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POSSIBILITY ESTIMATION OF GENERATING INTERNAL WAVES IN THE NORTHWEST PACIFIC OCEAN USING THE FUZZY LOGIC TECHNIQUE

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POSSIBILITY ESTIMATION OF GENERATING INTERNAL WAVES IN THE NORTHWEST PACIFIC OCEAN USING THE FUZZY LOGIC TECHNIQUE

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Key words: internal waves, fuzzy logic, generation predictions.

ABSTRACT

Possibility estimation of generating internal waves has been recognized as a difficult problem because of the complex generation mechanisms and insufficient in situ observation data of internal waves. In this study, a inference model based on the fuzzy logic technique was developed for estimating the generation possibility of internal waves. The marine environmental factors causing the occurrence of internal waves were distilled from ocean data and used as the inputs of the fuzzy inference model, and the generation possibilities of internal waves were used as the output of the model. The developed model was applied to the northwest Pacific, and the results were verified using satellite remote sensing images. The satisfactory results indicate that the inference model based on fuzzy logic is a useful first step in the development of generation estimation of internal waves and can be used as a supplement of traditional methods, which will be helpful for the risk assessment of ocean engineering.

I. INTRODUCTION

Internal waves have large amplitudes, generate in the stratified water and exist in the pycnocline. They often propagate over hundred kilometers and transport both mass and momentum which can bring about strong convergence of seawater and sudden strong currents. These can impose unexpectedly large stresses on ocean engineering structures, e.g. offshore oil-drilling rigs and pipelines. Therefore, the accurate generation estimation of internal waves is very important and significant.

According to the previous studies, the methods of studying internal waves can be grouped into four types: field monitoring method; satellite remote sensing method; laboratory experiment method and numerical simulation method.

Field monitoring method is the earliest method of studying internal waves [3]. Apel *et al*. [1] made an experiment on the observation of internal waves in the Sulu Sea and explained the generation of internal solitary waves using the "hill-back wave" mechanism. Ebbesmeyer *et al*. [8] found the close relationship between the intensities and the cycle periods of internal waves by analyzing the field monitoring data of internal waves in the South China Sea (SCS). The field monitoring method can provide us the first-hand information of internal waves, but has an obvious disadvantage: its data coverage is limited while the cost is huge.

Comparing to field monitoring method, satellite remote sensing method has many advantages: wide coverage, high resolution and relative lower cost. Liu *et al*. [20] and Zhao *et al*. [38] found that internal waves in the northern South China Sea mainly generated inside the Luzon Strait by plotting the distribution of internal waves using hundreds of satellite remote sensing images. The distribution map complied from a number of SAR images by Hsu and Liu [14] showed that the geographical distribution of internal waves was very large in the SCS and the wave crest line could reach more than 200 km.

Laboratory experiment can simulate the specified generation mechanisms which can't be obtained by satellite remote sensing method. Maxworthy [23] firstly brought forward the generation mechanism of "lee wave" by performing the experiments in the tank. Flynn *et al*. [9], Sutherland and Linden [31], and Sutherland and Linden [32] explained the generation mechanism of internal waves with the mechanism of interaction between tide currents and bottom terrain by putting different shapes of barriers in the experiment tanks.

Numerical simulation method is based on the basic equations of internal waves, the details of which are described in a number of literatures [12, 18, 19, 22]. Cai *et al*. [4] adopted a composite model which consisted of a generation model of internal waves and a regularized long wave propagation model to study the generation and evolution of internal solitary waves in three possible straits among the Luzon Strait, and

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explained the reasons of the asymmetry of their propagation.

The above four methods have their own advantages and disadvantages. Considering the generation estimations of internal waves, field monitoring method is not suitable because of the limited coverage and high cost. Satellite remote sensing method can cover wide area but the lagged time is fatal to the estimation. In the real marine environment, the generation mechanisms of internal waves are nonlinear coupling, so the laboratory experiment are also not very suitable to be used to estimate them. As for the numerical simulation method, it seems very suitable to estimate the generation of internal waves just like the meteorological models applied in the weather forecast if given the proper initial and boundary conditions. But in fact, the current numerical models of internal waves are too coarse and contain many hypotheses, such as the ignorance of bottom friction and viscosity of seawater. This is because the relationship between the marine environmental factors and the generation mechanisms of internal waves are so complex and nonlinear coupling so that we cannot establish a series of perfect dynamical and thermodynamic equations to describe the generation processes of internal waves. However, a mass of expert knowledge and experiences of the generation mechanisms of internal waves have been accumulated since the beginning time when we studied the internal waves. These knowledge and experiences are fuzzy and qualitative, and are hard to describe using traditional mathematical methods. However, they are just suitable to describe using fuzzy logic.

In this research, a novel method for the generation estimations of internal waves is presented. This method is based on the fuzzy logic technique, which has been widely used in many scientific fields, such as computer science and medicine. The fuzzy logic technique has been verified very effective and robust in solving many complex and nonlinear problems [13, 37] that cannot be done by traditional methods, but its application in the generation estimations of internal waves is rare. The paper focuses on the generation estimations of internal waves using fuzzy logic technique and it is organized as follows: in Section 2, fuzzy logic algorithm is introduced. A fuzzy-logic-based inference model for the generation estimations of internal waves is developed in Section 3. Its implementation in the northwest Pacific is presented and verified in Section 4, and this is followed by summary and conclusions in Section 5.

II. FUZZY LOGIC ALGORITHM

Fuzzy logic is a very useful tool for solving complex, nonlinear problems. Fuzzy logic is well suited to applications in linear and nonlinear control systems, diagnosing cancer diseases and clutter identification [2, 6, 16, 30]. The pioneering work in fuzzy logic was done by Zadeh in 1965. In his work, the fuzzy sets broke the limits of 'zero' and 'one' in the traditional sets [35]. The core of fuzzy logic algorithm is to establish a linguistical-analytical mathematical model for a complex system or process, which can express the expert knowledge or practical experiences in the form of fuzzy sets and fuzzy rules. While the fuzzy logic technique has been successfully applied in many engineering sciences, its applications in the meteorological and oceanographic studies are relatively limited [10, 36].

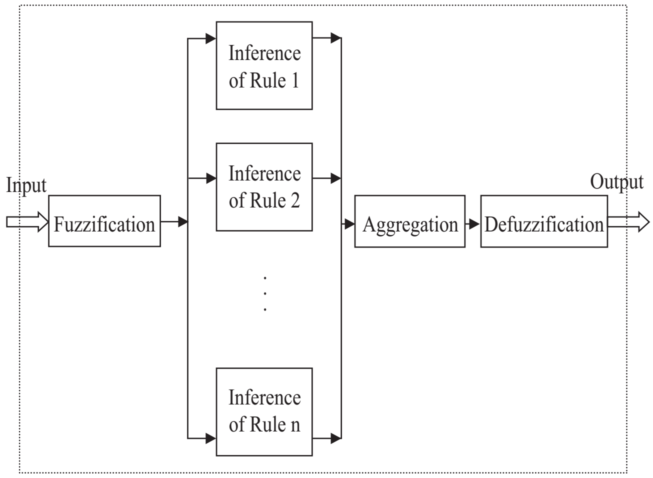

Fig. 1. Block diagram of a general fuzzy logic algorithm.

A complete fuzzy logic algorithm consists of four parts: fuzzification, rule inference, aggregation, and defuzzification [21]. The block diagram of the general fuzzy logic system is shown in Fig. 1.

1. Fuzzification

The function of the fuzzification block is to convert the crisp inputs to the fuzzy sets with a corresponding membership degree. A specified crisp input can belong to different fuzzy sets but with different membership degrees.

2. Inference

In the fuzzy logic system, fuzzy rules are used to describe linguistically the complex relationship between the input and output fuzzy variables in the form of IF-THEN statements. Typically, the rule is composed of several antecedents in the IF statement and one consequence in the THEN statement. The process of deducing the 'strength' of these consequents from the 'strength' of the antecedents is called rule inference.

3. Aggregation

The complete knowledge about a fuzzy model is contained in its rulebase which is a set of rules. We can use the inference methods to derive the strength of each rule, and then the aggregation method can be used to determine an overall fuzzy region.

4. Defuzzification

The output of aggregation process is a fuzzy set, so it is necessary for us to find a crisp value that can best represent the fuzzy set. This process is called defuzzification.

Table 1. The definitions of input parameters.

Name	Mathematical expression	Linguistic variables	Note
SSSW	$SSSW = -\frac{g}{\rho}\frac{d\bar{\rho}}{dz}$	Weak (W), Strong (ST)	The primary condition
HF	$HF = ui + vj$	Small (S), Medium (M), Big (B)	It is vector
UP	$UP = +\omega$	Small, Medium, Big	'+' means the ascending vertical current speed
ISF	$ISF = N^2/v'^2$	Small, Medium, Big	N is buoyancy frequency, and v' is speed shear
TG	$TG = \nabla H$	Small, Big	Terrain grads
ITTC	$ITTC = \lvert\overline{TC}\rvert\lvert\overline{HF}\rvert\sin\theta$	Small, Big	θ is the angel between TG and HF
VASSP	$VASSP = \frac{\Delta P}{\Delta t}$	Small, Big	The variable pressure of every six hours
OS	[0~1]	Exist (E) or Not (N)	Existence of other sources

III. THE DESIGN OF THE FUZZY-LOGIC-BASED INFERENCE MODEL FOR THE GENERATION PREDICTIONS OF INTERNAL WAVES

The concept of internal waves is wide and mainly consists of three kinds of internal waves: internal tide, internal solitary wave and high-frequency random internal wave. Their generation mechanisms are not the same. However, in this study, we don't distinguish the kind of internal waves, all called by a joint name "internal wave".

1. Features used for the Generation Estimations of Internal Waves

Lots of work has been done on the generation mechanisms of internal waves [11, 26, 33]. It is recognized that the stable stratified seawater is the primary condition for the generation of internal waves. In general, the generation sources of internal waves can be divided into two categories: the exterior sources and interior sources.

The exterior sources mainly consist of the wind pressure on the sea surface, ruleless oscillation of atmospheric pressure and the earthquakes in the seabed. These three sources can excite internal waves in two ways: one is resonant interaction, such as the interaction between the wind stress pressure and internal wave, the other is the vertical movement of seawater.

The recognized interior sources are mainly as follows: the interaction between the tide currents and the bottom topography [27], the resonant interaction among the surface waves [34], the shearing instability of the currents [24], the reflection of internal tides by the ocean boundaries [29], the interaction between the currents and waves in the zone of ocean fronts [17], the fluctuation of pycnocline caused by the upwelling passing through the pycnocline interface [15].

As have been discussed above, the generation mechanisms of internal waves are so complicated and nonlinear that we cannot study them using accurate traditional mathematical theory. So we resort to the fuzzy logic technique.

From the accumulated knowledge about the generation mechanisms of internal waves, we put forward eight marine environmental factors as the input parameters of the fuzzy inference model: the stratified stabilization of seawater (SSSW), the horizontal flow (HF), the upwelling (UP), the instability of shear flow (ISF), the terrain grads (TG), the interaction between terrain and tide currents (ITTC), the variable atmospheric sea surface pressure (VASSP) and other sources (OS) (e.g. ocean eddies, fronts, typhoons and earthquakes). The mathematical expressions and linguistic variables are shown in Table 1. We choose these eight expressions to describe the input parameters for two reasons. First, the expressions must accord with the physical definitions and essences of the marine environmental factors. Second, on the basis of the first condition, the forms of the expressions are as simple as possible due to the inference efficiency, and most importantly the expressions can be directly got or calculated from ocean data. As for the last input parameter: OS, it is impossible to give the mathematical expression because it can't be measured numerically as the other seven parameters. It is considered as a background field from the historical oceanic and atmospheric records, such as the activities of typhoons, earthquakes and ocean eddies observed from satellite images, and we have to compile these records to generate this historical background field. The generation possibility of internal wave (GPIW) was used as the output factor. The linguistic variables very low (VL), low (L), high (H), very high (VH) were used for the fuzzification of GPIW.

2. Fuzzy Rules and Membership Functions

One of the key issues in all the fuzzy sets is how to determine the fuzzy membership functions. The membership function fully defines the fuzzy set and provides a measure of the degree of similarity of an element to a fuzzy set. Since there is some degree of subjectivity involved in the producing membership functions, they are usually defined as simple curves (the most common membership functions are triangular, trapezoidal, piecewise linear and Gaussian and bell-shaped, etc. [25]). Compared with other membership functions, Gaus-

Table 2. Fuzzy rules.

Rule No.	SSSW	HF	UP	ISF	TG	ITTC	VASSP	OS	GPIW	Weight
Rule 1	W	—	—	—	—	—	—	—	VL	0.5
Rule 2	ST	B	—	—	B	—	—	—	H	0.75
Rule 3	ST	—	—	—	B	B	—	—	VH	0.9
Rule 4	—	—	—	—	S	S	—	—	L	0.25
Rule 5	ST	—	B	—	—	—	—	—	H	0.9
Rule 6	ST	—	—	B	—	—	—	—	H	0.75
Rule 7	W	—	—	M	—	—	S	—	VL	0.5
Rule 8	ST	—	—	—	—	—	—	E	H	0.75
Rule 9	W	—	—	S	—	—	—	—	L	1
Rule 10	ST	—	—	—	B	—	B	—	H	0.5
Rule 11	W	—	S	S	—	S	—	N	L	1
Rule 12	W	S	—	S	S	—	—	—	L	0.9

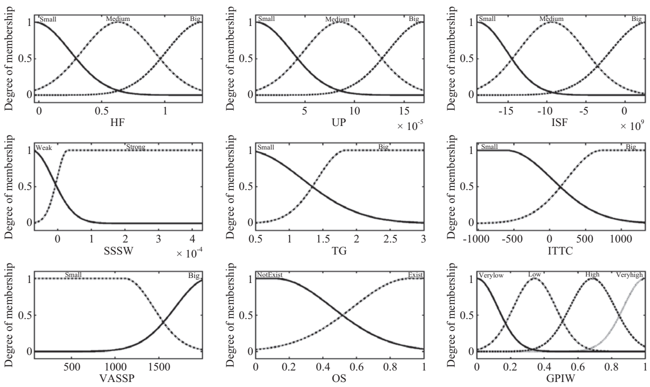

Fig. 2. Membership functions for the eight input parameters and one output parameter.

sian membership functions are found to demonstrate a smoother transition in its intervals and a smoother output, and the achieved results are closer to the actual effort [28]. In this study, we choose Gaussian membership functions for the three input parameters (HF, UP, ISF) and the output parameter (GPIW) of which each contains three linguistic variables, and Gaussian2 membership functions for the other five input parameters (SSSW, TG, ITTC, VASSP, OS) of which each contains two linguistic variables (Fig. 2). The parameters of Gaussian membership functions were selected by a long process of trial and error correction.

Fuzzy rules are also the sticking points of the fuzzy inference model. According to the recognized generation mechanisms and expert experiences, twelve rules were distilled to combine the output from the above membership functions (Table 2). The process of selection was mainly subjective. In practice, the list of rules was built up and verified through a trial and error correction process, ensuring the maturity and compatibility of fuzzy rules.

Fuzzy rules can be represented in the form of IF-THEN:

$$\text{if x is A then y is B} \quad \text{(a)}$$

a is the weight that describe the uncertainty of assessment on the rule. A guide about weights would be out of question (1), very confident (0.9), confident (0.75), no telling whether confident or not (0.5), less confident (0.25), not confident (0.1). For example, Rule 2 can be interpreted as follow:

Rule 2: If SSSW = ST and HF = B and TG = B, then GPIW = H, i.e. if the stratified stabilization of seawater is strong, the horizontal flow is big and the terrain grads is big, then the generation possibility of internal wave is high.

After the input and output parameters were distilled, and the membership functions and fuzzy rules were established, the Mamdani max-min inference method was employed as the interference mechanism. Finally, the whole fuzzy-logic-based inference model was developed (Fig. 3).

IV. RESULTS AND DISCUSSION

1. Data and Experiment Area

We use the Global Ocean Data Assimilation System (GODAS) data in $1° \times 0.333°$ grids from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center. The data time period spans from 1980 to 2010. The data of bathymetry is the TerrainBase data on a regular 5-minute grid. The TerrainBase dataset was created by the National Geophysical Data Center and World Data Center-A for Solid Earth Geophysics in Boulder, Colorado. To satisfy the grid points with the TerrainBase, we use a spline interpolation to reconstruct the GODAS data.

The experiment area (Fig. 4) is the northwest Pacific Ocean. The longitude range is from 105°E to 145°E, and the latitude range is from 0 to 40°N. The terrain of this area is very complicated, in which there are many kinds of terrains such as continental shelves, continental slopes and deep ocean basins. There exist many channels such as Luzon Strait through which the tide wave in the Pacific can transmit to the South China

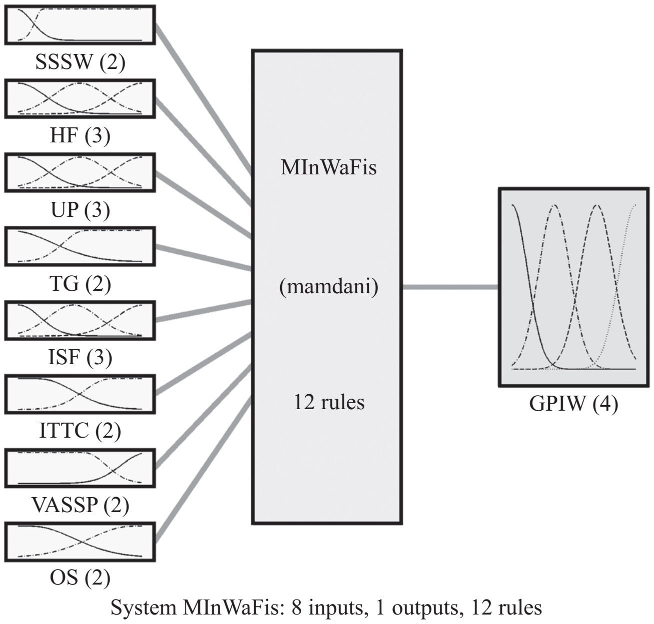

Fig. 3. Structure of the fuzzy-logic-based inference model. It contains three parts: eight input parameters (SSSW, HF, UP, TG, ISF, ITTC, VASSP, OS), Mamdani inference method with 12 rules, and the output parameter (GPIW). The numbers in the parentheses behind the parameters mean the number of their linguistic variables.

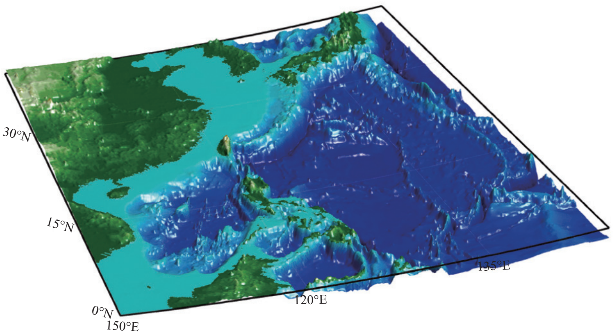

Fig. 4. Bathymetry map of the expetiment area. The longitude range is from 105°E to 145°E and the latitude range is from 0 to 40°N. Land and islands are painted in green, shallow seas (depth ≤ 2000 m) in Cambridge blue, and deep seas and ocean (depth > 2000 m) in navy blue.

Sea. Ocean eddies, ocean fronts and typhoons often occur in this area. These factors are all beneficial to the generation of internal waves.

2. Implementation of the Developed Model

The eight input parameters of the fuzzy-logic-based model for the experiment area were calculated according to the mathematical expressions in Table 1. These input parameters were imported into our developed inference model to predict the generation possibility of internal waves. We chose one point (121°E, 22°N) near the Luzon Strait. The values of the eight

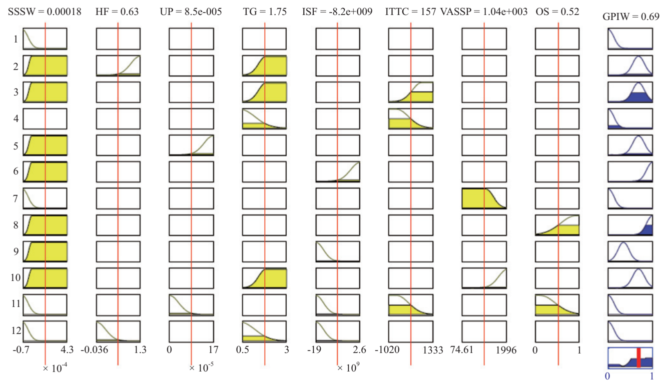

Fig. 5. Calculation of the value GPIW for one point (121°E, 22°N). Each row of subplots corresponds to each fuzzy rule, and the number on the left side indicates the number of each fuzzy rule. The red lines show the position of each input value on the top of each line in their own range indicated by the two numbers at the bottom of each line. The subplots colored in yellow (blue) show how the input (output) variables are applied into the fuzzy rules.

input parameters (SSSW, HF, UP, TG, ISF, ITTC, VASSP, OS) are 1.8×10^{-4}, 0.63, 8.5×10^{-5}, 1.75, -8.2×10^{9}, 157, 1040, 0.52 at this point, respectively. Firstly, the input parameters are fuzzified using their own membership functions to determine the fuzzy sets that the inputs belong to. For our multi-input inference system, we have to do the integrated calculation. Secondly, the outputs can be got by means of the fuzzy implication method for every IF-THEN rule. Thirdly, the outputs of all the fuzzy rules are aggregated by means of max method provided by the Mamdani inference method. Finally, the aggregated result is defuzzfied using the method centroid by the formula:

$$u_c = \frac{\int_U \underset{\sim}{U}(u)u\,du}{\int_U \underset{\sim}{U}(u)\,du} \tag{1}$$

where $\underset{\sim}{U}$ is the fuzzy set of the variable u on the universe U. Fig. 5 shows the calculation result of GPIW at this point is 0.69. This means that the generation possibility of internal waves at this point is 69%. Therefore, the prevention methods should be made ahead of time.

The generation predictions of internal waves for the whole experiment area are shown in Fig. 6. We choose March, June, September, and December as the representatives of spring, summer, autumn and winter, respectively. It is observed that the distribution forms of internal waves are generally similar in the four seasons. The high possibility (P > 0.7, in red color) areas of generation of internal waves are mainly four zones from north to south: Zone 1 is the western bank of the Korea Peninsula, Zone 2 is northeast of Taiwan Island, Zone 3 is west of Luzon Strait, Zone 4 is northeast of Borneo. The four zones have several factors in common: the stable stratified sea water, the complicated terrain where the depth varies tempestuously

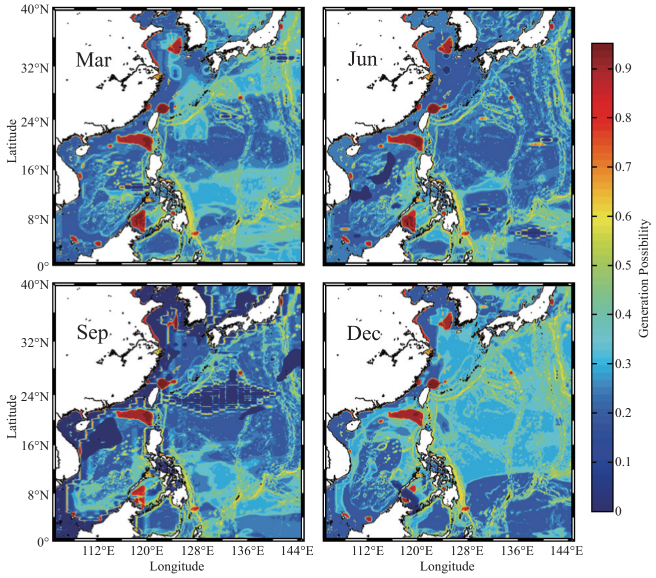

Fig. 6. Generation possibilities of internal waves in March, June, September, and December, 2009, respectively. The lands are shown in white color. Color bar indicates generation possibility.

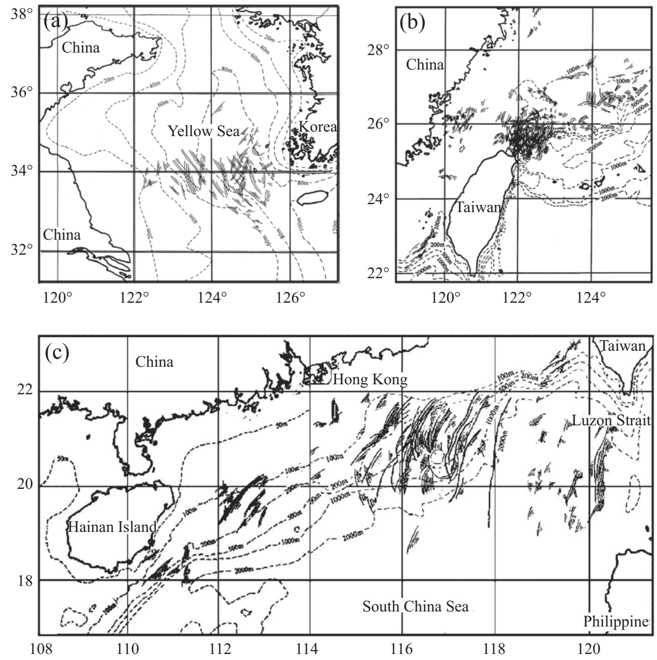

Fig. 7. Geographic distribution of internal waves in (a) the Yellow Sea, (b) East China Sea, and (c) South China Sea compiled from hundreds of SAR images. (After [14] and [15]).

and the steep gradient, the existence of the tide currents, and the effects of Kuroshio. The coupling combination of these factors creates fitting conditions for the generation of internal waves.

The middle possibility ($0.7 \geq P \geq 0.5$, in green color) areas are generally the estuaries of the Yellow River and Yangtze River, the seacoast of Fujian Province of China, south of Hainan Island and the outer sea of Vietnam. The estuaries are the junctions of the salt and fresh water, and very apt to form ocean fronts. There are upwelling and tide currents near the seacoast of Fujian Province of China. Ocean fronts, upwelling and tidal mixing are all beneficial to the generation of internal waves.

The low possibility ($P < 0.5$) areas are generally the deep ocean areas far from the land. Since the terrain is not so complicated and not variable as the shallow sea and the disturbance sources such as eddies and fronts are not frequent and concentrated, we can explain why the generation possibilities of internal waves in this area are lower than those in the mentioned above parts.

3. Validation of the Results

1) Comparison with the Statistic Results

The first-hand in situ monitoring data of internal waves are very limited due to the high cost and restrictions of observation technologies. The only available in situ monitoring data of internal waves are scattered and dispersive, and they are discontinuous on the time series, so we can't use these scattered data for the validation and comparison. The data used for the validation are the satellite remote sensing images, which can provide us the generation information of internal waves with extensive coverage. Hsu *et al*. [14, 15] plotted the geographic distribution of internal waves in the Yellow Sea, the East China Sea and the South China Sea compiled from hundreds of SAR images (Fig. 7). In this section, we will compare our experiment results with their statistic results to validate our experiment results.

Fig. 7(a) shows most of internal waves are located off the southwestern coast of Korea in the Yellow Sea. All the internal waves appear to generate by the interaction between the tidal currents and the shallow bathymetric features among the small islands located off in that area. Our studies (Fig. 6) can match well with this in this area. The distribution of internal waves in the East China Sea (Fig. 7(b)) shows that numerous generations of internal waves in the northeast of Taiwan and along the east coast of China Mainland, which can be seen from our results too. The distribution of internal waves in the South China Sea covers mainly four regions: the region between the Luzon Strait and Hainan Island (Fig. 7(c)), the region along the Vietnamese coast, the region between Vietnam and Borneo, and the Sulu Sea [5, 7, 14]. It is seen that the distribution map of our studies can match well with the compiled map from satellite images.

2) Comparison with the Atlas of Internal Waves

To further validate our experiment results, we chose ten points in the experiment area (Fig. 8). The geographical positions of the ten selected points are very representative, such as in the strait (F), in the deep ocean (E, J), in the area surrounded by many small islands (H) and on the bank of Peninsular (A), etc. Table 3 shows the values of the eight input

Table 3. The eight input parameters and the output GPIW at each position respectively (in row) and validation examples in the last line. IW = 1 means internal waves generated at this position, and IW = 0 means internal waves didn't generate at this position.

Serial No.	SSSW ($\times 10^{-6}$)	HF	UP ($\times 10^{-6}$)	TG	ISF ($\times 10^{-6}$)	ITTC	VASSP	OS	GPIW	IW
A	1.2966	0.0310	1.5925	0.7071	-4.2279	-0.0110	364.0468	0.2863	0.66	1
B	3.0230	0.1934	4.3837	1.1180	-8.9033	-0.0440	170.0654	0.1423	0.28	0
C	1.3987	0.3545	5.0702	16.8077	11.0320	5.5095	226.6074	0.0045	0.34	0
D	2.5949	0.2566	29.733	9.8615	-2.0805	2.2258	216.7676	0.6905	0.78	1
E	2.4932	0.0343	0.5381	32.5346	-3.7162	1.0802	109.2238	0.0841	0.21	0
F	1.9183	0.1602	0.3326	6.6708	0.0058	0.0408	235.6368	0.5808	0.82	1
G	4.4271	0.0930	4.3797	372.5765	4.8850	11.7706	437.5487	0.0031	0.17	0
H	2.7092	0.0783	2.5185	368.2180	-0.0558	28.8033	294.0604	0.8077	0.93	1
I	4.8424	0.0939	1.7020	17.0013	15.933	-1.5732	538.8678	0.0065	0.10	0
J	3.5505	0.1957	1.6082	19.8116	-0.9437	-2.7540	619.9869	0.4514	0.26	0

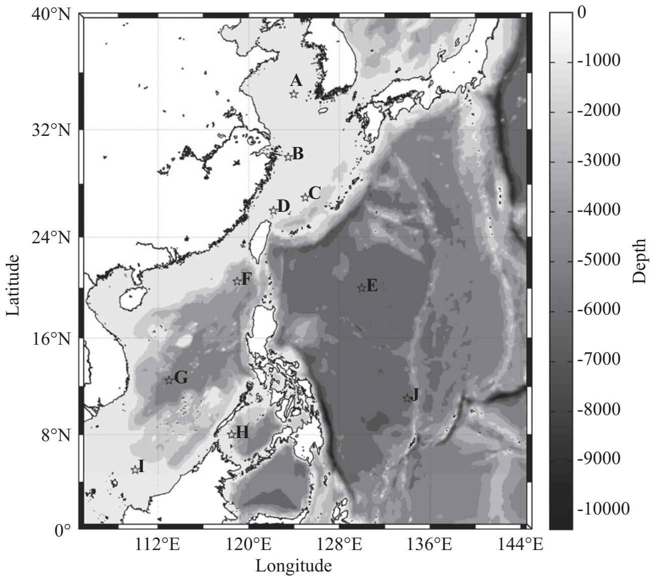

Fig. 8. Positions of the ten points for further validation, marked with the asterisks. The shaded gray color indicates the bathymetry in the ocean. The lands are shown in white color.

parameters calculated from GODAS and the generation possibilities of internal waves from our developed fuzzy logic model at each position, respectively. Ten examples of internal waves in this area recorded in the SAR images were selected from the atlas of internal waves provided by the Global Ocean Associates. As can been seen from Table 3, where SAR images reveal that internal waves generated (i.e. IW = 1), the generation possibilities predicted by our model are 0.66~0.93; where SAR images reveal that internal waves didn't generate (i.e. IW = 0), the generation possibilities predicted by our model are 0.10~0.34. It can be found from the comparison that the results are nice and encouraging, thus this fuzzy-logic-based technique for estimating the generation of IW is scientific and reliable.

V. SUMMARIES AND CONCLUSIONS

A fuzzy-logic-based inference model for estimating the generation possibilities of internal waves was developed. The northwest Pacific Ocean was selected as the experiment area to demonstrate the approach. In order to verify the results, previous statistical results and the atlas of internal waves were employed. The satisfactory comparison results show that our developed model based on the fuzzy logic technique is effective and reliable in estimating the generation possibilities of internal waves.

Compared to the conventional methods, our fuzzy-logic-based model has the following advantages: first, as the marine environment factors are described as fuzzy variables in our model, they can reflect the marine conditions more realistically and flexibly. Second, the model fully incorporates the knowledge of experts in the form of IF-THEN rules, and is suitable to describe the nonlinear coupling interaction between the generation mechanisms of internal waves, which is hard to accomplish with the conventional ocean dynamics. Finally, this model can provide us the estimation of generation possibility of internal waves in the specified ocean area at little cost.

This technique will be developed further by increasing the knowledge rules and integrating with neural networks. More experiments will be carried out in other ocean areas and a global possibility estimation model of generating internal waves is expected to be developed in future work.

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