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Regime shifts of hydrometeorological factors in the Jiaozhou Bay and their potential ecological impacts

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Abstract The wavelet transform was applied to studying the regime shifts of hydrometeorological factors (i.e., precipitation, air temperature, sea surface temperature and sea surface salinity) during the period of 1961–2000 in the Jiaozhou Bay (JZB). The results indicated clearly that these factors show variability of multiple timescales, with interannual and decadal periods. The local abrupt changes such as the 1978–1979 and 1988–1989 shifts feature the physical environment variation, which is consistent with the Southern Oscillation and Arctic Oscillation in the northern hemisphere. In regard to the JZB ecosystem, the benthic diatom cell abundance (BEN) showed a decrease shift in 1978–1979, which is closely related to the precipitation abrupt decrease, while the shellfish mortality disaster in the JZB greatly released the predating pressure of diatom growth, possibly resulting in BEN increase shift in 1995.

Key words regime shift; multiple timescale; ecological impact; Jiaozhou Bay

1 Introduction

The coastal physical environment on a local spatial scale features a significant variation in long-term evolution trend. The physical forces, including wind speed and thermohaline structure with interannual and decadal variations, affect the circulation pattern dramatically, resulting in ecosystem instabilities. For instance, the sea temperature anomalies alter the patterns of net surface-heat fluxes, turbulent mixing, and horizontal transport in southern California Current, which is the most important mechanism for the observed plankton decline, and subsequent ecosystem changes (Mcgowan et al., 2003).

Regime shift is defined as a relatively brief time period when key state variables of a system are in transition between different quasi-stable states (Mantua, 2004). Since it always represents rapid reorganization of the ecosystem under study, it is usually re-

garded as one of the foremost important phenomena among the kinds of temporal evolutions in a coastal area. The occurrence of a major shift is helpful for the researchers and planners in their strategy-setting for more comprehensive analysis of complex environment variation and in sound decision-making processes (Chu Paoshin and Zhao Xin, 2003). During the past several decades, more and more evidence has been developed to support that regime shifts occurred in the early 1920s, the mid 1940s, the 1970s and the late 1980s (Graham, 1994; Minobe, 1997; Hare and Mantua, 2000; Denman and Pena, 2002).

It has been realized by many studies that long-term change may inherently feature multiple timescale oscillation (Chylek et al., 2009; Miettinen et al., 2012). These periodic oscillations were proved to be non-stable in the time-frequency domain (Torrence and Compo, 1998). The ocean-atmosphere system has variability on three distinct timescales: interannual,

decadal and interdecadal scales (Mann and Park, 1996). Therefore, it is reasonable to study regime shift on multiple timescales. In other words, regime shift on different time scales might not be the same. However, it is relatively seldom reported how regime shift depends on the timescale selected.

In addition, the physical environment variation on a local scale may be strongly affected by climate change on a basin-wide or even global scale through teleconnection. For instance, if there are decadal oscillations intrinsic to the tropical Pacific, they would be likely to teleconnect to the mid-latitudes and produce decadal variations there which resemble the interannual patterns associated with El Nino (e.g. Zhang Yuan et al., 1997). In regard to the coastal area, most studies on local environmental variability focus on intensive human activities (e.g. land reclamation, warm water discharge, and eutrophication), but fail to give priority to climatic regime shift on a global scale.

In this study, the multiple timescales regime shift, as well as periodic oscillation of hydrometeorological factors in the Jiaozhou Bay, a small coastal bay heavily influenced by human activities, was analyzed by wavelet transform. Special attention was paid to the similarities of local and global climate changes and relations of regime shifts between physical and biological factors.

2 Study area

The Jiaozhou Bay (JZB), with a surface area of about 400 km², is located along the western coast of the Yellow Sea (YS) (35°58'–36°18'N, 120°04'–120°23'E), and it is a partly enclosed waterbody with

a channel that connect the bay with YS (Fig. 1). The JZB features high primary production and supports greatly the economic development in the surrounding areas. For instance, the marine culture area in the JZB is about 150 km² (Guo Yonglu et al., 2005). The annual production of scallops was about 8.1×10^{-4} t in 1995 (Lu Jiwu et al., 2001). In the mean time, like other eutrophicated coastal areas in China (e.g. Changjiang Estuary), the marine environment around the JZB suffers from strong human activities, such as eutrophication and biodiversity reduction. It is widely emphasized that human impact (such as marine aquaculture) plays a foremost role in driving these changes in the JZB (Liu Sumei et al., 2010). However, whether the local climate variability around the JZB features abrupt changes related to global change and whether these abrupt changes can dramatically affect the marine ecosystem, even resulting in regime shift, are not clear.

3 Data and methods

3.1 Data collected

Listed in Table 1 are the data sources. The collected historical hydrographical, meteorological and biological data for the period from 1961–2000 in the Jiaozhou Bay were analyzed, including: (1) sea surface temperature (SST), (2) sea surface salinity (SSS), (3) air temperature (AT), (4) precipitation (PR), and (5) benthic diatom cell abundance (BEN). The first four data, i.e., hydrographical and meteorological data, are recorded, respectively, at Xiaomaidao (XM) and

Fig. 1. Topography (m) of the JZB with the location map inserted on the lower left, and sampling stations around the JZB. TD and XM are, respectively, the stations for measuring meteorological and hydrographical parameters. The benthic diatom cell abundance from the sediment record is given in B.

Table 1 The brief description of the observation data used in this study

No.	Abbreviation	Full name	Period	Interval	Source
1	SST	Sea surface temperature	1961–2000	1 month	XM station
2	AT	Air temperature	1961–2000	1 month	TD station
3	PR	Precipitation	1961–2000	1 month	TD station
4	SSS	Sea surface salinity	1961–2000	1 month	XM station
5	SOI	Southern Oscillation Index	1961–2000	1 month	NOAA*
6	AO	Arctic Oscillation	1961–2000	1 month	NOAA*
7	YS SST	Yellow Sea surface temperature	1961–2000	1 month	NCEP
8	BEN	Benthic diatom cell abundance	1961–2000	1 year	Liu Dongyan, 2004

Note: * <http://www.cdc.noaa.gov/Pressure/Timeseries/>

Tuandao (TD) (Fig. 1). The BEN was taken from the doctoral dissertation by Liu Dongyan (2004). The original sediment data include those collected in the period of 1889–2001 with a total of 100 records; by the interpolation method, the subsets were taken in the time period from 1961 to 2000, the same period as the physical data. The three stations are quite nearby, with the maximum distance of <25 km. The physical data in this study are of continuity, high sample resolution, with longer lifespan, compared with the data used in previous studies on China's coastal environmental variability (Lin Chuanlan et al., 2001; Fang Guohong et al., 2002) and the data derived from network stations of the State Oceanic Administration of China (Lin Chuanlan et al., 2005).

To analyze the local response to the environmental change on the Pacific-scale and marginal sea-basin scale, the monthly data—South Oscillation Index (SOI), SST in the Yellow Sea (YS-SST), and Arctic Oscillation (AO) are employed. SOI can be used to describe the ENSO events. YS-SST, with the resolution of 2° latitude×2° longitude, was retrieved from the global gridded optimally interpolated SST dataset of Reynolds and Smith (1994). In this study, the series of YS-SST is the spatial mean of the total 9 water grids in YS. In the large-scale mode of atmospheric variations, AO is derived as the leading principal of global winter sea level pressure, which is centered on the Arctic and extends southward into the North Atlantic and Pacific (Thompson and Wallace, 1998). According to Thompson and Wallace (1998), AO and ENSO play an equal and profound role in the variability of the north hemisphere climate system.

3.2 Wavelet transform

Wavelet, a multi-resolution analytical tool commonly used in geophysics, can be used to determine time series containing non-stationary power by decomposing the time series into time-frequency space (Daubechies, 1992). In this study, two mother wave-

lets are employed, Morlet and Haar. By Morlet wavelet transform, we revealed whether the time series features multiple-timescale oscillation, and the power spectrum is obtained, while Haar wavelet is used to detect regime shift. Since Morlet has been widely applied in geoscience studies (e.g. Miettinen et al., 2012), only the theory and algorithm of Haar wavelet transform is shown.

The earmarks of “regime shifts” are the abrupt transition from one stable state to another. Haar wavelet basis function is the best candidate for describing regime change because of its step-like character (Eq. 1). Haar wavelet basis function is

$$\Psi\left(\frac{t-\tau}{s}\right) = \begin{cases} 1 & t \in [\tau-s/2, \tau) \\ -1 & t \in [\tau, \tau+s/2] \\ 0 & t \notin [\tau-s/2, \tau+s/2] \end{cases} \quad (1)$$

where, t , s and τ are the time, scale and time moving factor, respectively. Given a time series $[x(t)]$ and a certain scale (s), the wavelet coefficient series, $W(t, s)$, can be obtained by the convolution below

$$W(t, s) = \frac{1}{\sqrt{s}} \int_T x(\tau) \Psi'\left(\frac{t-\tau}{s}\right) d\tau \quad (2)$$

where, t is the time range, and Ψ' is the conjugate of Ψ . Clearly, shift occurs when $t=\tau$. With the moving of t , the step-like variation is obtained; and as the scale is flexed, the temporal variation for regime shifts on multiple timescales can be revealed (Eq. 2).

The details of the significance test for real wavelet power (including Haar) can be found in Torrence and Compo (1998). Here, only main procedures and formulae are briefly introduced. Red noise is supposed to be the time series background in geoscience. Its power spectrum after normalizing is

$$P_s = \frac{1 - \alpha^2}{1 + \alpha^2 - 2\alpha \cos(2\pi/s)} \quad (3)$$

where α is the autocorrelation coefficient with lag time of one sampling interval, and s is the examined timescale with unit in sampling interval. $W^2(t, s)$ is distributed as $\sigma^2 P_{s x_1^2}$, where σ^2 is the variance of $[x(t)]$, and x_1^2 means chi-square distribution with one degree of freedom. After choosing a specified confidence level ($p=0.05$, in this study) for x_1^2 , if $W^2(t, s) \geq \sigma^2 P_{s x_1^2}$, t can be regarded as the time when the regime shift occurs at $0.5s$ -period. Since Haar uses a downward step function, the positive (negative) wavelet coefficient is associated with a decreasing (increasing) trend on a given timescale.

4 Results and discussion

4.1 Interannual and decadal variabilities

The monthly means of SST, AT, PR and SSS are, respectively, 13.7 and 12.6°C, 56 mm, and 31.17. All the parameters feature a unimodal temporal pattern (Fig. 2a, c, e, g). SST and AT reach their maxima in August and minima in February and January, respectively. A remarkable monthly difference was found in PR distribution. For instance, the precipitation in August contributes over 21.7% to the annual total, but less than 1.5% in January. SSS is high in winter and spring with the peak value of 31.49 in March and low in summer and autumn.

There are remarkable interannual variations in hydrographical and meteorological data (Fig. 2b, d, f, h). According to the linear regression results, the trends of the annual means SST, AT, PR and SSS are, respectively, 0.025 and 0.028°C·a⁻¹, -5.06 mm·a⁻¹, and 0.028 a⁻¹. During 1961–2000, these linear trends for the annual mean parameters resulted in an increase of 1.00°C for SST, 1.12°C for AT and 1.12°C for SSS, and a decrease of 202 mm for PR, respectively. The interannual trends are of significant difference during each decade. SST and AT were characterized by reduction in the 1960s, while increasing thereafter. SSS showed a positive trend in the 1960s and 1970s and a negative one in the 1980s and 1990s (Table 2). The temporal distribution of PR has an opposite phase to that of SSS.

A-SST, A-AT, A-PR, and A-SSS (the normalized monthly anomalies for the SST, AT, PR, and SSS) are obtained by subtracting the monthly means from original data and then dividing them by their standard deviations. The power spectra of the anomalies for the hydrological and meteorological regimes have peaks mainly on interannual or decadal timescales (Fig. 3). On decadal time scales, significant peak values are seen to occur at ~13-year, with this variability playing the most important role for A-AT and A-SSS, while energy component of other scales cannot be compared

with that of decadal timescale. A-SST decadal fluctuation is not as strong as that of A-PR. In regard to the interannual timescales, all the parameters feature a ~5-year wave component. A-SST and A-SSS are also considerably affected by the ~2.5-year oscillation; however this energy component is clearly lower than that of ~5-year. ~8-year period variability is predominant for A-AT, while this component is not significant for A-SST.

Table 2 The linear trends of the JZB physical parameters in each decade and the entire 40-years period

Period	SST (°C·a ⁻¹)	AT (°C·a ⁻¹)	PR (mm·a ⁻¹)	SSS (a ⁻¹)
1961–1970	-0.119	-0.109	-30.93	0.148
1971–1980	0.052	0.037	-20.44	0.072
1981–1990	0.027	0.037	35.16	-0.081
1991–2000	0.135	0.077	26.55	-0.031
1961–2000	0.025	0.028	-5.06	0.028

A continuous wavelet analysis, with Morlet transform, was performed to investigate the time-frequency variance for each parameter. The results are shown in Fig. 4 with the year on the abscissa and the return period (years) on the denary-logarithm scaled ordinate. Variability in time-frequency pattern of A-SST is apparently identical to that of A-AT, which is also consistent with correlation and spectrum analysis. Energy in low frequencies (10–20 years) was stable throughout the 40 years, while that in the mid-range (5–8 years) became steady after 1970. The higher frequencies (2–5 years) exhibited a notable period-transition during 1972–1980. For instance, the most important period for interannual timescales involved 2–2.5 years in 1972–1975, and 3–4 years thereafter. The patterns of time-frequency variability in A-SST and A-AT also had a few differences particularly after 1990 when high frequencies (1–2 years) appeared to be stronger in A-SST than A-AT. Similar to A-SST and A-AT, the time-frequency patterns of A-SSS and A-PR exhibited a close relationship featuring identical intensity, but an opposite phase (Fig. 4c and d). The low-frequencies band was much stronger in the 1970s and 1980s than that in the last two decades. The mid-range was steady in the 1970s, while the energy in this band was obviously higher in A-PR than in A-SST. After 1985, the mid-range energy maxima in A-PR shifted to 5–6-year periods. In the meantime, both decadal and interannual cycles were remarkably weakened.

Fig. 2. The seasonal (left) and interannual (right) variations of physical parameters in the JZB. The bold lines in the interannual variation curves show their linear regression result. The dashed lines indicate the ENSO events.

Fig. 3. Power spectrum analysis of the physical parameters on monthly anomalies [A-AT (a), A-SST (b), A-PR (c) and A-SSS (d)] as well as AO (e) and SOI (f).

Fig. 4. Morlet wavelet transform coefficients of the physical parameters monthly anomalies [A-AT (a), A-SST (b), A-PR (c) and A-SSS (d)] as well as AO (e) and SOI (f)].

4.2 Multiple timescale regime shifts

According to Haar wavelet analysis, the 1976–1978 regime shift proves itself to be significant for the temporal change in the first two primary components (EOF1 and EOF2 in Table 3) for all the physical parameters throughout the examined scales, while the 1988–1989 shift in the second primary component is only on a short scale (2-year period). This suggests that the small spatial scale region, like JZB, might be affected significantly by global-scale climate events, AO and ENSO, and the first world-wide global change (1976–1977 shift) is more important for the JZB system. In regard to decadal variation for A-SST, the shift in 1977 made SST increase by 0.54°C . Although A-SST is highly correlated to A-AT, the 1977 shift is not significant on such a scale, and neither is YS A-SST. This suggests that the origination of decadal shift for A-SST is not due to the linear process of heat flux at the interface between bay water and air, nor water exchange between JZB and YS. Therefore, the nonlinear process might be the only potential factor corresponding to such phenomenon. Another interesting phenomenon is that A-SST continuously increased after 1988 and so did A-AT on an interannual scale. However, a lot of literature reported that the basin-scale shift in 1988–1989 brought the global climate system to a colder regime, although this regime was still warmer than that before 1976–1977. This phenomenon is confirmed in the North and East Pacific (Hare and Mantua, 2000). The A-AT and YS A-SST also showed an increasing trend around 1989, which results in A-SST increase. Nevertheless, what drives AT over JZB and SST in YS varies at opposite phase with global change should be examined on a larger spatial scale focusing on the western part of the

Pacific. SSS change could be explained by the combination of the river discharge, precipitation, evaporation, and intrusion of YS with high salinity. However, the recent 40-years salinity data on YS are rare. Precipitation can provide freshwater input for the JZB, since the surrounding seasonal rivers discharge is dependent on precipitation. Although the decrease of evaporation in 1977–1978 on a 5-year scale might increase salinity in the JZB, A-SSS shows an evident increase owing to precipitation decrease itself and the induced river discharge decrease. The shift on 20-year scale for A-PR plays a dominant role for A-SSS shift in 1980, with a lag time of <1 year.

The A-PR shift in the early 1970s may be related to the variability of the Siberia High and Aleutian Low (Savelieva et al., 2000), the alternation of its position and intensity over the North Asia induced a different pattern of atmospheric circulation, and further precipitation. The 1980 shift for A-SSS was consistent with that of the Bohai (Lin Chuanlan et al., 2001). Other shifts such as those in 1985 for A-SSS as well as A-AT may be related to the local scale climate change.

The findings in this study accord with other research work in central and eastern North Pacific (Table 4 and Fig. 5). Analyzing the 32 data series in Hare and Mantua (2000) showed that a total of 25 series feature significant abrupt changes ($p < 0.1$). Most of the abrupt changes happened at about 1977 and 1988. Fishery resources' dramatic changes appear along with climate variations (e.g. central Alaska coho catch). Combined with the results of this study, such a conclusion can be drawn that the abrupt changes due to global change as well as their ecology impacts are significant not only in the central and eastern parts of the North Pacific, but also in the marginal seas' coastal regions of the West Pacific.

Table 3 The abrupt changes of the monthly physical parameters anomalies, their primary components, Yellow Sea SST anomaly, SOI and AO

Name	Scale (a)	Time for abrupt change	Type
A-SST	10	August, 1966	↓
		January, 1973	↑
	20	December, 1972	↑*
		August, 1977	↑*
A-SSS	10	June, 1966	↑*
	20	May, 1980	↑
A-AT	10	November, 1967	↓*
		November, 1972	↑*
	20	July, 1988	↑*
		December, 1989	↑*
A-PR	10	April, 1966	↓*
		September, 1970	↑*
	20	July, 1979	↓*
		August, 1979	↓*
EOF1	10	July, 1977	↑*
		April, 1984	↓
	20	August, 1977	↑*
EOF2	10-year	February, 1966	↓*
		May, 1970	↑
		July, 1977	↓*
		April, 1984	↑
	20	July, 1979	↓*
YS-SSTA	10	February, 1966	↓
		January, 1972	↑*
		June, 1977	↓*
	20	June, 1989	↑*
		May, 1981	↓*
		December, 1990	↑*
SOI	10	July, 1971	↑*
		July, 1976	↓*
		May, 1988	↑*
	20-year	May, 1993	↓*
		July, 1976	↓*
		March, 1986	↑*
AO	10	June, 1976	↑*
	20	March, 1988	↓
		July, 1976	↑*

Note: '↓' and '↑' stand for decrease shift and increase shift, respectively. The shift is confirmed if its significance level is over 90% (* for 95%).

Table 4. The abrupt changes of the 32 selected series with the lifespan of 1965–1997, retrieved from Hare and Mantua (2000), in the central and eastern of the North Pacific Ocean

No.	Abbreviation	Full name	Shift period
1	NPATMOS	North Pacific Atmospheric Pressure Index	1977(↑*) 1988(↓)
2	PDOWIN	Pacific Decadal Oscillation-winter index	1977(↑*) 1989(↓*)
3	PDOSUM	Pacific Decadal Oscillation-summer index	/
4	NINO34WIN	ENSO 3.4-winter index	1979(↑)
5	NINO34SUM	ENSO 3.4-summer index	1970(↓)
6	KSAT	King Salmon, AK air temperature	1977(↑*)
7	CBAT	Cold Bay, AK air temperature	1988(↓)
8	PISST	Pribilof Islands sea surface temperature	1989(↓*)
9	EBSPOLL	Eastern Bering Sea walleye Pollock recruitment	1983(↓*)
10	CAK_CO	Central Alaska coho catch	1977(↑*)
11	CAK_PI	Central Alaska pink catch	1976(↑*)
12	SAK_CO	Southeast Alaska coho catch	/
13	SAK_PI	Southeast Alaska pink catch	/
14	SKEESTR	Skeena River stream flow	1977(↓*) 1988(↑)
15	KISST	Kains Island sea surface temperature	1971(↓) 1977(↑*)
16	U51N131W	Upwelling at 51N, 131W	1980(↓*) 1988(↑)
17	NDR	Northern diversion rate	1978(↑) 1991(↑)
18	BC_PI	British Columbia pink salmon catch	1992(↓*)
19	FORAT	Forks, WA air temperature	1974(↑*)
20	NEWAT	Newport, OR air temperature	/
21	EURAT	Eureka, CA air temperature	1980(↑*)
22	COLSTR	Columbia River stream flow	/
23	8RIVSTR	8 Rivers index	1980(↑*); 1987(↓*)
24	SCRSTT	Scripps' pier sea surface temperature	1977(↑*)
25	U48N125W	Upwelling at 48N, 125W	1983(↓)
26	U42N125W	Upwelling at 42N, 125W	/
27	U36N122W	Upwelling at 36N, 122W	/
28	OCI	Oyster Condition Index	1980(↓*)
29	WCMACK	West Coast mackerel recruitment	1976(↑*)
30	WA_CO	Washington coho catch	1992(↓*)
31	WA_PI	Washington pink catch	1981(↓*)
32	OR_CO	Oregon coho catch	1992(↓*)

Note: The abbreviations for the data series are plotted in Fig. 5. '↓' and '↑' stand for decrease shift and increase shift, respectively. The test is conducted on the timescale of 10-year. The shift is confirmed if its significance level is over 90% (* for 95%).

4.3 Potential ecological effect of the regime shift

Physical environment abrupt change was proved to have resulted in regime shift in the biology field (Hare and Mantua, 2000). In regard to the JZB ecosystem, BEN showed a decreasing shift in 1978 on a decadal timescale ($p < 0.1$) (Fig. 6), which is consistent with A-PR decrease and A-SST increase. In the JZB, silicate, which comes from seasonal fluvial loads, is one of the most important limiting elements for diatom growth (Yang Dongfang et al., 2005, 2006). The river discharge varied along with precipitation. Clearly, the A-PR decrease has a significant potential impact on diatom cell abundance. A-SST increase may accelerate the photo-

synthesis and metabolism processes in the mean-time. The decrease of diatoms responding to A-SST increase suggests that the cold species may contribute to total phytoplankton biomass. Besides the 1978 shift, BEN shows two minor abrupt changes, negative shift in 1972 and positive shift again after 1996. The 1972 shift might be ascribed to SST increase in the early 1970s. There is no regional dramatic change corresponding to the 1996 shift. The only causative reason might be related to the great aquaculture disaster in 1995 when shellfish in the JZB suffered from the accidental mortality (Jiao Nianzhi, 2001). Shellfish mortality greatly released the predating pressure of diatom growth, possibly resulting in BEN increase.

Fig. 5. The abbreviations for the physical and biological time series in the central and eastern parts of the North Pacific Ocean. They are geographically plotted in the places where the variables are measured or have influence.

Fig. 6. The normalized benthic cell abundance during 1961–2000. The brown vertical solid line and two dashed lines indicate, respectively, the 1978 shift in the 10-year period and 1972 and 1995 shifts in the 5-year period. The black dashed line indicates the separation of two regimes by the notable 1978 shift.

5 Conclusions

During the period of 1961–2000, the physical environment was characterized by significant variations. AT, SST and SSS showed positive trends, while PR showed a negative trend. Anomalies of the local environment accord with global climate change indices, i.e., SOI and AO. Power spectrum analysis and wavelet transform revealed that the variability for the physical environment has features of the interannual (about 2–3 years and 5–6 years) and decadal (about 10–11 years) periods with these different wave components being dominated in the fluctuations in different stages.

Abrupt changes on multiple timescales play an essential role in the physical environment temporal variations. Most of these significant shifts, such as the 1976–1978 and 1988–1989 shifts are consistent with climate regime shift in the Northern Hemisphere induced by atmosphere circulation variability. SST and PR regime shifts around 1978 have a notable impact on the BEN abrupt decrease in the decadal period. The BEN minor shift in 1972 is due to the SST shift in the early 1970s. The abundance showed a positive trend again after 1995, possibly because of shellfish mortality in 1995. This study provides evidence suggesting that the regime shift due to global change as well as its ecologic impact is significant not only in the central and eastern parts of the North Pacific region, but also in the marginal seas' coastal regions of the West Pacific region which is highly influenced by local human activities.

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