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Development of an Interpolation Method of NOAA/AVHRR Images and its Application to Warm Water Intrusion into Kagoshima Bay

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Abstract

The instantaneous field of view (IFOV) of NOAA/AVHRR images is 1.1km, which is not enough to study the warm water distribution in a small bay. We propose in this article, a linear interpolation method to improve the ground resolution of the NOAA/AVHRR image for the purpose of advanced use of the images. The linearly interpolated thermal infrared images in winter are employed for observing the movements of the warm water filaments emanating from the Kuroshio Current and the associated water intrusions into Kagoshima Bay. These images indicate that the intrusion occurs when the warm water touches the bay water at the mouth of the bay and also provide information on the warm water intruding routes and their distributions in the bay.

Introduction

Earth observation satellite images are advantageous for the studies on the surface conditions in seas and bays because they are repeatedly obtained in time and instantaneously cover a wide area, although they have the disadvantage that the observation is limited to the sea surface. Satellite remote sensing is used to investigate the sea surface temperature[1] (SST), the turbidity and the chlorophyll[2),3)], the coral reef condition[4)], the oil detection[5)], the sea fog[6)], the sea surface altitude[7)], etc.; especially, SST is greatly useful for not only the oceanography but also the fishery.

In 1995, the receiving and analyzing devise of NOAA/AVHRR satellite images made by ELM Co. was introduced into the united graduate school of agricultural sciences at Kagoshima University and has been fully operated since 1997 April. The data obtained are transferred to each user's computer through inter Univ. LAN.

Making use of the dedicated analyzing software, the original data are rectified radio metrically, are cut out to 1024 x 1024 pixels regions and are corrected geometrically. Next, changing the original 10 bits HRPT data to 16 bits integer data, analysis is performed using the hand-made[8)] visual basic software. We have examined 344 data from the spring of 1997 to the spring of 2002.

Linear interpolation of NOAA/AVHRR image data

Although there is an advantage that more than 4 images are obtained in a day, the instantaneous field of view (IFOV) of NOAA/AVHRR image is 1.1km, which is not enough to investigate the sea surface

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conditions in small coastal bays. In contrast, images of other earth observation satellites, such as Landsat/TM (IFOV=30 m for bands 1 to 5 and band 7, IFOV=120 m for band 6) and Aster/TIR (IFOV=90 m), have enough resolutions, but their recurrent is too long as 17 days to examine the process of warm water intrusions. For the purpose of overcoming this difficulty, we try to interpolate NOAA/AVHRR image data virtually improving their ground resolutions.

In this article, the simple linear interpolation is adopted. That is, average the neighboring two raw data and then set the average at a new middle point between them. One operation of the interpolation makes the resolution two times improve virtually, and two times operations four times, and so on. We first examine whether the linear interpolation gives useful images or not.

In the last 20 years, Landsat/TM has observed three events of warm water intrusions into Kagoshima Bay. We use the event on 1st April 1997 to evaluate the interpolation method. The resolution of the Landsat/TM data is set to 30 m for all bands including band 6. Image a1 in Plate 1 is obtained by averaging 9x9 pixels of the Landsat/TM band 6 data, whose the virtual resolution is 30x9 = 270 m. Image a2 (image a3) averages 2x2 (4x4) pixels of image a1, giving the virtual resolution of 270x2 = 540 m (270x4=1080 m). We take image a3 as an NOAA image improvised, although it seems to provide clearer view than the real NOAA images.

The improvised NOAA image, image a3 in Plate 1, is then linearly interpolated. One operation (two operations) of the linear interpolation gives image b2 (image b1) in Plate 1, the virtual resolution of which is 1080/2 = 540 m (1080/4=270 m). Image b2 (image b1) is a little more monotonous than image a2 (image a1). However, we can identify structures clearer with images b1 and b2 than image a3. Thus we conclude that the simple linear interpolation works well for the improvised NOAA image.

The effect of the linear interpolation to a real NOAA/AVHRR image is explained with images c1 to c3 in Plate 1. The source image c3 is once (twice) interpolated, giving resultant image c2 (image c1). Images c1 and c2 are clearer than the source image c3: that is, they are finer in the distribution of the warm water and more distinctive in the coastal topography.

Application to the warm water filament

Kagoshima Bay is located at the southern end of Kyusyu, Japan (Fig. 1). The Kuroshio Current, which is one of the biggest currents in the world, flows across the Tokara Strait just south of Kagoshima Bay. The Kuroshio turns clockwise from the northeast to the southeast in the area west of Yakusima Island. Warm water filaments[9] emanated from the Kuroshio extend eastward and approach to

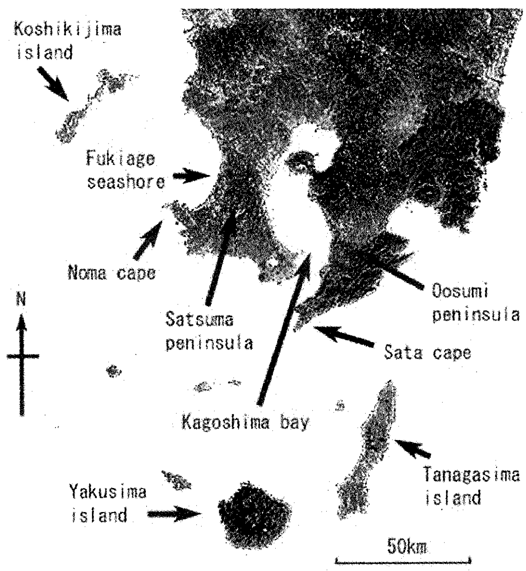

Fig. 1 Map of the sea south of Kyusyu, Japan.

the mouth of Kagoshima Bay. Kohno et al.[10] showed that the warm water intrusion into the bay begins when a filament touches to the mouth of the bay. In this section, we present the once interpolated NOAA/AVHRR images to study the movement of the warm water filament emanated from the Kuroshio. The virtual resolutions of such images are 1100/2=550 m.

In Plate 2 are shown four successive images from 21st March to 1st April 2001. The color of each image expresses SST; the colder hue represents lower SST and the warmer hue higher SST. Since the absolute value of SST is affected by the diurnal cycle and also suffered a little significant error, only the relative value of SST is meaningful. The color is so selected as to show the movements of the filaments as plainly as possible.

In image a at 19:06 21st March, the Kuroshio swells in the area west of Yakusima Island. The warm water emanated from the Kuroshio approaches to the southern end of Satsuma Peninsula and its part begins to intrude into Kagoshima Bay at Cape Sata. Another warm water filament with a little low SST approaches to the Fukiage coast.

In image b at 05:28 22nd March, the crest of Kuroshio moves eastward and approaches to Yakusima Island. The head of warm water intruded up to off Oonejime on the eastern coast of Kagoshima Bay. One of the thin warm water filaments arrives at the Fukiage coast and another one to Koshikijima Island.

In image c at 18:53 26th March, the crest of the Kuroshio wraps Yakusima Island. The warm water intruded into Kagoshima Bay begins to develop an anticlockwise vortex in the center of the bay. Another warm water filament is generated in the area about 80 km south of Koshikijima Island.

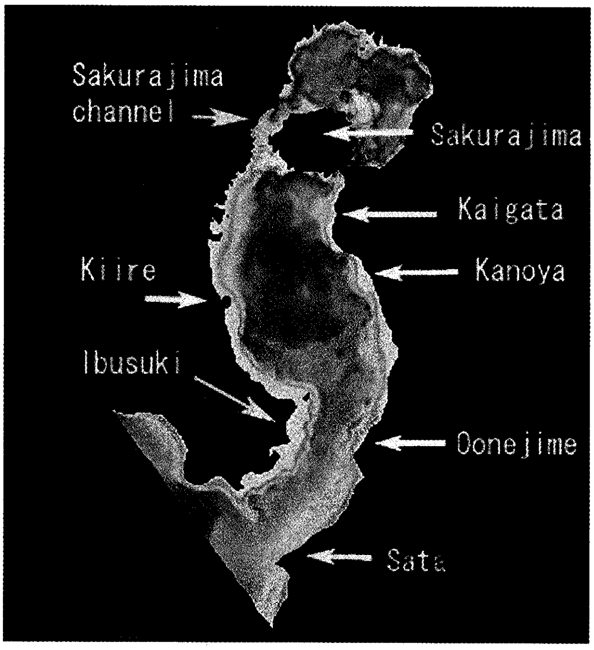

Fig. 2 Map of Kagoshima Bay.

In image d at 19:58 1st April, the crest of Kuroshio disappeared. It might be divided by the cold water mass, which is developed at the south of the new warm filament in image c. The cold water mass extends southeastward around the southwest of Yakusima Island. The anticlockwise vortex in the center of Kagoshima Bay can be seen distinctly.

In Plate 3 are shown some examples of the warm water filaments and their intrusions into Kagoshima Bay.

In image a at 02:26 1st April 1997, two warm filaments are shown. One is located between Satsuma Peninsula and Yakusima Island. Another filament extending northeastward is seen in the area about 80 km west from Koshikijima Island. The warm water intrudes into Kagoshima Bay along the eastern coast of the bay up to the southern coast of Sakurajima.

In image b at 18:00 28th January 1999, an anticlockwise thin filament at the south of Koshikijima Island is conspicuous. The southeastward extension of the cold water at the southwest of

Yakusima Island is similar to the one in image d of Plate 2 (19:58 1st April 2001). The warm water intrusion is observed only at the mouth of Kagoshima Bay.

In image c (17:40 25th Feb. 1999) and image d (02:19 1st April 2002), the swell of the warm water is going to be divided. These images might be situated between image c (18:53 26th March 2001) and image d of Plate 2 (19:58 1st April 2001). In image d (02:19 1st April 2002), there exists another filament similar to that in image a (02:26 1st April 1997), but stretching northward.

Application to the warm water intrusion

Kagoshima Bay (Fig. 2) is a long and narrow bay with the south-north length of about 75 km and the west-east width of about 25 km. The bay is open to the south and the Kuroshio flows in the area about 100 km south of the mouth of the bay. It has two deep basins separated by the Sakurajima Channel of about 4 km wide and 40 m deep. The bay water exchange is considered mainly causing by the density flow[11),12)] in winter. However, the intermittent intrusion of the warm water may affect to the water conditions in the bay.

The intermittent warm water intrusion into Kagoshima Bay was observed by using current meters[13)] moored at the sill in the mouth of the bay, by the thermometer[14)] mounted on the bottom of a ferryboat and by the buoy robots[15)] moored in fishery farms. These observations, however, were not able to clarify the distribution and the route of the warm water intrusion, for which the satellite observation is the best suited. In this section, we present the twice-interpolated NOAA/AVHRR images to investigate warm water intrusions into Kagoshima Bay. The virtual resolutions of the images are 1100/4=275 m.

Images a1 to a3 in Plate 4 show a time sequence from 31st March to 1st April 1997. In image a1, a head of an intruding warm water is located off Kanoya, and about 8.5 hours later, it arrives at the southern coast of Sakurajima as shown in image a2. In image a3, the warm water forms a clear anti clockwise vortex in the center of the southern basin. The SST near the western coast of the bay is higher than that near the eastern coast, and another warm water begins to intrude. The warm water also seems to intrude into the northern coast of Sakurajima in the northern basin through Sakurajima channel.

We have collected some intruding events in images b to g in Plate 4. The intrusion route up to off Kanoya shown in image b has almost common character in all intrusions. That is, it is winding around the mouth of the bay and then proceeds along the eastern coast. After passing off Kanoya, the route shown in image c seems to be the most general; the warm water continues to proceed northward and arrives at the southern coast of Sakurajima.

Another pattern is shown in image d, where the warm water detaches from the eastern coast of the bay near off Kanoya and turns anticlockwise toward the western coast. Similar patterns as in image d are sometimes observed. The route of the warm water intrusion in image e contains both patterns shown in images c and d.

Two of the present authors numerically studied[16)] what conditions cause to the difference of the intrusion route. Several boundary conditions at the mouth of the bay were tested; i.e. the boundary velocity, the temperature and the thickness of the warm water and the forcing period of the warm water. However, these conditions do not affect to the intruding route. All simulations exhibit the same route shown in image b. To realize the route shown in image d or in image e, the effects of the sea surface wind and/or the two successive intrusions should be taken into account.

The pattern in image f is obtained only once in which, the anticlockwise vortex is formed in the northern part of the southern basin. The distribution shown in image g, where SST is higher in the western part of the southern basin than in the eastern part, probably shows the final stage of the intrusion phenomenon.

Summary

Although there is an advantage that more than four images are obtained in a day, the IFOV of NOAA/AVHRR is 1.1 km, which is not enough to study coastal currents and the warm water distributions in a bay. For the purpose to improve the ground resolution, a method of linear interpolation of NOAA/AVHRR image data has been proposed. First the availability of the linear interpolation method is tested using Landsat/TM data. Then the interpolated NOAA/AVHRR images have been applied to study the movements of the warm water filaments emanated from the Kuroshio and to investigate the route of the warm water intruding into Kagoshima Bay.

It is found that the warm water begins to intrude into Kagoshima Bay when the Kuroshio filament comes into touch with the bay water. The crest of the Kurosio in the area west of Yakusima Island proceeds eastward, wraps Yakusima Island, and finally disappears, being divided by the cold water extending southeastward in the area southwest of Yakusima Island.

The warm water intrusion route into Kagoshima Bay up to off Kanoya is almost common: winding around the mouth of the bay and proceeding along the eastern coast. After passing off Kanoya, three routes are discovered, i.e. one continues to proceed northward and arrives at the southern coast of Sakurajima, another detaches from the eastern coast of the bay and turns anticlockwise toward the western coast and third contains above two patterns.

The convenient method of the linear interpolation proposed in this article could also be applied to other satellite images, such as Modis, Landsat and Aster. The applications to these satellite images are now in progress.

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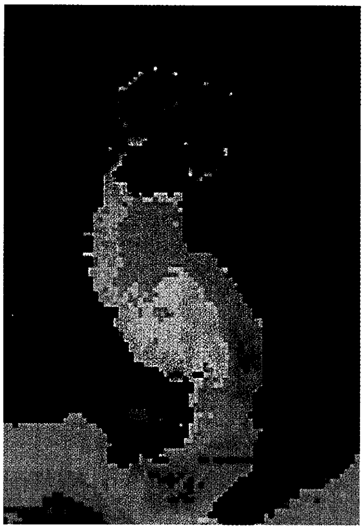
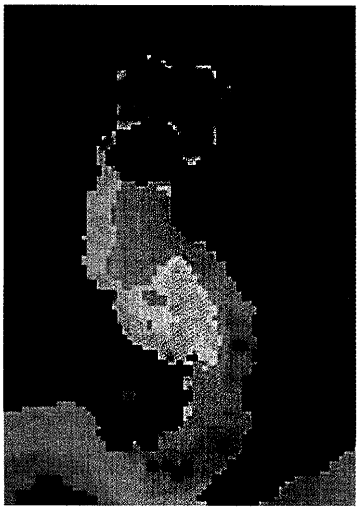
a1 Source (Res. 270)



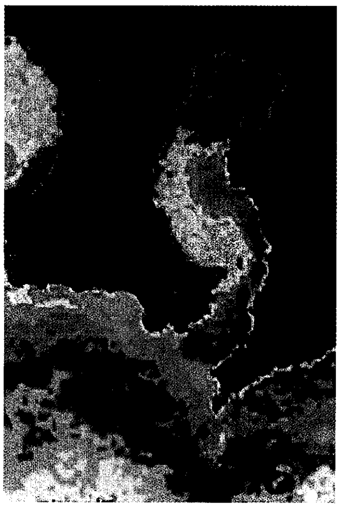
a2 Source (Res. 540)

a3 Source (Res. 1080)

b1 Twice interpolated

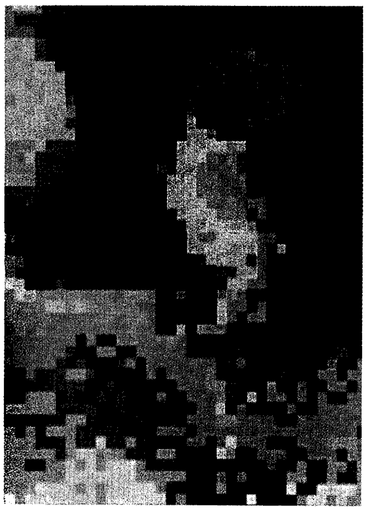


b2 Once interpoleted



c1 Twice interpolated

c2 Once interpolated



c3 Noaa source image

Plate 1 Test images of linear interpolation.

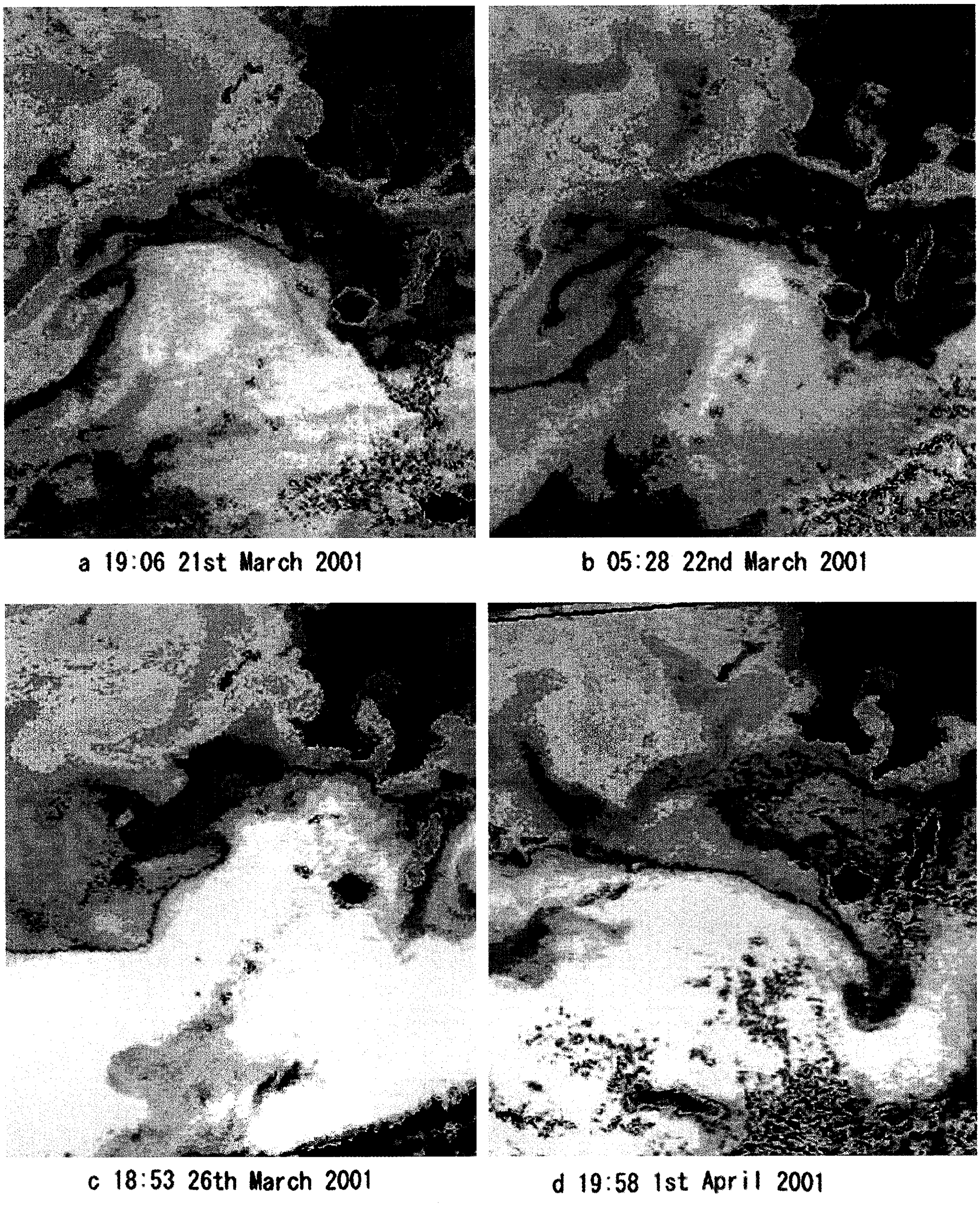


Plate 2 Successive images of warm water motions from 21st March to 1st April 2001.

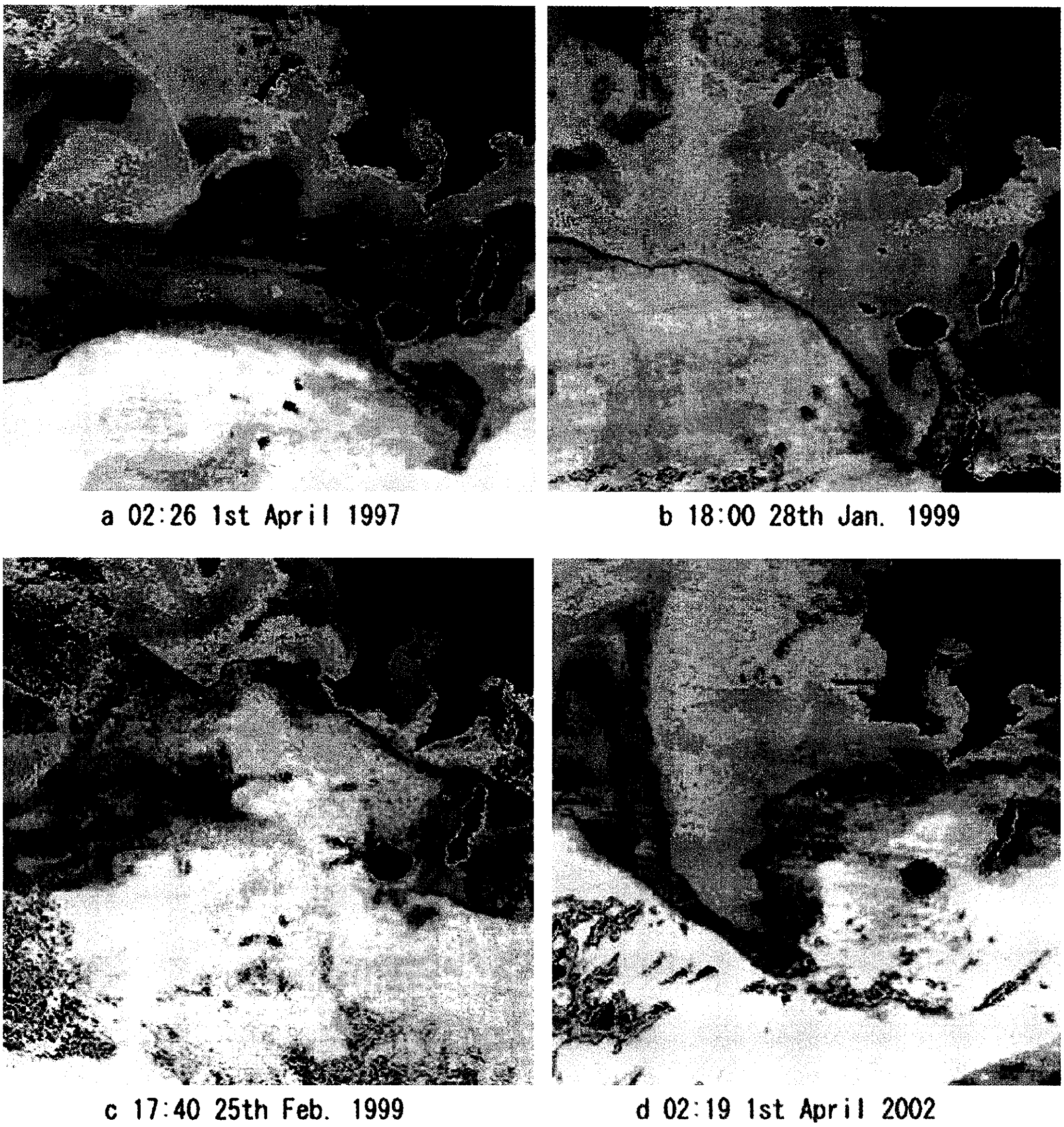


Plate 3 Examples of warm water filaments and intrusions into Kagoshima Bay.

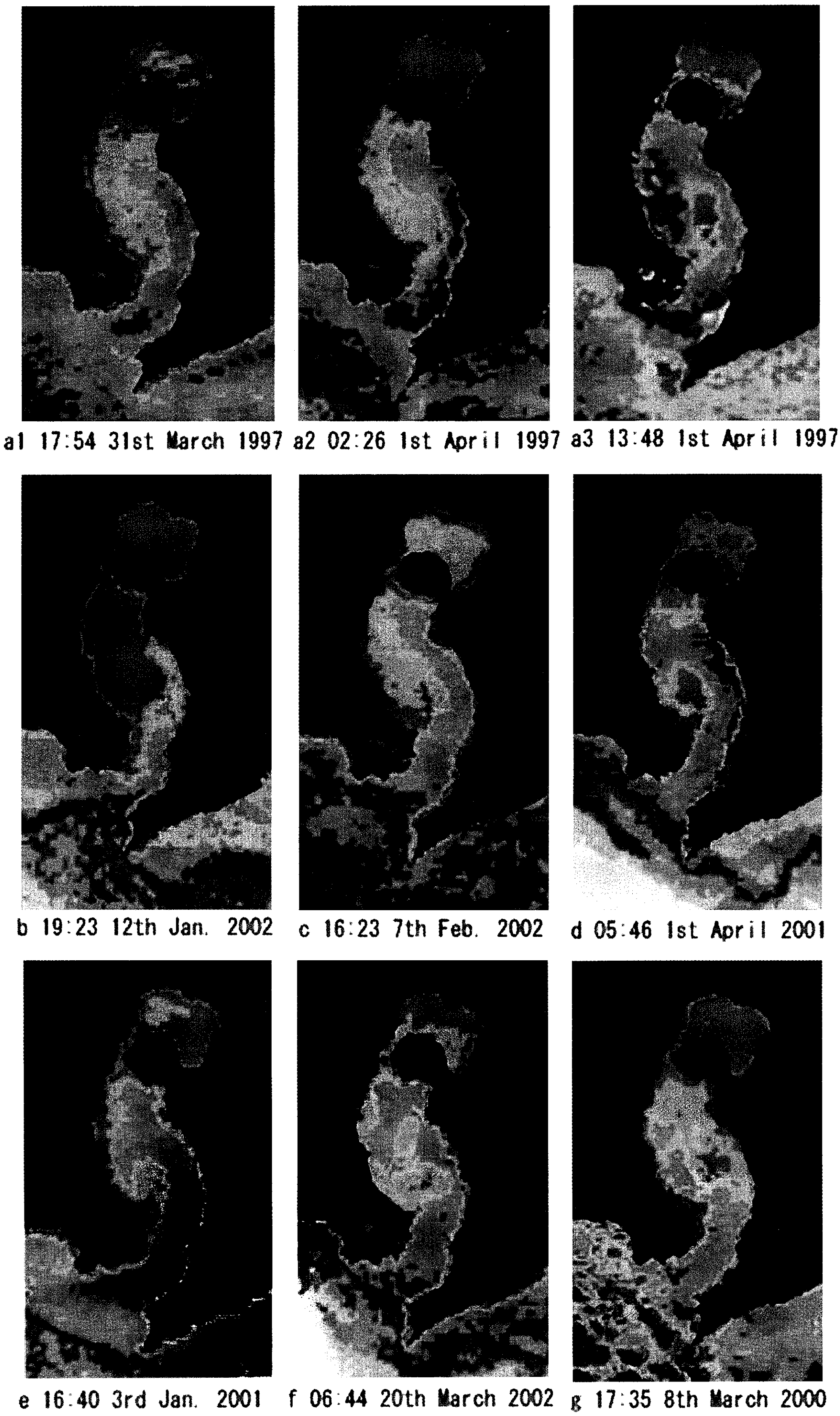


Plate 4 Successive images of warm water intrusion into Kagoshima Bay from 31st March to 1st April 2001 (images a1 to a3) and some intrusion events (images b to g).