A Method for Retrieving Sea Surface Temperature in Local Regions Using NOAA AVHRR:

A Case Study in Japan Sea

Yoichi KAGEYAMA* and Makoto NISHIDA*

Abstract

NOAA AVHRR (Advanced Very High Resolution Radiometer) is a useful sensor for monitoring environmental changes; however, some oceanic processes are too small to be resolved by the ground resolution of NOAA AVHRR (i.e., 1.1 km immediately beneath the satellite) on a horizontal scale. Therefore, this paper proposes a method to retrieve the sea surface temperature (SST) of the sub-pixels derived from the pixels in the NOAA AVHRR image by combining the band-6 data of Landsat TM (Thematic Mapper), which has a higher ground resolution, with that of the NOAA AVHRR. In this method, sub-pixel elements masked by the poorer ground resolution are retrieved using the properties of the NOAA SST chart and band-6 data of Landsat TM. The proposed method comprises three procedures: fuzzy regression analysis, fuzzy level-slice processing, and estimation of sub-pixel elements. The case study showed that the proposed method could be applied to consider the fuzziness in the remotely sensed data, the use of the information of neighboring pixels, and retrieving the SST of sub-pixels in NOAA AVHRR images.

Key words : sea surface temperature (SST), NOAA, Landsat, fuzzy regression analysis, sub-pixel, local regions

1. Introduction

Many small-scale environmental events develop into mesoscale ones; and some of these, in turn, develop into large-scale ones; therefore, the analysis of small-scale events is also necessary to understand global events. Remote sensing serves as a powerful technique for monitoring environmental changes. Presently, various remotely sensed data are used

according to the required purpose. With land use/land cover changes in local regions, high spatial but low temporal resolution satellite data -such as that obtained by Landsat TM- have been widely used. The TM ground samples have two resolutions: 30 m for bands 1 through 5 and 7 and 120 m for band-6 (NASDA, 1982). However, the regression period of the Landsat satellite is 16 days, and cloud cover conditions reduce the number of

* Department of Computer Science and Engineering, Faculty of Engineering and Resource Science, Akita University

useful images, impeding continuous monitoring. Two or more satellite output signals with poorer resolution, such as those obtained by NOAA AVHRR, are available daily. The ground resolution of the NOAA AVHRR is 1.1 km; this indicates that the digital number (DN) of each pixel expresses the average land cover conditions over 1.1 km (Kustas *et al.*, 2003).

SST distribution plays an important role in understanding the changes in the information on the ocean, and the wide-area SST is measured using satellite sensors. The NOAA AVHRR data have been conveniently used for SST observations in the ocean (McMillan, 1975; Bernstein, 1982; Tanba *et al.*, 1988; Sakaida and Kawamura, 1992; Shaw and Vennell, 2000). While the NOAA AVHRR provides wide-area images frequently, its resolution impedes the detection of smaller variabilities in the coastal processes even in the ocean. Moreover, the DNs of the NOAA AVHRR data contain some effects due to some ambient disturbances and noises, e.g., path radiance, sun glitter, atmospheric scattering and absorption, water surface waves, system noise, and others (Inomata *et al.*, 1992). It is necessary to consider these effects in data processing.

The more precise the knowledge of sea temperature distribution, the more useful is the data (Anding and Kauth, 1970). Therefore, this paper proposes a method for retrieving accurate SST information on the sub-pixel level using the NOAA AVHRR. In other words, by using the properties of the NOAA SST and band-6 data of Landsat TM, the sub-pixel elements expressing the information spoiled by the poor resolution of the NOAA AVHRR are effectively retrieved for monitoring local regions.

II. Study site and materials

1) Study site

The resolution of the NOAA SST data is satisfactory when monitoring general oceanic phenomena; however, higher resolution is required for investigating coastal processes because the scale of change in the coastal phenomena is smaller. This study aims at retrieving the smaller variabilities in SST in the coastal regions from the satellite for comparison with the surface truth data. Since the SST truth data is available from the ocean data buoys of JMA (see 2.5) close to Awashima Isl. in the Japan Sea, we selected the coastal regions around Awashima Isl. in the Japan Sea as the study site.

2) NOAA SST data

Japan Fisheries Information Service Center (JAFIC) has received NOAA AVHRR data and has produced SST charts. We used the SST output signals for August 1999, in this study.

Remotely sensed data are composed of pixels with a DN. Two or more NOAA AVHRR images were received daily, and the largest DN of the same position (pixel) in each pixel was chosen. Then, NOAA SST charts were created using these values. If the value of the DN is 0 or 255, the pixel represents land area or clouds. A difference of 0.2°C can be expressed with the NOAA SST charts. One of the NOAA SST scenes, recorded on August 4, 1999, is shown in Fig. 1; area A is the Awashima Isl.

3) Band-6 data of Landsat TM

The SST on a sub-pixel level was estimated from band-6 of 7 bands of Landsat TM observed on August 1, 1999 (Path-Row: 108-33). The bandwidth and ground resolution are 10.4 to 12.5 μm and 120 m, respectively (see

Fig. 1 NOAA SST chart produced by the JAFIC, recorded on August 4, 1999, Japan Sea.

Fig. 2 Band-6 scene of Landsat TM recorded on August 1, 1999 (Path-Row: 108-33).

NASDA (1982) for the other 6 bands). Fig. 2 shows this band-6 scene.

4) Creation of data set for analysis

Although both NOAA AVHRR and Landsat TM have different ground resolutions, they would experience the similar systematic and ambient efforts, resulting in similar noises. In order to examine the relationship between the NOAA SST charts and band-6 data of Landsat TM, 10 pixels (points) in a NOAA SST chart were selected by the operator. Subsequently, the band-6 information of Landsat TM for the same areas as these pixels was sampled manually; 380 pixels were acquired in each NOAA SST pixel to compensate for the difference in the position due to the difference in resolution. The details of the NOAA SST and band-6 of Landsat TM recorded on August 1, 1999, are summarized in Table 1. Temperature information (Landsat SST outputs) was computed from the DN's of band-6 of Landsat TM using a conversion type (NASDA, 1982), and this information

was subsequently used.

5) Buoy SST data

The Japan Meteorological Agency (JMA) has operated ocean data buoys at a station (No. 21002; 37-55N, 134-33E) in the Japan Sea. One of the sensors was used for measuring seawater temperature at a depth of 1 m every three hours. The largest value of the daily measurements was used as the buoy SST, and the measurements for August 1999 were used for comparison with the estimates.

III. Estimation method for information on the sub-pixel level

The method applied for estimating the SST on the sub-pixel level from the original SST remote sensing information consists of (i) fuzzy regression analysis for the NOAA SST and Landsat SST outputs, (ii) fuzzy level-slice processing, and (iii) estimation of sub-pixel elements using information on neighboring pixels. The proposed method is described in the subsequent sections.

Table 1 The details of the NOAA SST chart and the band-6 data of Landsat TM taken on August 1, 1999.

No.	NOAA SST	TM Band 6 data		
		Average	Maximum	Minimum
1	26.2	128.9	131	128
2	26.6	130.2	131	129
3	27.0	131.3	132	130
4	27.2	131.6	132	131
5	27.6	131.6	133	131
6	28.0	133.0	135	132
7	28.6	134.1	135	133
8	29.0	135.0	136	134
9	29.4	136.4	137	135
10	29.8	137.0	138	137

1) Fuzzy regression analysis

Fuzzy set theory provides useful concepts and tools to address uncertainties (Zadeh, 1965). The fuzzy regression model based on the fuzzy set theory assumes that the difference between observation data and the model prediction indicates system fuzziness, showing the relationship between input and output (Tanaka *et al.*, 1982).

The difference in the ground resolutions of the Landsat SST outputs and the NOAA SST charts will impede the position specification of pixels. While the DNs expressed with a resolution of 120 m are different from those with a resolution of 1.1 km at the same positions, it is necessary to associate the elements acquired from the abovementioned two types of data for estimating information in local regions. Given these restrictions, the DNs include fuzziness (Nishida and Otsuka, 1995). We assume that the DNs of the pixels are fuzzy numbers.

We computed Equation (2) in order to perform the fuzzy regression analysis (e.g., Ishibuchi, 1992), using the NOAA SST information and the Landsat SST outputs.

$$Y(X_p) = A_0 + A_1X_{p1} + \cdots + A_nX_{pn} \quad (1)$$

$$= (a(X_p), e(X_p))_L, \quad (2)$$

where

$$a(X_p) = a_0 + a_1X_{p1} + \cdots + a_nX_{pn}, \quad (3)$$

$$e(X_p) = e_0 + e_1|X_{p1}| + \cdots + e_n|X_{pn}|. \quad (4)$$

A_i is a fuzzy coefficient, $Y(X_p)$ is an estimate (fuzzy number), $a(X_p)$ is the mean of $Y(X_p)$, and $e(X_p)$ is the width of $Y(X_p)$. Equation (2) is a fuzzy regression model with the center and width of the fuzzy number as parameters. The fuzzy regression model in this study is the one-input and one-output type such that four variables (a_0 , e_0 , a_1 , e_1) are obtained by the following equations:

$$Y(X_p) = A_0 + A_1X_p \quad (5)$$

$$= (a_0, e_0)_L + (a_1, e_1)_LX_p, \quad (6)$$

where X_p is the NOAA SST; A_1 , the triangular fuzzy number; a_1 , the mean of the fuzzy number; e_1 , the width of the fuzzy number; and $Y(X_p)$, the estimated fuzzy output interval. The mean value of the Landsat SST outputs obtained from 380 pixels and the triangular fuzzy number were used for analysis. The triangular fuzzy number was produced

by a vertex (a_i) and the width (e_i), which indicates the difference between the maximum and minimum values in 380 pixels.

In fuzzy regression analyses, linear programming problems referred to as Min. and Max. problems can be formulated on the given interval data (Ishibuchi, 1992). Here, the Min. problem is a process that requires a linear regression model with a width minimum that includes all interval data. On the other hand, the Max. problem is a process that requires a linear regression model with a width maximum that includes all interval data.

2) Fuzzy level-slice processing

The fuzzy output interval obtained by the fuzzy regression model shows that the information of the Landsat SST outputs corresponds to the forecast range obtained by the estimated NOAA SST. In order to estimate the accurate SST, fuzzy level-slice processing that employs simplified fuzzy reasoning (Mizumoto, 1992) was carried out. We assume that the Landsat SST outputs show the possibility of correspondence to the specific level of the SST set in the optional range. Further, we assume that the NOAA SST information lies in the range between the maximum and minimum values of 380 pixels in the Landsat SST outputs. Therefore, the difference (range) of the Landsat SST outputs was used as the width of the NOAA SST.

The production rule for estimating the SST is as follows:

$$\left. \begin{array}{l} \text{Rule 1: } Y_1 \rightarrow Z_1 \\ \dots\dots\dots \\ \text{Rule } n: Y_n \rightarrow Z_n \\ \hline \text{Input: } S \\ \text{Output: } Z_0 \end{array} \right\}, \quad (7)$$

where $Y_i (i=1, \dots, n)$ is an estimated fuzzy

(a) A fuzzy regression model.

(b) A fuzzy set.

Fig. 3 An example of a fuzzy regression model and a fuzzy set.

set of the DN value of the SST in proportion to the slice level and $Z_i (i=1, \dots, n)$ is the SST in each rule. Output Z_0 is given by

$$Z_0 = \frac{\sum_{i=1}^n h_i Z_i}{\sum_{i=1}^n h_i} \quad (8)$$

When input S is given, h_i is the compatibility coefficient for obtaining Z_i . The rule number corresponds to the slice number. The level-slice processing was carried out at intervals of 0.2°C . Fig. 3 provides an example of a fuzzy regression model and a fuzzy set.

Fig. 4 Relationship among the sub-pixel elements and the neighboring pixels, and the weight coefficients used in the study.

3) Sub-pixel element estimation using information on neighboring pixels

Information on the individual pixels in remotely sensed data is not independent, but is closely related to the features of the neighboring pixels (Kageyama and Nishida, 2001). Therefore, it is possible to obtain both local and accurate information by dividing a pixel into sub-pixel elements. We divided each NOAA pixel into 9 sub-pixel elements based on the results of fuzzy level-slice processing and the values and locations of the 8 neighboring pixels.

Fig. 4 (a) shows the relationship among the sub-pixel elements (i.e., elements *a* to *i*) and the neighboring pixels (i.e., pixels *A* to *I*). In the example, sub-pixel element *a* is related to 3 neighboring pixels: *A*, *B*, and *D*. Based on the results obtained from the test study, the weight coefficients for each sub-pixel element are shown in Fig. 4 (b). The central pixel element *e* has the largest value. As shown in Fig. 5, the estimation of suitable information is never performed, without using the central pixel. Therefore, the process using the central pixel was carried out. The values of oblique

elements are expected to be smaller than those of horizontal and vertical elements. For instance, the DNs of pixel elements *a* and *b* are computed as follows:

$$a = \frac{1 \times DN_a + 2 \times DN_b + 2 \times DN_d + 4 \times DN_e}{1 + 2 + 2 + 4} \quad (9)$$

$$b = \frac{2 \times DN_b + 4 \times DN_e}{2 + 4}, \quad (10)$$

where DN_a , DN_b , DN_d , and DN_e are the DNs of the neighboring pixels *A*, *B*, *D*, and *E*, respectively (see Fig. 4).

IV. Results and discussion

1) Fuzzy regression analysis

For the NOAA SST data and the Landsat SST outputs obtained on August 1, 1999, the results of the fuzzy regression analysis for the Min. and the Max. problems were as follows:

Min. problem:

$$y = (0.970 \pm 0.004)x + (1.020 \pm 0.817) \quad (11)$$

Max. problem:

$$y = (1.114 \pm 0.000)x + (-3.128 \pm 0.189) \quad (12)$$

There were only 10 cloud-free days for ob-

Fig. 5 An example for sub-pixel elements estimation using the central pixel or not.

Table 2 Accuracy of estimates derived from the NOAA SST chart by the fuzzy regression models.

Date	Buoy	NOAA SST	Min. problem	Max. problem
August 4	24.7	25.4	24.9	25.4
August 5	25.0	25.6	25.1	25.7
August 6	25.0	25.6	25.2	25.7
August 8	25.6	27.4	27.0	27.3
August 10	26.8	27.6	27.2	27.4
August 11	27.2	28.6	28.2	28.4
August 12	28.4	28.6	28.2	28.4
August 18	26.9	27.2	26.9	27.2
August 19	26.5	28.0	27.6	27.8
August 21	26.3	27.2	26.9	27.2
average	26.2	27.1	26.7	27.0
difference		0.9	0.5	0.8

taining the NOAA SST information at the buoy observation point in August 1999; hence, the models for the Min. problem and the Max. problem were applied to the 10 NOAA SST charts. The estimated results for the SST are shown in Table 2. The NOAA SST is 0.9 °C higher than the buoy SST on the average. While the results obtained with the Max. problem (0.8 °C) are comparable to the NOAA SST, the Min. problem retrieves the SST better as

compared with the buoy SST. On an average, the Min. problem is able to estimate the SST with an error range of ± 0.5 °C. The finding in this case study indicates that the estimates obtained with the Min. problem were superior to those obtained with the Max. problem. Further, this study suggests that the fuzzy regression model for the Min. problem obtained from the data for August 1 can be applied to the other data acquired in August. Therefore, the

Fig. 6 Band-6 image of Landsat TM of area A.

Fig. 7 3×3 magnified NOAA SST output signals of area A.

following examination is performed by using the Min. problem results.

2) Estimation results for sub-pixel elements of the NOAA SST chart

Figs. 6 and 7 show the band-6 image of Landsat TM and the 3×3 magnified NOAA SST output signals of area A, recorded on August 1, 1999, respectively. In Fig. 6, the white-colored region represents the Awashima Isl. in Fig. 7, the linear transform of the SST information from 26.0°C to 31.0°C was carried out for the values from 0 to 255. The use of the band-6 image of Landsat TM facilitates the investigation of the SST conditions around the Awashima Isl. For the upper part of the island, the values of the DN are fairly low, which indicates that the SST is low for the upper part of the island as compared with the other parts. The resulting magnified image is in a mosaic state, which impedes the understanding of the SST around the island (see Fig. 7).

Fig. 8 shows the estimated result in area

Fig. 8 Estimated result in area A by the proposed method.

A by the proposed method (after conversion of DNs as well as the SST information around the island, as shown in Fig. 7). The proposed method retrieves 9 sub-pixel elements in each original pixel and the DNs of

the sub-pixel reveal the accurate SST in local regions. The SST conditions obtained by the proposed method agree with those obtained by the band-6 image of Landsat TM (see Fig. 6); the SST conditions in the upper part of the island are low. The estimated result indicates that the proposed method is capable of retrieving the local SST with greater accuracy as compared with the magnified NOAA SST chart.

Nearest neighbor interpolation and cubic convolution interpolation are used widely for resampling (Takagi and Shimoda, 1991). In order to examine the usefulness of the proposed method for retrieving SST information on a sub-pixel level, the above methods were applied to the NOAA SST of area A to obtain 3×3 magnified information. As evident from Figs. 9 and 10 (after conversion of DN_s as well as the SST information around the island as shown in Fig. 7), the estimated results are not necessarily consistent with the conditions expressed in the band-6 image of Landsat TM (Fig. 6). The results in figure 9 are in a near mosaic state, such that the distinction of the SST conditions in the local regions is impeded. In addition, the SST around Awashima Isl. obtained by the cubic convolution interpolation (Fig. 10) is extremely high, unlike the Landsat TM image (Fig. 6). The results differ completely from the actual conditions. Consequently, it is found that the conventional methods, such as the nearest neighbor interpolation and cubic convolution interpolation, are unable to estimate the SST conditions in local regions with sufficient accuracy. Therefore, these results suggest that the proposed approach, which employs sub-pixels, is suitable for retrieving SST information.

Fig. 9 Estimated result in area A by the nearest neighbor interpolation.

Fig. 10 Estimated result in area A by the cubic convolution interpolation.

3) Application of the proposed method to other image

NOAA AVHRR images have been obtained at Akita University since 2001. The proposed method was applied to an SST image con-

Fig. 11 NOAA SST chart obtained on August 19, 2001, at Akita University.

Fig. 12 Estimated result in area A by the proposed method.

verted from the NOAA AVHRR observations recorded on August 19, 2001, at Akita University. Fig. 11 shows the NOAA SST chart used for the examination. Figs. 12 and 13 show the results in area A by the proposed method and the 3×3 magnification procedure, respectively. The result shown in Fig. 13 is in a mosaic state, such that the SST information around the island is fairly obscure. With regard to the estimates obtained by the proposed method, the SST conditions obtained from the NOAA AVHRR at Akita University as well as the result shown in Fig. 8 are satisfactory. The use of the properties of the NOAA SST and the Landsat SST outputs facilitates the estimation of the SST in local regions. Therefore, it is evident that the proposed approach using the sub-pixel elements allows reliable retrieval of the SST information in local regions from the NOAA AVHRR observations.

Fig. 13 3×3 magnified NOAA SST output signals of area A.

V. Conclusions

This paper has proposed a method to retrieve information in local regions from the NOAA SST chart by combining it with the band-6 data of Landsat TM. The following

conclusions were obtained:

1) While, on an average, the original NOAA SST information is 0.9°C higher than the buoy SST, the proposed method with the Min. problem is able to estimate the SST with $\pm 0.5^{\circ}\text{C}$ of error.

2) The fuzzy regression model using the properties of the NOAA SST chart and the band-6 data of Landsat TM in the proposed method is applicable to other SST images acquired in August 1999.

3) The proposed method enables the use of the features of the neighboring pixels. Subsequently, the proposed method using sub-pixel elements estimates the SST information in local regions with good accuracy.

Uncertainties related to the accuracy of the results are yet to be clarified; their quantification is a subject for future study.

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NOAA AVHRR を用いた局所領域における海面温度推定法

— 日本海における解析例 —

景 山 陽 一* 西 田 眞*

広域にわたって生じる環境問題の多くは、局所的な事象から発生していることが知られている。従って、地球規模の環境変化を理解するためには、局所的な解析も行う必要がある。

一方、目的や解析対象に応じて多種多様なリモートセンシングデータが用いられている。例えば、NOAA AVHRR データは1日に数シーン取得されているものの、分解能は1.1 km であるため、分解能に埋もれた局所領域における情報の推定は困難である。従って、高分解能センサで取得される詳細な情報を低分解能センサで取得されたデータを介して広い範囲に外挿し、高精度な情報を広範囲・多頻度で推定することのできる手法の開発が望まれている。

そこで本論文では、NOAA AVHRR を用いた局所領域における海面温度推定法を提案する。すなわち、NOAA AVHRR データとランドサット TM データ（第6バンドデータ）との関連情報を求め、NOAA AVHRR データから局所領域の海面温度を推定する手法である。提案手法はファジィ回帰分析、ファジィレベルスライス処理、並びにサブピクセル要素の推定処理から構成され、リモートセンシングデータの有するあいまいさを考慮するとともに、近傍画素との関連情報に着目し処理を行っている。日本海を対象とした検討の結果、提案手法はNOAA AVHRR の分解能に埋もれた海面温度情報を精度良く推定可能であることが明らかとなった。

キーワード：海面温度，NOAA，ランドサット，ファジィ回帰分析，サブピクセル，局所領域

* 秋田大学工学資源学部情報工学科