Response to Reviewer #1

Review of os-2021-96

"Air-sea heat flux during warming season determines the interannual variation of bottom cold water mass in a semi-enclosed bay" by Junying Zhu et al.

Recommendation:

Major revision

Summary:

The authors investigated the interannual variation of a bottom cold water mass (BCWM) formed in the summer in Iyo-Nada, the Seto Inland Sea, based on ship-based hydraulic observations and a three-dimensional hydrodynamic model. The results indicate that the heat transport during the stratification season may affect the interannual variation, in addition to water temperature before the season (so-called pre-conditioning). They also considered that control factors of interannual variations differ depending on the size of BCWMs, through comparison of BCWMs in some regions. These results are important in understanding changes in coastal seas and predicting future changes under climate change. I recommend that the paper be published in Ocean Science after some major revisions. My concerns are listed in *Major comments* below.

Thanks for your careful reading and comment. Following your comments, we have finished a comprehensive revision on the original manuscript. Below is a point-to-point response.

Major comments:

1. As a central result of this paper, Figure 5 shows that the interannual variation of the Iyo-Nada bottom cold water mass (INCWM) depends on both the local water temperature in April (the horizontal axis) and the water temperature at the strait in July (the vertical axis). This means that the INCWM are affected by both the early pre-conditioning and the horizontal heat advection during the stratification season (summer). I think this is the most important result of this paper, but is that okay? If so, it appears to be inconsistent with discussion of Sec. 4.1, which emphasizes sea surface heat

flux as the main factor based on model results. I suggest to reconsider the title of the paper, too.

Thanks for your careful reading. We analyzed the processes influencing the interannual variations of the INCWM in Section 3.3. According to Fig. 5, we found that the influencing processes are not only the early pre-conditioning, but also the vertical and horizontal heat advection during warming season. Since the temperature in April which means pre-conditioning and that at Hayasui Strait in July (which showed the horizontal heat advection) is easier to obtain than the index for vertical heat advection in summer, so we plotted the Figure 6 to show the relationship between the two factors and INCWM intensity. However, the vertical heat transfer is also important which is not easily indicated by observed water temperature in Fig. 6. We modified the description to avoid this misunderstanding in Section 3.3.

"As a summary, the temperature change of INCWM in July on an interannual scale is controlled by three heat transfer processes, i.e., the local retention of bottom low water temperature from early spring, local vertical heat diffusion from May to July and horizontal heat advection originating from Hayasui Strait in July (Fig. 6). Since the water temperatures in April and that at Hayasui Strait in July are easy to obtain from observation. The relationship between them with the INCWM intensity is shown in Fig. 7. A strong INCWM corresponds to a combination of a low local initial water temperature in April (11.0-12.5 ℃) and a low water temperature at 10-50 m deep at station R in July (19.5-20.3 ℃). Conversely, a weak INCWM usually corresponds to a combination of a high local initial water temperature in April (11.7-14.1 ℃) and a high water temperature (19.8-20.9 ℃) in the Hayasui Strait at depths of 10-50 m in July. This provides an intuitive understanding about the INCWM intensity and its relationship with initial water temperature before formation and remote horizontal heat advection in July. However, it is noted to say that local vertical heat transfer during warming seasons is not included in Figure 7."

Global climate change affects coastal seas via regional sea surface forcing. Previous studies had suggested that air-sea heat flux is the key factor for water temperature variation inside the Seto Inland Sea (Tsutsumi and Guo, 2016) and an important factor influencing the variation of other BCWMs (Zhu et al., 2018). Combined with observation results, we discussed the influence of air-sea heat flux to INCWM characteristics using a hydrodynamic model in Section 4.1 and several sensitivity numerical experiments. The Section 4.1 is a further discussion based on Figure 6 and it is consistent with Figure 6.

In this study, we demonstrated the interannual variation of INCWM and its influence process using long-term observation data, and discussed the sensitivity of INCWM to air-sea heat flux changes. According to your suggestion and our deep thinking, we changed the title to "Interannual variation of a bottom cold water mass in the Seto Inland Sea, Japan" in the revised manuscript.

(a) P.9 L. 213-220

Please emphasize that important results were obtained indicating that the interannual variation depends on both.

Thanks and changed as your suggestion. We demonstrated the importance of not only water temperature before INCWM formation, but also the heat transport processes (horizontal and vertical) during warming seasons for interannual variation of INCWM in the last paragraph in Section 3.3.

(b) P.11 L.245 *we conclude that the vertical and horizontal heat transport processes in the warming season, rather than the initial condition preserved from the previous winter, are responsible for interannual variation in the INCWM in July.*

First, the evaluation of the vertical heat flux seems to be inconsistent with the observational results, and so an explanation to address it is needed. Next, Fig. 5 shows that the initial temperature is also important. I do not think the expression "rather than" is grounded.

Thanks for your comment. The Fig.5 has been changed as Fig. 6 in the revised manuscript. First, for influencing process on interannual variation of INCWM, we demonstrated the importance of early pre-conditioning, the vertical heat transport during warming season (from May to July) and horizontal heat advection in July according to observation data (Figure 5). Figure 6 just provides an intuitive understanding about INCWM intensity and initial water temperature before formation and horizontal heat advection in summer. We did not compare the relative importance among the three processes based on observation data.

In the old manuscript, we tried to quantify the contribution of sea surface forcing on interannual variation of INCWM using an index (*cr*). However, *cr* has no clear physical meaning and is not suitable to assess the contribution rate. Therefore, we remove the information about *cr* in the revised manuscript. We just evaluated the sensitivity of INCWM to air-sea heat flux changs.

By comparing sensitivity coefficient q in the vertical and horizontal plane, as well as heat content of INCWM change (Table 2), the conclusion was changed as "*From the three sensitivity numerical experiments, we concluded that INCWM characteristics were more sensitive to air-sea heat flux changes during warming seasons than those in the previous winter*" in the last paragraph in Section 4.1.

(c) P.12 L.281 *we found that the vertical and horizontal heating processes during the warming season, rather than the initial temperature before warming, were the dominant factor for interannual variation in the INCWM.*

Reconsider this part following the above comment (b).

Refer to the answer for the previous question, according to sensitivity numerical experiments, we have changed the sentence as "*INCWM was more sensitive to air-sea heat flux change in summer than that in the previous winter*" in the third paragraph in Section 4.2.

(d) P.14 Table 3

As explained above, I do not think that the "Main factor" of "Iyo-Nada" is only "Air-sea heat flux during stratified seasons".

We reconsidered the influence factor based on the results of sensitivity numerical experiments and changed as "*more sensitive to air-sea heat flux change during warming seasons than that in the previous winter*" in Table 3.

(e) P.17 *Therefore, with respect to interannual variation in the INCWM, the heat transport process during the warming season is more important than the initial temperature after the cooling season.*

As noted above, I do not think that "more important" is well-founded.

As answered above, we changed as "*Sensitivity numerical experiments showed that the air-sea heat flux change during the warming season plays an important role in the interannual variation of the INCWM its sensitivity coefficient is larger than that in the previous winter. This means that the heat transport process during the warming season impacted by air-sea heat flux change might be the priority with respect to interannual variation in the INCWM*" in the first paragraph in Section 5.

2. Temperature distribution of the INCWM should be shown, not only for the average, but at least for a strong-INCWM year and a weak-INCWM year. In July of Fig.2a alone, the reader does not know what kind of interannual change have occured as a whole. It is also necessary to explain that the July analysis is sufficient. (The same result can be obtained for August, right?)

Thanks for your suggestions. We add the temperature distribution of the INCWM in July from 1994 to 2015 in the Supplementary Fig. 3 and characteristics of INCWM in July in Supplementary Table 2. Meanwhile, we add the relevant description about the interannual variation of INCWM in Section 3.1.

In August, the INCWM also exists in the vertical transect (Supplementary Fig. 4) with minimum water temperature ranging 18.52℃ (1996) – 20.75℃ (2014) which is 2℃-3 ℃ higher than that in July. We calculated the average temperature and area surround by an isotherm of 20℃ as Supplementary Fig. 4 shown. The results also showed significant negative correlation between average temperature and area which is consistent with the relationship in July. However, there was no significant correlation for interannual variation of INCWM characteristics between July and August. Because more typhoons pass through Japan in August than in July (http://www.data.jma.go.jp/obd/stats/data/bosai/tornado/stats/monthly.html), we use the INCWM in July to explore the interannual variation of INCWM in this study to avoid the episodic impact of typhoon as far as possible. The information about INCWM in August has added in the second paragraph in Section 3.1.

3. A schematic diagram will help the reader's understanding. I want the figure to include a estuary circulation. It would also be better if the figure could be applied to the discussion of "cylinder" in Sec. 4.2.

Thanks for your suggestion. We plotted the schematic diagram (below) of seasonal evolution of INCWM from the previous winter to this summer according to Takeoka (2002), Yu et al. (2016) and Yu and Guo (2018) as Fig. 6 in the revised manuscript. In summer, a density-induced gravitational circulation occurs as the bottom water flows from the Hayasui Strait to Iyo-Nada, whereas the surface water flows in the opposite direction. This circulation can be enhanced in July by an abrupt increase in river discharge into the Seto Inland Sea. The figure helps to understand the heat transport process about INCWM.

In Section 4.2, we simplified BCWM as a cylinder as the horizontal scale of BCWM is much larger than vertical scale. However, the vertical scale is enlarged in the schematic diagram for appropriate presentation (Fig. 6). The schematic diagram is not suitable for the discussion of ”cylinder” in Section 4.2. We showed the ”cylinder” in Fig. 8 to present the discussion result in Section 4.2, which means that the size of INCWM is an important factor for investigating interannual variation of BCWMs.

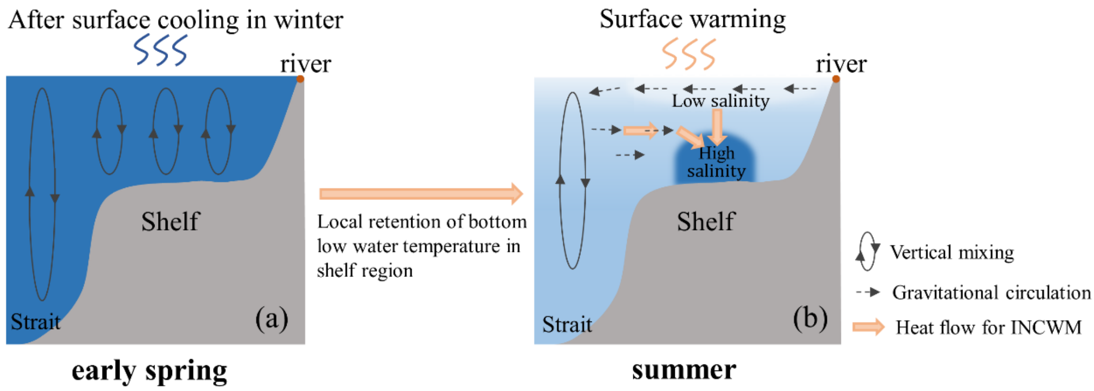


Figure A schematic diagram of seasonal evolution of INCWM from early spring to summer, which is drawn from references Takeoka (2002), Yu et al. (2016) and Yu and Guo (2018). Low water temperature is indicated by dark blue while high water temperature by light blue.

4. Descriptions of the observation and the model specifications are insufficient. Please enrich the explanations.

(a) P.3 Sec. 2.1

It is not enough to explain the observation data only in the first paragraph. Please supplement information on observation methods and accuracy. Are there any documents to refer to?

The observation data was collected from Ehime Prefectural Fishery Research Centers (https://www.pref.ehime.jp/h35115/ehime-suiken.html), we have added relevant description in the first paragraph in Section 2.1 and Supplementary Table 1. The water temperature was measured by ALEC CTD carried by survey vessel “Yoshuu” (よしゅう). The measurement accuracy is 0.001 degree. We add the information in Section 2.1.

(b) P.5 Sec. 2.2

Although written in Zhu et al. (2019), this paper should also outline the model. The following explanations are necessary at least.

i. Model specifications: horizontal resolution, vertical resolution, region, basic classification of model (hydrostatic model? depth-coordinate model?), settings of tides

ii. Experimental settings: initial value, integration period, lateral boundary conditions, sea surface boundary conditions (moved from Sec. 2.3 to Sec. 2.2), rivers

iii. The purpose of using multi-year average (climatological normal) data, instead of actual historical data, for sea surface forcings.

Thanks for your suggestions. We have added the detailed model configuration formation in the first paragraph in Section 2.2.

"Model domain is 130.98°E-135.5°E, 32.8°N-34.8°N covering the entire Seto Inland Sea. The model has a horizontal resolution of around 1 km (1/80° in the zonal direction and 1/120° in the meridional direction), and a vertical resolution of 21 sigma levels. The initial temperature and salinity fields in January were produced by merging the Marine Information Research Center dataset in the SIS region and the model results of Guo et al. (2003). The boundary conditions including de-tided current velocity, temperature, salinity, and surface elevation were obtained from the diagnostic model of Guo et al. (2004). Four major tidal constituents (M2, S2, O1 and K1) were considered and the daily river discharges averaged over 24 years (1993–2016) from the Ministry of Land, Infrastructure and Transport were used in the model. Multi-year averaged daily surface fluxes of momentum, heat and fresh water was used to drive model (Zhu et al., 2019). The daily wind stress was based on hourly averaged results of wind stress, which was calculated by wind velocity from the Grid Point Value of Meso-Scale Model (GPV-MSM) (http:// database.rish.kyoto-u.ac.jp/arch/jmadata/data/gpv/) during 2007–2016 provided by the Japan Meteorological Agency with the resolution of 1/16°×1/20°, adopting the drag coefficient of Large and Pond (1981). The daily shortwave radiation was based on the newly released of Japanese Ocean Flux Data Sets with Use of Remote Sensing Observation (J-OFURO3) (https://j-ofuro.scc.u-tokai.ac.jp/) with a resolution of 1/4°×1/4° and averaged during 2002 to 2013. The daily longwave, sensible heat flux and latent heat flux were calculated and averaged by adopting bulk formula (Gill, 1982) using hourly air temperature, sea surface temperature, relative humidity, cloud cover, and wind velocity from the GPV-MSM (2007–2016). Daily evaporation was obtained by calculating the latent heat flux. The daily precipitation was provided by the GPV-MSM and averaged hourly from 2007 to 2016."

5. It is necessary to improve the structure of the paper to make it easier to understand. I think it is better

that explanation of the analysis method is moved from Sec. 2 to the result sections. Please consider the following modifications.

（a）P.5 The first paragraph

Move it to Sec 3.1。

Thanks and changed as your suggestion.

（b）P.6 Sec. 2.3

Move the explanation of the sensitivity coefficient *q* to Sec. 4.1, since it is used only there. Also, by moving it after defining INCWM, the explanation will be easier to understand. In addition, I could not follow what *cr* means. The authors need to brush up the explanation. I think that the explanation of the experimental cases should be moved to Sec. 2.2.

Thanks for your suggestions. We tried to explore the sensitivity of INCWM to sea surface forcing changes in Sec. 4.1, according to peer reviews and deep thinking, the *cr* was removed in the revised manuscript because it could not account for the contribution of one factor on interannual variation of INCWM.

The sensitivity coefficient *q* was used to quantify the response of INCWM to sea surface forcing changes. As your suggestion, we move the explanation of the sensitivity coefficient *q* to Section 4.1 and move the explanation of the experimental cases to Sec. 2.2.

Minor Comments:

6. P.1 L.14: *The interannual variation in water temperature inside the INCWM showed a negative correlation with the area of the INCWM,*

It is difficult to understand what kind of interannual variations has been observed. Please give a brief explanation using rough numbers, such as temperature and volume in strong-INCWM years and weak-INCWM years.

Response:

Thanks and changed as suggestion. We changed the sentence as "*Surrounded by 18 ℃ isotherm, The observed multi-year average water temperature inside the INCWM was 17.58 ℃ with a standard deviation of 0.27 ℃, while the mean area of INCWM was 5.73×105 m2 with a standard deviation of 4.35×105 m2. Their interannual variation showed a negative correlation with the area of the INCWM that indicates a low temperature corresponds to a big area*".

7. P.5 L.100 *The mean range of change over the entire study period is denoted by the mean value of the absolute value of* ΔX_i

I think that the standard deviation is usually used, when the magnitude of variation over time is investigated. Explain why you use this definition.

Thanks your suggestion. As your suggestion, we have already used the standard deviation to get the intensity of INCWM. Using the standard deviation, we only get one strong INCWM year (2006) and two weak INCWM years (1997 and 2014). The INCWM intensity in other year was not recognized which is not beneficial to analyze characteristic of strong and weak INCWM years in Fig. 5. To widely identify the intensity of INCWM, we used the method described in the paper which have been applied to Yellow Sea Cold Water Mass (Zhu et al., 2018) to get the intensity of INCWM. By this method, the strong INCWM year (2006) and weak INCWM years (1997 and 2014) identified by the standard deviation were also recognized, meanwhile, it recognized the INCWM intensity in other years which is beneficial to analyze characteristic of strong and weak INCWM years in Fig. 7. Therefore, it was better to get the INCWM intensity using this method than the standard deviation.

8. P.7 L.156 *the average water temperature and area inside the 18 C isotherm were calculated.*

Please write the formula for calculating the area-averaged value from the observation data, in order to show the treatment of the area.

Thanks your suggestion. We add the following description of the calculation method in the first paragraph of Section 3.1.

"*When calculating the average temperature and area of INCWM along the vertical across-section, we first interpolated the observed water temperature into a rectangular mesh grids (0.01 ° × 1 m) to get a temperature field, and then calculated the area of grids where temperature less than 18 ℃ and average temperature within these grids. If there was no water temperature less than 18 ℃ in the vertical transection, the observed temperature at the average location of the INCWM (50 m deep at station 3) as the average temperature and the area is set to zero*."

9. P.12 L.266 *Compared with these BCWMs,*

I think the expression "In the same way as in these BCWMs" is better to indicate that the INCWM has the same characteristics as BCWMs in other regions.

Thanks and changed as suggestion.

10. P.12 L.285

Clarify the purpose of the analysis in the rest of this section.

Thanks for your suggestions, we added the sentences "*It is suggested that influence factors for interannual variations of BCWMs vary in different coastal seas though their seasonal cycles and formation processes are similar. This shows the unique response of different shelf seas to climate change. Since BCWMs have important effects on ecosystem and fishery, this finding also provides an insight to understand the different interannual changes of ecosystem and fishery in coastal seas with BCWMs*.

11. P.15 L.335 *As R is much larger than H (at least 1000 times), the influence of* Δm *is supposed to be more important than that of* Δn.

Is it true? The heat flux fluctuation due to horizontal advection, Δn, can be larger by several orders of magnitude than the air-sea heat flux fluctuation, Δm. And, this sentence seems to be inconsistent with the argument that horizontal advection from the strait is more important for interannual variation than the local sea surface heat flux during the stratification season, based on the results of Fig. 4 and Fig. 5.

Kindly, based on Fig. 5, we demonstrated the importance of early pre-conditioning, the vertical heat transport during warming season (from May to July) and horizontal heat advection in July. However, we did not compare the relative importance among the three processes based on observation data. As for Fig. 7, we just showed the relationship between INCWM intensity and local water temperature in April, water temperature of Hayasui Strait in July. We changed the description of Fig. 5 and Fig. 7 to avoid this misunderstanding in the revised manuscript.

Thanks for your comment. For the sentence, Δm is the variation value of air-sea heat flux on an interannual scale, and Δn is the variation in the lateral heat flux on an interannual scale. Since Δn is not easily to be evaluated, this statement is too arbitrary though R is much larger than H (at least 1000 times). We changed this sentence as "*As* Δn *is not easily to be evaluated, we could not evaluate the importance of* $\Delta m \cdot R$ *and* $\Delta n \cdot H$*, though* R *is much larger than H (at least 1000 times)*" in Section 4.2.

12. P.17 L.368 *The interannual variation of the mean water temperature inside the INCWM and that of*

its area show a significant negative correlation.

Explain in detail the interannual variation. (See my comment No.6.)

Thanks for your comment. We have added the description about the interannual variation of INCWM in the Section 5.

"*Observation shows that the INCWM is not significant in 2007 with water temperature higher than 18 ℃. The mean water temperature inside the INCWM was 17.58 ℃ with the lowest temperature 17.04 ℃ (2006) and the highest temperature 18.23 ℃ (2007), while the mean area of INCWM was 5.73×106 m2 with the smallest area 0 m2 (2007) and the largest area 1.46× 106 m2 (2006). The interannual variation of the mean water temperature inside the INCWM and that of its area show a significant negative correlation*"

13. P.17 L.383 *As an extension, we analyzed the control processes on interannual variation of water temperature in the five BCWMs reported in the literatures using a cylinder column to represent their shape.*

This sentence alone is difficult to understand. It is desirable to add a schematic diagram.

Thanks for your suggestion. We added a schematic diagram of seasonal evolution of INCWM in Fig. 6 and "cylinder column" in Fig. 9 to make it clear. we simplified BCWM as a cylinder as the horizontal scale of BCWM is much larger than vertical scale. In Fig. 9, the cylinder at the bottom means the size of BCWM for which the horizontal and vertical are not proportional.

14. P.4 Fig. 2

Add a panel number for each month, such as Fig.2 (a) for January, Fig.2 (b) for April etc.

Thank you and changed as suggestion.

15. P.6 Table 1

Add the CONTROL experiment to the table.

Thank and changed as suggestion.

16. P.7 Fig. 3

The "area" means "vertical cross-section area"? It may be misunderstood like a horizontal area.

Thanks for your suggestion. The "area" means "vertical cross-section area" and we have changed the wording in Fig. 4.

17. P.8 Fig. 4

The example marks at the bottom right of the figure should be changed from an open circle and star to a closed circle and star.

Thank you and changed as suggestion.

18. P.8 Fig. 4

This figure does not plot observation points with the significant difference level of 0.95 or less, right? Since it looks as if there had been no observations, those points should be also indicated (maybe black dots?).

Thanks for your suggestion. We repainted the Fig. 5 and marked correlation coefficients and significant difference levels at all observation depth of each station.

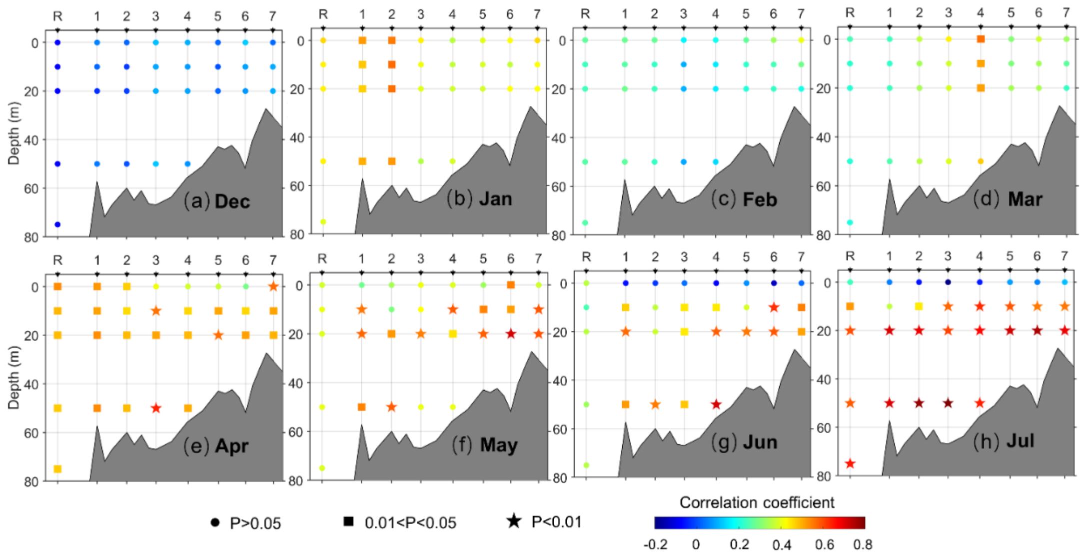


Figure 5: Correlation coefficients for interannual variation of water temperature at each station from previous December to July (a-h) and that of the Iyo-Nada bottom cold water mass (INCWM) mean water temperature in July during 1994-2015. Circles indicate that the significant difference level is less than 0.95, squares indicate a significant difference level is between 0.95 and 0.99, and stars indicate a significant difference level of more than 0.99.

Anonymous Referee #2

Referee comment on "Air-sea heat flux during warming season determines the interannual variation of bottom cold water mass in a semi-enclosed bay" by Junying Zhu et al., Ocean Sci. Discuss., https://doi.org/10.5194/os-2021-96-RC2, 2021

This paper focuses on the interannual variability of the cold water mass in Iyo-Nada, Japan, using both observations along a transect and three sensitivity runs of a hydrodynamic model (POM). The main conclusion of this study is that it is the heat transport during the warming season (May-July), rather than initial temperature before warming (Dec-Feb) that dominates the cold water mass's interannual variability. In the end, this paper also compares with other coastal cold water masses using idealized equations to explain why the inter annual variability of the INCWM is not dominated by initial temperature in winter.

This is an interesting topic, however, the major conclusion is not successfully delivered through the three sensitivity runs. As Table 1 suggests, the authors increased local and remote air-sea heat fluxes by 10% during the winter (Dec-Feb) and warming (May-July) seasons, in order to evaluate whether it is initial temperature change in winter or heat transports in warming season that dominates the interannual variability of the cold water mass. Design of these sensitivity runs does not separate these two roles at all, thus not convincing at all. Their reasoning is like this, process A + process B will lead to phenomenon C. The authors changed 1.1A kept B the same, and it leads to 1.3C, but the combination of A and 1.1B leads to larger change in C, so B is the dominant role for C, instead of A, which is funny.

For example, authors finally found Case 2 - increase air-sea heat flux by 10% during May- July that brings the largest q and cr(T) values. In this case, the interannual signal in initial temperature is still kept in the model, it is not convincing to conclude as the authors suggested, only if the initial temperature signal on interannual time scale is totally removed. On the other hand, the increase value (10%) is tricky as well. Authors at least need other runs with different increase values to make sure this 10% is not sensitive and the conclusion is still valid. Not to say the results suggested by cr(A) are not supporting, which also need reasonable explanation.

Another confusing and disappointing point is, the authors do use a numerical model to study the inter-annual variability of this cold water mass, but none of heat budget terms from the model is analyzed, which is super crucial for determining which physical process that is mainly contributing. The authors write many texts for the last part (Section 4.2), which is actually not that interesting. Too many idealized assumptions, e.g. no interannual variabilities in rho, R, and H? And the final conclusion of this part is obvious without these texts.

Therefore, this paper is suggested to modify their reasoning method (three sensitivity runs) and the paper structure (too many uninteresting texts in discussion and few analysis about heat budgets). Other comments are listed below.

Thanks for your careful reading and comments. Following your comments, we have finished a comprehensive revision on the original manuscript. Below is a point-to-point response.

We conducted a climatological simulation in the study. The two roles (initial temperature change in winter or heat transports in warming season) were not separated in the sensitivity runs because the climatological run did not contain the signals of interannual variability. The target of sensitivity runs about "1.1 process A + process B" and "process A + 1.1 process B" is to and explore the sensitivity of INCWM on air-sea heat flux. As your comment, it is not enough to get the dominant role for C, however, it can test for sensitivity. Though changed by 10% of a factor, we investigate the response of INCWM.

In the old manuscript, we try to quantify the contribution (*cr*) of one factor to interannual variation of INCWM using sensitivity coefficient q and the range of interannual variation of the factor (delta *f*). According to peer reviews and our deep thinking, *cr* has no significant physical meaning and is not suitable to account for the contribution of one factor on interannual variation of INCWM. Therefore, the content about *cr* is removed in the revised manuscript and focus on the sensitivity of INCWM rather than discussing the dominant factor.

After the comparison of different BCWMs with different influencing process for its interannual variation, we tried to explore the relationship among them which is helpful to understand the response of bottom water in coastal seas to climate change from a comprehensive perspective. The idealized derivation helps us to understand theoretically in Section 4.2 and this part is an extension of the study, so we keep this part. The structure of this paper has been reorganized in the revised manuscript.

Major Comments:

1. Section 2.1 does not include the time information of the observational dataset. Is it only collected in

Jan/Apr/July/Oct each year for all eight stations? It seems not true, because Figure 2b compares between observational datasets and model results on a time scale of multi-year monthly climatology. Also, How many obs. in each month are collected? Do you calculated monthly averages first?

Thanks for your comment. We added the observation year for each month in Iyo-Nada and Hayasui Strait during 1994-2015 (Supplementary Table 1) and the relevant information about observation in Section 2.1. We collected the observation data from January to December and calculated monthly average first. In Fig. 2, We add the vertical spatial distribution of monthly average temperature in the revised manuscript.

2. Figure 2a. In the text, it says the R station has a depth of 75m, but the figure only shows the upper 50m. In the caption, it says the 18°C isotherm is considered to define the studied cold water mass, which is better to be illustrated in the main text, e.g. the method section.

   Thanks for your comment and suggestion. Observation only has a depth of 75 m at R station, while the deepest observation at other stations are around 50 m and 20 m. To avoid unreliable interpolation, we did not show the water temperature at 75 m of station R. In the Section Introduction, we demonstrated that “The depth of Hayasui Strait is more than 100 m and the water temperature is homogenous throughout the year because of strong tidal mixing (Kobayashi et al., 2006)” to illustrate the vertical water temperature at station R. Also, we added the vertical distribution of multi-year average water temperature at station R in Supplementary Fig. 1 to show the seasonal variation of water temperature at Hayasui Strait in Section 2.1.

   A fixed isotherm is often used as the boundary of a cold water mass, such as 2 °C for Bering Sea Cold Water Mass (Zhang et al., 2012), 10 °C for the Middle Atlantic Bight Cold Pool (Yang et al., 2014) and 10 °C for Yellow Sea Cold Water Mass (Chen et al., 2018). As for INCWM in this study, we can see obvious bottom cold water below 18 °C occupying the central Iyo-Nada in the spatial distributions of temperature in July from 1994 to 2015 in Supplementary Fig. 3. Therefore, we use 18°C isotherm to define the INCWM in the study. We add relevant illustration in Section 2.1 and Section 3.1 in the revised manuscript.

3. Section 2.2 Model validation: This paper focuses on the interannual variability of the cold water mass, but only verified it on the multi-year average seasonal cycle (Figure 2b), and concluded that “Therefore, this model is suitable for examining the factors influencing the interannual variation in

the INCWM via sensitivity experiments. ” More comparisons between obs. and model results are needed to confirm model validation, including episodic and interannual time scales, transections comparisons.

Thanks for your comments. In the study, the model is driven by multi-year averaged daily surface fluxes of momentum, heat and fresh water. The primary aim of using numerical model is to study the response of INCWM to atmospheric changes by sensitivity experiments. Under the circumstances, a climatological model is applicable to do some sensitivity numerical experiments. Therefore, we validated the seasonal evolution of INCWM by the comparison with multi-year averaged observation data. We add information about the model configuration in Section 2.2 to make it clear.

4. Does the CONTROL run only have seasonal climatology or actually it is an interannual hindcast of this region? It should be clearly stated in the main text. If it only has seasonal climatology, it is not reasonable to compare with the three sensitivity runs, and evaluate the contributions of air-sea heat flux. If it is actually a hindcast, why authors do not show any interannual comparisons with observations to validate the model? Without validation of this model on interannual time scale, it’s really hard to trust and interpret the interannual results from the sensitivity runs. On the other hand, if authors do have a hindcast of this model from 1994-2015 and it shows solid results comparing with observations, it is pretty interesting to quantify the cold water mass properties on interannual time scale using the model as well. Because the observational dataset is only present at 8 stations with very coarse spatial resolution, however, the model has a three dimensional distribution of the cold water mass.

   Thanks for your comments. we used climatological forcing (multi-year average) in numerical model rather than an interannual hindcast. We add information in Section 2.2 to make it clear. In the study, we investigated the interannual variation of INCWM using long-term observation for the first time. The model was used for just evaluating the response of INCWM properties to sea surface forcing changes. As you said, we plan to conduct a hindcast to quantify the INCWM properties on interannual time scale detailly as a continuation of this work. Your comments also give us a lot of help. We show the shortcoming of the work and future plans in the last paragraph in Section 5.

   For the three-dimensional distribution of INCWM, we add the horizontal and vertical distribution of simulated INCWM based on model results in Section 2.1 and Section 4.1.

5. Ln 136-141: How the f time series is calculated? Is it area-averaged for each domain? How about delta f? Do they have units? If so, please add them to Table 2. The q is the absolute value of the relative change of Temp/Area. Therefore, it is not sure if it is a decrease or an increase in Temp/Area in sensitivity runs. Also, in Table 2, the q value for each case is ground to one value. Is it a multi-year average? More details needed for the calculations.

   Thanks for your comments. The calculation of q is changed as $q = \frac{T_{case} - T_{control}}{T_{control}}$ to show a decrease or an increase in Temp/Area in sensitivity runs. The q is calculated to demonstrate the relative change of INCWM characteristics between two cases (sensitivity run and Control). It is not a multi-year average. We changed the description in Section 4.1. As answered above, the content about cr is removed in the revised manuscript. As for f, it is only used in the calculation of cr. Therefore, we deleted the content about index (cr) and f in the revised manuscript.

6. Ln 193-194: April is selected as the initial month of the water mass formation, but figures only starts from April. To make the point, authors are suggested to show correlation panels at least for March as well. Ln95-97: the authors stated that "water temperature in April depended mainly on the cooling process, the initial temperature of the INCWM is likely associated with local air-sea heat flux from winter to early spring", any reference for it?

   Thanks for your suggestion and comment. As your suggestion, we added the figures of correlation coefficients from previous December to March in Fig. 5 which have little significant correlation.

   The sentence "water temperature in April depended mainly on the cooling process, the initial temperature of the INCWM is likely associated with local air-sea heat flux from winter to early spring" locates at Ln 195-197. Before April, the water mixes well under surface cooling and increasing wind in the previous winter, the air-sea sea heat controls the process of surface cooling, therefore, the air-sea heat flux is closely related to the water temperature at the early spring. Tsutsumi and Guo (2016) suggested the heat content inside the Seto Inland Sea (except for Bungo Channel and Kii Channel) from January to July mainly depended on air-sea heat fluxes through heat budget. Therefore, air-sea heat flux is an important factor for water temperature in April.

We changed the sentence as "*The water temperature in April is the result of cooling process in the previous winter. Tsutsumi and Guo (2016) suggested the heat content inside the Seto Inland Sea (except for Bungo Channel and Kii Channel) from January to July mainly depended on air-sea heat fluxes. the initial temperature of the INCWM is likely associated with local air-sea heat flux from winter to early spring*".

Reference:

Tsutsumi E, Guo X. Climatology and linear trends of seasonal water temperature and heat budget in a semi-enclosed sea connected to the Kuroshio region. Journal of Geophysical Research: Oceans, 2016, 121(7): 4649-4669.

7. Ln 198-199: "correlation coefficient below 10 m is larger in May-July than in April (Figs. 4b-d)" Actually it is not true based on Figure 4. Most of the markers show almost the same values, some even decreases, only two particular markers show the increase.

   Thanks for your carefully reading. We have changed the colormap to make the information clear. From the Figure 5 in the revised manuscript, it is clear to show that the correlation coefficient below 10 m in Iyo-Nada (Sta. 1-7) increased from April to May-July, especially May and July. In addition, the significant difference levels gradually enhanced from $0.01<p<0.05$ to $p<0.01$ from April to July.

   Correspondingly, we changed the sentence as "*As Fig. 5e-h shown, the correlation coefficient below 10 m in Iyo-Nada (Sta. 1-7) increased from April to May-July, especially in May and July. In addition, the significant difference levels gradually enhanced from $0.01<p<0.05$ to $p<0.01$ during this period, which indicated that heat transport into the INCWM from May to July is also important for the interannual variation of the INCWM in July*." in the second paragraph in Section 3.3.

8. Figure 5. The blue dots does not match those in Figure 3. Some dots are not denoted with years. Please add their years in the figure.

   Thanks for your careful reading. We checked the dots and corresponding years and found two strong years (2006 and 2008) were omitted in Fig. 4. As your suggestion, we added table (Supplementary Table 1) to show strong and weak years of INCWM and replot Fig. 4 and Fig. 7 in the revised manuscript.

9. Ln 245-247: This is a really confusing conclusion. cr(A) and cr(T) provide opposite results, which is obviously weird, as T and A are always strongly related, but clearly authors choose to trust cr(T) instead of cr(A). More explanations needed here.

   As mentioned above, according to peer reviews and our deep thinking, *cr* has no significant physical significance and is not suitable to account for the contribution of one factor on interannual variation of INCWM. Therefore, the content about *cr* is deleted in the revised manuscript.

10. Ln 253-256: Winds are weak during the warming season, how about cooling season, Dec-Feb? Case 1 should not be small, right? 0.006 and 0.06 are for case 2 and 3?

    Sorry for the rough description caused you to misunderstand. We mean that all the sensitivity coefficient in the experiments about wind are less than 0.00r and 0.06 for the temperature and area of the INCWM in the old manuscript. In the revised manuscript, considering the presence of essential strong wind in summer in the climatological model, we removed the results of wind experiments, and focus on the results of experiments about air-sea heat flux.

11. Section 4.2 Repeated texts for the different cold water masses. e.g. Ln 275-279 vs. Ln 323-329

    Thanks for your comment. We removed description on Ln 323-329.

Minor Comments:

12. Some sentences need to be improved in language., e.g. Ln 49-50: This sentence is suggested to be rephrased: “This study focuses on …”.

    Thanks for your suggestion. We rephrased the sentence as “*In this study, we focuses on the BCWM in Iyo-Nada, which connects the Bungo Channel with the Hayasui Strait (Fig. 1b)*” in the third paragraph in Section 1.

13. Ln 148: 1994-2012 or 1994-2015?

    In the old manuscript, the air-sea heat flux and wind stress provided by Japanese 55 year

Reanalysis (JRA55) are from 1994 to 2012. In the revised manuscript, we removed the relevant content about the index *cr*, so we deleted the information about the JRA 55 dataset which only used in the calculation of *cr*.

14. Ln 169: Figure 3 and caption do not match. It says authors used “18.23°C” as the average temperature, but the figure suggests 18°C for that year. Should it change to “18°C” to match the figure?

    Thanks for your comment. In the old manuscript, we used a red star to indicate 18.23°C but plot at the location of 18°C for facility performance. In the revised manuscript, we changed the red star in Fig. 4 to match 18.23°C.

15. The color scheme of Figure 4 is too similar from 0.45 to 0.75, and the markers are too small. Values where $p>0.05$ are also suggested to show, in order to see the correlation patterns.

    Thanks for your suggestion. We have changed the colormap and size of markers in Figure 5, and show the correlation coefficients with $p>0.05$ to see the correlation patterns.

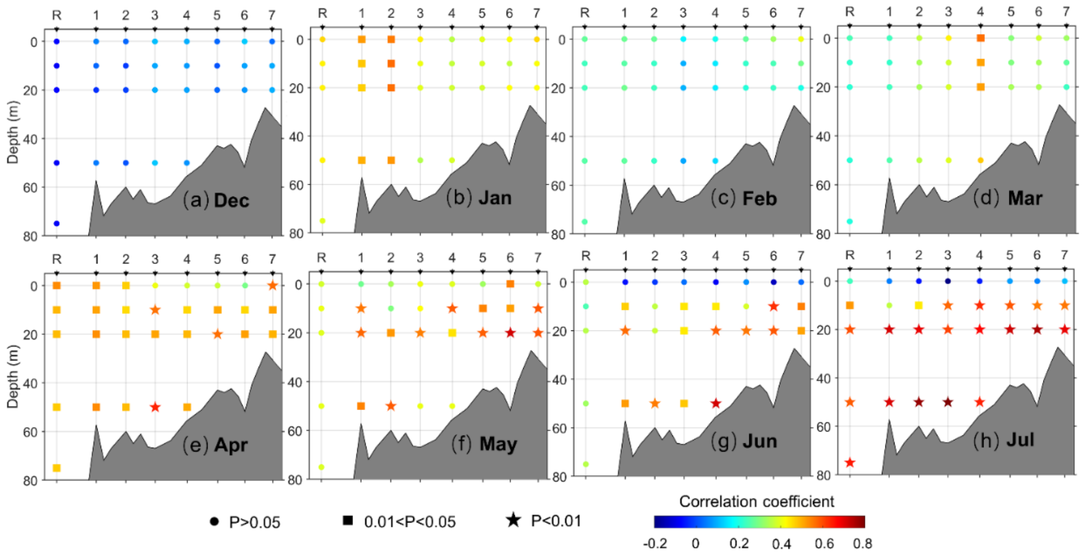


Figure 5: Correlation coefficients for interannual variation of water temperature at each station from previous December to July (a-h) and that of the Iyo-Nada bottom cold water mass (INCWM) mean water temperature in July during 1994-2015. Circles indicate that the significant difference level is less than 0.95, squares indicate a significant difference level is between 0.95 and 0.99, and stars indicate a significant difference level of more than 0.99.

Anonymous Referee #3

Referee comment on "Air-sea heat flux during warming season determines the interannual variation of bottom cold water mass in a semi-enclosed bay" by Junying Zhu et al., Ocean Sci. Discuss., https://doi.org/10.5194/os-2021-96-RC3, 2021

General comments

In this study, the determining factors of the intensity of cold bottom pools in shelf seas and bays are studied. The major study site is a semi-enclosed bay in Japan, but also generalisations to comparable bay are made. The major conclusion is that the strength of the cool pool sometimes depends on the previous winter SST (other studies) or on the air sea buoyancy flux during the warming season (this study). While these results are potentially interesting, I think that their value is limited here, since the methods used are not state of the art. The quantification of the cold pool strength depends on a highly site-specific empirical measure, rather than on energy considerations.
Furthermore, the applied numerical model uses climatological forcing rather than realistic forcing. With this, a comparison between model results and field observations is not possible and interannual variability, a major focus of this study, cannot be assessed. For these reasons, I recommend to reject the manuscript at this stage and motivate resubmission of a manuscript that uses state-of-the-art methods.

Thanks for your careful reading and comments. Following your comments, we have finished a comprehensive revision on the original manuscript. Below is a point-to-point response.

In this study, we demonstrated the interannual variation of INCWM and explored its influencing factor using observation and numerical model. For the bottom cold water in Seto Inland Sea (Japan), this paper is the first time to report its interannual variation, therefore, we focused on its interannual variation and preliminarily analyzed influencing processes.

As you said, the quantification of the cold pool strength depends on a highly site-specific empirical measure. The prefectural fishery research centers carried out regular hydrographic observations at monthly intervals in the Seto Inland Sea (stations are shown in Fig. 1). Yu et al. (2016) studied the location change of front around INCWM using the data from Station 1 to Station 7 (Fig. 1 here). They also showed the temperature difference between the surface layer (0 m) and bottom layer (the deepest sampling depth at each station) in the climatology data from April to September (Fig. 2 here). As Fig. 2 (below)shown, INCWM occurs from May to September and locates at the central area of Iyo-Nada. The temperature difference between surface and bottom reaches its maximum in July. The transection (Sta.1 to Sta. 7 in Fig. 1) we used in the study just across the middle of INCWM. Therefore, the measurements of water temperature along the transect from Sta. 1 to Sta. 7 are supposed to be suitable to explore its cold pool strength and interannual variation. In our model, the location of INCWM (Fig.3 in the revised manuscript) is consistent with observation.

In the development of cold pool when water volume changes from mixed water to thermocline, heat transport process is the key to maintain INCWM and influence its strength. Therefore, based on the results of observation, we considered the energy change when analyzing the influencing factor of

INCWM strength. In the discussion part, we compare the different BCWMs in different coastal seas from the viewpoint of energy. We thought that highly site-specific empirical measure and energy considerations are complementary. The discussion about energy helps us to understand BCWMs variation with limited observation. Of course, more site-specific empirical measure is indispensable for a deeper understanding of BCWMs.

In terms of numerical model, we actually use climatological forcing in numerical model rather than realistic forcing. The primary aim of using numerical model is to study the response of INCWM to atmospheric changes by sensitivity experiments. Under the circumstances, a climatological model is applicable. Therefore, we ran model using climatological forcing and validated model using climatology observation data. This is our first work to study the interannual variation of INCWM, and in the future work, we will apply realistic forcing to drive model for intensive study on interannual variation of BCWMs in the Seto Inland Sea.

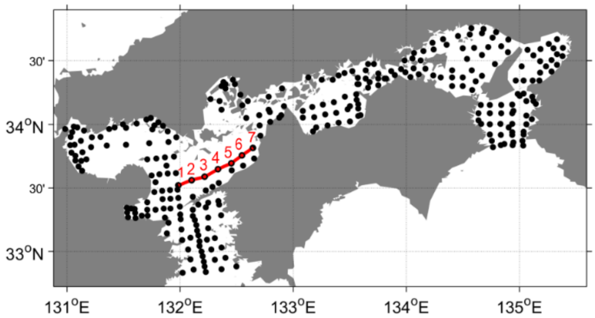


Fig. 1 All observation sites in Seto Inland Sea. Sta. 1-7 is used to study INCWM in our study.

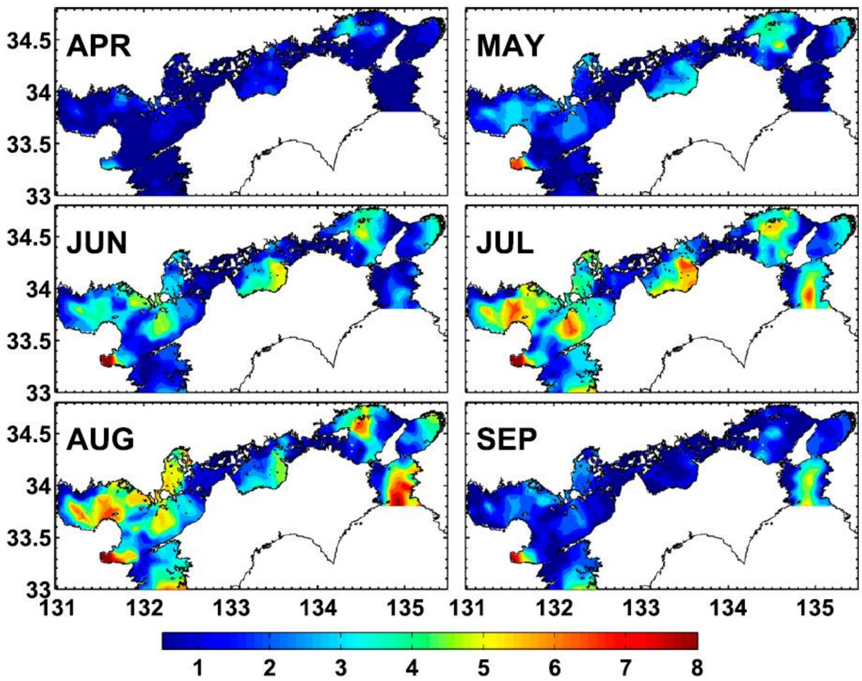


Fig. 2 Temperature difference between the surface layer (0 m) and bottom layer (the deepest sampling depth at each station) in the climatology data from April to September, obtained as averages of

data collected in the same months between 1971 to 2000. (from Yu et al., 2016)

Note: We collected the observation data from 1971 to 2015. However, the observation of Sta. 4 (around the central area of INCWM) starts from 1994, so we analyzed the interannual variation of INCWM from 1994 rather than 1971.

Specific comments

32-34: What defines a BCWM to be strong or weak? The temperature of it will certainly increase during spring and summer, such you probably define strength thought some temperature differences? Please specify.

Thanks for your suggestions. We have already considered to define BCWM intensity using temperature difference between spring and summer. However, this definition ignores the retention of water temperature in winter and only considers the temperature change from spring to summer. it is not suitable to define the NCWM intensity. Since BCWM steadily occurs almost every year, its performance characteristics, such as temperature and area, changes every year, are appropriate indicators to indicate its intensity. Therefore, we used the characteristics of water temperature and area of INCWM to define its intensity.

37: better "… and the Middle Atlantic Bight Cold …"

Thank and changed as your suggestion.

40: Isn't it more simply and more directly the winter temperatures of the vertically well mixed shelf sea waters and then probably also the summer SST that determine the strength of the BCWM? In addition to the heat fluxes, also laterally advective exchanges could set the temperatures. This is basically what you argue in lines 41-43.

Thanks for your comment. In lines 41-43, we just presented the result of Chen and Curchitser (2020) about the Middle Atlantic Bight Cold Pool whose interannual variation is related to the previous winter temperature and abnormal warming/cooling due to oceanic advection (including vertical and horizontal advection). In the paper, they also concluded that the winter (mid-January to March) temperature anomaly was the primary factor in determining the interannual variability of temperature anomaly near bottom cold pool region during the stratified seasons by a long-term numerical simulation. We did not emphasize the influence of laterally advective exchanges.

We are sorry that the improper expression caused your misunderstanding, we changed the sentence as "*Chen and Curchitser (2020) suggested that its temperature interannual variations during stratified seasons were controlled by both the previous winter temperature and abnormal warming/cooling due to total oceanic advection, and the winter (mid-January to March) temperature anomaly was the primary factor in determining the interannual variability of temperature anomaly near bottom cold pool region during the stratified seasons*." in lines 45-49 in the revised manuscript.

In terms of the factors determine the strength of the INCWM in this study, we calculated the correlation coefficients between the average temperature of the INCWM in July and the water temperatures at all the depths of each station from 1994 to 2015 for each month (from previous December to July). As shown in Fig. 5 in the revised manuscript, the water temperature of INCWM in July is not significantly related to winter well-mixed water temperatures and so is the summer SST. So, we could not use them to determine the strength of the INCWM. This also demonstrated the difference in control factors between INCWM and other bottom cold water masses (the Yellow Sea Cold Water Mass and the Middle Atlantic Bight Cold Pool).

74: make sure that you avoid double brackets “)(“.

Thank and we have rewritten the sentence to avoid double brackets in the first paragraph in Section 2.1.

94-96: This measure certainly depends on the position of the transect relative to the cold water pool. Therefore, it is not a suitable measure. Also temperature itself is not a good measure, because it is too site-specific. Temperatures differences between surface and bottom need to be involved. A better measure would for example be the thermal contribution of the potential energy anomaly, integrated over an entire bay. Or you could use the thermal contribution to the Available Potential Energy (APE) of the bay. This can easily be calculated by means of a numerical model. Measurements can be used to reconstruct this as well, when some assumptions about the geometry of the cold pool are made. The measure could be converted into a mixing time scale by division by the kinetic energy supply through tides and wind (plus/minus surface buoyancy flux contributions).

Thanks for your comments. As mentioned before, the measure in this study across the central area of INCWM. Although there is only a vertical transection, it is the best measured data for analyzing the long-term variation of INCWM at present. We add description about the seasonal temperature difference between surface and bottom in the revised manuscript (Fig. 3).

This is the first time to explore the interannual variation of INCWM using long-term regular observation data. In this study, we focus on showing the interannual variation of INCWM and preliminary discuss its influence factor. As you said, more stations and observed hydrological parameters are needed to clarify detail dynamic mechanism controlling interannual variation of INCWM. On the basis of this work, we plan to perform more detailed observations and model simulations in the future to deeply study the dynamic mechanism, your suggestions give us many helps.

96: With the two indices you probably mean the transect area and the temperature.

The two indices are the averaged water temperature inside the INCWM and the area of INCWM along the observational transect. For better reading, we changed the sentence as "the intensity of the INCWM was defined by two indices, i.e., the spatially averaged water temperature inside the INCWM and the area of INCWM along the observational transect.". And move the description from Section 2.1 to Section 3.1.

100: This measure is highly empirical and not physically based, see above.

Kindly, the prefectural fishery research centers carried out regular hydrographic observations at monthly intervals in the Seto Inland Sea (stations are shown in Fig. 1) to monitor hydrological conditions and fishery resources. The stations are designed based on both physical oceanography and fishery distribution. High primary production and abundant fishery resources usually occurs where the cold water mass locates in many coastal seas (Yoon et al., 2000; Narváez et al., 2015; Abe et al., 2015; Coakley et al., 2016). As shown in Fig. 1 and Fig. 2 in the revised manuscript, the long-term observation transection (from Sta. 1 to Sta. 7) across the interior of INCWM and could present the temporal and spatial variation of INCWM well. The observation data is the best field survey data we can find to analyze the variation of INCWM although it just shows the vertical structure of INCWM.

References:

Abe K, Tsujino M, Nakagawa N, et al. Characteristic of Si: P: N ratio in bottom water in central Suo-Nada, western Seto Inland Sea. Journal of oceanography, 2015, 71(1): 53-63.

Coakley S J, Miles T, Kohut J, et al. Interannual variability and trends in the Middle Atlantic Bight cold pool//OCEANS 2016 MTS/IEEE Monterey. IEEE, 2016: 1-6.

Narváez D A, Munroe D M, Hofmann E E, et al. Long-term dynamics in Atlantic surfclam (Spisula solidissima) populations: the role of bottom water temperature. Journal of Marine Systems, 2015, 141: 136-148.

Yoon W D, Cho S H, Lim D, et al. Spatial distribution of Euphausia pacifica (Euphausiacea: crustacea) in the Yellow Sea. Journal of Plankton Research, 2000, 22(5): 939-949.

115-117: The model is forced by some kind of climatological wind, which leads to underestimation of the wind-energy input and mixing. The method for calculating the surface buoyancy flux is not mentioned. Since the wind is climatological, the reviewer can assume that also the buoyancy fluxes are idealised. Also, no information is given about open boundary conditions and riverine freshwater forcing. For an investigations like this one, is would be state of the art to apply a model with realistic forcing. Some information on the surface buoyancy forcing is given in lines 146-151, and it seems indeed that this forcing is climatological as well.

The following sections include some interesting discussions, but since the study is based on a highly site-specific empirical measure for the size of the cold pool and the numerical model is highly idealised, I propose that the authors do first improve their methods according to the above suggestions and then repeat the study.

Thank for your comment.

We actually use climatological forcing in numerical model rather than realistic forcing. The detailed model configurations have added in the first paragraph in Section 2.2.

"*Four major tidal constituents (M2, S2, O1 and K1) at the open boundary were considered and the daily river discharges averaged over 24 years (1993–2016) from the Ministry of Land, Infrastructure and Transport were used in the model. Multi-year averaged daily surface fluxes of momentum, heat and fresh water was used to drive model (Zhu et al., 2019). The daily wind stress was based on hourly averaged results of wind stress, which was calculated by wind velocity from the Grid Point Value of Meso-Scale Model (GPV-MSM) (http:// database.rish.kyoto-u.ac.jp/arch/jmadata/data/gpv/) during 2007–2016 provided by the Japan Meteorological Agency with the resolution of 1/16°×1/20°, adopting the drag coefficient of Large and Pond (1981). The daily shortwave radiation was based on the newly released of Japanese Ocean Flux Data Sets with Use of Remote Sensing Observation (J-OFURO3) (https://j-ofuro.scc.u-tokai.ac.jp/) with a resolution of 1/4°×1/4° and averaged during 2002 to 2013. The daily longwave, sensible heat flux and latent heat flux were calculated and averaged by adopting bulk formula (Gill, 1982) using hourly air temperature, sea surface temperature, relative humidity, cloud cover, and wind velocity from the GPV-MSM (2007–2016). Daily evaporation was obtained by calculating the latent heat flux. The daily precipitation was provided by the GPV-MSM and averaged hourly from 2007 to 2016*"
The seasonal variation is shown in below figure.

The information in lines 146-151 in the old manuscript is about the dataset JRA55 which has been removed in the new manuscript.

Kindly, we first demonstrated the interannual variation of INCWM and explored its influencing factor in the study using long-term observation and a numerical model.

We are the first time to explore the interannual variation of INCWM and its influence factors. Model driving by climatological forcing could capture the evolution of INCWM and it can be competent to discuss the response of INCWM to air-sea heat flux changes by sensitivity numerical experiments. Based on this work, we plan to conduct a continuous run with realist forcing to detailly explore dynamic mechanism controlling the interannual variation of INCWM. We show the shortcoming of the work and future plans in the last paragraph in Section 5.

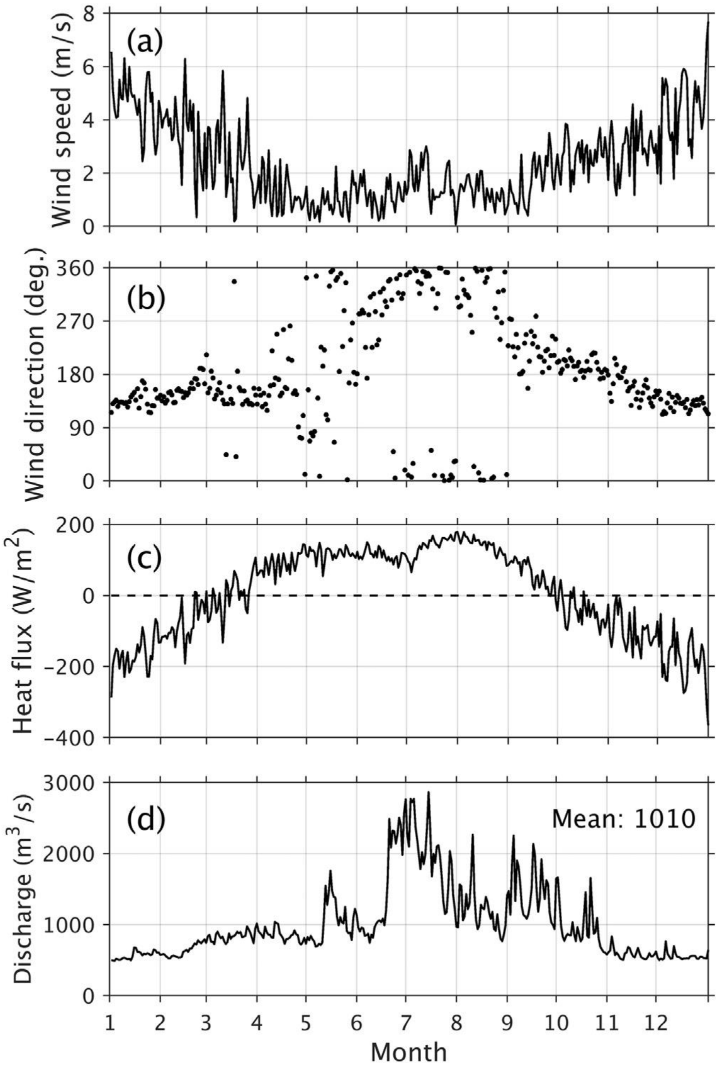


Fig. 3. Daily variations in multi-year averaged (a) wind speed, (b) wind direction, (c) air-sea heat flux, and (d) river discharges used in case Control. The wind direction in (b) is clockwise and the direction of southerly wind is 0. Positive values in (c) indicate that the ocean gains heat, while negative values indicate the opposite situation. (from Zhu et al., 2019)

~~Air-sea heat flux during warming season determines the interannual variation of bottom cold water mass in a semi-enclosed bay~~Interannual variation of a bottom cold water mass in the Seto Inland Sea, Japan

Junying Zhu[1], Jie Shi[2,3], Xinyu Guo[4]

[1]College of Marine Sciences, Hainan University, Haikou 570228, China
[2]Key Laboratory of Marine Environment and Ecology, Ocean University of China, Ministry of Education, 238 Songling Road, Qingdao 266100, China
[3]Laboratory for Marine Ecology and Environmental Sciences, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266071, China
[4]Center for Marine Environmental Studies, Ehime University, 2-5 Bunkyo-Cho, Matsuyama 790-8577, Japan

Correspondence to: Xinyu Guo (guoxinyu@sci.ehime-u.ac.jp)

Abstract. A bottom cold water mass (BCWM) is a widespread physical oceanographic phenomenon in coastal seas, and its temperature variability has an important effect on the marine ecological environment. In this study, the interannual variation of the BCWM in Iyo-Nada (INCWM), a semi-enclosed bay in the Seto Inland Sea, Japan, from 1994 to 2015 and its influencing factors were investigated using monthly observational data and a hydrodynamic model. Surrounded by 18 °C isotherm, The ~~interannual variation in~~observed multi-year average water temperature inside the INCWM was 17.58 °C with a standard deviation of 0.27 °C, while the mean area of INCWM was 5.73×10^5 m^2 with a standard deviation of 4.35×10^5 m^2. Their interannual variation showed a negative correlation with the area of the INCWM that indicates a low temperature corresponds to a big area~~,~~. In addition, the interannual variation of average temperature inside INCWM showed ~~and~~ positive correlations with the local water temperature from April to July and with remote water temperature below 10 m in an adjacent strait in July. Differing from previously studied BCWMs, which had interannual variations depending closely on the water temperature before the warming season, the interannual variation of INCWM ~~depends strongly~~is more sensitive to ~~on~~ the air-sea heat flux during the warming season than that in the previous winter.~~ via local vertical heat transport and lateral heat advection~~. Further, by comparing several BCWMs, we found that the BCWM size is a key factor in understanding the ~~mechanisms~~ heat transfer process responsible for the interannual variation of BCWMs in coastal seas. These findings will help to predict bottom water temperatures and improve the current understanding of ecosystem changes in shelf seas under global climate change.

1 Introduction

With global climate change, interannual variations in water temperature in coastal oceans are attracting significant attention (Lin et al., 2005; Park et al., 2015; Chen et al., 2020). However, most studies consider sea surface temperature. The lack of long-term observations limits the studies on the bottom water temperature, even though its interannual variations are important for understanding how coastal oceans respond to atmospheric changes (Simpson et al., 2011; Turner et al., 2017).

A bottom cold water mass (BCWM), also called “cold pool”, is the water trapped on the bottom layer as a result of seasonal thermoclines during stratified seasons. It is characterized by lower temperatures than the surrounding waters and has been reported to occur in many shelf seas, such as the Yellow Sea (Wei et al., 2010), Irish Sea (Hill et al., 1994), Middle Atlantic Bight (Lentz, 2017), North Sea (Brown et al., 1999), Bering Sea (Zhang et al., 2012) and Seto Inland Sea (Yu and Guo, 2018). As BCWMs occur every year with an annual cycle of forming during the warming season (from spring to summer), being the strongest in summer, and dissipating in early fall, they are good indicators to demonstrate the response of the coastal sea to climate change. In addition, interannual variations in BCWMs have been reported to affect marine ecosystems (Stabeno et al., 2012; Wang et al., 2014; Abe et al., 2015). Therefore, clarifying their interannual variations and controlling factors are helpful for understanding marine ecosystem changes.

Limited by the absence of long-term observations, only the Yellow Sea Cold Water Mass and the Middle Atlantic Bight Cold Pool have been studied for their interannual variation and causes (Yang et al., 2014; Coakley et al., 2016; Li et al., 2017; Zhu et al., 2018; Chen and Curchitser, 2020), both of which exhibited apparent interannual variations. Specifically, the interannual variations of the Yellow Sea Cold Water Mass are closely related to the air-sea heat flux in the previous winter (Wei et al., 2010; Park et al., 2011; Li et al., 2015; Zhu et al., 2018). After studying the Middle Atlantic Bight Cold Pool, Chen and Curchitser (2020) suggested that its temperature interannual variations during stratified seasons were controlled by both the previous winter temperature and abnormal warming/cooling due to total oceanic advection, they also pointed out that the winter (mid-January to March) temperature anomaly was the primary factor in determining the interannual variability of temperature anomaly near bottom cold pool region during the stratified seasons. Nevertheless, there remains little information regarding the interannual variations of BCWMs in other coastal seas.

The Seto Inland Sea is the largest semi-closed coastal sea in western Japan, with an average depth of 38 m and a surface area of 23,000 km^2 (Fig. 1a). It opens to the Pacific Ocean via Bungo Channel and Kii Channel and is divided into several shallow basins by narrow straits. The presence of a BCWM in summer has been confirmed in several of its wide basins, including the Iyo-Nada (Takeoka et al., 1993; Yu et al., 2016), Suo-Nada (Chang et al., 2009), Hiuchi-Nada (Guo et al., 2004), and Harima-Nada (Chang et al., 2009). In this study, we~~This study~~ focuses on the BCWM in Iyo-Nada, which connects the Bungo Channel with the Hayasui Strait (Fig. 1b).~~,~~ The depth of Hayasui Strait is ~~which has a depth of~~ more than 100 m ~~(Fig. 1b).~~ and t~~T~~he water temperature ~~in the Hayasui Strait~~ is homogenous throughout the year because of strong tidal mixing (Kobayashi et al., 2006). From May to July, a density-induced gravitational circulation occurs as the bottom water flows from the Hayasui Strait to Iyo-Nada, whereas the surface water flows in the opposite direction (we draw this circulation in a schematic diagram in Fig. 5). This circulation can be enhanced in July by an abrupt increase in river discharge into the Seto Inland Sea (Yu et al., 2016; Yu and Guo, 2018).~~.~~

Previous studies have examined the seasonal change in the BCWM in Iyo-Nada (hereafter, we use "INCWM" to denote the Iyo-Nada BCWM). With the development of stratification, the water temperature of the INCWM increases by 8-10 °C from early April to August. Yu and Guo (2018) suggested that seasonal warming in the INCWM results from both lateral heat advection from the surrounding water and vertical diffusion from the surface layer, in which lateral heat advection contributes more than vertical diffusion. However, it is still unknown how the INCWM changes under climate change and how these lateral and vertical processes affect the INCWM on an interannual scale.

The remainder of this study is organized as follows. In Section 2, we introduce the long-term observation data and a hydrodynamic model. In Section 3, we describe the interannual variation in the INCWM and its relationship with the surrounding water. In Section 4, we discuss the ~~factors~~ sensitivity of INCWM characteristics to air-sea heat flux changes by several sensitivity numerical experiments. ~~controlling the interannual variation of the INCWM and~~ Then we compare the ~~them~~INCWM with ~~those of~~other BCWMs in ~~other~~ coastal seas. Finally, we summarize the main results in Section 5.

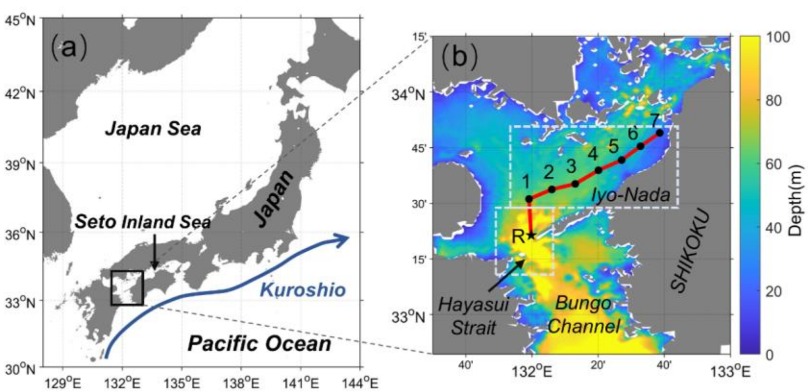


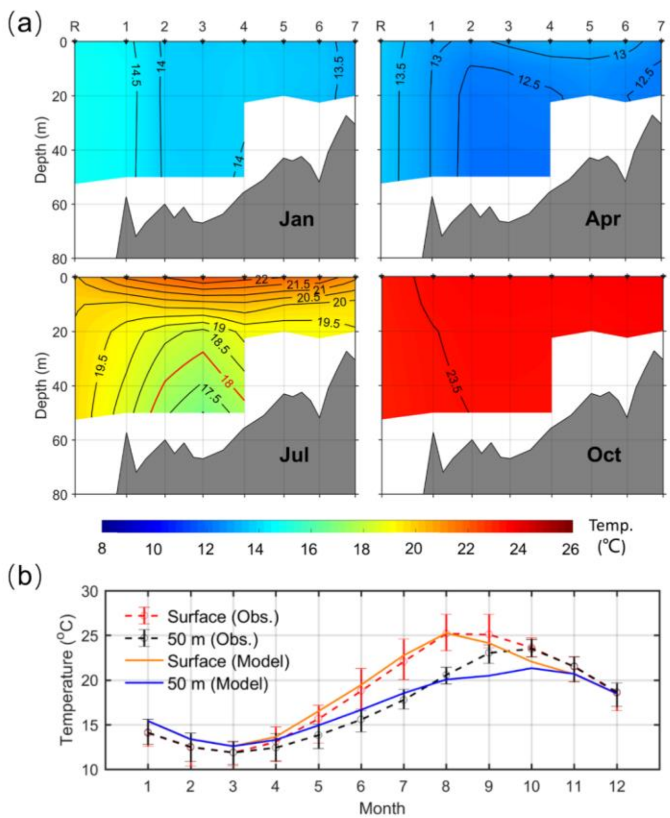
Figure 1: Location of (a) Seto Inland Sea and (b) observation stations. Stations are represented by black dots and stars. The areas enclosed in the dotted boxes in (b) represent Iyo-Nada (131.9-132.8°E, 33.45-33.~~-~~75°N) and the Hayasui Strait (131.8-132.1°E, 33.15-33~~-7~~.45°N), which were used in the numerical sensitivity experiments.

2 Methods

2.1 Long-term observation data

The Prefectural Fishery Research Centers around the Seto Inland Sea have conducted ship-based hydrographic observations almost every month since 1971 to monitor water quality. For this study, we collected the observed water temperature data inside the Iyo-Nada (stations 1-7) and the Hayasui Strait (station R) during 1994-2015 from Ehime Prefectural Fishery Research Centers (https://www.pref.ehime.jp/h35115/ehime-suiken.html)~~the Iyo-Nada (stations 1-7) and the Hayasui Strait (station R) (Fig. 1b) from 1994 to 2015 (no data for 2000)~~. The locations of stations are shown in Fig. 1b. The water temperature was measured by ALEC CTD carried by survey vessel "Yoshuu". The measurement accuracy is 0.001 degree. Observation year for each month in Iyo-Nada and Hayasui Strait during 1994-2015 are shown in Supplementary Table 1. For each month, there are at least 17 years of observations in Iyo-Nada. The observation data almost cover depths of 0 m, 10 m, 20 m, and 50 m at all stations as well as additional 75 m deep measurements at station R though the depth of observation varies slightly in different years. We interpolated water temperature to the deepest observed location at each station to show the vertical distribution of temperature.

The spatial distributions of multi-year (1994-2015) averaged water temperature along a transection (Station R to Station 7) ~~in~~ from January~~, April, July, and October~~ to December are shown in Fig. 2a~~-~~-l. The water is well mixed in winter, while thermocline occurs during spring and summer and vanishes in fall in Iyo-Nada (Sta. 1-7). However, water temperature at Hayasui Strait is almost homogeneous throughout a year (Fig. 2a-l, Supplementary Fig. 1). Seasonal bottom cold water exists locally in the Iyo-Nada. Overall, the INCWM exhibits a prominent seasonal evolution that forms in April, matures in July, and disappears in October. The seasonal cycle is consistent with that of other BCWMs (Horsburgh et al., 2000; Zhang et al., 2012; Chen et al., 2018; Zhu et al., 2018). The main part of the INCWM in July is located at stations 1-4 and below a depth of 20 m (Fig. ~~2a~~2g). According to the time series of the multi-year (1994-2015) averaged water temperature at the sea surface and 50 m deep for stations 1-4 (Fig. ~~2b~~2m), the water column mixed well from October to March. Meanwhile, the water temperatures at the sea surface and 50 m deep diverged from April to September, during which the water temperature rose at a rate of 3.0 ℃ month^{-1} at the sea surface and 1.8 ℃ month^{-1} at 50 m deep. The water temperature difference between the sea surface and 50 m deep reached 5.5 ℃ in July. Then, enhanced wind and surface cooling break this stratification in the fall, and consequently, the INCWM disappears in October.~~ As more typhoons pass through Japan in August than in July (), we selected July to examine the interannual variations of the INCWM.~~



(a)
R
1
2
3
4
5
6
7
Depth (m)
Jan
Apr
Jul
Oct
Temp. (℃)
(b)
Surface (Obs.)
50 m (Obs.)
Surface (Model)
50 m (Model)
Temperature (°C)
Month

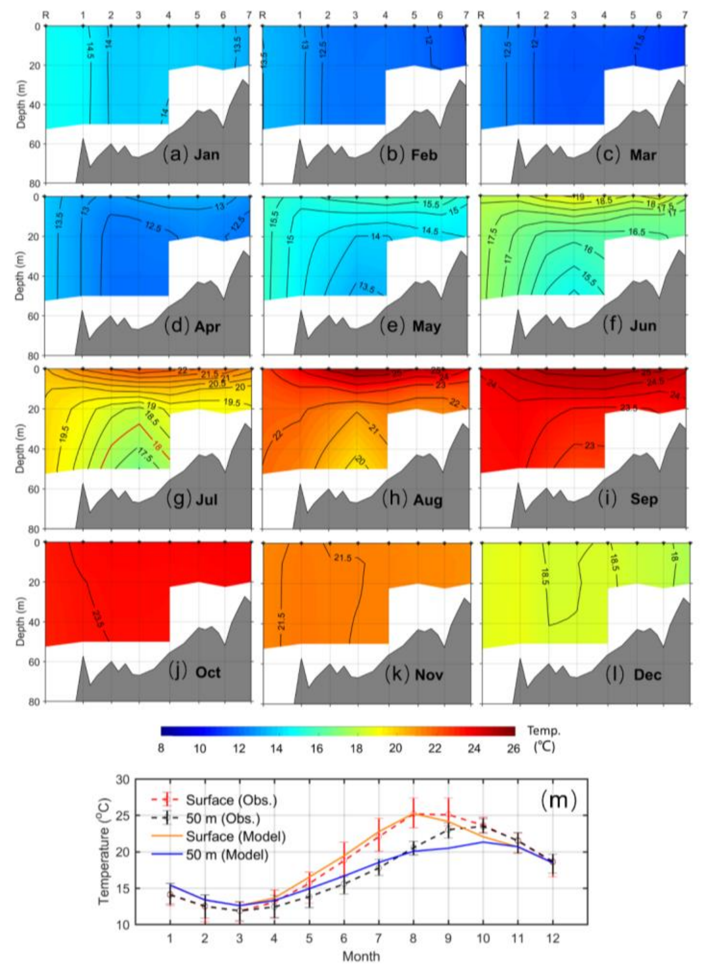


Figure 2: ~~(a)~~ Spatial distributions of multi-year (1994-2015) averaged water temperature along a vertical transect (station R to station 7) ~~in~~ from January to December (a-l)~~, April, July, and October~~. (~~b~~m) Time series of observed and simulated water temperatures averaged for stations 1-4 at the surface and 50 m deep. The red line of the 18 °C isotherm in (a) is used to define the

Iyo-Nada bottom cold water mass (INCWM). The red and black bars in (b) represent the ranges of observed water temperatures at the surface and 50 m deep, respectively.

~~The intensity of the INCWM can be defined by the spatially averaged water temperature inside the INCWM and the area of INCWM along the observational transect (Fig. 1b), which was used in Zhu et al. (2018) to study the Yellow Sea bottom cold water. Briefly, X is set to be any of the two indices, and X_0 is the mean value of X from 1994 to 2015. Thus, ΔX_i is the anomaly of X_i at year i:~~

$$\cancel{\Delta X_i = X_i - X_0.}$$

~~The mean range of change over the entire study period is denoted by the mean value of the absolute value of ΔX_i:~~

$$\cancel{p = \frac{1}{n}\sum_{i=1}^{n} |\Delta X_i|,}$$

~~where n is the total number of data points. A strong INCWM year is characterized by a low water temperature and a large area, while a weak INCWM year is characterized by a high water temperature and a small area. When the water temperature anomaly in a year is smaller than its $-0.5p$ and the area anomaly in a year is larger than its $0.5p$, the year is defined as a strong INCWM year. Conversely, when the water temperature anomaly in a year is larger than its $0.5p$ and the area anomaly is smaller than its $-0.5p$, the year is defined as a weak INCWM year. Note that any other situation is defined as a normal INCWM year.~~

2.2 Model configuration and validation

Herein, we used a three-dimensional ~~hydrodynamic~~ free-surface primitive equation ocean model to examine the factors influencing interannual variation in the INCWM. This model is based on the Princeton Ocean Model, and its configuration is described in detail by Zhu et al. (2019). Model domain is 130.98°E-135.5°E, 32.8°N-34.8°N covering the entire Seto Inland Sea. The model has a horizontal resolution of around 1 km (1/80° in the zonal direction and 1/120° in the meridional direction), and a vertical resolution of 21 sigma levels. The initial temperature and salinity fields in January were produced by merging the Marine Information Research Center dataset in the SIS region and the model results of Guo et al. (2003). The boundary conditions including de-tided current velocity, temperature, salinity, and surface elevation were obtained from the diagnostic model of Guo et al. (2004). Four major tidal constituents (M_2, S_2, O_1 and K_1) were considered and the daily river discharges averaged over 24 years (1993–2016) from the Ministry of Land, Infrastructure and Transport were used in the model. Multi-year averaged daily surface fluxes of momentum, heat and fresh water was used to drive model (Zhu et al., 2019). The daily wind stress was based on hourly averaged results of wind stress, which was calculated by wind velocity from the Grid Point Value of Meso-Scale Model (GPV-MSM) (http:// database.rish.kyoto-u.ac.jp/arch/jmadata/data/gpv/) during 2007–2016 provided by the Japan Meteorological Agency with the resolution of 1/16°×1/20°, adopting the drag coefficient of Large and Pond (1981). The daily shortwave radiation was based on the newly released of Japanese Ocean Flux Data Sets with Use of Remote Sensing Observation (J-OFURO3) (https://j-ofuro.scc.u-tokai.ac.jp/) with a resolution of

1/4°×1/4° and averaged during 2002 to 2013. The daily longwave, sensible heat flux and latent heat flux were calculated and averaged by adopting bulk formula (Gill, 1982) using hourly air temperature, sea surface temperature, relative humidity, cloud cover, and wind velocity from the GPV-MSM (2007–2016). Daily evaporation was obtained by calculating the latent heat flux. The daily precipitation was provided by the GPV-MSM and averaged hourly from 2007 to 2016. In the study, we want to explore the sensitivity and response of INCWM to sea surface forcing changes, therefore, multi-year average sea surface atmospheric forcing was first used to simulate (named as Control), and then conducted several numerical experiments to analysis the response of INCWM to sea surface forcing changes. ~~Note that the sea surface atmospheric forcing used was the multi-year average.~~Model validations of residual current, water temperature, and salinity in the Seto Inland Sea of Control have been reported in previous studies (Chang et al., 2009; Yu et al., 2016; Zhu et al., 2019).

~~As an example of~~For the model results related to the INCWM, spatial distributions of simulated averaged water temperature in the vertical transection (Supplementary Fig. 2) show a distinct seasonal variation of INCWM which is similar with observation (Fig. 2a-l). Fig. ~~2b~~ 2m shows the ~~seasonal variation~~ time series of the simulated water temperature at the sea surface and 50 m deep for stations 1-4. It is likely that the model captured the seasonal evolution of the INCWM given by the observed data up to August. In addition, simulated temperature differences between surface and bottom from April to September are shown in Fig. 3, which could indicate the position of INCWM. The temperature difference in July was the maximum up to 6 °C and it located at the central area of Iyo-Nada which corresponds to the location of observed INCWM (Fig. 1b and Fig. 2g). For the horizontal distribution of INCWM, the spatial distribution of water temperature at 50 m depth is presented in Fig. 3g. On the west side of INCWM, there is a bottom temperature front with an obvious temperature difference (around 2°C) between INCWM and the water on the west side. The INCWM gradually disappears in September (Fig. 2m and Fig. 3f) both in observation and simulation. However, the difference between the simulated and observed water temperatures in the vertical transection increased in September and October (Fig. 2m). The reason for it is that the model is driven by the multi-year average daily wind field, which cannot fully represent episodic strong wind events, especially typhoons, which are the most active in September ~~and October~~ (http://www.data.jma.go.jp/obd/stats/data/bosai/tornado/stats/monthly.html). Therefore, the kinetic energy input to the ocean in this simulation (Supplementary Fig. 2) is much lower than the realistic situation (Fig. 2a-l) during this period. However, our simulation target is the formation and maintenance of the BCWM from the previous winter to summer, which is only slightly related to the model results in September and October. ~~Therefore~~In general, this model captures the main characteristics and seasonal evolution process of INCWM. ~~is suitable for examining the factors influencing the interannual variation in the INCWM via sensitivity experiments. The climatological simulation of the INCWM is named CONTROL, and sensitivity experiments are described in Section 4.2.~~

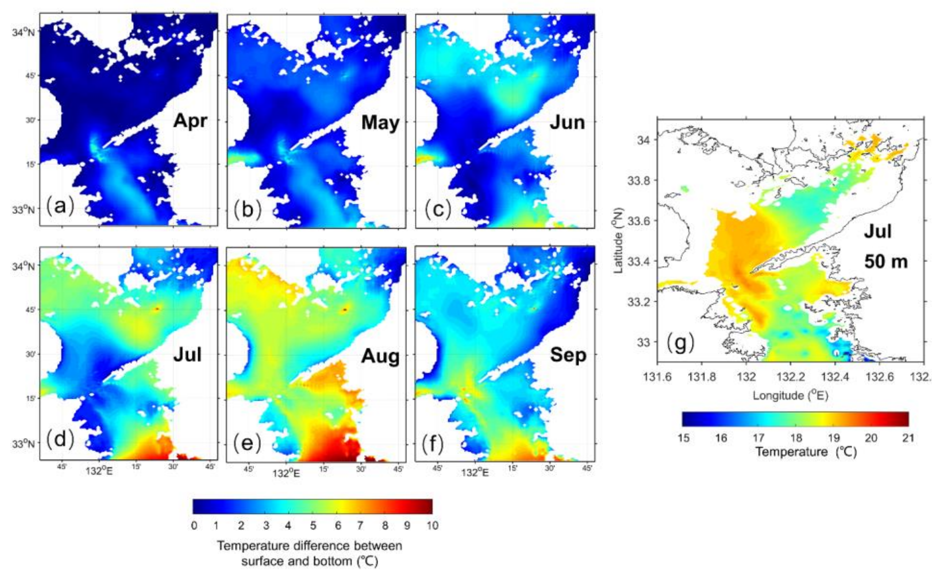


Figure 3: Simulated temperature differences between surface and bottom from April to September (a-f) and the spatial distribution of water temperature at 50 m depth (g).

~~**2.3 Method quantifying the influence of sea surface forcing on interannual variation of the INCWM**~~

To investigate the response of the INCWM to sea surface forcing changes, we conducted three numerical sensitivity experiments (Table 1) in Section 4.1. ~~In each sensitivity experiment, the air-sea heat flux over the target area was 10 % different from CONTROL. The sensitivity coefficient q is defined to quantify the response of the INCWM along the transect, as shown in Fig. 1b. Using water temperature as an example, q can be calculated using the following formula:~~

$$\cancel{q = \left|\frac{T_{case}-T_{control}}{T_{control}}\right|, \qquad (1)}$$

~~where $T_{control}$ is the average water temperature in the area enclosed by a specific isotherm (18 °C, Fig. 2a, July) in the CONTROL, and T_{case} is the corresponding variable in one of the sensitivity experiments. If there is no water below 18 °C, the water temperature at the mean location of the INCWM is used for T_{case}.~~ The Seto Inland Sea loses heat in winter and gains heat in summer. To determine the effects of local air-sea heat flux at different stages of the INCWM (based on results of observation data), we increased the air-sea heat flux loss/gain over Iyo-Nada (light blue dotted box in Fig. 1b) by 10 %

from previous December to February (cooling season) in Case 1 and from May to July (warming season) in Case 2. In addition, to determine the effects of remote air-sea heat flux in July, we increased the air-sea heat flux over the Hayasui Strait (light blue dotted box in Fig. 1b) in July by 10 %~~ from May to July~~ in Case 3.

Table 1: List of numerical experiments and conditions.

Experiments	Conditions
Control	climatological sea surface forcing
Case1	The surface heat loss in Iyo-Nada in the previous winter increased by 10 %
Case2	The surface heat gain in Iyo-Nada from May to July increased by 10 %
Case3	The surface heat gain in ~~the~~ Hayasui Strait ~~from May to~~in July increased by 10 %

~~Regarding the interannual variation of INCWM, the influence of sea surface forcing is evaluated not only by the sensitivity coefficient q but also by the changing range of forcing. To quantify the relative contributions of air-sea heat flux to the interannual variation of the INCWM, we first calculate the multi-year mean seasonal variation and then eliminate seasonal change signals in order to obtain the interannual variation sequence in the air-sea heat flux. For a certain period, the standard deviation of the interannual variation sequence ($std(f)$) is used to represent the change range of air-sea heat flux, and its influence cr is evaluated using the results of the sensitivity experiment via the following relationship:~~

$$\cancel{\frac{cr}{std(f)} = \frac{q}{\Delta f},} \qquad \cancel{(2)}$$

~~where f is the interannual variation sequence of the air-sea heat flux, which eliminates the seasonal signals, and Δf is the change value in the sensitivity experiment (Table 1) for the air-sea heat flux. For the size of the INCWM, T_{case} and $T_{control}$ in Eq. (1) are replaced by the area enclosed by the 18 °C isotherm in the corresponding experiments. If there is no water below 18 °C, the area of the INCWM is set to 0. The cr can be used to evaluate the relative contribution of the air-sea heat flux to the interannual variation of the INCWM. Meanwhile, $cr(T)$ and $cr(A)$ represent the relative contribution of air-sea heat flux to the temperature and area of the INCWM, respectively.~~

~~With the exception of the air-sea heat flux, the contribution of wind stress to the interannual variation of the INCWM was also quantified using the aforementioned method. Note that the forcing values used in this calculation, such as the air-sea heat flux and wind stress during 1994-2012, were derived from the climate dataset DSJRA-55, which is a regional downscaling based on the Japanese 55-year Reanalysis (JRA-55; Kobayashi et al. 2015) (https://jra.kishou.go.jp/), provided by the Japan Meteorological Agency. The data are provided hourly with a horizontal resolution of 5 km to appropriately represent phenomena associated with Japan's uneven terrain (Kayaba et al., 2016).~~

3 Results

3.1 Interannual variations of the INCWM in July

The temperature is lower inside the INCWM than in its surrounding waters in summer. Spatial distributions of water temperature in July along the vertical transection in Iyo-Nada (Fig. 1b) were shown in Supplementary Fig. 3. The water body below 20 m in the central Iyo-Nada was occupied by cold water around 17-19 ℃ while sea surface temperature was high with the variation of 20 ℃ - 25 ℃. The lowest observed temperature ~~in July along the transect~~ ~~in Iyo-Nada (Fig. 1b) was~~ ranged from 15.74 ℃ (2006) and 18.23 ℃ (2007)~~15.74-18.23 ℃~~ during 1994-2015（Supplementary Table 2）. A fixed isotherm is often used as the boundary of a cold water mass (Zhang et al., 2012; Yang et al., 2014; Chen et al., 2018), here, we used the 18 ℃ isotherm to define ~~The~~ the boundary of INCWM ~~was defined by~~ ~~the 18 ℃ isotherm~~ in July (Fig. ~~2a~~2c), and the average water temperature and area inside the 18 ℃ isotherm were calculated. When calculating the average temperature and area of INCWM along the vertical across-section, we first interpolated the observed water temperature into a rectangular mesh grids (0.01° × 1 m) to get a temperature field, and then calculated the area of grids where temperature less than 18 ℃ and average temperature within these grids. If there was no water temperature less than 18 ℃ in the vertical transection, the observed temperature at the average location of the INCWM (50 m deep at station 3) as the average temperature and the area is set to zero. ~~As~~ Results were shown in Fig. ~~3~~4 and Supplementary Table 1, there was a prominent interannual variation in the water temperature and area of the INCWM. ~~The lowest average water temperature in the INCWM was 17.04 ℃ in 2006. Meanwhile, t~~The multi-year average temperature of the INCWM was 17.58 ℃ with a standard deviation of 0.27 ℃. Meanwhile, the lowest average water temperature in the INCWM was 17.04 ℃ in 2006. Overall, consistent interannual variation was observed for the average and lowest water temperature of the INCWM (figure not shown), exhibiting a correlation coefficient of 0.98 ($p < 0.01$). The mean area of INCWM was 5.73×10^5 m^2 with a standard deviation of 4.35×10^5 m^2. The smallest area was 0 m^2 in 2007 and the largest area was 1.46×10^6 m^2 in 2006.

A significant negative correlation ($r = -0.86$, $p < 0.01$) was found between the average water temperature and the area of the INCWM, indicating that when the water temperature of the INCWM is low in a year, the area of the INCWM is large and the INCWM ~~intensity~~ is strong.

With increased solar radiation in August, sea surface temperature could reach to 23.85℃ (2007)-29.48℃ (2008). The INCWM also exists in the vertical transect (Supplementary Fig. 4) with minimum water temperature ranging 18.52℃ (1996) – 20.75℃ (2014) which is 2℃-3 ℃ higher than that in July. In order to show the interannual variation of INCWM in August, we calculated the average temperature and area surround by an isotherm of 20℃ as Supplementary Fig. 4 shown. The results also showed significant negative correlation between average temperature and area which is consistent with the relationship in July. However, there was no significant correlation for interannual variation of INCWM characteristics between July and August. As more typhoons pass through Japan in August than in July (http://www.data.jma.go.jp/obd/stats/data/bosai/tornado/stats/monthly.html), we use the INCWM in July to explore the interannual variation of INCWM in this study to avoid the episodic impact of typhoon as far as possible.

Based on observation data in July, the intensity of the INCWM was defined by two indices, i.e., the spatially averaged water temperature inside the INCWM and the area of INCWM along the observational transect (Fig. 1b), according to the method used in Zhu et al. (2018) studying the intensity of Yellow Sea bottom cold water. Here, we also used this method to get the intensity of the INCWM. Briefly, X is set to be any of the two indices, and X_0 is the mean value of X from 1994 to 2015. Thus, ΔX_i is the anomaly of X_i at year i:

$$\Delta X_i = X_i - X_0 \, .$$

The mean range of change over the entire study period is denoted by the mean value of the absolute value of ΔX_i:

$$p = \frac{1}{n}\sum_{i=1}^{n} |\Delta X_i| \, ,$$

where n is the total number of data. A strong INCWM year is characterized by a low water temperature and a large area, while a weak INCWM year is characterized by a high water temperature and a small area. When the water temperature anomaly in a year is smaller than its $-0.5p$ and the area anomaly in a year is larger than its $0.5p$, the year is defined as a strong INCWM year. Conversely, when the water temperature anomaly in a year is larger than its $0.5p$ and the area anomaly is smaller than its $-0.5p$, the year is defined as a weak INCWM year. Note that any other situation is defined as a normal INCWM year. As a result, the INCWM was strong in 1994, 1996, 2006, 2010, 2012, 2013, and 2015, normal in 1995, 1998-2002 and 2005, ~~and~~ while weak in 1997, 2003, 2004, 2007, 2009, 2011, and 2014 (Fig. ~~3~~4 and Supplementary Table 2).

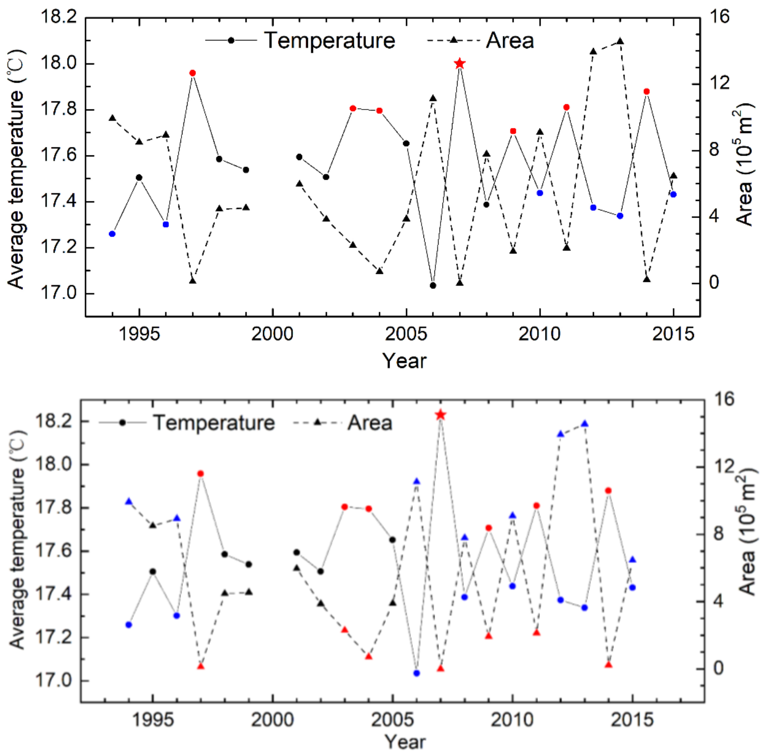
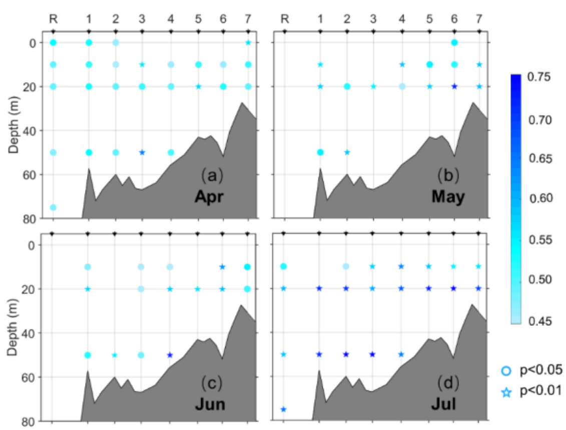


Figure ~~3~~4: Time series of mean water temperature (solid line) and vertical cross-section area (broken line) of the Iyo-Nada bottom cold water mass (INCWM) in July during 1994-2015. A strong INCWM year is marked by blue ~~circles~~, while a weak INCWM year is marked by red ~~circles~~. The red star indicates that we did not identify a BCWM in 2007 because the water temperature was higher than 18 ℃ along the entire transect. For this case, we used the observed temperature (18.23 ℃) at the average location of the INCWM (50 m deep at station 3) as the average temperature and specified a zero area.

3.2 Correlation between INCWM with surrounding waters

As shown in Fig. ~~2b~~2m, the water temperature at the place of the INCWM was homogeneous in January before gradually forming a distinct dome under the sea surface heating during spring and summer. To explore the influence of the water temperature at different stages during its formation process on the intensity of INCWM in July, we calculated the correlation coefficients between the average temperature of the INCWM in July (Fig. ~~3~~4) and the water temperatures at all the depths of each station from 1994 to 2015 for each month (from previous December to July) shown in Fig. 5.



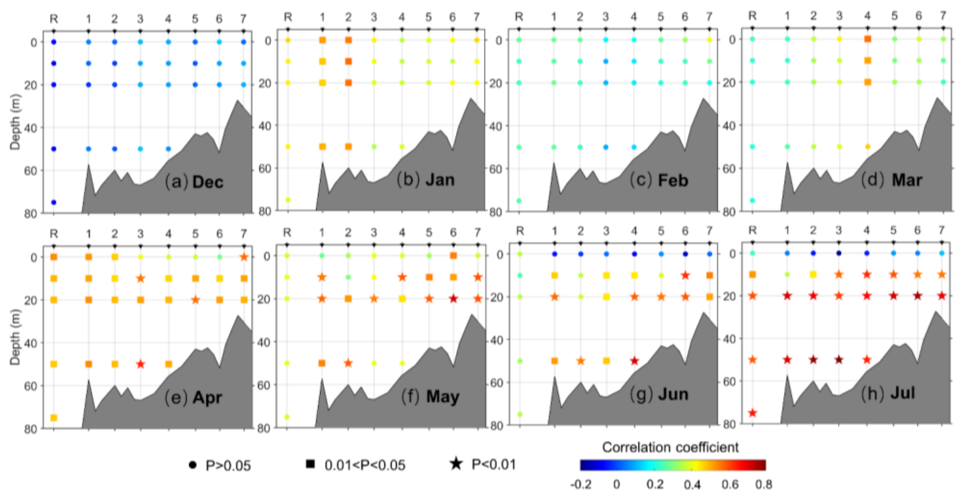


Figure ~~4~~5: Correlation coefficients for interannual variation of water temperature at each station from ~~April~~ previous December to July (a-h) and that of the Iyo-Nada bottom cold water mass (INCWM) mean water temperature in July during 1994-2015. Circles indicate that the significant difference level is ~~more~~less than 0.95, squares indicate a significant difference level is between 0.95 and 0.99, and stars indicate a significant difference level of more than 0.99.

Overall, more significant correlations appeared from April to July (Fig. ~~4~~5) than from previous December to March. In April, the water temperatures at almost all stations and depths were significantly correlated with the average water temperature of the INCWM in July (Fig. ~~4a~~5a). From May to July (Figs. ~~4b~~5b-d), although the significant correlations at the sea surface and station R disappeared, the water temperature below 10 m at stations 1-7 still showed significant correlations with the average water temperature of the INCWM in July. The relationship among all the stations and depths was likely enhanced in July, as shown by the correlation coefficients larger than 0.60 ($p < 0.01$) (Fig. ~~4d~~5d). In addition, a significant correlation below 10 m at station R was observed in July but disappeared in May and June, indicating a distinct connection in July between the interannual variation of the INCWM and the water around station R, which is the Hayasui Strait.

3.3 Processes influencing the interannual variations of the INCWM

According to the seasonal evolution of the INCWM, the difference in water temperature between the sea surface and 50 m deep begins in April (Fig. ~~2b~~2m). The water temperature in April was selected as the initial value for the formation of the INCWM in the following months (Fig. 6a). The significant correlations shown in Fig. ~~4~~ 5 demonstrate that the local water temperature below 10 m in April is closely related to the interannual variation of the INCWM in July. ~~Because t~~The water temperature in April is the result of~~depended mainly on the~~ cooling process in the previous winter~~,~~. Tsutsumi and Guo (2016) suggested the heat content inside the Seto Inland Sea (except for Bungo Channel and Kii Channel) from January to July mainly depended on air-sea heat fluxes. the initial temperature of the INCWM is likely associated with local air-sea heat flux from winter to early spring.

During the warming season, the effect of local water temperatures below 10 m persists. As Fig. 5e-h shown, the correlation coefficient below 10 m in Iyo-Nada (Sta. 1-7) increased from April to May-July, especially in May and July. In addition, the significant difference levels gradually enhanced from $0.01<p<0.05$ to $p<0.01$ during this period, which indicated ~~The correlation coefficient below 10 m is larger in May-July than in April (Figs. 4b-d), indicating~~ that heat transport into the INCWM from May to July is also important for the interannual variation of the INCWM in July. Using the temperature difference between the sea surface and 20 m depth at stations 1-4 as the thermocline strength, a significant negative correlation ($r = -0.44$, $p < 0.05$) was obtained for the thermocline strength in July and the average water temperature of the INCWM in July, indicating that a stronger thermocline strength corresponds to a stronger INCWM. Because there is no significant correlation between the INCWM and sea surface temperature at stations 1-5 from May to July (Fig. ~~4~~5), the stronger thermocline strength acts to reduce the downward heat transport from the sea surface to the INCWM.

In addition, river discharge around the Seto Inland Sea increases during the warming season, facilitating the occurrence of an estuarine-like density circulation with the bottom flow from the Hayasui Strait to Iyo-Nada (Fig. 6b), which ultimately promotes horizontal heat transport into the INCWM (Yu and Guo, 2018). When river discharge reaches a peak in July (Zhu et al., 2019), the bottom horizontal density flow is enhanced, causing more heat to be laterally transported to the INCWM in July than in other months. This process is supported by the significant correlation coefficient of approximately 0.6 ($p < 0.01$) (Fig. ~~4d~~5d) below 10 m at station R in July. Therefore, the lateral heat transport from the Hayasui Strait to Iyo-Nada is another important process that influences the interannual variation of the INCWM in July.

As a summary, the temperature change of INCWM in July on an interannual scale is controlled by three heat transfer processes, i.e., the local retention of bottom low water temperature from early spring, local vertical heat diffusion from May to July and horizontal heat advection originating from Hayasui Strait in July (Fig. 6). Since the water temperatures in April and that at Hayasui Strait in July are easy to obtain from observation. The relationship between them with the INCWM intensity is shown in Fig. 7. A strong INCWM corresponds to a combination of a low local initial water temperature in April (11.0-12.5 °C) and a low water temperature at 10-50 m deep at station R in July (19.5-20.3 °C). Conversely, a weak INCWM usually corresponds to a combination of a high local initial water temperature in April (11.7-14.1 °C) and a high water temperature (19.8-20.9 °C) in the Hayasui Strait at depths of 10-50 m in July. This provides an intuitive understanding about the INCWM intensity and its relationship with initial water temperature before formation and remote horizontal heat advection in July. However, it is noted to say that local vertical heat transfer during warming seasons is not included in Figure 7. As it is not easy to address the relative importance of each process to the interannual variation of the INCWM from only observations, we would discuss their influence on INCWM characteristics using numerical model in Section 4.1.

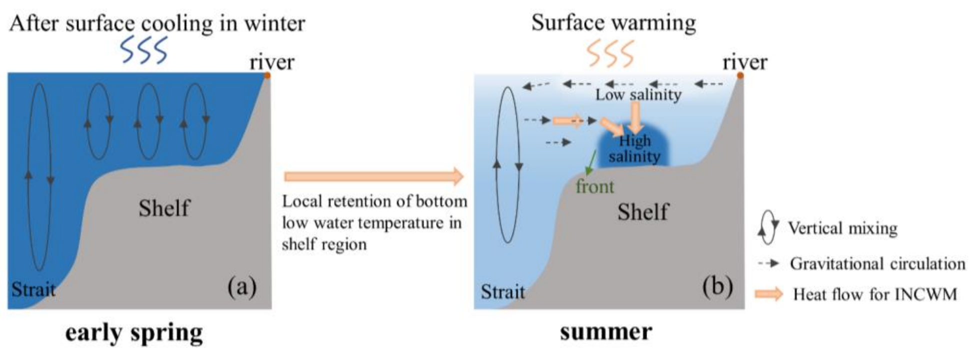
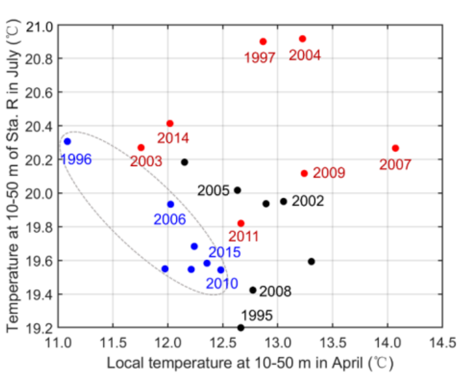


Figure 6: A schematic diagram of seasonal evolution of INCWM from early spring to summer, which is drawn from references Takeoka (2002), Yu et al. (2016) and Yu and Guo (2018). Low water temperature is indicated by dark blue while high water temperature by light blue.

~~Based on these findings, the interannual variation in INCWM temperature is not only dependent on the initial water temperature before its formation but also on the heat transport processes (horizontal and vertical) during warming seasons. As shown in Fig. 5, a strong INCWM (surrounded by gray dotted line) corresponds to a combination of a low local initial water temperature in April (11.0-12.5 °C) and a low water temperature at 10-50 m deep at station R in July (19.5-20.3 °C). Conversely, a weak INCWM usually corresponds to a combination of a high local initial water temperature in April (11.7-14.1 °C) and a high water temperature (19.8-20.9 °C) in the Hayasui Strait at depths of 10-50 m in July. Since the local vertical heat transport is not included in Fig. 5, it is not easy to address the relative importance of each process to the interannual variation of the INCWM from only observations.~~



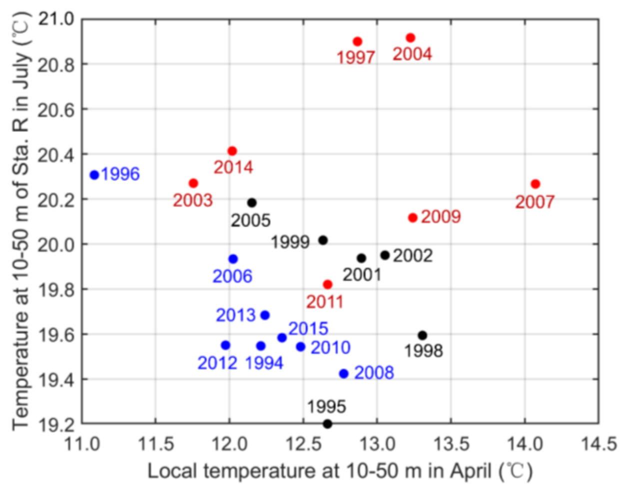


Figure ~~5~~7: Scatter plot for the Iyo-Nada bottom cold water mass (INCWM) ~~strength~~ intensity (color) according to local water temperature below 10 m in April (x-axis) and water temperature below 10 m at station R in July (y-axis). Blue, black, and red solid circles represent strong, normal, and weak INCWM years, respectively, which is consistent with the results found in Fig. 3.

4 Discussion

4.1 Sensitivity of INCWM characteristics to air-sea heat flux~~Contribution of sea surface forcing~~ changes ~~to interannual variation of the INCWM~~

Global climate change affects coastal seas via regional sea surface forcing. Air-sea heat flux is the main heat source to the Seto Inland Sea (Tsutsumi and Guo, 2016) and affects each stage of the INCWM by directly local input or remote input through horizontal heat transport from adjacent areas (Fig. 6). Based on the climatological simulation of the INCWM described in Section 2.2 (~~CONTROL~~Control), we conducted three sensitivity numerical experiments (Table 1) to address the ~~relative~~ response of INCWM characteristics~~contribution of~~ on local and remote air-sea heat flux changes. According to analyse of observation data (Fig. 6), three factors were designed in the sensitivity experiments which were the local air-sea heat flux in the previous winter (Case 1) and that from May to July (Case 2), remote (Hayasui Strait) air-sea heat flux in July (Case 3). ~~to the interannual variation of the INCWM in July. The Seto Inland Sea loses heat in winter and gains heat in summer. To determine the effects of local heat flux at different stages of the INCWM, we increased the air-sea heat flux loss/gain over Iyo-Nada (light blue dotted box in Fig. 1b) by 10 % from previous December to February (cooling season) in~~

~~Case 1 and from May to July (warming season) in Case 2. In addition, to determine the effects of remote heat flux, we increased the air-sea heat flux over the Hayasui Strait (light blue dotted box in Fig. 1b) by 10 % from May to July in Case 3.~~ By these sensitivity numerical experiments, the sensitivity coefficient q, which means the relative change of INCWM characteristic, is defined to quantify the response of the INCWM in July. Using water temperature as an example, q can be calculated using the following formula:

$$q = \frac{T_{case} - T_{control}}{T_{control}}, \qquad (1)$$

where, $T_{control}$ is the average water temperature in the area enclosed by a specific isotherm (18 ℃, Fig. 2c, July) along the vertical transect (Fig. 2a-l) in the Control run, and T_{case} is the corresponding variable in one of the sensitivity numerical experiments. If there is no water below 18 ℃, the water temperature at the mean location of the INCWM is used for T_{case}. For the size of the INCWM, T_{case} and $T_{control}$ in Eq. (1) are replaced by the area enclosed by the 18 ℃ isotherm along the vertical transect (Fig. 2a-l) in the corresponding experiments. If there is no water below 18 ℃, the area of the INCWM is set to 0. Except the vertical transection, the q of horizontal INCWM characteristics at 50 m deep layer (mean temperature and area surround by 18℃ isotherm) was also calculated to indicate the response of horizontal INCWM. In addition, we investigated the three-dimensional changes of INCWM by calculating its heat content. The sensitivity coefficient of heat content of INCWM (HC) was calculated to address the response of heat content on air-sea heat flux changes. HC equals to $\int \rho C_p T dV$, where C_p is the specific heat capacity of seawater (4096 J·kg^{-1}·℃$^{-1}$), ρ is the seawater density (1025 kg·m^{-3}), T is average water temperature (℃) of INCWM, V is the volume (m^3) of INCWM indicated by the 18℃ isotherm.

The results of sensitivity numerical experiments showed that ~~As listed in Table 2,~~ the INCWM characteristics changed obviously in all three experiments (Fig. 8 and Table 2). When sea surface water in Iyo-Nada lost more heat in the previous winter in Case 1, the heat content of INCWM in July increased (q = 0.40) with the volume of INCWM enlarging (q = 0.35 in the vertical plane and q = 0.13 in the horizontal plane) and the average temperature decreasing (q = -1.99×10^{-3} in the vertical plane and q = -1.59×10^{-3} in the horizontal plane). In Case 2, When increasing local air-sea heat flux from May to July, the heat content of INCWM in July decreased (q = -0.92) along with decreasing volume of INCWM (q = -1.0 in the vertical plane and q = -0.4 in the horizontal plane). In Case 3, increased remote (Hayasui Strait) air-sea heat flux in July also caused heat content of INCWM decreasing (q = -0.68) along with reduced volume of INCWM. On the whole, the responses of INCWM characteristics in Case 2 and Case 3 were much higher those in Case 1, indicating the importance of air-sea heat flux during stratified season on interannual variation of INCWM.

When changing local air-sea heat flux during warming seasons, the water temperature of INCWM at 50 m depth in July changed around -0.2℃ and 0.4℃ in Case 1 and Case 2, respectively (Fig. 8a, b). However, there seemed a limit of heat transfer around bottom front area (Fig. 8a, b). However, when changing the remote air-sea heat flux in Hayasui Strait, apparent heat transfer occurred across the bottom front area from the west side into INCWM (Fig. 8c). As we changed the same proportion of air-sea heat flux in the three sensitivity experiments, these results suggested that horizontal heat transfer (Fig. 6b) caused by the changes of remote air-sea heat flux in July was an important dynamic process when addressing the dynamic mechanism of interannual variation of INCWM. Nevertheless, Comparing the responses of INCWM in Case 2 and Case 3, they were similar but larger q occurred in Case 2 than those in Case 3 (Fig.8 and Table 2). This meant that INCWM was more sensitive to local air-sea heat flux change from May to July than remote air-sea heat flux change in July.

In terms of INCWM changes in the vertical and horizontal plane, the q in the vertical plane was larger than that in the horizontal plane (Table 2). This suggested that INCWM characteristics in the vertical plane were more likely to change when surface net heat flux changed. From the three sensitivity numerical experiments, we concluded that INCWM characteristics were more sensitive to air-sea heat flux changes during warming seasons than those in the previous winter. Besides, the vertical heat transport process influenced by local air-sea heat flux change in summer seemed more important than horizontal heat advection process influenced by the same change of remote air-sea heat flux in July.

~~both the sensitivity coefficients q of water temperature and area of the INCWM were much higher in Case 2 and Case 3 than in Case 1, indicating that the air-sea heat flux was more important in the warming season than in the cooling season. Regarding the interannual variation range of air-sea heat flux, the relative contributions of water temperature ($cr(T)$) and area ($cr(A)$) to the INCWM revealed some disagreement. For water temperature, the contributions of local and remote air-sea heat flux during the warming season were approximately 4.0 and 2.5 times, respectively, those during the cooling season, suggesting that the heat transport in the warming season is the dominant process influencing the interannual variation of the INCWM water temperature in July, to which the local air-sea heat fluxes contribute a little more than the remote air-sea heat fluxes. With respect to area, the $cr(A)$ in Case 1 was slightly larger than those in Case 2 and Case 3, indicating the importance of the winter cooling process. From three numerical experiments, we conclude that the vertical and horizontal heat transport processes in the warming season, rather than the initial condition preserved from the previous winter, are responsible for interannual variation in the INCWM in July.~~

Table 2: ~~Contributions~~ Sensitivity coefficient of INCWM characteristics~~air-sea heat flux to interannual variation of the bottom cold water mass in Iyo-Nada (INCWM)~~ in three sensitivity numerical experiments.

~~Experiments~~	~~Sensitivity coefficient q~~		~~Variation of the air-sea heat flux ($std(f)$)~~	~~Variation in experiments (Δf)~~	~~cr~~	
	~~Temp.~~	~~Area~~			~~$cr(T)$~~	~~$cr(A)$~~
~~Case 1~~	~~1.99×10^{-3}~~	~~0.35~~	~~65.35~~	~~13.69~~	~~9.49×10^{-3}~~	~~1.67~~
~~Case 2~~	~~2.47×10^{-2}~~	~~1.00~~	~~22.17~~	~~14.26~~	~~3.84×10^{-2}~~	~~1.55~~
~~Case 3~~	~~1.57×10^{-2}~~	~~0.87~~	~~22.77~~	~~14.58~~	~~2.44×10^{-2}~~	~~1.28~~

Experiments	Sensitivity coefficient q				
	Vertical transection		Horizontal 50 m depth		3-D space
	Temp.	Area	Temperature	Area	Heat Content

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Case 1	-1.99×10^{-3}	0.35	-1.59×10^{-3}	0.13	0.40
Case 2	2.47×10^{-2}	-1.00	-8.39×10^{-3}	-0.40	-0.92
Case 3	1.40×10^{-2}	-0.80	-1.41×10^{-3}	-0.23	-0.68

Note: As the vertical area of INCWM is 0 in Case 2, the sensitivity coefficient of the area in the vertical transection is 1.00.

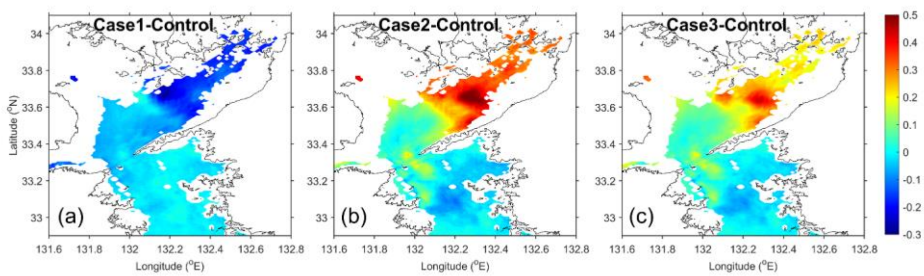


Figure 8: The spatial distribution of temperature difference (°C) between sensitivity numerical experiments and Control run at 50 m depth in July.

~~Wind-induced surface mixing is another factor affecting vertical heat transport. Thus, we conducted the same numerical experiments we did for air-sea heat flux for wind stress. However, the sensitivity coefficients q of wind were less than 0.006 and 0.06 for the temperature and area of the INCWM, respectively, which were much smaller than those of the air-sea heat flux experiments (Table 2). The weak sensitivity to wind stress is because of the presence of essential weak wind during the warming season in the study area. Consequently, air-sea heat flux is the main atmospheric forcing influencing interannual variation in the INCWM in July.~~

4.2 Comparison with BCWMs in other coastal seas

We investigated the interannual variation of a BCWM in a semi-enclosed coastal sea in Japan using long-term observations and a hydrodynamic model. As previously mentioned, BCWMs have been reported in continental seas worldwide. Overall, most of their seasonal evolutions and formation mechanisms, for example, being a part of remnant water from the previous winter, are similar (Horsburgh et al., 2000; Zhang et al., 2012; Lentz, 2017; Yu and Guo, 2018). Thus, we compared the similarities and differences among several coastal sea BCWMs ~~regarding their interannual variation~~.

The interannual variations of the Middle Atlantic Bight Cold Pool and Yellow Sea Cold Water Mass and their influencing factors have been described by Chen and Curchitser (2020) and Zhu et al. (2018). ~~Compared with these BCWMs~~In the same way as in these BCWMs, the coherent negative relationship between water temperature and size of BCWM was preserved in our study area, indicating a strong BCWM year featuring a low water temperature and a large size (area or volume).

Therefore, as an essential feature of a BCWM, its water temperature and size (area and volume) experience a consistent relationship among different coastal seas, presenting an inherent property that the water temperature inside the BCWM has a negative correlation with the spatial scale of the BCWM over an interannual time scale. Specifically, when heat enters the BCWM from the surrounding water, the water temperature inside the BCWM increases, causing the boundary of the BCWM defined by a specific water temperature to shrink.

Although similarly distinct interannual variations have been observed for these three BCWMs (Yellow Sea Cold Water Mass, Middle Atlantic Bight Cold Pool, and INCWM), their major ~~causes~~ influencing factors are different. Zhu et al. (2018) suggested that interannual variation in the Yellow Sea Cold Water Mass in summer depends mainly on the water temperature in the previous winter, which is controlled by local air-sea heat flux during the cooling season. Chen and Curchitser (2020) suggested that the temperature anomaly during winter and spring (mid-January to March) is the primary factor responsible for the interannual variability of the Middle Atlantic Bight Cold Pool temperature during the stratified season. Therefore, for these BCWMs, the initial temperature associated with the air-sea heat flux during the cooling season is important to their interannual variation in summer. However, in this study, we found that INCWM was more sensitive to air-sea heat flux change in summer than that in the previous winter. ~~the vertical and horizontal heating processes during the warming season, rather than the initial temperature before warming, were the dominant factor for interannual variation in the INCWM.~~ It is suggested that influence factors for interannual variations of BCWMs vary in different coastal seas though their seasonal cycles and formation processes are similar.~~This indicates that the primary influencing process on BCWMs interannual variation can vary, even though their seasonal cycles and formation processes are similar.~~This shows the unique response of different shelf seas to climate change. Since BCWMs have important effects on ecosystem and fishery, this finding also provides an insight to understand the different interannual changes of ecosystem and fishery in coastal seas with BCWMs.

Furthermore, we tried to explore the relationship among different BCWMs to help understand the response of bottom water in coastal seas to climate change from a comprehensive perspective. Interannual variation in BCWM temperature consists of two parts: the initial temperature after the cooling season, and the increasing range during the warming season. Because the water column vertically mixes in winter, the initial temperature of the BCWM is closely related to the local air-sea heat flux during the cooling season (Chen et al., 2016; Zhu et al., 2018). The increasing range of water temperature inside the BCWM during the warming season is controlled by the heat input from the surrounding water.

Based on above results, we discuss the water temperature of BCWMs from an idealized model. Because the horizontal scale of BCWM is much larger than vertical scale, a~~A~~s an approximation, we assume that a BCWM has the simple form of a cylinder with radius R (i.e., horizontal ~~range~~ size of BCWM) and height H (i.e., average thickness of BCWM). The initial water temperature of the BCWM is homogenous and the vertical heat diffusion coefficient is a constant. Further, during the warming season, the heat exchange flux with the surrounding water caused by sea surface heat flux is a constant m, and that caused by lateral heat flux is a constant n. Thus, on a seasonal scale, the following two equations can be established according to the conservation principle of heat:

$$\rho V C_p \frac{dT_1}{dt} = m \cdot \pi R^2 \ , \qquad (\cancel{3}2)$$

$$\rho V C_p \frac{dT_2}{dt} = n \cdot 2\pi R \cdot H \ , \qquad (\cancel{4}3)$$

where T_1 is the BCWM temperature change caused by sea surface heat flux, T_2 is the BCWM temperature change caused by lateral heat flux. ~~ρ is the seawater density, C_p is the heat capacity, and~~ V is the volume of the cylinder ($V = \pi R^2 H$). Using Eq. (~~3~~2) and Eq. (~~4~~3), we can obtain the following relationship:

$$\frac{dT_1}{dt} \propto \frac{m}{H}, \frac{dT_2}{dt} \propto \frac{2n}{R}, \qquad (\cancel{5}4)$$

Equation (~~5~~4) reveals that temperature change in the BCWM caused by sea surface heat flux is inversely proportional to H and that caused by lateral heat flux is inversely proportional to R. If we use T to represent the temperature of the BCWM, then its variation during the warming season can be given as:

$$\frac{dT}{dt} = \frac{dT_1}{dt} + \frac{dT_2}{dt} = \frac{1}{\rho C_p}\left(\frac{m}{H} + \frac{2n}{R}\right), \qquad (\cancel{6}5)$$

$\frac{dT}{dt}$ is inversely proportional to the size of BCWM (H and R), suggesting that the larger the size of the BCWM, the smaller the BCWM temperature changes during the warming season.

On this basis, we collected the information of five BCWMs (Table 3). The horizontal size of the BCWMs (R) varies widely from 40 km×30 km (Iyo-Nada) to 500 km×300 km (Bering Sea), whereas the average thickness of BCWMs (H) changes from around 30 m to 50 m. Because the horizontal size of the BCWMs and their variation are much larger than those in the vertical size, the water temperature variation of BCWM depends mainly on R.

As listed in Table 3, the water temperature rising rate during the warming season increases with decreasing horizontal BCWM size, which is consistent with the~~ previous~~ analysis. ~~Therefore, t~~The importance of local initial water temperature after a cooling season on the BCWM's temperature in summer is enhanced with an increase in the horizontal size of the BCWM. Note that the increasing rate of temperature ~~increase~~ in the Middle Atlantic Bight Cold Pool is the same as that of the BCWM in the Irish Sea, although the size of the Middle Atlantic Bight Cold Pool is larger (Table 3). Such difference ~~is~~ seems to be the result of an along-isobath mean current of 5 cm s^{-1} in the Middle Atlantic Bight that develops with the cold pool (Lentz, 2017), which leads to increased heat advection into the cold pool. For Iyo-Nada in this study, the size of INCWM is small and it is adjacent to a strait and the relatively strong horizontal density current exists between the strait and BCWM in July, thereby increasing the rate of temperature rise in the INCWM during the warming season (Yu et al., 2016).

Table 3 Characteristics of bottom cold water mass (BCWMs) in five coastal seas.

Coastal seas	Horizontal size of BCWM (km^2)	Average thickness of BCWM (m)	Temperature rising rate during warming season (℃ $month^{-1}$)	~~Main factor influencing~~Influence factors of interannual variation in the BCWM	References
Bering Sea	500 km×300 km	50	< 0.15	--	Goes et al. (2014); Wang and Zhao (2011)
Yellow Sea	300 km×300 km	40	approximately 0.2	Air-sea heat flux in the previous winter	Zhu et al. (2018)
Middle Atlantic Bight	100 km×300 km	50	approximately 1.2	Initial winter temperature and abnormal warming/cooling due to advection during stratified seasons	Lentz (2017); Chen et al. (2018)
Irish Sea	100 km×100 km	50	approximately 1.2	--	Holt and Proctor (2003)
Iyo-Nada	40 km×30 km	30	approximately 1.8	~~Air-sea heat flux during stratified seasons~~ more sensitive to air-sea heat flux change during warming seasons than that in the previous winter	Yu and Guo (2018); this study

Considering the influencing factors on the interannual variation of the three BCWMs (Yellow Sea Cold Water Mass, Middle Atlantic Bight Cold Pool, and INCWM), BCWM size may also be a key factor (Table 3). ~~As listed in Table 3, for a large size BCWM (such as Yellow Sea Cold Water Mass), the initial temperature is the dominant factor of interannual variation (Zhu et al., 2018) because of the low rate of temperature increase during the warming season. For a small BCWM (such as INCWM), atmospheric forcing (such as air-sea heat flux) during the warming season has a greater effect on interannual variation because of the large heat exchange rate with surrounding waters that are sensitive to atmospheric forcing. For the Middle Atlantic Bight Cold Pool, which is between the Yellow Sea Cold Water Mass and INCWM, both initial temperature and abnormal warming/cooling due to advection during the warming season are its primary drivers (Chen and Curchitser, 2020).~~ Here, we considered the influence of air-sea heat flux and lateral heat flux on the interannual variation of the BCWM temperature according to Eq. (~~6~~5). For a BCWM of a certain size (H and R are constant), the interannual variation of $\frac{dT}{dt}$ during the warming season ($\Delta\frac{dT}{dt}$) is calculated as follows:

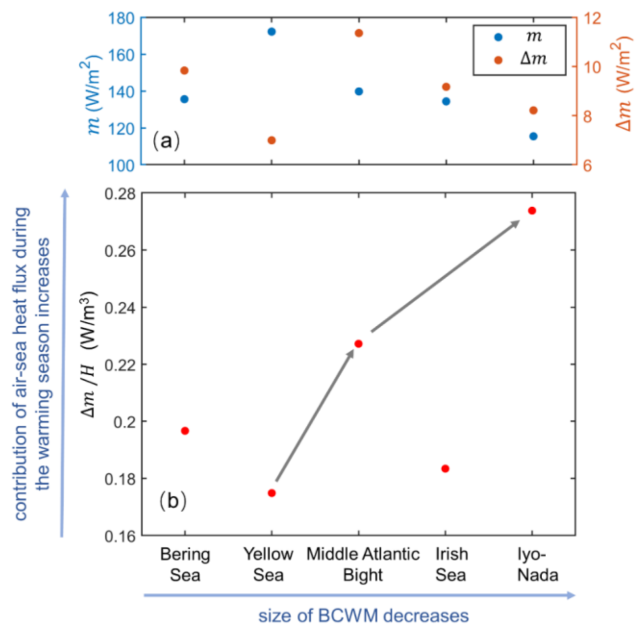
$$\Delta\frac{dT}{dt} = \frac{1}{\rho C_p}\left(\frac{\Delta m}{H}+\frac{2\Delta n}{R}\right) = \frac{1}{\rho C_p}\cdot\frac{\Delta m\cdot R+2\Delta n\cdot H}{HR}, \qquad (\cancel{7}6)$$

where Δm is the variation value of air-sea heat flux on an interannual scale, and Δn is the variation in the lateral heat flux on an interannual scale. Note that the influence of Δm is increased by R, while the influence of Δn is increased by H. ~~As R is much larger than H (at least 1000 times),~~As Δn is not easily to be evaluated, we could not evaluate the importance of $\Delta m \cdot R$ and $\Delta n \cdot H$, though R is much larger than H (at least 1000 times). ~~the influence of Δm is supposed to be more important than that of Δn. Furthermore~~Here, we discussed the ~~importance~~ role of air-sea heat flux during the warming season (Δm) on the interannual variations of the five BCWMs. ~~was discussed~~.

According to Eq. (~~5~~6), the temperature change in a BCWM caused by the interannual variation of air-sea heat flux is proportional to $\frac{\Delta m}{H}$ (W m^{-3}), which can be used to compare the contribution of air-sea heat flux during the warming season to the interannual variation of BCWMs in different coastal seas. Monthly air-sea heat flux (total of surface net solar radiation, surface net thermal radiation, surface latent heat flux, and surface sensible heat flux) data during 1979-2020 from the ERA5 dataset (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5, spatial resolution of 0.25°×0.25°) were used in the calculation. We used the standard deviation of air-sea heat flux during the warming season (from May to July) to address Δm (Fig. ~~6~~9). Overall, Δm in the five coastal seas ranged from 7.0 W m^{-2} (Yellow Sea) to 11.4 W m^{-2} (Middle Atlantic Bight) (Fig. 6a). After the adjustment of BCWMs thickness (H), the value of $\frac{\Delta m}{H}$ (approximately 0.27 W m^{-3}) was the biggest in Iyo-Nada, followed by the Middle Atlantic Bight (approximately 0.23 W m^{-3}), and the smallest value (approximately 0.17 W m^{-3}) occurred in the Yellow Sea (Fig. ~~6b~~9b). It has been suggested that the air-sea heat flux during the warming season is more ~~important~~ sensitive for the interannual variation of the INCWM than that of the Middle Atlantic Bight Cold Pool and the Yellow Sea Cold Water Mass. Thus, a distinct effect of the BCWM thickness was addressed, especially for the INCWM, which has a thin H (approximately 30 m) (Table 3) and small Δm (Fig. ~~6a~~9a). Regarding the interannual variation of the

Yellow Sea Cold Water Mass, the contribution of air-sea heat flux during the warming season was the smallest among the five BCWMs, suggesting the importance of local initial water temperature, which is supported by the results of previous studies (Wei et al., 2010; Li et al., 2015; Zhu et al., 2018). For the BCWMs in the Bering Sea and the Irish Sea, it was inferred that the contribution of air-sea heat flux during the warming season is between that of the Yellow Sea and the Middle Atlantic Bight (Fig. ~~6~~9).

~~Abou~~As for~~t~~ the relative importance of vertical heat diffusion and horizontal heat advection during the warming season, it depends closely on local features, including the topography of each coastal sea, and therefore must be clarified case by case. ~~For the INCWM, the results show that the local air-sea heat flux that affects vertical diffusion of heat is more important than the remote air-sea heat flux that affects horizontal heat advection (Table 2).~~



(a)
m
Δm
m (W/m^2)
Δm (W/m^2)
180
160
140
120
100
12
10
8
6
(b)
$\Delta m/H$ (W/m^3)
0.28
0.26
0.24
0.22
0.2
0.18
0.16
contribution of air-sea heat flux during the warming season increases
Bering Sea
Yellow Sea
Middle Atlantic Bight
Irish Sea
Iyo-Nada
size of BCWM decreases

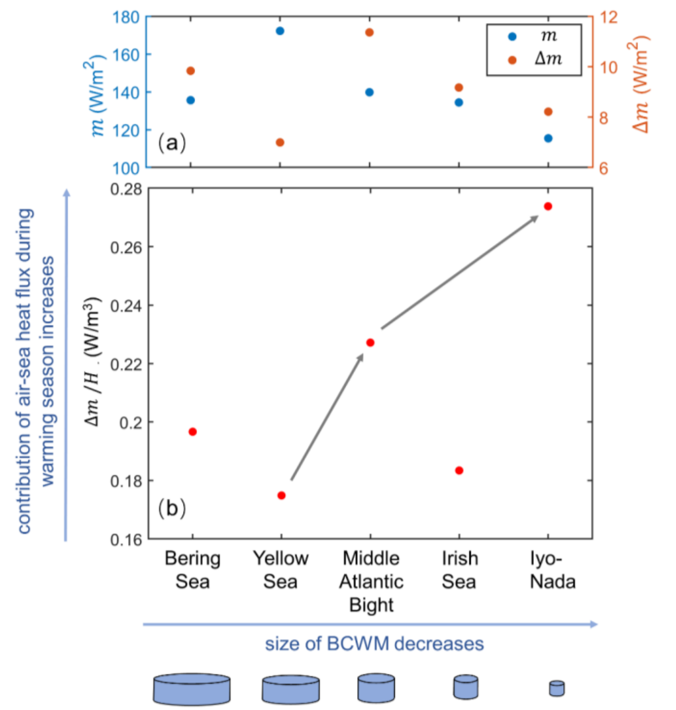


Figure ~~6~~9: Values of (a) air-sea heat flux during warming season (m) and corresponding interannual variation (Δm), and (b) $\frac{\Delta m}{H}$ values in the five coastal seas. The directions of gray arrows in (b) indicate an increased contribution of air-sea heat flux during the warming season to interannual variation in the bottom cold water mass (BCWM). The cylinder at the bottom means the size of BCWM for which the horizontal and vertical are not proportional.

5 Conclusions

In this study, we investigated the interannual variation of the INCWM from 1994 to 2015 using observational data along a transect across the INCWM~~. We~~ and further analy~~s~~zed the ~~influencing factors~~response of INCWM characteristics to~~ and quantified the contribution of sea surface forcing to interannual variation in the INCWM~~ air-sea heat flux changes. Observation shows that the INCWM is not significant in 2007 with water temperature higher than 18 ℃. The mean water temperature inside the INCWM was 17.58 ℃ with the lowest temperature 17.04 ℃ (2006) and the highest temperature

18.23 °C (2007), while the mean area of INCWM was 5.73×10^{6} m^{2} with the smallest area 0 m^{2} (2007) and the largest area 1.46×10^{6} m^{2} (2006). The interannual variation of the mean water temperature inside the INCWM and that of its area show a significant negative correlation. The interannual variation of water temperature inside the INCWM depends on both the water temperature in April (initial temperature) and the vertical and horizontal heat ~~transport~~ transfer into the INCWM during ~~the~~ warming seasons. A strong INCWM corresponds to a low local water temperature in April and a low water temperature in the Hayasui Strait in July. Sensitivity n~~N~~umerical experiments showed that the air-sea heat flux change during the warming season plays ~~a key~~an important role in the interannual variation of the INCWM~~,~~ its sensitivity coefficient is larger than that in the previous winter. ~~contributing 6.6 and 1.7 times to the mean water temperature and area of INCWM, respectively, than the air-sea heat flux in the cooling season. Therefore, with respect to interannual variation in the INCWM,~~ This means that the heat transport process during the warming season impacted by air-sea heat flux change might be the priority with respect to interannual variation in the INCWM. ~~is more important than the initial temperature after the cooling season.~~ Conversely, for the Yellow Sea Cold Water Mass, the initial temperature after the cooling season is more important than heat transport during the warming season. This difference is likely related to the size of the BCWMs. A larger BCWM has a weaker dependence on heat transport during the warming season, but a stronger dependence on the initial water temperature before the warming season. This simple relationship will be helpful for understanding the responses of bottom water in different coastal seas to changes in atmospheric forcing.

~~BCWM is a widespread physical oceanic phenomenon. This~~Our study examined the interannual variation of INCWM characteristics for the first time and evaluated its sensitivity to air-sea heat flux change by a climatological model. ~~water~~ The three heat transfer processes (Fig. 6) influencing INCWM characteristics changes are discussed qualitatively here. As a future work, a long-term simulation with realistic forcing would be applied to investigate the detail dynamic mechanism controlling the interannual variation of INCWM. ~~temperature and its controlling factor for a BCWM in the Seto Inland Sea. As an extension, we analyzed the control processes on interannual variation of water temperature in the five BCWMs reported in the literatures using a cylinder column to represent their shape. Our analysis results are consistent with previous studies on the interannual variations of the Yellow Sea Cold Water Mass and the Middle Atlantic Bight Cold Pool. For other BCWMs, although there is no study on their interannual variations, this study provides a direction to know the influencing factor on the interannual variation of water temperature. On the other hand, our simplification with a cylinder column to represent the BCWMs does not consider the variation in bathymetry, which is however expected to affect the current structure around the BCWMs. Although this issue is difficult, it should be one of our future research topics.~~ Another issue is the biogeochemical aspects around the BCWMs, especially the transport of nutrient across the BCWMs, which has considerable effects on the phytoplankton growth around the BCWMs. This is an inverse pathway to the heat transport and is expected to be large in some BCWMs.

Code availability. The source code of numerical model used in this study is available on request. Please contact Xinyu Guo (guoxinyu@sci.ehime-u.ac.jp)

Data availability. The sea surface forcing used for calculation in Section 4 are from DSJRA-55 product (https://jra.kishou.go.jp/) provided by Japan Meteorological Agency and ERA5 product (https://www.ecmwf.int/en/forecasts/datasets/) provided by ECMWF. The observation data is collected from the Prefectural Fishery Research Centers around the Seto Inland Sea which is available on request. Please contact Xinyu Guo (guoxinyu@sci.ehime-u.ac.jp)

Author contribution. Junying Zhu: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Software, Validation, Visualization, Writing – original draft preparation, Writing – review & editing; Jie Shi: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Writing – original draft preparation, Writing – review & editing; Xinyu Guo: Conceptualization, Methodology, Resources, Software, Validation, Supervision, Writing – review & editing

Competing interests. The authors declare that they have no conflict of interest.

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