Response to Referee #1:

Please find our responses below, with reviewer's comments in italics, authors' responses in standard format, and author's changes in manuscript in blue words.

GENERAL COMMENT

This is an interesting research. The aim of this work is to develop a warming system for fishery to predict exceptionally cold water days in the southern Taiwan Strait. The authors used ONI and wind speed as indicators to predict the days and found that both proxies can be at lead times of 60 - 210 days and 0 - 30 days, respectively. This analysis results are useful for the regional warming system and worth publishing. Thus, this reviewer recommends the manuscript to be accepted for publishing after doing the following minor revisions.

Reply:

We would like to thank the reviewer for providing constructive comments and suggestions.

1. *The aim of this study is to assess the predictability of exceptionally cold water in the Taiwan Strait and to develop a warning system. Therefore, the tests conducted using relative operating characteristics curves (ROC) need to be careful because ROC plots could be misleading when applied in imbalanced classification scenarios. However, Precision/Recall (PRC) plots can provide an accurate prediction of future classification performance (Saito and Rehmsmeier, 2015, The Precision-Recall Plot Is More Informative than the ROC Plot When Evaluating Binary Classifiers on Imbalanced Datasets, PLOS one). This reviewer suggests the authors apply PRC plots to confirm the predictability.*

Reply:

Thanks the reviewer for pointing this potential problem out. In a similar research work, McKinnon et al. (2016, Nature Geoscience) have used ROC curves to analyze SST and successfully predicted 321 hot days from the 2040 summer days in imbalanced classification scenarios. Both of ROC and PRC are statistical methods to find out a threshold depending on the tolerance for the TPR, FPR, and PPV. As suggested by the reviewer, we have incorporated PRC method in our revised manuscript. By using PRC method, the lead time are 60-120 days and 0-25 days for the ONI-based prediction and the wind-based predictions, respectively. We have added the consequent discussion in the revised manuscript.

Please see lines 23-29 in page 6 and lines 17-18 in page 7.

Lines 23-29 in page 6:

Further, Saito and Rehmsmeier (2015) indicated the precision-recall curves (PRC) could be more informative than the ROC curves on imbalanced datasets. PRC is a trade-off between positive predictive values (PPV), defined as $\sum_{\mathrm{TP}}/[\sum_{\mathrm{TP}}+\sum_{\mathrm{FP}}]$, and TPR. Therefore, we also utilize the PRC to examine the predictability of cold water days (Fig. 5b). Although the baseline of ROC is fixed, the baseline of PRC is decided by $[\sum_{\mathrm{TP}}+\sum_{\mathrm{FN}}]/[\sum_{\mathrm{TP}}+\sum_{\mathrm{FN}}+\sum_{\mathrm{FP}}+\sum_{\mathrm{TN}}]$. As a result, the baseline is PPV=0.07 (a grey dashed line in Fig. 5b) and the prediction of cold water days become significant when the AUC of PRC is greater than 0.15. The results shows that cold water days could be predicted with a lead time of 60–120 days, shorter than ROC method (60–210 days).

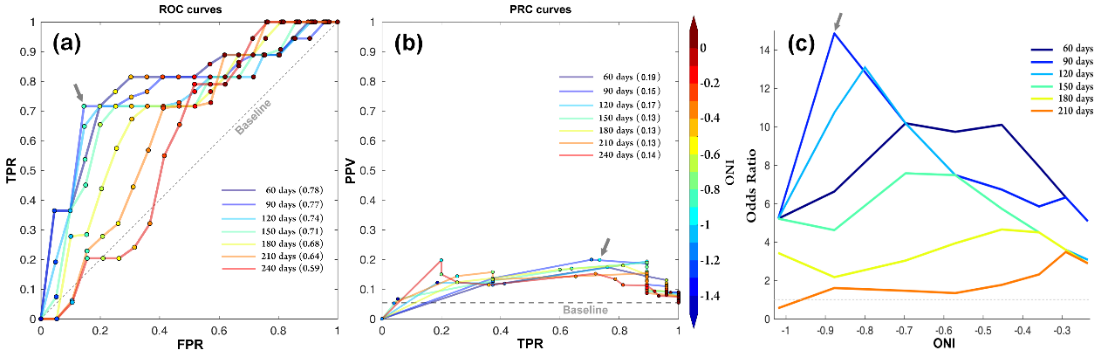


Figure 5: (a) ROC curves for predicting cold water days at lead times of 60, 90, 120, 150, 180, 210, and 240 days using the negative ONI. Numbers in parentheses in the legend are ROC scores for each lead time. The thresholds used to calculate TPRs and FPRs are showed from the 100th (lower left squares) to the 0th (upper right squares) percentile of negative ONI in decrements of 5%. ONIs at the dots are indexed by the colorbar. ROC scores ≥ 0.6 indicate a significant ($p < 0.05$) proxy for predictability. (b) As in Fig. 5(a) but plotting PRC curves. AUC of PRC ≥ 0.15 indicate a significant ($p < 0.05$) proxy for predictability. (c) Odds ratios vary with ONI thresholds at lead times of 60, 90, 120, 150, 180, 210, and 240 days. Arrows denote the point with a -0.9 threshold at a 90-day lead time.

Lines 17-18 in page 7

Moreover, the wind-based predictions were also examined through PRC (Fig. 7b). The results shows that it has significant prediction skill for lead times from 0 to 25 days.

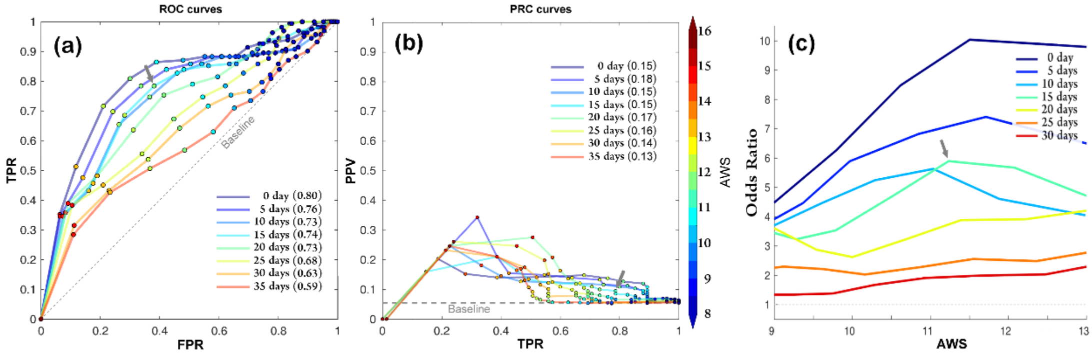


Figure 7: As in Fig. 5, but for predictions of cold events at lead times of 0, 5, 10, 15, 20, 25, 30, and 35 days using the wind speed with an averaged time of 10 days. Arrows denote the point with an 11.5-m/s threshold at a 15-day lead time.

2. *Page 2, lines 2-3. It is better to have some references to support the statement.*

Reply:

Yes, two relevant papers, Wang et al. (2000) and Lau et al. (2006), were added in the revised manuscript. Please see lines 3-5 in page 2.

"It is known the cold phase of ENSO, La Niña, tends to intensify the East Asian winter monsoon, which often accompanies strong northerly winds and sharp air temperature drops. By contrast, the warm phase, El Niño, suppresses the East Asian winter monsoon (Wang et al., 2000; Lau et al., 2006)."

3. *Page 2, lines 20-21. The critical temperatures for different fished are different. What is the critical temperature defined in this study for exceptionally cold water?*

Reply:

Yes, we understand the critical temperatures inducing the death of different fishes are not consistent. We have incorporated the known critical temperature for the fish kind associated with the cold disaster event in the revision. However, for cold disaster prediction, the relationship between fish death and critical temperature is questionable because (1) no fish death occurring west of Penghu Island (onshore of mainland China), where the water temperature is much lower than near Penghu Island, and (2) the fish could escape from the cold water zone, where the water temperature reach critical value. There must be some unknown physical and biological processes and their interaction. As a result, we won't focus on exploring the value of critical temperature. Instead, this manuscript studies exceptionally cold water, as indicated in the title of this manuscript, which might potentially trigger "cold damage" (we will name it as cold disaster, referring to the events of large amount of fish death, in the revised ms) in the TS and assess the predictability of exceptionally cold water. In this study, exceptionally cold water (cold water day) is defined by SSTAs < −2.5 °C, translating into temperature about 17°C. We have added a figure in the supplement. Please see lines 24-27 in page 3.

“The cold disaster is biological or ecological response to low water temperature as defined in introduction. The critical temperatures inducing the death of different fishes are not consistent. Chang et al. (2013) indicated the activity of reef fish is declined at water temperature lower than 16 °C. Feeding activity of Cobia, a major species of cage aquaculture fish around Penghu Islands, is declined as lower than 18 °C and fish may die as lower than 15 °C (Lu et al., 2012). The sophisticated prediction for the cold disaster require the understanding of the detailed physical and biological processes and will need the information about marine resource. Unfortunately, we don’t have data associated with marine resource or aquaculture production. The most relevant information is the date of occurrence of cold disaster in 2000, 2008 and 2011, indicating from the previous literature (Chang et al., 2013; Lu et al., 2012). Therefore, we won’t focus on exploring the value of critical temperature. Instead, a goal of this paper is developing a warning system to predict the exceptionally cold water around the Penghu Islands in the southern Taiwan Strait. It is expected that the presence of the exceptionally cold water points to the high possibility of the occurrence of cold disaster (referring to the events of large amount of fish death).

During the winter days (60 coldest days of winter as defined in Section 2), further cooling days are expected to happen the exceptionally cold water which may have the greatest implications for aquaculture (hereafter referred to "cold water days"). This study focused on hindcasting the occurrence of cold water days during the winter days. Regarding that the long-term observations of water temperature around Penghu are absent (~20–year time series needed), the cold water days were characterized by remotely sensed SST anomalies (SSTA) lower than a threshold (SSTA<-2.5 °C, i.e. SST< about 17°C). SSTA is a deviation from the daily climatological average (Supplementary Fig. 1) and the threshold is estimated by 1.6 times the standard deviation (approximately 95% interval of normal distribution) of SSTA. To obtain a quantity representative of the magnitude of low SSTA, we selected the targeting area as a box in 23.5–24.5°N and 119–120°E (the white dash rectangle in Fig. 1), mainly off north coast of Penghu Island, covering the coolest SST deviation feature in Figure 3c, and a high correlation (r=0.94, p<0.05) with observational water temperature (Supplementary Fig. 3).”

<u>Figure S1</u>

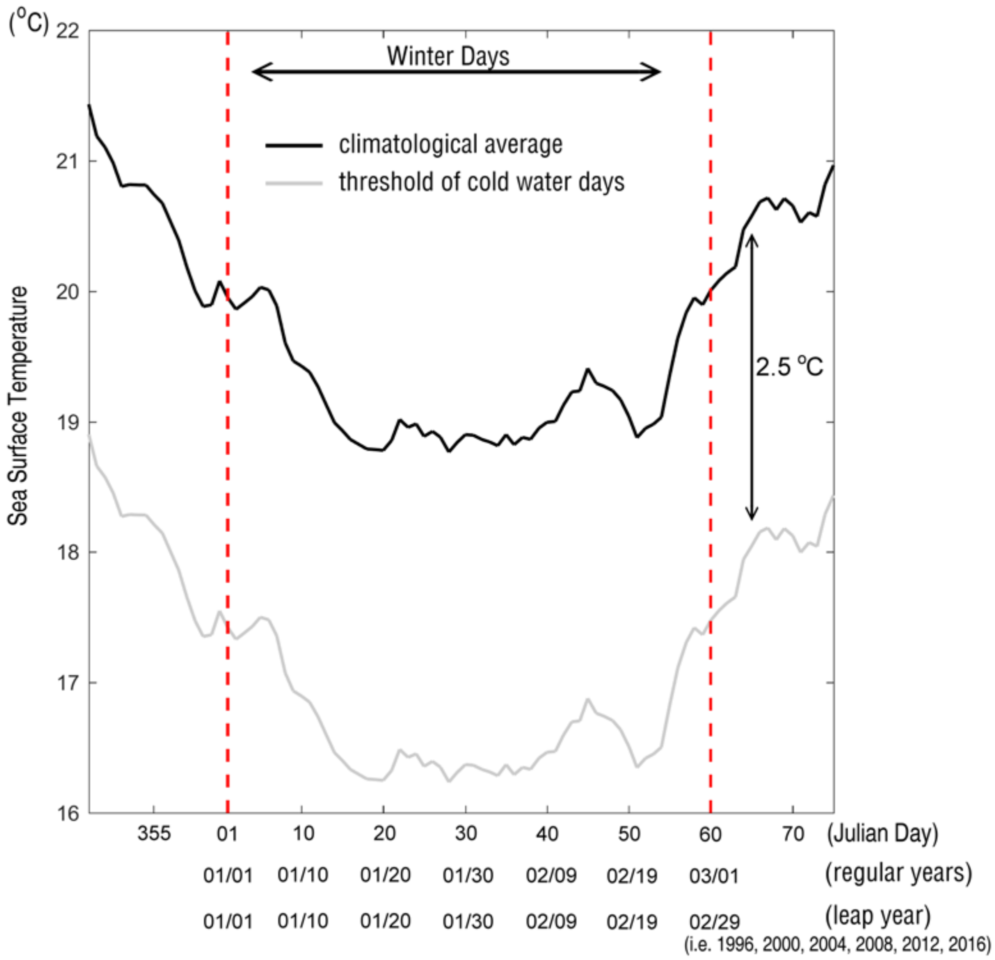


Figure S1: time series of climatological SST (black line) across the southern TS (the white dash rectangle in Figure 1) and the threshold of cold water days (gray line). Red dash lines reveal the period of winter days.

4. *Page 2, line 18. Does the winter of 2008 mean from December 2007 to January 2008 or from December 2008 to January 2009? Please make it clear.*

Reply:

The winter season in this area is from December to the following February. We have clarified it in the revised manuscript. Please see lines 18-20 in page 2.

"In the winter of 2008 (December 2007 to February 2008), exceptionally cold water affect the southern TS and hit the marine natural resources around the Penghu Islands in the southwestern TS, causing damage to the aquaculture and high fish mortality rates; this phenomenon is referred to as "cold disaster"."

5. *Page 3, line 4. This study used sea surface temperature (SST) as the indicator of temperature. However, the influence of temperature on fish is not only SST but also the temperature at subsurface layer. Is the temperature at sea surface and subsurface the same in the study area?*

Reply:

Thanks. Because the Taiwan Strait is shallow and the wind is very strong in winter, it is excepted water column is well mixed in the vertical. The climatological temperature profile during winter (averaged in December to February, 1985-2017) near the Penghu (23.75°N, 119.75°E) is displayed in Figure S2. Indeed, the figure showed insignificant temperature difference between surface and subsurface in this region (< 1.2°C). As a result, we believe SST is a suitable indicator depicting the water temperature of whole layers. We have added the above results in the revised manuscript. Please see lines 11-16 in page 3.

"The influence of temperature on fish is important not only in the surface layer but also in the subsurface layer. Although the methodology in the study is based on SST, it is excepted water column is well mixed in the vertical due to shallow bathymetry in the TS and the strong wind in winter. An insignificant temperature difference between surface and subsurface in this region (< 1.2 °C) is shown by the climatological temperature profile (Supplementary Fig. 2) during winter (averaged in December to February, 1985–2017) near the Penghu (23.75°N, 119.75°E). Thus, SST could be a suitable indicator depicting the water temperature of whole layers."

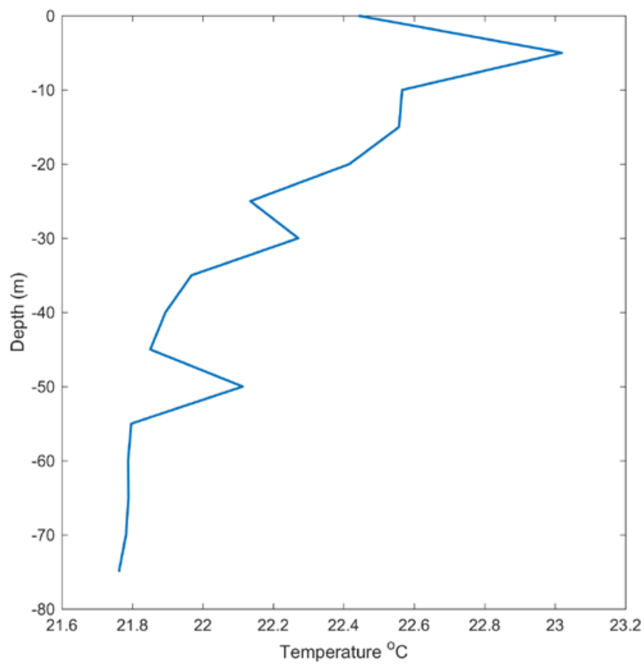


Figure S2: A climatological temperature profile during winter (December to February, 1985–2017) near the Penghu (23.75oN, 119.75oE), provided by the Ocean Data Bank of Taiwan.

6. *Page 3, line 25. Is it 1320 winter days or 1380? Please check and confirm it. If the*

span of data is from January 1995 to May 2007, the reviewer's calculation is 1380?

<u>Reply:</u>

Thanks. It is 1380. We have corrected it in the revised manuscript. Please see lines 15-16 in page 4.

"According to these definitions, 1,380 winter days of the study period, 95 cold water days and a total of 9 cold events (triangles in Fig. 2; Table 1)"

7. *The authors gave the ONI time series in Figure 2. Are these ONI values calculated by the authors self or an official data from NOAA CPC? If it was calculated by authors, it's better to indicate the relative time period for calculating the SSTA?*

<u>Reply:</u>

ONI used in this manuscript are downloaded from NOAA CPC (https://goo.gl/V6CtMD). We have added essential illustration in the revised version. Please see lines 17-19 in page 3.

"The Oceanic Niño Index (ONI) values, defined as a 3-month running mean of SST anomalies in the region of 5°N–5°S and 120°W–170°W, are taken from NOAA Climate Prediction Center (CPC; https://goo.gl/V6CtMD). The values are used for classifying the ENSO cycle into El Niño (ONI ≥ 0.5 °C) and La Niña (ONI ≤ −0.5 °C) (Huang et al. 2015)."

8. *Page 4, line 17. It better to show and discuss the results of air-sea heat fluxes in El Niño and La Niña events instead of just giving the temperature difference in Figure 3.*

<u>Reply:</u>

Thanks for the reviewer's suggestions. We have added figures of heat flux and associated discussion in the revised manuscript. Please see lines 6-9 in page 5.

"The stronger wind generating turbulence mixing would likely lead to increased air–sea heat fluxes (Fig. 3f) and would substantially affect the extent of cold water in the TS. Figure 3d–3f shows surface total heat fluxes provided by NCEP/NCAR 40-year reanalysis project (Kalnay et al., 1996). More heat energy can be transferred from the ocean to the atmosphere in the La Niña (Fig. 3f) than that in the El Niño (Fig. 3e)."

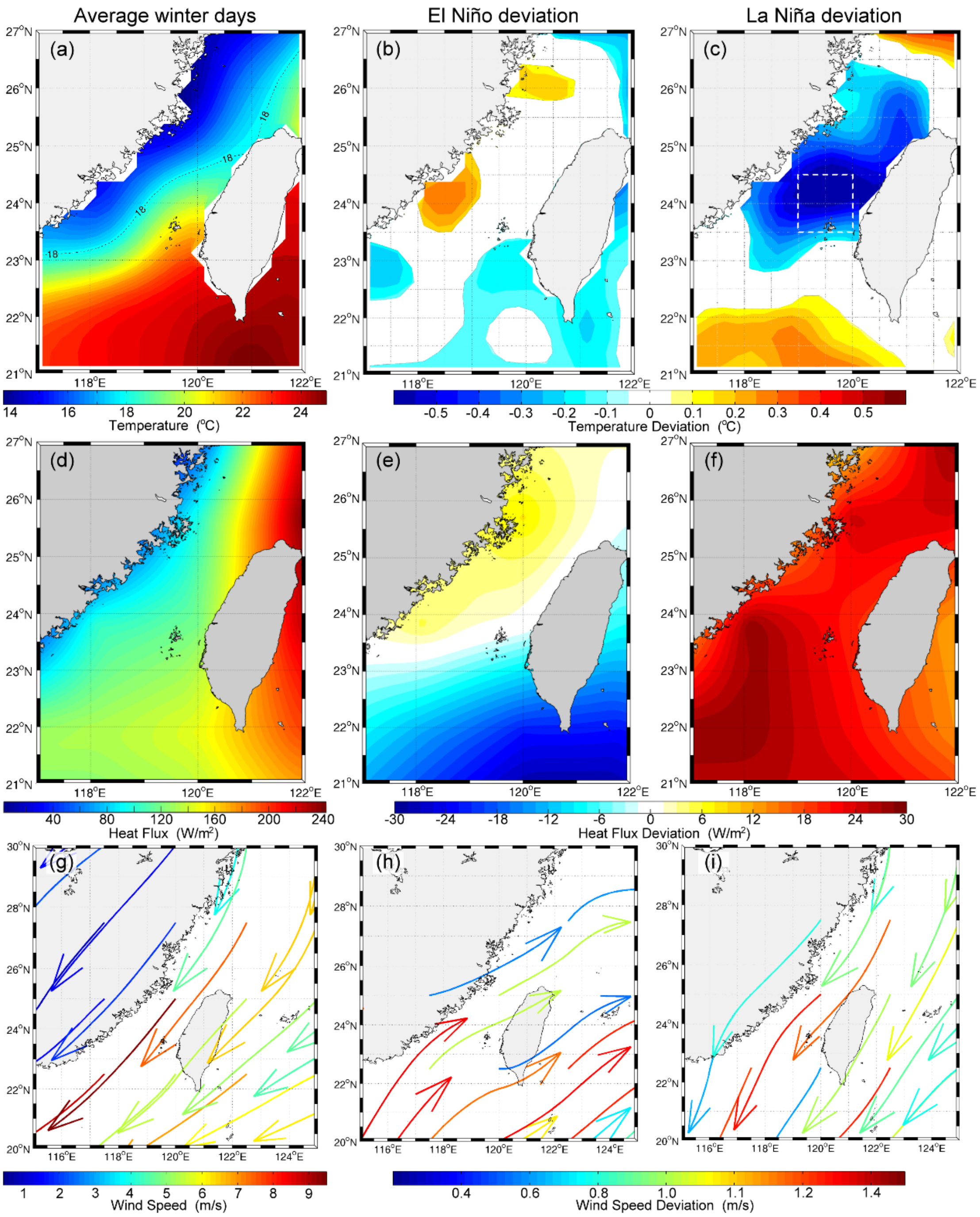


Figure 3: Composite of SST (a to c), surface total heat fluxes (d to f), and surface wind fields (g to i) for (a, d, g) average winter days, (b, e, h) El Niño deviation, and (c, f, i) La Niña deviation. Only deviations above the 95% confidence level are shown. Positive heat flux values represent heat energy gain to the atmosphere.

9. *Is it possible to list all during dates of "cold events" in a new table? Figure 2 (a) does not show clearly, for example, events 2 and 3, and events 7 and 8.*

Reply:

Thanks for reviser's suggestion. We have clarified it in Table 1 in the revised manuscript.

Table 1: A list of cold events during 1995-2017

Number	Date (yyyy/mm/dd)
Event 1	1996/02/23—1996/02/29
Event 2	2000/02/02—2000/02/15
Event 3	2000/02/23—2000/02/29
Event 4	2006/01/09—2006/01/14
Event 5	2008/02/11—2008/02/20
Event 6	2011/01/30—2011/02/02
Event 7	2012/01/16—2012/02/12
Event 8	2012/02/18—2012/02/20
Event 9	2013/01/16—2013/01/19

10. The English of the manuscript is understandable, but still needs to be carefully polished.

Reply:

Thanks for the suggestion. The manuscript has been through English editing before submission. We will revise it more carefully in the revision.

Response to Referee #2:

Please find our responses below, with reviewer's comments in italics, authors' responses in standard format, and author's changes in manuscript in blue words.

GENERAL COMMENT

It is very delighted to see these authors to describing the Exceptionally cold water days in the southern Taiwan Strait: their predictability and relation to La Niña. This manuscript tried to assess the predictability of exceptionally cold water and to develop a warning system in the Taiwan Strait (TS). It was clearly written, and already to develop one warning system using the Oceanic Niño Index and integrated wind speed. But it is still difficult to apprehend whether the authors were mainly concerned of "Exceptionally cold water days in the southern Taiwan Strait".

<u>Reply:</u>

We would like to thank the reviewer for providing constructive comments and suggestions.

1. *Firstly, the authors need to clearly define the cold waters days or the hotspot area (such as Penghu islands) as they demonstrate exceptionally cold water hit the marine natural resources around the Penghu Islands in the southwestern TS, causing considerable damage in marine aquaculture.*

<u>Reply:</u>

As mentioned in the Sections 2 and 3 of manuscript, cold water days in this manuscript are defined as SSTAs < −2.5 °C, i.e. the temperature is lower than about 17°C (we have added a figure to further explain in the Supplementary). SSTA is a deviation from the daily climatological average. In a similar research work, McKinnon et al. (2016, Nature Geoscience) have used the same method to analyze SST and successfully predicted extreme hot days in summer in US. The hot spot area has been re-defined as suggested by the reviewer. We will illustrate in the reply to the reviewer's second point.

Please see lines 5-9 page 4.

"Regarding that the long-term observations of water temperature around Penghu are absent (~20–year time series needed), the cold water days were characterized by remotely sensed SST anomalies (SSTA) lower than a threshold (SSTA<-2.5 °C, i.e. SST< about 17°C). SSTA is a deviation from the daily climatological average (Supplementary Fig. 1) and the threshold is estimated by 1.6 times the standard deviation (approximately 95% interval of normal distribution) of SSTA."

<u>Figure S1</u>

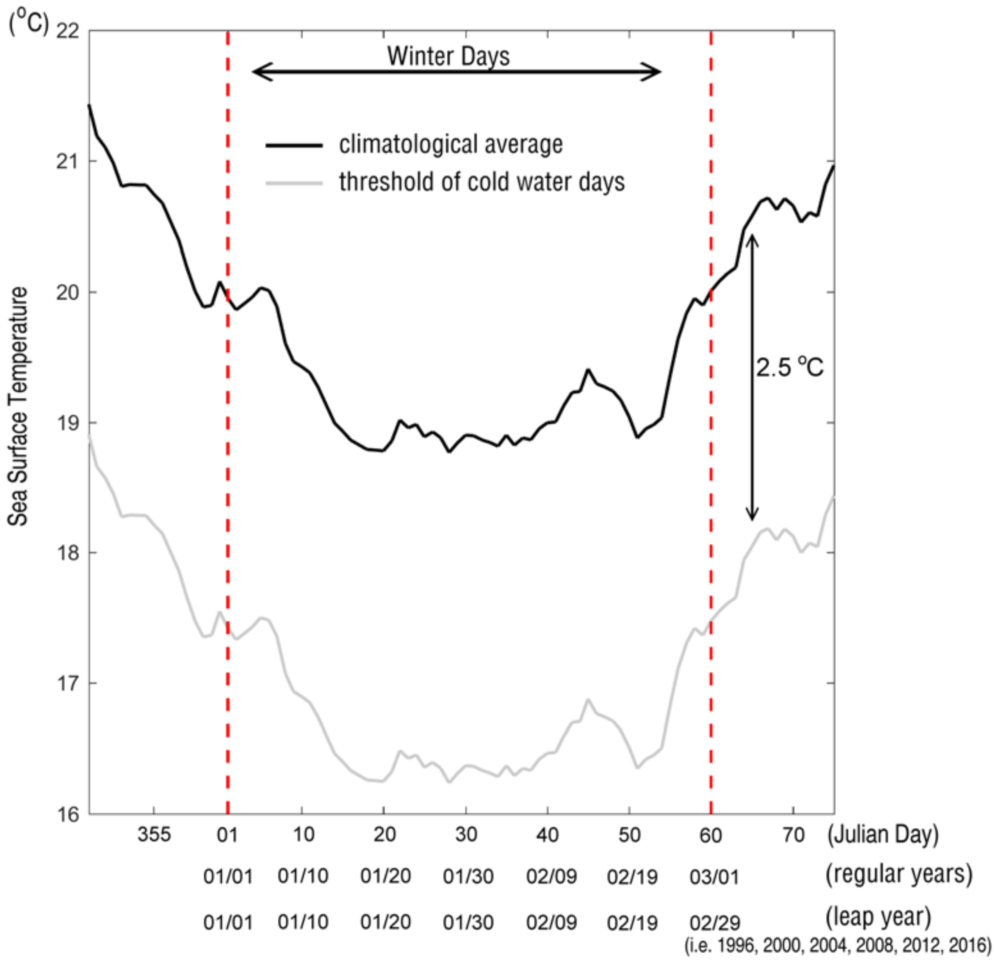


Figure S1: time series of climatological SST (black line) across the southern TS (the white dash rectangle in Figure 1) and critical temperature of cold water days (gray line). Red dash lines reveal the period of winter days.

2. *Secondly, "cold damage" is still unclear. Based on the description in this submission, the "cold damage" should be a kind of biological or ecological response to low water temperature in the waters around Penghu islands. Therefore, the authors need to consider where is the optimum area for developing the warning system on "Cold damage". And, the analysis or observation on the impact of marine resource or aquaculture production of hotspot area (NOT equal to the blue dotted quadrilateral in Figure 1) may important in the session of result or discussion. For example, the author showed a moderate SST belt extending from southwest to northeast, and an isotherm of nearly 18 ◦C across the northern Penghu Islands in fig.3a. It might reveal to separate the colder water in the west from the warmer water in the waters of northern Penghu Islands (Not in the southeastern TS).*

Reply:

Yes, the cold damage is biological or ecological response to low water temperature. To be specific, in the revised ms, we have defined "cold disaster" referring to the serious fish death induced by exceptionally cold water around the Penghu Island. In this ms, we aim to develop a warning system to predict the cold water days in the southern Taiwan Strait, as indicated in the title of our manuscript. It is expected that the presence of the cold water days points to the high possibility of the occurrence of cold disaster. Regarding that the long-term observations of water temperature around Penghu are absent (~20- year time series needed), the cold water days were characterized by remotely sensed SSTA lower than a threshold.

We agree with the reviewer that it is important to find the “optimum area” to calculate SSTA and evaluate its impact on biological environment for the development of the warning system. Unfortunately, we don’t have data associated with marine resource or aquaculture production. The most relevant information is the date of occurrence of cold disaster in 2000, 2008 and 2011, indicating from the previous literature. The information should be sufficient for the present goal for this work, to predict the cold water days. But the sophisticated prediction for the cold disaster require the understanding of the detailed physical and biological processes and will need the information about marine resource. This is certainly our next goal.

As mentioned by the reviewer, the targeting area we selected covers a frontal area as shown in Figure 3a, which may not be suitable for the index of cold water days. We have re-selected the targeting area as a box in 23.5-24.5^{o}N and 119-120^{o}E, mainly off north coast of Penghu Island, covering the coolest SSTA feature in Figure 3c, and a high correlation ($r=0.94$, $p<0.05$) with observational water temperature (Figure S3). SST from buoy sited on the north of Penghu Islands (red star in Figure 10a) is the most suitable indicator monitoring the water temperature around Penghu Island, but unfortunately buoy SST can be used after January 2007 and lost efficacy in 2013-2016. As mentioned in the above reply, the long-term observations of water temperature around Penghu are absent. Although the satellite SST in the targeting area is overall higher than SST measured by the buoy (Figure S3), it has a high correlation with observational SST and should be sufficient for the present goal for this work.
Please see from line 24 in page 3 to line 12 in page 4.
“The cold disaster is biological or ecological response to low water temperature as defined in introduction. The critical temperatures inducing the death of different fishes are not consistent. Chang et al. (2013) indicated the activity of reef fish is declined at water temperature lower than 16 °C. Feeding activity of Cobia, a major species of cage aquaculture fish around Penghu Islands, is declined as lower than 18 °C and fish may die as lower than 15 °C (Lu et al., 2012). The sophisticated prediction for the cold disaster require the understanding of the detailed physical and biological processes

and will need the information about marine resource. Unfortunately, we don’t have data associated with marine resource or aquaculture production. The most relevant information is the date of occurrence of cold disaster in 2000, 2008 and 2011, indicating from the previous literature (Chang et al., 2013; Lu et al., 2012). Therefore, we won’t focus on exploring the value of critical temperature. Instead, a goal of this paper is developing a warning system to predict the exceptionally cold water around the Penghu Islands in the southern Taiwan Strait. It is expected that the presence of the exceptionally cold water points to the high possibility of the occurrence of cold disaster (referring to the events of large amount of fish death).

During the winter days (60 coldest days of winter as defined in Section 2), further cooling days are expected to happen the exceptionally cold water which may have the greatest implications for aquaculture (hereafter referred to "cold water days"). This study focused on hindcasting the occurrence of cold water days during the winter days. Regarding that the long-term observations of water temperature around Penghu are absent (~20–year time series needed), the cold water days were characterized by remotely sensed SST anomalies (SSTA) lower than a threshold (SSTA<-2.5 °C, i.e. SST< about 17°C). SSTA is a deviation from the daily climatological average (Supplementary Fig. 1) and the threshold is estimated by 1.6 times the standard deviation (approximately 95% interval of normal distribution) of SSTA. To obtain a quantity representative of the magnitude of low SSTA, we selected the targeting area as a box in 23.5–24.5°N and 119–120°E (the white dash rectangle in Fig. 1), mainly off north coast of Penghu Island, covering the coolest SST deviation feature in Figure 3c, and a high correlation (r=0.94, p<0.05) with observational water temperature (Supplementary Fig. 3).”

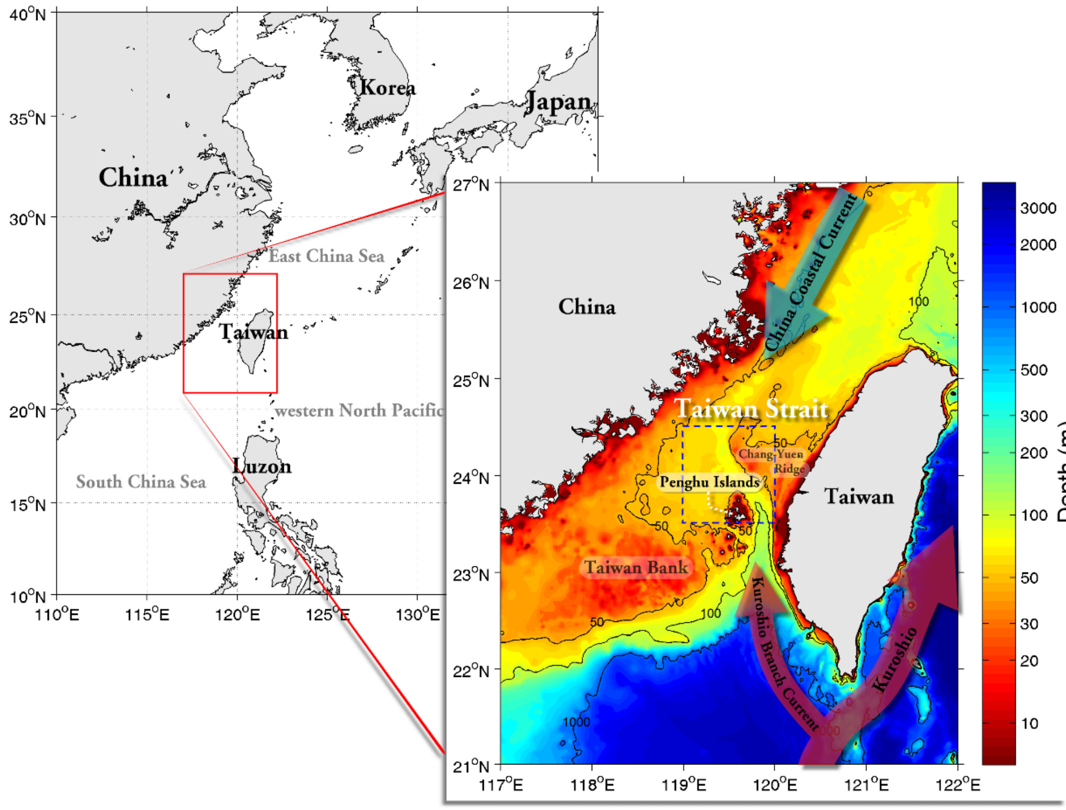


Figure 1: Bathymetric chart (shaded color) and sketches of the China Coastal Current, Kuroshio, and Kuroshio Branch Current.

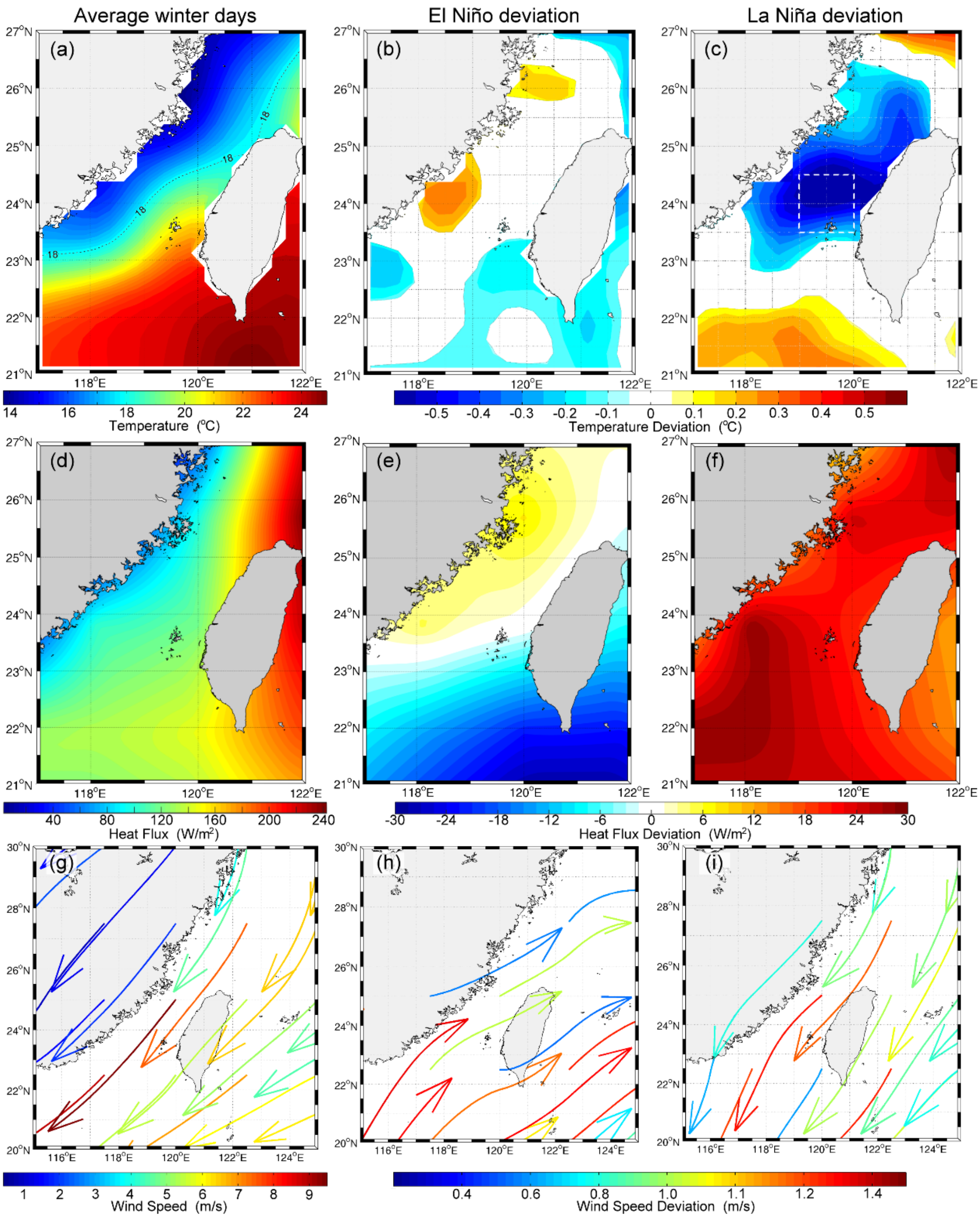


Figure 3: Composite of SST (a to c), surface total heat fluxes (d to f), and surface wind fields (g to i) for (a, d, g) average winter days, (b, e, h) El Niño deviation, and (c, f, i) La Niña deviation. Only deviations above the 95% confidence level are shown. Positive heat flux values represent heat energy gain to the atmosphere.

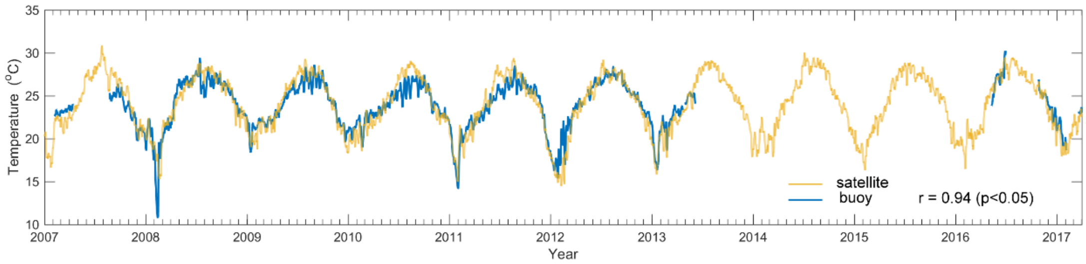


Figure S3: Time series of SST observed by satellite (yellow line) and buoy (blue line). Please note that buoy SST can be used after January 2007 and therefore the figure shows the correlation between satellite SST and buoy SST after January 2007.

3. *Thirdly, risk definition is also unclear. I did not know whether the risk include both of the vulnerability and impacts. I was also tried to search similar report for Coral Bleaching Products of NOAA (http://www.ospo.noaa.gov/Products/ocean/coral_bleaching.html) for high risk influenced by the vulnerability and impacts. They indicate the accumulation of thermal stress (i.e. Degree Heating Weeks, DHWs) that coral reefs have experienced over the past 12 weeks. At the same time, they also define the magnitude of impact levels as : the minor (<25% affected), moderate (26–50% affected), and severe (>50% affected) bleaching responses observed at the study sites. If possible, please try to explain the risk in this manuscript.*

Reply:

Thanks for the suggestion. We can't define the magnitude of impact levels or impact area as done by NOAA because it requires large amount of biological and fishery data in the vast ocean. Three different risks in the manuscript mean three different probability of occurrence. The revised manuscript has estimated the occurrence probability within various degree of risk.

Please see lines 2-9 in page 3.

"A hindcast of cold water days over the period 1995–2017 (Fig. 9) was obtained by using the warning mechanism in Table 2. The results clearly demonstrate high-risk warnings for the winters of 2000, 2008, 2011, and 2012. By monitoring the number of fish deaths around the Penghu Islands, Chang et al. (2013) and Lu et al. (2012) reported finding a large number of dead farmed fish in exceptionally cold water in the winters of 2000, 2008, and 2011. This agrees with the periods of high risk identified by this warning mechanism. Based on the results of hindcast and cold disasters in historic records (Chang et al., 2013; Lu et al., 2012), occurrence probabilities could be estimated within three warning thresholds (Table 2). For example, three of the high-risk years (red dots in Fig. 9) did indeed happen damage in historic records, indicating occurrence probability of damage is about 75% within a high-risk warning."

Table 2: Warning thresholds suggested for exceptionally cold water days

Type	Conditions	Possible Occurrence Time	Probability of Occurrence
Warning	ONI ≤ -0.9	around the next 90 days (30 days[a])	50%
Moderate risk	10-day AWS ≥ 11.5	around the next 15 days	60%
High risk	20-day AWS ≥ 12.5	around the next 5 days	75%

[a] real lead time considering when the ONI value can be obtained.

4. *Fifthly, the warning system found the high risk (or hazards) happened in the years of 2000, 2008, 2011 and 2012. But the reference only indicates the "cold damage" happened in 2008 and 2011 (Chang et al., 2013), How about the condition in 2000 and 2012. I suppose there are weak cold damages in years of 2000 and 2012. If so, the authors should consider to explain or discuss about what's the difference of marine environment or wind condition between cold damage (2008 and 2011) and weak or non-cold damage (2000 and 2012) years. And if possible, please add one sub-figure for cold events in 2000 to compare the annual variations in figure 11, as the authors describe the cold damage around the Penghu Islands has occurred three times: 2000, 2008, and 2011 (line 30-31, page 2).*

Reply:

As mentioned in Section1 & 6, cold disaster in historic records happened not only in 2008 and 2011 (Chang et al., 2013; Lu et al., 2012) but also in 2000 (Lu et al., 2012). The manuscript studies exceptionally cold water, which might potentially trigger disaster in the TS. A hindcast by the warning system showed high-risk warnings for the winters of 2000, 2008, 2011, and 2012, but it doesn't necessarily mean cold disaster must happen in these years. The results indicated that cold disaster likely happen in these four years. Actually, three of the high-risk years did indeed happen damage (2000, 2008, and 2011; Chang et al., 2013, Lu et al., 2012) in historic records, indicating occurrence probability of damage is about 75% within a high-risk warning.

Because the SST shown in Fig. 11 is observed by a buoy working after 2007, we don't have SST data in 2000 (Figure S3). However, we have added a sub-figure of SST observed by satellite in 2000 and do some discussions.

Please see line 2-9 in page 3.

"Figure 11 shows SST in 2008 and 2011 are more lower than that in 2000 and 2012. The lowest SST appears in February in most years except in 2012. 10-day AWS stronger than 12 m/s mainly appears from January to February in 2000, 2008 and 2011, but that appears from December to January in 2012; besides, AWS stronger than 14 m/s maintains a longer time in 2008 and 2011. The results imply damage could be more serious in 2008 and 2011 (mentioned by Chang et al., 2013 and Lu et al., 2012) than in 2000 (mentioned by Lu et al., 2012). However, SST in winter of these four years all can be lower than 16 °C (Fig. 11), which is cold enough to induced the death of caged fish around Penghu Islands (Chang et al. 2013). Notably, the SST variability over a ~10-day period in February 2012 might be dominated by a sub-mesoscale process, which agrees with the higher correlation between the SST and 10-day AWS in Fig. 6a."

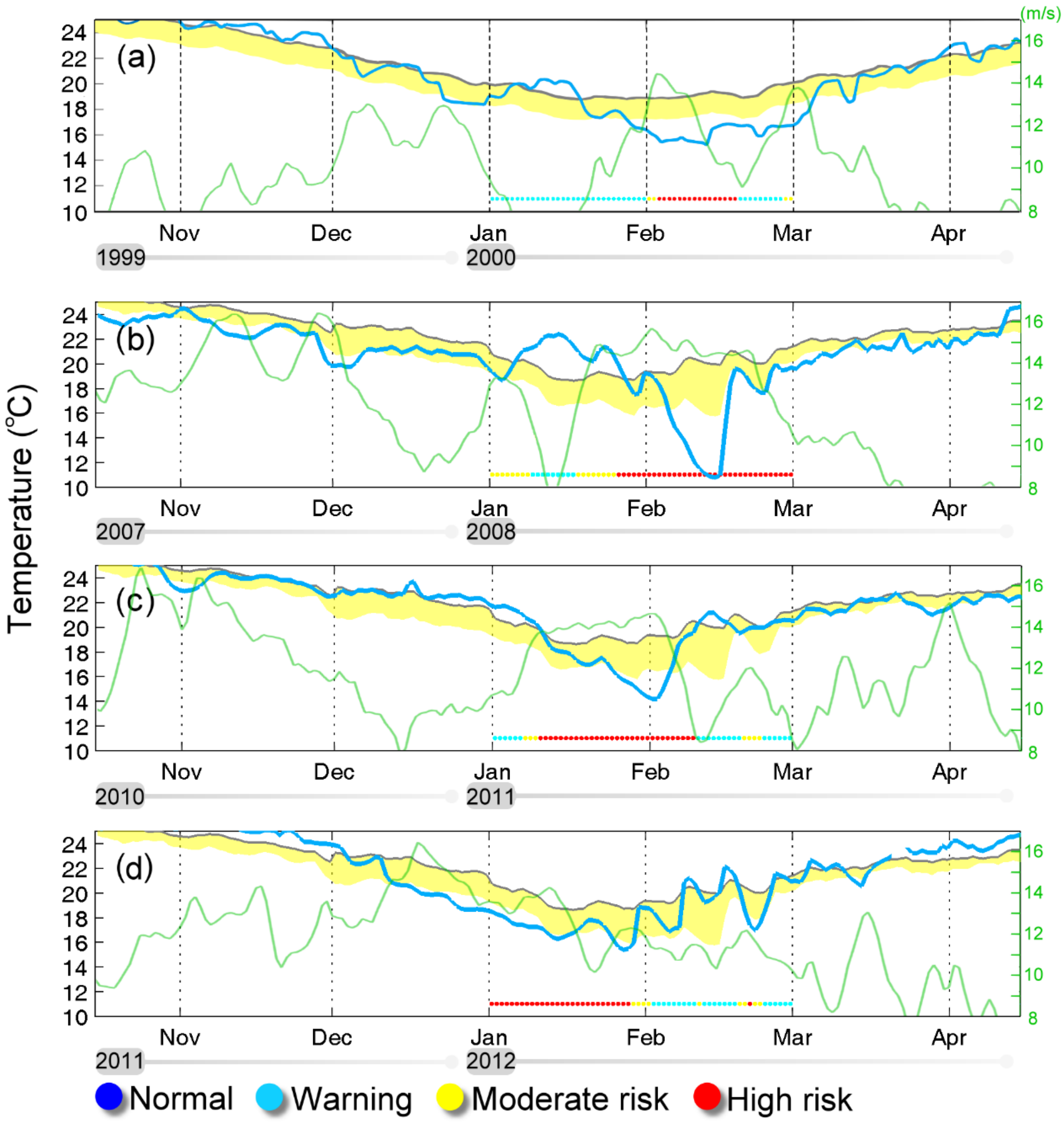


Figure 11: Cold events in (a) 2000, (b) 2008, (c) 2011 and (d) 2012. Blue line: SST observed (a) by satellite and (b, c, d) by buoy; gray line: 10-year climatological average; yellow shading: range of standard deviation below the average; green line: 10-day AWS. Color dots are warning lights (only shown from January to February).

5. *Otherwise, the Oceanic Niño Index (ONI), defined as a 3-month running mean of SST anomalies, is describe in the line 10, page 3. However, the ONI indexes in January, February and March 2012 are -0.8, -0.6 and -0.5, respectively. It seems that the 2012 winter did not match up with the first definition of <-0.9 C. Why? And whether the author is considered to describe or discuss about the long-term variation or trend in Taiwan Strait as the topic is focus on Exceptionally cold water days". If so, a new publish was suggested as your reference "Kuo et al., 2017 or 2018, Long-term observation on sea surface temperature variability in the Taiwan Strait during the northeast monsoon season, International Journal of Remote Sensing".*

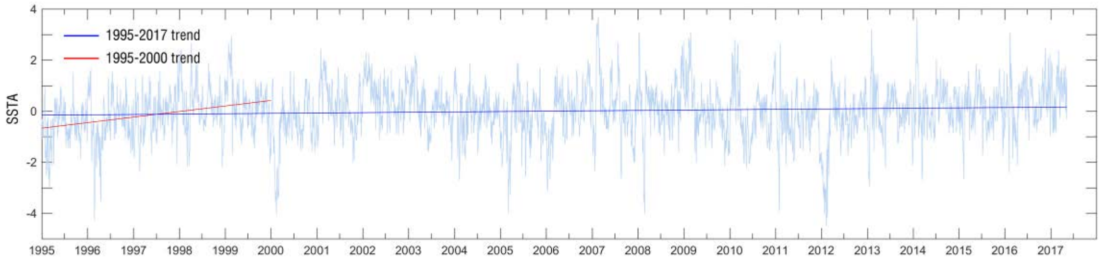
<u>Reply:</u>

Yes. As mentioned in Section 4.1 of the manuscript, ONI values used in this manuscript are downloaded from NOAA CPC. They are estimated according to the 3-month running mean of monthly SSTAs in the Nino3.4 region (https://goo.gl/XRFVM3). Because of the running mean needed, the ONI value has a delay time of two month; in other words, the latest ONI value obtainable in this month (April) is the value for February (as the AC2-Figure 2 screenshot shown). Actually, the ONI indexes used in January, February and March 2012 are -1.1(Nov.), -1.0(Dec.) and -0.8(Jan.), respectively.

Year	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
2010	1.5	1.3	0.9	0.4	-0.1	-0.6	-1.0	-1.4	-1.6	-1.7	-1.7	-1.6
2011	-1.4	-1.1	-0.8	-0.6	-0.5	-0.4	-0.5	-0.7	-0.9	-1.1	-1.1	-1.0
2012	-0.8	-0.6	-0.5	-0.4	-0.2	0.1	0.3	0.3	0.3	0.2	0.0	-0.2
2013	-0.4	-0.3	-0.2	-0.2	-0.3	-0.3	-0.4	-0.4	-0.3	-0.2	-0.2	-0.3
2014	-0.4	-0.4	-0.2	0.1	0.3	0.2	0.1	0.0	0.2	0.4	0.6	0.7
2015	0.6	0.6	0.6	0.8	1.0	1.2	1.5	1.8	2.1	2.4	2.5	2.6
2016	2.5	2.2	1.7	1.0	0.5	0.0	-0.3	-0.6	-0.7	-0.7	-0.7	-0.6
2017	-0.3	-0.1	0.1	0.3	0.4	0.4	0.2	-0.1	-0.4	-0.7	-0.9	-1.0
2018	-0.9	-0.8										

AC2-Figure 1. ONI values from https://goo.gl/XRFVM3

The trend in our studying region has a gentle slope (0.01°C/year), which is not significant, during the studying period of 1995-2017 (dark blue line in AC2-Figure 2). We have added the above results and Kuo et al. (2017) as reference.



AC2-Figure 2. time series of SSTA. Blue line is a trend from 1995 to 2017 (0.01°C/year); red line is a trend from 1995 to 2000 (0.21°C/year).

Please see lines 19-22 in page 4.

"Kuo et al. (2017) indicated SST in the TS was warming with a trend of about 0.15 °C/year during the period between 1980 and 2000. The possible interaction between the warming trend and cold events is unclear at this moment. However, the long-term trend of SST in the targeting area is gentle and its influence is insignificant (0.01 °C/year) during our studying period of 1995–2017."

SPECIFIC COMMENT

1. *There are too many errors of reference forms in the reference sections. For example, the format in line 17 and 25 of page 9 for references are different as following: Line 17: Kuo N-J, Ho C-R (2004). . .. Line 19: Lau N-C, Nath MJ (2006). . . Line 25: Lu Yi-Lin, Hsien I-L, Chung C-S, Lin, C-Y, Chen S-C, Tsai W-S (2012) Please check in detail by yourself.*

Reply:

Thanks. We have modified that in the revised manuscript.

2. *L19~20 of page 1, The authors may consider to modify the geographic term, for example, the average depth is 50 m, as they also use the description "approximately 30 m" for the Taiwan Bank.*

Reply:

"The average depth is 50 m" give a description of the Taiwan Strait rather than of the Taiwan Bank. We have clarified it in the revised manuscript.

Please see lines 21-22 in page 1.

"The average depth of TS is 50 m and two major shallow water regions, Taiwan Bank and Chang-Yuen Ridge, are about 30 m (Fig. 1)"

3. *Please try to explain the importance of this sentence "A lag-0- to lag-6-month correlation between rainfall anomalies in western Pacific and the peak La Niña was also observed by Wang et al. (2000)." (line 29-30, page). Did author try to say*

something using this sentence.

__Reply:__

We would like to mention a lag correlation is shown not only between cold event and La Niña but also between rainfall and La Niña. We have clarified it in the revised manuscript.

Please see lines 16-19 in page 4.

"All of the cold events revealed in Figure 2 were determined to occur during the La Niña events. Furthermore, the cold phase peak of ENSO tends to occur toward the end of a year and a lag correlation reflects the cold events in January–February after the negative peak of ENSO. A similar lag correlation (0–6 months) between rainfall anomalies and ONI values during the La Niña events was observed in western Pacific (Wang et al., 2000)."

4. *L8~L9 of page 3, the authors use "the 60 coldest days of winter based on the climatologically averaged SST (January 6–March 6 in non-leap years, and January 6–March 5 in leap years)" is not easy to understand the coldest days. The authors may consider to add one figure or supplement figure for this.*

__Reply:__

Thanks. We have added a figure in the Supplementary. Please note that the 60 coldest days of winter has been modified as January 1–March 1 (regular years) and January 1–February 29 (leap years) due to the change of targeting area as suggested in the review's GENERAL COMMENT 2.

Please see lines 7-10 in page 3.

"In this study, we confined the analysis to the 60 coldest days of winter based on the climatologically averaged SST (January 1–March 1 in regular years, and January 1–February 29 in leap years; Supplementary Fig. 1). During these climatologically coldest days of winter (hereafter referred to as just "winter days"), further cooling days may be expected to have the greatest implications for aquaculture."

__Figure S1__

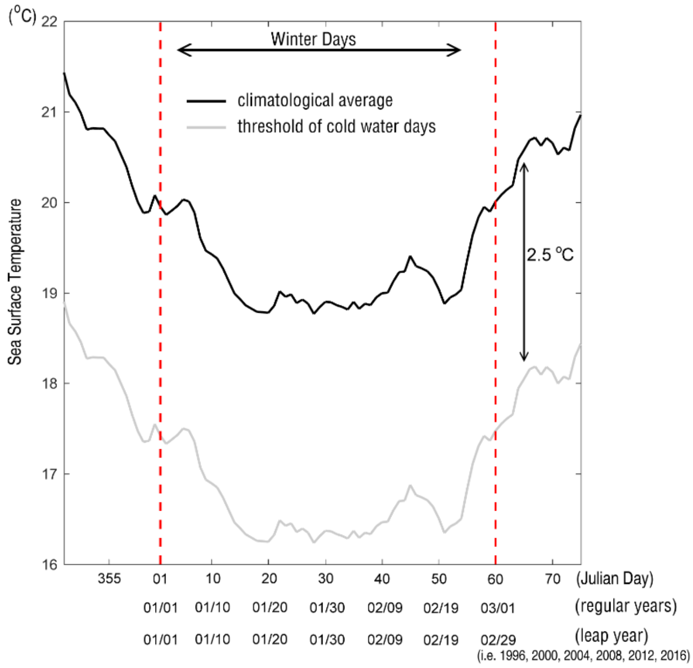


Figure S1: time series of climatological SST (black line) across the southern TS (the white dash rectangle in Figure 1) and critical temperature of cold water days (gray line). Red dash lines reveal the period of winter days.

5. *In addition, please confirm the definition of SSTA in line 17 of page 3. The sea surface temperature anomaly (SSTA) is the difference between the observed SST and the climatological SST. Did author use which the climatological daily SST is? In general, the SSTA is good indicator to see the long-term warming or cooling trend.*

Reply:

Yes. SSTA is a deviation from the daily climatological average (we will add a figure to clarify in Supplementary) and the time series of SSTA can be an indicator to study long-term trend. However, the trend in our studying area has a gentle slope (0.01°C/year) during the studying period of 1995-2017 (dark blue line in AC2-Figure 3). Actually, we can see a significant warming trend (0.21 °C/year) from 1995 to 2000 (red line), which is similar to the results of Kuo et al. (2017, Int. J. Remote. Sens.; 1980-2000 trend is about 0.15 °C/year) and Belkin et al. (2014, Clim. Change; 1978-1998 trend is about 0.07 °C/year). A trend has large variability depending on a sampling window, so you can't see an obvious long-term trend during the studying period. We have added a sentence for note in the revised manuscript.

Please see lines 21-22 in page 4.

"However, the long-term trend of SST in the targeting area is gentle and its influence is insignificant (0.01 °C/year) during our studying period of 1995–2017."

Exceptionally cold water days in the southern Taiwan Strait: their predictability and relation to La Niña

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Abstract. The objectives of this study were to assess the predictability of exceptionally cold water in the Taiwan Strait (TS) and to develop a warning system on the base of scientific mechanism, which is a component of the information technology system currently under development in Taiwan to protect aquaculture against extreme hazards. Optimum interpolation sea surface temperature (SST) data were used to find exceptionally cold water days from January 1995 to May 2017. We found that the SST and wind speed over the TS are low and strong in La Niña winters, respectively. According to tests conducted using relative operating characteristic curves, predictions based on the Oceanic Niño Index and integrated wind speed can be employed at lead times of 60–~~210~~120 and 0–~~30~~25 days, respectively. This study utilized these two proxies to develop a possible warning mechanism and concluded four colors of warning light: (1) blue, meaning normal~~;~~ (0% occurrence probability); (2) cyan, meaning warning~~;~~ (~50% occurrence probability); (3) yellow, meaning moderate risk~~;~~ (~60% occurrence probability); and (4) red, meaning high risk~~.~~ (~75% occurrence probability). Hindcasting winters over the period 1995–2017 successfully predicted the cold water hazards in the winters of 2000, 2008, and 2011~~, and 2012~~ in prior to the coldest day ~20 days.

1 Introduction

The Taiwan Strait (TS) is a northeast-to-southwest passage, with a length of 300 km and width of 180 km, from the East China Sea to the South China Sea. The average depth of TS is 50 m~~,~~ and two major shallow water regions, ~~the~~ Taiwan Bank and Chang-Yuen Ridge, are ~~approximately~~about 30 m (Fig. 1). Circulation in the TS, exhibiting strong seasonal variation, is mainly dominated by monsoon forcing and topography (Jan et al. 2002). The China Coastal Current brings cold and brackish water into the northern TS during winter from December to the following January (Jan et al. 2006; Chen et al. 2016). In addition, the strong northeast monsoon reduces the northward transport of the Kuroshio Branch Current, bringing warm and saline water from the western North Pacific. In summer, the southwestern monsoon replaces the northeast monsoon and dominates the circulation in the TS. During the southwest monsoon season, the northward transport is intensified and brings South China Sea water into the TS (Jan et al. 2006).

El Niño–Southern Oscillation (ENSO), which develops in the tropical Pacific and is caused by the mediation between surface wind stress and sea surface temperature (SST) variations (McPhaden et al. 2006), is an interannual climate fluctuation.

Although ENSO originates in the tropical Pacific, it significantly influences patterns of weather variability worldwide, shifting the probability for droughts, floods, heat waves, severe storms and extreme events (e.g., Alexander and Scott, 2002; Philippon et al., 2012). ~~The~~It is known the cold phase of ENSO, La Niña, tends to intensify the East Asian winter monsoon, which ~~always~~often accompanies strong northerly winds and sharp air temperature drops. By contrast, the warm phase, El Niño, suppresses the East Asian winter monsoon (Wang et al~~.~~., 2000; Lau ~~and Nath~~et al., 2006). In addition, Kuo and Ho (2004) indicated that the stronger northeast monsoon during a La Niña winter may modulate the sea surface currents in the TS and further cause the lower SST. For example, the southward water transport was larger and the water in the TS was generally colder in November 2000 (La Niña winter) than that in 2002 (El Niño winter). The predominance of the cold China Coastal Current, and the weakness of the warm Kuroshio Branch Current, resulted in the water temperature of the TS decreasing in the early winter of 2000 (Wu et al. 2007). By contrast, when El Niño broke out in the winter seasons from 1997 to 1998, the warm water area (2°C above the regional mean) in the TS increased by 25% and nutrient concentrations decreased (Shang et al. 2005). Zhang et al. (2015) suggested that less Kuroshio water enters the southeastern TS during La Niña than El Niño events, which might modulate the interannual variability of SST in the TS. However, less severe but longer lasting phenomena, such as SST variability, may have catastrophic consequences or can be a trigger for other threats (Ustrnul et al. 2015). For example, the extreme cold or hot temperature can threaten life on earth and may even trigger a disaster (Mora and Ospina 2002). Previous studies have identified a correlation between local wind and circulation in the TS, and they have suggested that a La Niña winter would be a weather condition supporting cold-event occurrences, which are more likely to trigger cold disasters in the TS.

In the winter of 2008~~,~~ (December 2007 to February 2008), exceptionally cold water affect the southern TS and hit the marine natural resources around the Penghu Islands in the southwestern TS, causing ~~considerable~~ damage ~~in marine~~to the aquaculture and high fish mortality rates; this phenomenon is ~~hereafter~~ referred to as "cold ~~damage~~disaster". Cold sea temperatures below the critical minimum for fish could lead to a high ~~rate of~~ fish ~~deaths~~mortality (Hsieh et al. 2008). The death of wild fish was at least 73 t, and 80% of cage aquaculture fish were damaged (Chang et al. 2013). Chang et al. (2009) used satellite SST images around the Penghu Islands to show that the minimum SST (12.6 °C) in February 2008 was lower than the February climatological temperature (20 °C). The strong northeast monsoon in the winter of 2008, associated with La Niña, may drive the cold China Coastal Current to intrude more southward into the southern TS and can even suppress the northward warm Kuroshio Branch Current intruding the TS (Chen et al. 2010; Lee et al. 2014). Liao et al. (2013) suggested that the cold ~~damage~~disaster in 2008 can be divided into three stages: First, the branch of the China Coastal Current moved cold water from the western strait to the central strait; then, a strong northeast wind intensified the southwest current; and finally, cold water gradually retreated to the north due to weakened wind.

~~Previous studies have revealed one single case of cold damage in the southern TS.~~ Specifically, ~~according to the~~cold disaster in historic records happened not only in 2008 but also in 2000 (Lu et al., 2012~~ newsletter by the Fisheries Research Institute of Taiwan, cold damage around the Penghu Islands has occurred three times: 2000, 2008,~~) and in 2011~~.~~ (Chang et al., 2013). The cold ~~damage~~disaster in 2008 is ~~among~~ the most serious event among other events occurring in the Penghu Islands. Thus, reducing the negative consequences of damage is a major concern. Although numerous studies on the single event of cold ~~damage~~disaster in 2008 have been performed using satellite-observed data and numerical models, there is no operational system for rapidly transmitting current information on potential sea threats to mariculturists or citizens at large. The main purposes of the current study were to ~~clarify~~assess the predictability of exceptionally cold ~~events~~water, that might potentially trigger cold ~~damage~~disaster in the TS, and to present a feasible warning system with respect to marine hazards around the Penghu Islands.

2 Data and methods

The optimum interpolation daily SST dataset from the National Oceanic and Atmospheric Administration (NOAA) are calculated from blended analyses, which is derived by combining multi-satellite data, ship observations, and buoy data (Reynolds et al. 2007). The dataset is averaged onto a 1/4° × 1/4° spatial grid and covers the period from 1981 to the present; however the current study used only the data from January 1995 to May 2017. ~~We focused on the SST variability across the southern TS, and~~In this study, we confined the analysis to the 60 coldest days of winter based on the climatologically averaged SST (January ~~6~~1–March ~~6~~1 in ~~non-leap~~regular years, and January ~~6–March 5~~1–February 29 in leap years~~).~~; Supplementary Fig. 1). During these climatologically coldest days of winter~~,~~ (hereafter referred to as just "winter days"), further cooling days may be expected to have the greatest implications for ~~health and~~ aquaculture.

The influence of temperature on fish is important not only in the surface layer but also in the subsurface layer. Although the methodology in the study is based on SST, it is excepted water column is well mixed in the vertical due to shallow bathymetry in the TS and the strong wind in winter. An insignificant temperature difference between surface and subsurface in this region (< 1.2 °C) is shown by the climatological temperature profile (Supplementary Fig. 2) during winter (averaged in December to February, 1985–2017) near the Penghu (23.75°N, 119.75°E). Thus, SST could be a suitable indicator depicting the water temperature of whole layers.

The Oceanic Niño Index (ONI~~),~~) values, defined as a 3-month running mean of SST anomalies in the region of 5°N–5°S and 120°W–170°W, ~~is~~are taken from NOAA Climate Prediction Center (CPC; https://goo.gl/V6CtMD). The values are used for classifying the ENSO cycle into El Niño (ONI ≥ 0.5 °C) and La Niña (ONI ≤ −0.5 °C) (Huang et al. 2015). In addition, the daily surface wind fields used in this study were derived from the National Centers for Environmental Prediction global analyses at 2.5° spatial resolution and can be applied from 1980 to the present, which were downloaded from https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.html.

3 Cold events

The ~~current~~cold disaster is biological or ecological response to low water temperature as defined in introduction. The critical temperatures inducing the death of different fishes are not consistent. Chang et al. (2013) indicated the activity of reef fish is declined at water temperature lower than 16 °C. Feeding activity of Cobia, a major species of cage aquaculture fish around Penghu Islands, is declined as lower than 18 °C and fish may die as lower than 15 °C (Lu et al., 2012). The sophisticated prediction for the cold disaster require the understanding of the detailed physical and biological processes and will need the information about marine resource. Unfortunately, we don't have data associated with marine resource or aquaculture production. The most relevant information is the date of occurrence of cold disaster in 2000, 2008 and 2011, indicating from the previous literature (Chang et al., 2013; Lu et al., 2012). Therefore, we won't focus on exploring the value of critical temperature. Instead, a goal of this paper is developing a warning system to predict the exceptionally cold water around the Penghu Islands in the southern Taiwan Strait. It is expected that the presence of the exceptionally cold water points to the high possibility of the occurrence of cold disaster (referring to the events of large amount of fish death).

During the winter days (60 coldest days of winter as defined in Section 2), further cooling days are expected to happen the exceptionally cold water which may have the greatest implications for aquaculture (hereafter referred to "cold water days"). This study focused on hindcasting the occurrence of ~~low~~ cold water days during the winter days. Regarding that the long-term observations of water temperature around Penghu are absent (~20–year time series needed), the cold water days were characterized by remotely sensed SST anomalies (~~SSTAs) during the 60 coldest days of winter (hereafter referred to as just "winter days").~~SSTA) lower than a threshold (SSTA<-2.5 °C, i.e. SST< about 17°C). SSTA is a deviation from the daily climatological average (Supplementary Fig. 1) and the threshold is estimated by 1.6 times the standard deviation (approximately 95% interval of normal distribution) of SSTA. To obtain a quantity representative of the magnitude of low ~~SST, we calculated the SSTAs deviating from the daily climatological average and spatially averaged the SSTAs across the southern TS (the blue dotted quadrilateral~~SSTA, we selected the targeting area as a box in 23.5–24.5°N and 119–120°E (the white dash rectangle in Fig. 1), mainly off north coast of Penghu Island, covering the coolest SST deviation feature in Figure ~~1).~~3c, and a high correlation (r=0.94, p<0.05) with observational water temperature (Supplementary Fig. 3). Figure 2 shows the time series of SSTAs and highlights the SSTAs for the winter days (dots in Fig. 2a) from 1995 to 2017. ~~During these winter days, further cooling days may be expected to have the greatest implications for health and aquaculture (hereafter referred to "cold water days"), which were defined as those whose SSTAs was lower than 1.6 times the standard deviation (approximately 95% interval of normal distribution) below the mean (i.e., −2.0 °C). Moreover, two~~Moreover, three or more consecutive cold water days were grouped into cold events; if any cold events were less than 4 days apart, they were grouped into a same event. According to these definitions, 1,~~320~~380 winter days of the study period, ~~107~~95 cold water days and a total of 9 cold events (triangles in Fig. 2; Table 1) were observed. All of the cold events revealed ~~using the SSTAs~~in Figure 2 were determined to occur during the La Niña events~~ (Fig. 2b).~~. Furthermore, the cold phase peak ~~for ONI~~of ENSO tends to occur toward the end of ~~the calendar~~a year and a lag correlation reflects the cold events in January–February after the negative peak of ENSO. A similar lag~~-0- to lag-~~ correlation (0–6~~-month correlation~~ months) between rainfall anomalies and ONI values during the La Niña events was observed in western Pacific ~~and the peak La Niña was also observed by~~ (Wang et al~~. (2000).~~., 2000). Kuo et al. (2017) indicated SST in the TS was warming with a trend of about 0.15 °C/year during the period between 1980 and 2000. The possible interaction between the warming trend and cold events is unclear at this moment. However, the long-term trend of SST in the targeting area is gentle and its influence is insignificant (0.01 °C/year) during our studying period of 1995–2017.

To clarify the interannual variability of cold events in the southern TS, we performed composite analyses of SST and surface wind fields for the winter days from 1995 to 2017. The spatial pattern of the long-term average for winter days was observed to show a moderate SST belt extending from southwest to northeast, and an isotherm of nearly 18 °C across the northern Penghu Islands was revealed to separate the colder water in the west from the warmer water in the southeastern TS (Fig. 3a). The cold-water China Coastal Current flows southwestward along the coast of China and meets the warm-water northward Kuroshio Branch Current near the Penghu Islands, forming a strong sea temperature front. The SST variability is obviously affected by the delicate balance between the southward China Coastal Current and the northward Kuroshio Branch Current, both of which are associated with the magnitude of the northeast monsoon (Kuo and Ho 2004). Wind fields around Taiwan are strictly dominated by the East Asian monsoons. Wind data derived from weather stations across the TS (Jan et al. 2006) showed that a northeast monsoon occurs from September to the following May and that a southwest monsoon occurs during the rest of the year. During the winter days, the northeast monsoon dominates the environmental conditions around Taiwan (Fig. 3d), which illustrates it can drive the cold SST front into the southern TS.

Figure 3b, c shows the ~~SSTA~~SST deviation relative to the long-term average for the winter days. The SST across the TS was observed to get warmer along the China coast (Fig. 3b) when the northeast monsoon was weakened during the El Niño events, thus resulting in the wind anomaly fields illustrating southwest wind (Fig. ~~3e~~3h). By contrast, a negative ~~SSTA was~~SST deviation is shown to dominate all of the TS and to expand into the southern Penghu Islands during the La Niña events (Fig. 3c). The lowest ~~anomaly~~deviation was approximately −0.6 °C near the central TS. In addition, a positive ~~anomaly~~deviation regarding northeast wind was observed (Fig. ~~3f~~3i), which may intensify the northeast monsoon. The stronger wind generating turbulence mixing would likely lead to increased air–sea heat fluxes (Fig. 3f) and would substantially affect the extent of cold water in the TS. Figure 3d–3f shows surface total heat fluxes provided by NCEP/NCAR 40-year reanalysis project (Kalnay et al., 1996). More heat energy can be transferred from the ocean to the atmosphere in the La Niña (Fig. 3f) than that in the El Niño (Fig. 3e). These results imply that the SST variability in the TS is strongly associated with the ENSO cycle. Given the environmental conditions, exceptionally cold water is more likely to affect the southern TS and more potentially trigger cold ~~damage~~disaster during La Niña than during El Niño events.

According to above results we summarize two possible physical mechanisms for triggering cold events in the TS. One is the balance between the southward China Coastal Current and the northward Kuroshio Branch Current, and the other one is local wind-driven entrainment. However, both processes are associated with the magnitude of wind. During the La Niña events (Fig. 4), a northeast monsoon dominates the environmental conditions around the TS with strong wind stresses. The cold China Coastal Current will have more chance to intrude into the southern TS and the warm Kuroshio Branch Current will even be suppressed by strong southwestward winds. In addition, strong wind stresses can drive turbulence mixing and enhance air-sea interaction to further cool the sea water across most of the TS. Therefore, ONI and local wind speed are used as prognostic indexes to find the cold days in the following study.

4 Predictability of cold events

4.1 Predicting by ONI

The results of the preceding analysis identify a significant correlation between cold water days and La Niña events. The association between them can be through the increased wind stress of the northeast monsoon, which may intensify the southwestward cold current. We extended this study by understanding the relationship with monthly ONI and evaluating the prediction skill as a function of lead time.

In this study, we primarily experiment with two-class prediction problems. The ENSO cycle was quantified using the ONI, and cold water days were predicted based on the ONI falling below a threshold. There are subsequently four possible results from the binary classification test: (1) the outcome predicted a cold water day is identical to the actual value (true positive, TP); however, (2) if the actual value is not a cold water day, it is classed as a false positive (FP). Conversely, (3) a true negative (TN) has been found while both the prediction state and the actual state are not cold water days; (4) the outcome predicted no cold water day is exactly opposite to the actual value (false negative, FN). For the following evaluations, an ONI −0.9 was set as the threshold, and lead days were counted ahead of the cold day. For predictions at a 90-day lead time, ONI values below the threshold can be considered to correspond to the probability of cold water days occurring with a true positive rate (TPR, hit rate) of 72% and a false positive rate (FPR, false alarm rate) of 15% (the arrow in Fig. 5a). The hit rate is defined as $\sum \mathrm{TP} \big/ [\sum \mathrm{TP}+\sum \mathrm{FN}]$ $\underline{\sum \mathrm{TP} \big/ [\sum \mathrm{TP}+\sum \mathrm{FN}]}$ (i.e. the percentage of cold water days which are correctly identified as having the condition), and false alarm rate is calculated as $\sum \mathrm{FP} \big/ [\sum \mathrm{FP}+\sum \mathrm{TN}]$ ~~=~~ $\underline{\sum \mathrm{FP} \big/ [\sum \mathrm{FP}+\sum \mathrm{TN}]}$. In addition, we could examine the suitability of a threshold at a special lead time by an odds ratio, defined as $[\mathrm{TPR}(1\text{-}\mathrm{FPR})] \big/ [\mathrm{FPR}(1\text{-}\mathrm{TPR})]$. In the above case, the odds ratio was 14.8, which implies the probability of correct predictions are almost a 15-fold increase (the arrow in Fig. ~~5b~~5c).

Depending on the tolerance for the TPR and FPR, the choice of threshold for a prediction can be varied; more negative ONI thresholds reduce both the TPR and FPR. This trade-off is presented by relative operating characteristic (ROC) curves (Hanley and McNeil 1982) that represent the relationship between the TPR and FPR as a function of threshold (Fig. 5a). ROC curves are quantified by integrating the area under the curve, called ROC score or ~~AUC.~~area under the curve (AUC). The score is used as the proxy throughout the analysis because it is appropriate for assessing unusual events (Stephenson et al. 2008; McKinnon et al. 2016). When a ROC score is higher, it would be a more discriminating prediction method. In this study, the skill of the ONI-based prediction was shown to peak at a lead time of 60 days, with an ROC score of 0.78, and generally decreased with increasing lead time. Moreover, significance can be estimated through the creation of a null distribution of the quantity of interest by using a block bootstrap (McKinnon et al. 2016), and significant results above the 95% confidence level are presented throughout this article. ~~An~~We considered an ROC score greater than ~~or equal to~~ 0.6 ~~is designated~~ to be statistical significant ~~for~~in the predictions of cold water days. As shown in Fig. 5a, ROC scores decreased with lead time and were no longer significant by a lead time of 240 days. Notably, the ONI provided by NOAA CPC was estimated according to the 3-month running mean of monthly SSTAs in the Niño 3.4 region (5ºN–5ºS, 120º–170ºW). Because of the running mean needed, the ONI value has a delay time of two month; in other words, the latest ONI value obtainable in December is the value for October. Hence, the ONI-based prediction of cold water days can actually be employed with a lead time of 0–150 days. For simplicity, we still used the time of the ONI ahead of the cold ~~day~~water days to describe the lead time in the subsequent analysis.

Further, Saito and Rehmsmeier (2015) indicated the precision-recall curves (PRC) could be more informative than the ROC curves on imbalanced datasets. PRC is a trade-off between positive predictive values (PPV), defined as $\sum TP / [\sum TP + \sum FP]$, and TPR. Therefore, we also utilize the PRC to examine the predictability of cold water days (Fig. 5b). Although the baseline of ROC is fixed, the baseline of PRC is decided by $[\sum TP + \sum FN] / [\sum TP + \sum FN + \sum FP + \sum TN]$. As a result, the baseline is PPV=0.07 (a grey dashed line in Fig. 5b) and the prediction of cold water days become significant when the area under the curve (AUC) of PRC is greater than 0.15. The results shows that cold water days could be predicted with a lead time of 60–120 days, shorter than ROC method (60–210 days).

4.2 Predicting by wind

The relationship between wind stress and cold water can be understood through local wind-driven entrainment, whereby a strong La Niña episode results in an enhanced winter monsoon and strong wind stress increases turbulent mixing in ~~favor~~favour of heat fluxes.

We next focused on the relationship between wind speed and the probability of cold water days. Wind speed variability across the TS could be quantified using an ~~integrated~~average wind speed (~~IWS~~AWS) over a pre-specified period. The ~~IWS~~AWS was calculated using ~~integration~~averaged periods of 1 to 30 days, and the correlation coefficients between ~~IWS~~AWS and SSTAs are shown in Fig. 6a. The 10-day ~~integration~~averaged period was observed to have the highest correlation with the SSTA variability, and the correlation coefficient was approximately –0.~~43~~39 ($p < 0.05$). Therefore, we focused on the ~~IWS~~AWS with a ~~running integration~~moving averaged period of 10 days in the subsequent analysis. Figure 6b shows the water temperature to drop following a stronger ~~IWS~~AWS.

As indicated by the ROC curves, the wind-based prediction had an ROC score of 0.8 at a lead time of 0 days, which is counted following the last day over which wind speed is ~~integrated~~averaged (Fig. 7). This result is consistent with the expected relationship between wind speed and sensible cooling. The wind-based predictions were observed to have significant prediction skill for lead times from 0 to 30 days (ROC score ≥ 0.6), and the prediction skill generally decreased with increasing lead time. For predictions at a 15-day lead time, the highest odds ratio (6.0) was determined using a threshold of ~~115~~11.5 m/s. An ~~IWS~~AWS below the special threshold was determined to correspond to the occurrence of cold water days with a TPR of 78%

and an FPR of 38%. Moreover, the wind-based predictions were also examined through PRC (Fig. 7b). The results show that it has significant prediction skill for lead times from 0 to 25 days.

5 Warning mechanism for Penghu Islands

According to the analysis of predictability presented in the preceding section, cold water days can be predicted using the ONI for a long-lead prediction (60–~~210~~120 days) and the ~~IWS~~AWS for middle- to short-lead predictions (0–~~30~~25 days). We established a warning mechanism based on the ONI and ~~IWS~~AWS. The ONI-based prediction was employed to predict cold water days at a lead time of around 90 days. Hence, the ONI of –0.9, which engendering the highest accuracy (0.78) and odds ratio (14.8), was selected as the threshold. Moreover, the ~~IWS~~AWS-based prediction was employed for middle- and short-lead predictions. As shown in Fig. 8, the ROC scores varied with the integration periods and lead time. The prediction conducted at a lead time of around 15 days and integration period of 10 days had an ROC score of approximately 0.74. The threshold was set at ~~115~~11.5 m/s because this was observed to result in the highest accuracy (0.70) and odds ratio (6.0). In addition, the prediction conducted at a lead time of around 5 days and integration periods of around 20 days had higher ROC scores compared with those conducted at other integration periods. Regarding the prediction of cold water days at an integration period of 20 days, the prediction conducted with a threshold of ~~250~~12.5 m/s had an accuracy of 0.76. Therefore, a warning mechanism could be established based on this analysis (Table ~~1).~~2). The three warning thresholds mean various degree of risk with different probability of occurrence.

6 Hindcasting cold water days

A hindcast of cold water days over the period 1995–2017 (Fig. 9) was obtained by using the warning mechanism in Table ~~1~~2. The results clearly demonstrate high-risk warnings for the winters of 2000, 2008, 2011, and 2012. By monitoring the number of fish deaths around the Penghu Islands, Chang et al. (2013) and Lu et al. (2012) reported finding a large number of dead farmed fish in exceptionally cold water in the winters of 2000, 2008, and 2011. This agrees with the periods of high risk identified by this warning mechanism. Based on the results of hindcast and cold disasters in historic records (Chang et al., 2013; Lu et al., 2012), occurrence probabilities could be estimated within three warning thresholds (Table 2). For example, three of the high-risk years (red dots in Fig. 9) did indeed happen damage in historic records, indicating occurrence probability of damage is about 75% within a high-risk warning.

To illustrate specific predictions that could be made using the warning mechanism, we conducted a case study for the winter of 2011. Figure 10 displays the developing process of a cold water event from six satellite SST maps. Before the occurrence of the cold water event, the SST in the TS was 16 °C (Fig. 10a). An obvious cold front crossed from the Taiwan bank to the Chang-Yuen ridge and approached the Penghu Islands. Cold water (approximately 14 °C) developed along the coast of China on January 29, 2011 (Fig. 10b), and it extended to the southern TS afterward (Fig. 10c, d). When the exceptionally cold water intruded into the southern TS, the Penghu Islands were surrounded by extremely cold water below 16 °C. Finally, at the end of the cold event, warmer water above 22 °C was re-established through the channel to the east of Penghu Islands (Fig. 10e, f), and the cold water gradually retreated to the north due to the weakening wind (Fig. 10g). ~~Moreover, to examine satellite~~Furthermore, observational SST~~,~~ from buoy~~ measurements of SST~~ provided by the Central Weather Bureau of Taiwan (red star in Fig. 10a) were used~~. Although the~~ to examine satellite SST. The temporal variation of satellite SST ~~is~~ overall is similar to observational SST, but the magnitude of Satellite SST is often higher than that ~~measured by the buoy,~~ of observational SST (Fig. 10g~~ shows the variations~~). It should be note that the coldest day detected by satellite SST have some time difference with the one detected by buoy SST. Even though the satellite SST used in ~~both SST measurements to be largely consistent. In addition~~this study is an optimum interpolation dataset combining multi-satellite data, the quality of SST is still low while over a long period of cloudy time. Because the most days of winter is under a cold front in TS often with a heavy coverage of clouds and the quality of satellite SST is sensitive to water vapour in the atmosphere, high quality satellite SST is often not available in the TS during winter (Li et al., 2006). The result implies that observational water temperature is necessary when we would like to make a sophisticated prediction for the cold disaster. However, satellite SST in the targeting area could overall fit observational SST (r=0.94, p<0.05; Supplementary Fig. 3). It should be sufficient for the present goal for this work, to develop a warning system to predict the cold water days in the southern TS. Furthermore, the SST variability was observed to be associated with the 10-day ~~IWS.~~AWS in Figure 10g. When the ~~IWS~~AWS remained at approximately ~~140~~14 m/s from January 10, the SST kept decreasing to approximately 14 °C until the ~~IWS~~AWS decreased on February 2. After wind speed weakening, the SST around the Penghu Islands rose immediately, which agrees with the sequence of SST maps shown in Fig. 10d–f. A similar process was observed in the other cold events of 2000, 2008, and 2012.

~~Buoy~~ SST ~~measurements~~measured by buoy provide a means for examining the applicability of the warning mechanism. The buoy ~~sited on the north of Penghu Islands~~(red star in Fig. 10a) measures SST ~~from~~after January 2007~~ to the present~~. The observational period includes three extremely cold winters whose warning level reached high risk: 2008, 2011, and 2012. Winter 2008 has the severest cold event over the past decade~~,~~ and the minimum SST (approximately 11 °C) broke the record temperature~~ (a fact~~, discussed in numerous previous studies~~;~~ (e.g., Chen et al. 2010; Liao et al. 2013; Lee et al. 2014). Through the application of the warning mechanism, the hindcast of the 2008 winter showed that a high-risk warning could precede the coldest water day by 19 days (Fig. ~~11a~~11b); similarly, the high-risk warnings for 2000, 2011 and 2012 could lead by 10, 22 and ~~21~~26 days, respectively. It should be noted that the warning lights in Fig. 11 are only shown from January to February because cold disasters in historic records are almost happen in February.

Figure 11 shows SST in 2008 and 2011 are more lower than that in 2000 and 2012. The lowest SST ~~was just 16 °C in the~~ appears in February in most years except in 2012. 10-day AWS stronger than 12 m/s mainly appears from January to February in 2000, 2008 and 2011, but that appears from December to January in 2012; besides, AWS stronger than 14 m/s maintains a longer time in 2008 and 2011. The results imply damage could be more serious in 2008 and 2011 (mentioned by Chang et al., 2013 and Lu et al., 2012) than in 2000 (mentioned by Lu et al., 2012). However, SST in winter of ~~2012, whereas the SST was~~these four years all can be lower than ~~the standard deviation of the climatological average (yellow shading in~~ 16 °C (Fig. 11), which is cold enough to induced the death of caged fish around Penghu Islands (Chang et al. 2013). Notably, the SST variability over ~~an approximately~~ a ~10-day period in February 2012 might be dominated by a sub-mesoscale process, which agrees with the higher correlation between the SST and 10-day ~~IWS~~AWS in Fig. 6a.

7 Summary

We used optimum interpolation SST data to identify exceptionally cold water over the southern TS during the period 1995–2017. The results reveal a total of 107 cold water days and 9 cold events likely to trigger cold disasters in the TS. Cold water develops along the coast of China and extends to the southern TS with sustained strong winds. In addition, these exceptionally cold water days always occur during La Niña events, and climatological maps show that the SST and wind speed over the TS are extremely low and strong in La Niña winters compared with normal or El Niño winters. A correlation was also obtained for SSTAs and 10-day ~~IWS~~AWS, with a correlation coefficient of −0.~~43~~39 ($p < 0.05$).

According to the results associated with ENSO and wind speed, the predictability of cold water days can be estimated by ROC and PRC curves; when ROC scores were higher than or equal to 0.6, methodologies based on the ONI or 10-day ~~IWS~~AWS were observed to be significant (above the 95% confidence level) for predictions of cold water days. The ONI- and ~~IWS~~AWS-based predictions could be conducted at lead times of 60–~~210~~120 and 0–~~30~~25 days, respectively. Given this predictability, a possible warning mechanism based on the ONI and ~~IWS~~AWS was established. In this mechanism, if the monthly ONI is lower than or equal to −0.9, a cyan warning light indicating required action is triggered~~; This~~ (~50% occurrence probability); this light turns yellow if the 10-day ~~IWS~~AWS is ~~stronger than or equal to 115~~≥ 11.5 m/s, meaning a moderate risk of exceptionally cold water~~.~~ (~60% occurrence probability). Red light ~~signaling~~signalling high risk (~75% occurrence probability) displays when the 20-day ~~IWS~~AWS is ~~greater than or equal to 250~~≥ 12.5 m/s. After the application of the warning mechanism, a hindcast of cold water days over the period 1995–2017 revealed four winters (2000, 2008, 2011, and 2012) with a high risk of cold event potentially triggering damage. Three of the high-risk years (2000, 2008, and 2011~~, and 2012).~~) did indeed happen damage in historic records.

The warning mechanism evidently fulfills the requirements of the recently developed methodology of early warning systems for weather-related hazards, as implemented by the Central Weather Bureau of Taiwan. Warning lights based on the ONI and ~~IWS~~AWS indicate characteristics of exceptionally cold water affecting the Penghu Islands, and they thus facilitate identifying possible periods of exposure to extremely cold water. The warnings thus generated can be sent in an efficient and timely manner to mariculturists.

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References

Alexander, M~~.,~~. and Scott, J~~ (2002)~~.: The influence of ENSO on air-sea interaction in the Atlantic~~.~~, Geophys. Res. Lett., 29~~:~~, 46-41-46-44~~ doi:10.1029/2001GL014347~~, 2002.

Chang, Y~~.,~~., Lee, K~~-~~.-T~~.,~~., Lee, M~~-~~.-A~~.,~~., and Lan, K~~-~~.-W~~ (2009)~~.: Satellite Observation on the Exceptional Intrusion of Cold Water in the Taiwan Strait~~.~~, Terr. Atmos. Ocean. Sci., 20~~:~~, 661-669~~ doi:10.3319/TAO.2008.08.07.01~~, 2009.

Chang, Y~~.,~~., Lee, M~~-~~.-A~~.,~~., Lee, K~~-~~.-T~~.,~~., and Shao, K~~-~~.-T~~ (2013)~~.: Adaptation of fisheries and mariculture management to extreme oceanic environmental changes and climate variability in Taiwan~~.~~, Marine Policy, 38~~:~~, 476-482 ~~doi:10.1016/j.marpol.2012.08.002~~, 2013.

Chen, C~~ TA,~~.-T. A., Jan, S~~.,~~., Huang, T~~-~~.-H~~.,~~., and Tseng, Y~~-~~.-H~~ (2010)~~.: Spring of no Kuroshio intrusion in the southern Taiwan Strait~~.~~, J. Geophys. Res. Oceans, 115~~ doi:10.1029/2009JC005804~~, 2010.

~~Chen H-W et al. (2016)~~Chen, H.-W., Liu, C.-T., Matsuno, T., Ichikawa, K., Fukudome, K.-i., Yang, Y., Doong, D.-J., and Tsai, W.-L.: Temporal variations of volume transport through the Taiwan Strait, as identified by three-year measurements~~.~~, Cont. Shelf Res., 114~~:~~, 41-53~~ doi:10.1016/j.csr.2015.12.010~~, 2016.

Hanley~~ JA,~~, J. A. and McNeil~~ BJ (1982)~~, B. J.: The meaning and use of the area under a receiver operating characteristic (ROC) curve~~.~~, Radiology, 143~~:~~, 29-36~~ doi:10.1148/radiology.143.1.7063747~~, 1982.

Hsieh, H~~.,~~., Hsien, Y~~-~~.-L~~.,~~., Jeng, M~~-~~.-S~~.,~~., Tsai, W~~-~~.-S~~.,~~., Su, W~~-~~.-C~~.,~~., and Chen, C~~ (2008)~~.: Tropical fishes killed by the cold~~.~~, Coral reefs, 27~~:~~, 599-599~~ doi:10.1007/s00338-008-0378-3~~, 2008.

~~Huang B et al. (2015)~~Huang, B., Banzon, V. F., Freeman, E., Lawrimore, J., Liu, W., Peterson, T. C., Smith, T. M., Thorne, P. W., Woodruff, S. D., and Zhang, H.-M.: Extended reconstructed sea surface temperature version 4 (ERSST. v4). Part I: upgrades and intercomparisons~~.~~, J. Climate, 28~~:~~, 911-930~~ doi:10.1175/JCLI-D-14-00006.1~~, 2015.

Jan, S~~.,~~., Sheu~~ DD,~~, D. D., and Kuo, H~~-~~.-M~~ (2006)~~.: Water mass and throughflow transport variability in the Taiwan Strait~~.~~, J. Geophys. Res. Oceans, 111~~ doi:10.1029/2006JC003656~~, 2006.

Jan, S~~.,~~., Wang, J~~.,~~., Chern, C~~-~~.-S~~.,~~., and Chao, S~~-~~.-Y~~ (2002)~~.: Seasonal variation of the circulation in the Taiwan Strait~~.~~, J. Marine Syst., 35~~:~~, 249-268~~ doi:10.1016/S0924-7963(02)00130-6~~, 2002.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., and Woollen, J.: The NCEP/NCAR 40-year reanalysis project, B. Am. Meteorol. Soc., 77, 437-471, 1996.

Kuo, N~~-~~.-J~~.,~~. and Ho, C~~-~~.-R~~ (2004)~~.: ENSO effect on the sea surface wind and sea surface temperature in the Taiwan Strait~~.~~, Geophys. Res. Lett., 31~~ doi:10.1029/2004GL020303~~, 2004.

Kuo, Y.-C., Chan, J.-W., Wang, Y.-C., Shen, Y.-L., Chang, Y., and Lee, M.-A.: Long-term observation on sea surface temperature variability in the Taiwan Strait during the northeast monsoon season, Int. J. Remote Sens., doi: 10.1080/01431161.2017.1387311, 2017. 1-13, 2017.

Lau, N~~-~~.-C~~.,~~. and Nath~~ MJ (2006)~~, M. J.: ENSO modulation of the interannual and intraseasonal variability of the East Asian monsoon-A model study~~.~~, J. Climate, 19~~:~~, 4508-4530~~ doi:10.1175/JCLI3878.1~~, 2006.

Lee, M.-A., Yang, Y.-C., Shen, Y.-L., Chang, Y., Tsai, W.-S., Lan, K.-W., and Kuo, Y ~~(2014)~~.-C.: Effects of an unusual cold-water intrusion in 2008 on the Catch of Coastal Fishing Methods around Penghu Islands, Taiwan, Terr. Atmos. Ocean. Sci., doi: 10.3319/TAO.2013.08.06.01, 2014. 2014.

Liao, E., Jiang, Y., Li, L., Hong, H., and Yan, X ~~(2013)~~.: The cause of the 2008 cold disaster in the Taiwan Strait, Ocean Modelling, 62, 1-10 ~~doi:10.1016/j.ocemod.2012.11.004~~, 2013.

Li, C., Hu, J., Jan, S., Wei, Z., Fang, G., and Zheng, Q.: Winter-spring fronts in Taiwan Strait, J. Geophys. Res. Oceans, 111, 2006.

Lu ~~Yi-Lin,~~, Y.-L., Hsien, I.-L., Chung ~~C-S, Lin~~, C ~~-Y,~~.-S., Lin, C.-Y., Chen, S.-C., Tsai, W.-S ~~(2012)~~.: Aquaculture management during a cold spell in the Penghu Islands. Newsletter of Fisheries Research Institute (in Chinese) 37: 21-25, 2012.

McKinnon ~~KA,~~, K. A., Rhines, A., Tingley ~~MP,~~, M. P., and Huybers, P ~~(2016)~~.: Long-lead predictions of eastern United States hot days from Pacific sea surface temperatures, Nature Geosci., 9, 389-394 ~~doi:10.1038/ngeo2687~~, 2016.

McPhaden ~~MJ,~~, M. J., Zebiak ~~SE,~~, S. E., and Glantz ~~MH (2006)~~, M. H.: ENSO as an Integrating Concept in Earth Science, Science, 314, 1740-1745 ~~doi:10.1126/science.1132588~~, 2006.

Mora, C., and Ospina, A ~~(2002)~~.: Experimental effect of cold, La Nina temperatures on the survival of reef fishes from Gorgona Island (eastern Pacific Ocean), Marine Biology, 141, 789-793 ~~doi:10.1007/s00227-002-0862-1~~, 2002.

Philippon, N., Rouault, M., Richard, Y., and Favre, A ~~(2012)~~.: The influence of ENSO on winter rainfall in South Africa, Int. J. Climatol., 32, 2333-2347 ~~doi:10.1002/joc.3403~~, 2012.

Reynolds ~~RW,~~, R. W., Smith ~~TM,~~, T. M., Liu, C., Chelton ~~DB,~~, D. B., Casey ~~KS,~~, K. S., and Schlax ~~MG (2007)~~, M. G.: Daily high-resolution-blended analyses for sea surface temperature, J. Climate, 20, 5473-5496 ~~doi:10.1175/2007JCLI1824.1~~, 2007.

Saito, T. and Rehmsmeier, M.: The precision-recall plot is more informative than the ROC plot when evaluating binary classifiers on imbalanced datasets, PloS one, 10, e0118432, 2015.

Shang, S., Zhang, C., Hong, H., Liu, Q., Wong ~~GTF,~~, G. T. F., Hu, C., and Huang, B ~~(2005)~~.: Hydrographic and biological changes in the Taiwan Strait during the 1997–1998 El Niño winter, Geophys. Res. Lett., 32, n/a-n/a ~~doi:10.1029/2005GL022578~~, 2005.

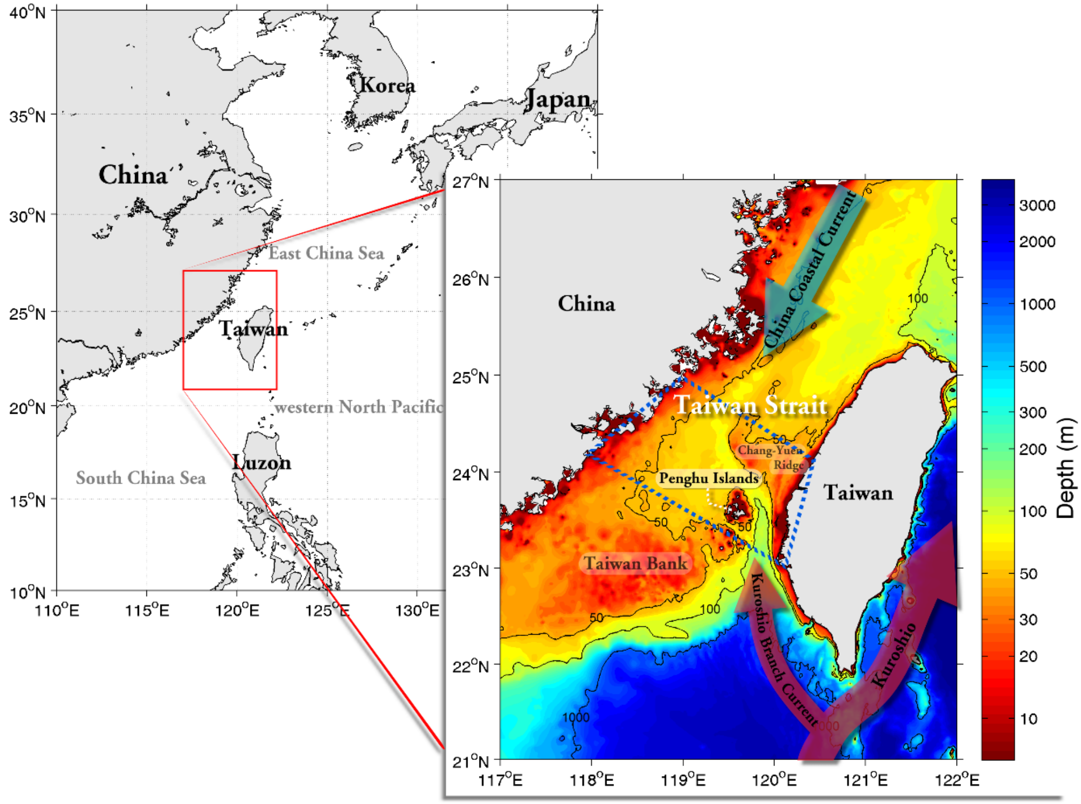
Stephenson ~~DB,~~, D. B., Casati, B., Ferro ~~CAT,~~, C. A. T., and Wilson ~~CA (2008)~~, C. A.: The extreme dependency score: a non-vanishing measure for forecasts of rare events, Meteorol. Appl., 15, 41-50 ~~doi:10.1002/met.53~~, 2008.

Ustrnul, Z., Wypych, A., Henek, E., Maciejewski, M., and Bochenek, B ~~(2015)~~.: Climatologically based warning system against meteorological hazards and weather extremes: the example for Poland, Natural Hazards, 77, 1711-1729 ~~doi:10.1007/s11069-015-1673-2~~, 2015.

Wang, B., Wu, R., and Fu, X ~~(2000)~~.: Pacific–East Asian teleconnection: how does ENSO affect East Asian climate?, J. Climate, 13, 1517-1536 ~~doi:10.1175/1520-0442(2000)013<1517:PEATHD>2.0.CO;2~~, 2000.

Wu, C~~-~~.-R~~;~~., Chao, S~~-~~.-Y~~;~~., and Hsu, C~~ (2007)~~.: Transient, seasonal and interannual variability of the Taiwan Strait current~~.~~, J. Oceanogr., 63~~:~~, 821-833~~ doi:10.1007/s10872-007-0070-1~~, 2007.

Zhang, W~~;~~., Zhuang, X~~;~~., Chen~~ CA;~~, C. A., and Huang, T~~ (2015)~~.: The impact of Kuroshio water on the source water of the southeastern Taiwan Strait: numerical results~~.~~, Acta Oceanologica Sinica, 34~~:~~, 23-34~~ doi:10.1007/s13131-015-0720-x~~, 2015.



Korea
Japan
China
East China Sea
Taiwan
western North Pacific
Luzon
South China Sea
China Coastal Current
Taiwan Strait
Chang-Yuen Ridge
Penghu Islands
Taiwan Bank
Kuroshio Branch Current
Kuroshio
Depth (m)

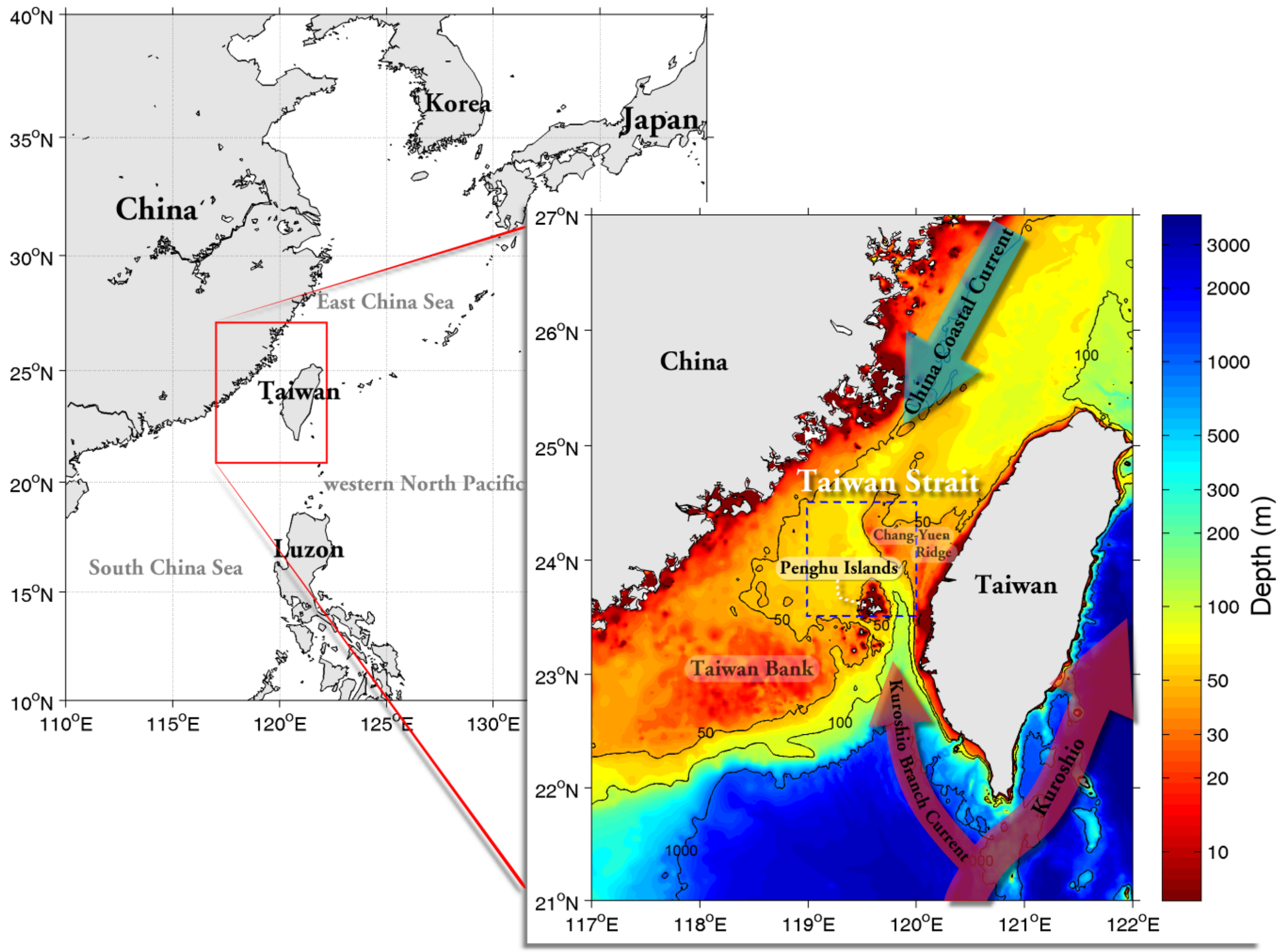
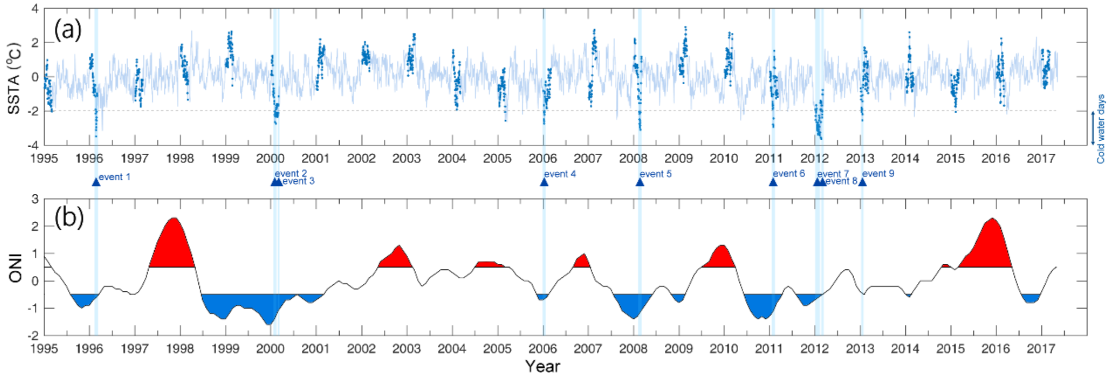


Figure 1: Bathymetric chart (shaded color) and sketches of the China Coastal Current, Kuroshio, and Kuroshio Branch Current.



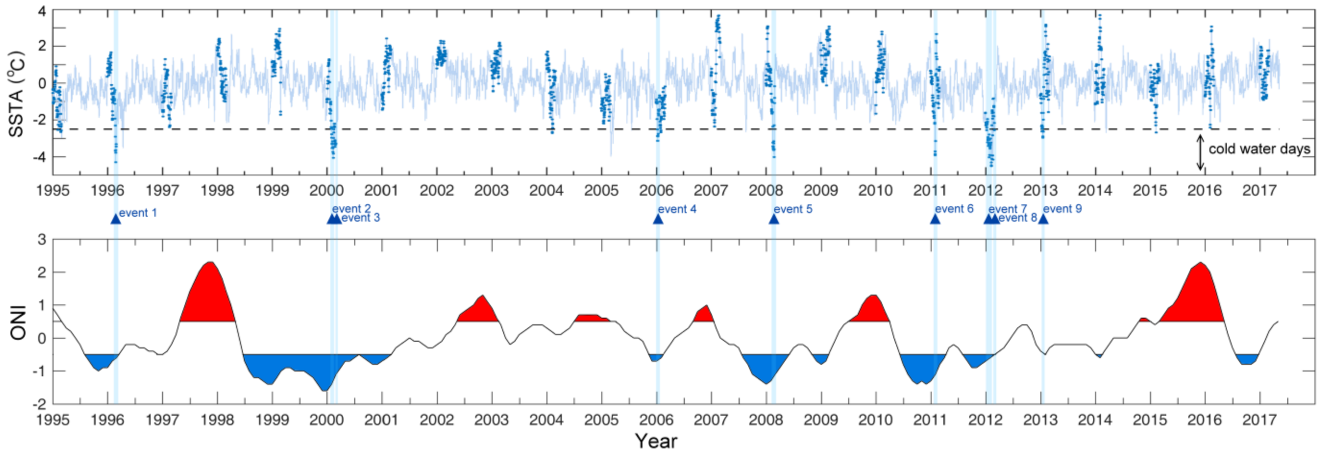
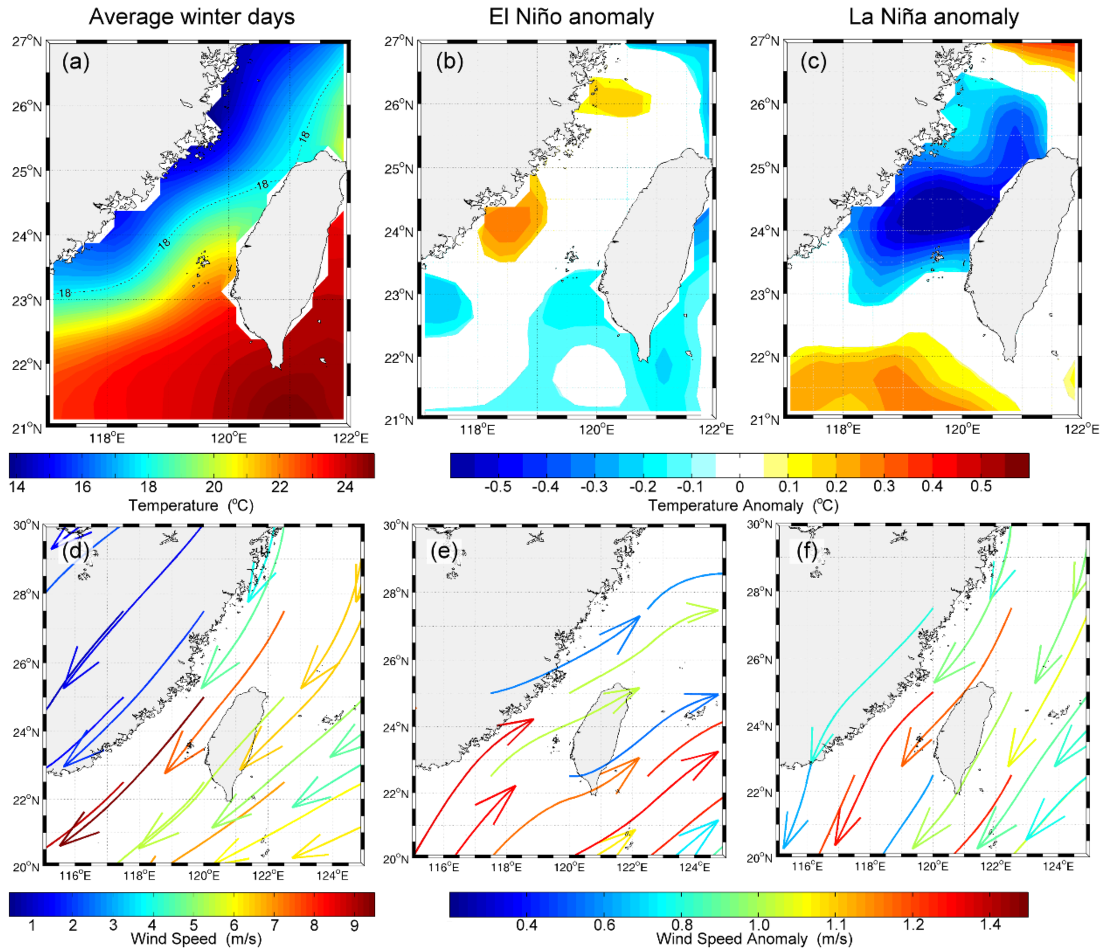


Figure 2: (a) Time series of SSTAs (shading line) and that during the winter days are highlighted in dots. The dashed line denotes a magnitude of 1.6 times the standard deviation below the mean SSTA. (b) ONI time series within January 1995 and May 2017. Positive anomalies (≥0.5 °C, shaded red) indicate El Niño events, and negative anomalies (≤−0.5 °C, shaded blue) indicate La Niña events. Blue bars and triangles denote the occurrences of cold events.



Average winter days
El Niño anomaly
La Niña anomaly
(a)
(b)
(c)
(d)
(e)
(f)
Temperature (°C)
Temperature Anomaly (°C)
Wind Speed (m/s)
Wind Speed Anomaly (m/s)

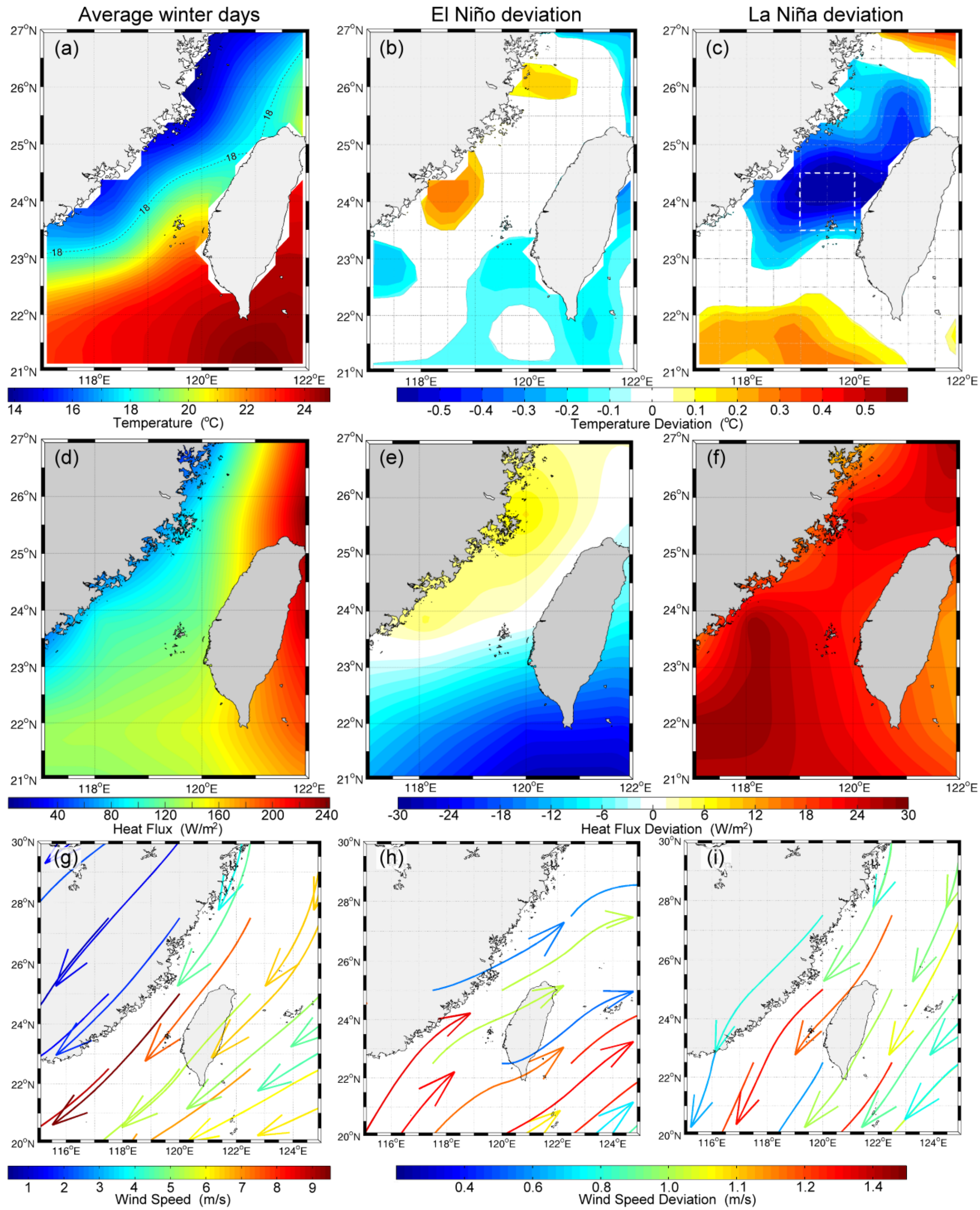

Average winter days
El Niño deviation
La Niña deviation
(a)
(b)
(c)
Temperature (°C)
Temperature Deviation (°C)
(d)
(e)
(f)
Heat Flux (W/m2)
Heat Flux Deviation (W/m2)
(g)
(h)
(i)
Wind Speed (m/s)
Wind Speed Deviation (m/s)

Figure 3: Composite of SST (a to c~~)~~), surface total heat fluxes (d to f), and surface wind fields (~~d~~g to ~~f~~i) for (a, d, g) average winter days, (b, e, h) El Niño ~~anomaly~~deviation, and (c, f, i) La Niña ~~anomaly~~deviation. Only ~~anomalies~~deviations above the 95% confidence level are shown. Positive heat flux values represent heat energy gain to the atmosphere.

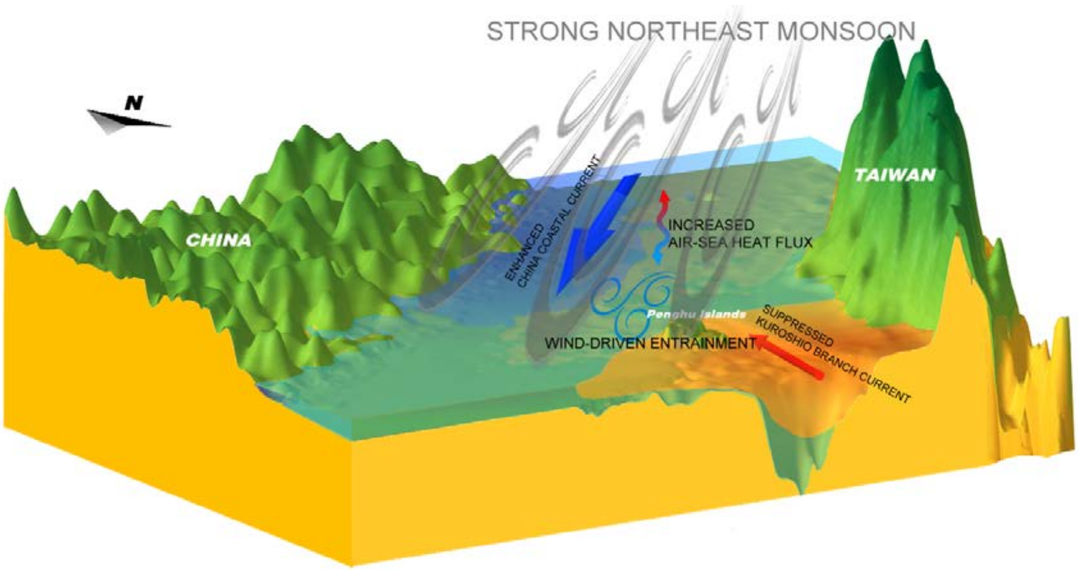
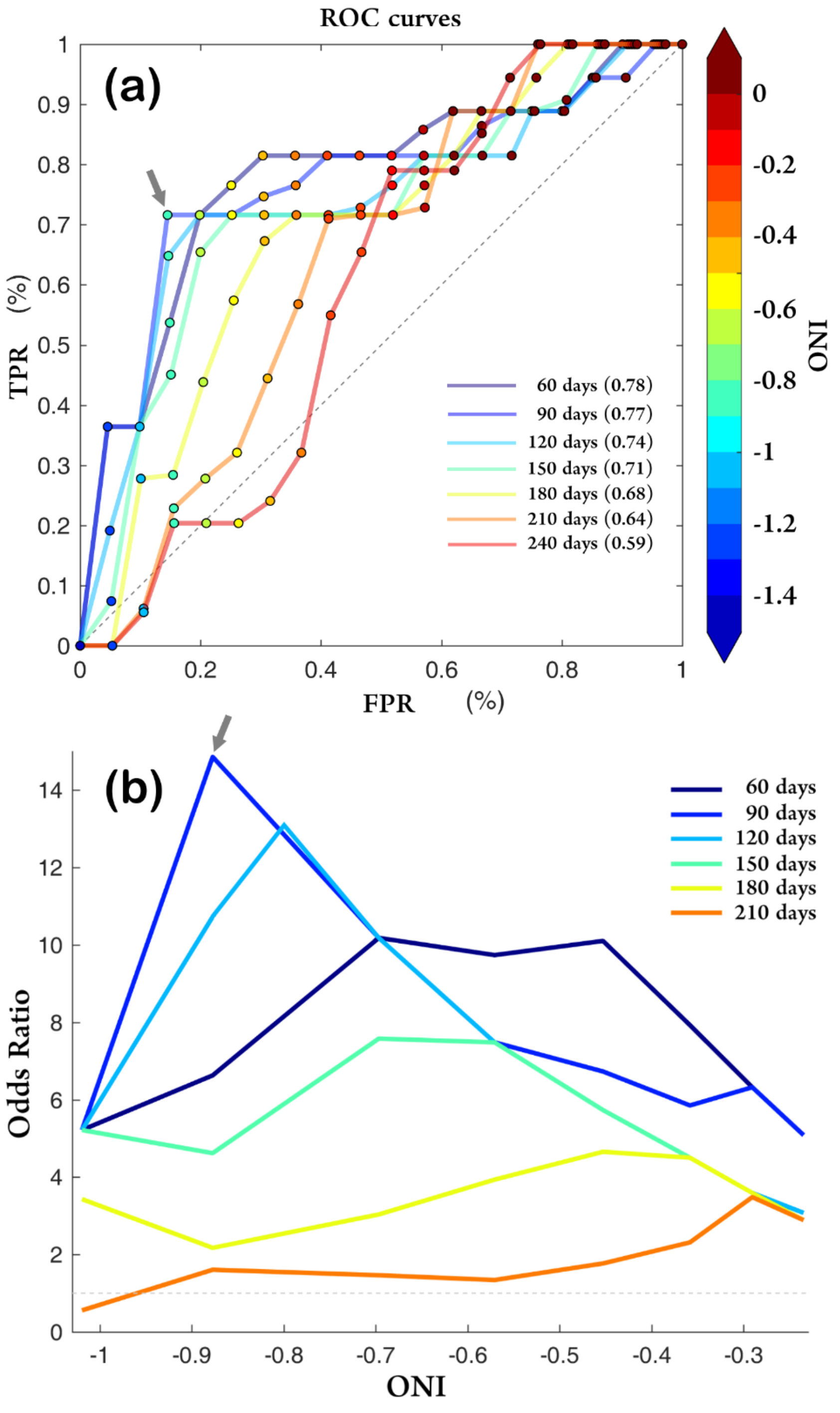


Figure 4: A cold-event sketch during La Niña events.


ROC curves
(a)
TPR (%)
FPR (%)
60 days (0.78)
90 days (0.77)
120 days (0.74)
150 days (0.71)
180 days (0.68)
210 days (0.64)
240 days (0.59)
ONI
(b)
Odds Ratio
ONI
60 days
90 days
120 days
150 days
180 days
210 days

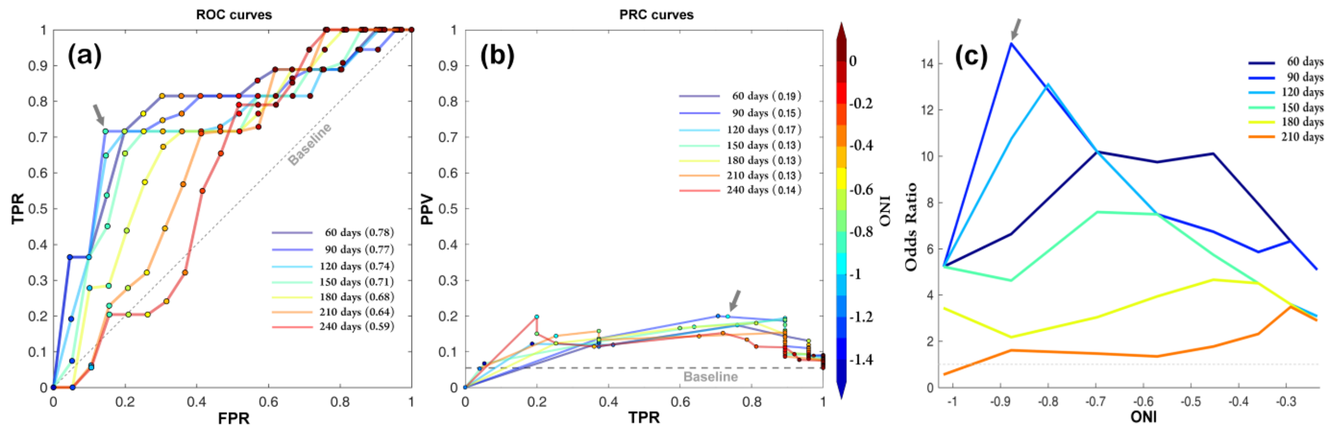
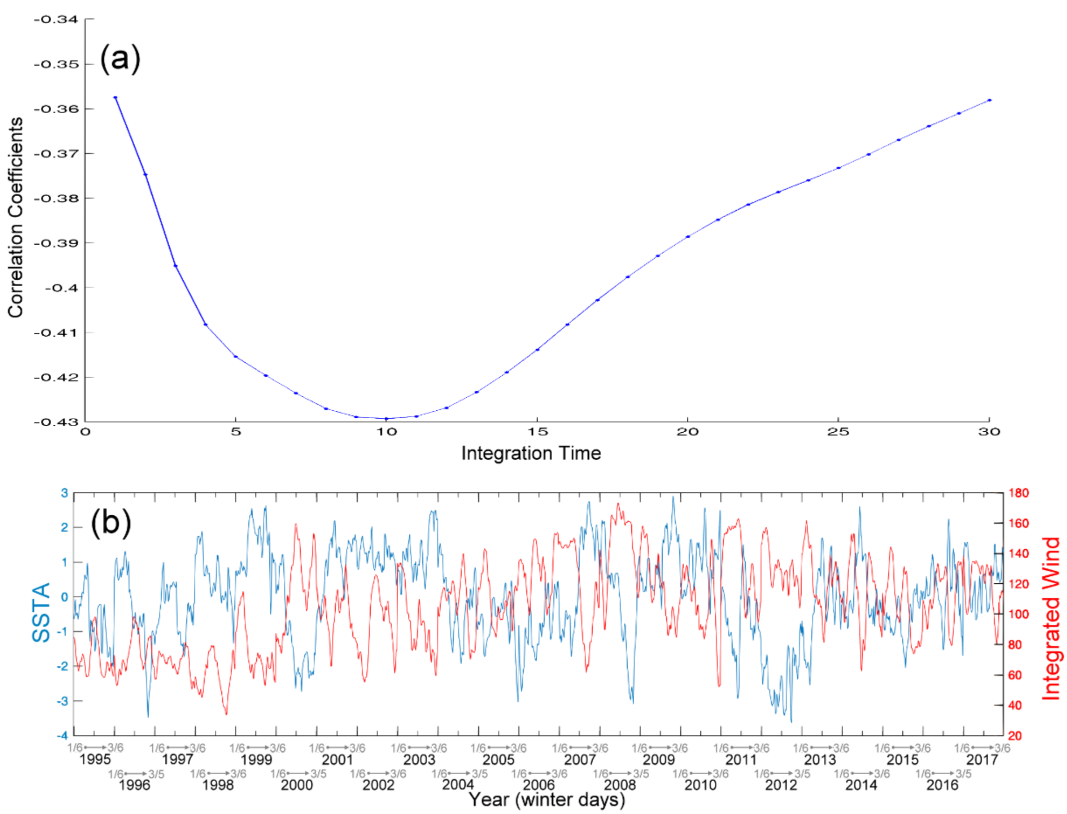


Figure 5: (a) ROC curves for predicting cold water days at lead times of 60, 90, 120, 150, 180, 210, and 240 days using the negative ONI. Numbers in parentheses in the legend are ROC scores for each lead time. The thresholds used to calculate TPRs and FPRs are showed from the 100th (lower left squares) to the 0th (upper right squares) percentile of negative ONI in decrements of 5%. ONIs at the dots are indexed by the colorbar. ROC scores ≥ 0.6 indicate a significant ($p < 0.05$) proxy for predictability. ~~(b~~(b) As in Fig. 5(a) but plotting PRC curves. AUC of PRC ≥ 0.15 indicate a significant ($p < 0.05$) proxy for predictability. (c) Odds ratios vary with ONI thresholds at lead times of 60, 90, 120, 150, 180, 210, and 240 days. Arrows denote the point with a -0.9 threshold at a 90-day lead time.



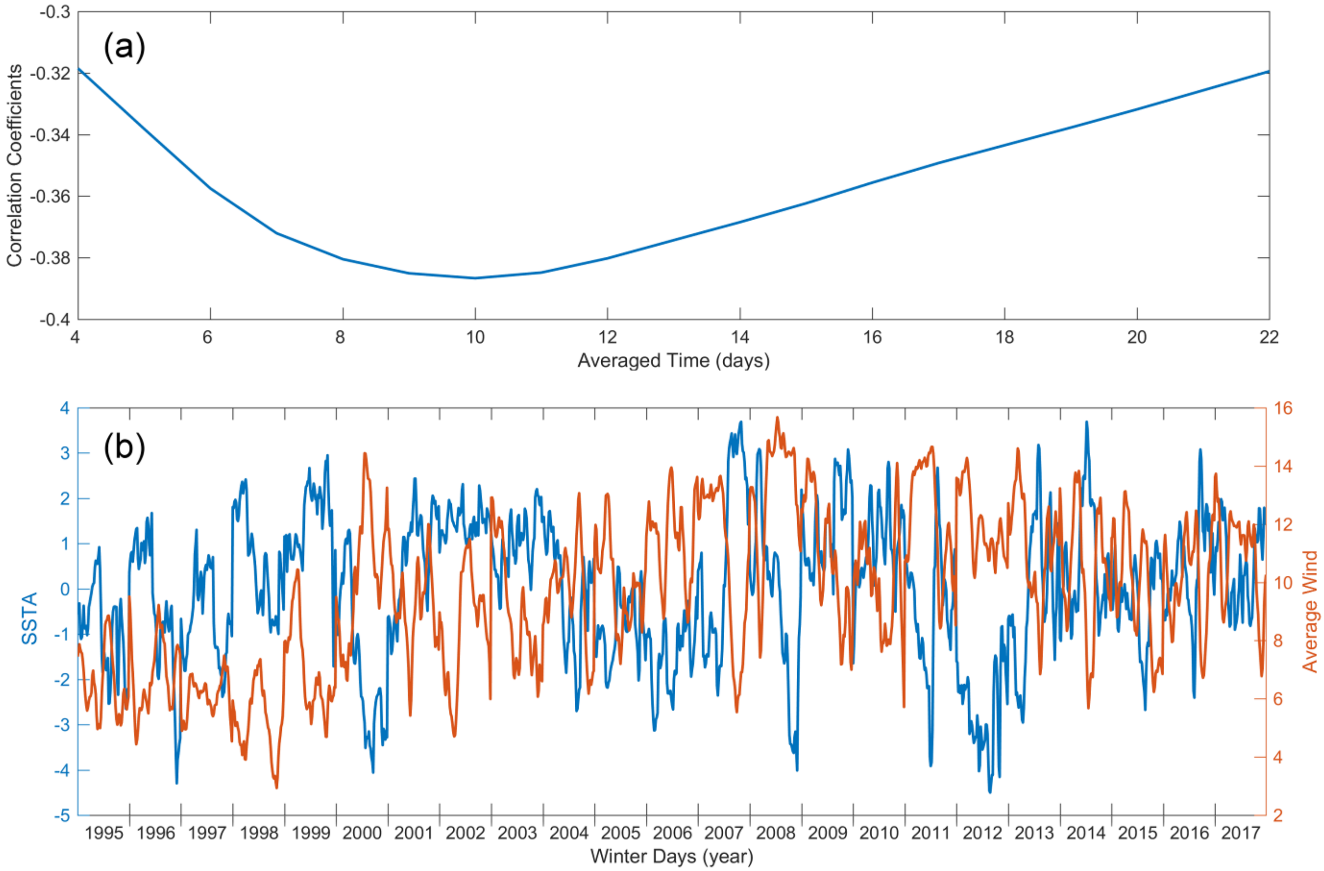
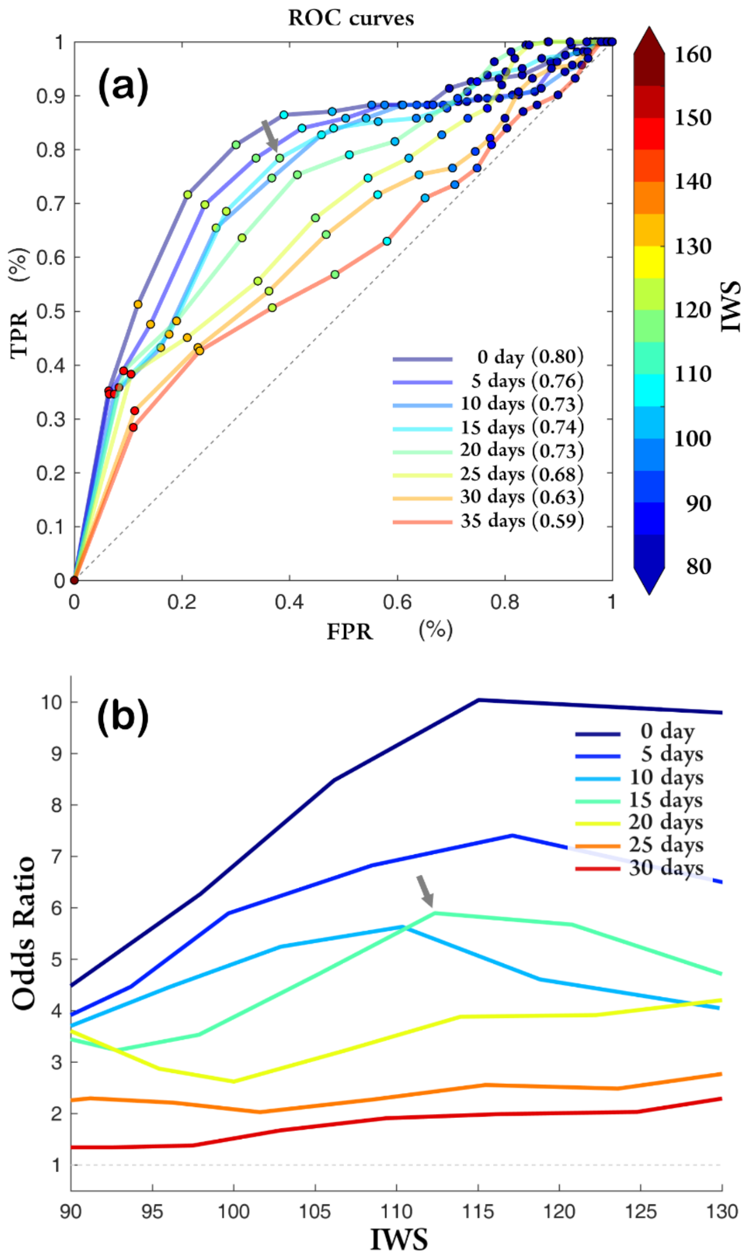


Figure 6: (a) Correlation coefficients varied with integration time. (b) Time series ~~of SSTAs for~~during the winter days of SSTAs and ~~IWS~~AWS with an ~~integration~~averaged time of 10 days.


ROC curves
(a)
TPR (%)
FPR (%)
0 day (0.80)
5 days (0.76)
10 days (0.73)
15 days (0.74)
20 days (0.73)
25 days (0.68)
30 days (0.63)
35 days (0.59)
IWS
(b)
Odds Ratio
IWS
0 day
5 days
10 days
15 days
20 days
25 days
30 days

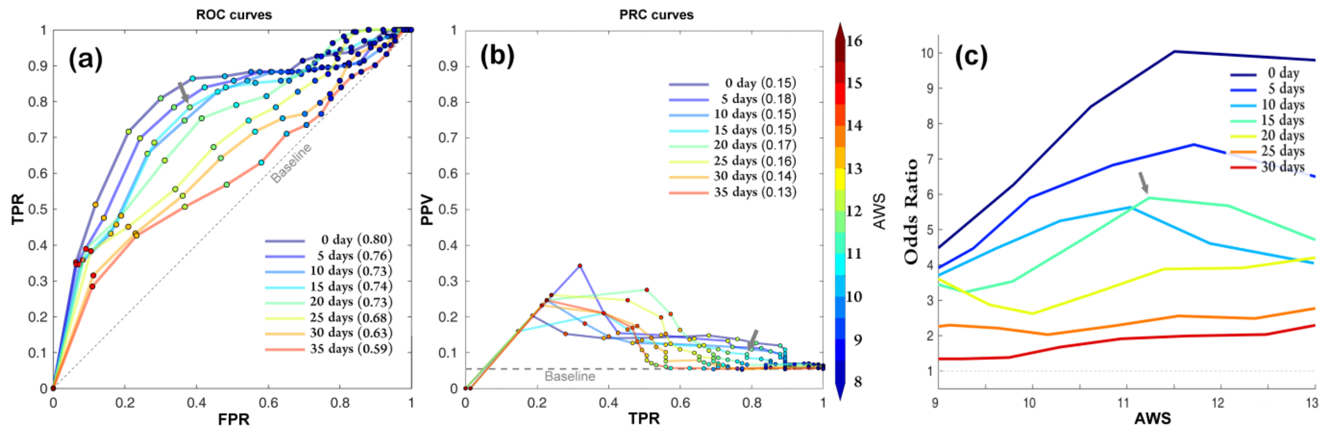
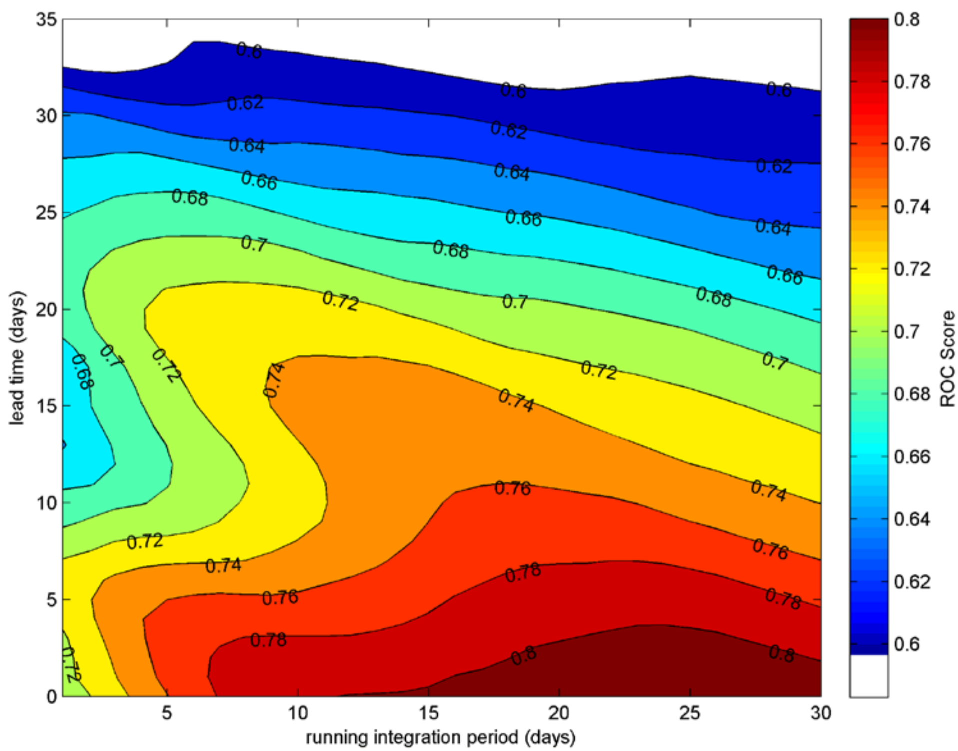


Figure 7: As in Fig. 5, but for predictions of cold events at lead times of 0, 5, 10, 15, 20, 25, 30, and 35 days using the wind speed with an ~~integration~~averaged time of 10 days. Arrows denote the point with ~~a 115~~an 11.5-m/s threshold at a 15-day lead time.



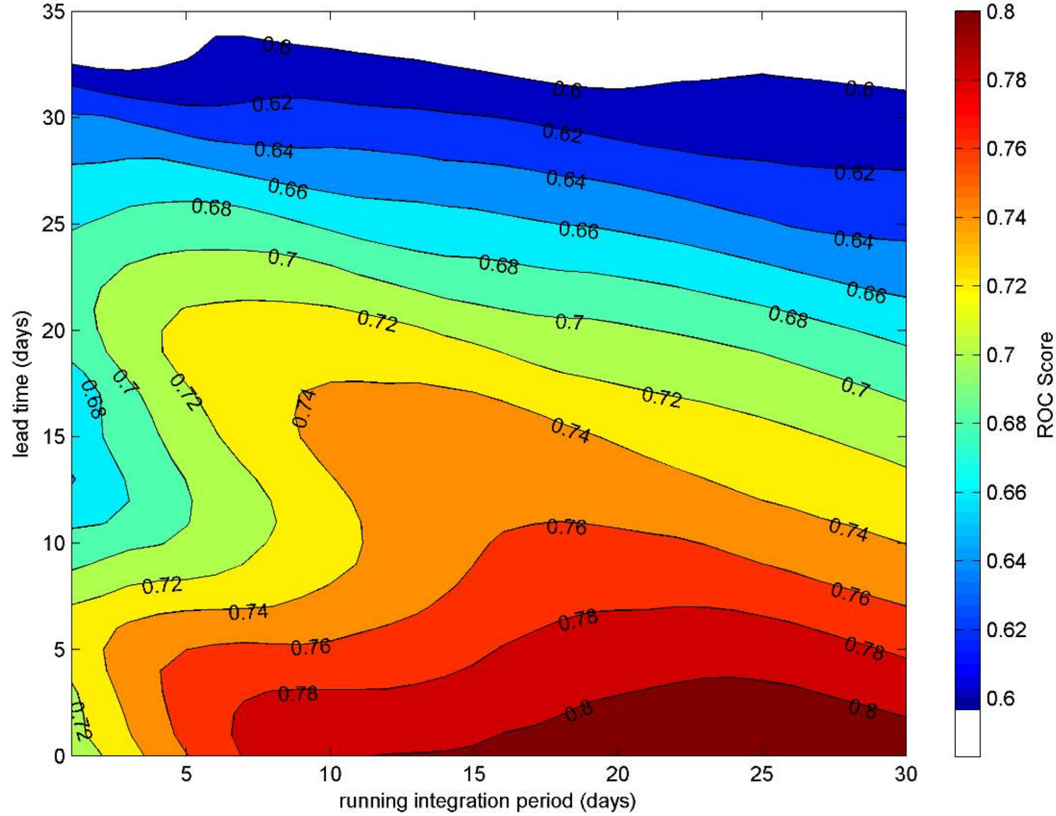
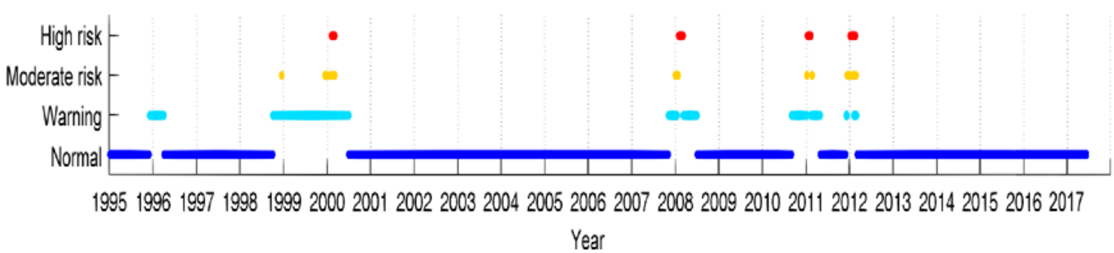


Figure 8: ROC score diagram of ~~IWS~~AWS-based prediction. The white color masks nonsignificant regions, where ROC scores are below the 95% confidence level.



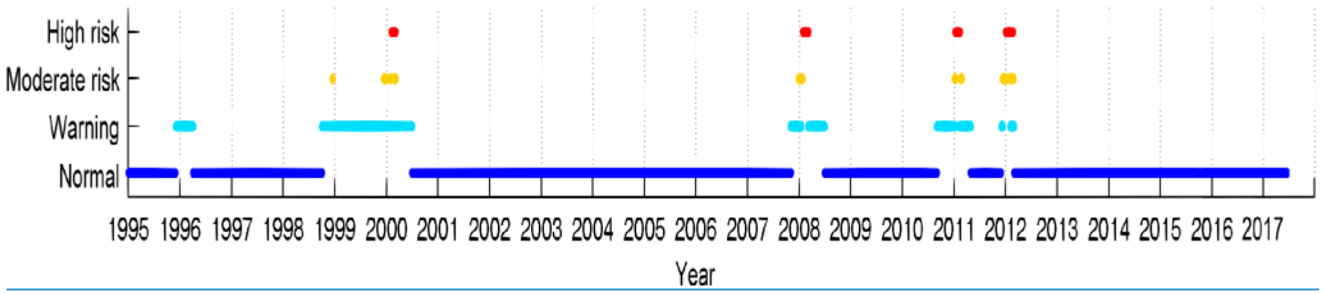
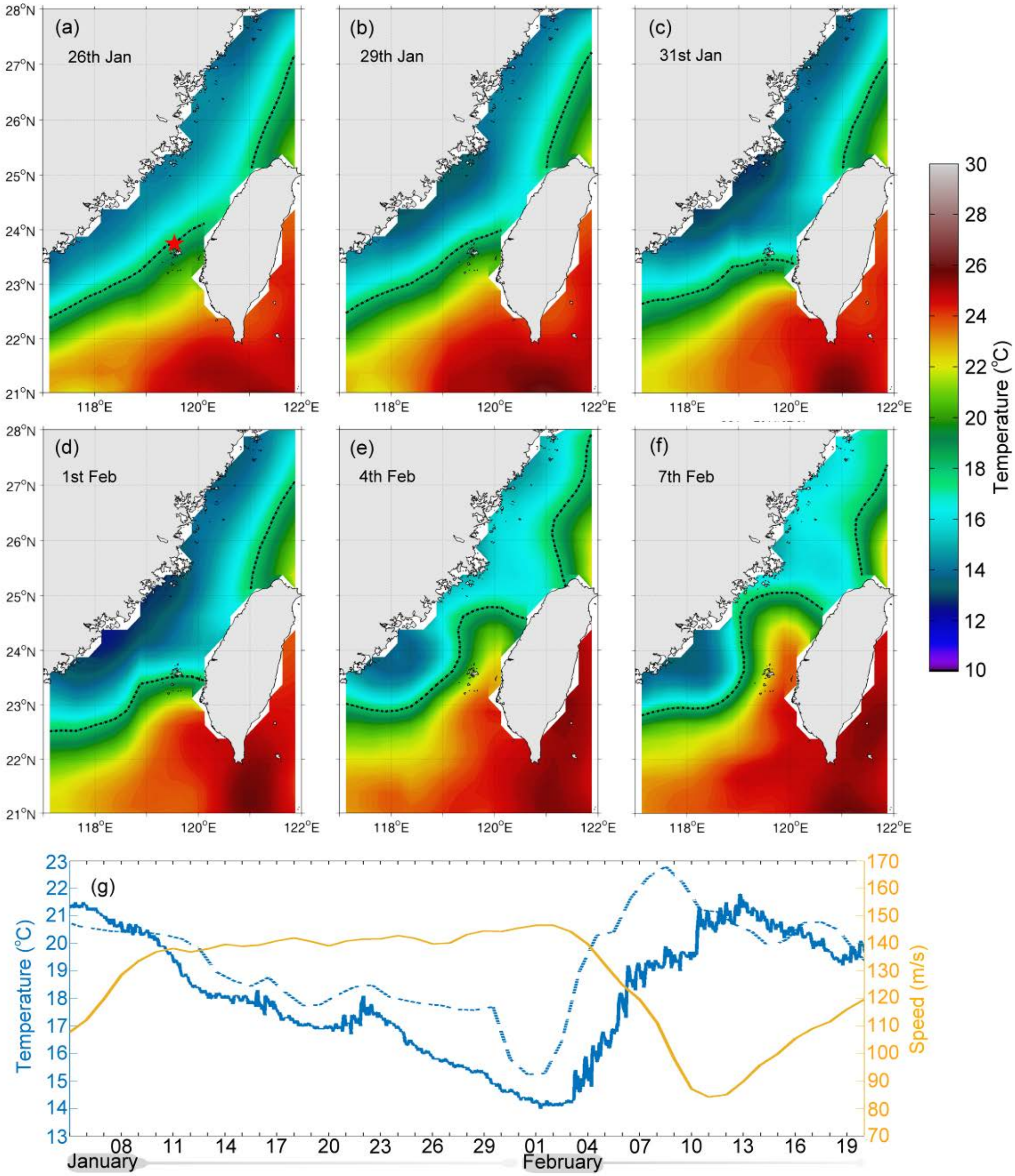
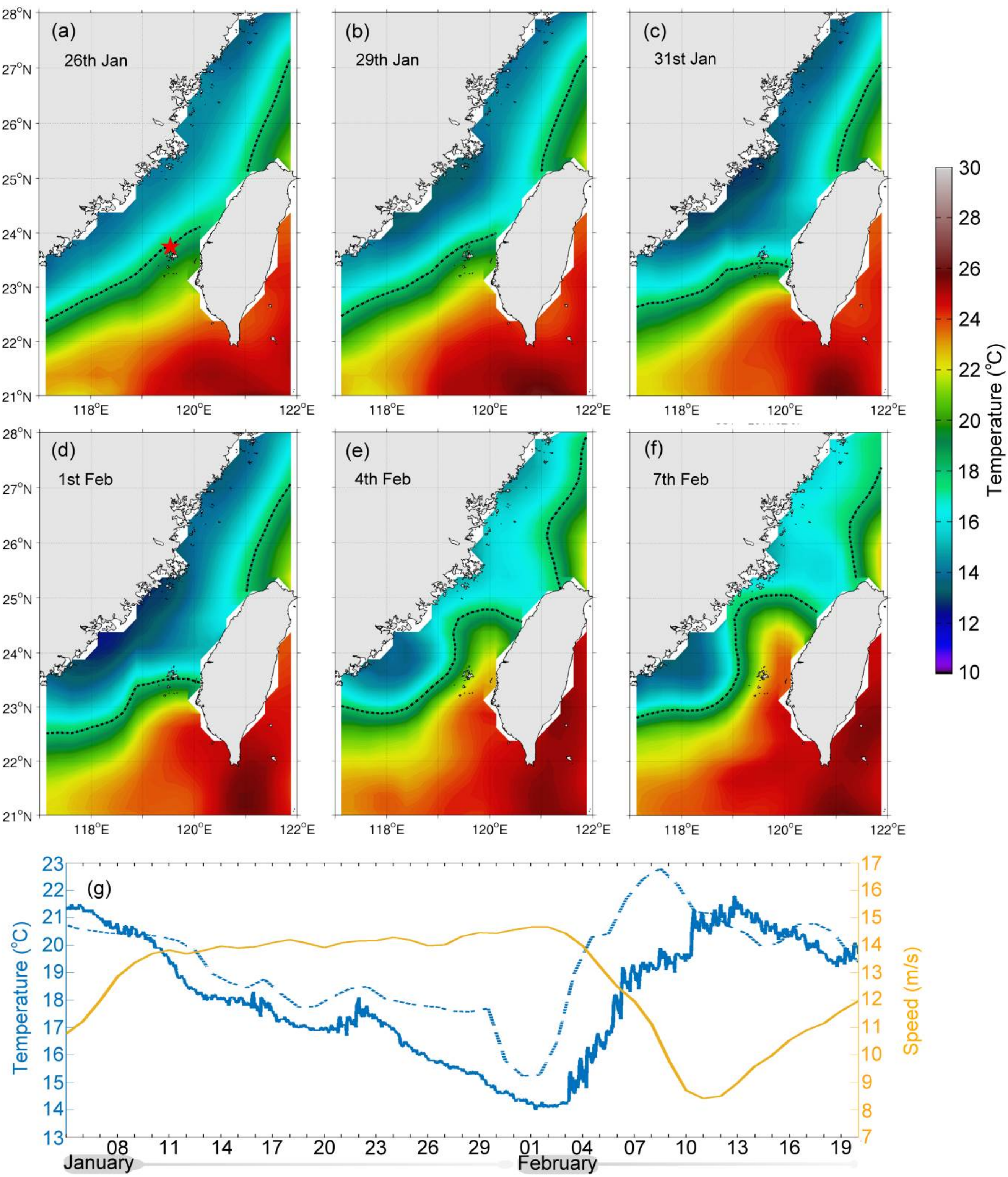


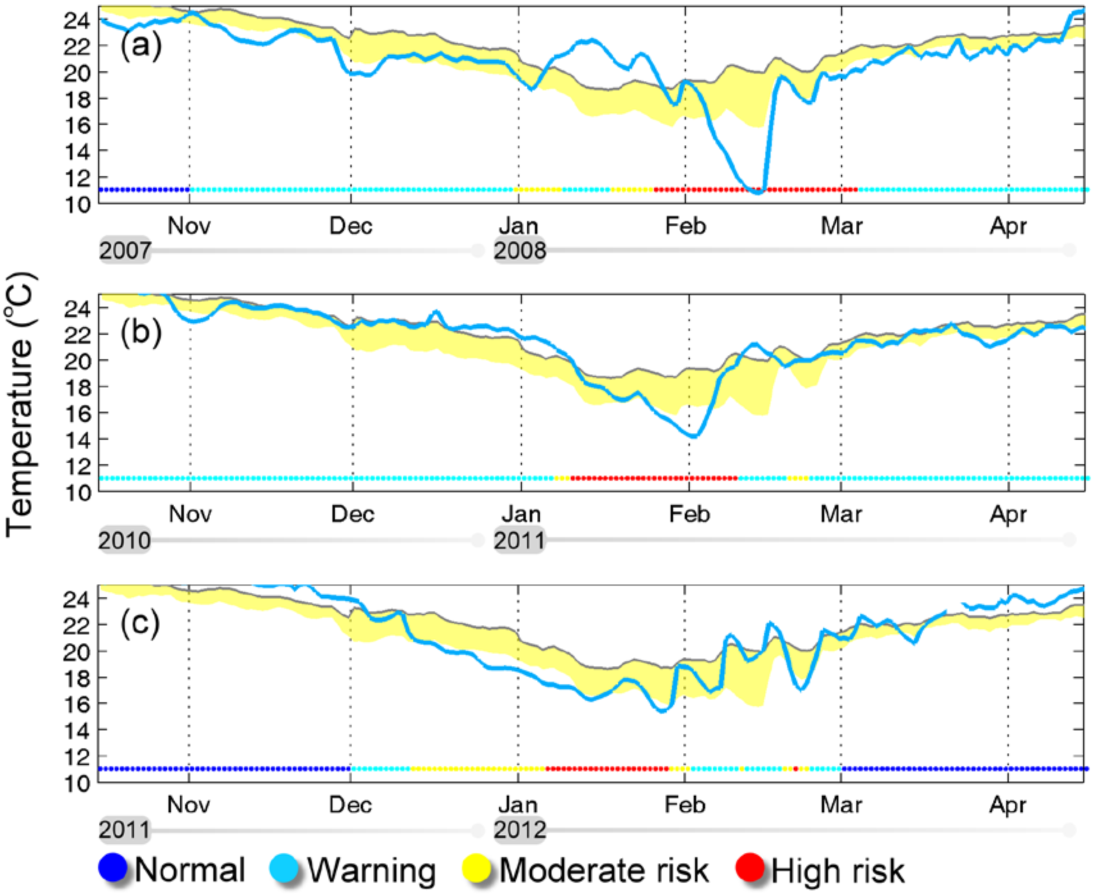
Figure 9: Warning lights of cold water days for Penghu Islands.


(a)
26th Jan
(b)
29th Jan
(c)
31st Jan
(d)
1st Feb
(e)
4th Feb
(f)
7th Feb
Temperature (°C)
(g)
Temperature (°C)
Speed (m/s)
January
February



(a)
26th Jan
(b)
29th Jan
(c)
31st Jan
(d)
1st Feb
(e)
4th Feb
(f)
7th Feb
Temperature (°C)
(g)
Temperature (°C)
Speed (m/s)
January
February

Figure 10: Cold event in the winter of 2011. (a to f) A map sequence of satellite SST. The red star indicates the position of the buoy from the Central Weather Bureau of Taiwan. Dashed lines are isotherm lines of 18 °C. (g) Time series of satellite SST (blue dashed line), buoy SST (blue line), and 10-day ~~IWS~~AWS (yellow line) on the red star location from January 5 to February 20.



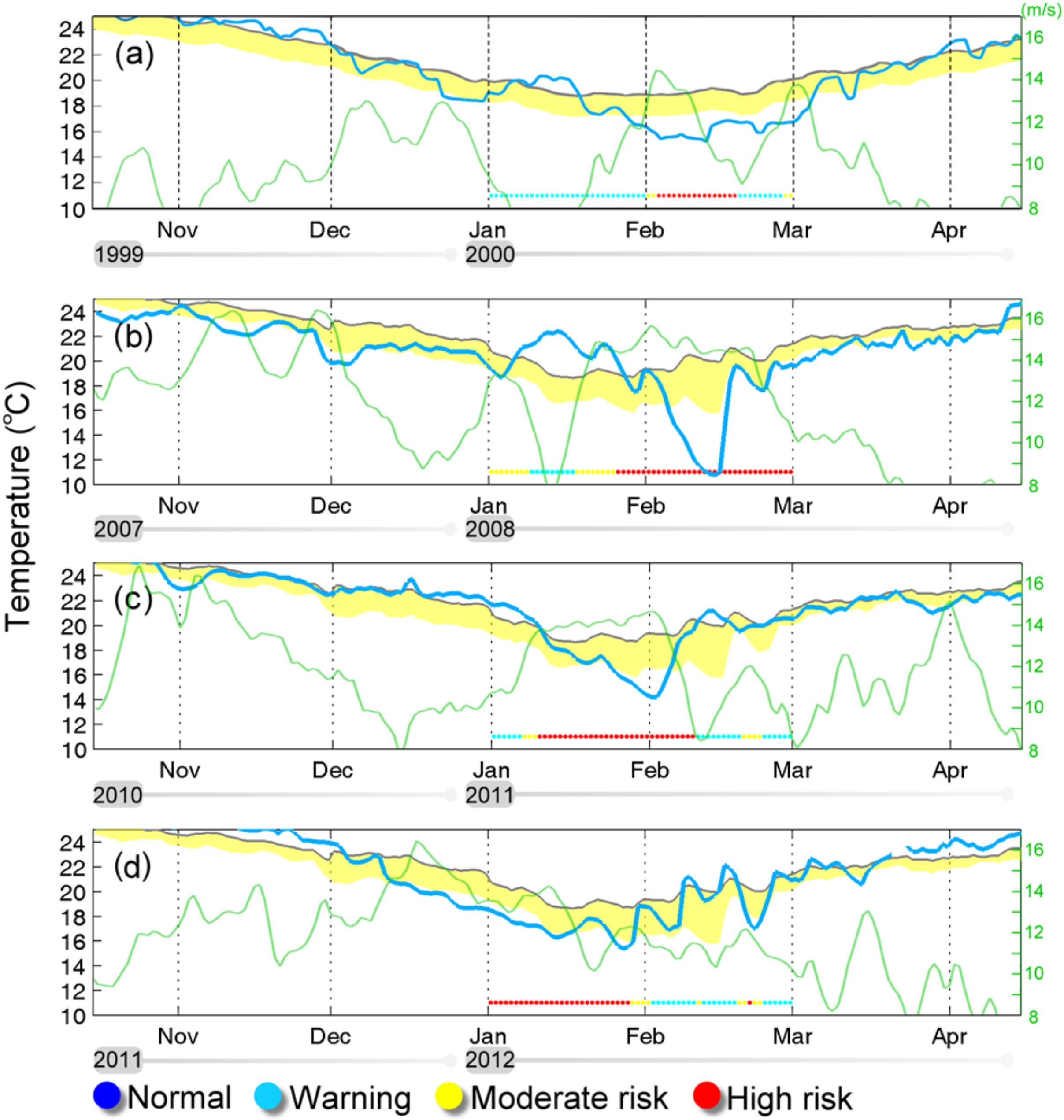


Figure 11: Cold events in (a) 2000, (b) 2008, (~~b~~c) 2011~~,~~ and (~~c~~d) 2012. Blue line: SST observed (a) by satellite and (b, c, d) by buoy ~~measurements of SST~~; gray line: 10-year climatological average; yellow shading: range of standard deviation below the average~~.~~; green line: 10-day AWS. Color dots are warning lights.

Table 1: A list of cold events during 1995-2017

Number	Date (yyyy/mm/dd)
Event 1	1996/02/23—1996/02/29
Event 2	2000/02/02—2000/02/15
Event 3	2000/02/23—2000/02/29
Event 4	2006/01/09—2006/01/14
Event 5	2008/02/16—2008/02/25
Event 6	2011/01/30—2011/02/02
Event 7	2012/01/16—2012/02/12
Event 8	2012/02/18—2012/02/20
Event 9	2013/01/16—2013/01/19

Table 2: Warning thresholds suggested for exceptionally cold water days

Type	Conditions	Possible Occurrence Time	Probability of Occurrence
Warning	ONI ≤ -0.9	around the next 90 days (30 days[a])	50%
Moderate risk	10-day ~~IWS ≥ 115~~AWS ≥ 11.5	around the next 15 days	60%
High risk	20-day ~~IWS ≥ 250~~AWS ≥ 12.5	around the next 5 days	75%

[a] real lead time considering when the ONI value can be obtained.