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A Rarely Witnessed Summertime Upwelling Event Northwest Off the Hainan Island

Aijun Pan*, Fangfang Kuang, Kai Li and Xu Dong

Third Institute of Oceanography, Ministry of Natural Resources, China

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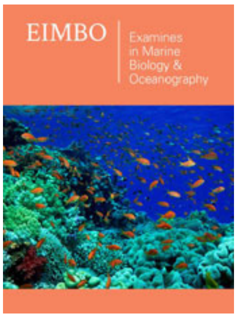

***Corresponding author:** Aijun Pan, Ocean Dynamics Lab, Third Institute of Oceanography, Ministry of Natural Resources, China

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Abstract

A field survey revealed a rare realization of upwelling event in the northwestern Hainan Island (UNWHI) on July 24, 2015. Model experiments suggest that the UNWHI is not locally generated, but can be treated as northward extension of the upwelling southwest off Hainan Island (USWHI) under favorable wind conditions. Therefore, presence of the USWHI is vital for the UNWHI occurrence. Tidal mixing is testified to be the primary driving force for the USWHI, whilst southerly winds plays an essential role in the induction of the UNWHI. Moreover, it is demonstrated that the UNWHI is not a stable, but intermittent coastal upwelling system. Shallow basin of the Beibu Gulf makes the interior circulation vulnerable to local monsoon changes. Given the favorable southerly winds, a cyclonic gyre northwest off Hainan Island will be induced and which, leads to northward coastal current and consequently, the UNWHI is to be formed due to the northward transport of the USWHI. Conversely, the UNWHI vanishes during northerly winds period, because the basin-scale anticyclonic gyre results in a southward current west off the Hainan Island and which, acts to push the upwelled water of the USWHI offshore and away from the northwestern Hainan Island. In addition, our diagnostics indicates that contributions from surface heat fluxes to the UNWHI occurrence is negligible. Besides, it also reminds us that application of a high-frequency, much closer to reality wind field is necessary for the coastal upwelling simulation.

Keywords: Upwelling; Northwestern Hainan island; Southerly winds; Tidal mixing; Beibu Gulf

Introduction

Upwelling is not only an important dynamic phenomena but commonly is referred as a crucial ecosystem in coastal regions. It lifts cold and nutrient-rich waters upward to the upper ocean and favors the bloom of the phytoplankton and thus has an important ecological meaning Takahashi et al. [1], Mann & Lazier [2] and Pennington & Chavez [3]. As to its dynamics and impacts on marine ecosystems, lots of studies have been performed in last few decades Andrew et al. [4] and Menge & Menge [5]. Wind-induced offshore Ekman transport and positive Ekman pumping are usually treated as two main causes for summertime coastal upwelling in northern hemisphere, though their contributions may differ slightly in different regions Jing et al. [6] and Menge & Menge [5].

Hainan Island is located in the northern South China Sea (SCS), where two main upwelling regimes, i.e., the eastern coast, and the southwestern coast of the island, have been identified Jing et al. [6], Guan & Chen [7], Dong et al.[8] and Li et al.[9] (Figure 1). Most previous studies focused on the summer upwelling phenomena in the eastern coast of Hainan Island (UEHI), which is triggered by the onshore compensation flow due to surface offshore Ekman transport Jing et al. [6]. Recently, a new summertime upwelling has been identified in the west region off Hainan Island (UWHI) from AVHRR remote sensing Sea Surface Temperature (SST) and historical observations Lu et al. [10] and Gao et al. [11] verified the existence of UWHI by detection a distinct low temperature zone in the western coast of Hainan Island and which, is believed to lie below 20m and is coordinated by heat flux and tide mixing. Shi [12] suggested that the upwelling between Chang jiang Estuary and Yingge Sea is caused by the offshore transportation due to anti-cyclonic circulation. Li et al. [9] pointed out that tidal mixing and strong background summer stratification are two main causes for the upwelling southwest off the Hainan Island (USWHI) occurrence. For convenience, both the UWHI and the USWHI will be referred as the USWHI in following analysis (Figure 1). Regime surrounding the Hainan Island is divided into three zones by rude-dashed line and represented by E (eastern), SW (southwestern) and NW (northwestern) , respectively.

As shown in Figure 1, two apparent upwelling cores denoted by the 28 °C isotherm can be identified in east and southwest off Hainan Island, respectively, which corresponds well with the well-known UEHI & UWSHI Jing et al. [6], Guan & Chen [7] and Li et al. [9]. Even if we adopt 28.5 °C isotherm as the outer rim of the upwelled water, the regime of upwelling is still being confined southern of the Chang jiang. Hence, there is no upwelling signal in the northwestern Hainan Island. Meanwhile, from the traditional point of view, the prevailing southerly winds does not support the upwelling occurrence too (Figure 2). However, under support of National Program on Global Change and Air-Sea Interaction, a field survey with total of 5 CTD stations along one transect in northwestern Hainan Island was conducted on July 24, 2015 (Figure 2a). Except for the temperature and salinity observations, ocean current profiles were measured at the same time (Figure 2b-2e). It is very interesting and worthy noting that an apparent uplift of cold, saline water climbing up along the continental shelf can be identified (Figure 2b, 2c). The upwelled water can reach up to the sea surface and moreover, offshore current from surface to middle layer and significant onshore compensating flow from middle to bottom depths, demonstrating itself as an canonical upwelling pattern, can be detected (Figure 2d, 2e). Therefore, the field survey does provide us proof that there is upwelling occurrence northwest off Hainan Island in summer and which, obviously is incoherent with our common sense that local southerly winds seems unlikely to support the upwelling occurrence. Besides, monthly remote sensing SST observations show no upwelling signal too (Figure 1). So, why is that?

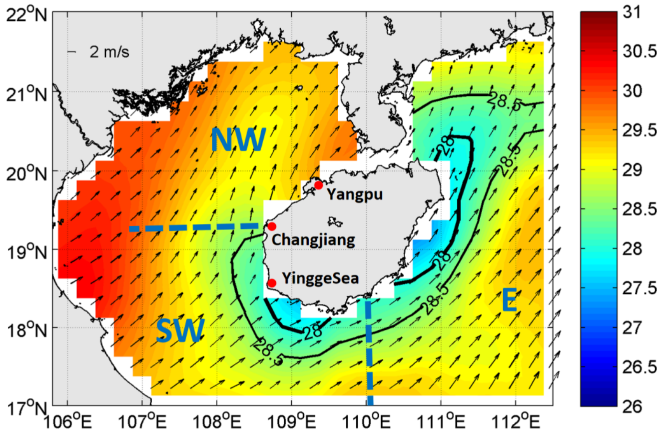

Figure 1: Remote sensing sea surface temperature (SST, °C) and winds in July 2015.

As is well known, usually results from field survey is robust and most reliable for ocean science exploration. For this contradiction between human's common sense, SST observation and field survey result, we deduce there might be two explanations in sponsor, firstly, our common sense on wind-driven upwelling perhaps misguide us in northwestern Hainan Island, that is, UNWHI maybe is triggered by a different mechanism rather than local winds. Secondly, SST appearance in Figure 1 could also mislead us because it is monthly averaged outcome and as a result, it might shelter the upwelling occurrence signal from the background SST. To clarify this issue, a Regional Ocean Model (ROMS) is built up for the research regime and utilized to explore the occurrence features and generation mechanism of the UNWHI. The paper is organized as follows: Section 2 describes the field survey observations, the remote sensing data, model configuration and validation. Experiments design is given in Section 3. Section 4 presents the results of sensitive experiments and diagnostic analysis. A conclusion is provided in Section 5.

Data and Methodology

Field survey data

A total of 5 CTD stations along one transect in northwestern Hainan Island was conducted aboard the R/V Qiong qionghai 09338 on July 24, 2015. These 5 CTD stations were located in the coast regime within 40m isobath (Figure 2a). Layer profiles of temperature and salinity were measured using a Sea & Sun® CTM920 Conductivity-Temperature-Depth/pressure system (CTD). Meanwhile, one WHS 300 kHz ADCP was utilized to acquire the ocean current data.

Remote sensing data

The remote sensing ASCAT Wind data is downloaded from French Marine Development Research Institute (ftp://ftp.ifremer.fr/ifremer/cersat/products/), with spatial resolution of 0.25°×0.25° and a time frequency of 1 day. Sea level anomaly (SLA) data is derived from the gridded multi mission sea surface heights computed with respect to a twenty-year mean. It has the same spatio-temporal resolution as that of ASCAT winds and is provided by AVISO (https://www.aviso.altimetry.fr/en/data/products/). The remote sensing SST data selects NOAA Optimum Interpolation SST V2 (OISST), which combines SST observations from both satellites and field stations by using optimal interpolation method (https://www.ncdc.noaa.gov/oisst/data-access). It has a spatial resolution of 0.25°×0.25° and time frequency of 1 day.

Model description and configuration

The Regional Ocean Model (ROMS) is utilized to explore the features of the UNWHI and its mechanism. Model domain is shown as in Figure 3, with horizontal resolution of 1/30° and vertical division as 24 layers. The minimum water depth is set to be 5m. The bathymetry data is adopted from GEBCO 2014 Grid, a global 30 arc-second interval grid (https://www.gebco.net/data_and_products/). Both the initial fields and lateral boundaries are provided by SODA's multi-monthly averaged temperature, salinity, and ocean current data. Tidal forcing at the open boundary employs results from OSU Tidal Inversion Software (OTIS) global tidal current model (http://volkov.oce.orst.edu/tides/YS.html). During the spin-up phase, the model is driven by wind stress, heat fluxes and fresh water fluxes deduced from monthly ASCAT winds and CFSR (NCEP Climate Forecast System Reanalysis, https://www.hycom.org/dataserver/) meteorological elements (air temperature, humidity, precipitation, short-wave radiation and long-wave radiation) according to the BULK formula. The model is run for 36 months and practically, the kinetic energy curve indicates the model has reached a steady state after 24 months' running. During the hindcast phase, daily winds and meteorological elements are adopted as surface forcing fields and model outputs in January are used as the initial fields. The simulation period is from January to June 2015.

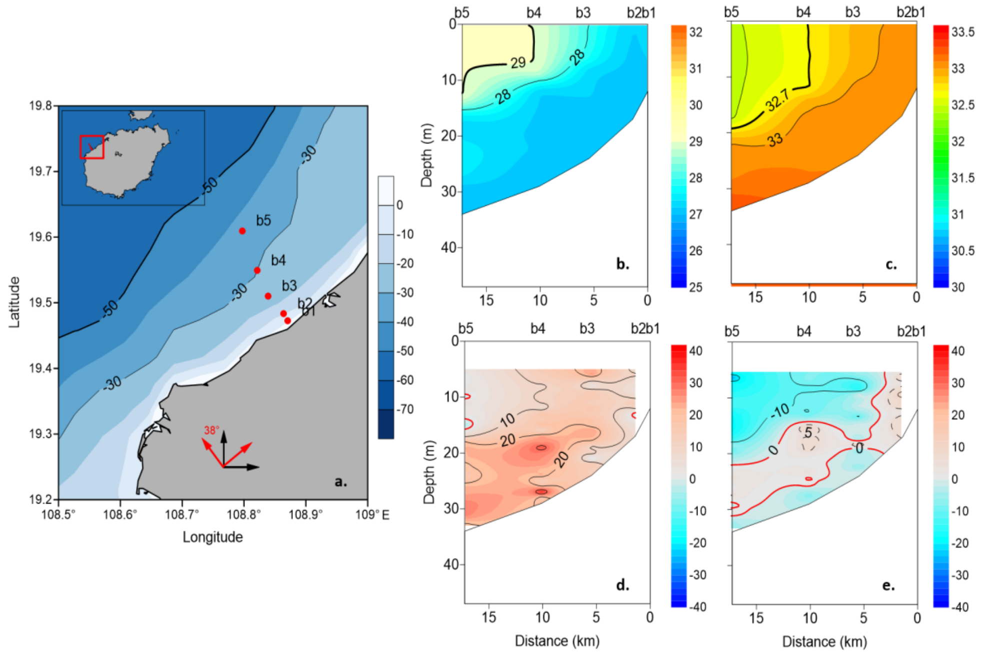

Figure 2: Field survey in the northwestern Hainan Island on July 24, 2015. Where Red circle denotes the CTD stations (b1-b5), profiles of temperature (°C), salinity (Psu), alongshore and cross shore flow (cm/s) are shown in b, c, d and e, respectively. In addition, the coordinate of ocean current is rotated anti-clockwise by 38° to obtain the alongshore and cross shore component.

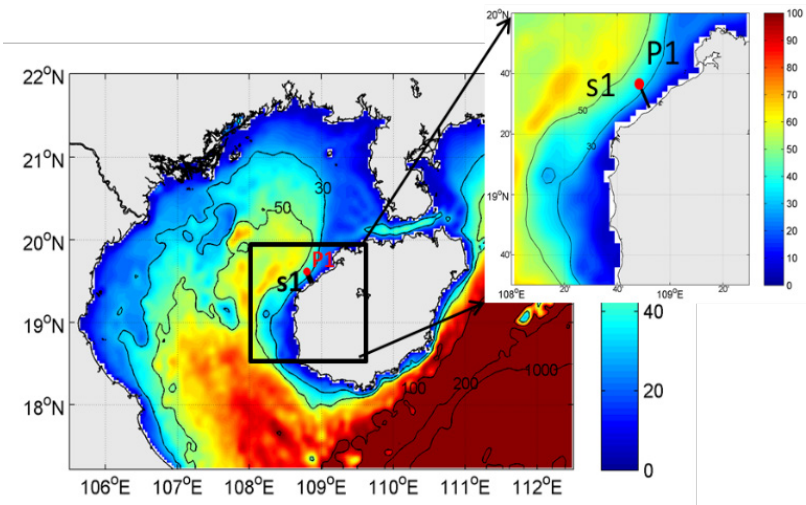

Figure 3: Numerical model domain with bathymetry overlaid (m) one representative section (S1) symbols the field survey and a key point (P1) are marked.

Model validation

Figure 4 compares the distribution of sea level anomaly between the model simulation and satellite remotely sensed AVISO in July 2015. It can be found that the model can reproduce well features of sea level anomaly around the Hainan Island, especially the low SLA in the eastern and southwestern off Hainan Island, the relative high SLA inside of the Beibu Gulf, meaning that the model is capable of duplicating circulation patterns around the Hainan Island.

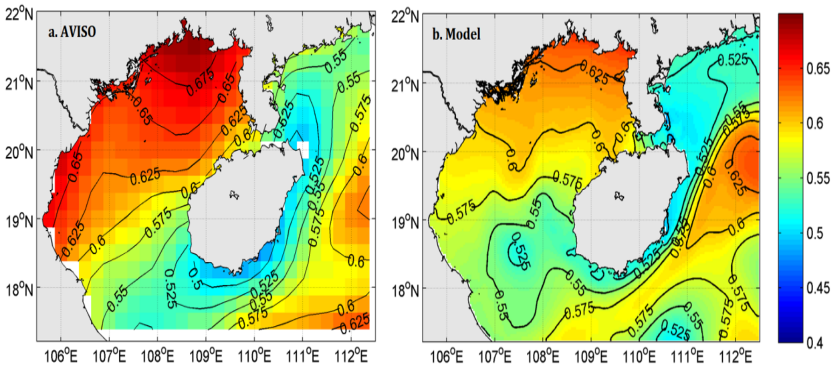

Figure 4: Distribution of sea level anomaly in July 2015 (unit: m).
a) AVISO
b) Model

Experiment Design

In order to clarify the formation mechanism of the UNWHI and solve the contradiction between the field CTD survey and the remote sensing SST observations, four types of experiments are designed to investigate effects of tides, winds and heat fluxes, respectively (Table 1). Each experiment uses the hindcast outputs on June 30, 2015 as the initial field, and the simulation period is from July 1 to July 30, 2015. Run0 is a standard one, with forcing fields of tides, daily winds and meteorological elements. Run1 is a no-tide experiment and can be adopted to study effects of tidal mixing by comparison with Run0. Run2 uses the July averaged winds as surface forcing and therefore, impacts of high variable winds on modulation of the USWHI can be differentiated from Run0. Like Run2, Run3 is driven by July averaged meteorological forcing and is used to assess influences of short-term changes in heat fluxes on the USWHI (Figure 5).

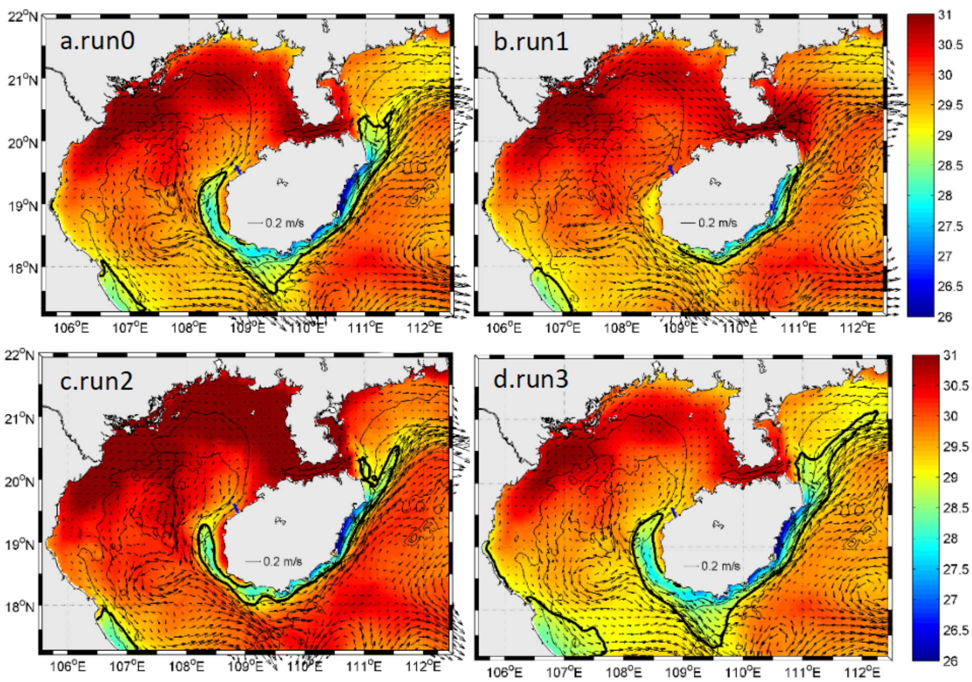

Figure 5: Modeled SST and ocean current from each experiment 29 °C isotherm is denoted by rude-solid line, 30 and 50m isobaths are shown by thin-solid line, besides, a rude-blue bar in northwest of Hainan Island is used to symbol the field survey regime**.**

Table 1: Experiment design.

Exp.x	Tide	Winds	Meteorological Elements	Purpose
Run0	Yes	Daily	Daily	Standard run
Run1	No	Daily	Daily	To study effects of tidal mixing
Run2	Yes	Monthly	Daily	To explore impacts of high variable winds
Run3	Yes	Daily	Monthly	To assess influences of short-term changes in heat flux

Diagnostics of Model Result

Figure 5a shows the modeled SST and ocean current distributions of the standard experiment. Here, 29 °C isotherm is utilized to represent the outer rim of the upwelling regime. It is clear that upwelling features of UEHI & USWHI are well reproduced with SST cold cores highly in coherence with OISST observations (Figure 1). Hence, model results is considered to be reliable and can be used for further comparison analysis. Meanwhile, simulated ocean current northwest off Hainan Island is oriented northeastward and is consistent with Wang [13] and Gao et al. [14]'s studies.

By comparison, other three sets of experiments can all reproduce the UEHI, whilst for the no-tide experiment in Run1, USWHI does not occur (Figure 5b-e), suggesting that on one hand, UEHI is a classical wind-driven upwelling Jing et al. [6] and on the other hand, USWHI's occurrence depends on the tidal mixing Li et al. [9]. In addition, when the model is driven by monthly averaged wind forcing, ranges for both of the UEHI and USWHI are seriously narrowed (Figure 5c). Although the ocean circulation pattern remains almost the same as in Run0, the range of low temperature zone is significantly reduced, suggesting that for coastal region simulations, especially for the upwelling generation, the more accurate daily wind forcing is needed. Comparatively, upwelling pattern does not change much for the monthly forcing of meteorology elements (Figure 5d), meaning that contributions from changes of heat fluxes in the induction of UNWHI is negligible.

Effects of tidal mixing

As presented in Figure 5a, 5c, 5d, coastal currents southwest off Hainan Island is oriented northward in experiments with tidal forcing (Run0, Run2, Run3) and correspondingly, there is a stable upwelling occurrence in southwestern Hainan Island. Whilst for the experiment without tide influences (Run1), coastal current flows southward in southwestern Hainan Island and synchronously, the USWHI vanishes. To further examine effects of tidal mixing on upwelling generation, differences of temperature and current (Run0-Run1) at 15m is shown in Figure 6. It is clear that the presence of tides remarkably changes the near-shore circulation structure both in the southwest and northwest of the Hainan Island, where coastal currents turns northward and meanwhile, water temperature decreases significantly. Generally, tidal mixing tends to play a vital role in the excitation of the USWHI. Since Li et al. [9] has conducted an detailed study and emphasized the impacts of tidal mixing and ocean stratification on USWHI generation, here we won't explore the effects of tidal mixing further. where the rude-solid line and the rude-blue bar are the same as in Figure 5.

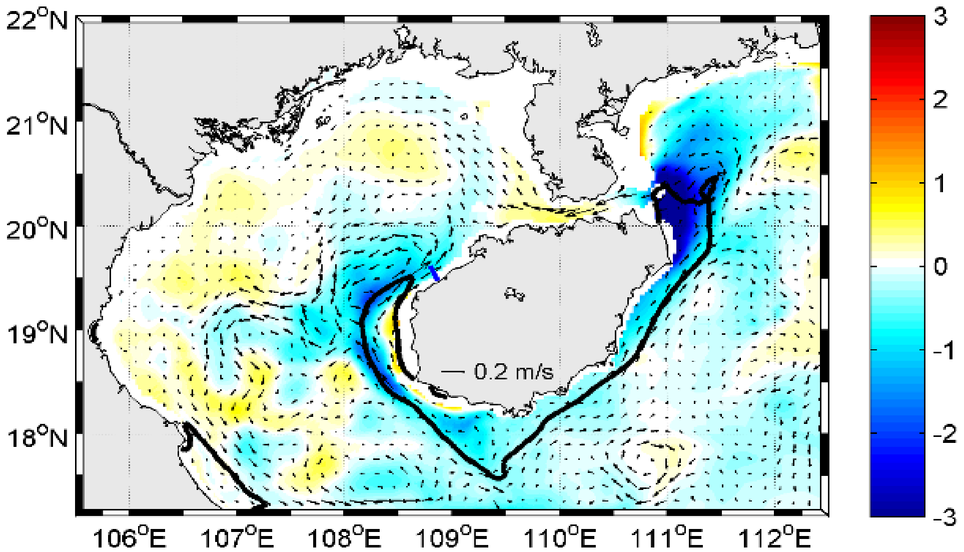

Figure 6: Difference of temperature (°C) and ocean current at 15m (Run0-Run1).

Impacts from wind variations

The above analysis indicates that given the influence of tides, a relatively stable upwelled water as USWHI occurs southwest off Hainan Island. As regard to the UNWHI revealed by field survey, there seems no obvious upwelling signal from model results and it looks like the remote sensing SST observations. However, from the more accurate, realistic standard run, two positive clues can be obtained. On one hand, ocean current flows northward along the west coast of Hainan Island and it can intrude into the northwestern Hainan Island by extending to Yangpu. On the other hand, although the upwelling rim does not takeover totally the northwestern Hainan Island, it does crossover Chang jiang and enter the realm of the northwestern Hainan Island (Figure 5a). Given that the field survey was performed on July 24, that is, only one day, whilst presentation of Run0 is practically the monthly averaged result, it is assumed that UNWHI might not be a stable phenomenon but with short duration. Therefore, the monthly averaged outcome from Run0 would have confused or even sheltered signals of UNWHI from background field.

In order to clarify this issue, we need to check in detail the model outputs from Run0 day by day. Before that, we scrutinize the local wind changes northwestern off Hainan Island (Figure 7). Obviously, though the monthly averaged winds demonstrates as southerly winds (Figure 1), actually the local winds is highly variable, wind direction changes swiftly with about 6 days period. It can be seen that northerly winds prevails from July 7 to July 12 and southerly winds takes in place between July 16 and July 28.

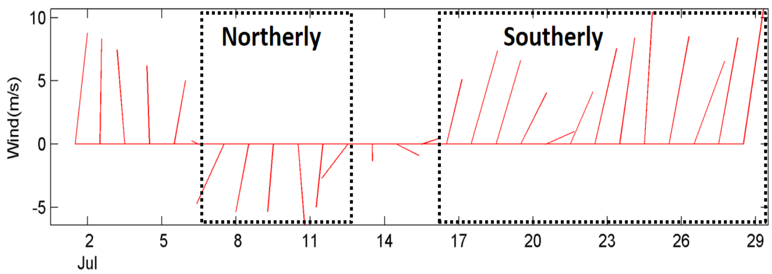

Figure 7: Time series of daily wind vectors at P1 in July

Because the study regime of UNWHI is located inside of the Beibu Gulf, as regard to the summer coastal circulation northwest off Hainan Island, there still exist many disputes. For example, both Yu & Liu [15] and Wu et al. [16] claimed the current flows southwestward, while Gao et al. [11] and Wang [13] believed it is in the opposite orientation as northeastward. Shi [12] put forth that a northward current exists all year round in the west of Yangpu Port, whilst a southwest oriented flow occurs western off the Chang jiang River. Using model simulation, Gao et al. [14] suggested that summer ocean circulation within northern Beibu Gulf tends to be modulated by the local monsoon forcing. Therefore, given the shallow water depth of the Beibu Gulf, local high variable winds might trigger quick responses of the oceanic circulation. b.d.f are the same as above but for the southerly winds period (July 16-28). In addition, the rude-solid line and the rude-blue bar are the same as in Figure 5**.**

Run0 modeled SST, surface ocean current and temperature profiles along the representative section S1 are shown for periods with surface wind forcing as northerly winds (July 7-12) and southerly winds (July 16-28), respectively (Figure 8a-8f). Meanwhile, the corresponding spatial distribution of the winds and wind curl are presented in Figure 8ab. It is found that during the period of northerly winds, the Beibu Gulf is mainly controlled by a negative wind curl (Figure 8a) and which, drives an overwhelming anticyclonic gyre with two small anticyclonic rings within the gulf (Figure 8c). As a result, coastal currents in northwestern of Hainan Island flows southwestward and the outer fringe of USWHI is pushed southward, offshore away from the west coast of Hainan Island (Figure 8c). At the same time, temperature profile at the representative section (S1) shows that cold water lower than 29 °C is suppressed below 20m and kept about 10km away from the coast (Figure 8e). Thus, under the influences of northerly winds, UNWHI does not occur.

By contrast, when southerly winds prevails in the Beibu Gulf, positive wind curl dominates most of the Gulf (Figure 8b). Resulted gulf circulation is a bit complicated, with a pair of anticyclonic and cyclonic gyre located in the southern and northern gulf, respectively. Besides, there are also four small rings spreading over the gulf. It is notable that the cyclonic gyre induces northward coastal current in west of Hainan Island, transporting upwelled water from the USWHI to the northwestern Hainan Island and consequently, the UNWHI is being formed. Synchronously, the upwelling rim is held close to the coast and it can reach northward over the field survey locus to Yangpu (Figure 8d), which is further verified by the temperature profile at S1, where cold water lower than 29 °C is uplifted to surface and drawn close to the coast (Figure 8f).

Conclusion

A new summertime upwelling regime northwest off Hainan Island is identified in this paper. The mechanism responsible for the UNWHI occurrence is investigated in detail using all available observations such as field survey, remote sensing, etc, in conjunction with ROMS experiments. It is revealed that the UNWHI is not locally formed, but a result from the northward transport of the USWHI under favorable southerly winds. In some sense, the UNWHI can be treated as an accessory of the USWHI. Therefore, occurrence of the

USWHI is a precondition for the UNWHI generation. As regard to the formation mechanism of the USWHI, model experiments testify the indispensable role played by tidal mixing Li et al. [9]. Moreover, the UNWHI is not a stable, but intermittent coastal upwelling system. It is very sensitive to changes of surface wind forcing. Since the Beibu Gulf is very shallow, the interior gulf circulation tends to response quickly to local monsoon changes Gao et al. [14]. Model experiments illustrate that provided with favorable southerly winds, a cyclonic gyre northwest off Hainan Island will be induced and which, gives rise to the northward flow along the west coast of the Hainan Island. Consequently, the UNWHI would be triggered due to the northward transport of the USWHI. Comparatively, as northerly winds prevails in the Beibu Gulf, the UNWHI will not occur, because the adjusted coastal current induced by the gulf-scale anticyclonic gyre tends to push the upwelled water of USWHI southward and away from the northwestern Hainan Island. In addition, our diagnostics also suggest that contributions from surface heat fluxes to the UNWHI occurrence is negligible.

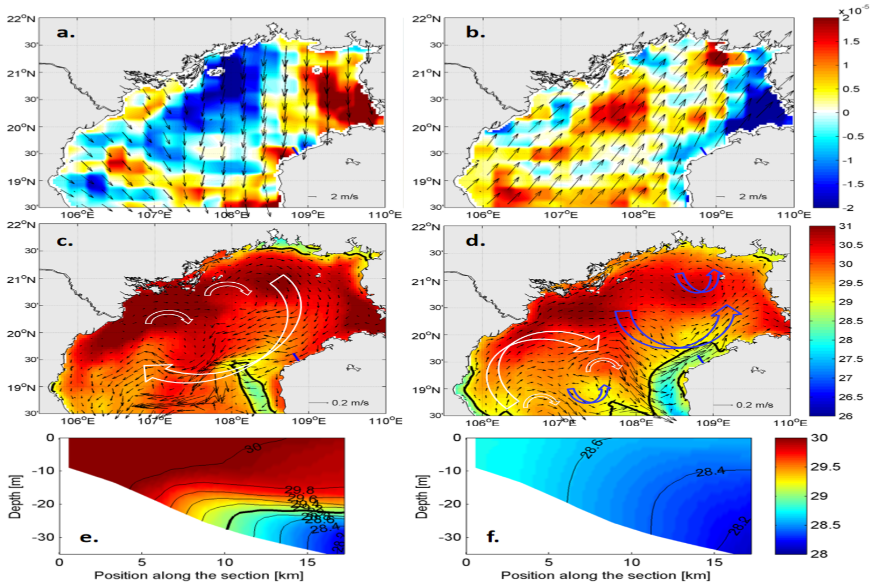

Figure 8: Distribution of a. winds (m/s) & wind curl (rad/s) from ASCAT, c. SST (°C) & surface ocean current (m/s) and e. temperature profile along section S1 for northerly winds period (July 7-12) from Run0, where white & blue hollow arrow represents the anticyclonic and cyclonic gyre, respectively. b,d,f are the same as above but for the southerly winds period (July 16-28). In addition, the rude-solid line and the rude-blue bar are the same as in Figure 5

Generally, a rarely seen upwelling phenomena northwest off Hainan Island is uncovered in this paper, with observational features, formation dynamics being explored in detail. However, due to the insufficient field data, there are many issues remain in vague. For instance, what is exactly the 3-D responses of oceanic circulation to monsoon changes in Beibu Gulf? What is the impact of the external water intrusion (e.g., South China Sea) on the Beibu Gulf circulation? All these questions require more observations and diagnostics from model simulations.

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References

1. Takahashi M, Ishizaka J, Ishimaru T, Atkinson LP, Lee TN, et al. (1986) Temporal change in nutrient concentrations and phyto-plankton biomass in short time scale local upwelling around the Izu Peninsula, Japan. Journal of Plankton Research 8(6): 1039-1049.
2. Mann KH, Lazier JRN (1996) Dynamics of marine ecosystems: Biological-physical interactions in the ocean. (2nd edn.), England.
3. Pennington JT, Chavez FP (2000) Seasonal fluctuations of temperature, salinity, nitrate, chlorophyll and primary production at station H3/M1 over 1989-1996 in Monterey Bay, California. Deep-Sea Research II 47(5-6): 947-973.
4. Andrew B, David BF, ANA RR, et al. (2010) Greenhouse gas, upwelling-favorable winds, and the future of coastal ocean upwelling ecosystems. Global Change Biology 16(4): 1213-1228.
5. Menge B, Menge D (2013) Dynamics of coastal meta-ecosystems: The intermittent upwelling hypothesis and a test in rocky intertidal regions. Ecological Monographs 83(3): 283-310.
6. Jing ZY, Qi YQ, Hua Z (2009) Numerical study on the summer upwelling system in the northern continental shelf of the South China Sea. Cont Shelf Res 29(2): 467-478.
7. Guan BX, Chen SJ (1964) Ocean current system in east china sea and south china sea. Chinese Academy of Sciences (in chinese), China.
8. Dong X, Huang HN, Zheng N (2017) Acidification mediated by a river plume and coastal upwelling on a fringing reef at the east coast of Hainan Island, northern south china sea. J Geophys Res Oceans 122(9): 7521-7536.
9. Li YN, Peng SQ, Wang J (2018) On the mechanism of the generation and inter-annual variations of the summer upwellings west and southwest off the Hainan Island. J Geophys Res 123(11): 8247-8263.

10. Lu XG, Qiao FL, Wang GS, Guansuo W, Changshui X, et al. (2008) Upwelling off the west coast of Hainan Island in summer: Its detection and mechanisms. Geophysical Research Letters 35(2): L02604.
11. Gao JS, Chen B, He XY (2014) Numerical study of upwelling and warm pools in the west bank of Hainan Island. Guangxi Science 21(4): 331-337.
12. Shi MC (2014) Review of the study on the circulation of the Beibu Gulf. Guangxi Science 21(4): 313-324.
13. Wang D (1998) Research on the dynamic-thermal mechanism of the Beibu Gulf Cold Water Group. Ocean University of China, China.
14. Gao JS, Chen B, Shi MC (2015) Summer circulation structure and formation mechanism of Beibu Gulf. Science in China: Earth Science 58(2): 286-299.
15. Yu MG, Liu JF (1993) South China sea circulation system and circulation situation. Ocean Forecast 10: 13-17.
16. Wu DX, Wang Y, Lin XP, et al. (2008) On the mechanism of the cyclonic in Gulf of Tonkin in the summer. J Geophys Res 113(C9): C09029.

