Ann. Limnol. - Int. J. Lim. 2020, 56, 1
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https://doi.org/10.1051/limn/2019026

Available online at:
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RESEARCH ARTICLE

# Long-term wind induced internal response mechanisms at Meiliang Bay of large, shallow Lake Taihu

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Received: 4 July 2019; Accepted: 18 December 2019

**Abstract** – The internal response of shallow lakes to external factors is very important to investigate for understanding their role in long-term changes of the shallow lake ecosystem. The current study investigated the impacts of long-term wind dynamics on in-lake processes of the degraded shallow lake. The long-term high-frequency wind field, water quality, and *Chlorophyll-a* data analysis showed that there were two groups of variables found with higher internal similarity at Meiliang bay of large, shallow Lake Taihu. The temporal trends of wind, temperature, and *Chl-a* found highly consistent while dissolved oxygen (DO), total nitrogen (TN), total phosphorus (TP), suspended solids (SS) and Secchi depth were not significantly correlated in long-term temporal trends analysis. The results showed that *Chl-a* and other shallow lake ecosystem variables (abiotic) are strongly related to long-term wind field. The changes in nutrients and lower mixing scenarios trigger the growth of *Chl-a* and onshore lower winds help in the formation of colonies. There was a shift in wind and internal response variables before and after 2006. Wind and internal water quality parameters were highly variable before 2006 whereas, decline in wind speeds along with stable wind directional switching caused intense blooms formation along with thermal stratification (warming) for a longer period of time (after 2006) in the shoreline areas. The current study can help to understand the internal ecosystem response mechanisms in long-term interactions with wind field to control the eutrophication and algal blooms.

**Keywords:** Lake Taihu / Wind dynamics / response mechanism / generalized additive model

## 1 Introduction

The persistent and abrupt reorganization of aquatic communities have been found increasing due to certain large-scale changes in climatic-patterns (Boucek and Rehage, 2014; Hare and Mantua, 2000; Kortsch *et al.*, 2012; Smol *et al.*, 2005). Lakes are highly sensitive to respond environmental changes (Parker *et al.*, 2008; Williamson *et al.*, 2009). In particular, shallow lakes are highly vulnerable to the eutrophication processes due to internal and external nutrients loading along with wind-induced forcing. Many lakes around the globe faced severe water quality degradation due to excessive contamination and in-lake processes causing eutrophication. Shallow lakes in China are mostly surrounded by densely populated areas where those lakes are a major source of freshwater (Janssen *et al.*, 2014). These lakes have been experiencing severe *algal* blooms, which resulted in water supply cutoff especially at Lake Taihu (Guo, 2007; Kuiper *et al.*, 2015; Michalak *et al.*, 2013; Paerl *et al.*, 2014; Zhang *et al.*, 2015).

Wind has vital importance as a control parameter in the functioning of shallow lakes internal ecosystem. The dominant effects of wind dynamics to shallow lake ecosystem includes (but not limited to) the thermal destratification/water column mixing, nutrients and sediments resuspension, and *algal* blooms formation. The local wind speed and directional switching control the hydrodynamic structure, and unsteady high-frequency winds cause internal mixing of nutrients and sediments at Lake Taihu (Liu *et al.*, 2018). Wind has a dominant impact on the phytoplankton distribution in shallow lakes (Paerl *et al.*, 2006). Jalil *et al.* (2017) studied the impacts of wind field at the eastern bay of Lake Taihu and found that wind field played a major role in nutrients and sediment resuspension. Schoen *et al.* (2014) investigated wind circulation patterns and associated directional switching, and found that these circulations cause intermittent water exchange and mixing between the lake basins at an estuarine lake St Lucia,

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South Africa. The internal response mechanisms of Lake ecosystem to wind dynamics need to be thoroughly investigated in already degraded shallow lakes. The internal nutrients loading mainly influence the in-lake processes due to wind-induced mixing and thermal stratification (Jalil *et al.*, 2018). Therefore, it is important to identify the internal response mechanisms and interactions while considering long-term wind dynamics as a major component of the hyper-eutrophic shallow lake environment.

Despite the recognition of wind dynamics impact on shallow lake ecosystem as a major factor, the deep insight into changes in wind speed dynamics, along-with changes in the directional switching patterns still needed to investigate thoroughly. Wind dynamics can play a vital role in understanding the shallow lake internal system transition. It is also important to investigate the long-term wind induced thermal destratification in shallow lake environment. Especially, how the changes in wind patterns impact thermal scenarios, which further leads to the *algal* blooms formations. The present study used long-term internal physio-chemical water quality and *chlorophyll-a* data along-with wind field data. The internal response mechanisms has been determined while considering wind as a control variable in the already degraded shallow lake ecosystem.

The aim of the present investigation was to determine the effects of wind forcing and thermal scenarios on the internal processes in a shallow lake environment. Therefore, the objectives of present study were to (i) determine the long-term trends in wind dynamics of the eutrophic shallow lake to study the response of internal variables of lake to wind field, (ii) determine the major groups of response variables through long-term multiple internal responses between different variables and (iii) identify the wind-induced positive and negative changes in the internal ecosystem conditions within the shallow lake environment. The present study could provide a deep inside into the role of wind as an external driver in controlling the degraded shallow lake internal processes by describing different internal response mechanisms and internal system transitions in long-term interactions.

## 2 Materials and methods

### 2.1 Study region

Lake Taihu is a third largest freshwater lake in Yangtze Delta of China having more than 2338 km$^2$ of water surface area (Zhao *et al.*, 2011) with a mean depth of 1.9 m and a maximum depth of 2.6 m, and an elevation of 3.0 m a.s.l. (Qin, 2008). The earlier occurrence of intensive *cyanobacterial* bloom led to the drinking water crisis in late May 2007, which affected more than 2 million people in the surrounding areas of Lake Taihu (Qin *et al.*, 2010). The main function of Lake Taihu is water supply, to Wuxi, Shanghai, and Suzhou along with aquaculture, tourism, water diversions/irrigation, fisheries, and navigation. Lake Taihu is also important for connecting major cities by boats for small goods transportation. Lake Taihu is facing severe *algal* blooms and eutrophication since last 2 decades. The Meiliang bay of large shallow Lake Taihu was selected to study the long-term impacts of wind field on internal processes. Meiliang bay is a highly eutrophic bay of Lake Taihu with high internal nutrients resuspension and presence of *algae* (Gao *et al.*, 2017; Liu *et al.*, 2014; Zhu *et al.*, 2013). Meiliang Bay is a semi-enclosed bay having a surface area of 129.3 km$^2$, 1.9 m average depth and is located northern part of Lake Taihu (Gao *et al.*, 2017; Huang, 2004). Annual average wind speed ranges from 3.5 m/s to 5.0 m/s at Meiliang Bay of Lake Taihu (Wu *et al.*, 2013).

### 2.2 Data collection

Wind field data (10 minutes average daily wind speed and wind direction) collected from Taihu Lake Laboratory for Lake Ecosystem Research (TLLER) from January 2000 to December 2016. The internal lake environmental variables which includes water temperature, dissolved oxygen (DO), total nitrogen (TN), total phosphorus (TP), pH, electrical conductivity (EC), Secchi depth, *Chl-a* concentrations, suspended solids (SS), Chemical oxygen demand (COD), total organic carbon (TOC), and total inorganic carbon has been obtained from Meiliang bay (Fig. 1), 3 times/day for the same period of time. The water quality samples were collected 50 cm below the water surface and from the near bottom zone (50 cm above the bottom). Both samples were mixed to estimate complete vertical profile of water quality at Meiliang bay of Lake Taihu. Secchi disk had been used to measure Secchi depth at the sampling site.

The 10 minutes averaged daily data of wind field has been used for estimation of long-term precise wind field scenarios. Wind speeds were converted into the intervals of 0.1–3.0, 3.1–6.0 and 6.1–9.0 m/s. Wind directions were divided into 16 intervals for estimating long-term wind direction patterns in the study area. The different hypotheses were tested to check the linear and non-linear correlations among internal and external lake ecosystem drivers.

### 2.3 Statistical analysis

Hierarchical agglomerative cluster analysis was performed by means of Ward's method using Euclidian distance as a measure of similarity to check the similarity between different groups of variables. The 17 years daily data of variables (DO, COD, TP, TN, *Chl-a*, SS, Temperature, pH, EC, Wind, TOC, and Secchi) included in all types of analyses. The data frequency for physio-chemical and *Chl-a* was three times daily, while wind data frequency was 10 minutes averaged daily. The data were log-transformed, and standardized by Z scores before cluster analysis. The data were tested for normality, homogeneity of variance for multivariate evaluation of data, and significance was measured within and between groups. The principal component analysis (PCA) along with the rotation method of varimax with Kaiser Normalization on the raw data has been used to check the distance among different ecosystem drivers. The hierarchical cluster analysis and PCA were performed in SPSS 20 package (SPSS Inc.). Linear regression analysis was performed to check the significance ($p \leq 0.05$) of correlation between the ecosystem drivers on annual basis. The generalized additive model (GAM) has been applied to draw temporal trends and relation between ecosystem drivers (log-transformed data) in RStudio

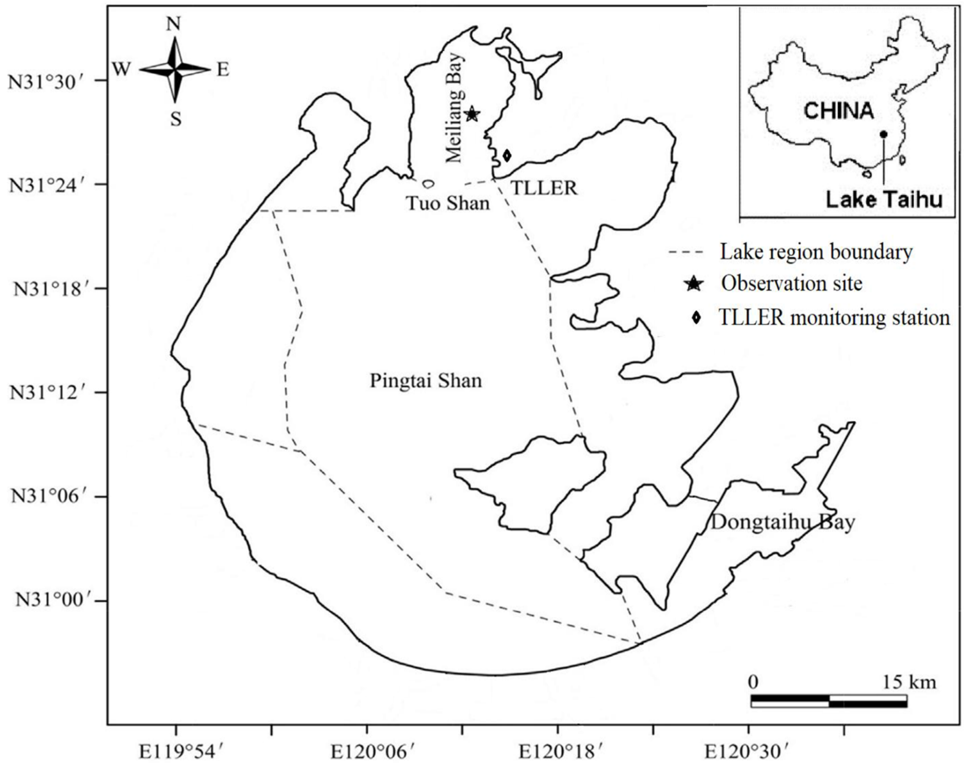


**Fig. 1.** Geographical description of Lake Taihu along with present study water quality and wind field data collection site.

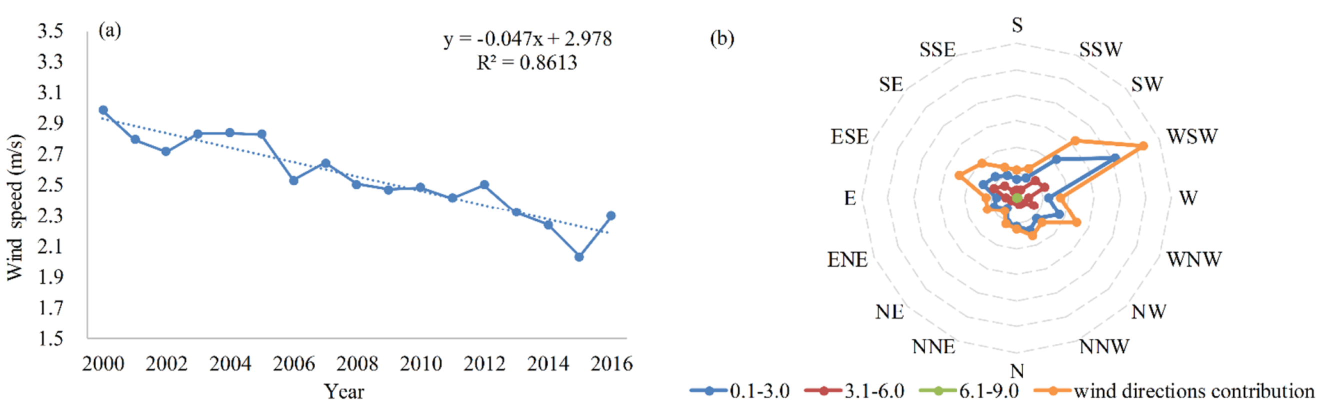


**Fig. 2.** Average annual (a) wind speed trends and (b) frequency distribution of wind speeds for different wind directions from Jan, 2000 to Dec, 2016.

1.1.453 software (RStudio Inc.). GAM was performed by using gam function (family = Gaussian, with bootstrap smoother) in mgcv package (Wood, 2007) in R. Based on results obtained from linearly fragmented temporal trends of ecosystem drivers, the PCA biplot of physio-chemical variables along with *Chl-a* concentrations and wind speed were drawn by using standardized data for two conditions to separate the pre-2006 and post 2006 scenarios of drivers response mechanisms by using PAST 3.20 (Hammer, 2018). The structural equation model (SEM) was performed to draw the conclusion of the internal response of the ecosystem to wind dynamics.

## 3 Results

Wind speed data analysis showed that there was a dominant decrease observed in the wind speed with an annual decrease of 0.0406 (m/s) during 17 years period (from January 2000 to December 2016) (Fig. 2a). The results of wind speed frequency distribution showed that wind speed interval of 0.1–3.0 (m/s) was most prevailing (74%) wind speed followed by 3.1–6.0 (m/s) of 26% and 6.1–9.0 (m/s) interval contributed 1% from January 2000 to December 2016 at Meiliang bay of Lake Taihu.

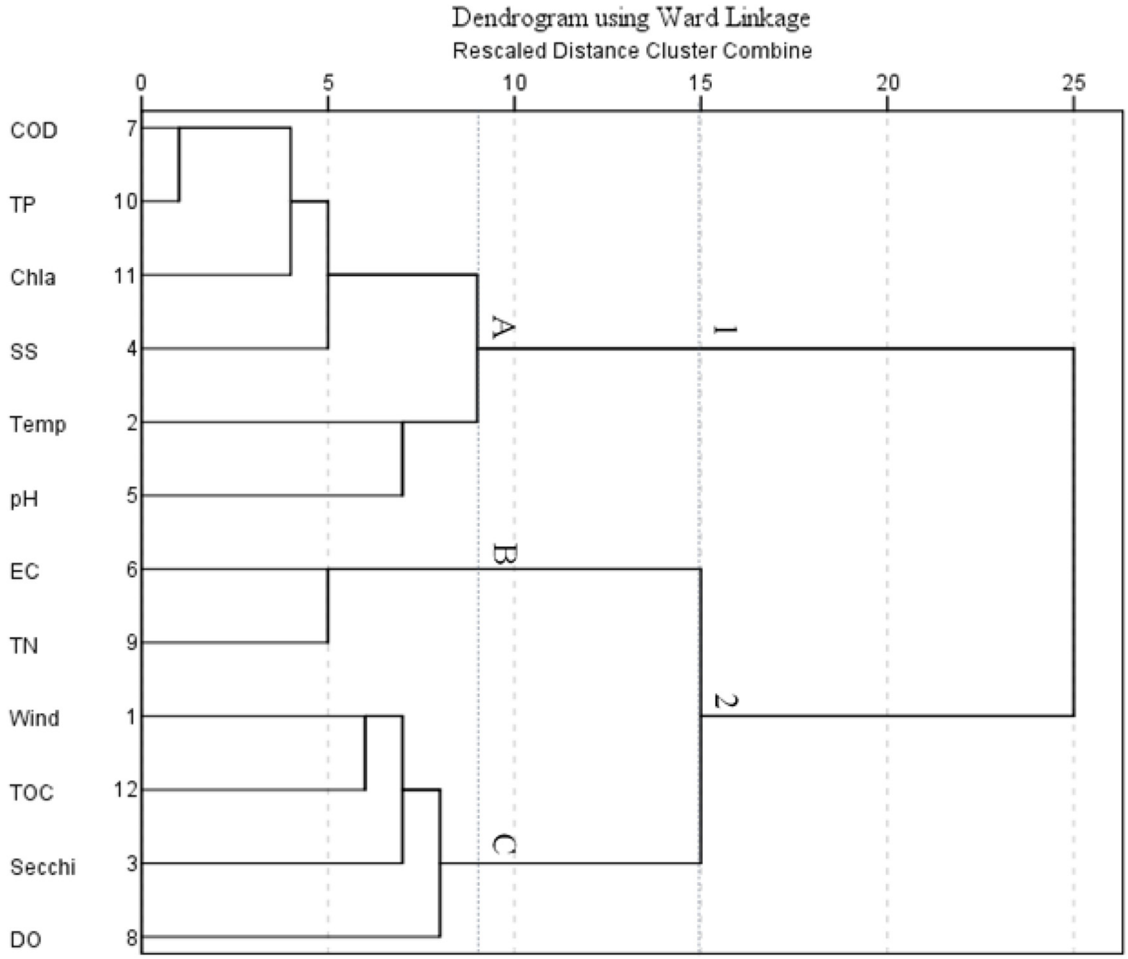


**Fig. 3.** Hierarchical cluster analysis of major drivers and response parameters at Meiliang Bay of large shallow Lake Taihu. There are two major groups found as result of cluster analysis, which has been mentioned as 1 and 2 in the figure.

Wind direction frequency estimations showed that there were six dominant wind directions observed from Jan 2000 to Dec 2016. There were four dominant onshore/prevailing wind directions and two offshore/non-prevailing during the entire study period. The onshore wind directions of west-southwestern (18.26%), south-western (11%), east-southeastern (8.24%) and southeastern (6.57%) contributed dominantly whereas, offshore wind directions of west-northwestern (8.64%) and north-northwestern (5.52%) have been observed major wind directions during the study period (Fig. 2b).

### 3.1 Groups of variables

There were two major groups of clusters found (using hierarchical cluster analysis) in the present study, which has been marked as 1 and 2 in Figure 3. These two groups have been found with higher distance at which they combine due to the higher Euclidean distance between both groups of data samples. More precisely, there were three subgroups, which have been marked as A, B, and C in the figure below. The subgroup A (containing TP, *Chl-a*, pH, Temperature, SS and COD) has been found with higher Euclidean distance from B (EC and TN) and C (Wind, TOC, Secchi and DO) whereas, B and C had a smaller Euclidean distance from each other. The above-mentioned groups showed internal correlations between different variables in highly degraded/hyper-eutrophic shallow Lake Taihu. These two major groups have the higher level of internal similarity in long-term and each variable in a certain group may have the ability to play its role as the positive or negative impact variable on others.

The results of PCA verified the groups formed through hierarchical agglomerative cluster analysis. There was also a clear similarity based correlation found between group "A" parameters of cluster analysis in PCA. The results of PCA confirmed the positive or negative interrelationship between the drivers and response variables as mentioned in Table S1.

The linearity of the internal drivers and response parameters with wind speed, water temperature, and DO was tested by using regression analysis. The results showed that there was not clearly significant linear correlation found among the ecosystem variables of large shallow lake Taihu. The higher frequency of data caused this non-significant linear correlation, due to which the generalized modelling approach has been used. The results showed only a linear correlation between wind speed and *Chl-a* concentrations with the significance value of 0.0073 as mentioned in Table S2.

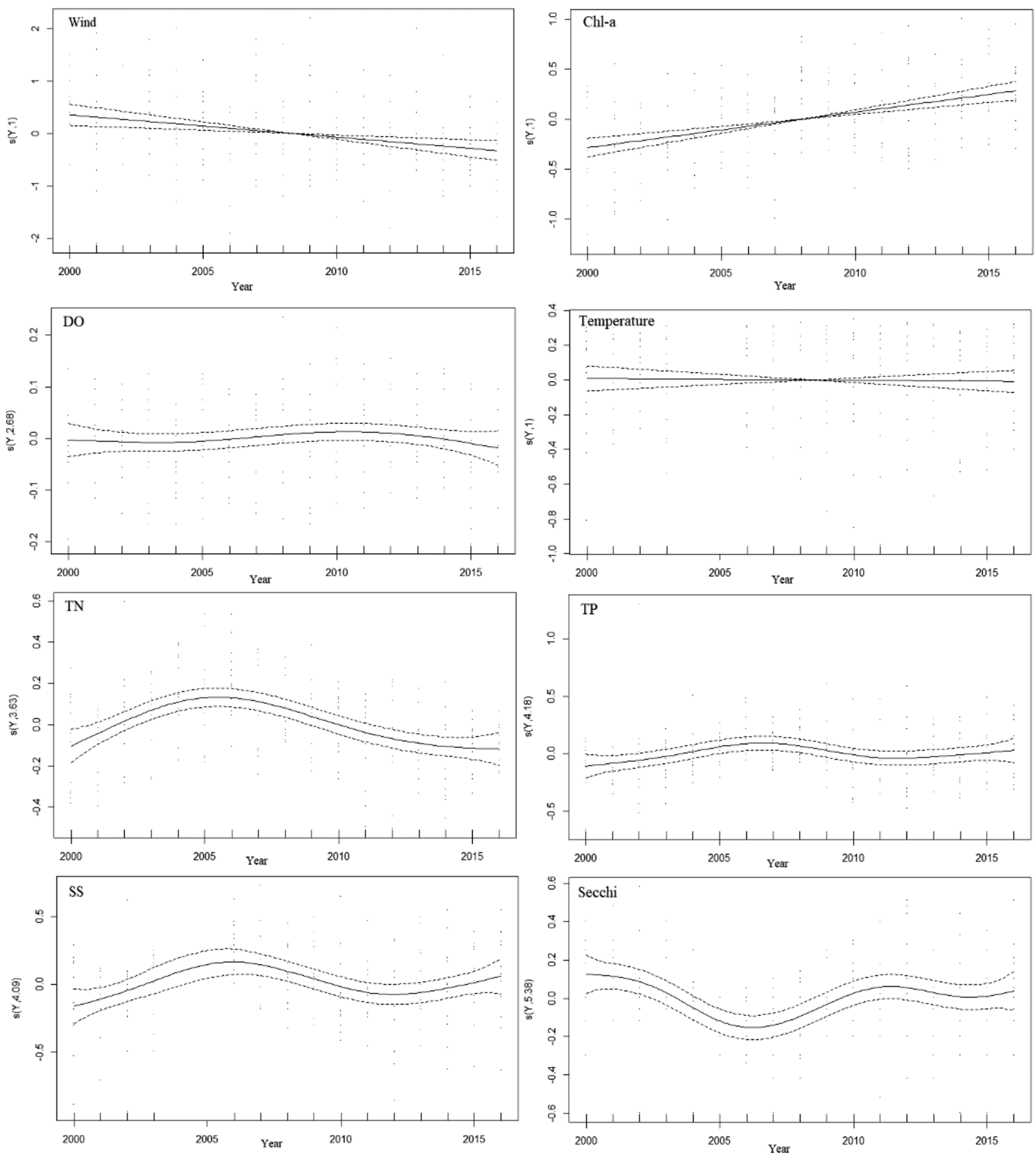


**Fig. 4.** Long-term temporal trends in wind speed and water quality variables (log-transformed) with 95% confidence of interval drawn using bootstrapping calculation method estimated degree of freedom is provided along the *y*-axis of each variable plot.

### 3.2 Long-term temporal trends at Meiliang Bay of Lake Taihu

The annual means of all the ecosystem variables were unevenly distributed and most of them changed their response after a point, which was 2006 in most of the cases (Fig. S1). Wind speed distribution patterns showed that there was a decreasing trend from 2000 to 2006 but it increased abruptly in 2007 from where it started to decline again. Therefore, 2006–2007 was the duration where wind speed patterns increased abruptly to a critical level and then gradually decreased after that period of time. The other variables which includes DO, *Chl-a*, TN, TP, Secchi depth and SS concentrations showed direct positive or negative response to wind field whereas, temperature trends were continuously changing within 15 °C to 19 °C throughout the annual monitoring period but still 2006–2007 was the time period after which internal temperature trends changed abruptly (Fig. S1). We divided wind field data to further clarify the difference between two ecosystem states *i.e.* from 2000–2006 and from 2007–2016.

The Nonlinearity in the temporal trends of wind and internal ecosystem variables (Tab. S2, Fig. S1) led us to investigate about generalized modeling of individual variables. We checked the residuals distribution, and bootstrap smoother was applied to draw 95% confidence of intervals. Moreover, the statistical comparisons were explained by using smoother $p$ values, $R^2$, and GCV for a better understanding of the results of the GAM model. The estimated degree of freedom (edf) is the indicator of the estimated degree of nonlinearity (*e.g.* edf closer to 1 shows a linear relationship whereas, edf >1 indicates progressively higher-order relationship).

The results showed consistently decreasing temporal trends of wind speed and temperature, while *Chl-a* has been observed consistently increasing during the investigation period. The other drivers have been found with higher temporal variations with higher degree of freedom. Therefore, there were three ecosystem drivers, which have shown higher temporal consistency in the present study.

### 3.3 Internal response mechanisms at Meiliang bay of Lake Taihu

The results of wind field analysis showed that the period from 2000–2006 showed higher fluctuations in wind speed and wind directions whereas, the period from 2007–2016 showed comparatively lower fluctuations in wind speed and directions. There were four dominant onshore winds including WSW, SW, ESE, and SE while WNW and ENE were dominant offshore wind directions during the first transition period (2000–2006). The wind speeds have been found higher during the first period (2000–2006) and wind speed intervals of 0.1–3.0 m/s and 3.1–6.0 m/s were dominant wind speeds.

The most dominant onshore wind direction was WSW followed by SW, ESE, and SE while NNW, and WNW dominant wind directions during the second transition period (2007–2016). There were slow winds observed with low fluctuations with the most dominant wind speed interval of 0.1–3.0 m/s during the second transition period (Fig. 5b).

The PCA biplot was drawn to clarify the pre-2006 and post-2006 scenarios of ecosystem response and slowing down mechanisms in the degraded shallow lake environment. The chronological clustering of the mentioned variables showed 2006 as a change point in the time series, which ultimately indicated the marked changes in the in-lake physio-chemical, biological variables, and wind dynamics (Fig. 5c). Wind speed showed fewer changes as compared to all other variables but has shown a negative correlation with most of the variables in both pre-2006 and post-2006 conditions (Fig. S1). TN, TP, *Chl-a*, COD, SS, pH and Secchi depth have shown high variability (the circles mentioned in PCA biplot are 95% ellipses). Secchi, DO and TOC has been found in a negative correlation. The results of biplot show that wind speed, water temperature, DO, SS, COD, and TP were very close to PC2 with eigenvalues of −0.72, 0.55, 0.82, 0.93 and 1.13 respectively. Whereas, EC and TN were found closer to PC1 with eigenvalues of 1.92 and 2.05 respectively.

### 3.4 Long-term wind impacts

The linear regression between wind, water temperature, DO and other dependent variables have been calculated which showed a nonlinear correlation between them (Tab. S2).

The GAM has been applied in the current study to evaluate the impact of long-term wind dynamics at large, shallow Lake Taihu. There was significant correlation observed between wind and other environmental variables after applying bootstrap smoothing (Fig. 6). The estimated degree of freedom can be seen along with the state axis ($x$-axis). The results have shown that 2.3 m/s was the critical wind speed observed at which all parameters have shown a higher response to wind field.

## 4 Discussion

The heterogeneity and connectivity of the systems are important components to understand dynamic processes in it. The shallow lake internal processes are also connected to each other, and with external factors. Shallow lakes response to external forces is non-linear (Beklioglu *et al.*, 2010; Jeppesen *et al.*, 1999; Jeppesen *et al.*, 2012; Moss, 2009; Scheffer *et al.*, 1993). Wind plays important role in defining hydrodynamic and water quality status of shallow lakes (Jalil *et al.*, 2017). The shallow lakes fragility to slow systematic change can lead to an alternate state after an abrupt event of a catastrophe. However, along with slow changing conditions, the system as a whole reaches a certain tipping point from where it starts to revert back, which can be called as "systematic shift". The sharp changes can also be the result of a sudden big external impact in shallow lakes especially wind induced impacts.

The directional switching also plays a vital role for the dispersion and colony formation of *algae* in shallow lakes as mentioned by Schoen *et al.* (2014) in terms of wind circulation effects through mixing and intermittent water exchange. The current study showed the decreasing wind speeds during the last two decades, which might be due to changes in the global circulations in recent decades due to global warming (Mcvicar *et al.*, 2012). The decrease in the wind speed leads to the stability in the water column, which results in a reduction of wind-induced vertical turbulent mixing (Zhang *et al.*, 2018). If the wind-induced nutrients release is weaker, then it is the indication of the reduction of pulse increase in phytoplankton biomass (Yang *et al.*, 2016) but the nutrients in the vertical column of Lake Taihu are sufficient for the growth of *algae*. The results of the current study showed long-term slowing down of wind speeds in the study area. There can be different positive and negative correlations among certain indicators, which can be grouped together based on their correlation with each other. For instance, the results of the current study showed that there were two groups of internal drivers and response parameters as mentioned in the form of two major clusters (Fig. 3) to which drivers and response parameters are directly

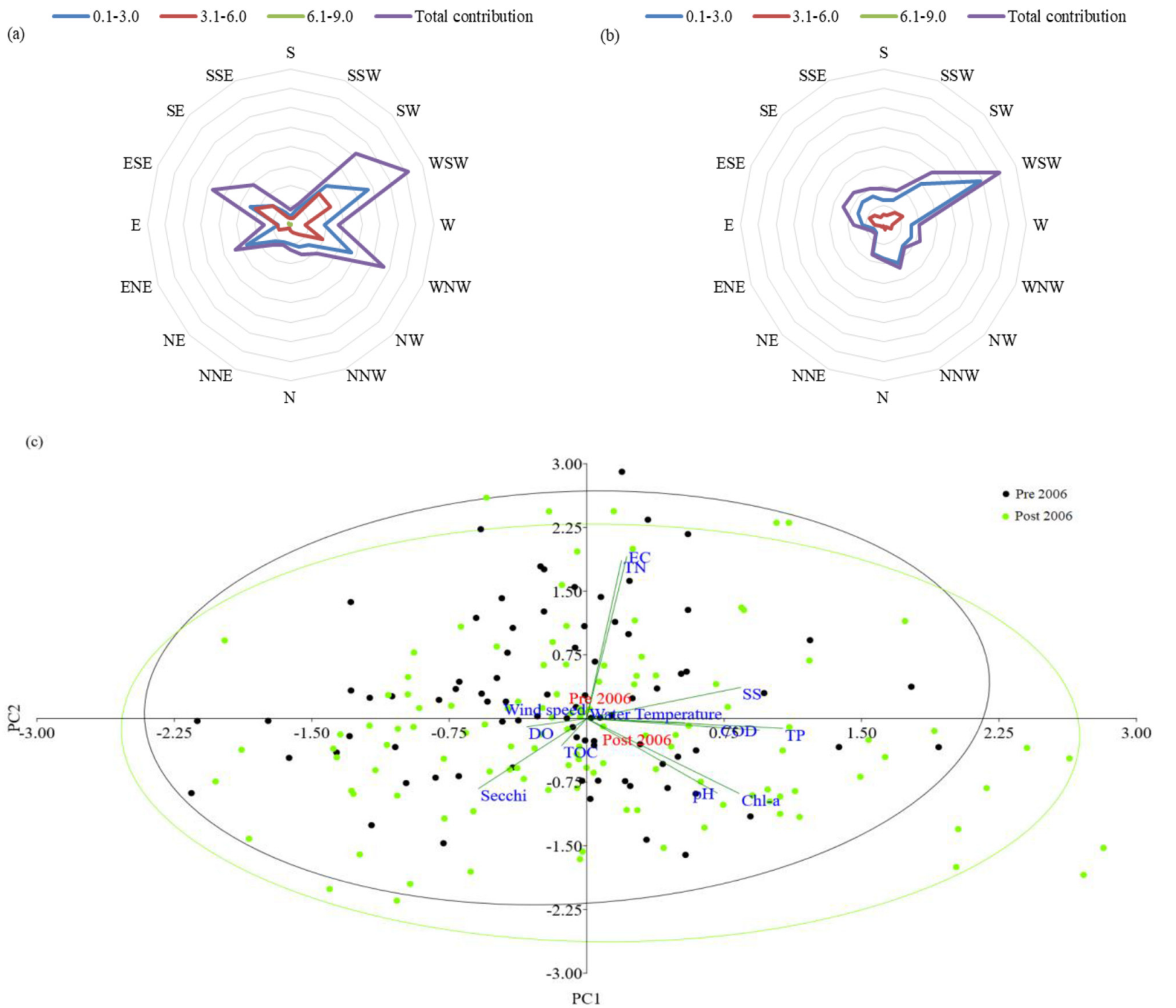


**Fig. 5.** The frequency distribution of wind speeds and directions (a) from Jan 2000 to Dec 2006, (b) from Jan 2007 to Dec 2016 and (c) the biplot of environmental variables pre-shift and post-shift at Lake Taihu. The length of the arrow lines represents the variance. The black and green dots represent a partition of time series into two groups with circles representing 95% confidence of interval for each group. The positive and negative correlations of Environmental variables are presented in positive and negative quadrants of biplot.

related to each other. In group A, as *algal* and *cyanobacteria* biomass is driven by TP and temperature and the pigment in turn, governs pH through photosynthetic uptake of inorganic carbon and can be responsible for lots of suspended particles in a eutrophic bay (SS). Group B are parameters independent of the *Chl-a* and wind and suggest that TN is likely in excess because of high dissolved inorganic nitrogen and EC is a conservative property reflecting groundwater and river input. Group C contains wind strongly linked to the three lake variables, *i.e.*, wind could control aeration of the bay (introduction of oxygen from the atmosphere) and perhaps resuspension of sediment to reduce light penetration (Secchi) and release organic carbon from bottom sediment pools.

The bootstrapping method of GAM provides a clear evidence of a significant temporal trend of key variables (Wind, temperature, and *Chl-a*) with 1 estimated degree of freedom. Whereas TN, SS, and Secchi were found in a non-significant temporal trend with a comparatively higher estimated degree of freedom 3.63, 4.09 and 5.38 respectively. The remaining environmental variables (DO and TP) showed significant non-linear temporal trends (GAM results in Fig. 4 and Tab. S3).

The PCA also mentioned the parameters, which are positively or negatively correlated with each other. Wind, Secchi, DO, and TOC were also closely related to each other in long-term data frequencies (Fig. S2). The long-term changes in the indicators can be non-linear but can also be linear in different spans (Figs. S2 and S3). The two contrasting alternative scenarios were observed in the Meiliang bay of Lake Taihu and the tipping point for the long-term change was observed before 2006 and after 2006.

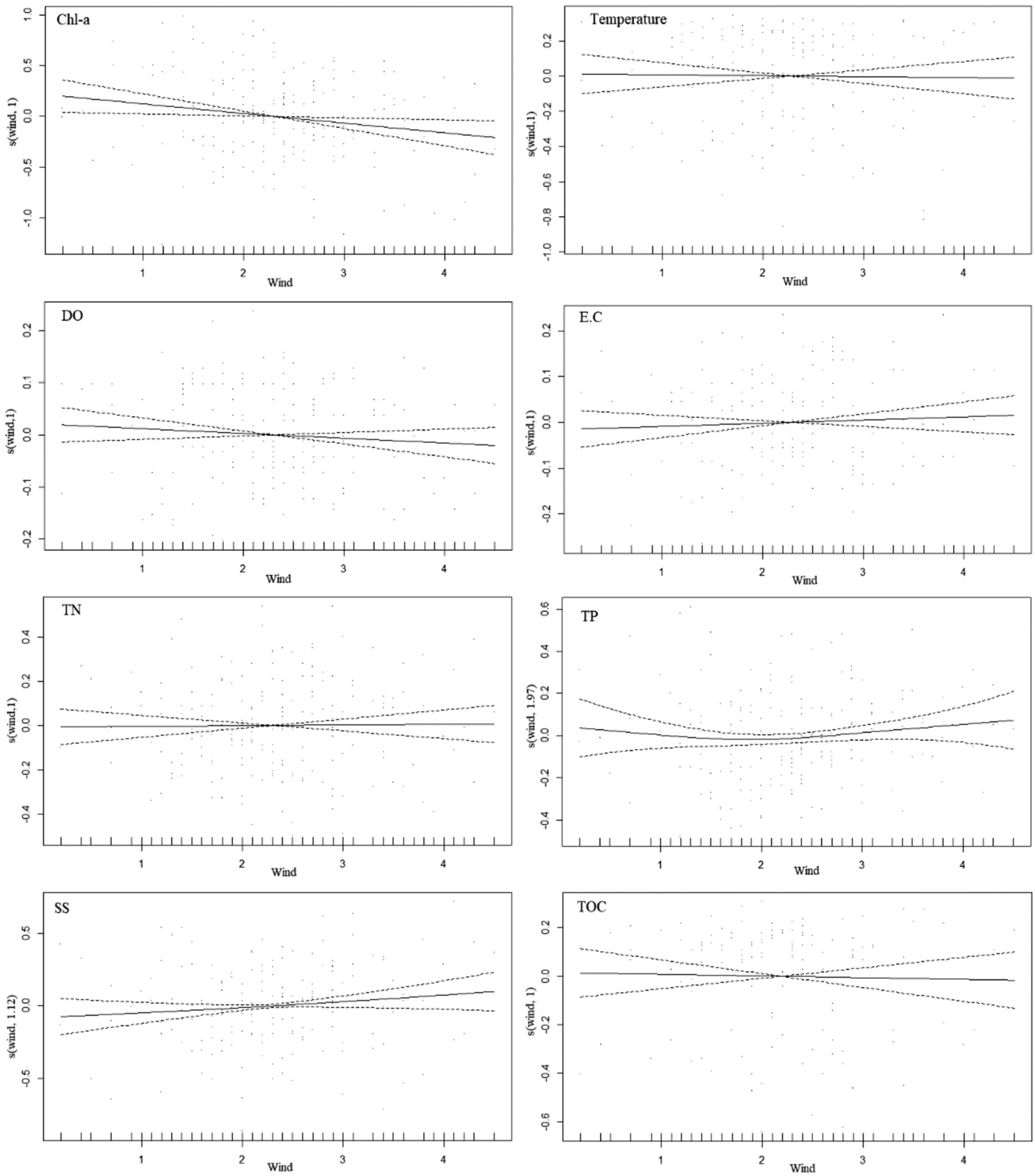


**Fig. 6.** Long-term wind impacts on environmental variables by using GAM model. The small dots are the residuals extracted after GAM model. The 95% confidence of intervals were calculated from bootstrapping. The number of parentheses on the y-axis indicates the estimated degrees of freedom.

The variability in TP concentrations has traditionally been used as an indicator to determine the threshold for switching between two alternative stable states (Scheffer *et al.*, 1993). The present study showed an annual increase of 0.0022 mg/L in TP concentrations during 17 years of observations whereas, TN concentrations decreased by 0.065 mg/L annually in the degraded shallow lake environment. There was a continuous annual increase of approximately 2.1 µg/L in *Chlorophyll-a* concentrations during the period of mentioned observations. The results of the present study showed that there was a positive correlation found between TP and *Chl-a* presence in the long run at Lake Taihu. The concentrations of TP were increasing before the tipping point whereas concentrations were found in polynomial correlation after the tipping point. There was the same trend of increase in *Chl-a* concentrations was observed at Lake Taihu from 2000 to 2016. Water temperature and DO has been found the fast-changing variables in the present study whereas, all other variables were changing slowly with positive or negative response in relation to the major internal or external drivers. Zhang *et al.*, (2018) also mentioned that there was an increasing trend of TN concentrations before 2007 and started to decrease after 2007 at Lake Taihu. The TN concentrations decreased after the implementation of management practices at Lake Taihu after 2007. The wind speed decreased to 1.4 m/s since the 1970s (Zhang *et al.*, 2018). The slow and fast variables response to oscillatory variables with the positive and negative response has been discussed in a study by Van Nes *et al.* (2007) which mentioned that the moderately strong feedbacks can result in alternative stable states in a shallow lake environment. Similarly, water level changes and wind dynamics have been considered as major reasons for triggering a shift in ecosystem state of shallow lakes (Jeppesen *et al.*, 2005; Meerhoff and Jeppesen, 2009). The classical alternative stable states theory mentioned that lakes are more vulnerable to the disturbances when they are near the tipping point (Van Nes and Scheffer, 2007). There was a decrease of approximately 0.041 m/s wind speed observed in the present study. Wu *et al.* (2016) observed that there was approximately 0.022 m/s annual decrease in wind speed from 1970 to 2013 at Lake Taihu. Along with total slowing down of wind speeds, there was a less variability pattern in directional switching was observed after the observed tipping point of 2006 in the present study. These declined wind speeds along with consistent wind directions triggered the warming, which caused abrupt changes in water temperature after the tipping point due to higher stratification. Qin *et al.* (2018) mentioned that the slow to moderate wind induced disturbances would help the formation and enlargement of colony size of cyanobacteria through minimizing the mixing and strong stratification at Lake Taihu. Therefore, it can be predicted based on present wind field analysis that slowing down of the winds along with deceased directional variability, *algal* blooms will be intensified at Lake Taihu. It is notable that strong events of typhoons Morakot (August 12–14, 2009) and Soulik (July 12–13, 2013) have not been found with higher impacts on the long-term changes in the dynamics of lake internal regime changes. Therefore, it can be concluded that Lake Taihu internal ecosystem changes are mainly caused by long-term slowing down of the major driver (wind speed and directional switching). When we focus on total phytoplankton biomass in shallow lakes then the disturbance induced changes in the internal environmental variables (abiotic) will be more important than the competitive interactions between different groups of phytoplankton (Houlahan *et al.*, 2007).

The regression analysis showed the non-significant linear correlation between long-term wind and other environmental variables (except *Chl-a*) at Meiliang bay of Lake Taihu (Tab. S2). The results of the GAM model further explored the possibility of a level of significance in general modeling at a

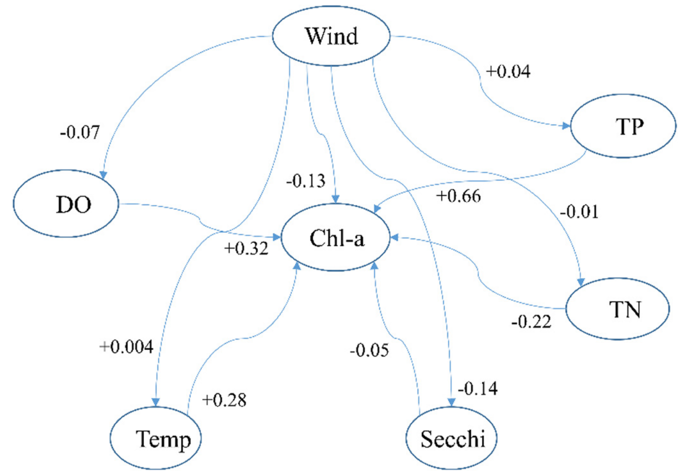


**Fig. 7.** The estimated positive and negative effects (direct and indirect) of wind and other environmental drivers on *Chl-a*. Similarly, wind effects on shallow lake internal ecosystem drivers to elaborate their response determined by SEM model results.

certain estimated degree of freedom between wind speed and environmental variables. The results of GAM showed the level of significance between wind and other environmental variables. There was a significant correlation observed between wind and other environmental variables after applying bootstrap smoothing (Fig. 5 and Tab. S4). The generalize model results of $R^2$ and lower estimated degree of freedom between wind and other environmental variables also showed significant correlations. The temperature, EC, TN, and TOC found in significantly negative correlation with wind speed whereas; other environmental variables found positively correlated with the low percent of variance (Tab. S4). Therefore, on the basis of GAM results, we can conclude that the smoothing trends were significant and hence the correlation between wind and environmental variables was significant.

More precisely, the wind speed of 2.3 m/s has been found as critical wind speed before and after which the confidence of interval (CI) increased for all environmental variables (Fig. 6). The correlation of wind speed was significantly positive or negative with other environmental variables before and after critical wind speed (2.3 m/s).

The SEM provided a deep insight of wind-induced response of environmental drivers and showed that wind has played important role in altering the ecosystem through controlling internal drivers. The results showed that *Chl-a* and other shallow lake ecosystem drivers (abiotic) are strongly related to long-term wind-induced effects (Fig. 7). The changes in nutrients and lower mixing scenarios triggers the growth of *Chl-a* and onshore lower winds help in the formation of colonies at Meiliang bay of shallow lake Taihu. The water column stability is being controlled by wind dynamics, which ultimately alters the community structure and biomass of phytoplankton in shallow lakes as mentioned by (Howarth *et al.*, 2011; Jiang and Xia, 2017). The higher stratification limits the nutrients resuspension in a shallow lake environment as mentioned by (Jalil *et al.*, 2018; Jiang and Xia, 2017). Cyr (2017) mentioned that horizontal and vertical transportation of phytoplankton is dependent on wind speed. Our results showed that onshore winds were mainly stronger which might have caused the larger scale transportation of *Chl-a* towards shoreline areas. Deng *et al.* (2018) mentioned that the water column mediated by wind speed had indirect effects on the phytoplankton and higher stability in the water column stimulated phytoplankton growth at Lake Taihu.

The studies mentioned about the wind speed impacts on internal ecosystem through resuspension of nutrients and sediments (Jalil *et al.*, 2017; Søndergaard *et al.*, 2003; Zhu *et al.*, 2005) and long-term changes in DO concentration occasionally create hypoxic conditions (Jalil *et al.*, 2018). These changes in the water column might lead to the higher availability of dissolved nutrients, which may provide alternative supplement (Deng *et al.*, 2018) for *algal* blooms at Lake Taihu. However, the present study indicated that the decline in wind speeds along with stable wind directional switching (as observed after 2006) causes intense blooms formation for a longer period in the shoreline areas.

## 5 Conclusion

The shallow lakes internal processes are highly connected to the wind dynamics in short-term and long-term scenarios. The shallow lake internal ecosystem response to wind field in long run has been investigated in the current study. The long-term wind dynamics analyses provided the evidence of decreasing wind speeds while wind directions were mainly found towards the shoreline at Meiliang bay of large, shallow Lake Taihu. The long-term TN annual concentrations have been found decreasing (0.065 mg/L annually) whereas, TP concentrations increased by 0.0022 mg/l annually from January 2000 to December 2016. The *Chl-a* concentrations were increasing by 2.1 μg/L annually during the last 17 years. There were two groups of environmental variables found highly connected to each other in hierarchical cluster analysis. Whereas, the principal component analysis showed the groups of drivers which were positively or negatively correlated to each other. The results of non-linear temporal trends showed that the key environmental variables (wind, temperature, and *Chl-a*) were significantly correlated whereas, other environmental variables were not significantly correlated temporally. There were two scenarios found in most of the environmental variables during the 17 years observation data analysis (before 2006 and after 2006). The wind field and other environmental drivers were highly variable during the time from 2000 to 2006 but there was a shifting of scenarios after 2007 at Meiliang bay of Lake Taihu. Therefore, there was a shifting of the response of ecosystem drivers observed before and after 2006–2007. The GAM results between wind and other environmental variables showed a significant correlation (with 1 estimated degree of freedom). Therefore, for understanding deep shallow lakes internal response mechanisms, wind is the key driver, which plays an important role for internal system transition much more than the competitive interactions between different groups of phytoplankton/biotic components. The management of temporal lakes (such as Lake Taihu) through artificial mixing and oxidation along with other technological innovations might help to reduce the impacts of decreasing wind speed and stable directional switching on the internal processes of degraded shallow lake environment.

*Acknowledgments.* The current study was supported by National Science Foundation of China (NSFC) (41772378), a National Basic Research Program of China (NBRPC) (2017YFA0605200) and "One Hundred Talent Program" of Chinese Academy of Science (Y6SL011001).

## Supplementary Material

The Supplementary Material is available at https://doi.org/10.1051/limn/2019026.

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**Cite this article as**: Jalil A, Zhang K, Qi L, Li Y. 2020. Long-term wind induced internal response mechanisms at Meiliang Bay of large, shallow Lake Taihu. *Ann. Limnol. - Int. J. Lim.* 56: 1