeast of Luzon to the southwest of Taiwan.

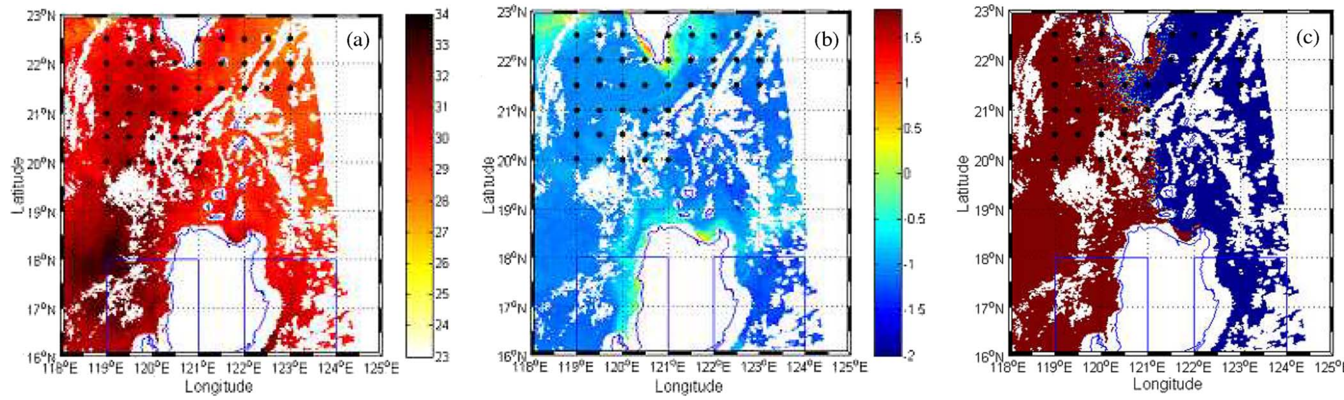

Fig. 3. (a) Satellite SST image taken at 05:50 UTC on July 11, 2004. The unit is in degrees Celsius. (b) Same as (a) but for Chl-a concentration. The unit is in milligrams per cubic meter. The color bar is in logarithm scale. (c) Water-type classifications derived from ANN show a clear Kuroshio front in the Luzon Strait. Color convention is the same as in Fig. 2.

Spatial patterns of water masses in the Luzon Strait derived from the ANN classifier in conjunction with satellite images (Fig. 2) are compared with the *in situ* measurements of JHS2006 (Fig. 1), and the results from both methods are listed in Table II for each station. The ANN classification of a certain pixel which is closest to the corresponding JHS2006 station is selected to validate the *in situ* result. Of the total 41 JHS2006 stations, 13 stations were covered by clouds (marked as X in Table II) and 28 stations were cloud free. Within the cloud-free areas, the classification result in each station from the ANN is consistent with that from the *in situ* measurements of JHS2006 except for station 27. At station 27, the ANN classifier's prediction is the Kuroshio water type while its T-S characteristics can be categorized as the SCS water type based on our criteria. The T-S plot at station 27 shows a strong mixing in the upper layer. This may be the reason why the classification does not agree with the measurement at the station. Note that station 4 lacks *in situ* T-S data; therefore, the comparison between *in situ* and ANN results cannot be made. However, according to the neighboring T-S characteristics of that area (Table II), this station should be categorized as the SCS waters with little doubt. The overall comparison indicates that the ANN model has good performance to classify water mass into the Kuroshio and SCS types correctly by analyzing satellite SST and ocean-color data. By sorting out the ANN classification function, the result shows that the middle thermal band and remote sensing reflectance centered at 412 and 488 μm contribute more to the Kuroshio front detection.

Originated from the equatorial Pacific and the west Philippine Sea, the Kuroshio waters have some distinctive characteristics. The difference between the two water types of Kuroshio and SCS is more significant in winter than in other seasons. Furthermore, there are usually seasonal phytoplankton blooms in the northern Luzon coastal area in winter [10]. When the Kuroshio intrudes into the SCS, which occurs mostly during the wintertime, this pattern of bloom might be carried into the northeastern SCS by the strong currents. Thus, the boundary or front between the Kuroshio and SCS waters in winter is more substantial to be observed in satellite images. However, the front becomes smeared in summer because both the warm SST and the low Chl-a by the heating effect are uniformly distributed in the Luzon Strait. The ANN model proposed in this letter, however, could provide a solution to this problem. This method optimizes the classification based on the characteristics of SST and ocean-color data in the source regions of Kuroshio and SCS water masses in one satellite image without using the threshold values of SST or Chl-a. No matter how close the characteristics in the two water masses are, the ANN could learn and classify the two water types correctly. The advantage of the ANN is that, being an objective method, it allows the system to adapt to the analysis of data in response to the training which is conducted on the network. An example of Kuroshio front detection in the Luzon Strait in summer is demonstrated here, with a satellite image acquired from MODIS at 05:50 UTC on July 11, 2004. Shown in Fig. 3(a) and (b) are the SST and Chl-a distributions, respectively, around the Luzon Strait. It can be seen that both the SST and ocean-color images have uniform spatial distribution in this region, and therefore, the Kuroshio front and Kuroshio intrusion will not be detected simply by the threshold values. On the other hand, after applying the ANN model to the same image, a clear Kuroshio front can be observed in the Luzon Strait [Fig. 3(c)]. One can see that the Kuroshio penetrates from the northern coast of the Luzon island to the southwestern tips of Taiwan. At the same time, an anticyclonic intrusion of the Kuroshio was present in the Luzon Strait, which was confirmed previously by Yuan *et al.* [9].

IV. Summary and Conclusion

An objective ANN method has been developed for the classification between the Kuroshio and SCS water masses in the Luzon Strait, and the boundary or front between the two water masses thus determined can be viewed as the evidence of Kuroshio intrusion. The essence of this method is that an optimized ANN model was established based on the training process of satellite SST and ocean-color data in the source regions of the Kuroshio and SCS. Validation and testing of the data sets indicate a highly accurate result of classification.

The major advantage of the method is its objective and adaptable natures to determine the Kuroshio front, even in summer, when the heating effect makes the SST and ocean-color distribution more uniform. Once the accurate classification between the Kuroshio and SCS waters has been made around the Luzon Strait, the detected Kuroshio front will benefit for practical applications of the Kuroshio intrusion in the Luzon Strait. The unequivocal front can be applied to analyze spatial and temporal distributions for the Kuroshio intrusion in future studies. It is important not only for the understanding of mass and heat transport between the Kuroshio and SCS waters but also for understanding the dynamics of Kuroshio intrusion into the SCS through the Luzon Strait.

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