Seasonal and Mesoscale Variation in the Surface Temperature and Salinity at the Coastal and Shelf Region off Shikoku, Japan

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A three-year-long time series of water temperature and salinity observed on a ferryboat in the shelf region off Shikoku Japan was analyzed, focusing on the phenomena with a time scale of more than one month. We found two remarkable fronts in the seasonal variations. One is the well-known Kii Channel Front. This front remains as a haline front in summer while a thermohaline front in winter. The other, which is formed near Cape Ashizuri-misaki, is newly found. Density gradient across the front in winter is in the opposite direction to that in summer. Next, focusing on phenomena with a shorter time scale, we found the simultaneous variation in water temperature over the observational region, the time scale of which is about three months. It has a good coherence with the variation in air temperature observed at the coast, which implies that this variation has something to do with a phenomenon including the atmospheric system. Warm water intrusion from the Kuroshio is also correlated with this variation. Short-period variations such as the eastward progression of warm water mass tend to be active when the simultaneous variation in water temperature is in the warming phase, i.e., water temperature is increasing.

1. Introduction

The coastal and shelf regions along the south coast of western Japan (Fig. 1) is an interesting region for oceanographers. The Kuroshio almost flows close to the coast off Shikoku whether it is in a large meandering state off Enshuu-nada or not. Then, the warm and salty Kuroshio water is always supplied to this region. On the other hand, north of this region, has an inland sea called “the Seto Inland Sea”, which stores a large amount of fresh water from many rivers and supplies it to the shelf region. Thus, the phenomena in this region occurs under the influence of both coastal and offshore (Kuroshio) waters which have different characters mutually. In other words, the study on the shelf region off Shikoku is very important on understanding the heat and mass transport between the coastal and the Kuroshio regions (e.g., Imasato and Qiu, 1987).

The Kii Channel Front is one of the most typical phenomena in this region (e.g., Kunishi et al., 1971; Yoshioka, 1971). This front was formed between cold and fresh coastal water and warm and salty offshore water in winter. Its variation is caused by warm water intrusion from the Kii Channel Approach, the shelf region off the Kii Channel (Yoshioka et al., 1977). Yoshioka (1983, 1988) described a schematic model explaining how the Kii Channel Front is affected by warm water intrusion from the Kuroshio region. However, the warm water intrusion itself was not
Fig. 1. The course of the ferry service. The letters indicating the turning points (O, T, I, M, A, and H) also are used in the following figures. The bold arrows denote the entries to the Seto Inland Sea.

clearly explained.

Nishi and Kunishi (1985) examined the physical processes in the shelf region off Shikoku by using the sea surface temperature and salinity observed on a ferryboat course (Fig. 1). They reported that the warm water west of Cape Ashizuri-misaki often progresses to the east (Fig. 2). This is called “the eastward progression of warm water mass”. It often progresses across Tosa Bay, passes through the Kii Channel Approach and reaches the Kii Channel to sharpen the front. Recently, using the satellite imagery, Toda et al. (1988) and Toda (1992) showed that the eastward progression of warm water mass on the ferryboat course represents the intrusion of the Kuroshio water into Tosa Bay when the Kuroshio axis on the downstream side moves offshore (e.g., around Cape Shiono-misaki). It is also reported that a large amount of heat is transported into Tosa Bay during this event.

In this paper, we first analyze a three-year-long data of temperature and salinity obtained on the ferryboat course to describe in detail the physical process with a longer time-scale (more than one month) than that examined by Nishi and Kunishi (1985) in the shelf region off Shikoku. Next, the relation of such processes to other environments, like, air temperature, water sea level and so on, and shorter-period processes, say, the eastward progression of warm water mass, is investigated.

2. Observation

We used the sea surface temperature and salinity recorded by the automatic data recording system on the ferryboat “St. Polia” running along the southern coast of western Japan (Fig. 1). Sea water at 3–5 m deep is continuously drawn into the boat. The water is mainly used to cool the engine and to circulate within the boat for miscellaneous use. We built a sensor system in one
of the branch lines of this circulation.

The data were processed as a time series at 181 data points every 2.5 km on the course. Each point was numbered serially from Osaka to Hyuga (several point numbers are shown in Fig. 1). The boat runs every night (leaves 17:30 and arrives 8:30). Then, temperature and salinity data are obtained at each point every day. We analyzed a time series of these data from Oct. 1, 1981 to Sep. 30, 1984. However, the data from these dates, Oct. 8 to Nov. 9, 1983, Aug. 31 to Sep. 12, 1982, Sep. 1 to 8, 1983 and Sep. 3 to 12, 1984 are lacked for the maintenance of the boat, recorder troubles and so on. There are additional 95-day lacks owing to the course change or cruise suspension for bad weather. Such lacks do not continue for 7 consecutive days. As a result, data for 907 days are available and those for 159 days lacked.
3. Seasonal Variation

3.1 Temperature

In order to simply reveal the behavior of long-term variations in the sea surface temperature and salinity off Shikoku, we processed the obtained data as a time series at each point on the course of the ferryboat. A time series of temperature at several points is shown in Fig. 3. An apparent feature in this figure is that the temperature variation at each point roughly matches a year-period sinusoidal curve. Then, to find the seasonal variation, raw data are processed by the least square method as follows. Let the data be

\[ f(x,t) = A(x) \sin \left( \frac{2\pi t}{T(x)} - \theta(x) \right) + C(x) + R(x,t) \]  

(1)

where \( x \) and \( t \) are the observational point and time, \( A(x) \), \( \theta(x) \) and \( C(x) \) the amplitude, phase and the average value of the sinusoidal variation respectively, and \( R(x,t) \) is the residual to be minimized. For our purpose, \( T(x) \) is assumed to be 365.2422 days \textit{a priori}. Thus, the least square calculation became linear (to assume the phase \( \theta(x) \) be unknown does not make the calculation nonlinear as noted in Appendix). Now then, the most suitable function \( \tilde{f}(x,t) \)

\[ \tilde{f}(x,t) = f(x,t) - R(x,t) = A(x) \sin \left( \frac{2\pi t}{T(x)} - \theta(x) \right) + C(x) \]  

(2)

represents the sinusoidal variation at each point. Figure 4 shows the horizontal distribution of \( \tilde{f}(x,t) \) (bold lines) together with the standard deviation of \( R(x,t) \) (thin lines). The amount of the standard deviation of \( R(x,t) \), about 1°C, is small enough compared to the amplitude of \( \tilde{f}(x,t) \) which is more than 5°C in the shelf region (left of point M) and more than 10°C in the coastal region (right of point I). We therefore regarded \( \tilde{f}(x,t) \) as the seasonal variation in temperature and examine it in this section. The examination of \( R(x,t) \) is left to the later section.

The phase of the seasonal variation is almost the same (only 10-day or less difference) in the entire region (top panel of Fig. 4), but its amplitude largely differs from some region to other (lower panel of Fig. 4). High amplitude (~10°C) is found in the coastal region while low amplitude (~5°C) in the shelf region. Taking account of a remarkable decrease in temperature in the coastal region during winter, the difference in amplitude is caused by difference in heat capacity (or water depth) between the two regions as well as the influences of the Kuroshio warm water.

The most striking feature is that two fronts appear in winter. One is the Kii Channel Front near Ishima Island (point I), which is consistent with the results of many previous observations (e.g., Yoshioka, 1971). Across the front, difference in temperature reaches about 5°C in midwinter. The other is formed near Cape Ashizuri-misaki (point A), which has never been reported. From now on, this front is referred to “the Ashizuri Front”. Temperature difference across the front is less than 1.5°C in maximum, which is much smaller than that of the Kii Channel
Fig. 3. Temporal variation in the temperature at some points on the course. The numbers at the left side indicate the point numbers (same as that in Fig. 1). The heights of the left end of the broken lines at the left side stand for $20^\circ$C, and their intervals stand for $0.5^\circ$C.
Fig. 4. Seasonal variation in the temperature. The three bold lines indicate the maximum \((C(x) + A(x))\), average \((C(x))\), and minimum \((C(x) - A(x))\) value of the year-period sinusoidal variation. The thin lines beside them indicate the standard deviation of \(R(x, t)\), the deviation from this seasonal variation. The upper panel represents the phase \((\theta(x))\) in terms of the day when the maximum of the sinusoidal variation occurs.

Front. These fronts will be examined in detail, taking account of the features in salinity and density distributions.

3.2 Salinity

Figure 5 is the counterpart of Fig. 3 for salinity, showing that the seasonal variation in salinity is far from sinusoidal as seen in temperature. Then, the same method as used in temperature is not applicable to salinity for getting its seasonal variation. We instead processed raw data in the following procedure. As seen in Fig. 5, salinity decreases largely in summer and not in other seasons, mainly because fresh water from adjacent rivers overlies the salty sea water in summer. Therefore, we first averaged salinity values in the whole year except summer (bold lines in Fig. 5). The mean value is hereafter referred to as “the basic value”. We next applied EOF analysis to the deviation from the basic value, because we may expect that the phase of the seasonal variation in some region matches with that in the other regions and EOF analysis is very sensitive to such coherent variation. Figure 6 shows the first six EOF modes for the deviation from the basic value. Among them, the first mode, which represents a simultaneous decrease in salinity over the whole region, is predominant (about 80% of the deviation). Then, we regarded the sum of the basic value and the first EOF mode as the seasonal variation in salinity (Fig. 7).

Figure 7(a) is the spatial distribution of the seasonal variation in salinity, showing that there
Fig. 5. Same as Fig. 3 but for the salinity. The heights of the left end of the broken lines at the left side stand for 33% and their intervals stand for 0.2%. The bold lines under the time scale indicate the period used to calculate “basic value”.
exist the Kii Channel Front (point I) and the Ashizuri Front (point A) in winter, like in the
temperature distribution. Moreover, we found the following features different from those in the
temperature distribution. Both the fronts remain as a haline front even in summer; in particular,
concerning the Ashizuri Front, its sharpness is more intense in summer than in winter. Other haline
fronts appear near the coast (both ends of the observational region) while they are not in the
temperature distribution. These differences are understood by considering the origin of low
salinity and high temperature, and the sea surface heat flux. In the observational region, low
salinity is originated in fresh water supply from rivers while high temperature mainly by warm
water intrusion from the Kuroshio. Sea surface heating in summer causes a strong stratification
in the surface layer while cooling in winter forms the vertically well-mixed coastal water and the
mixed layer reaching a depth of about 100 m in the shelf region. Then, in winter, a remarkable
thermal front is formed between the cold and fresh coastal water and the warm and salty offshore
water (e.g., Yoshioka, 1971), and a haline front is weakened since less saline coastal water is well
mixed with the underlying saline water in the shelf region (e.g., off Cape Ashizuri-misaki). On
the other hand, in summer, fresh water discharge makes a haline front remarkable and a thermal
front almost disappears since the strong stratification covers the influence of the warm Kuroshio
water.

A time series data for three years shows a remarkable decrease in salinity during summer in
1982 (Fig. 7(b)). Observation by the River Bureau, Ministry of Construction (Table 1) shows that

![Fig. 6. Eigenfunctions of the major EOF modes (whose contribution exceeds 1%) of the deviation of the salinity data from the “basic value”. Each eigenfunction is scaled by the mean amplitude of each mode at each location. The marks at the left side indicate the average of the mean amplitude. The contribution of each mode is 78, 5.6, 2.6, 1.6, 1.3, and 1.2%, respectively.]

<table>
<thead>
<tr>
<th>Name of river</th>
<th>annual mean</th>
<th>in July and August</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yodo</td>
<td>267.76</td>
<td>251.36</td>
</tr>
<tr>
<td>Yoshino</td>
<td>127.30</td>
<td>102.38</td>
</tr>
<tr>
<td>Shimanto</td>
<td>129.57</td>
<td>94.82</td>
</tr>
</tbody>
</table>
Fig. 7. Seasonal variation in the salinity estimated as the sum of the “basic value” and the first EOF mode of its deviation from the “basic value”. (a) Spatial distributions of some typical phases of the seasonal variation. The line 0 indicates the basic value, the line 1 indicates the sum of the basic value and the standard deviation of the first EOF mode, and the line 2 indicates the sum of the basic value and twice of the standard deviation of the first EOF mode. (b) Temporal evolution of the variation. The horizontal lines 0, 1, and 2 correspond to those in panel a.
the annual mean discharge of rivers emptying into the observational region in 1982 does not differ so much from those in 1983 and 1984. However, the discharge is concentrated on July and August in 1982. Therefore, we may recognize that this concentration of discharge is responsible for the remarkable decrease in salinity in 1982.

3.3 Density

For the dynamical interest, it is important to examine the density distribution. Figure 8 shows the density distribution calculated from the previously estimated seasonal variations in temperature and salinity. Error in density introduced by this calculation is at most 0.1 in $\sigma_t$ unit. This value has no influence on the features in density discussed below.

Density near the Kii Channel Front (point I) is almost constant in winter, which is consistent with the results of previous observations (e.g., Yoshioka, 1971). However, there appears a density gap across the front in summer since the Kii Channel Front is a haline one in summer, as described in the last subsection. Although for the past two decades many studies have proposed the physical models for frontogenesis at the Kii Channel in winter (Endoh, 1977; Harashima et al., 1978; Oonishi et al., 1978; Harashima and Oonishi, 1981; Akitomo, 1988; Akitomo et al., 1990a, b), this fact suggests that a new physical model for the frontogenesis in summer is required.

Another remarkable feature is found in the density gradient across the Ashizuri Front. The density gradient directs eastward in winter while it directs westward in summer. This reversion is caused by the seasonal variations in temperature and salinity described before (Figs. 4 and 7).

Fig. 8. Seasonal variation in the density (sigma-t) calculated from that of the temperature (Fig. 4) and salinity (Fig. 7(a)).
Surface cooling makes water density heavier in Tosa Bay than offshore in winter while fresh water supply from adjacent rivers makes water density lighter there in summer. Besides these seasonal variations, we can see significant fluctuations of density in Fig. 8, probably because of the intrusion of warm salty water from the Kuroshio. In fact, Toda (1992) reported that eddy generation associated with variations in the Kuroshio takes place around Cape Ashizuri-misaki at an interval of about 10 days and much affects the oceanographic conditions in the shelf region off Shikoku: The detailed discussion concerning this point is desired in future.

4. Mesoscale Variation

4.1 Mesoscale temperature variation

Figure 9 represents \( \bar{R}(x, t) \) of temperature defined by Eq. (1). We can notice several short-period phenomena (less than one year) in this figure. For example, the eastward progression of warm water mass is clearly detected (indicated by downward arrows for typical cases). We also found that \( R(x, t) \) often varies simultaneously at almost all points from Osaka to Hyuga (indicated by arrows on the top of the figure). This variation is remarkable except in the Kii Channel (in the neighborhood of point 43). To examine this simultaneous variation, we define the spatial average \( \bar{R}(t) \) as

\[
\bar{R}(t) = \frac{1}{N} \sum_x R(x, t)
\]  

where \( N = 181 \) is the number of the observational points. Line A in Fig. 9 indicates the time change of \( \bar{R}(t) \). The root-mean-square amplitude of \( \bar{R}(t) \) is about 0.8°C. The temporal evolution of \( \bar{R}(t) \) shows a non-periodic oscillation whose time scale is about three months. To examine the spatial structure of this oscillation, we applied the EOF analysis to \( R(x, t) \). The first EOF mode shown in Fig. 10 corresponds to the simultaneous variation since its eigenfunction has a roughly constant amplitude in space and is dominant (as much as 45%). The difference between the temporal evolution of the first EOF mode (line E in Fig. 9) and \( \bar{R}(t) \) is small enough (5.5 × 10^{-5} ± 2.7 × 10^{-2}°C).

The amplitude of the eigenfunction of the first EOF mode in Fig. 10 shows that the simultaneous variation is weaker in Osaka Bay and west of Cape Ashizuri-misaki (left of point A) than off Tosa Bay (between points A and M). This implies that the influence of the Kuroshio is most dominant off Tosa Bay and that the observational region can be divided into three areas. Since this division coincides with the geometrical feature (the observational region is divided into three by Capes Ashizuri-misaki and Muroto-misaki), the simultaneous variation or the influence of the Kuroshio is controlled by the geometrical feature. We will refer to this simultaneous variation as “the mesoscale variation” and investigate its relation to other phenomena occurring in this region.

4.2 Relation to some environments

In this section, we examine the relation of the mesoscale variation \( \bar{R}(t) \) to the counterparts of some environments, i.e., air temperature and sea level. The air temperature is observed by Japan Meteorological Agency (JMA) at six coastal points, i.e., Cape Ashizuri-misaki, Kochi, Cape Muroto-misaki, Tokushima, Wakayama and Cape Shiono-misaki (see Fig. 1). The sea level
Fig. 9. Same as Fig. 3 but for the deviation from the seasonal variation. The heights of the left end of the broken lines at the left side stand for no deviation and their intervals stand for $1^\circ$C. The lowermost two lines represent the mesoscale temperature variation estimated by two methods; the upper one (line A) is the plain average of the entire data along the course, and the lower one (line E) is the temporal variation in the first EOF mode shown in Fig. 10.
Fig. 10. Eigenfunctions of the major EOF modes (whose contribution exceeds 2%) of the deviation of the temperature data from its seasonal variation. Each eigenfunction is scaled by the mean amplitude of each mode at each location. The marks at the left side indicate the average of the mean amplitude. The contribution of each mode is 45, 10, 7.9, 5.2, 4.1, 3.3, 2.8, and 2.1%, respectively.

is also observed by JMA at seven points, i.e., the above six points and Komatsushima. The counterparts of $R(x, t)$ were estimated from the air temperature data and the sea level data. They have a very large first EOF mode that is approximately equal to the counterpart of $\bar{R}(t)$, just the same as the sea water temperature data. The temporal evolutions of the first EOF mode of the sea water temperature, the air temperature and the sea level are denoted by thin lines in Fig. 11. The bold line superimposed on each thin line represents the long-term variation component estimated by the Hanning filter of 30 days length.

Figure 11 clearly shows that the long-term variations in the sea water and air temperatures have a very high correlation (as much as 0.67). The peaks of their short-term variations, i.e., the deviations from the long-term variations, are also correlated (0.25). The amplitude of the long-term (short-term) variation in the air temperature is about four (ten) times larger than the counterpart of the sea water temperature. This suggests that the mesoscale variation $\bar{R}(t)$ is originated in a larger phenomenon including the atmospheric system.

In contrast, there is a poor correlation (only 0.06 for the long-term variations) between the coastal sea level and the sea water temperature. This result is consistent with that of Nishi and Kunishi (1985) who examined the sea water temperature and the sea level observed at two points, Capes Muroto-misaki and Ashizuri-misaki. They also found that the difference in sea water temperature between the two capes is highly correlated with the difference in sea level, especially in winter. From these results, they speculated that the long-term variation in sea level consists of two parts with and without relation to the variation in sea water temperature. This problem will be discussed in the forthcoming paper by one of the authors, Nishi.

The mesoscale variation is expected to be related to the Kuroshio. However, the location of the Kuroshio axis off Cape Muroto-misaki obtained by Hydrographic Department of Maritime Safety Agency, Japan (also shown in Fig. 11) has a poor correlation (only 0.07) to the long-term mesoscale variation in the sea water temperature. This means only that the mesoscale variation
has no direct relation to the Kuroshio path variation. The influence of the Kuroshio will be discussed in the last part of the next section.

4.3 Relation to local phenomena

Previous studies reported some interesting phenomena in this region. One of them is the eastward progression of warm water mass, first reported by Nishi and Kunishi (1985) (Fig. 2). Another similar phenomenon is found in Fig. 12. That is, cold and fresh water progresses from Ishima Island (point I) to Cape Muroto-misaki (point M), which is referred to “the westward progression of fresh water”. Imasato et al. (1986) was the first to report this event. Then, we
Fig. 12. The “westward progressions of fresh water” from the Kii Channel (shown by arrows).

examine here the relation of these local phenomena, especially the eastward progression, to the mesoscale temperature variation.

Figure 13 shows the occurrence time of the eastward progression and other local phenomena, compared with the mesoscale temperature variation $\bar{R}(t)$. We can see that the eastward progression occurs frequently in winter and spring while scarcely in summer (column E). Moreover, a close examination of this figure clarifies the following feature. When $\bar{R}(t)$ is increasing (warming period), the eastward progression occurs more frequently; for example, March of 1982, January of 1983, April of 1984 and so on. On the other hand, the eastward progression scarcely occurs in from February to March of 1983 and 1984 when $\bar{R}(t)$ is decreasing (cooling period). These facts show that the eastward progression of warm water mass is highly correlated to a simultaneous increase in temperature over the observational region, i.e., an increase in $\bar{R}(t)$. As for other temperature variations with smaller time scales, the above tendency holds true; $E_2$, $E_3$, $W_1$, and $S_1$ appears when $\bar{R}(t)$ is increasing, and $E_0$, $W_0$, and $S_0$ appears when $\bar{R}(t)$ is decreasing.

Using satellite imagery, Toda *et al.* (1988) found that the eastward progression of warm
Fig. 13. Comparison of the mesoscale variation in the temperature with the eastward progression of warm water mass. The vertical bars in column E indicate the days of the departure of the warm water mass from Cape Ashizuri-misaki. The graph in column T represents the mesoscale variation in the temperature (the scale at the left side represents the variation of 1°C in average). The letters in column D are the descriptions of the local phenomena with the following classifications.

Q: Both the temperature and the salinity are almost quiet. There are some tiny eastward progressions in the temperature.
E: The temperature varies much, but the salinity do not.
   E': The variations are relatively small, but eastward progressions are apparent.
   E₀: There are large variations in the Bungo Channel, but not in Tosa Bay and the Kii Channel.
   E₁: There are large variations in the entire region, but they are is not systematic, i.e., no apparent eastward progressions exist.
   E₂: Large variations with eastward progressions.
   E₃: Small eastward progressions exist very often (about once in three days).
W: There also are small variations in the salinity including the westward progressions of fresh water (Fig. 12).
   W₀: There is almost no temperature variation in Tosa Bay.
   W₁: There are some temperature variations with eastward progression in Tosa Bay.
S: There are very large and complex variations in the salinity, but variations in the temperature are small.
   S₀: There is almost no variation in the temperature except the region to the north of the Kii Channel.
   S₁: There are some tiny variations in the temperature.
water mass represents the intrusion of the warm Kuroshio water into Tosa Bay. Further, Toda (1992) revealed that this intrusion tends to occur when the Kuroshio axis on the downstream side moves offshore (e.g., around Cape Shiono-misaki). Therefore, the mesoscale temperature variation, i.e., the simultaneous increase in temperature over the observational region, might be considered to represent heat transport onto the shelf by this process. Thus the mesoscale temperature variation is strongly related to the Kuroshio. However, the mesoscale variation was poorly correlated with the position of the Kuroshio axis off Cape Muroto-misaki (Fig. 11). This means that the variation in space of the Kuroshio axis is not appropriate index for the mesoscale variation in the shelf region around Cape Muroto-misaki.

5. Conclusion

The seasonal feature in the shelf region off Shikoku is characterized by two remarkable fronts; the Kii Channel Front and the Ashizuri Front. The Kii Channel Front is well known as a thermohaline front formed in winter (Yoshioka, 1971) and has been regarded to vanish in summer. However, we found that a haline front remains even in summer. Whereas the density of the waters on the both sides of the front is almost the same in winter, there is a large density gradient in summer. The Ashizuri Front is newly found and is formed between the waters of Tosa Bay and the Bungo Channel Approach. The most remarkable feature of the Ashizuri Front is that the density gradient in summer is in the opposite direction to that in winter. This is because the difference in density on the both sides of the front is determined by salinity in summer while by temperature in winter.

We also found a mesoscale variation in temperature, i.e., a simultaneous variation in the observational region, the time scale of which is about three months. The mesoscale variation is highly correlated with the variation in air temperature whose amplitude is larger than that of sea water temperature. This fact implies that the mesoscale variation is caused by a larger phenomenon including the atmospheric system. When the mesoscale temperature variation is in the warming phase, i.e., temperature is increasing simultaneously, the eastward progression of warm water mass off Tosa Bay tends to occur frequently as well as other local temperature variation.

The Kuroshio largely affects the processes in the observational region. Waters on the offshore side of the fronts are originated in the warm and salty Kuroshio water. Further, the eastward progression of warm water mass is caused by the time-dependent, warm water intrusion from the Kuroshio (Toda et al., 1988; Toda, 1992). On the experimental side, Awaji et al. (1991) pointed out that the variation in the Kuroshio causes a large water movement in the shelf region. Thus, the influence of the Kuroshio variation is essential to understand the physical processes in the shelf region completely.

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Appendix

To determine the phase $\theta(x)$ is not a nonlinear calculation. Equation (1) can be rewritten in the complex form as

$$f(x,t) = A(x)\exp\left(\frac{2\pi t}{T(x)}\right) + C(x) + R(x,t)$$

where $A(x) = A(x)\exp(-\theta(x))$ is the complex amplitude. To determine unknown $A(x)$ is a complex linear calculation.

There is another explanation. Equation (1) also can be rewritten as

$$f(x,t) = A_1(x)\sin\left(\frac{2\pi t}{T(x)}\right) + A_2(x)\cos\left(\frac{2\pi t}{T(x)}\right) + C(x) + R(x,t)$$

where $A_1(x) = A(x)\cos\theta(x)$ and $A_2(x) = -A(x)\sin\theta(x)$. To determine unknown $A_1(x)$ and $A_2(x)$ is, of course, a linear calculation and it is easy to determine $A(x) = \sqrt{(A_1(x))^2 + (A_2(x))^2}$ and $\theta(x) = \tan^{-1}(-A_2(x)/A_1(x))$.

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