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COASTAL ENVIRONMENT SYSTEM AND ITS NUMERICAL SIMULATION
-Observation and Prediction of Coastal Environment in the Tanabe Bay-

Masato NIKI*

* COE Researcher, DPRI, Kyoto University

Synopsis

The observation in Tanabe bay was conducted to aim further understanding of the bottom water intrusion mechanism. POM-based computer simulation study on internal tide and water exchange in the bay was also conducted by this study. From the observation, it can be found that when the Kuroshio moves toward the Kii Peninsula, warm water intrudes in to the bay in the surface layer and block the cold-water intrusion near the bottom. The gradient of atmospheric pressure may be an important factor which induces water exchange in the Tanabe Bay. Numerical result supported such observation result.

Keywords: water exchange, internal Kyucho, Kuroshio Current, POM

1. Introduction

The Tanabe Bay is located in the central part of Wakayama Prefecture, an entrance of the Kii Channel, facing the North-West Pacific Ocean. The marine climate is warm and mild because it is strongly affected by a branch of Kuroshio current. The temperature of the surface water near the tip of the cape is 20 ℃in annual average, and seldom become less than 12 ℃. Salinity ranges from 31 to 35 (PSU), and tidal range is 1.4 -2.0 m. The water depth at the central part of the bay is around 30 m. Shirahama Oceanographic Observatory, Disaster Prevention Research Institute (DPRI), Kyoto University is located in the inner part of the bay. According to observational results by the Tanabe Nakajima Storm Surge Observation Tower (DPRI's field research facility) located at the entrance of the bay, water exchange under the stratified condition in summer is done by amplification of internal tides and bottom intrusion of cold and high salinity water caused by on/off-cost migration of Kuroshio branch and/or coastal upwelling due to Ekman transport (Yoshioka at el, 1998). Under the condition of strong stratification, active water exchange is hard to be expected without these mechanisms through the bay mouth.

A number of harmful red-tide blooming has been observed in early summer to autumn since 1970s in the inner part of the bay because of active

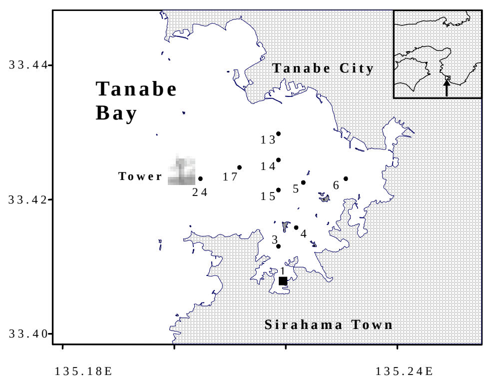


Fig.1 Measuring points on Tanabe Bay

aquaculture in the semi-closed bay. The red-tide prediction project in the bay has been launched in 1997 as a joint research program of Shirahama Oceanographic Observatory and the Fisheries Laboratory of Kinki University. This study is a part of extension of this joint research. The observation in 2003 was conducted by the author and other collaborators in DPRI to aim further understanding of the bottom water intrusion mechanism. POM-based computer simulation study on internal tide and water exchange in the bay was also conducted by this study. Using the developed numerical model, several numerical experiments for better understanding of the water intrusion mechanism were carried out and compared with observations inside the bay.

2. Observation of Coastal Water Environment in Tanabe Bay in 2003

2.1 Outline of observation

The period of the observation was one month between July 4 to August 4. The water quality (water temperature, salinity, chlorophyll-a and dissolved oxygen) was measured every day using CTD (Sea-Bird-Electronics SBE-25) at the aquaculturing raft of Kinki University (St.1 in **Fig.1**,) together with water sampling for phytoplankton cell measurement with Bandon water sampler. Spatial distribution of water quality was also observed using the observation boat with CTD on days of July 7, 11, 15, 16, 17, 18, 21, 22, 24, 25, 27, 29, 31, August 1and 4.

Oceanographic and meteorological measurements, (air temperature, air pressure, wind, solar radiation, wave, tidal height and water temperature) were conducted at the bay mouth with Tanabe-Nakashima Strom Surge Observation Tower (TNSSOT) of DPRI. Current profile was measured at the point of 30m in depth near the TNSSOT using ADCP (Acoustic Doppler Current Profiler of 1200kHz).

2.2 Observational results

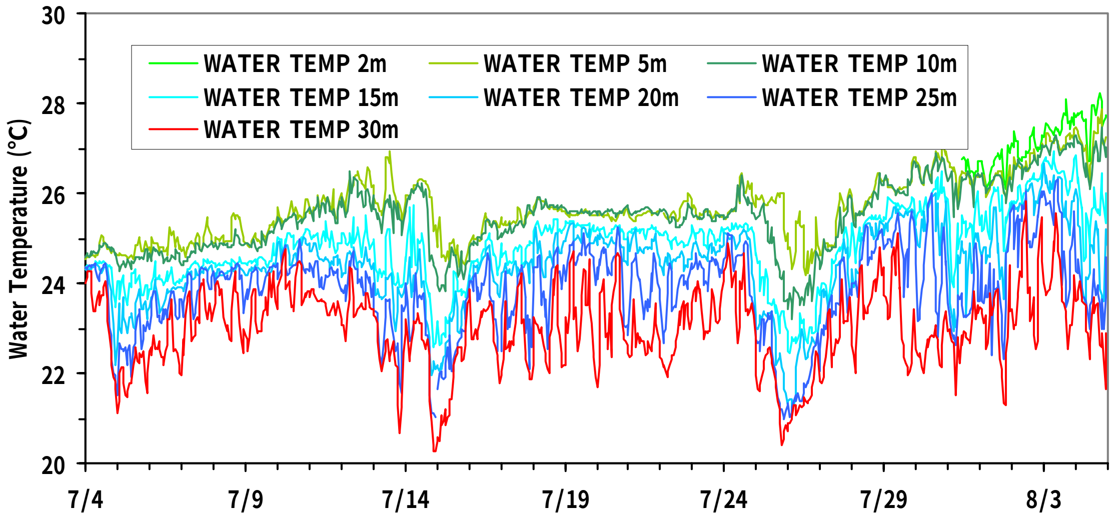


Fig.2 Time series of water temperature at TNSSOT

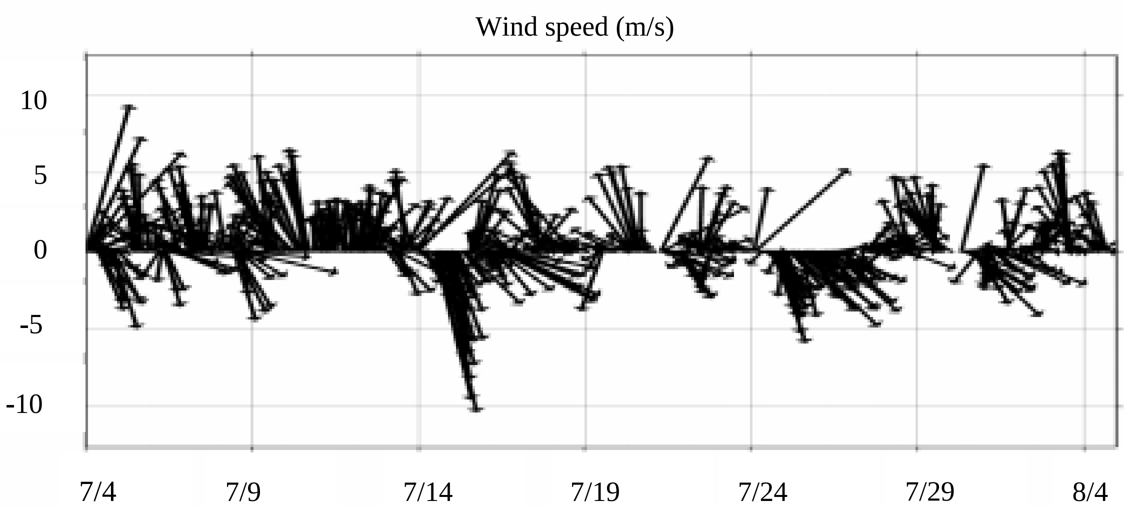


Fig.3 Stick diagram of winds at TNSSOT

Figure 2 shows the temporal variation in water temperature distribution observed by the thermistor chain at TNSSOT from July 4 to August 4, in which sea water temperatures at 3, 5, 7･･･ 30m deep were measured. Remarkable events of rapid temperature drop near the bottom with different period from tidal constituents are observed on days of July 4, 15, 25 and August 4. Causes of these events will be discussed in the section 3 and numerical experiments to hindcast the events will be done in the section 4.

Sea surface wind is one of important causes for both vertical and horizontal water circulation in the coastal region. It is well-known that Ekman transport causes coastal upwelling near the coastal sea. This is considered a main cause of water exchange in the Tanabe Bay. **Figure 3** shows the temporal changes in the 10-min averaged wind vectors observed at the point of 10m-height from MSL at TNSSOT. It can be seen that a dominant wind direction in summer is from south. It is found, however, from **Figs.2** and **3**, that remarkable events of rapid temperature drop near the bottom were observed during the periods of north wind events. This observational fact may indicate a coastal upwelling due to Ekman transport along the east coast of the Kii Channel.

Figure 4 shows the spectra of water temperatures measured thermistor chain. Temperature variation below the 15m in depth has a peak frequency at 12 hours. A clear thermocline growths in summer at the middle layer (about 15m) with variation of internal tide whose amplitude is about 2 ~ 3 ℃in water temperature. On the other hand, a rapid temperature drop near the bottom with non-tidal variation has am amplitude ranging 3 ~ 5 ℃in water temperature. Yoshioka et. al. (1998) defined such kind of changes “internal kyucho” which is a multiple water temperature variation of internal tide and coastal upwelling caused by north wind. It is one of major mechanisms of sea water exchange under the condition of stratification in a semi-closed bay, such as the Tanabe Bay. Possible mechanisms for water exchange in the bay may be listed below as:

1) Bottom water intrusion due to on/off-cost migration of Kuroshio branch.
2) Atmospheric pressure changes
3) Coastal upwelling caused by north wind
4) Internal tide
5) Multiple mechanism of 1)-4).

In the following sections, these mechanisms will be discussed with oceanographic and meteorological data observed in 2003. First the influence of Kuroshio branch is discussed then the effect of atmospheric pressure field and these multiple mechanisms will be discussed.

3. Causes of Water Exchange

3.1 Bottom water intrusion due to on/off-cost migration of Kuroshio branch

A cold water intrusion in the bottom layer affects the variation in water temperature at the surface layer. A intrusion of hot water in the surface layer slightly affects on the variation in water temperature in the bottom layer as shown in **Fig.1**. High temperature water intrusion in the surface layer is related to the 25-hr moving-averaged sea level changes (SL-25), as shown in **Fig.5**. SL-25 may represent the sea level anomaly of non-tidal changes. Migration of Kuroshio branch on/off the coast of the Kii Peninsula is one of possible generation mechanisms of SL-25. It can be found that when the Kuroshio moves toward the Kii Peninsula, the sea level rises and warm water intrudes in to the bay in the surface layer. Meanwhile the Kuroshio moves offshore, SL-25 starts to go down. According to the weekly data of Kuroshio Current axis observed by the Maritime Safety Agency(MSA), Japan, the axis was nearest position from the Kii Peninsula in July 8-15, then it moves offshore detached from the Kii Peninsula in the end of month. These MSA’s Kuroshio data is consistent with SL-25 shown in **Fig.5**.

3.2 Atmospheric pressure changes

Figure 6 shows the relation between sea level

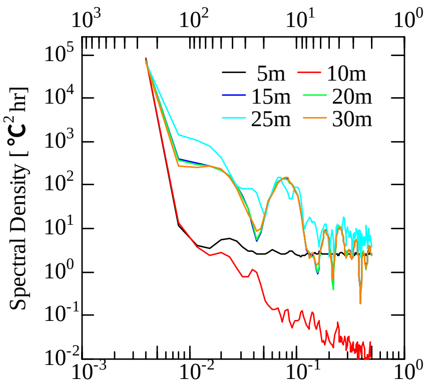


Fig.4 Power spectra of water temperature at TNSSOT

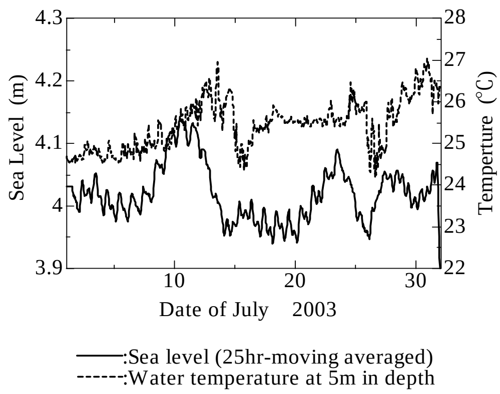


Fig.5 Time series of water temperature and the 25-hr moving-averaged sea level

difference and atmospheric pressure difference of Tanabe-Komatsujima (east coast of Shikoku Island). Atmospheric pressure decrease is defined positive in the figure. Changing tendency of sea level and pressure drop has clear correlation except the period on July 25 to 29. **Figure 7** shows the time series of the water temperature in the bottom layer and the atmospheric pressure difference. It has also clear correlation between bottom water temperature and atmospheric pressure drop. This is clearly shown in the data of July 15 and 25, when a sudden drop of atmospheric pressure was observed in the Tanabe Bay. On the other hand, amplitude of internal tide itself neither has correlation to the variation of atmospheric pressure nor bottom water temperature drop. The gradient of atmospheric pressure and the gradient of sea level may be a important factor which induces water exchange in the Tanabe Bay.

3.3 Detail discussions

Figure 8 shows the observed tide, wind and current profile measured by ADCP. For detail discussion, data from July 8 to 27 is divided into 4 periods of, 1st: 8-12, 2nd:13-17, 3rd:18-22, and 4th:23-27. In the following discussion, the definition of surface layer is the data at 7.4m deep, the middle layer is 15.4m and the bottom layer is 25.4m, and the north and east current are defined positive.

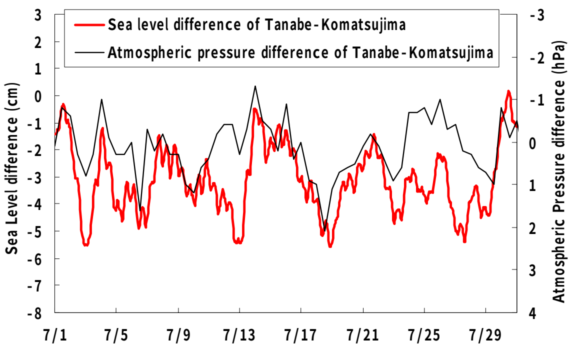


Fig.6 Time series of sea level difference and atmospheric difference of Tanabe-Komatsujima

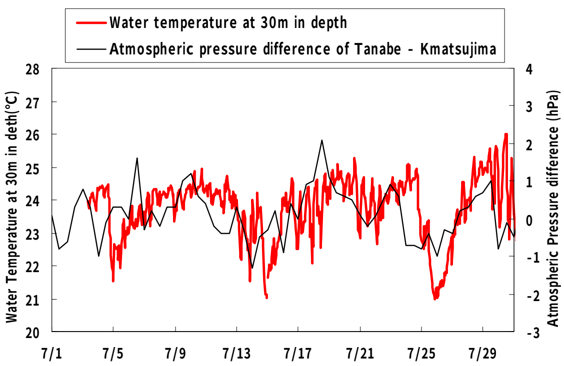


Fig.7 Time series of the water temperature at bottom layer and atmospheric pressure difference of Tanabe-Komatsujima

(a) 1st period (July 8 to 12): Wind direction was southwest (typical summer wind) except July 8. ADCP data in the surface layer shows that the direction of inflow was northeast and that of outflow was southwest. The major component of current data comes from semi-diurnal tide. Amplitude of current in the middle layer is smaller than the surface. The current amplitude in the bottom layer can not be clearly detected, however, spectrum analysis shows its energy peak in the period of 12hr (**Fig.4**).

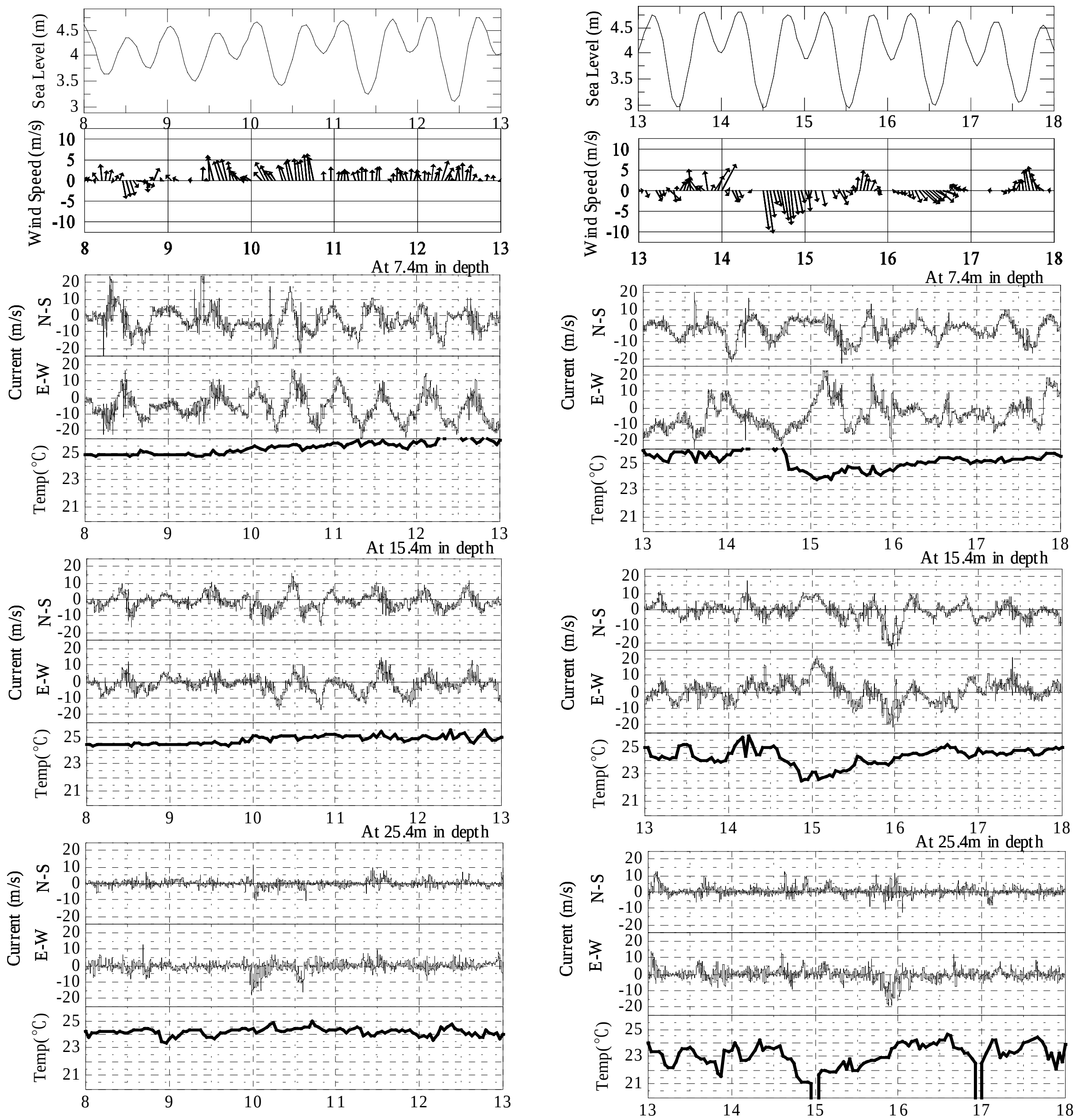
As described in the section 2, it is found that the water temperature in the surface layer is affected by the migration of Kuroshio branch in 1st period. The amplitude of the variation in water temperature at middle and bottom layer is small comparing with sea water temperature variation in the surface which is strongly affected by warm current of Kuroshio branch.

(b) 2nd period (July 13 to 17): The wind direction was north from 13 to 16. Under this wind condition, the spectrum period of current variation in the surface layer is not clear. Water temperature dropped in all layers simultaneously in data of July 15. In the ebb phase from lower high water on the afternoon of July 14 to higher low water the direction of flow was not west (tidal current direction) but east in all layer. This flow is opposite to the direction of ebb tide. This phenomenon induced the sudden changes in water temperature.

(c) 3rd period (July 18 to 22): Wind direction was southwest (a typical summer wind). The inflow direction was from the northeast and the outflow was from southwest with semi-diurnal tide period. Although the current direction and its period show same trend as 1st period (July 8 to 12) in which cold water did not intrude, the current amplitude of 3rd period was larger than 1st period. This difference may be caused by migration of Kuroshio Current offshore.

The amplitude of the variation in water temperature at bottom layer is large comparing with in the 1st period, in spite of the amplitude of tide is small It can be assumed that warm water of Kuroshio may block the cold water near the bottom when Kurosh Current approaches the Kii Peninsular like a 1st period. While in this period Kurosh Current detaches, the cold shelf water inflows into kii channel along the continental shelf slope and intrude into bottom layer.

(d) 4th period (July 23 to 27): North wind was observed from 24 to 27. Unlike the 2nd period (July 13 to 17), water temperature did not drop in all layers simultaneously. Water temperature in the bottom layer dropped on July 24 and that in the middle layer and surface layers dropped on July 25. These water



(a) 1st period (July 8 to 12)

(b) 2nd period (July 13 to 17)

Fig.8 (a) Time series of the tide, wind and current at TNSSOT

temperature drops occurred during phase of ebb tide.

Figure 9 shows the spatial distribution of water temperature, salinity, dissolved oxygen, chlorophyll-a measured by boat in the bay at the time when the cold water appeared near the bottom layer. On July 15, low temperature and high salinity water was observed in the entire bay, while cold water intrusion appeared only near the bottom at the west side of bay mouth on July 25. It is found that there are some patterns about bottom intrusion.

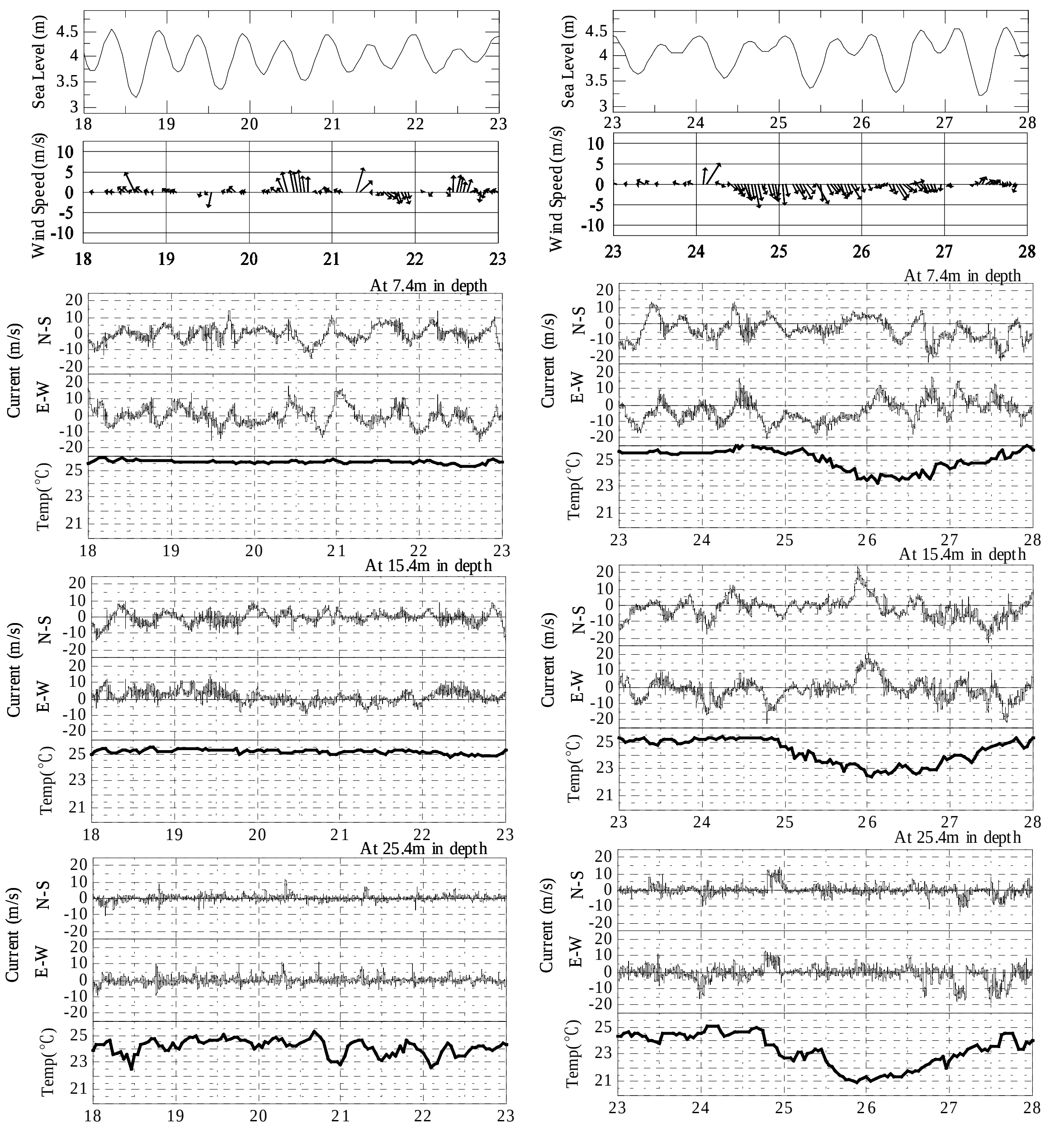
It is noticed that these discussions are only based on the data fragments, such as ADCP data at the bay mouth and the boat observation data. To understand continuous structure and behavior of coastal water exchanges, we may need the aid of numerical model.

4. Numerical Experiment

4.1 POM modification

Current field and scalar transportation are simulated by the Princeton Ocean Model (POM), which is open-domain software to simulate ocean circulation. POM is fully three-dimensional model with free surface in the sigma coordinates. Its basic equations and a more extensive discussion of the features of model can be seen in the reference of Blumberg and Mellor (1987).

To overcome the numerical error in computing the horizontal pressure gradient forcing in water temperature and salinity computation, we use the



(c) 3rd period (July 18 to 22)   (d) 4th period (July 23 to 27)

Fig.8 (b) Time series of the tide, wind and current at TNSSOT

method by Stelling and van Kester (1994) in this study. Stelling and van Kester (SVK) method is the revision method for the calculation of horizontal pressure gradient in sigma coordinates models.

In order to take the influence of Kuroshio Current into the computation, the data of JCOPE (Japan Coastal Ocean Predictability Experiment) supplied by the Earth Frontier Project was employed. JCOPE is an experimental research to study possibility of marine-state forecast for the seas around Japan. Since its dataset is two-day averaged, we cannot use is as a boundary condition of our computation. Then, we first re-computed oceanographic states in the computational domain including the Kii Channel (the largest computational domain) by using JCOPE data as its boundary condition. Two-time nesting was done to focus on the computational domain of Tanabe Bay (**Figure 10**). Horizontal grid sizes are 10km, 2km and 400m for three nesting computational domains, respectively and the number of vertical layer is 35 for all domains. The Grid Point Value (GPV) supplied by the Japan Meteorological Agency (JMA) was used for meteorological forcing and the simulation period is eight days from July 8 to 16.

4.2 Results and discussions

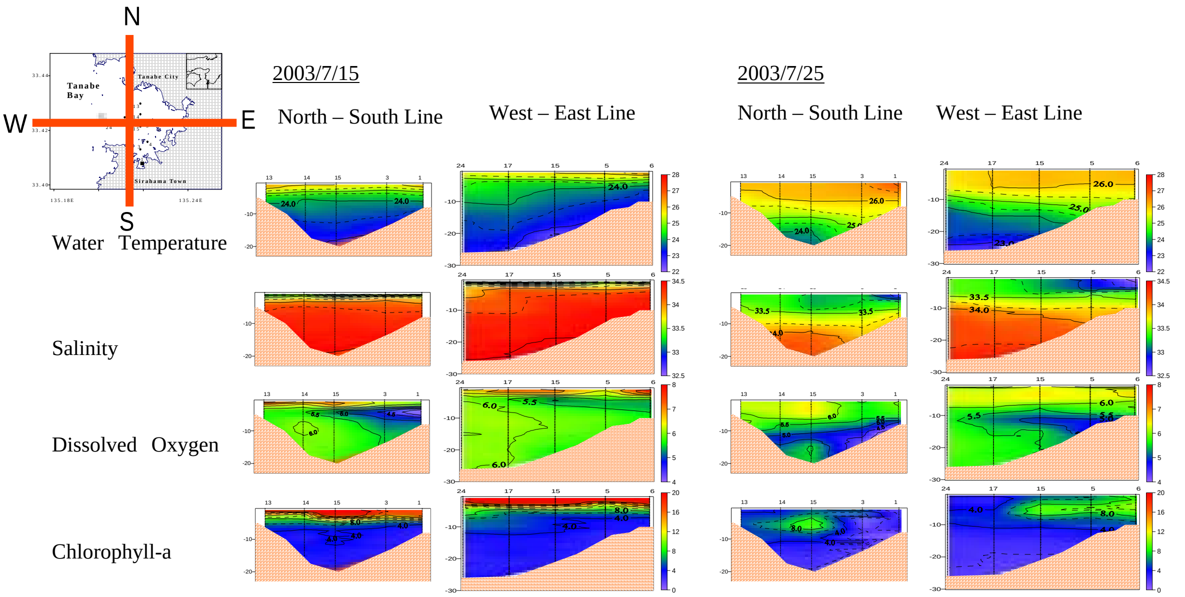


Fig.9 The spatial distribution of water temperature, salinity, dissolved oxygen, chlorophyll-a measured by boat in the bay at the time

Figure 11 shows the computational results of the vertical distribution of current along the output line of middle of Kii Channel on July 14, when the pressure gradient was large. In order to examine the atmospheric pressure effects on computed current field, two cases of computation were conducted , by using practical and fixed atmospheric pressure conditions. Since the sea surface currents is strongly affected by the surface winds, the difference of two current field computed is not so large in **Fig.11**. On the other hand, the computed currents in the middle and bottom layer using a practical atmospheric pressure condition is 2-3 cm/s lager than the results computed with the fixed atmospheric pressure condition.

Figure 12 shows the computation result of the vertical distribution of water current at the mouth of Tanabe Bay. This is the result on July 14 afternoons when the cold water intrusion started. Although the vertical profiles show the similar trend to the observation, the computed peak intensity is a little bit small. One possible reason is that the structure of internal tide in the Tanabe Bay is not reproduced well in the model. **Figure 13** shows the computation result of the distribution of water temperature along the east-west line in Tanabe Bay. The computational results show that bottom intrusion on July 15 is reproduced well by the modified POM. The model roughly predicts the distribution of water temperature and salinity caused by the bottom intrusion of cold water. However the computed water temperature and salinity are higher than observed one because the computed current peak is lower than observation.

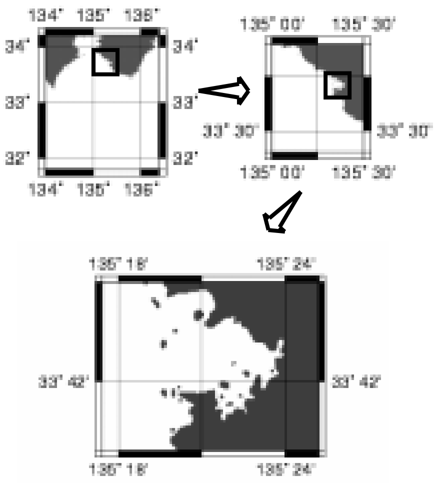


Fig.10 Computation domain

5 Conclusions

1. It can be found that when the Kuroshio moves toward the Kii Peninsula, the sea level rises and warm water intrudes in to the bay in the surface

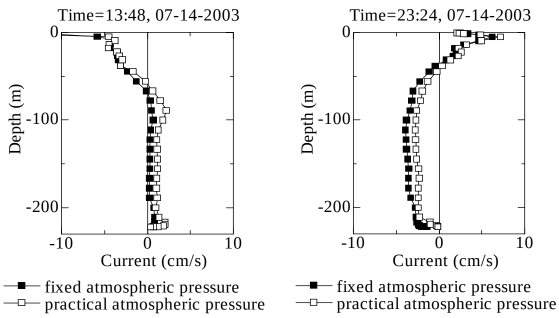


Fig.11 Computational results of the vertical distribution of current along the output line of middle of Kii Channel on July 14

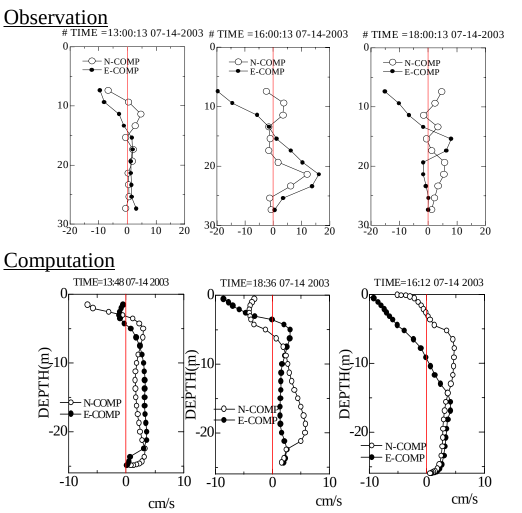


Fig.12 Vertical distribution of water current at the mouth of Tanabe Bay

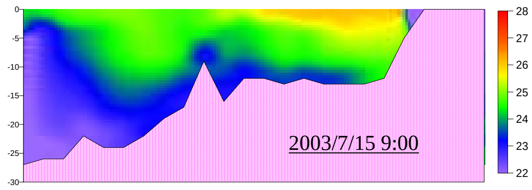


Fig.13 Computation result of the distribution of water temperature along the east-west line in Tanabe Bay

layer and block the cold water near the bottom.

2. It has also clear correlation between bottom water temperature and atmospheric pressure drop. This is clearly shown in the data of July 15 and 25, when a sudden drop of atmospheric pressure was observed in the Tanabe Bay. The gradient of atmospheric pressure and the gradient of sea level may be a important factor which induces water exchange in the Tanabe Bay.
3. In the ebb phase from lower high water on the afternoon of July 14 to higher low water the direction of flow was not west (tidal current direction) but east in all layer. This flow is opposite to the direction of ebb tide. This phenomenon induced the sudden changes in water temperature.
4. On 7/15, low temperature and high salinity water spread into entire of the bay, while on 7/25, bottom intrusion appeared only near the bottom at the west side of bay mouth. It is found that there are some patterns about bottom intrusion.
5. To understand seawater exchange on Tanabe Bay, the numerical model is established and roughly predicts the distribution of water temperature and salinity caused by the bottom intrusion of cold water. However the computed water temperature and salinity are higher than observed one because the computed current peak is lower than observation

Acknowledgements

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References

Blumberg, A. F. and G. L. Mellor (1987): A description of a three-dimensional coastal ocean circulation model, In N. S. Heaps (Ed.), *Three-Dimensional Coastal Ocean Models*, American Geophysical Union, Washington, DC, Vol. 4, pp. 1-16.

Stelling, G .S. and J. A. Th. M. vanKester (1994): On the approximation of horizontal gradients in sigma co-ordinates for bathymetry with steep bottom slope, *Int. J. numer. methods fluids*, 18 pp.915-935.

Yoshioka, H. S. Serizawa, T. Takayama and Y. Tanaka (1998): The Water Exchange of Tanabe Bay in Summer Induced by Internal Kyusho, *Proc. Coastal Eng.*, JSCE, Vol.45., pp.456-460.(in Japanese)

要　旨

田辺湾において，進入外洋水の湾内挙動の把握を目的とした広域観測を実施し，さらに，数値モデルによる追算を行うことで，海水交換機構および進入外洋水の湾内での挙動を検討した。その結果，黒潮の影響による表層への暖水の進入や，底層への外海水の浸入阻害が確認された。また，大気圧勾配に駆動される大規模な海水流動により，外洋の底層水が湾内に進入する可能性が指摘され，数値計算もこうした結果を支持するものであった。

キーワード：海水交換，内部急潮，黒潮，POM

COE-15

田辺湾への外洋水侵入過程の数値シミュレーション

○仁木将人

1．研究の目的

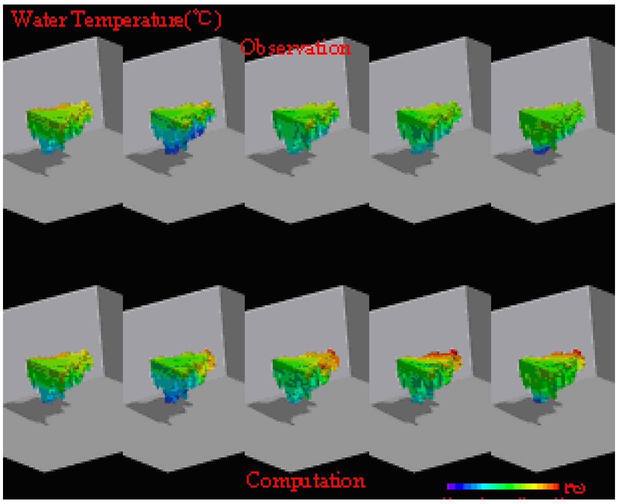
和歌山県の田辺湾では，夏期における湾内での海水交換機構解明のため，1998 年から海域環境モニタリングが行われるようになり，現在6年目を向かえている．その結果，北東風に起因する外洋水の進入が内部潮汐と結合する内部急潮の存在を確認し（吉岡ら，1998），湾奥での植物プランクトンの増減を湾口水質の変化と関連づけるニューラルネットワークによる予測モデルの構築（朴ら，2003）が行われた．一方で西側湾口を紀伊水道に面する田辺湾では，その内湾水質に対して黒潮蛇行の影響が考えられることから，外洋水の進入に関して風および黒潮流路，両者の視点から考察が求められる．

2003 年度海域環境モニタリングでは，進入外洋水の湾内挙動の把握を目的として，観測船を利用した湾内広域観測を例年の 3〜5 倍の頻度で重点的に行った．また，広域観測結果を数値モデルにより追算し，時空間的に補完することにより，田辺湾での海水交換機構および進入外洋水の湾内での挙動を考察しようと試みている．本講演では，数値モデルによる追算に関して詳説する．

2．モデルの概要

海域の物理現象を精緻に予測するためには，大気・海洋間の運動量の交換を表現可能な，大気・波浪・海洋連結モデルが必要である．また，本研究のように沿岸域への外洋の影響を見積もろうとするためには，沿岸域での計算のみならず外洋といった大領域での計算結果をネスティングし小領域の計算に反映させることが求められる．そこでまずは，連結モデルの一つの核となる準３次元海洋循環モデルである，POM(Prinston Ocean Model)を用いて田辺湾の流動および物質輸送の追算を行いその課題を検討する．

POM はσ座標を採用しているため海底地形形状の再現性に優れるが，急勾配の地形での物質の移流・拡散を計算する場合，水平方向に隣り合うメッシュの水深が異なり，互いに水深の異なる地点の物質量どうしを比較してしまう．このため，実際には生じない密度勾配が生じ，水平圧力勾配や水平拡散勾配の計算に誤差が発生する．こうした数値誤差をおさえる手段として，2 つの座標系を採用することで歪みを小さくするものや，水平勾配や圧力勾配の計算に補正を加えるものが考えられている．本研究では，σ-z 座標系の組み合わせによるモデル，水平圧力勾配の計算に補正を加える SVK 法ならびにスカラー輸送について z 座標系に変換したモデルでの計算を比較検討する．



計算結果と観測結果