Satellite Thermal Monitoring of Storm Flood Spreading around Kuroshio Flow

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Abstract

This work concerns a satellite thermal monitoring of storm flood spreading around the Kuroshio flow. Some specific variations of the thermal pattern off the Shirahama Oceanographic Observatory are introduced in order to demonstrate what pattern can be taken as an effect of the storm floods to the thermal patterns between the coast and the Kuroshio flow. Referring to the observed data obtained at the offshore tower station, the satellite thermal pattern can locally be well adjusted. For the author's convenience, the APT picture (automatic picture transform) is utilized in this work.

1. Introduction

This work is on the satellite thermal monitoring of storm flood spreading on the sea surface between the coast and the Kuroshio flow. The author wishes here to delineate the specific thermal patterns reduced from the NOAA APT (automatic picture transform) pictures in order to demonstrate what can be found from the satellite thermal patterns. The aim of this work is partly to clarify what data is already known referring to the observed results by the survey ships. The main purmose of this work is to demonstrate what has not been noticed upto this time. Any shearing flow between the coast and Kuroshio as a western boundary current in the ocean has yet to be discussed even in the field of "satellite oceanography". The author has decided to introduce satellite thermal imagery obtained by satellite thermal monitoring because the author found several thermal patterns suggesting the shearing flow. In this report, the author will report his findings of the serial satellite thermal patterns employing only a limited number of shots of the patterns.

As for the methods of satellite oceanography, Stewart (1984)[1] has given an introduction to the various applications of the satellite information helping us to realize what is available at present for our survey and research. Nevertheless, it is essential to adjust any satellite thermal pattern of the sea surface referring to the data in situ. For this purpose, an offshore tower station is the best to obtain the results of observations of the pertinent factors. In the Shirahama Oceanographic Observatory, an offshore tower station was established in 1961 to perform the observations and to record the pertinent data in and on the sea. Hence, these observation records can now be utilized to adjust the satellite thermal patterns around the station.

Recently, the Observatory has introduced a NOAA–satellite thermal imgery system which has as a function obtaining real time information from successive NOAA APT pictures. The APT picture informs us of the sea surface thermal pattern presented as a mosaic with a set of four–kilometer square pixels after processing the signal from the satellites. The other finer information can be obtained by utilizing AVHRR (advanced very high resolution radiometer). The AVHRR imagery is formed by a set of one–kilometer square pixels of the signal from the NOAA satellites. As of this time, much research has been undertaken referring to AVHRR imagery in order to detect the sea surface thermal patterns. Subsequently, the author was able to uncover further findings in the APT pictures.

At his situation, the author believes that the APT picture can be introduced as a tool for natural hazard research, especially in the coastal zones. The APT picture informs us quickly of thermal patterns, through a simple system for receiving signal directly from the NOAA satellites. Hence, serial images of the satellite thermal patterns can be easily obtained as real time information, making it possible to find specific thermal patterns of which we never have been aware before even by AVHRR imagery.

A study on storm run–off across the Kuroshio in the sea surface was presented by Nakamura (1990)[2] in terms of thermohaline densimetry and employing APT picture along with the reference data of the Japan Meteorological Agency (JMA). One of the traditional works is a synoptic study referring to the data of the survey ships (for example, Nakamura, 1988)[3]. In this case, the reference was simply to the synoptic charts issued by the Hydrographic Office, the Maritime Safety Agency, Japan (HO–MSA). Additional supporting data can be used referring to the observed data at the Shirahama Oceanographic Tower Station (cf. Hayami et al., 1963)[4].

In the present work, several patterns of flood spreading on the sea surface are introduced first. Specific examples of floods in April, in October and in December are then illustrated in order to realize the thermal variations involved in the patterns. These specific examples are discussed in relation to the storms and precipitation observed previously in the neighbouring areas. The passage of a typhoon in also discussed. In addition, a bold assumption is introduced to simplify modelling which may help in the understanding of the author's dynamical hypothesis.

2. A Flood in April

Specific cases are to be found in the interaction between the Kxroshio flow and the coastal waters in the western North Pacific. The author here introduces one such specific example, a case which occurred in April 1991.

Before introducing the APT pictures involved, the related data and information are noted as seen below. Referring to the monthly meteorological report in Wakayama, it is seen that a local rain fall was recorded by the stations on April 18th, 1991 in the area concerned around the Shirahama Oceanographic Tower Station, an offshore fixed station. The weather maps issued by the Japan Meteorological Agency shows that this rainfall could have been caused by passage of a barometric trough at the south of the Japanse Islands where the area of interest was included. This rainfall caused a delayed river flood spreading in the coastal zone. The author then traced this, especially in the sea area between the coast and the Kuroshio flow.

In **Fig. 1**, the APT thermal pattern at 08h18m on 22nd April 1991 is introduced. In order to demonstrate what is specific, pseudo–colouring technique is utilized. This technique has been widely utilized in the field of "satellite monitoring". On the left, a photo is shown and its illustrative line drawing is on the right. In the drawing, two isotherms are intensified by two lines, S–S for 17℃ and T for 16℃. These isotherms clearly indicate the locations of the maximum of the thermal gradient on the sea surface in the area. The arrows show possible current direction as can be expected referring to the APT picture. The notations, K, E and X indicate the location of the Kii Peninsula, the Enshu–nada coast and the Izu Peninsula, respectively. The isotherm of S–S reflects the undulation of the existing Kuroshio flow, and the isotherm of T shows a sharp kink which might be taken as the start of a filament formation rather than a thermal tongue. Here, the term 'kink' means that an isotherm has a hair–pin curve with a radius of about ten kilometers at the tip. This kink shows an existing strong shear between the Kuroshio main flow and the coast. The kink shown in **Fig. 1** would distort from time to time, and finally formed a warm ring with a cold core as shown in **Fig. 2** after a warm filament elongating off the Kii Peninsula to the Enshu–nada coast.

As for **Fig. 2**, the APT picture was obtained in a similar way to **Fig. 1**. The APT thermal pattern at 19h12m on 30th April 1991 is shown in **Fig. 2**. The time interval between the two photographs in **Figs. 1** and **2** is eight days. In this drawing, the lines S–S and T are 17℃ and 16℃, respectively. The isotherms are the apparent ones, having been adjusted referring to the observed results at the tower station. The sea water temperature at the offshore station was

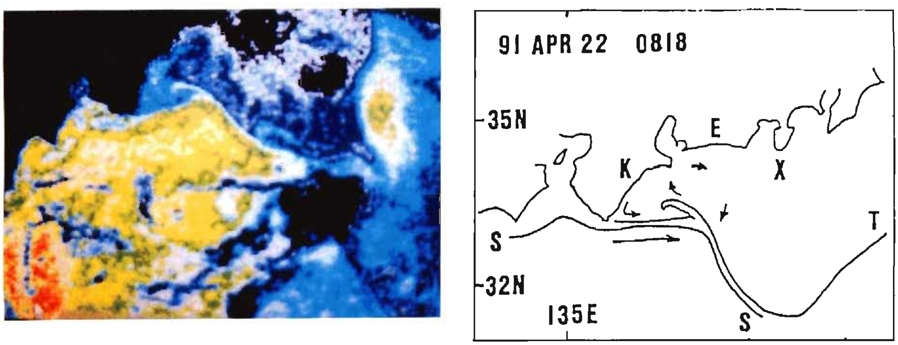


Fig. 1 Thermal pattern on the sea surface at 08h18m on 22nd April 1991.

1) The APT picture of the NOAA–10 colored conveniently and scaled in order to demonstrate the apparent isotherms on the sea surface.
2) The marks of "K", "E" and "X" denote the location of Kii Peninsula, Enshunada coast and Izu Peninsula, respectively.
3) The isotherms of 'S–S' and 'T' are for 17℃ and 16℃, respectively. The kink of the isotherm of 'T' off Kii Peninsula shows an effect of the storm floods in the coastal zone. The arrows demonstrate relative flow pattern of a shear flow around Kuroshio.

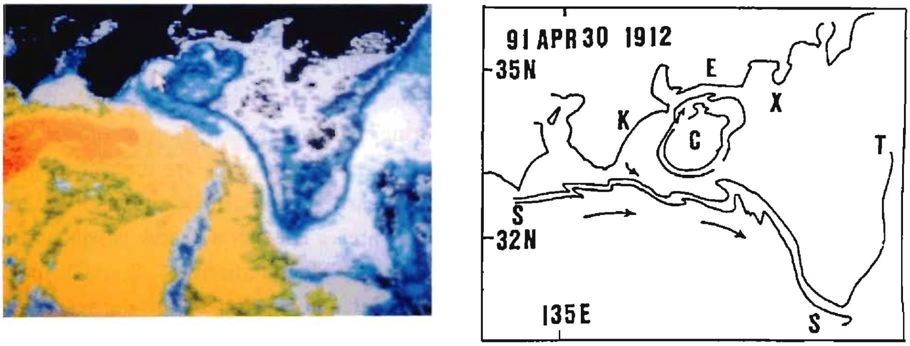


Fig. 2 Thermal pattern on the sea surface at 19h12m on 30th April 1991.

1) The APT picture of the NOAA-10 by the same color scaling as in Fig. 1.
2) The mark of "C" shows the cold water mass with a warm filament or a warm ring found on the sea surface.
3) The isotherms of 'S–S' and 'T' are for 17 and 16℃, respectively. The temperature of the cold water mass is apparently 14℃ on the sea surface around the mark 'C' in the picture.

19.4℃ at the time for the APT picture in **Fig. 2** although the apparent sea surface temperature around the offshore tower station was about 15℃ as can be seen in **Fig. 2**. Hence, there should be an adjustment of 4.4 for **Fig. 2** in order to see a more realistic thermal pattern. In **Fig. 2**, the two isutherms of 16℃ and 17℃ are intensified to show the Kuroshio flow pattern variation in a short time. This pattern is wavy even in the Kuroshio main flow after assuming that the Kuroshio main flow is a geostrophic one. In this case, the scale of the wavy pattern is less than one hundred kilometers in length. For simplicity, no details of the wavy pattern are discussed. In addition, no consideration is payed to the so-called 'meanderina' of the Kuroshio main flow.

At this time, the author decided not to include other factors related to the problem at hand. Although it is natural to consider the meterological conditions and the coastal or the Kuroshio variations in detail, the author here purposely introduced a simple specific example without consideration of the related factors which are to be taken as having insignificant effect or to be outside the author's scope in this work. This does not mean that the related factors can be excluded aribitrarily. The author, however, has decided to simply concentrate on specific interesting thermal patterns even while aware of the actual phenomena in the area.

Nevertheless, a variation of the Kuroshio main flow can be seen after comparing the two photographs in **Figs. 1** and **2** and comparing their isothermal patterns, especially of S–S and T. There is a successive distortion of the thermal pattern for S–S and T in the time period between 22nd April 1991 (**Fig. 1**) and 30th April 1991 (**Fig. 2**).

It can be seen that a low temperature C in **Fig. 2** (14℃) is encircled by the two isotherms forming a warm ring. Hence, there is a cold core gyre with a clockwise rotating flow around the mark C in **Fig. 2**. Judging from this, the gyre was likely established more than ten days after the rainfall. Nevertheless, it is hard to know the thickness of the gyre by referring to the satellite thermal picture. The process of the grye's establishment can be seen by looking at the serial pictures during the pertinent time period, rather than the two simple pictures of **Figs. 1** and **2** introduced in this section.

In this section, the author has introduced one specific case in order to demonstrate the flood spreading on the sea surface after a rainfall and to show the impact of this spreading to form a kink in an isotherm forming a warm ring with a cold core as a gyre as a result. The calm days after the rainfall allowed the tracing of the serial satellite thermal patterns to find the distorting process of an isotherm, and thus demonstrate effect of the flood spreading and the formation of a warm ring with a cold core as a gyre.

3. Flood Caused by Typhoon in October

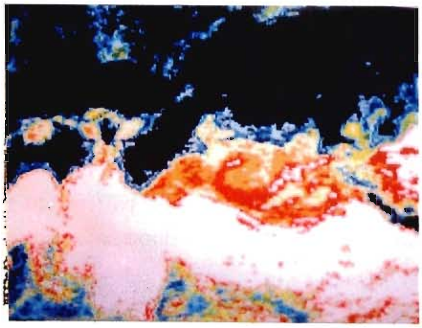
Typhoons have always brought intense rainfalls to the Japanese Islands with occasional rainfall causing storm floods in the area hit by the typhoon.

As previously noted (1988)[3], several specific typhoons had enough force to shift the Kuroshio main flow northward. This fact suggests that the shift of the Kuroshio main flow can be a possible factor in raising the sea level on the Pacific coast. The significance of this effect in the area must increase where the typhoon's thermal effect is significant. Adding to that, the flood can cause a rise in the sea level along the coast. Little is known about the factors which control the sea level along the coast during the passage of a typhoon. As one of the factors, storm flood spreading should be studied. In this study, a simple case is given referring to the APT picture obtained after the passage of the typhoon 9121 (the 21st typhoon formed in 1991).

Before introducing the APT picture, the meterological conditions are introduced have first. Referring to the monthly meteorological report for Wakayama (issued by the Japan Meteorological Agency), a significant rainfall for several deys at the passage of typhoon 9121 by 14th October 1991 can be seen. The weather chart shows that this rainfall was mainly caused directly by this typhoon. The typhoon caused a specific storm flood spreading on the sea surface of the northweszern Pacific. This storm flood spreading can be seen in the APT picture of the area involved just neighbouring the Shirahama Oceanographic Tower Station with the storm flood spreading appearing in a distorted form in the APT picture after the influence of the shearing induced by the Kuroshio main flow.

In **Fig. 3**, the apparent isotherms of 24 and 23℃ (S–S and T) show the north edge of the Kuroshio flow, and a warm water clockwise intrusion is formed from the mark X in the illustrative drawing. Later, this could be seen to be a final stage of the interaction of the waters between the flood spreading and the Kuroshio flow.

At a glance, the illustration in **Fig. 3** must look complicated though the essential process was rather simple. The effect of the Earth's rotation can be taken as a minor factor when considering the storm flood spreading even though the Kuroshio flow should be taken as a geostrophic one. The author now intends to introduce a specific pattern of the storm flood spreading after the passage of a typhoon referring to the APT picture and the reference data of the related functions.



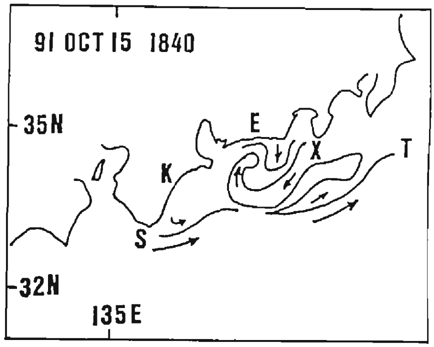


Fig. 3 Thermal pattern on the sea surface at 18h40m on 15th October 1991.

1) The APT picture of the NOAA-10 by the same color scaling as in Fig. 1.
2) The river discharge spreads at the south of "E" as well as at the south of "K". This must be caused to from the complicated thermal pattern.
3) The isotherms of 'S-S' and 'T' are for 24 and 23℃, respectively. The arrows show the relative flows.

A spread of the coastal water from the mark E is demonstrated by the apparent isotherm of 22℃ off the coast. There must be other effects of the storm flood spreading. For example, the surface wind or thermal and dynamical effects must be important during the time period of the typhoon's passage in the interested area. However, these effects could not be estimated because of the thick clouds covering the sea surface so that no other data was available except that of the offshore station. The arrows in **Fig. 3** indicate expected currents which were estimated referring to the serial thermal pattern seen in the APT pictures, as seen at the left side of **Fig. 3**.

At 15h00m on 10th October 1991, the apparent sea surface temperature was 24.9℃. Nevertheless, the thermistor sensor at the offshore station recorded a temperature higher than the above value. A local adjustment of the temperature just around the station could be easily made. In this section, the APT picture at 18h40m on 15th October 1991 is shown as in **Fig. 3**. In **Fig. 3**, the storm flood spreading initiated from the area around the mark K resulting in the shearing effect to the south of the mark X between the coast and the Kuroshio main flow (the marks S and T). The other storm flood spreading is found just south of the mark E.

The APT picture shows that the storm flood spreading was effective in controlling the sea surface temperature in the interested area even between the coast and the Kuroshio main flow.

4. Flood after Cold Front Passage in December

One of the specific patterns in the APT pictures is the case of a flood discharge after an atmospheric cold front passage. In this section, the APT picture at 07h07m on 5th December 1991 is introduced in **Fig. 4**.

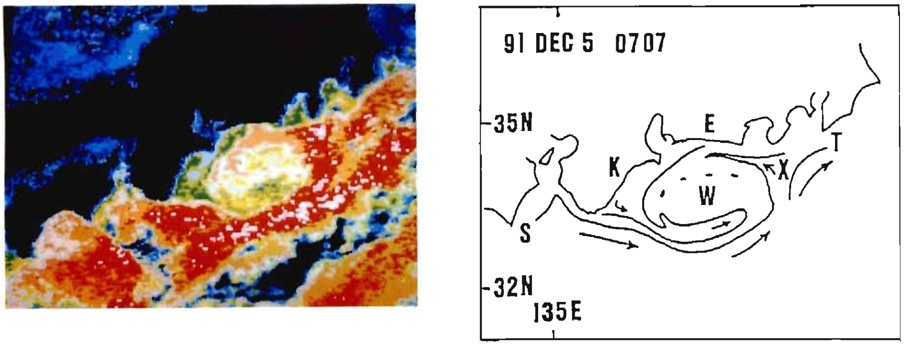


Fig. 4 Thermal pattern on the sea surface at 07h07m on 05th December 1991.

1) The APT picture of the NOAA-10 by the same color scaling as in Fig. 1.
2) The mark of "W" is a warm water mass which is driven by Kuroshio and the storm floods in the coastal zone south of the mark of "K". The picture shows what is the extent of the storm floods in the form of a tongue.
3) The isotherms of 'S' and 'T' are for 23 and 24℃, respectively. The isotherm of 22℃ demonstrates the motion of the storm flood in the western half of the warm water mass. The kink of the isotherm is found at the south of Izu Peninsula ("X") intruding into the Enshunada coast. The other minor kink is at the west part of the warm water mass.

The related meterological condition is noted in advance to discuss on the APT picture in **Fig. 4**. On 28th November and 3rd December 1991, a low pressure with a cold front passed eastward off the south coast of the Japanese Islands. This cold front caused a heavy rainfall on the south part of the Japanese Islands according to the monthly meteorological report in Wakayama (issued by the Japan Meteorological Agency).

In **Fig. 4**, the APT isotherms of 23 and 24℃ (S and T) delineate the northern edge of the Kuroshio flow. The isotherm of S indicates a wedge shaped intrusion of the Kuroshio water from the point X westward. This was formed compensatively as an effect of the flood spreading around the mark K, though the Kuroshio main flow was directed to the east.

The heavy rainfall at the cold front passage caused a storm flood spreading which appeared as a tongue-like isotherm elongating to the east from the mark K. The active effect of the storm flood spreading induced a compensative flow which is indicated by a wedge-like isotherm just south of the mark E. The isotherm of 22℃ corresponds to the tongue-like contour in **Fig. 4**. The illustration in **Fig. 4** shows the formation of counterclockwise gyre with a warm core as a result of the storm flood spreading.

5. Discussion

In this study, four specific APT pictures were shown in order to demonstrate the storm flood spread between the coast and Kuroshio main flow just around the Shirahama Oceanographic Tower Station. The records at the station were utilized and used for any adjustment of the apparent sea surface temperature in the APT picture.

As is well known, the Kuroshio flow should be understood as the western boundary current in the North Pacific. Thus, it is essential to consider the effect of the Earth's rotation. In his discussion of the specific storm flood spreading on the sea surface between the coast and the Kuroshio flow, the author has assumed that the Earth's rotation is an insignificant factor. He believes that the distortion of the isotherm between the coast and the Kuroshio flow can be an indicator of the storm flood spreading in the area considered. Nevertheless, it is possible to know what is essential when considering storm flood spreading even if no consideration is given to the Earth's rotation.

As for the meteorological factors, several factors have been considered though the other factors have not been considered. For example, if a fortunate calm condition persisted for about ten days after a rainfall, the atmospheric effect on the sea surface in the interested area was simply the barometric effect and other factors could be taken as insignificant.

The bathymetry of the interested area is complicated. On the other hand, the thickness of the Kuroshio main flow can be taken to be less than 200 m. The author (1990) has earlier discussed the storm flood spreading in relation to thermohaline densimetry from the coast to the offshore area beyoud the Kuroshio flow.

What has been introduced in this study are only four cases of the many possible ones as can be found in the serial APT pictures of the involved area. In this work, the author has intended to demonstrate clearly four specific thermal patterns in relation to the storm flood spreading between the coast and the Kuroshio flow.

The author has already presented a simplified model based on a unique assumption (1992)[5], which could be called a 'Couette flow model'. A limitation of the author's simplification could be the omission of the winds on the sea surface, the bathy-metric configulations, the effect of the Earth's rotation and the other possible significant factors. Nevertheless, the author here purposefully introduced a concept for understanding the four specific APT pictures. The explanation of the essential point found in the pictures and in his model, should be seen as the basis of one concept : a concept firmly based on hydrodynamics.

This work aimed to introduce satellite thermal monitoring of storm flood spreading by using serial APT pictures instead of using AVHRR imagery. In near future, a more advanced technology will be developed to advance and confirm the concept.

6. Concluding Remark

In this work, a satellite thermal monitoring of storm flood spreading was studied in the area between the coast and the Kuroshio flow in the northwestern Pacific. For the purpose, APT photographs were utilized instead of the AVHRR imagery. First, a specific case of flood in April 1991 was introduced. Successively, the flood caused by the typhoon in October 1991 and the flood after the cold front passage in December 1991 were also introduced. Adjustment and modelling in a simple form were discussed, though no consideration was given to the affect of the Earth's rotation, meteorological conditions, bathymetry and the other possibly related factors. The author believes that an advanced model can be constructed in future with advanced technology that surpasses and replaces both the APT technique and the AVHRR imagery application.

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