SEASONAL VARIATION OF THE OCEANIC WATER INTRUSIONS INTO KAGOSHIMA BAY DERIVED FROM THE SATELLITE SST AND CHL-A IMAGES

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ABSTRACT: Seasonal distribution of the oceanic water intrusion was investigated using satellite SST (sea surface temperature) and chl-a (chlorophyll-a) images taken by the MODIS Aqua sensor. The warm water mass emanating periodically from the meandering Kuroshio Current brings the oceanic water intrusion, known as the 'Kyucho' phenomenon, into Kagoshima bay during the winter. Satellite SST images and buoy robot data show that this warm water intrusion has the characteristics of a semigeostrophic gravity current influenced by the Coriolis effect. However, it is difficult to find the oceanic water intrusion during the summer season considering that it is accompanied by thermal stratification, and SST shows almost the same temperature between the inner side of the bay and the ocean. In this research, the satellite chl-a images taken by MODIS Aqua were employed instead of SST images to reveal the oceanic water intrusion in each season. The enclosed bay has the tendency to undergo eutrophication caused by organic materials from land and differences in chl-a concentration of the bay water and the oceanic water. As a result, distribution of low concentration chl-a with oceanic water intrusion in summer season shows almost the same pattern in winter season. On the other hand, in spring season, both SST and chl-a images are available to differentiate the oceanic water intrusion. Therefore, applying the suitable satellite sensor images for each season is effective in the monitoring of oceanic water intrusion. Moreover, in this area, SST and chl-a distribution reveal not only the oceanic water intrusion into Kagoshima bay but also the intrusion at Fukiage seashore facing East China Sea.

KEY WORDS: MODIS, Chlorophyll a, Sea surface temperature, Kagoshima bay, Oceanic water intrusion

1. INTRODUCTION

Southern Kyushu consists of deep and shallow basins such as Kagoshima bay and Fukiage seashore (Fig. 1). Kagoshima bay is located in the southern end of Kyushu with the length of about 75km. This bay has two deep basins connected by Sakurajima channel. And there is a sill with the depth of about 100m with its mouth opening to the south. Fukiage seashore is 44km long and is shallow farther from the shoreline. The Kuroshio Current progresses mainly in a deep course from Tokara Islands to the Pacific Ocean through the south of Yakushima Island.

During winter season, as shown in Fig. 2, there is intermittent warm oceanic water intrusion into Kagoshima bay that is known as the '*Kyucho*' phenomenon and it flows toward the north along the east coast of the bay. This intrusion has two typical patterns, and a speed of about 12cm/s that is estimated from field observation, satellite sea surface temperature (SST) observation and numerical simulation (Ohtani et al.,1998; Sakurai et al., 1983; Kohno et al., 2004). In addition to Kagoshima bay, SST observation reveals the warm water intrusion along Fukiage seashore (Hosotani and Kikukawa, 2006). These phenomena are important in taking into consideration the water exchange.

The warm oceanic water intrusion into Kagoshima bay is caused by the warm water mass formed as filaments, which emanate periodically from the meandering Kuroshio Current at the East China Sea which brings the warm water mass to the southern coast of Kyushu (Akiyama, 2006). The intrusion occurs when the warm water comes in contact with the bay water at the mouth location, and also depends on the warm water conditions in that specific area. This intruding mechanism of the semigeostrophical density gravity flow is studied in detail by Kubokawa and Hanawa (1984). The result of numerical simulations with simple conditions shows that the intrusion in the case of Kagoshima bay is also caused by the semigeostrophic gravity flow influenced by the Coriolis effect. The characteristics of this intrusion do not change significantly given the various temperature conditions at the mouth of the bay (Kohno et al., 2004). However, all the previous studies mentioned above were done during the winter season. That is because it is difficult to observe by using only SST images during other seasons, because the SST distribution is uniform due to a strong thermal stratification with the increasing surface heating effect.

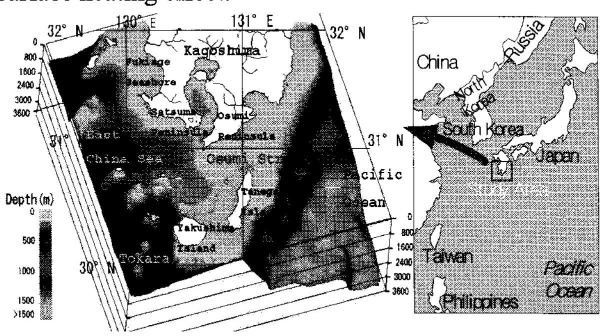
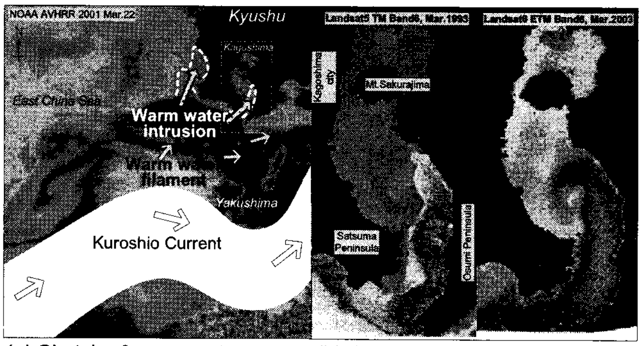


Figure 1. Bottom topography of study area.



(a) Sketch of warm water mass (b) Oceanic warm water intrusion in to Kagoshima bay

Figure 2. Behaviour of the warm water mass; (a) Sketch of the warm water mass which makes the oceanic water intrusions using NOAA/AVHRR SST image. (b) Scenes of Landsat (band 6) show two typical patterns.

In this research, seasonal variation of the oceanic water intrusion was investigated using chlorophyll a (chl-a) and SST satellite images. When the SST images are less sensitive, chl-a images are effective in the summer season for the Kuroshio front detection (Takahashi and Kawamura, 2005). The results of field observation (Kobari et al., 2002) suggest that average chl-a concentration is maintained at more than 0.5mg/m^3 throughout the year in Kagoshima bay, and the difference between the inner bay and ocean would be clearly shown.

2. DATA AND METHODS

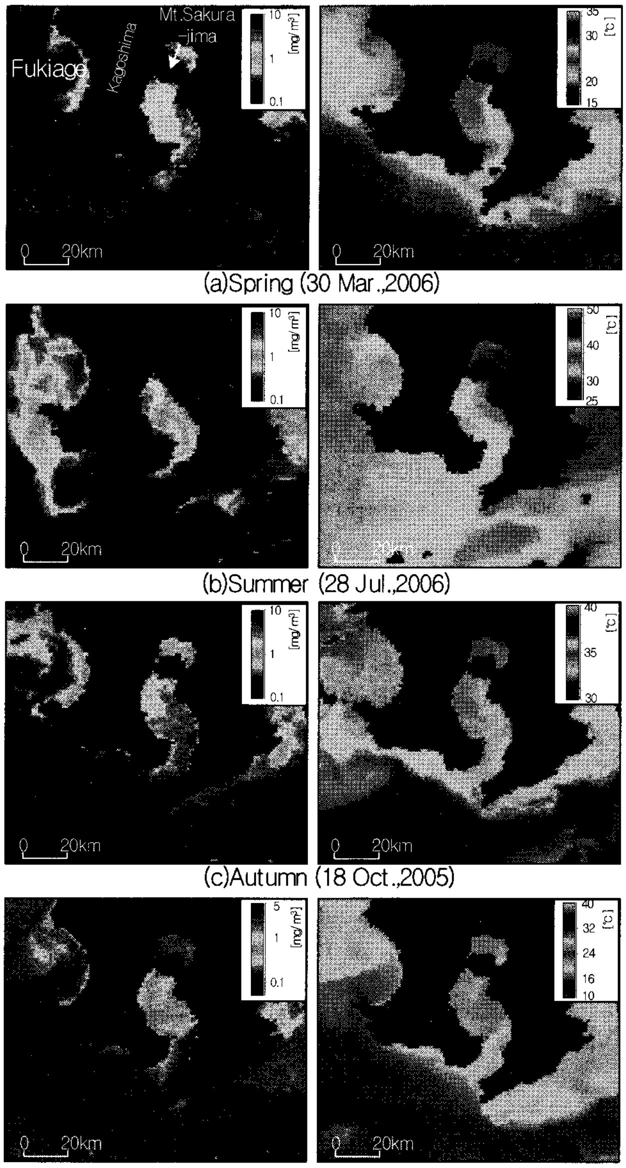
In this research, truly synoptic chl-a and SST images derived from the MODIS/Aqua Ocean Color sensor were performed. The concentration of chl-a of the seawater flow inside the bay could be differentiated because the concentration is high due to its being a closed shape bay and the possibility of eutrophication. The chl-a and SST dataset (Level 2) with 1km resolution of the Aqua sensor within the MODIS satellite, which are released by JAXA/Tokai University, were applied for this purpose. These data sets were given radiometric, atmospheric and geometric compensation. SeaDAS data processing software was applied to analyze and visualize the downloaded binary formatted data. Here, the MODIS/Aqua sensor is a passive-type sensor. Since it depends on the chl-a data of seawater on phytoplankton, it will be influenced more than SST dataset not only from atmospheric conditions but also from environmental materials such as nutritive salt conditions that will also change drastically in the daily data.

3. RESULTS AND DISCUSSION

3.1 Seasonal variation of oceanic water intrusion

The examples for each season showing the oceanic water intrusion are presented in Fig. 3. The left images show chl-a on the sea surface and the right images show SST, respectively. Fig. 3(a) is focused on the spring season. In this season, phytoplankton increases tremendously and thermal stratification becomes strong. The SST image shows that the high temperatures are along the east to west side coast of the central bay section and in the northern section. For the oceanic water intrusion, the contrast of the SST image is not strong with a 2-3 degree difference. On the other hand, the chl-a image also shows the distribution of low concentration according to the oceanic water intrusion from the mouth of the bay to southern Sakurajima.

Fig. 3(b) is focused on the summer season. In this season, plankton also increases in huge numbers and thermal stratification becomes the most remarkable. The SST of inner bay is relativity high and shows no sign of oceanic water intrusion. On the other hand, the chl-a image shows clearly the intrusion from the mouth of the bay with a rotating pattern in the central basin.



(a)Spring (30 Mar.,2006)

(b)Summer (28 Jul.,2006)

(c)Autumn (18 Oct.,2005)

(d)Winter (21 Feb.,2006)

Figure 3. Seasonal variation of oceanic water intrusions by chl-a images (left) and SST images (right).

Fig. 3(c) is focused on the autumn season. In this season, there is still the tendency to make a strong thermocline the same as in the spring season. But the oceanic water intrusion is still not visualized clearly in this SST image. On the other hand, the chl-a image shows oceanic water intrusion, which intrudes and spreads in the central basin.

Fig. 3(d) is focused on the winter season. In this season, the oceanic water intrusion (probably, it may be called a warm water intrusion in this case) can be shown both in the SST and chl-a images clearly.

In these chl-a and SST images, the oceanic water intrusions were shown not only in Kagoshima bay but also in Fukiage seashore. As shown in Fig. 3(c) and Fig. 3(d), although they have low contrasts, chl-a and SST images show the oceanic water mass which moves in the north direction along the eastside coast.

A correlation diagram that shows the relationship between SST and chl-a under intruding condition along the survey line (A-A') is shown in Fig. 4. During autumn to spring, plots show significant correlation. These plots are basically clear and the results show that chl-a value tends to be low with the rise of SST. This characteristic shows that the water mass with low chl-a concentration intrudes simultaneously with warm oceanic water. However, in the case of the summer (including early summer), they show flat shapes which means that there is no correlation established. Each image shows a high concentration of chl-a with many nutrients at the west side of central basin, where it is the offshore area of a city section. Thus, after the water intrusion has been fully distributed, the chl-a distribution pattern should differ from the advection-diffusion of SST.

The chl-a distributions in this article show clearly that it is easy to recognize the oceanic water intrusion. However, there are so much unclear data because chl-a depends on many factors such as water temperature, salinity, observation time, rainfall or nutritive-salts from land, and it shows drastic change on a daily basis. Thus, analysis using chl-a image should pay attention to bioenvironmental behavior.

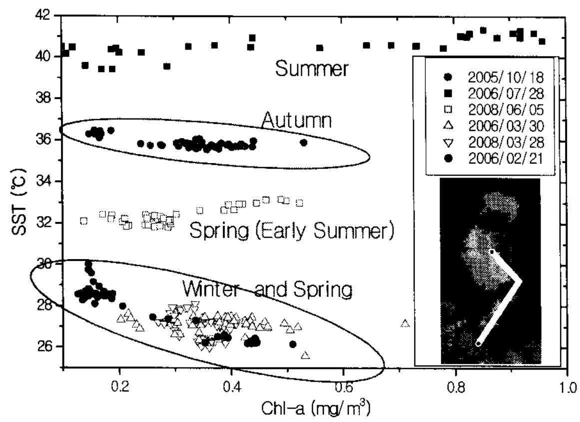


Figure 4. Correlation diagram of chl-a vs. SST of "A-A'"

3.2 Intruding patterns and estimated intruding speed

The examples of representation that show clear intruding patterns by chl-a are depicted in Fig. 5. Fig. 5(a) shows typical pattern where oceanic water intrudes from the mouth of the bay to southern Sakurajima. Fig. 5(b) shows the anti-clockwise rotation in the central basin. Fig. 5(c) shows a widely spread pattern in the central bay, taken in the autumn season. Fig. 5(c) shows the low-concentration water distributed over two forks. It is still an assumption whether the flow has separated, and that this is where light seawater including a lot of fresh water from offshore of Kagoshima-city experiences eutrophication. The existence of this eutrophication in water distribution offshore from the city area can be gathered also from the reports of the environmental assessment which are performed periodically for the evaluation of water quality observation and ecosystem.

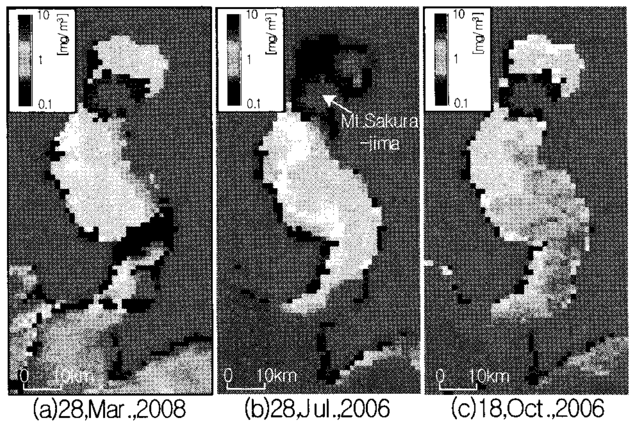


Figure 5. Typical intruding patterns by chl-a distributions. Pattern (a) and (b) are similar to the warm oceanic water intrusions in the winter season. However, pattern (c) is less common in winter.

Fig. 6 shows a time series of chl-a images to estimate intruding speed in the summer season. The estimated intruding speed was calculated using the traveled distance of the core of low-concentration, since chl-a tends to be influenced by environmental factors as described above. Since real time satellite imagery is influenced by weather conditions, it is difficult to take time series scenes showing clear concentrations, especially in summer season in the monsoon area. Therefore, this intrusion speed should be considered as a rough estimation. As shown in Table 1, the estimated speed was about 7cm/s to 12cm/s, which is the same order as that of the case of the warm water intrusion in winter (Kohno et al., 2004).

In the case of winter, NOAA/SST images, which can make more than four scenes per day, make it easy to estimate the intermittent production term of the oceanic water intrusions. However, in the case of other seasons, especially the summer season, the small amount of samples makes it more difficult to estimate the intermittent term.

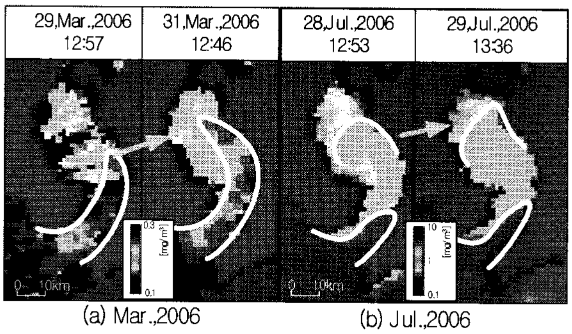


Figure 6. Time series of the oceanic water intrusions.

Table 1. Estimated intruding speed

Case	Speed	Source
Winter	12cm/s	Field observation by buoy robot (Ohtani et al.,1998).
	7-15cm/s	NOAA AVHRR SST images (Hosotani and Kikukawa, 2006)
	15-25cm/s	Numerical simulation (Kohno et al.,2004)
Spring	**9cm/s**	MODIS/Aqua chl-a images (Fig. 6)
Summer	**7-12cm/s**	MODIS/Aqua chl-a images (Fig. 6)
	15cm/s	Numerical simulation (Hosotani and Winarso, 2007)

3.3 Discussion for the seasonal monitoring of oceanic water behavior.

As described in the above section, the satellite chl-a and SST images show that distributing patterns of the oceanic water intrusion into Kagoshima bay or Fukiage seashore in each season are basically almost the same. The results of numerical simulation which was carried out under a simple assumption suggested that even in the summer season, a thick warm water mass is brought to the southern coast of Kyushu (Hosotani and Winarso, 2007). This can make a semigeostrophic gravity flow enough to intrude into the bay the same as in the winter season. Simulated intruding patterns are similar and estimated intruding speeds at both seasons are about 15-25cm/s although some features such as generation of the inflow from the middle layer showed a different tendency. But it is not a well-argued feature because of lack of field observation data and satellite remote sensing data. Seasonal monitoring operations of oceanic water intrusion into Kagoshima bay can be established with the choice and selection of an appropriate sensor image suitable for seasonal conditions. This will provide useful data and information for environmental research.

4. CONCLUSION

It is important to monitor oceanic water intrusion for all seasons because this event will contribute to the water exchange in the coastal environment. This research is aimed at figuring out oceanic water intrusion for each season by satellite SST and chl-a images using the MODIS/Aqua ocean color sensor. The seasonal variations of oceanic water intrusion into Kagoshima bay have similar tendency of a semigeostrophic gravity flow influenced by the Colioris effect in spite of various conditions. Complementary application of SST and chl-a image is effective to achieve consecutive monitoring and analysis.

However, clear scenes are still not enough because of atmospheric conditions. It is further recommended to use a few days of composite images to bring better and improved results.

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