INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **36**: 3770–3780 (2016)
Published online 29 December 2015 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.4591

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Impacts of and adaptation to inter-decadal marine climate change in coastal China seas

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ABSTRACT: The coastal China areas stretching from tropical to temperate zone represent major environmental and economic assets. However, knowledge of climate change and its impact in coastal seas, which is very critical for marine resource and risk-management issues, is relatively poor compared with that on land. Here, we show that the coastal China seas experienced a long-term surface warming with a rate of 0.015 °C year^{-1} and an obvious sea level rise along the coast, particularly along the East China Sea with a rate of more than 3.2 mm year^{-1} since the late 1950s. The Eurasian atmospheric circulation underwent clearly inter-decadal changes in the past decades due to the tropical ocean thermal changes including warming hiatus and conversely influenced the higher latitude coastal marine conditions through regional air–sea interaction. Marine climate variables including sea surface temperature, sea surface height, and atmospheric cyclonic circulation have formed a favourable condition for phytoplankton blooms such as harmful algae blooms (e.g. red tides) and *Enteromorpha prolifera* blooms (green tides). These algae blooms could strongly lower oxygen levels in the seawater and have been posing threats for the health of coastal and marine ecosystems since the late 1970s. The impacts and key risks of climate change risks in coastal China seas and the coastal zone are reviewed and analysed as follows: frequent occurrences of red tides and green tides, distribution shifts of marine species and changes in their seasonal behaviour, reduction of coastal habitat, decline of marine ecosystem services, flooding and coastal inundation, seawater intrusion, and threats to coastland community security and marine industries, etc. Furthermore, the accumulated effects of human activity, such as reclamation, sewage discharge, and overfishing, have led to an apparent increase in climate-related vulnerabilities. Adaptation issues and risk-management strategies in response to climate change are discussed and proposed as well.

KEY WORDS coastal China seas; sea surface temperature; sea surface height; atmospheric circulation anomalies; inter-decadal changes; key risk; adaptation

Received 11 August 2015; Revised 1 November 2015; Accepted 7 November 2015

1. Introduction

The ocean covers 71% of the earth's surface. It plays an important role in human welfare, providing food, resources, transportation, and other benefits. In the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the chapter of the ocean reported that coastal seas are highly productive areas, comprising 10.6% of ocean primary production and global fisheries production; marine ecosystems within the coastal boundary systems, including coastal China seas and adjacent seas, are sensitive to increasing sea temperatures, and the productivity of coastal ocean water is likely to have been changed. These changes are very likely to increase the vulnerability of coastal community through the coastal boundary systems (Hoegh-Guldberg *et al.*, 2014). Coastal China seas and adjacent waters (hereafter referred to as coastal China seas; Figure 1) are the marginal seas of the northwest Pacific, encompassing the Bohai Sea, Yellow Sea, East China Sea (ECS), and South China Sea (SCS), which are greatly influenced by climate change through the East Asian monsoon, the Kuroshio Current, run-off from major rivers, and other features and phenomena (Cai, 2010; Cai *et al.*, 2011a). More than 42% of China's population dwells in its coastal zone, which accounts for only about 14% of China's total land area but produces more than 60% of China's gross domestic product [Chinese Academy of Sciences (CAS), 2014a]. The AR5 assessed the impacts of climate change on coastal China seas and indicated that primary productivity, biomass yields, and fish capture rates in coastal China seas have experienced large changes over the past decades, posing ecosystem and fisheries at risk (Hoegh-Guldberg *et al.*, 2014). However, the impacts of climate change, combined with non-climate-related human activities on coastal China seas, had not been fully analysed and discussed in AR5

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due to limitation of the report's space. For example, the spatial pattern of the sea surface temperature (SST) and sea surface height (SSH) with the increased amplitudes are poorly known; moreover, the impacts of marine climate change combined with local human interference activities, such as large-reclamation, land-source sewage discharge, and overfishing on the health of coastal and marine ecosystem on inter-decadal timescales need further exploration. Therefore, more focused discussion on the knowledge and data gaps of climate effect on coastal China seas is needed, and more appropriated adaptation measures to marine climate change need to be proposed for coastal China seas and coastal zone.

In this study, marine climate change dynamics and effects, together with some non-climate-related human activities such as reclamation, sewage discharge, and overfishing in coastal China seas and adjacent coastal areas are therefore analysed and reviewed. It is undoubtedly that the global average SST and sea level rise rate have significantly increased since 1950s due to the enhanced greenhouse gas effects (AR5, IPCC). We hence firstly used the latest high resolution oceanic and atmospheric reanalysis data sets and linear fitting method to investigate the variations in SST and SSH within coastal China seas and analysed the related Eurasian atmospheric circulation anomalies in terms of the global ocean SST changes, particularly recent warming hiatus, then simply compared the concentration changes of chlorophyll-a in coastal China seas using satellite remote sensing data sets. We next review and summarize the impacts of climate change on marine ecosystems, coastal zone and associated risks using the related assessment reports, government bulletins, and previous studies as well. Primary non-climate-related human activities and their effects in the coastal zone are also discussed. Finally, a number of adaptation issues and strategies in the coastal areas in respond to climate change are assessed and summarized from a risk-management perspective.

2. Study area and data

2.1. Coastal China seas and its coastal zone

The study areas in this study are coastal China seas and its coastal zone. Coastal China seas (Figure 1) is located at the south-eastern part of Asian continent and the western edge of the North Pacific Ocean, ranging from tropical to temperate, covering 4.73×10^6 km^2 with larger scale shallow continental shelf, many wide estuaries, and bays and reefs, and a length of about 1.8×10^4 km coast line along mainland China (Feng *et al.*, 1999). Coastal China seas and coastal area are suitable for a variety of marine organisms and form many commercial fisheries areas. Coastal China seas and coastal area are therefore of great significance for the sustainable development of society and economy in coastal China. In this study, coastal China seas and its adjacent waters and coastal zone are considered and analysed.

2.2. Data

In this study, the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) with a horizontal resolution of $1° \times 1°$(Rayner *et al.*, 2003), the simple ocean data assimilation (SODA) with a horizontal resolution of $0.5° \times 0.5°$ (Carton and Giese, 2008), and the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis products with a horizontal resolution of $2.5° \times 2.5°$(Kalnay *et al.*, 1996) were used to analyse the SST and SSH changes in coastal China seas, and Eurasian atmospheric circulation anomalies over the Northern Hemisphere during the period of 1958–2014, respectively. The climatological mean of monthly atmospheric circulation and SST for 1971–2000 are taken as the norm. The averaged concentrations of chlorophyll-a as a proxy for marine productivity in coastal China seas over the period of 1979–1999 and 2000–2014 (due to insufficient record for 1977–1978 and 1985–1997) were investigated using satellite remote sensing data sets of the Coastal Zone Color Scanner Experiment (CZSZ) and Sea-viewing Wide Field-of-view Sensor (SeaWiFs) National Aeronautics and Space Administration (NASA), with a horizontal resolution 9 km × 9 km.

3. Methods

The empirical orthogonal function (EOF) analysis method was performed to analyse the changes of SST of coastal China seas in this study. The EOF method has been widely used to enable analysis of data with spatial and temporal structures, which are decomposed into representative modes. The first few modes of EOF can keep significant portion of the total variance and can be ordered according to the percentage of total variance. Moreover, the modes are statistically uncorrelated with one another, and thus each isolated mode includes phenomena with differing spatial and temporal scales. We first carry out an EOF analysis on sea surface temperature anomaly (SSTA) of coastal China seas to identify modes of variability pattern in the period of 1958–2014. Secondly, the spatial pattern of linear SST and SSH changes in coastal China seas during the period of 1958–2014 and 1958–2008 were analysed using the linear fitting method, respectively. For a variable Y, its linear trend k can be obtained by linear fitting of the time series of Y_i, $Y_i = Y_0 + kX_i + \varepsilon_i$, where k is the linear variation trend of the variable Y, X_i is the time corresponding to the Y_i value in yearly records for the 1958–2014 period, and ε_i is the error term introduced to estimate the uncertainty of the fit. Then, the linear changes ΔY with time periods can be obtained using $\Delta Y = k(X_i - X_0)$. Meanwhile, according to the inter-decadal variations of global ocean SST changes, especially the ocean and coastal China seas warming hiatus, we extract and compare the clear three atmospheric circulation anomaly patterns in the periods of 1966–1976, 1977–1999, and 2000–2014, respectively, and further discuss the relations among the changes of atmospheric circulation, the average of chlorophyll-a concentrations, phytoplankton blooms, and harmful algae blooms (HABs).

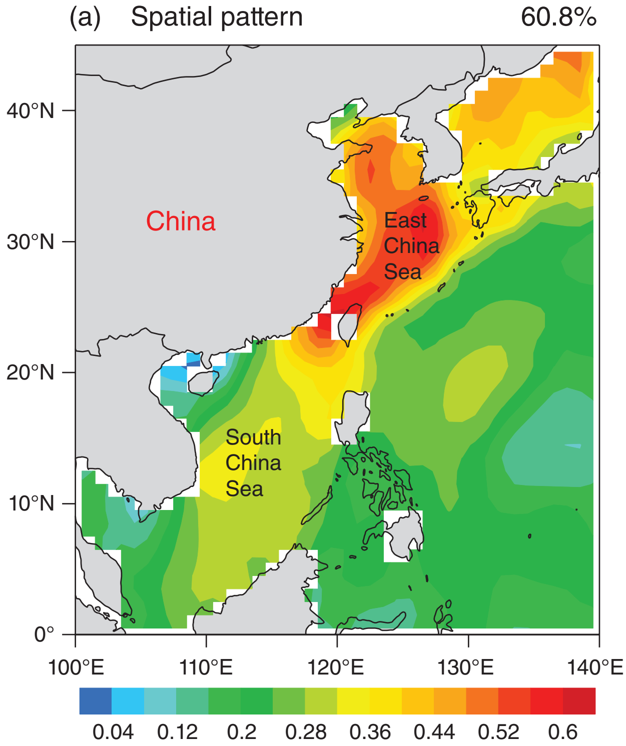

Figure 1. Study area. Sketch map of eastern China, coastal China seas, and adjacent seas; Spatial pattern (a) and time coefficient (b) of the leading EOF mode that explains 60.8% of variance for annual mean SSTA in coastal China seas for the period of 1958–2014. Data are from the HadISST.

Other data such as frequency of HABs and the reclamation area were obtained from the available literature (Zhang *et al.*, 2005; Chinese State Oceanic Administration (CSOA), 2000–2014; Zhao 2010; Chinese Academy of Sciences (CAS), 2014a, 2014b). Furthermore, based on the Second National Chinese Assessment Report on Climate Change, 2000–2014 Chinese Marine Environment Situation Bulletin, 2014 Chinese Sea Level Bulletin, 2014 Chinese Sea Disaster Bulletin, and the other available literatures, we review, analyse, and summarize the impacts and key risks of climate change on coastal China area, too.

In addition, the Bohai Sea, Yellow Sea, and ECS hereafter are simply referred to as the ECS due to all of them locating in the east of mainland China. The average monthly sea level of coastal China seas for 1975–1993 is taken as the norm, which is defined in the 2014 Chinese Sea Level Bulletin. The boreal summer as discussed in this article refers to June, July, and August (JJA).

4. Results and discussion

4.1. Impacts of climate change on coastal China seas

With global warming, SST of the Pacific Ocean has increased by 0.31 °C during the period of 1950–2009 (Hoegh-Guldberg *et al.*, 2014). The spatial–temporal characteristics of SST in coastal China seas were investigated and shown (Figure 1) through an EOF analysis using annual mean HadISST. The first EOF mode explains about 60.8% of the SST variability in coastal China seas for the period of 1958–2014. The EOF1 result indicates that SST in coastal China seas presented a clear warming trend, with the most significant warming in the ECS region. The long-term changes of SST in coastal China seas in the periods of 1958–2014 are analysed using the linear fitting method. The results indicated that the SST in coastal China seas has increased by 0.83[0.81–0.85]°C at 95% confidence interval in the period of 1958–2014 with a rate of 0.015 °C $year^{-1}$, particularly in the ECS with a long-term rise rate of about 0.021–0.038 °C $year^{-1}$ (Figure 2), and similar seawater warming in Korea waters and Japan Sea was measured using observation data (Tian *et al.*, 2012; Jung *et al.*, 2013). The largest SST increasing rate region spends from the vicinity of Changjiang Estuary in the ECS to the south of Taiwan Strait with the rate ranks of 0.021–0.037 °C $year^{-1}$. The changes of SSH along coastal China seas in the periods of 1958–2008 are also analysed using the linear fitting method. The results indicated that the mean banding area linear trend of the SSH along coastal China seas (colour shaded in Figure 3) has obviously increased by 2.39[2.28–2.50] cm at 95% confidence interval in the period of 1958–2008, especially along the ECS with a long-term rise rate of more than 3.2 mm $year^{-1}$.

Note that since the year 2000, SST of coastal China seas has not increased as rapidly as in the 1980s and 1990s, indicating a slowdown of warming trend consistent with the recent global-warming hiatus (Kerr, 2009; Met Office, 2013). As is our understanding, inter-decadal climate shifts of SST in central and eastern tropical Pacific also occurred around the mid- to late 1970s and the late 1990s (Huang *et al.*, 2006; Kosaka and Xie, 2013),

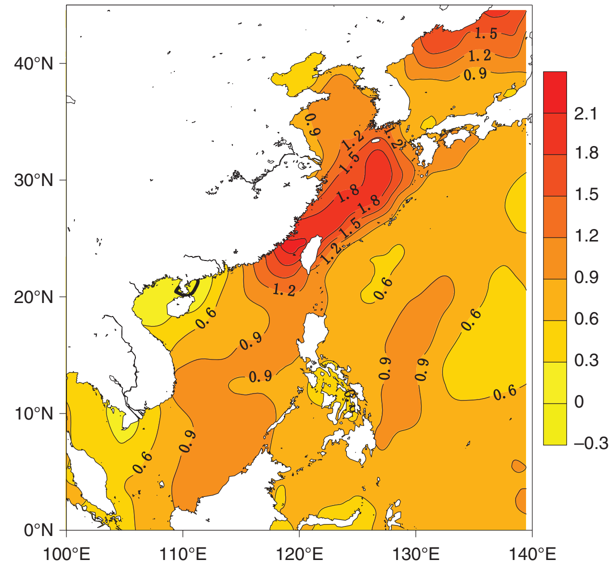

Figure 2. Spatial pattern of linear SST changes in the coastal China sea during the period of 1958–2008; the contour interval is 0.3 °C. The uncertainty range of linear trend for SST is ±0.02 °C, i.e. from 0.81 to 0.85 °C at 95% confidence. Data are from the HadISST reanalysis data sets.

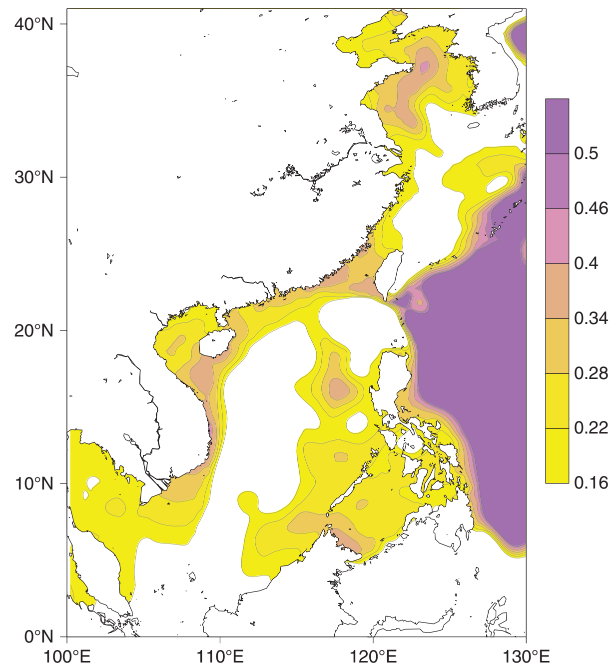

Figure 3. Spatial pattern of linear SSH changes along the coastal China sea during the period of 1958–2008; the banding areas with changes more than 0.16 m but less than 0.5 m are shaded. The uncertainty range of linear trend for SSH along the coastal China sea is ±0.11 cm, i.e. from 2.28 to 2.50 cm at 95% confidence. Data are from the SODA reanalysis data sets.

resulting in modulation of atmospheric circulation over the Northern Hemisphere, especially over the Eurasian continent and coastal China seas. Previous study also indicated that global climate had experienced a significant climatic jump around 1976/1977 with a large-scale atmospheric circulation modulation in the North Hemisphere (Miller *et al.*, 1994). Therefore, we then further investigate atmospheric circulation anomalies over the Northern Hemisphere in the period of 1966–2014 using NCEP/NCAR reanalysis data sets. The result (Figure 4) reveals the modulation of large-scale Eurasian atmospheric circulation in the North Hemisphere during 1966–2014, the lower atmospheric circulation over coastal China seas changed from anti-cyclonic circulation anomaly before 1976 to cyclonic circulation anomaly after 1977 (Figure 4(a) and (b)). In addition, despite the warming hiatus, since 2000, eastern mainland China and coastal China seas have still been mainly dominated by the atmospheric anomalous cyclone circulation in summer [Figure 4(c), indicated in blue clockwise arrow], as in the period of 1977–2002 (Cai and Tan, 2010). Moreover, the atmospheric cyclonic circulation anomaly over eastern China and coastal China seas has clearly been enhanced, with a slightly southward movement, which was closely linked to the atmospheric circulation anomaly distributions of Eurasian, East Asia–Pacific, and East Asia–Indian ocean pattern teleconnections [Figure 4(b) and (c), indicated in arrows and their sizes]. Previous studies have reported that the atmospheric cyclonic circulation anomaly prevailing over the ECS and its adjacent waters (ECS) after the late 1970s provided favourable climatic conditions for outbreak of red tides (HABs) through regional air–sea interaction and the strengthening of coastal upwelling with associated large amounts of nutrient influx and dormant algae cysts in the seabed sediments to upper ocean water (Figure 5) (Cai 2010; Zhang and Cai, 2013).

To investigate changes in marine primary productivity in the ECS under the background of atmospheric circulation anomalies over the ECS, the mean concentrations of chlorophyll-a signal as a proxy for marine productivity during the two periods of 1979–1999 and 2000–2010 were analysed using satellite remote sensing data (Figure 5(a) and (b)). Results indicate that the mean concentration of the chlorophyll-a in the ECS during the period of 2000–2010 was larger than that in the period of 1979–1999: from 1979 to 2010 chlorophyll-a mean concentration increased from 0.95 to 1.28 mg m^{-3} in the ECS (22°–41°N, 117°–130°E). Because the chlorophyll-a signal is considered as a reliable indicator for marine phytoplankton and biomass (Henson *et al.*, 2010), the analysed averaged concentrations of the chlorophyll-a can be linked to marine production. The results also suggest that the climate anomalies and marine conditions in the ECS were favourable for the phytoplankton blooms and HABs occurrence which could strongly lower oxygen levels in the seawater (Cai *et al.*, 2011b) and the coastal and marine ecosystem would be more endangered with the spreading of coastal hypoxic zone (Melnzer *et al.*, 2013) during these two periods, which is consistent with Cai and Tan (2010) hypothesis. The hypothesis (Cai and Tan, 2010) suggests that stronger convergence and cyclonic vorticity in the lower atmosphere favour stronger upwelling in the ocean as confirmed by Zhang and Cai (2013) using numerical experiment, which in turn helps to transport the

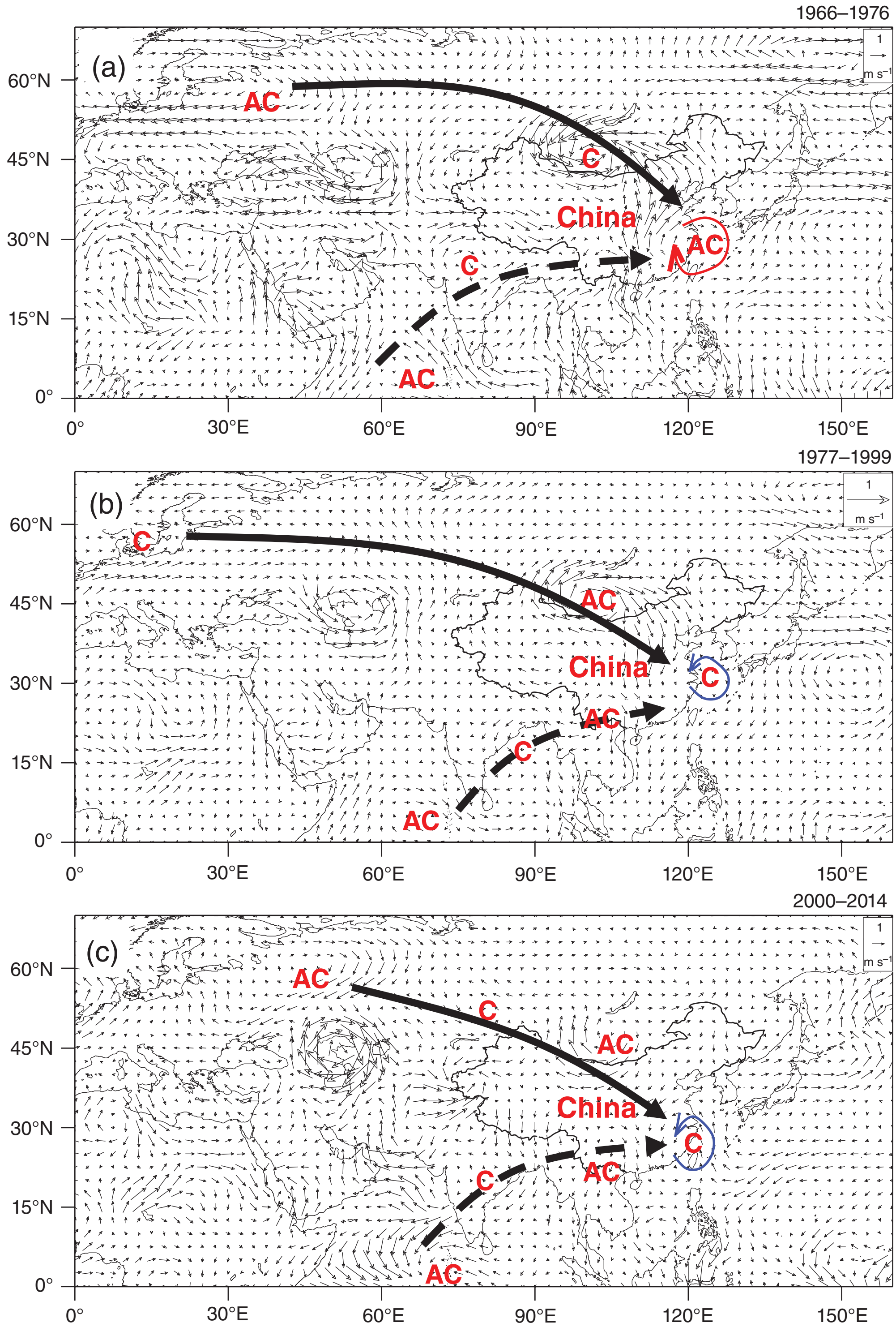

Figure 4. Inter-decadal variations of summer (June to August) circulation anomalies at 925 hPa over East Asia: (a) 1966–1976; (b) 1977–1999; and (c) 2000–2014. 'AC' and 'C' refer to 'anti-cyclone' and 'cyclone' anomalies, respectively. The climatological mean of monthly circulation for 1971–2000 is taken as the norm. Data are from the NCEP reanalysis data sets.

deposited nutrients and dormant algae cysts in the coastal surface sediments to sea surface layer and contributes to the occurrence of HABs (Figure 6). Furthermore, seawater warming in the ECS advanced the zooplankton community alternation in late spring and early summer, and the structure of zooplankton community would be greatly affected due to the increase in the seawater temperature. This is because warm water would generally be favourable for the reproduction of warm zooplankton species but not for the reproduction of warm-temperate species, especially for temperate marine zone such as the ECS. Particularly, seawater temperature would affect the zooplankton much greater than phytoplankton. With the seawater warming in late spring and early summer, the

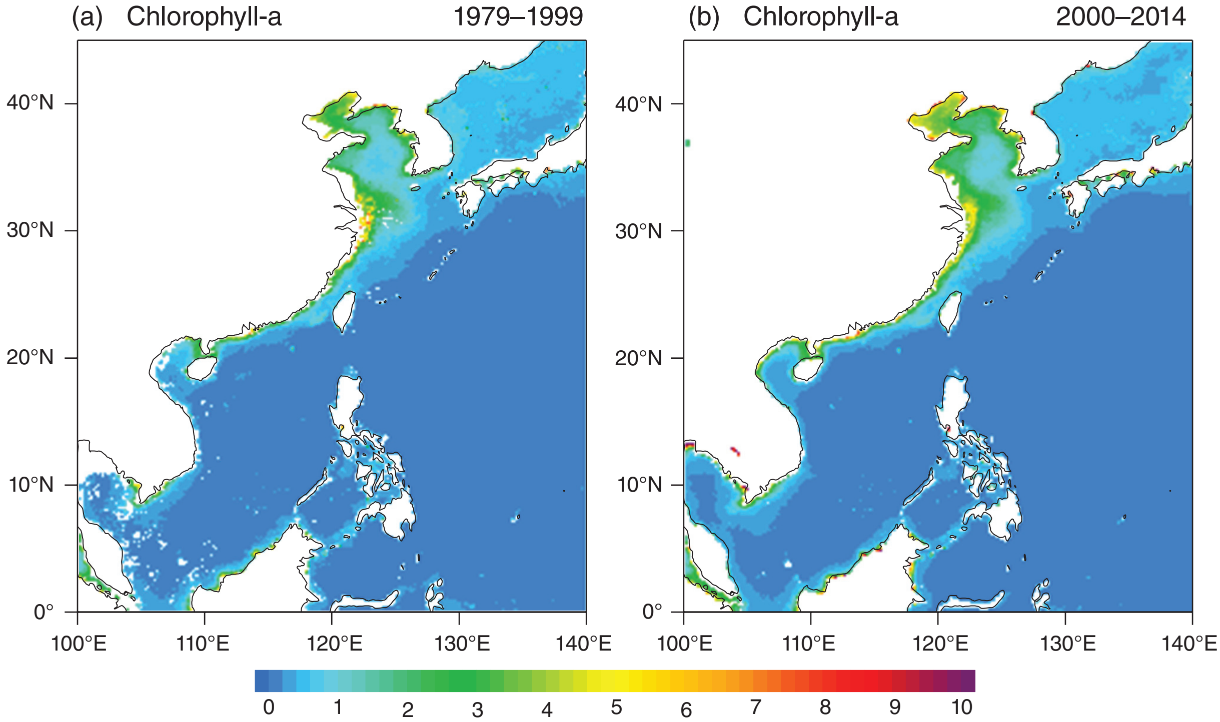

Figure 5. Mean concentrations of chlorophyll-a signal as a proxy for marine productivity in coastal China seas over the period from 1 April to 30 September (a) 1979–1999 and (b) 2000–2014. Satellite remote sensing data sets of CZSZ used in (a) and SeaWiFs used in (b) are from NASA data sets.

abundance of warm-temperate species in the ECS would greatly decrease and could not be fully offset by increased abundance of the warm-water species in the same period, reducing hence grazing pressure on phytoplankton and losing the balance between the phytoplankton and zooplankton. Then, the phytoplankton blooms and the frequent HABs would form and appear (Cai 2010). In Figure 7, it is observed that the outbreak frequencies of red tides in the ECS during the period of 1960–2014 were statistically counted using the data taken from the literature (Zhao 2010; Chinese State Oceanic Administration (CSOA), 2000–2014). The statistical results indicate that the occurrences of HABs have shown decadal variations since the late 1970s (Figure 7). Especially, the frequency of HABs in the ECS has two peaks around 1977–1999 and 2000–2014, respectively. The results also show that the occurrence of HABs in the ECS after 2000 was more frequent than that in the period of 1977–1999. It is therefore suggested that the enhanced atmospheric cyclonic anomaly since 2000 and ocean warming could increase the probability of marine ecological hazards such as frequent HABs and related effects on marine ecosystem health and food security in coastal China seas.

4.2. Review on climate change impacts and key risks in coastal China seas and coastal zone

The inter-decadal robust surface warming and sea level rise along coastal China seas since the late 1950s have been observed and analysed in Section 4.1. (Figures 1–3); the analysed results reveal that the coastal China seas have been greatly impacted by climate change. A number of climate-related key issues over coastal China seas have also emerged in previous studies over the past recent years (Cai and Tan, 2010; Cai 2010; China-SNAP, 2011). However, the impacts of climate change combined with the local human interference activities on coastal China seas have not been sufficiently explored. Therefore, based on the recent related assessment reports, government bulletins, and other related studies, we here review and summarize the impacts and key risks of climate change combined with the influence of local human activities in coastal China seas and coastal zone with the aim to further arouse people attention and action in responses to climate change.

It was firstly reported that the spatial-temporal pattern of precipitation in eastern China has changed remarkably in recent decades, with deficient precipitation in North China and increased rainfall in the Yangtze valley as well as South China (China-SNAP, 2011). These changes in precipitation have affected river run-off into the sea, triggering changes in estuarine and coastal environments. Moreover, the East Asian monsoon both in winter and summer has weakened since the late 1970s, accompanied by reduced cold waves, frequent warm winters, and increased extreme events such as flood, drought, and heat waves causing major human suffering and economic damage (Ding *et al.*, 2008; Wang *et al.*, 2009; Cai 2010). In addition, recent studies indicate that the drop in pH of the Kuroshio intermediate water in the ECS is not only attributed to the anthropogenic CO_2 input from the atmosphere but also to an increase in apparent oxygen utilization (Lui *et al.*, 2015). Particularly, eutrophication due to the land-source nutrient inputs from local human activities could enhance

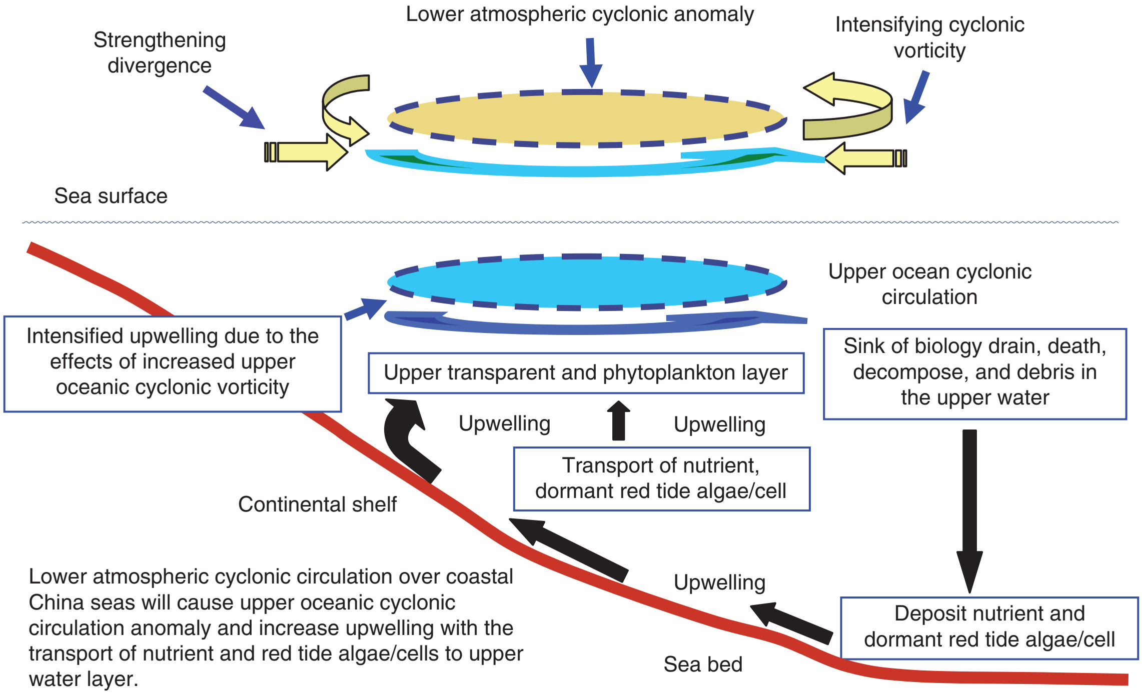

Figure 6. Illustration of the impact of atmospheric circulation anomaly over coastal China seas and adjacent water on the upwelling and nutrient transportation in the East China Sea (Reproduced from Cai and Tan, 2010).

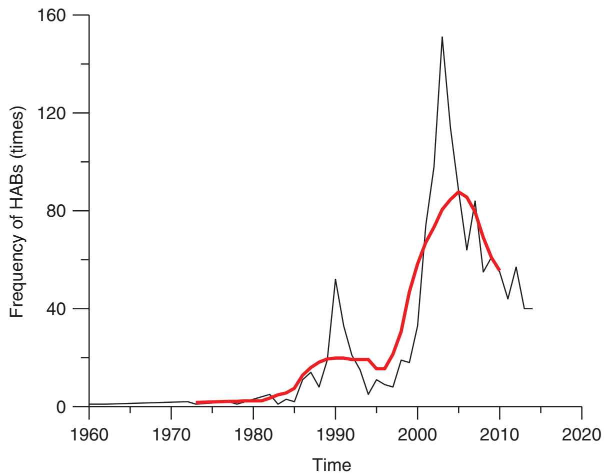

Figure 7. HABs frequency in the East China Sea during the period of 1970–2014; data are from Zhao 2010 and Chinese State Oceanic Administration (CSOA), 2000–2014. The thin line indicates the frequency of HABs in the East China seas, and the thick line indicates 9-year running mean of that in the ECS.

the acidification of subsurface coastal water, which lowers oxygen levels in the coastal water such as the ECS (Cai *et al.*, 2011b). Thus, climate change and related atmospheric and oceanic circulation changes, combined with human interference, have serious implications for coastal China seas.

The impacts and key risks of climate change are as follows. First, frequent outbreaks of red tides in coastal China seas, especially in the ECS, have been presenting decadal variation features since the late 1970s (Figure 7). After the mid-2000s, *Enteromorpha prolifera* macroalgae have frequently bloomed in the Yellow Sea, becoming green tides that are closely related to regional climate change, greatly influencing marine ecosystems (Qiao *et al.*, 2011). Therefore, the marine ecological disasters such as red tides and green tides in the ECS are very likely to become more serious due to ocean warming and climatic atmospheric circulation anomalies. Secondly, the bio-geographical distributions and compositions of marine species in coastal China seas and its adjacent seas have been changing remarkably over the past several decades. For instance, range shifts of marine fishes in Korea water and Japan Sea due to seawater warming have shown a northward extension (Tian *et al.*, 2012; Jung *et al.*, 2013). Several kinds of warm-water fish species living in the SCS have moved to subtropical waters, and the abundance and diversity of temperate-water species in the ECS are greatly reduced due to ocean warming; for example, some eurythermal species such as *Calanus sinicus* are now able to maintain their dominance, forming a single-dominant-species community structure with an associated decrease in species diversity. The attenuation time of peaked *C. sinicus* abundance advanced from June to May due to further increases in seawater temperature, leading to the reduction of zooplankton abundance, which would make it much easier for phytoplankton blooms and HABs occurrence (Cai 2010). Then, the health and services of marine ecosystems and related valuable benefits such as fisheries and tourism in the ECS are hence very likely at risk. In addition, coral bleaching and mortality in the SCS have become more severe as a result of ocean warming (China-SNAP, 2011).

Among many factors in climate change, sea level rise has been posing a great threat to China coastlands. As indicated in the 2014 Chinese Sea Level Bulletin (issued in February 2015), China's coastal sea levels rose by an average rate of 3.0 mm $year^{-1}$ for 1980–2014, which was faster than that of the global average, with highest rates since the 1990s relative to the average monthly sea level of the period during 1975–1993 (Figure 8). This continuous coastal sea level rise has been damaging the coastal zone in many ways including destruction of coastal wetlands, mangroves, and coral reefs; the decrease in marine biology diversity and associated deterioration of ecosystem services; and increased frequencies of coastal inundation, seawater intrusion, and coastal erosion. Furthermore, rising sea levels will reduce the functionality of coastal infrastructure and increase the risk of disaster caused by storm surges. Moreover, 2014 Chinese Marine Disaster Bulletin (issued in February 2015) also indicated that Chinese oceanic disasters were mainly due to strong storm surges, rough ocean waves, large-scale sea ice, and frequent red tides, causing a direct economic loss of 13.6 billion Chinese Yuan Renminbi (RMB) in 2014. However, it is worth noting that the Bulletin showed the economic loss and death involved in China marine disasters were strikingly lower in 2014 than the mean level for the period 2005–2014. This may be associated with improved adaptive abilities to the natural disasters.

In short, there is growing evidence that climate change has significantly affected coastal China seas and coastal zones over the past several decades. Improving our understanding of climate change impacts is central to managing risks and developing effective adaptation.

4.3. Influences of non-climate-related human activities on coastal China seas and coastal zone

Non-climate-related human activities such as large-scale reclamation, land-source sewage discharge that are main human inputs of nutrients, and overfishing have significant impacts on coastal China seas and coastlands. Because of three large-scale reclamations in the period of 1950–2003, China had lost an area of coastal wetland around 2.19×10^4 km^2, which accounts for about 50% of total coastal wetland along China seashore with the loss of about 70% natural mangroves and 80% coral reef in the coastal area (Zhang *et al.*, 2005). Furthermore, since the beginning of 21st century, with China's rapid economic and social development, a great deal of reclamation has been carried out in response to the shortage of land resources in the coastal areas. The coastal reclamation area was about 874.9 km^2 during the period of 2003–2011, providing large employment opportunities and contributing to the coastal area's economy [Chinese Academy of Sciences (CAS), 2014b]. Here, a few examples illustrate that non-climate-related human activities could increase the vulnerability of coastal ecosystem to climate change. During the period of 1928–2006, seawater area of Jiaozhou Bay in the coastal Yellow Sea had decreased from 559 to 352 km^2 due to the large-scale reclamation (Wu *et al.*, 2008); the intertidal benthos in Changkou tidal-flat of Jiaozhou Bay had sharply decreased from 141 to 10 in the varieties of benthonic organism species for the period of 1960–1990 (Yin and Lu, 2000). The types of birds over the coastal wetland had decreased from 87 to 47 with the decrease of coastal mangrove wetlands in Shenzhen Bay in the past 20 years (Xu and Li, 2002). In addition, eutrophicated river plum induced by human inputs of nutrients has enhanced the acidification of coastal subsurface waters in the ECS or the northern Gulf of Mexico (Cai *et al.*, 2011b), although the coupling between climate warming and the weakening winter monsoon could exacerbate coastal water acidification and threaten the coastal marine ecosystem in the SCS (Liu *et al.*, 2014). Thus, the non-climate-related human activities could pose serious threats for the health of coastal and marine ecosystems and increase their risks to climate change. It is noted that compared to global ocean acidification, there are few research and reports of the impacts of ocean acidification on the coastal ecosystem, which emphasizes the urgent need for the investigation of coastal acidification.

Non-climate-related human activities result in a number of key risks and vulnerabilities for coastal China seas and coastlands including rapid reductions in coastal wetlands and biological diversity, decline of wetland ecosystem goods and services, damage to bird and fish habitats, and decrease of coastal seawater quality. The 2014 Chinese Marine Environment Situation Bulletin that was released in March 2015 also revealed that seawater quality in some coastal areas is seriously poor due to high levels of land-source sewage pollution, and associated marine environmental hazards have frequently occurred. In addition, overfishing has serious implications for ecosystems of coastal China seas. The rapid degradation of coral reefs and mangroves in the SCS is closely related to non-climate-related human activities (China-SNAP, 2011). In summary, non-climate-related human activities have also greatly increased vulnerability to and risks from climate change in coastal China seas and coastlands.

4.4. Discussion on adaptation measures to climate change

In recent years, many marine adaptation policies and measures have been adopted in China to address climate change: coastal disaster prevention and mitigation, improvement of marine environment monitoring and disaster early warning capability, governance and renovation of islands, and other actions reported in the *China and Actions to Address Climate Change: 2014 Annual Report.* The impacts and risks due to climate change are caused by both vulnerability and exposure, which make risk management a much more complex and challenging goal because it must account for non-climate-related human activities such as pollution and overfishing. Therefore, in order to address the impact of future climate change, especially frequent climate extremes, much active oceanic adaptation such as effective control of large-scale reclamation, persistent reduction of sewage discharge, and management of overfishing must be implemented. Particularly, as AR5

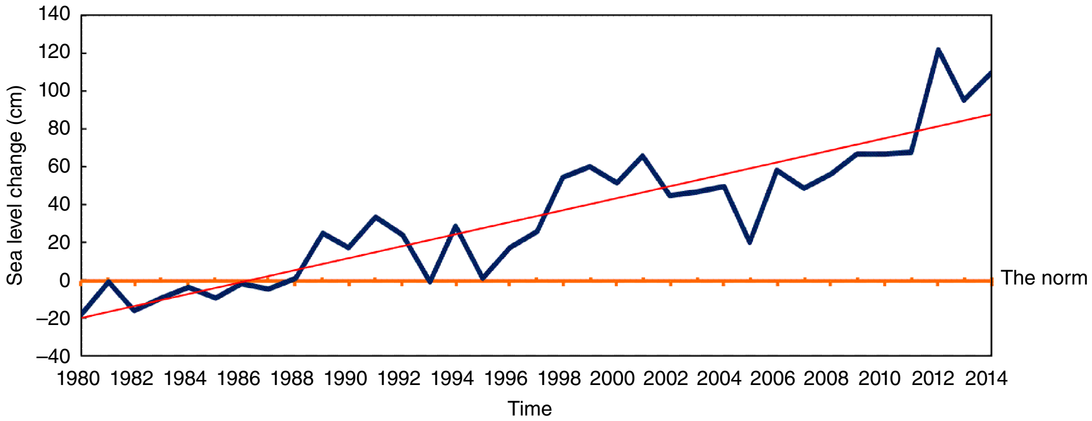

Figure 8. Annual mean sea level changes along coastal China seas in the period of 1980–2014 [Chinese State Oceanic Administration (CSOA), 2015]. The thick line indicates the observed changes of averaged sea level height on coastal China, the thin line indicates a linear trend of mean sea level height on coastal China, and the reference line indicates the norm of sea level of coastal China seas for 1975–1993.

pointed out that understanding the interactions between climate change and non-climate change drivers is a central part of the detection and attribution process in the costal boundary systems (Hoegh-Guldberg *et al.*, 2014). For that reason, in the first step of ocean adaptation to climate change, long-term observation and climate change impact assessment of marine ecosystem within coastal China seas should be emphasized and need to be further implemented, especially in some typical marine species habitat areas such as coastal wetlands, estuaries, mangroves, coral reef, and fisheries areas. Secondly, the changes of sewage discharge, reclamation, overfishing, and their effects on marine ecosystem along seashore, especially including coastal aquifers, river estuaries and lagoons, bays and harbours, and coastal industry zones, should be persistently monitored, assessed, controlled, and managed. Then, based on the above-mentioned assessment of impacts combined with climate change and human activities, marine ecological 'red lines' protecting coastal and offshore areas should be delineated as soon as possible, including coastal and marine resource use and protection planning. Next, climate-related coastal disaster prevention and management systems should be continuously improved in order to promote marine climate-disaster forecasting and response capability. Meanwhile, coastal infrastructure for flood protection and drainage should be reinforced and improved.

In addition, as a result of ocean's absorption of anthropogenic CO_2, the ocean would become more acidic, which will continually affect the marine and coastal ecosystems. The increase in acidity will impact on the water areas where eutrophication is an important issue with negative consequences for many calcifying organism (Cao *et al.*, 2007; Wong *et al.*, 2014). Hence, ocean acidification in coastal China seas and its impacts on coastal ecosystem urgently need exploration at present due to limited knowledge. As for China's coastal regions, the key risks of climate change and adaptation issues and strategies are analysed and summarized in Table 1.

5. Conclusions

In recent decades, especially since the end of the 1970s, climate change has greatly affected coastal China seas and coastal zones resulting from increase in SST, rise in sea levels, increase in frequency of storm surges, and coastal flooding. Surface seawater of coastal China has significantly warmed by about 0.83[0.81–0.85]°C at 95% confidence interval over the period 1958–2014 with a rate of 0.015 °C year^{-1}, particularly in the ECS with a long-term rise rate of about 0.021–0.038 °C year^{-1}. The SSH along coastal China sea had obviously increased by 2.39[2.28–2.50] cm at 95% confidence interval in the period of 1958–2008, especially along the ECS with a long-term rise rate of more than 3.2 mm year^{-1}. Moreover, the atmospheric cyclonic circulation anomalies over coastal China seas, especially over the ECS since the late 1970s, formed a favourable climate condition for the phytoplankton blooms and frequent HABs occurrence. This phytoplankton blooms could strongly lower oxygen levels in the seawater, and the coastal and marine ecosystem would be more endangered with the spreading of the coastal hypoxic zone. The health and services of marine ecosystems and related valuable benefits of fisheries, aquaculture, and tourism in the ECS are therefore very likely at further risk. There is also an apparent increase in climate-related vulnerability and key risks for marine ecosystems, coastland communities, and marine industries in coastal China seas and coastlands due to the accumulated effects of human activities such as large-scale reclamation, land-source sewage discharge, habitat destruction, destructive fishing, and overfishing.

Given the current rate of climate change and the frequent climate extremes expected in the future, coastal China seas and coastlands will face much more severe risks and disasters. To address climate change, it is therefore necessary and urgent to strengthen our coastal and oceanic adaptation, particularly to manage human activities and our uses of ocean resources in coastal areas.

Table 1. Climate-related drivers, local human activities, key risks, and adaptation issues and strategies.

Climatic drivers	Local human activities	Climatic key risks and non-climate-related risks	Adaptation issues and strategies for coastal China seas and coastal areas
• Rapidly increasing SST • Oceanic and atmospheric circulation anomalies • Sea level rise • Severe storm frequency • Precipitation anomalies • Extreme sea levels	• Land-source sewage discharge • Large-scale reclamation • Habitat destruction • Destructive fishing and overfishing	• Deterioration of ecosystem health and services due to much more and serious frequent marine ecological disasters such as red tide and green tide • Distribution shifts of marine species and changes in their seasonal behaviour • Reduction of marine and coastal habitat and biological diversity • Coral bleach and mortality • Reduction of marine foods and culture value from fisheries, aquaculture, and tourism • Flooding and coastal inundation • Seawater intrusion, coastal erosion, and soil salinization • Eutrophication and the related increase ocean acidification in the coastal water area • Large reduction of coastal wetlands • Invasion of alien or exotic species	• Observation, study, and assessment of climate change and ocean acidification should be further strengthened • Observation data and related network systems for sharing should be continuously implemented, especially in the management of large-scale reclamation, wastewater discharge, and overfishing • Marine resource use and protection planning should be constantly improved • Ecological 'red lines' protecting coastal and offshore areas should be delineated as soon as possible; that is, coastal zone and marine natural protection areas should be set up according to the characteristics of marine ecosystem goods and services • Climate-related coastal disaster prevention and management systems should be continuously improved in order to promote marine climate-disaster forecasting and response capability • Climate disaster risks and areas of large coastal existing engineering projects such as nuclear power plants, petroleum and chemical industries, and harbour and shipping industries should be regularly identified • Coastal infrastructure for flood protection and drainage should be reinforced and improved • National consciousness and actions for sustainable marine use and protection should be enhanced in the following fields: marine fisheries, aquaculture, tourism, shipping, human health, maritime safety, marine oil and gas, renewable energy sources, and other climate-critical areas • International cooperation in marine affairs should be strengthened to improve marine capture fisheries management and to carry out sustainable marine aquaculture

Acknowledgements

This research was supported by the Scientific Research Foundation Project of Third Institute of Oceanography, SOA (2015030), the Chinese Public Science and Technology Research Funds Project of Ocean (201005019), and the Chinese Special Scientific Research Project for Public Interest (201006021).

References

Cai RS, Tan HJ. 2010. Influence of interdecadal climate variation over East Asia on offshore ecological system of China. *J. Oceanogr. Taiwan* **29**(2): 173–183. (in Chinese, with English abstract).

Cai RS 2010. *The Influence of Climate Change on Chinese Offshore Ecology System*. Ocean Press: Beijing, 30–55. (in Chinese).

Cai RS, Chen JL, Tan HJ. 2011a. Variations of the sea surface temperature in the offshore area of China and their relationship with the East Asian monsoon under the global warming. *Clim. Environ. Res.* **16**(1): 94–104. (in Chinese, with English abstract).

Cai WJ, Hu X, Huang WJ, Murrell MC, Lehrter JC, Lohrenz SE, Chou WC, Zhai WD, Hollibaugh JT, Wang YC, Zhao PZ, Guo X, Gundersen K, Dai MH, Gong GC. 2011b. Acidification of subsurface coastal waters enhanced by eutrophication. *Nat. Geosci.* **4**(11): 766–770.

Cao L, Caldeira K, Jain AK. 2007. Effects of carbon dioxide and climate change on ocean acidification and carbonate mineral saturation. *Geophys. Res. Lett.* **34**: L05607, doi: 10.1029/2006GL028605.

Carton JA, Giese BS. 2008. A reanalysis of ocean climate using simple ocean data assimilation (SODA). *Mon. Weather Rev.* **136**(8): 2999–3017.

China-SNAP. 2011. *The Second National Chinese Assessment Report on Climate Change Chinese Government*. Science Press: Beijing, 245–256. (in Chinese, with English abstract).

Chinese Academy of Sciences (CAS). 2014a. *Evolution of Environmental Quality and Sustainable Development in the Southeast Developed Coastal Areas*. Science Press: Beijing, 34 pp. (in Chinese).

Chinese Academy of Sciences (CAS). 2014b. *A Number of Scientific Issues and Suggestions in China Marine and Coastal Ecological Safety*. Science Press: Beijing, 21 pp. (in Chinese).

Chinese State Oceanic Administration (CSOA). 2000–2014. *2000–2014 Chinese Marine Environment Situation Bulletin*, Beijing [EB/OL]. http://www.coi.gov.cn/gongbao/huanjing/ (accessed 10 September 2015).

Chinese State Oceanic Administration (CSOA). 2015. *2014 Chinese Sea Level Bulletin (issued in February 2015)*. Beijing, 1–2. [EB/OL]. http://www.coi.gov.cn/gongbao/haipingmian/

Ding YH, Wang ZY, Sun YF. 2008. Interdecadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: observed evidences. *Int. J. Climatol.* **28**(9): 1139–1161.

Feng SZ, Li FQ, Li SJ. 1999. *An introduction to marine science*. Higher Education Press: Beijing, 434–436. (in Chinese).

Henson SA, Sarmiento JL, Dunne JP, Bopp L, Lima I, Doney SC, John J, Beaulieu C. 2010. Detection of anthropogenic climate change in satellite records of ocean chlorophyll and productivity. *Biogeosciences* **7**: 621–640.

Hoegh-Guldberg O, Cai RS, Poloczanska ES, Brewer PG, Fabry VJ, Hilmi K, Jung S, Sundby S. 2014. The ocean. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Field CB, Barrows VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel BE, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds). Cambridge University Press: Cambridge, UK and New York, NY, 1655–1731.

Huang RH, Cai RS, Chen JL, Zhou LT. 2006. Interdecadal variation of drought and flood climate disasters in China and their association with the East Asian climate system. *Chin. J. Atmos. Sci.* **30**(5): 730–743. (in Chinese, with English abstract).

Jung S, Pang IC, Lee JH, Choi I, Cha HK. 2013. Latitudinal shifts in the distribution of exploited fishes in Korean waters during the last 30 years: a consequence of climate change. *Rev. Fish. Biol. Fish.* **24**: 443–462, doi: 10.1007/s11160-013-9310-1.

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Leetmaa A, Reynolds R, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Jenne R, Joseph D. 1996. The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Meteorol. Soc.* **77**(3): 437–471.

Kerr RA. 2009. What happened to global warming? Scientists say just wait a bit. *Science* **326**(5949): 28–29.

Kosaka Y, Xie SP. 2013. Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature* **501**(7467): 403–407.

Liu Y, Peng ZC, Zhou RJ, Song SH, Liu WG, You CF, Lin YP, Yu KF, Wu CC, Wei GJ, Xie LH, Burr GS, Shen CC. 2014. Acceleration of modern acidification in the South China Sea driven by anthropogenic CO_2. *Sci. Rep.* **4**(6): 1158–1159.

Lui HK, Chen CTA, Lee J, Wang SL, Gong GC, Bai Y, He X. 2015. Acidifying intermediate water accelerates the acidification of seawater on shelves: an example of the East China Sea. *Cont. Shelf Res.* 1–11, doi: 10.1016/j.csr.2015.08.014 (in press).

Melzner F, Thomsen J, Koeve W, Oschlies A, Gutowska MA, Bange HW, Hansen HP, Körtzinger A. 2013. Future ocean acidification will be amplified by hypoxia in coastal habitats. *Mar. Biol.* **160**(8): 1875–1888.

Met Office. 2013. *The recent pause in global warming (1): what do observations of the climate system tell us?* Met Office: Exeter, Devon, UK, 1–2.

Miller AJ, Cayan DR, Barnett TP, Graham NE, Oberhuber JF. 1994. The 1976-77 climate shift of the Pacific Ocean. *Oceanography* **7**(1): 21–26.

Qiao FL, Wang GS, Lu XG, Dai DJ. 2011. Drift characteristics of green macroalgae in the Yellow Sea in 2008 and 2010. *Chin. Sci. Bull.* **56**(21): 223602242.

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A. 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.* **108**(D14): 1063–1802, doi: 10.1029/2002JD002670.

Tian YJ, Kidokoro H, Watanabe T, Igeta Y, Sakaji H, Ino S. 2012. Response of yellowtail, Seriola quinqueradiata, a key large predatory fish in the Japan Sea, to sea water temperature over the last century and potential effects of global warming. *J. Mar. Syst.* **91**(1): 1–10.

Wang L, Huang RH, GuL CW, Kang LH. 2009. Interdecadal variations of the East Asian winter monsoon and their association with quasi-stationary planetary wave activity. *J. Clim.* **22**(18): 4860–4872.

Wong PP, Losada IJ, Gattuso JP, Hinkel J, Khattabi A, McInnes KL, Saito Y, Sallenger A. 2014. Coastal systems and low-lying areas. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel BE, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds). Cambridge University Press: Cambridge, UK, 361–409.

Wu WS, Xin HY, Wu LY, Li WW. 2008. The satellite investigation on the 2006 water area and coastline length of the Jiaozhou Bay and their historical evolution. *Coast. Eng.* **27**(3): 15–22. (in Chinese, with English abstract).

Xu YG, Li S. 2002. Destruction of urban construction on the ecological resources of mangrove in Shenzhen and its protective measure. *Resour. Dev. Ecol. Prot.* **3**: 32–35. (in Chinese).

Yin P, Lu YX. 2000. Environmental evolution and sustainable utilization of Jiaozhou Bay. *Coast. Eng.* **19**(3): 21–24. (in Chinese, with English abstract).

Zhang JP, Cai RS. 2013. Modeling the responses of East China Sea cold eddy to the interdecadal variation of East Asian monsoon. *Oceanol. Limnol. Sin.* **44**(6): 1427–1435. (in Chinese, with English abstract).

Zhang XL, Li PY, Li P, Xu XY. 2005. Present conditions and prospects of study on coastal wetlands in China. *Adv. Mar. Sci.* **23**(1): 87–95. (in Chinese, with English abstract).

Zhao DZ. 2010. *Occurrence of Red Tide Disaster in China Typical Marine Areas*. Ocean Press: Beijing, 341–388. (in Chinese).

