Sea temperature variation associated with the 2021 Haiti Mw 7.2 earthquake and possible mechanism

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**ABSTRACT**

A catastrophic earthquake (magnitude Mw 7.2) occurred on 14 August 2021 in Haiti. Sea surface temperature (SST) and sea potential temperature (SPT) observed from satellites show pronounced changes prior to the main earthquake event. The changes are observed near the epicenter and the boundary of the Caribbean Plate. Here we have carried out a detailed analysis of ocean, atmosphere and land surface parameters (sea water salinity, chlorophyll-a, latent energy flux, sensible heat flux, specific humidity, air temperature, methane and land surface temperature) using multiple satellite data to understand the possible mechanism of sea temperature changes. The strong coupling among these geophysical and geochemical parameters has been found within 2-week prior to the 2021 Haiti Mw 7.2 earthquake due to the interaction between ocean/land and atmosphere during the last phase of earthquake preparation period caused by the tectonic movement. The spatiotemporal distribution pattern of anomalies is discussed in view of the focal mechanism of the earthquake event.

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1. Introduction

Earthquakes are one of the most destructive disasters for humankind. During the final stage of earthquake preparation, energy accumulation and crustal stress enhancement in the hypocentral region (Wu et al. 2012), play a very important role. Thus, the pronounced changes on the earth’s surface, atmosphere and meteorological parameters from ground-based observations have been observed and reported by many researchers (Pierce 1976; King 1978; Leary and Malin 1984; Mogi et al. 1989; Biagi et al. 2000; King et al. 2000; Fujiwara et al. 2004). Prior to the earthquake, in a certain area, some anomalous geophysical and geochemical signals on the earth’s surface and atmosphere have been observed in many earthquakes in the past (Pulinets et al. 2006; Uyeda et al. 2009; Akhoondzadeh et al. 2010; Qin et al. 2011; Contadakis et al. 2015; Cui et al. 2017). Identifying and analyzing abnormal signals in different...
geophysical, geological and hydrological environments is a major challenge to the scientific community. Compared with traditional ground observation, satellite observation provides more temporal, spatial and spectral information. An increasing amount of satellite data has been used to detect anomalous signals associated with strong earthquakes around the world (Tronin 1996, 2000; Ouzounov and Freund 2004; Cui et al. 2011; Qin et al. 2013; Barkat et al. 2018; Qi et al. 2020). Satellite thermal infrared data and products, e.g. Outgoing Longwave Radiation (OLR), Surface Latent Heat Flux (SLHF), Land Surface Temperature (LST) and Surface Air Temperature (SAT), have been widely used to study thermal anomalies associated with earthquake activities (Singh et al. 2002; Dey and Singh 2003; Dey et al. 2004; Okada et al. 2004; Ouzounov et al. 2011; Piroddi and Ranieri 2012; Wu et al. 2012; Jing et al. 2013; Xiong and Shen 2017; Jing et al. 2018). Recently, Microwave Brightness Temperature (MWBT) data have also been used to study seismic thermal signals since they are unaffected by weather conditions (Jing et al. 2018; Qi et al. 2022). The diverse anomalies are well studied using satellite and ground observations associated with some major earthquakes, for example, the Gujarat Mw 7.7 earthquake of 26 January 2001 (Singh et al. 2002; Dey et al. 2004; Okada et al. 2004; Saraf and Choudhury 2005; Genzano et al. 2007; Singh, Kumar, et al. 2010), the Wenchuan Mw 7.9 earthquake of 12 May 2008 (Zhao et al. 2008; Singh, Mehdi, Gautam, et al. 2010; Jing et al. 2013; Li et al. 2015) and the Nepal Mw 7.8 earthquake of 25 April 2015 (Bhardwaj et al. 2017; De Santis et al. 2017; He et al. 2017; Jing et al. 2019; Qi et al. 2022).

To better understand the thermal anomalous signals preceding the earthquake, the hypothesis of earth degassing (Qiang et al. 1997), underground water responses (Asteriadis and Livieratos 1989) and heat generated by fault friction (Wu et al. 2000) have been proposed. In addition, the models of Lithosphere-Atmosphere-Ionosphere coupling (LAIC) (Pulinets and Ouzounov 2011) and Lithosphere-Coversphere-Atmosphere coupling (LCAC) (Wu et al. 2012) have been developed to explain the interaction among different geospheres during the final stage of earthquake preparation. The ionizing radiation by radon gas was considered to be the main source for the release of heat and other physical/chemical processes in the atmosphere (Pulinets et al. 2006). Another explanation was proposed by Freund (2002, 2003), who believed that the charge is generated and propagates in rocks due to the activated positive holes (P-hole) and flow out of the rock to cause the unusual signals in case of the build-up tectonic stresses prior to an earthquake.

However, coastal earthquakes have not been well considered in these hypotheses and models. The fluidity of seawater makes it possible for thermal anomalous signals to spread widely in the case of coastal earthquakes. Dey and Singh (2003) compared the behaviors of SLHF associated with inland and coastal earthquakes that occurred in different tectonic regions and found more obvious SLHF variation prior to the coastal earthquakes. Ouzounov and Freund (2004) observed decreased SST prior to earthquakes in the ocean and attributed it to the upwelling of cold near-bottom water caused by tectonic activity. Chakravarty (2009) proposed that the heat flow and SST increased with enhanced tectonic activity by analyzing submarine earthquakes in the Sumatra region. Recently, the spatial-temporal analysis showed an obvious SST anomaly preceding the northern Red Sea Mw 5.2 earthquake of 16 June 2020 (Mohamed...
et al. 2022). The results from retrospective analysis and statistical analysis (Jiao and Shan 2022) show both positive and negative SST anomalies occurred prior to the coastal earthquakes in different tectonic environments (occurred off or on the coast; controlled by thrust, normal, or strike-slip faults) and the mechanism is still unclear. Besides the thermal-related parameters, changes in oceanic chlorophyll concentrations (Singh et al. 2002, 2019), atmospheric and ionospheric parameters (Dey et al. 2004; Okada et al. 2004; Trigunait et al. 2004; Akhoondzadeh 2015) have also been found associated with coastal earthquakes. Nevertheless, the integrated analysis of multiple parameters in different geospheres for coastal earthquakes is still very limited.

In the current work, we focus on sea surface temperature (SST) and sea potential temperature (SPT) changes associated with the 2021 Haiti Mw 7.2 earthquake which occurred in a coastal region. SST and SPT in four key regions have been analyzed in detail. Additionally, a complementary analysis of multiple land, ocean and atmospheric parameters (land surface temperature, open water latent energy flux, open water sensible heat flux, 10-meter specific humidity, 10-meter air temperature, sea water salinity, chlorophyll-a and methane) and also a comparative analysis on the 2010 Haiti Mw 7.0 earthquake have been carried out to better understand the possible mechanism for sea temperature changes associated with the 2021 Haiti Mw 7.2 earthquake.

2. Regional tectonic environment and seismic activities

The Caribbean Plate is a mostly oceanic tectonic plate which is bordered by the North American Plate, the South American Plate, the North Andes Plate, the Panama Plate and the Cocos Plate (Figure 1). Frequent Earthquakes occur in this region, especially in the tectonic plate boundary. Haiti is located near the boundary of the Caribbean Plate and the North American Plate.
In August 2021, a Mw 7.2 earthquake struck the Tiburon Peninsula in the Caribbean nation of Haiti (hereinafter referred to as the 2021 Haiti earthquake). A total of 37 aftershocks with magnitude M 4.0-M 5.8 have been recorded within the following 14 days (source: USGS). The main earthquake event (red star in Figure 1) occurred near the boundary between the Caribbean plate and the North American plate. According to the solution of Global Centroid Moment Tensor (GCMT), this earthquake occurred at a shallow depth of 12 km and the seismogenic fault is an oblique strike-slip fault. A major deformation area is distributed along the Enriquillo-Plantain Garden fault (EPGF) zone. The maximum crustal deformation is greater than 80 cm and is located in the western part of the epicenter (https://www.gsi.go.jp/cais/topic20210814-e.html).

Within 500 km from the epicenter of the 2021 Haiti earthquake, a total of 37 earthquakes with M ≥ 5 were recorded from January 2010 to August 2021. In 2010, a deadly earthquake occurred in this region (magenta star in Figure 1). These two earthquakes in Haiti have different focal mechanisms. The 2010 Haiti Mw 7.0 earthquake occurred on a blind thrust fault while the 2021 Haiti Mw 7.2 earthquake occurred on a left-lateral strike-slip fault. The details of the two earthquakes are listed in Table 1.

### Table 1. The information of the two strong Haiti earthquakes (Source: USGS).

| No. | Time (UTC)         | Epicenter          | Magnitude (Mw) | Depth | Focal mechanism          |
|-----|--------------------|--------------------|----------------|-------|--------------------------|
| 1   | 2010-01-12 21:53:10| 18.443° N, 72.571° W| 7.0            | 13.0 km |                          |
| 2   | 2021-08-14 12:29:08| 18.434° N, 73.482° W| 7.2            | 10.0 km |                          |

3. Data and methods

3.1. Used data

3.1.1. Oceanic data

Sea surface temperature (SST), sea potential temperature (SPT), sea water salinity (SWS), open water latent energy flux (EFLUX), open water upward sensible heat flux (HFLUX) and chlorophyll-a (Chl-a) have been considered in the present study.

SST reflects the thermal regime of seawater and has periodic (day, month and year) and irregular changes caused by environmental factors. We have considered the daily optimum interpolation SST dataset with a spatial resolution of 0.25° from National Centers for Environmental Information (NCEI). The dataset was constructed by combining observations from different platforms (satellite data, ships, buoys and Argo data) on a regular global grid. The biases are −0.07 °C and −0.04 °C in the global ocean when compared with independent and dependent Argo observations, respectively (Huang et al. 2021). The heat content of a water parcel change only depends on mixing with other water when it moves within the ocean below the mixed layer (Stewart 2009). The temperature of a parcel of water at the sea surface
caused by a mass of water rising adiabatically from a certain oceanic depth is defined as potential temperature, which is calculated from the in-situ temperature in the water at depth and independent of the surrounding region (Stewart 2009). The SPT and SWS data with a spatial resolution of 0.083° at different levels have also been used to better understand the vertical change process of sea temperature. The mean errors of global SPT and SWS in the 0–100 m layer with respect to in-situ observation are −0.05 K and 0.005 PSU, respectively (Lellouche et al. 2019).

Latent heat (also known as latent energy) is the absorbed or released energy during the substance from one phase to another at a constant temperature. In the budget of the sea surface, latent heat flux and sensible heat flux are defined as the flux of heat carried by the evaporated water and the flux of heat from the sea due to conduction respectively (Stewart 2009). Latent heat flux is mainly influenced by wind speed and relative humidity while sensible heat flux is influenced primarily by wind speed and air-sea temperature difference. The EFLUX and HFLUX datasets from the second Modern-Era Retrospective analysis for Research and Applications (MERRA-2) with a spatial resolution of 0.5° × 0.625° have been analyzed to study the characteristics of oceanic heat flux variation associated with the earthquake. The datasets provide reliable quality for monitoring various ocean-atmospheric parameters in open water (Gelaro et al. 2017). The 9-km gap-filled Chl-a data merged from the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership (SNPP) and National Oceanic and Atmospheric Administration (NOAA)-20 have also been analyzed in this study (https://coastwatch.noaa.gov/cw_html/cwViewer.html). This dataset using the Data Interpolating Empirical Orthogonal Functions (DINEOF) method has high data quality with consistent statistical property and accuracy globally (Liu and Wang 2019).

### 3.1.2. Land and atmospheric data

To obtain the possible ocean-atmosphere and land-atmosphere coupling associated with the earthquake, 10-meter specific humidity (QV10M), 10-meter air temperature (T10M), methane (CH$_4$) and LST have been analyzed in the present work. QV10M and T10M data are from MERRA-2. The CH$_4$ data with a spatial resolution of 1.0° × 1.0° from the Atmospheric Infrared Sounder (AIRS) Level 3 daily grided product was used since only the data with the quality flag ‘best quality’ and ‘good quality’ were stored in Level 3 products. The Moderate Resolution Imaging Spectroradiometer (MODIS) LST 8-day 0.05° nighttime data were used in our work. We only analyzed the data with the quality flag ‘good quality’ to ensure the average LST error is less than 1 K. The nighttime data have been considered to minimize the influence of human activities and solar radiation.

### 3.2. Anomaly detection method

The difference between parameter values in earthquake year and background field value which is constructed based on long-term historical data is generally considered as seismic thermal anomalies (Qi et al. 2020). In the present work, a method derived from Robust Satellite Techniques (RST) has been applied to detect anomalies since
Figure 2. SST variations before and after the 2021 Haiti earthquake. (a) V-SST spatial variation during 1 - 25 August 2021. The coloured boxes show the regions with obvious SST anomalies prior to the main earthquake. (b) Location of the four key abnormal regions (named as A, B, C and D) chosen from (a). The base map in (b) is the raw SST on 14 August 2021. The brown lines represent the tectonic plate boundary. The green filled areas show the land surface, and the red star indicates the epicentre of the 2021 Haiti earthquake.
the best performance in discriminating anomalous thermal signals related to seismic activity (Genzano et al. 2021). RST approach is based on the Absolutely Local Index of Change of the Environment (ALICE) proposed by Tramutoli (1998, 2007), and has been successfully applied in the detection of seismic thermal anomalies, volcanic aerosols and dust-clouds (Harris et al. 1995; Pergola et al. 2004). The mean value $\mu_{(x,y,t)}$ and the standard deviation $\sigma_{(x,y,t)}$ of each pixel were computed using the following formulas:

$$\mu_{(x,y,t)} = \frac{\sum_{i=1}^{N} V_R^{(i)}(x, y, t)}{N}$$  \hspace{1cm} (1)

$$\sigma_{(x,y,t)} = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} \left| V_R^{(i)}(x, y, t) - \mu_{(x,y,t)} \right|^2}$$  \hspace{1cm} (2)

Where $V_R^{(i)}(x, y, t)$ is the value of target parameters at longitude $x$ and latitude $y$ on a certain day $t$ in the background years $i$. The data in the years from 2011 to 2020 were selected as background in the present study. The anomaly index is defined as:

$$V_i = \frac{V_{(x,y,t)} - \mu_{(x,y,t)}}{\sigma_{(x,y,t)}}$$  \hspace{1cm} (3)

Where $V_{(x,y,t)}$ is the value of the target parameter in the year of earthquake. Here, $V$-parameter indicates the anomaly index for the different parameters. For example, $V$-SST stands for the anomaly index of SST. In general, the $|V_i| > 2$ was considered as the anomalous signal (Jiao and Shan 2021).

According to the statistical results of the short-term seismic precursors (Fu et al. 2020; Genzano et al. 2021), the temporal window of 61 days (30 days before and after the earthquake) has been considered.

4. Observation results

4.1. Sea temperature

4.1.1. Sea surface temperature (SST)

4.1.1.1. General analysis. The SST anomaly index ($V$-SST) has been computed. The spatial distribution of the daily V-SST covered the Caribbean plate prior to and after the 2021 Haiti earthquake is shown in Figure 2a. The increased V-SST has been observed near the southwest of the Caribbean plate on 2 August 2021 (red box in Figure 2a). Eight days later (10 August 2021), high values of V-SST $>2$ appeared around the epicenter and its western area. Then they decreased to V-SST $<-2$ within one week after the earthquake (black box in Figure 2a). In addition, the high values of V-SST $>2$ were observed in the southeast of the study area during 10–15 August, which were close to the boundary between the Caribbean plate and the South American plate (magenta box in Figure 2a). The values of V-SST $< -2$ have been found along the terrain of Beata Ridge and Aruba Gap during 6–10 August 2021.
After the occurrence of the main earthquake, the values with $V_{\text{SST}} > 2$ moved from the epicentral region to the western Caribbean Plate and disappeared ten days after the main earthquake.

### 4.1.1.2. Regional analysis.

From the $V_{\text{SST}}$ variations prior to and after the 2021 Haiti earthquake, distinct changes in four regions close to the epicenter and the boundary of tectonic plates have been found (see their locations in Figure 2b). Further analysis was carried out in the four key regions.

1. **Region A**

   Region A covering the epicenter is located in the northern part of the Caribbean Plate. The increased $V_{\text{SST}}$ appeared around the epicenter on 8 August 2021 (6 days before the main earthquake) and with a larger scale and higher intensity on 9–11 August 2021. The high $V_{\text{SST}}$ ($V_{\text{SST}} > 2$) disappeared one day prior to the earthquake (Figure 3a). An obvious low $V_{\text{SST}}$ ($V_{\text{SST}} < 2$) has been observed on the post-event days (18–20 August 2021). Furthermore, we have analyzed the time series of $V_{\text{SST}}$ close to the epicentral region 30 days before and after the event (Figure 3b). For comparison, we also computed the $V_{\text{SST}}$ for the years 2011, 2014 and 2017 in which absence of $M > 5.0$ earthquake from July to September. It clearly shows a rise-normal-fall pattern in $V_{\text{SST}}$ variation, i.e. the distinct increase in $V_{\text{SST}}$ prior to the 2021 Haiti earthquake and the decrease after the event (red arrows in Figure 3b).
The maximum difference in V-SST before and after the main earthquake reached 4.5. A similar pattern of SST variation has been observed in the 2020 Northern Red Sea Mw 5.2 earthquake (Mohamed et al. 2022).

2. Region B

Region B is located at the junction of the Caribbean Plate and the North Andes Plate and covers a large area of Beata Ridge and Aruba Gap (see their locations in Figure 1). The south part of Region B covers the subduction border between the Caribbean Plate and the North Andes Plate. We observed the negative V-SST values within one week prior to the earthquake and a nearly symmetrical pattern of negative and positive V-SST on 10–14 August 2021 (Figure 4a). A sudden increase in V-SST occurred 2–3 days after the main event. The time series clearly shows the significant change, the maximum difference in V-SST before and after the main earthquake reached 5.9, which is totally different from the changes in the same period for those unperturbed years (Figure 4b).

3. Regions C and D

Regions C and D are located on the west and east sides of the subduction boundary of the Caribbean Plate respectively. Region C is close to the junction of the Caribbean, Panama and the North Andes Plates. Region D is on the junction of the Caribbean and the South American Plates. In Region C, the high values of V-SST >3
were observed on 2–3 August 2021 and distributed along the boundary of the tectonic plate (Figure 5a), which shows the most remarkable changes prior to the 2021 Haiti earthquake (Figure 5b). In Region D, a significant increase in SST (V-SST > 2) occurred on 10 August 2021 (4 days prior to the main earthquake event) and showed a downward trend with the arrival of the earthquake (Figure 6a), which can also be clearly seen from Figure 6b. Region D is affected by both the Caribbean Current and the North Brazil Current, where the largest amount of freshwater flows into the Caribbean during August to December that causes the increasing SST (Field 2005; Chérubin and Richardson 2007). Nevertheless, the transient spatiotemporal continuity of increasing V-SST prior to the 2021 Haiti earthquake (Figure 6a) and the unique behavior by contrast with the same period in the non-seismic years (Figure 6b) have appeared between the Caribbean Plate and the South American Plate during the final stage of earthquake preparation.

4.1.2. Sea potential temperature (SPT)

Besides the analysis of SST, the SPT data in various depths for the four regions were analyzed to better understand the vertical variation of sea temperature. The area-averaged SPT in the four interested areas (circles in Figures 3–6) have been considered for analysis.

The vertical distribution of SPT in Region A before and after the 2021 Haiti earthquake is shown in Figure 7a. The increasing SPT was observed at the depths of 0 – 10 m
since 8 August 2021, which corresponds to the significantly increased SST ($V\text{-SST} > 2$) during the same period (Figure 3a). According to the SPT variation, we can clearly see the increased SST does not come from deep water. Three upwellings were observed at the depths of 0–20 m which disturbed the balance of constant increasing temperature in shallow water on 10–25 August 2021 (white arrows in Figure 7a).

In Region B, an obvious upwelling was observed on 7–10 August (white arrow in Figure 7b). The upwelling system has been observed frequently in this region (Andrade and Barton 2005). The seasonal intensification of the Caribbean Current leads to enhanced upwelling. During the season of strong upwelling (June - August), the SSTs are always cooler than the other areas (Rueda-Roa et al. 2018). The SPT variation in this region clearly shows the significant decrease in SST ($V\text{-SST} < -2$) that have been observed before the earthquake event (Figure 4) was caused by the seasonal upwelling. After the event, the SPT rose immediately at the depths of 0 – 50 m.

Different from Region B, the upwelling in Region C appeared earlier and its intensity was weaker (white arrow in Figure 7c). In Region D, an obvious uplift was observed at the depth of 30–60 m on 10–15 August 2021 (white arrow in Figure 7d).

It should be noted that the results of SPT in shallow water in the four regions of interest are consistent with the aforementioned SST analysis, which is strong evidence to support the SST results in section 4.1.1.
4.1.3. Comparison with the 2010 Haiti Mw 7.0 earthquake

Besides the present case, another strong earthquake (Mw = 7.0) occurred in this region on 12 January 2010. Different from the 2021 event triggered by a left-lateral strike-slip fault, the 2010 event was controlled by a blind thrust fault (source: USGS). Obvious changes in OLR, SLHF, surface air temperature (SAT), relative humidity (RH) and ionospheric total electron content (TEC) associated with this event have been observed around the epicentral region from satellite data (Singh, Mehdi, et al. 2010; Xiong et al. 2010; Saqib et al. 2022) that showing the strong coupling between ocean/land and atmosphere.

For this case, we only analyzed the SST data due to the SPT data being unavailable. Compared with the 2021 Haiti earthquake, the different SST behavior in Region A (blue box in Figure 8a) and a similar pattern in Region B (red box in Figure 8a) have been observed. In Region A, an obvious decrease in SST (V-SST < 2) appeared one day prior to the 2010 earthquake (Figure 8b), which was different from the increased SST preceding the 2021 earthquake (Figure 3a). In Region B, similar to the 2021 event (Figure 4a), a nearly symmetrical spatial distribution of positive and negative V-SST values was observed (Figure 8c). Our analysis of the two major earthquakes in Haiti indicated the anomalous SST occurred not only in the epicentral region but also at the tectonic plate boundary. No obvious anomaly was found in Regions C and D.

4.2. Other oceanic, land and atmospheric parameters variations

4.2.1. Sea water salinity (SWS) and chlorophyll a (chl-a)

To further confirm the relationship between the changed SST in the four regions and the 2021 Haiti earthquake, SWS and Chl-a have been considered to explore the
response of oceanic parameters to the strong earthquake activity. The SWS shows obvious synchronous changes with SPT in all regions (Figure 9). Moreover, a distinct enhancement in Chl-a near the epicenter has been observed during 8\textendash18 August 2021 (Figure 10). The increased Chl-a has been observed in other coastal earthquakes (Singh et al. 2002, 2006, 2019; Tang et al. 2009). Our results show the salinity and Chl-a concentration at the sea surface (Figures 9 and 10) increased around the 2021 Haiti earthquake.
4.2.2. Land surface temperature (LST)
Furthermore, we analyzed the epicentral LST variation before and after the 2021 Haiti earthquake using MODIS 8-day LST night data (Figure 11). The enhanced LST (V-LST > 1) along the EPGF zone has been observed in late July. Especially on those days close to the earthquake (13–20 August 2021), the increased LST covered the main fault that reflects the stress buildup and tectonic activity associated with the earthquake. We also noted the increased LST in mid-September, but it is hard to relate it to the earthquake due to the large area distribution rather than depending on the distribution of geological structures.

4.2.3. Atmospheric parameters
Detailed analysis of EFLUX, HFLUX, QV10M and T10M data have been carried out. EFLUX and HFLUX both show the heat exchanges between the surface and the atmosphere. QV10M shows the ratio of the mass of water vapor to the total mass of air. The anomaly index for every parameter is computed using the method described in section 3.2. The characteristic variations for each parameter are shown in Figure 12. When the ocean is warmer than the atmosphere, energy is transferred from the ocean surface to the atmosphere, which caused an increase in EFLUX and HFLUX (V-EFULX > 0, V-HFLUX > 0). In Region A, one can see a simultaneous change of V-EFLUX > 2, V-HFLUX > 2, V-QV10M > 2 and V-T10M<1 around the epicenter on 12 August 2021 (2 days prior to the main earthquake). In Region B, the quasi-symmetric spatial distributions of positive (V-i > 1) and negative (V-i < 1) values of V-EFLUX, V-EHFLUX and V-T10M have been observed on 9 August 2021 (Figure 12), which is similar to the nearly symmetrical pattern of V-SST (Figure 4a). Regions C and D also show some slight changes. The changes in the four parameters do not occur on the same day, which is relate to the time delay of heat transfer and depends on the environmental factors.
The temporal variation of V-CH₄ in the epicentral region (1°×1°) shows two peaks (V-CH₄>3) on 5 and 9 August 2021 (Figure 13). No changes were observed in other unperturbed years (2011, 2014, 2017). It is hard to comment whether the anomalous signals of CH₄ come from land or ocean due to the mixed pixel caused by low spatial resolution (1°×1°), although the evidence of gas emission from sea/lake water and land preceding earthquakes due to the tectonic stress changes has been reported (Sugisaki et al. 1980; Hasiotis et al. 1996; Ding et al. 2021).

5. Discussion

5.1. Possible mechanism of sea temperature variation

A rise-normal-fall pattern in V-SST has been observed in Region A (Figure 3b). The increased SST prior to the earthquake may be caused by the release of thermal energy due to the changes in thermodynamic processes within the epicentral region.
Subsequently, the decreased SST was observed after the earthquake since the cooler water was uplifted to the sea surface by upwelling. Combined with the SPT vertical distribution in Region A, we considered that the sudden upwelling in the epicentral region could be attributed to ocean waves and coastal surf due to the intense ground shaking (Singh et al. 2002). The upwellings in the epicentral region before and after the 2021 Haiti earthquake could be triggered by the main earthquake and the moderate aftershocks (M ≥ 5.0). The initial structure of sea water would be disturbed due to ground shaking (Levin et al. 2006) and upwellings. However, prior to the 2010 Haiti earthquake, only a short-lived negative V-SST in the same region was observed (Figure 8b). The differences could be related to the different focal mechanisms for the two strong earthquakes.

The V-SST shows a fall-normal-rise pattern in Region B (Figure 4b), which is opposite to Region A. The SPT observation further confirms the existence of this pattern.
phenomenon (Figure 7b). Region B is located at the junction of the Caribbean Plate and the North Andes Plate, it provides the favorable tectonic condition (active tectonic activity and energy accumulation) for energy release from the Earth’s crust to the surface, that leads to the increased SST during the stage of earthquake preparation (Qiang et al. 1997; Wu et al. 2000; Ouzounov and Freund 2004; Chakravarty 2009; Wu et al. 2012; Mohamed et al. 2022). We have also observed frequent mid-year upwelling in Region B located in the Southern Caribbean Sea (Rueda-Roa et al. 2018), this could be the main reason for the contrasting SST behaviors in Regions A and B before and after the earthquake. Furthermore, the strong upwelling may mask the increasing SST in this region prior to the earthquake since the cooler sea water is lifted to the sea surface. It is worth noting that the negative V-SST of the 2010 Haiti earthquake in Region B is also attributed to the frequent upwelling in this region instead of the impact of earthquake activities (Figure 8c).

Distinct SST variations were observed in the two regions at the junction of tectonic plates (Regions C and D). The remarkable increase of SST (V-SST > 2) observed in the boundary of the Panama Plate and the Caribbean Plate (Figure 5a) is related to the accelerated movement of the adjacent tectonic plates prior to the strong earthquake. An obvious disturbance in SPT, which is associated with water temperature structure, has been shown in Figure 7c. A landward-dipping ocean crust beneath the North Panama fold belt (Kellogg et al. 1991) makes the northern Panama Plates more vulnerable to seismic activities due to the subduction between the adjacent tectonic plates (Lizarazo et al. 2021).

For Region D, the changes in SST and SPT prior to the strong earthquake (Figures 6b and 7d) should be attributed to the released energy in the Lesser Antilles Subduction zone where the South American Plate underneath the overlying Caribbean Plate may cause the abrupt variation of thermal structure in the subsurface (van Rijsingen et al. 2021).

Figure 14. A conceptual model of ocean/land-atmosphere coupling for the 2021 Haiti earthquake.
5.2 A Conceptual multi-parametric coupling model for the 2021 Haiti earthquake

Recently, Okuwaki and Fan (2022) based on the analysis of integrated seismological data, found that a blind thrust fault first broke down near the epicenter which jumped to a disconnected strike-slip fault (R1 and R2) (Figure 14) on the EPGF zone during 2021 Haiti earthquake. On this basis, combined with multi-parametric changes observed in the present work, the conceptual model of ocean/land-atmosphere coupling for the 2021 Haiti earthquake was proposed (Figure 14).

During the final stage of earthquake preparation, crustal stress builds up in the epicentral region (phase ① in Figure 14). The geophysical and geochemical processes (e.g. changes in surface/air temperature, underground water/gas) occur under this circumstance (Wu et al. 2012). The extension of cracks and enhanced stress caused by tectonic movement are conducive to gas emission from the Earth’s crust (Qiang et al. 1991). In the present study, we observed the distinct enhancement in CH₄ within 10 days prior to the 2021 Haiti earthquake (Figure 13). The release of carbonaceous gas from the friction of faults causes the local greenhouse effect around the epicentral region (phase ②). Combined with latent heat release stimulated by radon decaying and/or the activation of P-holes (Freund 2002, 2003; Pulinets et al. 2006), increased LST has been observed during this period (Figure 11). Such a warming pattern is spatially consistent with the distribution of thrust fault in the first phase of the 2021 Haiti earthquake as described in the reference (Okuwaki and Fan 2022), which also cause a slight SST warming near the epicenter and along the shoreline 6 days prior to the mainshock (phase ③ and phase ④). The sudden increase in SST prior to the event could also be attributed to the buildup of stress in the focal regime of the earthquake (Singh et al. 2006) and the changes in thermodynamic processes around the epicenter (Mohamed et al. 2022).

Many studies have discovered that SST fluctuates prior to strong coastal earthquakes due to the processing of mixing and upwelling (Choudhury et al. 2006; Singh et al. 2006, 2019). In the present study, a significant drop in SST due to upwelling caused by the intense ground shaking near the epicenter was observed. In the study area, the decreasing SPT was usually accompanied by increasing SWT in different layers (Figure 7 and Figure 9). The upwelling caused by the accelerated tectonic plate subduction brought the quasi-synchronous variations in SPT, SWS and Chl-a prior to the impending earthquake (phase ⑥). Additionally, the increasing SST and the intense ground-shaking lead to upwelling which brings cool water, salinity and nutrition to the upper ocean (Singh et al. 2002, 2006, 2019; Tang et al. 2009). The vertical variations of SST and SPT indicated the vertical structure of sea water was disturbed during the final stage of earthquake preparation. The flowing seawater shows upwelling when it is close to the coastal area. The sea water with lower temperatures and high salinity upwelling in the shallow water will lead to a decline in SST and an enhancement in Chl-a concentration.

The SST variation affects the air temperature and other atmospheric parameters (latent energy flux, sensible heat flux, and specific humidity). The water phase will change through the evaporation process when energy is transferred from the sea surface to the atmosphere (Wu et al. 2012; Ghosh et al. 2021). The process of
evaporation changes the latent heat flux and sensible heat flux, which was accompanied by the increasing specific humidity (phase 5). It is widely known that the wind field plays a major role in coastal upwelling and SST changes (Capet et al. 2004; Kim et al. 2014). According to the information of historical hurricane tracks from NOAA (https://coast.noaa.gov/hurricanes/#map=4/32/-80), no hurricane occurred during the period that showed the changes in SST. The anomalous SLHF variations prior to strong earthquakes, especially coastal earthquakes have been observed by many researchers (Dey and Singh 2003; Pulinets et al. 2006; Ghosh et al. 2021). In the present study, both EFLUX and HFLUX increased near the epicentral region during the period of rising SST. These anomalous signals disappeared two weeks after the 2021 Haiti earthquake. The anomalous signals within 2-week after the main event should be associated with the four moderate aftershocks (M ≥ 5) during this period due to the consistent spatiotemporal distribution. We also noted that the anomalous signals during this period are spatially close to the second rupture proposed by Okuwaki and Fan (2022). The analysis of the specific humidity and air temperature further discovered the process of ocean-atmospheric interaction associated with the impending earthquake.

6. Conclusion

In the present study, the sea temperature (sea surface temperature and sea potential temperature) changes associated with the 2021 Haiti earthquake which occurred in a coastal region have been analyzed in detail. For the first time, up to 10 parameters from ocean, land and atmosphere have been analyzed to better understand the possible physical mechanism for the unusual sea temperature changes preceding the coastal earthquake. The quasi-synchronous changes in different geospheres prior to the 2021 Haiti earthquake indicate the existence of strong coupling between ocean/land and atmosphere during the final stage of earthquake preparation. The comparative analysis with another Haiti major earthquake in 2010 indicates the differential distribution pattern of abnormal signals in space and time due to the different focal mechanisms. Our results clearly show the strong coupling between the hydrosphere/lithosphere and the atmosphere associated with coastal earthquakes, which is an essential part of the LAIC model. Comprehensive analysis of multi-parametric anomalies is crucial to understand the mechanism related to the pre-seismic anomalous signals. The conceptual model we proposed here provides a reference for future research on coastal/ocean earthquakes in other regions although the complexity and diversity of tectonic activity from place to place. Additionally, for specific regions, climate patterns and ocean current changes must be considered when analyzing the abnormal SST signals associated with earthquake activities.

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No potential conflict of interest was reported by the authors.

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**Data availability statement (DAS)**

The data that support the findings of this study are available from the author Lu Zhang upon reasonable request.

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