EXTRACTING THE SPATIAL-TEMPORAL RULES OF THE MESOSCALE OCEAN EDDIES IN THE SOUTH CHINA SEA BASED ON ROUGH SETS

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KEY WORDS: Mesoscale Ocean Eddy; Spatial-Temporal Relationship; Rough Sets; Rules Extraction; South China Sea

ABSTRACT:

Many different types of Mesoscale Ocean Eddies have been found in China's coastal and offshore since the 1970s. Domestic and foreign scholars are holding ongoing in-depth investigation and research in the South China Sea, especially since the TOPEX / Poseidon (T / P) data have been widely used. Due to the complex causes and numerous affecting factors of the Mesoscale Ocean Eddies in the South China Sea, the methods such as numerical simulation, quantitative statistics post limitations in analyzing the spatial-temporal relationships. This paper adopts rough sets theory to express the spatial-temporal relationships of the Mesoscale Ocean Eddies in the South China Sea, without adding any a priori information. Firstly, the paper extracts spatial-temporal rules of the Mesoscale Ocean Eddies in the South China Sea, by using the extracted eddy data from the remote sensing image. The decision making attributes respectively are sea area, time, and the eddy type. Then, the paper describes specific characters of the Mesoscale Ocean Eddies respectively from time and space, as well as the types. The results suggest this method effectively extracted the spatial-temporal rules of the Mesoscale Ocean Eddies from multi-source data sets, thus efficient support an in-depth understanding of the phenomenon of Mesoscale Ocean Eddies.

1. INTRODUCTION

Ocean eddies, the breakthrough understanding of the ocean environment in recent decades, play an important role in the impact of the exchange of the material and energy flux in the ocean. There is abundance of Mesoscale Ocean Eddies in the South China Sea, which has great significance in the country's military, production and environment and has attracted much attention of scholars home and abroad. The scholars (Huang Q Z, 1992; Guan B X, 1997; Sun X P, 1997; Li Y C, 2002; Lan J, 2006; Guan B X, 2006; Li L, 2002; Cheng X H, 2008) studied the Mesoscale Ocean Eddies in the South China Sea by using the quantitative methods as following: □ Numerical Simulation, Yang (Yang Q, 2000) simulated and analyzed the multi-eddy system in the northern South China Sea in winter by using a modified eddy-resolving the Princeton University Ocean Model (POM). Qian (Qian Y P, 2000) used the POM to numerically simulate the mechanisms of the formations of cold and warm eddies under the joint effects of the wind stress in the South China Sea. The numerical simulation method obtains the information of the flow field from particular sea area with boundary condition, and sets the affect conditions to indirectly analyze the eddies. This method could successfully simulate the currents, seabed topography, coastline, wind stress and other factors, but still restricted by the complex formation causes of eddies. When the spatial resolution is high, this method receives the computer capacity and speed limits. □ Remote Sensing Image Information Extraction, Ge (Ge Y, 2007) used a multifractal filtering technology to extract the ocean eddies. The extracted information contained shape, size, spatial distribution patterns and the direction of energy flow of eddies. This method is superior to the traditional extraction methods, but there are still shortcomings in the boundary effect problem. Using remote sensing image information extraction methods can extract a transient moment of the characteristics information of the Mesoscale Ocean Eddies, but it still relatively weak in extracting information of the Mesoscale Ocean Eddies as a whole moving process. □ Quantitative Statistics, Gu (Gu J S, 2007) tracked the mesoscale eddies in the northeastern South China Sea, using the data of sea surface height anomaly (SSHA) observed by TOPEX/POSEIDON (T/P) satellite altimeter and the altimeter optimum interpolation data in the modular ocean data assimilation system (MODAS), and statistically analyzed the characteristic values of the eddies. Cheng (Cheng X H, 2005) used the 11-yr (1993-2003) T/P, Janson and ERS1/2 altimeter data to acquire the temporal and spatial distribution characteristics of mesoscale eddies in the South China Sea. The seasonal and interannual variabilities as well as the forming mechanism of mesoscale eddies in the South China Sea were studied. Lin (Lin P F, 2007) identified and traced the mesoscale eddies in the South China Sea from 1993 to 2001 using T/P merged ERS1/2 altimeter data through several criteria, and statistically analyzed their space-time variation characteristics. This method limits by the observational data which can only quantitative analyze the localized Mesoscale Ocean Eddies during a particular time. There is a certain defect of model-based analysis of the Mesoscale Ocean Eddies. Due to the limitations of the quantitative methods mentioned above, the further study on the rules of spatial-temporal behaviour of the Mesoscale Ocean Eddies in the South China Sea is still needed.

Rough sets theory, whose distinct characteristic is not required any a priori information outside of the processed data (Wang G Y, 2001), is an approach of researching presentation, learning, concluding of the incomplete, uncertain knowledge and data (Miao D Q, 2008). This study adopts rough sets theory to express the spatial-temporal relationships and extracts the spatial-temporal rules of the Mesoscale Ocean Eddies in the South China Sea, and using the eddy data extracted from remote sensing image (Nov. 2003 to Jun. 2009) as an example. Firstly, the raw data is obtained from the U.S. Naval Research Laboratory, which includes sea surface height anomaly (SSH), sea surface temperature (SST) and the current field

(Current/Speed) data. The typical cases of the Mesoscale Ocean Eddies are derived from these raw data by experts. Secondly, two types of the Mesoscale Ocean Eddies attributes are calculated as the conditional attributes of rough sets decision-table, one is the Mesoscale Ocean Eddies's own characteristics and the other is characteristics of the spatial-temporal relationships. Different decision-tables are made with the different decision-making attribute, such as the area of occurrence, the time of occurrence, and the eddy type. The condition attributes and the decision-making attributes above composes the decision-table. Finally, this study applies Boolean discrete algorithms to discretize the decision-making table, and uses genetic algorithm to reduce the decision-making table and extracts the rules. A total of three tables are obtained to show the spatial-temporal relationship rules of the Mesoscale Ocean Eddies in the South China Sea.

2. METHODOLOGY

2.1 Expression of Spatial-Temporal Relationships of the Mesoscale Ocean Eddies based on Rough Sets

To extracting the spatial-temporal relationships of the Mesoscale Ocean Eddies, firstl express the spatial-temporal relationships of the Mesoscale Ocean Eddies quantitatively, replace them with the form of decision-making table by rough sets. Figure 1 shows the flow of expression of spatial-temporal relationships of the Mesoscale Ocean Eddies based on rough set.

(1) Selecting the spatial-temporal relationships of the Mesoscale Ocean Eddies: According to the prior knowledge, selecting the specific spatial-relationships of the Mesoscale Ocean Eddies as the object of study. For example, the distance relations/ topological relations/ direction relations between the aim eddy and the nearest one, whose generating time is the nearest to the aim one; the distance relations between the aim eddy and the mainland coastline.
(2) Quantitatively describing the spatial-temporal relationships of the Mesoscale Ocean Eddies: Using appropriate quantitative methods to describe the spatial-temporal relationships of the Mesoscale Ocean Eddies. For example, the topological relations can be described by the RCC-8 model (Randell DA, 1992; Randell, 1989).
(3) Creating the decision-making table of the spatial-temporal relationships of the Mesoscale Ocean Eddies: The rows of the decision table represent the instances of the Mesoscale Ocean Eddies. The columns are divided into conditional attributes part which represent the spatial-temporal relationships of the Mesoscale Ocean Eddies and decision-making attribute part which represents the results. The value of the each row is the results of the spatial-temporal relationships of the Mesoscale Ocean Eddies described by different methods (not including the decision attribute).

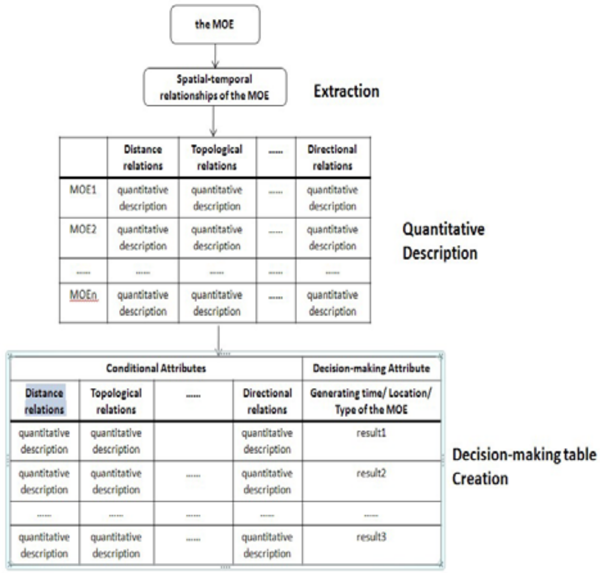

Figure.1 Flow chart of expression of the relationship of the Mesoscale Ocean Eddies based on rough sets

2.2 Extraction of the Spatial-Temporal Rules of the Mesoscale Ocean Eddies

(1) Expressing the spatial-temporal relationships of the Mesoscale Ocean Eddies based on rough sets: Representing the spatial-temporal relationships of the Mesoscale Ocean Eddies in the form of decision-making table showed by Figure 1.
(2) Discretizing the decision-making table: Using rough sets theory to deal with the decision-making table, the values of which are represented as discrete data (eg integer, string, enumeration). If certain conditional attributes or decision-making attributes are continuous range values (such as float), they must be discretized first. Therefore, discretizing the decision-making table which (1) got.
(3) Reducing the spatial-temporal relationships: Reducing the decision-making table in order to extract the high fitness rules of the decision-making table. After reduction of the decision-making table, calculating the Coverage (Wang G Y, 2001) and Confidence (Wang G Y, 2001) of the rules from the rules table of the spatial-temporal relationships.

The rough sets rules could be expressed as A⇒ B.
The Coverage of the rules:

$$\alpha = \frac{|X \cap Y|}{|X|} \tag{1}$$

The Confidence of the rules:

$$\beta = \frac{|X \cap Y|}{|Y|} \tag{2}$$

Which

$$X = \{x \mid x \in U \wedge A_x\}$$
$$Y = \{x \mid x \in U \wedge B_x\}$$

A_x indicates that the value of the conditional attributes of x satisfied with A; B_x indicates that the value of the conditional attributes of x satisfied with B. Set X is the instances whose conditional attributes satisfied with A; Set Y is the instances whose conditional attributes satisfied with B. The Confidence of the rules of the spatial-temporal relationships of the Mesoscale Ocean Eddies represents the credibility of the rules, and the Coverage represents the degree of support of the rules.

3. APPLICATION DEMONSTRATION

3.1 About the Experimental Area

The South China Sea is a semi-enclosed marginal sea located in 98.5 ° E -122.5 ° E, 0 ° N-24.5 ° N. Its area is about 3.5km × 106km, the average water depth is up to 1800m, and the maximum water depth of about 5000m (Wang G H, 2005). There are complex seabed terrain and lots of islands in the South China Sea, the water of which is shallow in the northwest and southwest part and deep in the central and eastern part. Through a number of straits, the South China Sea links with the ocean and the adjacent sea.

The South China Sea locates in the monsoon climate zone where the strong northwest winds are prevailing in winter and southwest monsoon in summer. In general, it's winter monsoon from October to March of the next year, summer monsoon from June to August, spring monsoon transition period from April to May, and autumn monsoon change period in September (Wang G H, 2005).The study have shown that the upper circulation is mainly affected by the monsoon-driven (Wang G H, 2005). In winter, the surface circulation of the South China Sea is in the cyclone-type situation; in summer, the surface circulation shows anti-cyclonic circulation trend (Huang Q Z, 1992; Li L, 2002; Wang J, 2003).

In the South China Sea, there are many active Mesoscale Ocean Eddies, which change seasonally and greatly influenced by the monsoon and heat exchange on the sea (Guan B X, 2006). The studies have shown that the Mesoscale Ocean Eddies mainly occurred in the southwest of Taiwan Island, and off the west coast of Luzon and the east sea of Vietnam (Wang G H, 2004). The regions of the Mesoscale Ocean Eddies are mainly located in the line of east of the southern part of Vietnam to the southwest of Taiwan, showing the northeast - southwest distribution (Lin P F, 2007; Wang G H, 2004). The warm eddies is more than the cold eddies(Lin P F, 2007; Wang G H, 2004). During the winter monsoon period, the Mesoscale Ocean Eddies of the South China Sea generate the most (Wang G H, 200 4), and very few of them come from Northwest Pacific (Lin P F, 2007). 80% of the Mesoscale Ocean Eddies move westwards with the change "Σ" type distribution in latitude (Lin P F, 2007). Therefore, the Mesoscale Ocean Eddies in the South China Sea distribute in certain amount of time and space laws, which need to be further in-depth quantitatively studied.

This research expresses the spatial-temporal relationships and extracts the spatial-temporal rules of the Mesoscale Ocean Eddies in the South China Sea based on the above method from November 2003 to June 2009. The raw data is obtained from the U.S. Naval Research Laboratory, which includes sea surface height anomaly (SSHA), sea surface temperature (SST) and the current field (Current/Speed) data. The SSHA data are assimilated from data of the ENVISAT, GFO and JASON-1, etc. The SST data are assimilated from IR data. The time resolution is one day, and the spatial resolution is (1 / 32) °. The typical cases of the Mesoscale Ocean Eddies are derived from these raw data by experts. The typical cases of the South China Sea is totally 391, in which warm eddies are 291, and the cold eddies are 100. Figure 2 shows a warm eddy case and the corresponding three kinds of environment elements field data.

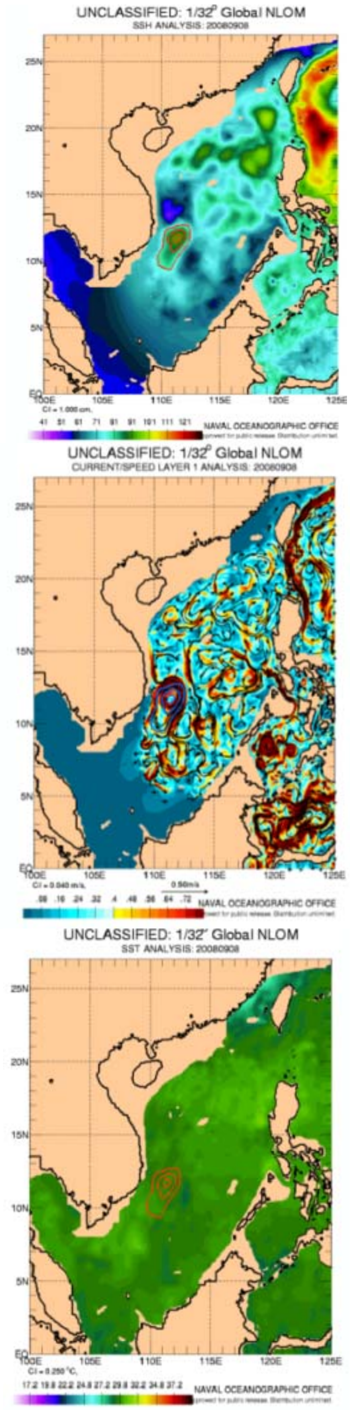

Figure.2 The example of the mesoscale ocean eddies in the South China Sea vector expression and the background field data

3.2 Expression of the Spatial-Temporal Relationships in the Experimental Area based on Rough Sets

Use the above-mentioned method to express the spatial-temporal relationships. Focus to different study of the Mesoscale Ocean Eddies, there are different choices of the decision-making attributes. For example, when the research emphasis on the rules of spatial-temporal relationships in different regions, the decision-making attribute is need to be the location of the Mesoscale Ocean Eddies; and if the research is focus on the rules of spatial-temporal relationships in different types of the Mesoscale Ocean Eddies, the decision-making attribute is need to be the type of the Mesoscale Ocean Eddies. In this research, the three decision-tables are made with the different decision-making attribute, which is the area of occurrence, the time of occurrence, and the eddy type.

Two types of the Mesoscale Ocean Eddies attributes are calculated as the conditional attributes of rough sets decision-table, one is the Mesoscale Ocean Eddies's own characteristics and the other is characteristics of the spatial-temporal relationships.

(1) Location of the Mesoscale Ocean Eddies where it generated (EddyZone): according to different physical characteristics of the marine environment of the South China Sea, divided the South China Sea into four sea areas, northeast part, central part, southeast part and southwest part.
(2) Time of the Mesoscale Ocean Eddies where it generated (EddyTime): divided by season, spring from March to May, summer from June to August, autumn from September to November, winter from December to February.
(3) Type of the Mesoscale Ocean Eddies (EddyType): the warm eddies and the cold eddies.
(4) Intensity of the Mesoscale Ocean Eddies (EddyIntensity): the amplitude difference of the center and the periphery, the unit is meter.
(5) Vorticity of the Mesoscale Ocean Eddies (Vorticity): the unit is s^{-2}.

$$\varsigma = \partial v / \partial x - \partial u / \partial y \approx 8gM / fD^2 \quad (3)$$

where M is the intensity of the Mesoscale Ocean Eddies

D is the diameter of the Mesoscale Ocean Eddies

f is Coriolis parameter

(6) Horizontal scale of the Mesoscale Ocean Eddies (Horizontal): half of the sum of east-west diameter and south-north diameter, the unit is meter.
(7) Temperature of the center of the Mesoscale Ocean Eddies (CenterTemp): the unit is degree Centigrade.
(8) Temperature difference of the Mesoscale Ocean Eddies (EddyTemp): the unit is degree Centigrade.
(9) Depth of the sea water (depth): the average of the sea water in the central part of the Mesoscale Ocean Eddies, the unit is meter.
(10) Distance relations (distance): the distance from aim eddy to the reference eddy[1], represented by Euclidean, the unit is meter.
(11) Directional relations (direction): the directional relation to the reference eddy, represented by eight directions.
(12) Topological relations (topology): the topological relation to the reference eddy, represented by RCC-8 Model (Randell DA, 1992; Randell, 1989).

Using ArcGIS secondary development VBA to achieve the above 12 attributes of the 391 typical Mesoscale Ocean Eddies in the South China Sea, the above-mentioned indicator (1), (2), (3), respectively, be the decision-making attributes, other indicators as conditional attributes of the rough sets decision-making table. Table 3 is the example of the decision-making table, whose decision-making attribute is location of the Mesoscale Ocean Eddies.

3.3 Spatial-temporal rules extraction

Using the specific software, Rosetta (Qhrn A, 1999), which cooperative R & D by the Department of Computer and Information Science of Norwegian University of Science and Technology and Institute of Mathematics of University of Warsaw Poland (Wang G Y, 2001), calculate and extract the rules.

(1) Import the decision-making table of the spatial-temporal relationships of the Mesoscale Ocean Eddies into Rosetta, whose decision-making attribute is location. (Table 3)
(2) Discretize the continuous range of values of the table, using the discrete method of combination of Boolean and the rough sets theory.
(3) Reduce the spatial-temporal relationships and extract the rules of the decision-making table which has been discretized, using the genetic algorithm. The specific method of implementation can be found in paper (Qhrn A, 1999).
(4) Similarly, changing the decision-making attributes and taking the above steps, obtain the spatial-temporal rules corresponding to the attributes.

[1] The reference eddy is the nearest eddy to the aim eddy in time. With the aim eddy as the center and radius as 1.83km × 60km, search the eddy whose time before and most neighboring the aim eddy within the buffer zone.

Conditional attributes											Decision-making attribute
Time	Type	Intensity	Vorticity	Horizontal scale	Temperature of center	Temperature difference	Distance relations	Directional relations	Topological relations	Depth	Location
Winter	Warm Eddy	0.0912	$0.692*10^{-6}$	150762.08	23.31	0.028	77340	East	Disjoint	2028	Central of the South China Sea
Summer	Cold Eddy	0.1845	$0.973*10^{-6}$	200655.8	29.94	0.0753	20074	Southeast	Touch	802	Southwest of the South China Sea
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Table 3 Decision table of spatial-temporal of the Mesoscale Ocean Eddies,whose decision attribute is the location

4. RESULTS

Analyze the spatial-temporal relationships of the Mesoscale Ocean Eddies respectively from location, time and type by convert the rules table, as shown in Table 4 to Table 6. In Table 4, from a regional point of view, due to the winter monsoon the Mesoscale Ocean Eddies generate mostly in in winter and spring in the northeast of the South China Sea, both warm and cold eddies appear, their temperature of the center is relatively low and vorticity is greater, and horizontal scale is in the low level. In the southeast of the South China Sea, there are more warm eddies, which generate mostly in winter (The warm eddies have taken place in the winter in Southwestern Luzon (Wang G H, 2004).); the temperature of the center is higher, the vorticity, intensity, horizontal scale and temperature difference are low; and the topological relation between the aim eddy and the reference eddy is overlap. In the southwest of the South China Sea, the horizontal scale of the Mesoscale Ocean Eddies is high, but the intensity is low; the Mesoscale Ocean Eddies generate mostly in where the water depth is lower than 1756m, and basically appear in the southern of the reference eddy.

Characteristic Attributes	Northeast of the South China Sea	Southeast of the South China Sea	Southwest of the South China Sea
Temperature of the center	<26.92°	[26.92°,28.53°)	
Vorticity/ s^{-1}	$>0.7*10^{-6}$	$<0.7*10^{-6}$	
Type	Warm, Cold Eddy	Warm Eddy	
Time	Winter, Summer	Winter	Summer
Horizontal scale/km	<172.6	<172.6	>194.9
Intensity/m		<0.08 or [0.08,0.12)	[0.08,0.11)
Temperature difference		[0.03°,0.16°)	
Average depth of the water/m		<1756 or >1897	<1756
Topological relations between the aim and the reference eddy		Overlap	
Directional relations between the aim and the reference eddy			South

Table 4 Rules of spatial-temporal of mesoscale eddies in different zones

In Table 5, from a time point of view, in winter, the temperature of center, the temperature difference and the intensity of the Mesoscale Ocean Eddies is low, but the vorticity is high; there are more warm eddies, which generate mostly in the central South China Sea; the topological relation between the aim and the reference eddy is overlap, and the Mesoscale Ocean Eddies basically appear in the northeast of the reference eddy. In autumn, the temperature of the center of the Mesoscale Ocean Eddies is relative low, but the intensity is high. There are mostly warm eddies which generate in the central South China Sea. In summer, there are more warm eddies, whose temperature difference is low, and they generate in the southwest of the South China Sea.

Characteristic Attributes	Winter	Autumn	Summer
Temperature of the center	<26.22°	[26.22°, 28.72°)	>29.59°
Type	Warm Eddy	Warm Eddy	Warm Eddy
Location	Central South China Sea	Central South China Sea	Southwest of the South China Sea
Topological relations between the aim and the reference eddy	Overlap		
Directional relations between the aim and the reference eddy	Northeast		
Vorticity/ s^{-1}	$>0.6*10^{-6}$		
Intensity/m	[0.08, 0.11)	>0.16	
Temperature difference	<0.18°		<0.18°
Average depth of the water/m	[1723, 1881)or [1881, 2092)		[1723,1881)

Table 5 Rules of spatial-temporal of mesoscale eddies in different times

In table 6, from a type point of view, the warm and cold eddies show a very clear spatial-temporal characteristics. The vorticity and the intensity of the warm eddies are relatively low, but they are high of cold eddies. The temperature of the center of the warm eddies is high, mostly higher than 29.02°, but the temperature of the center of the cold eddies is relatively low, in [27.72°, 29.02°) or lower. The warm eddies generate mostly in where the water depth is lower than 1741m, or [1723m, 1881m), but the cold eddies generate in where the water depth is higher than 2105m, or [1879m, 2105 m). The warm eddies is near the reference eddy, but the cold eddy is far away from the reference eddy. Also, the warm eddies mostly generate in the southeast of the South China Sea and central South China Sea in winter, but the cold eddies mostly generate in the southwest and northeast of the South China Sea.

Characteristic Attributes	Warm Eddy	Cold Eddy
Vorticity/ s^{-1}	$<0.7*10^{-6}$	$>0.9*10^{-6}$
Temperature of the center	>29.02°	<27.72° or [27.72°, 29.02°)
Distance relations between the aim and the reference eddy /m	<48.17	>48.17
Intensity/m	<0.1	>0.17

Average depth of the water /m	<1741 or [1741, 1879)	[1879, 2105) or >2105
Time	Winter	Autumn, Summer
Location	Southeast of the South China Sea, Central South China Sea	Southwest of the South China Sea, Northeast of the South China Sea

Table 6 Rules of spatial-temporal of different types of mesoscale eddies

5. CONCLUSION

According to the extracted spatial-temporal rules, following conclusions can be drawn. The warm eddies were produced in winter (which is same as Lin's (Lin P F, 2007) statistic result) and generated mostly in the southeast and middle of the South China Sea, where the place is relatively shallow. Their intensity and vorticity are relatively low, the temperature of their central region is high, and they only move a short distance. On the other hand, the cold eddies are produced in spring and autumn, and are generated mostly in the southwest and northeast of the South China Sea (which is same as Lin's (Lin P F, 2007) statistic result), where the place is relatively deep. Their intensity and vorticity are relatively high, the temperature of their central region is low (Consistent with the characteristics of the cold eddies), and they move a long distance.

6. DISCUSSION

This study adopts rough sets theory to express the spatial-temporal relationships and extracts the spatial-temporal rules of the Mesoscale Ocean Eddies in the South China Sea, by using the data extracted from the raw data (Nov.2003-Jun.2009) obtained from the U.S. Naval Research Laboratory. These rules not only describe the spatial-temporal relationships, but also specifically describe the characteristics of the two types of Mesoscale Ocean Eddies in the South China Sea. The results suggest this method effectively extracted the spatial-temporal rules of the Mesoscale Ocean Eddies from multi-source data sets. There are different choices of the decision-making attributes focus on different aims, and it's more flexible to extract the spatial-temporal rules, with the feasibility of practical application. However, the method requires a priori knowledge in the selection of the spatial-temporal relationships from the Mesoscale Ocean Eddies and the specific quantitative description of them. Selecting different spatial-temporal relationships, different results will obtain.

Besides, the experimental data is identified by digitizing the remote sensing data. The horizontal scale of some cold eddies is lower and the cycle is shorter, thus the number of the cold eddies is low. It is also the impact of the results. This work can also be augmented through the following means: □ increase in experimental data; □ select factors that can better reflect spatial-temporal relationships; □use other discretization and reduction algorithms based on rough sets theory and compared the results.

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