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Mangrove swamp expansion controlled by climate since 1988: a case study in the Nanliu River Estuary, Guangxi, Southwest China

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Abstract
In the Nanliu River Estuary of Guangxi, China, the naturally expanding process of a mangrove swamp (primarily consist of *Aegiceras corniculatum*) over past decades is studied by satellite images. From 1988 to 2013, the area of studied mangrove swamp increased significantly from 60 hm^2 to 134 hm^2. The expanding process is not gradual and the significant expansion only took place in some special periods. To reveal the dynamic of mangrove swamp expansion, the evolution of tidal flat elevation and the climate change in past decades are studied respectively. The hydrodynamic condition and nutrient supply are also analysed. The study results show that the climate factors of typhoon intensity and annual minimum temperature are crucial for controlling mangrove expansion. A large number of mangrove seedlings on bare tidal flats can survive only in special climate optimum periods, which are continuous years of low typhoon intensity and high annual minimum temperature. In past decades, the scarcity of climate optimum periods resulted in a non-gradual process of mangrove expanding and a time lag of 30 years between the elevation reaching the low threshold for mangrove seedling survival and the eventual emergance of the mangrove. Compared with the climate factors, the hydrodynamic condition and nutrient supply are not important factors affecting mangrove expansion. In the future, combined with global warming, the enhanced frequency and energy of landing typhoons will most likely restrain the further expansion of this mangrove swamp.

Key words: mangrove, climate change, typhoon, tidal flat elevation

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1 Introduction

Mangrove swamps, which are usually located on upper intertidal flats in tropical-subtropical zones, are beneficial to humanity for their role of keeping coastal ecological equilibrium (Ewel et al., 1998; Mumby et al., 2004; Komiyama et al., 2008), protecting the coast against storm surges (Blasco et al., 1996; Mazda et al., 1997; Vermaat and Thampanya, 2006) and tsunami (Danielsen et al., 2005), carbon sequestration (Bouillon et al., 2008; Chmura et al., 2003) and even trapping silty sediment and pollutants (Snedaker, 1995; Young and Harvey, 1996;). In China, the total area of mangrove swamps had decreased sharply from approximately 4×10^4 hm^2 in the 1950s to 2.4×10^4 hm^2 in the 2010s, which has mainly due to artificial activities such as reclamation and building sea embankment (Liao and Zhang, 2014; Jia, 2014). The remaining mangrove swamps are now protected, and their recovery potential under the conditions of sea level rise and climate change is a noteworthy scientific problem. However, more details regarding the mangrove swamp recovery process, which is affected by various environmental factors such as substrate elevation, hydrodynamic, climate and nutrient supply, is still rare in China. This prevents us from better forecasting the possible future fate of these existing mangrove swamps under the conditions of sea level rise and climate change. In this paper, the change in mangrove swamp area, the evolution of mangrove tidal flat elevation and the climate change over past decades are studied for an expanding mangrove swamp mainly consisting of *Aegiceras corniculatum* in the Nanliu River Estuary of Guangxi, Southwest China. The aim is to reveal the role of substrate elevation and climate factors in controlling the mangrove swamp expansion for a habitat where there is enough sediment supply.

2 Study area

Mainly consisting of *Aegiceras corniculatum*, the mangrove swamp in this study is located on the muddy upper tidal flat (several kilometers in width) in the Nanliu River Estuary, which is at the northeast edge of the Beibu Gulf in the South China Sea. The age of this mangrove swamp is approximately 50 years, and the mangrove plant height is between 1 m and 3 m. The Nanliu River

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has an annual water discharge of 1.7×10^9–8.0×10^{10} m^3 and an annual average suspended sediment flux of about 1.2×10^6 t. A diurnal tide with tidal range of 2–3 m is dominant in this area. Due to the southwest monsoon in summer and the trend of Beibu Gulf, the predominant energetic wave direction is south-west. Most of the wave energy usually is dissipated by the wide tidal flat before the wave reaches mangrove swamp under condition of normal weather. Controlled by a tropical monsoon climate, the annual average temperature since the 1960s is 22°C. In the study area, the extreme low temperature in winter usually can be observed after successive cloudy/rainy weather caused by strong cold air mass from north Asia, and is between 2–4°C over the past 30 years. The average annual rainfall is 1 600 mm, of which the proportion of summer rainfall is more than 70%. In almost every year, this area can be affected by typhoons, which can result in additional water and energetic storm surge. The relative sea level rise speed is 1.7 mm/a in the past 50 years.

3 Materials and methods

In this paper, the expanding process of the mangrove swamp from 1988 to 2015 is re-constructed by satellite remote sensing images of eight different years (collected from LANDSAT and Google Earth). The satellite images were originally assigned by positioning information in the World Geodetic System (WGS84). The images were then visualized and processed by the powerful software ENVI for Remote Sensing Image Processing. Firstly, the red, green, and blue spectral bands of the satellite images were displayed by the ENVI's viewer. With the Vector Create tool of ENVI, the polygons of the studied mangrove swamp were then identified and extracted from the images manually by using the visual color (green and light green) and texture according to our experiences. As the images were assigned by WGS84 positioning information, the actual area of the studied mangrove swamp can be finally estimated from the extracted polygons.

The elevation of the mangrove tidal flat surface was measured by a real-time kinematic GPS device (error less than 3 cm) along a path across the mangrove swamp. The minimum elevation for *Aegiceras corniculatum* seedling survival thus can be determined. Furthermore, to study the evolution of mangrove tidal flat elevation, the accretion rate of tidal flat is determined according to the excess ^{210}Pb activity profile in a sediment core (the position is shown in Fig. 1). In the State Key Laboratory of Lake Science and Environment in Nanjing of China, the radioactivity of ^{210}Pb and ^{226}Ra in all sample pieces was detected with an alpha spectrometric measurement. The excess ^{210}Pb activity in samples was determined by subtracting the ^{210}Pb from radium decay of ^{226}Ra from the total ^{210}Pb activity. Considering the notable variation of accretion rate in estuarine environment, the accretion rate of each depth in core was calculated by the constant rate of supply (CRS) modal (Appleby, 2001). In this modal, $R=\lambda A/C$, where R is sedimentation date of a certain depth, λ is the decay constant of ^{210}Pb, A is the integral of excess ^{210}Pb activity on depth, and C is excess ^{210}Pb activity of certain depth.

To study the possible relation between climate change and mangrove swamp expansion, the monthly records of atmosphere temperature, wind speed and rainfall were collected from the weather station of Hepu City (the position is shown in Fig. 1). The time series of annual maximum wind speed, minimum temperature and rainfall over the past 30 years were determined to analyze the change of landing typhoon intensity, winter cold event intensity and estuary salinity respectively.

4 Results

4.1 *Mangrove swamp expanding process*

According to the satellite remote sensing images of different years (Fig. 2), the expansion process of studied mangrove swamp from 1988 to 2015 is re-established. As shown in Figs 2a and 3, the expanding process of mangrove swamp is not gradual, the notable area expansion only took place in some special periods:

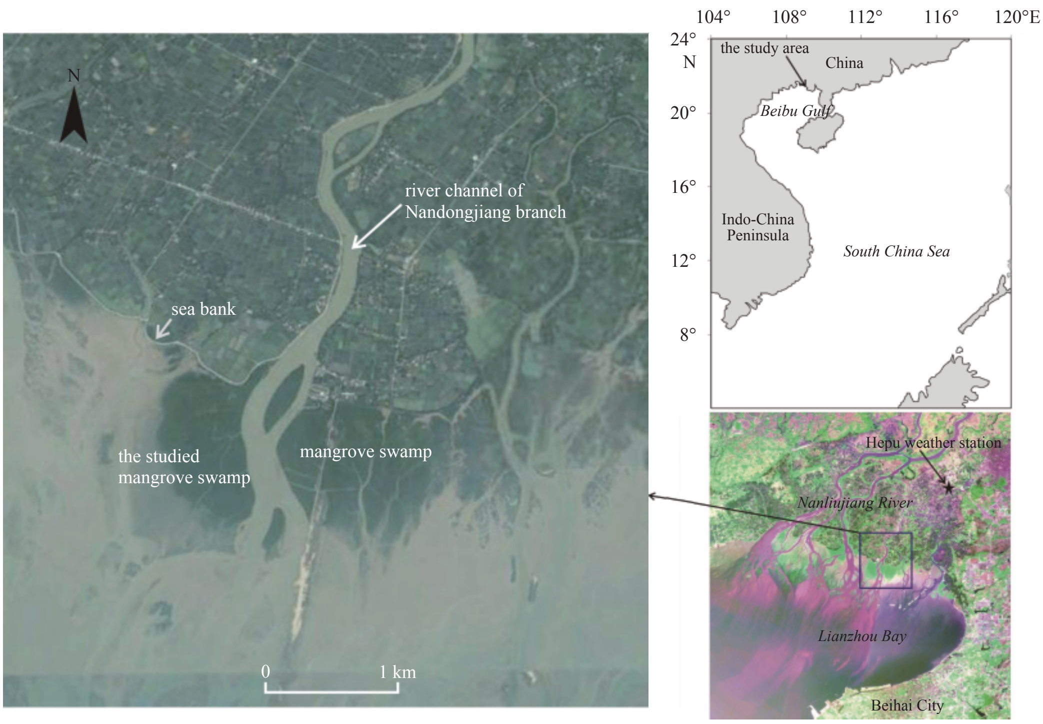

Fig. 1. The location of studied mangrove swamp and the geomorphology of the Nanliu River Estuary.

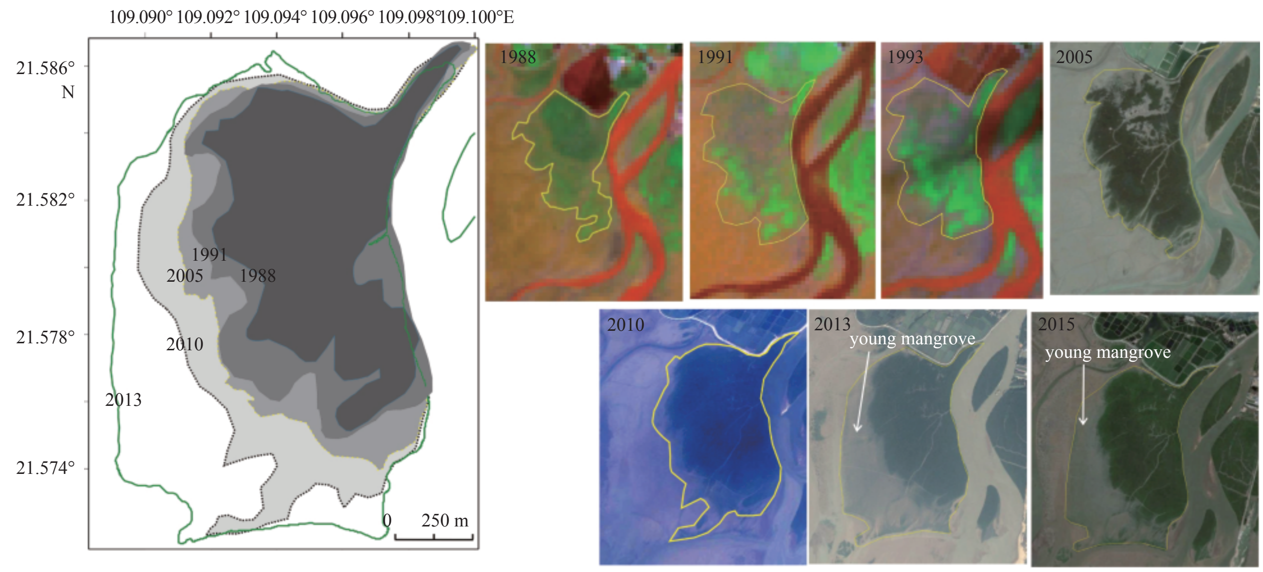

Fig. 2. Mangrove swamp of different years in satellite images, and the mangrove swamp expansion process.

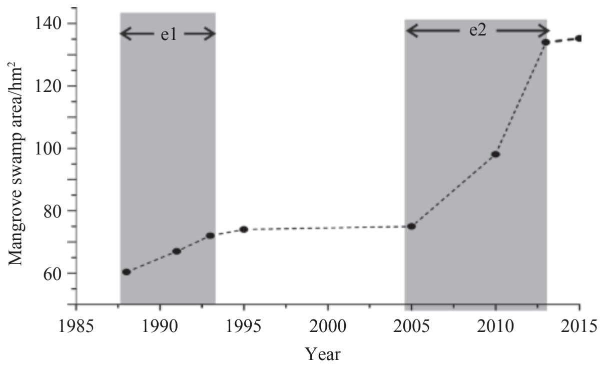

Fig. 3. The change of mangrove swamp area inferred by satellite images from 1988 to 2015, the main expansion period (e1, e2) is emphasized by shaded bars.

from 1988 AD to 1993 AD (e1) and from 2005 AD to 2013 AD (e2). During e1, the area of mangrove increased from 60.4 hm^2 to 72.0 hm^2 with an annual increasing rate of 2.1 hm^2/a. During e2, the area of mangrove increased from 75.0 hm^2 to 134.0 hm^2 with an annual increasing rate of 7.4 hm^2/a. During the period between e1 and e2, the change of mangrove swamp area is very little with a increasing rate of only 0.16 hm^2/a. Moreover, we can see obvious young mangrove patches (with light green color due to the light reflection of tidal flat through a sparse and small crown of young mangroves) in satellite images of e1 and e2 (for example: in 1991, 1993, 2013 and 2015). Given the fact that the mature Aegiceras corniculatum can generate a large number of seedlings every year, we can judge that the mangrove seedlings transported to bare flat only can survive during special short periods (e1 and e2) over the past 30 years.

4.2 *Mangrove tidal flat elevation and accumulation rate*

Mangroves can survive only when their substrate elevation exceeds a low threshold value, which is usually a little higher than the local mean seal level (Zhang et al., 1997; Ye et al., 2003). The colonization of mangroves over recent decades might be attributed to the elevation lifting of bare tidal flats. To reveal the possible relation between mangrove expansion and tidal flat elevation change, the history of the mangrove substrate elevation must be reconstructed. Firstly, the minimum elevation for *Aegiceras corniculatum* seedling survival is determined as 0.38 m above the local mean sea level, which was obtained by measuring the substrate elevation of mangrove seedling fringe on the slope of a channel bar (Fig. 4a, Figs 5a and b). The mangrove tidal flat elevation (in 2013) was detected along the main expansion direction of the mangrove swamp (Fig. 5a). The results show that the mangrove substrate elevation decreased from 1.4 m in the oldest mangrove patch to 0.4 m in the youngest mangrove patch (Fig. 5b). A core was collected at a position just in front of the mangrove fringe of 2005. The excess ^{210}Pb activity decreases in a fluctuation way down core, this indicates non-negligible time-varying of accretion rate. With the CRS model, the accumulation rate and sedimentation age of each depth in core can be calculated. As is shown in Fig. 5d, the accumulation rate in surface layer (0–10 cm) is much higher than that in the underling layer. The sedimentation age is calculated to be 10 years (in 2003) at depth of 10 cm, when the mangrove fringe had just reached the position of Core C7 (Fig. 5a). The high accumulation rate in surface layer is likely caused by mangrove colonization after 2003, which can favor sedimentation by reducing hydrodynamic energy. Without taking into account the sea level rising and the compaction of underlying sediment layer in past decades, the sedimentation age is about 40 years at the minimum elevation of mangrove survival in core, which means that the tidal flat elevation had reached the low threshold no later than 1973.

4.3 *Climate change over the past decades*

Mangrove vegetation can be greatly affected by climate factors such as temperature, precipitation and storm events. For example, mangrove seedlings or even mature mangrove trees can be frozen to death if extreme low temperature events emerge in winter (Woodroffe and Grindrod, 1991; Snedaker, 1995). Precipitation in the drainage basin can affect the sediment/nutrient flux into the sea and the estuarine salinity. High sediment/nutrient flux is favorable for mangrove seedling survival by increasing the accretion rate of tidal flat and the growing speed of mangrove seedling (Nardin et al., 2016). In storm events, the mangrove

Fig. 4. Graphic expression of minimum elevation for mangrove survival, which is determined by detecting the height of fringe line of mangrove seedlings on the slope of a channel bar (a); substrate erosion of mangrove seedlings, part of the root is exposed (b); the thick old mangrove trees with height of more than 2 m (c); and the sparse young mangrove trees with height of less than 1 m (d).

seedlings in front of the mangrove fringe can be threatened both by the prolonged inundation time and by the substrate erosion caused by strong storm surges (Baldwin et al., 2001; Sherman et al., 2001).

To reveal the relation between mangrove expansion and climate change, we collected annual meteorological records of 1975 AD to 2015 AD in the study area. Time series of annual maximum wind speed (MWS) during typhoon landing (indicating the maximum intensity of landing typhoons in a year; the value is set as 0 if no typhoon landing in a year), minimum temperature (indicating winter cold events) and precipitation (indicating the salinity of estuary) were analyzed together. This is shown in Fig. 6. The years with both low typhoon intensity (MWS is less than 10 m/s, the emergency probability of MWS greater than 10 cm/s is 50%) and high annual minimum temperature (more than an average value of 3.8°C) are determined as climate optimum periods for mangrove seedling survival. From 1975 AD to 2015 AD, the total duration of climate optimum period is 14 years, which account for 34% of the whole time span. It is notable that the two mangrove expanding events (e1: 1988 AD to 1993 AD, e2: 2005 AD to 2012 AD) started almost synchronously with the two longest climate optimum periods (P1: 1988 AD to 1993 AD, P2: 2004 AD to 2008 AD). It seems a large number of mangrove seedlings can survive successfully only during continuous years of low typhoon intensity and high minimum temperature in winter. The rain fall shows no direct relation with mangrove expansion; the mangrove expansion can take place both in the relative wet (e1) and dry (e2) period. It seems that the rain fall can not affect the mangrove expansion directly in this area.

5 Discussion

5.1 *The importance of climate factors in controlling mangrove expansion*

The elevation of the substrate exceeding a certain threshold is a precondition for mangrove seedling survival. According to this study, at the position of Core C7 collected, the surface elevation of tidal flat had reached the low threshold for mangrove seedling survival no later than 1973 AD. However, mangroves had not colonized there until 2003. There is a time lag of more than 30 years between the substrate elevation reaching low threshold and the emerging of mangroves. The distance from position of Core C7 to the oldest mangrove patch was about 200 m (Fig. 5a). The mangrove hypocotyls can be easily transported there by ebb current. This time lag reminds us there must be some other factors directly controlling the survival of mangrove seedling after the substrate elevation reaching the low threshold. If we only take into account the elevation of bare tidal flat in forecasting mangrove swamp expansion in time scale of decades, the result would be overestimated in this area.

The mangrove swamp in this study is located in an open estuary of Southwest China, which is in the region of northern tropic. The typhoon and cold events in winter (caused by strong East Asia Winter Monsoon) thus play very important roles in controlling mangrove seedling survival and the expansion of mangroves. According to this study, the notable mangrove expansion events can only be observed to take place synchronously with the continuous years of "climate optimum". In the separate year of climate optimum, the mangrove seedlings may survive temporarily, but they will be eroded by energetic storm surges or killed

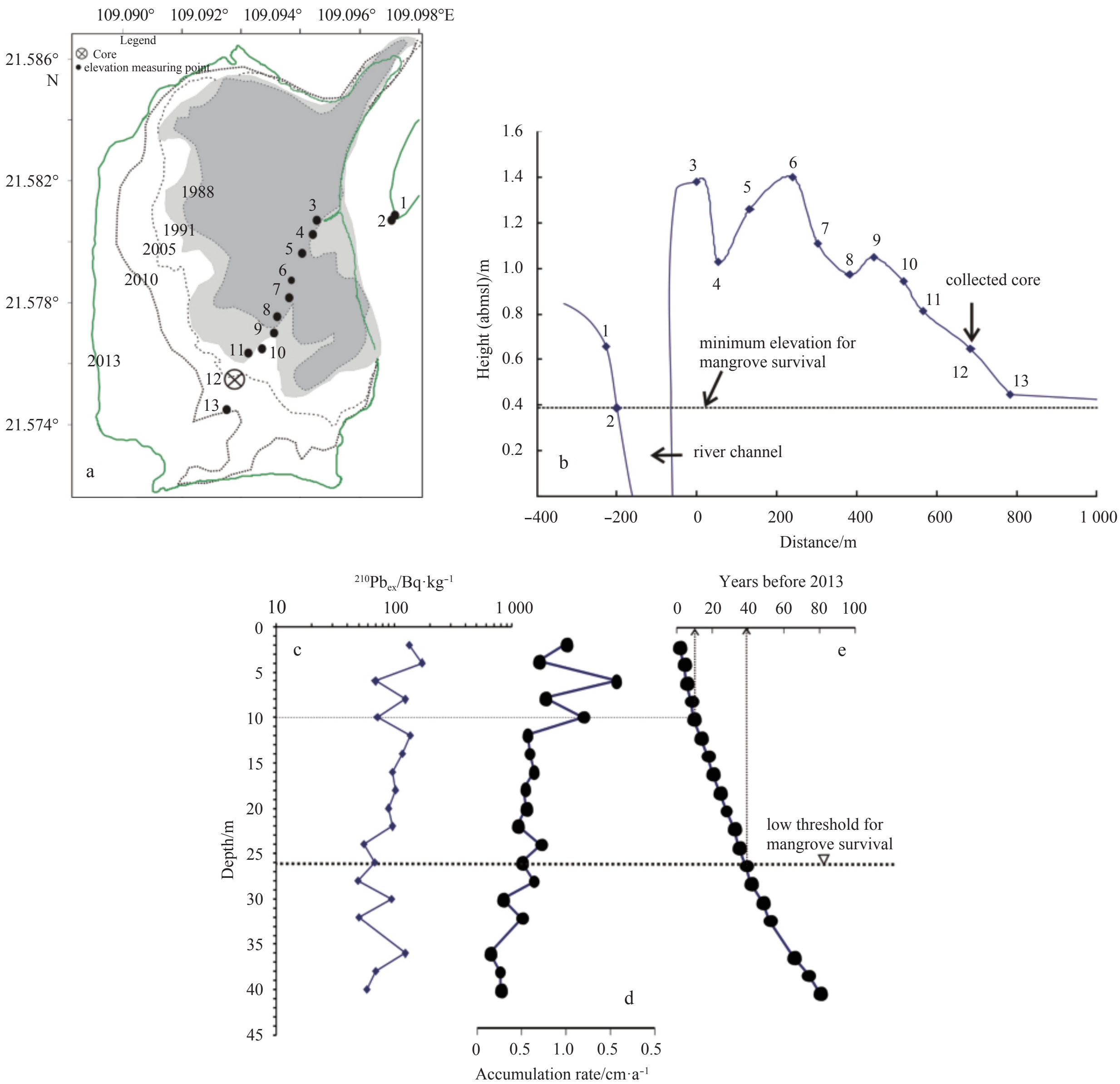

Fig. 5. The elevation (the elevation of local mean sea level is 0) and accretion rate of mangrove tidal flat. a. Position of elevation detecting points, b. mangrove tidal flat elevation in 2013, c . excess ^{210}Pb activity in the sediment Core C7, d. accretion rate profile in core, and e. sedimentation age profile in core. abmsl means above mean sea level.

by the cold events in the following years. For example, from 1998 AD to 2000 AD, there was no typhoon, but the low minimum temperature (3.6°C) in 1999 AD interrupt the continuous years of climate optimum. The time span of mangrove expanding events are longer than that of corresponding climate optimum period (Fig. 6), which might be caused by the time lag between the seedlings survival and their growing up enough to be identified in satellite images.

The mangrove expansion during this period thus is very little. During the past decades, continuous years of climate optimum are scarce, which caused a non-progressive expanding process of mangrove swamp (Fig. 7). Compared with typhoon intensity and annual minimum temperature, the rainfall shows no direct relation with mangrove expansion. The rainfall usually relates to mangrove expansion through affecting the accretion rate of tidal flat and the salinity of estuary water. In the study area, the substrate elevation is proven unable to control mangrove expansion directly in the time scale of decades. The rainfall of the drainage basin thus cannot control mangrove expansion by affecting the accretion rate of bare tidal flat. Moreover, the rainfall usually exceeds 1 500 mm/a in this area even in "dry" years during the past 40 years, the estuarine salinity can maintain a suitably low value for *Aegiceras corniculatum* seedlings.

Hydrodynamic conditions can affect the expansion of mangroves by controlling the sedimentation of mangrove seedlings. The decline of ebb current speed or wave energy thus can favor the expansion of mangroves. In the study area, most of the wave energy is dissipated by bottom friction due to the wide tidal flat (5–10 km in width) in condition of normal weather①. The wave disturbance is very weak in front of mangrove swamp and can

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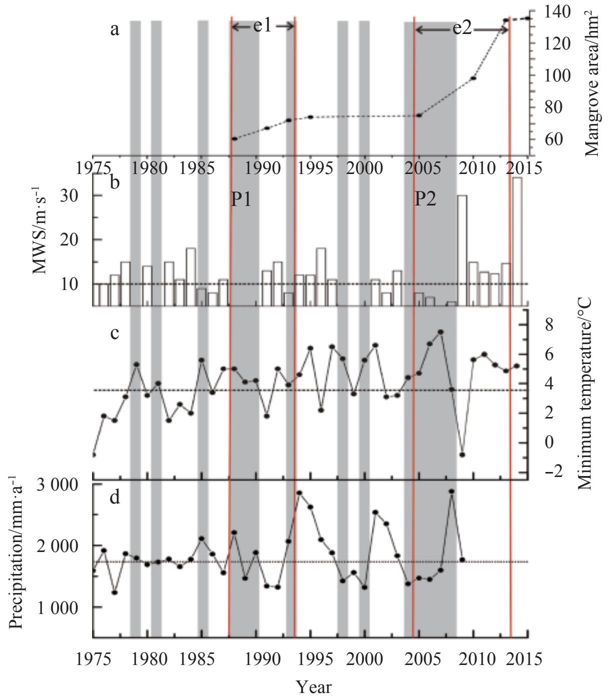

Fig. 6. Climate change over the past 40 years (the optimum climate periods for mangroves are shown by shaded bars; the main mangrove expansion periods P1 and P2 inferred from satellite photos are shown by rectangles).

not affect the sedimentation of mangrove seedlings significantly. The seedlings can settle down and survive on the channel bar slope, which habitat elevation is 0.38–0.63 m above mean sea level. Considering the fact that the ebb current speed on tidal flat is lower than that on the slope of channel bar with same elevation, the seedlings must be able to settle down and survive temporally on the tidal flat where Core C7 is collected no later than 1973 (Fig. 5e). However, the mangrove cannot colonized there until 2003. It seems that the decline of ebb current speed due to tidal flat accretion is not a key factor affecting mangrove swamp expansion in this area.

The N and P nutrient flux transported into estuary might also be a factor affecting mangrove swamp expansion. The N and P nutrient flux into the Nanliu River Estuary increased sharply after the 1980s due to the rapid development of local agriculture and aquaculture (Xia et al., 2011). Increased nutrients in the sediments might promote the growth and survival of mangrove seedlings (Koch and Snedaker, 1997), but cannot explain the discontinuity of the mangrove swamp expanding process either. Nutrients supply thus is not an important factor affecting mangrove swamp expansion in this area.

5.2 *The possible expanding trend of studied mangrove swamp in future*

The results of this study can help us predict the future fate of studied the mangrove swamp in consideration of future climate change and sea level rise. Due to global warming, the emerging frequency of energy cyclones is very likely to increase in the future (Emanuel, 2005). This climate change trend also can be observed in the study area (Fig. 6), which shows an overall increasing of the annual minimum temperature from the 1970s and a notable typhoon intensity increasing after 2009. If the landing frequency of powerful typhoons increases in the future, the climate optimum period for mangrove seedling survival will be more scarce, which will limit the further expansion of mangrove swamps. Moreover, more energetic storm surges can restrain the elevation lifting of bare tidal flat by their compressing and eroding effect (Van Santen et al., 2007), which also obstructs the mangrove swamp from expanding seaward. For example, the accretion rate of bare flat before the studied mangrove swamp is 3–5 mm/a (Fig. 5d) in the past decades, which will decease if the frequency of powerful typhoons increases in future. Considering the global sea level rise will be 28–98 cm at the end of 21centry (IPCC, 2013), the elevation of bare tidal flats will very likely be unable to keep up with the sea level rise, and the area of possible habitat for mangrove swamp will be reduced.

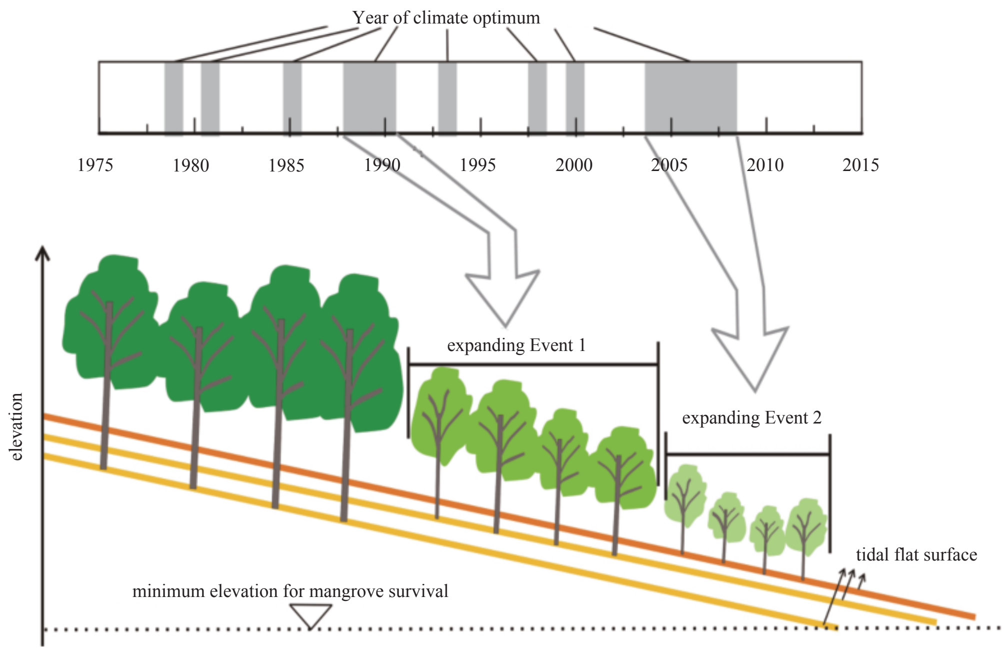

Fig. 7. Schematic diagram of mangrove expansion controlled by climate change in the study area.

6 Conclusions

(1) In the Nanliu River Estuary, a natural mangrove swamp expanded notably since 1988; its area increased from 60.4 hm^2 to 134.0 hm^2. The expanding process of mangrove swamp is not gradual and is controlled by the climate factors directly. A large number of mangrove seedlings on bare tidal flats can only survive during some special climate optimum periods, which are continuous years with low typhoon intensity and high minimum temperature in winter.

(2) Due to the scarcity of climate optimum period in the past decades, there is a time lag of more than 30 years between the elevation of bare tidal flat reaching the low threshold for mangrove seedling survival and the mangrove colonizing there successfully. Hydrodynamic condition and nutrient supply are not key factors affecting mangrove expansion in this area. Both of them cannot explain the expanding process of mangrove swamp over past decades.

(3) In the future, combined with the globe warming, the landing frequency of powerful typhoons will increase, which can restrict further expansion of studied mangrove swamp by reducing the emergency probability of climate optimum period for mangrove expansion. Furthermore, more frequent powerful typhoon will reduce the accretion rate of bare tidal flats, which also can limit the expansion of mangrove swamp under conditions of accelerated sea level rise.

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