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The Gulf Stream position influences the functional composition of phytoplankton in El Gergal reservoir (Spain)

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ABSTRACT

The Gulf Stream position influences the functional composition of phytoplankton in El Gergal reservoir (Spain)

The latitudinal position of the north-wall of the Gulf Stream influences the climatic conditions in the Atlantic North and Western Europe. Southerly movements of the Gulf Stream (low Gulf Stream Index values, GSI) typically induce unstable meteorological conditions in this region, while north displacements of the oceanic current (high GSI values) are associated with stable weather. In the present article we explore a seven years data set including annual GSI, meteorological records and phytoplankton community composition and abundance to demonstrate that the year-to-year changes in the position of the Gulf Stream and its influence on the prevailing weather conditions have an effect on the long-term variability of phytoplankton community in El Gergal reservoir, an ecosystem located in the Atlantic coast of Andalusia (SW Spain). Furthermore, we describe the response of each considered phytoplankton functional groups to changes in the Gulf Stream position. Thus, northerly displacements of the north-wall increased the abundance of $H + S_1$ cyanobacteria through a non-linear function with two marked GSI thresholds. GSI and L_m dinoflagellates abundance depicted a significant positive linear correlation, while groups B + P diatoms abundance was negatively linear correlated with GSI. Groups Y cryptophytes and X_1 + J chlorophytes abundance remained nearly constant for most of the studied years but developed an exponential increase at high GSI years. Implications for water quality management are pointed out.

Key words: Gulf Stream Index (GSI), Teleconnection, Climate, Long-term study, Phytoplankton functional groups, El Gergal reservoir.

RESUMEN

La posición de la Corriente del Golfo influye en la composición funcional del fitoplancton en el embalse de El Gergal (España)

Las condiciones climáticas en la fachada Atlántica europea están influidas por las variaciones temporales en la posición latitudinal de la Corriente del Golfo en el océano Atlántico. Así, el desplazamiento hacia el Sur de la Corriente del Golfo (valores bajos del Índice de la Corriente del Golfo, GSI) induce condiciones de inestabilidad meteorológica en la Europa occidental, mientras que los desplazamientos septentrionales de la corriente oceánica (elevados valores del GSI) están asociados con mayor estabilidad meteorológica en esta región. Este artículo estudia la influencia de los cambios interanuales en la posición de la Corriente del Golfo sobre la comunidad fitoplanctónica del embalse de El Gergal, un ecosistema localizado en la costa atlántica andaluza (SW España). Para ello, a lo largo de siete años se han registrado valores anuales de GSI, información meteorológica y datos sobre la composición y biovolumen del fitoplancton. El análisis de esta información permite describir cómo las variaciones anuales en la posición de la Corriente del Golfo afectan a las condiciones meteorológicas en el área de estudio, influyendo de esta manera sobre el biovolumen de cada uno de los grupos funcionales de fitoplancton considerados. Los desplazamientos hacia el Norte de la Corriente del Golfo favorecieron el incremento del biovolumen de cianobacterias de los grupos $H + S_1$ *a través de una función no lineal con dos valores críticos de GSI bien* *definidos. Por su parte, se encontró una relación lineal positiva entre el GSI y el biovolumen de dinoflagelados del grupo* L_m*, mientras que las diatomeas de los grupos B + P se relacionaron de forma inversa con el GSI. Aunque el biovolumen de clorofitas de los grupos* X_1 *+ J y de criptofitas del grupo Y permaneció estable durante la mayor parte de los años estudiados, se registró un notable incremento del mismo en aquellos años en los que el GSI mostró sus valores más elevados. Finalmente se apuntan algunas consideraciones sobre posibles implicaciones en la gestión de la calidad del agua embalsada.*

Palabras clave: *Índice de la Corriente del Golfo (GSI), Teleconexión, Clima, Estudio a largo plazo, Grupos funcionales de fitoplancton, Embalse de El Gergal.*

INTRODUCTION

It is well known that climatic conditions in the maritime Northern and Western Europe are strongly determined by the latitudinal position of the Gulf Stream (Taylor, 1996; Taylor, 2011; Taylor *et al.*, 1992; Taylor & Stephens, 1998; Taylor *et al.*, 2002), which depicts a marked annual variability (Taylor, 2011; Willis *et al.*, 1995). The Gulf Stream Position Index (GSI) characterizes the position of the north-wall of the Gulf Stream (Taylor & Stephens, 1980; Taylor, 1996) and is commonly related to regional-scale variations in weather conditions. Southward displacements of the Gulf Stream (low GSI values) are typically associated to unstable weather conditions, whilst northerly movements (high GSI values) induce a more stable weather pattern (George, 2000). In this context, Taylor (1996, 2002) reported that the sea level pressure and the distribution of storm tracks over the NE Atlantic in spring differed in extreme positive and negative GSI years. Thus, northwards displacements of the north wall are typically accompanied by high spring sea level pressure in the NE Atlantic region and the opposite occurs during low GSI years. Taylor (1996) also found that the number of storms in the North Atlantic were significantly lower when the Gulf Stream was located north.

Ecosystems act as integrators of subtle climatic signals and could be sensitive sensors of climatic processes (Taylor, 2011; Taylor *et al.*, 2002). Thus, this quasi-cyclical regional scale process influencing year-to-year weather variations have profound effects on the dynamics of diverse biological communities such as terrestrial vegetation (Willis *et al.*, 1995), marine plankton (Taylor & Stephens, 1980; Taylor *et al.*, 1992; Taylor, 1995; Planque & Taylor, 1998; Borkman & Smayda, 2009) and fish (Lavín *et al.*, 2007). It has also been demonstrated that annual variability in the Gulf Stream position influences the hydrological (Noges, 2004), physical (George & Taylor, 1995; George, 2000), biogeochemical (George, 2002; Jennings & Allott, 2006) and plankton dynamics of Northern Europe lakes (George & Taylor, 1995; Planque & Taylor, 1998; George & Hewitt, 1998; George, 2000; George *et al.*, 2010). Nevertheless, there is a lack of research on the effect of GSI variations on freshwater ecosystems in the Atlantic Southern Europe. Taking our wide knowledge on the factors influencing the phytoplankton dynamics in El Gergal reservoir (Atlantic coast of Andalucía, Southern Spain) as a starting point (Vidal *et al.* 2010, Moreno-Ostos *et al.* 2009a, Moreno-Ostos *et al.* 2009b, Hoyer *et al.* 2009, Moreno-Ostos *et al.* 2008, Moreno-Ostos *et al.* 2007, Moreno-Ostos *et al.* 2006, Cruz-Pizarro *et al.* 2005), in this paper we suggest that the year-to-year changes in this community could be significantly influenced by the Gulf Stream position. To achieve this objective, we have explored the long-term relationship between GSI, meteorological conditions and phytoplankton functional composition in El Gergal during a seven years period (2000-2006).

MATERIAL AND METHODS

Study site

El Gergal (37°34′13″ N; 6°02′57″) is a medium size (surface area: 250 ha; volume: 35 hm^3; maximum depth: 37 m; mean depth: 15.7 m) water supply reservoir located in the Rivera de Huelva basin, a tributary of the Guadalquivir River in the Atlantic coast of Andalucía (Southern Spain) (Fig. 1). The thermal regime of the reservoir has previously been described as warm monomictic (Moreno-Ostos *et al.*, 2009a; 2009b) and the functional composition and seasonal succession of phytoplankton is strongly associated to the development of the water column thermal structure and variations in the turbulent mixing dynamics (Hoyer *et al.*, 2009). Further information on the physical, chemical and biological features of El Gergal reservoir can be found elsewhere (Cruz-Pizarro *et al.*, 2005; Moreno-Ostos *et al.* 2006; Moreno-Ostos *et al.*, 2007; Moreno-Ostos *et al.*, 2008; Moreno-Ostos *et al.*, 2009a; Moreno-Ostos *et al.*, 2009b).

Environmental conditions

Hourly variations in surface water temperature, air temperature, wind speed and atmospheric pressure were recorded by a meteorological station mounted on a buoy as part of an automatic water-quality monitoring station (AWQMS) and deployed near the deepest point of the reservoir (see Moreno-Ostos *et al.*, 2009b). To record surface water temperature (among other water quality variables) the AWQMS was fitted with an YSI 6920 multiple-parameter sonde (Yellow Springs Instruments). Wind speed was measured with a Vector Instruments A100L2-WR cup anemometer. A Vector Instruments T302 aspirated platinum resistance sensor was used to measure air temperature. Barometric pressure was measured using a Druck PDCR 1830 semiconductor strain gauge. All the acquired meteorological data were stored in a Campbell Scientific data logger CR23X.

Estimates of the characteristic vertical turbulent velocity within the upper layers of the water column were derived using the familiar shear velocity (u^*) approximation (Denman & Gargett, 1983; Reynolds, 1997):

$$u* = (\rho_a\, c_1\, u_{10}^2/\rho_w)^{-0.5} \tag{1}$$

where ρ_a is the density of air, c_1 is the dimensionless coefficient for frictional drag upon water ($1.3 \cdot 10^{-3}$), u_{10} is the wind speed at 10 meters above the water surface and ρ_w is the density of water at the surface. The wind speed at 10 meters

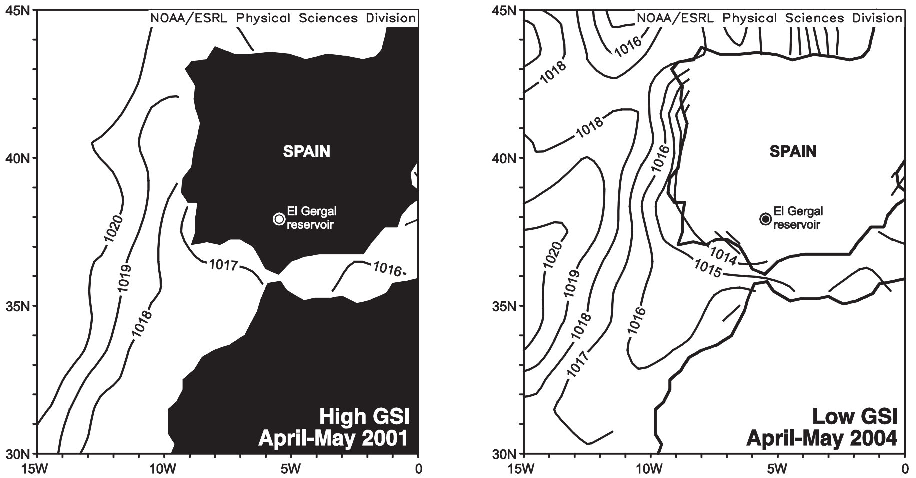

Figure 1. Geographical location of El Gergal reservoir and April-May averaged Sea Level Pressure (mbar) obtained from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) available at the Earth System Research Laboratory of NOAA (http://www.esrl.noaa.gov). Left panel correponds with the high GSI year 2001. Right panel corresponds with the low GSI year 2004. *Localización geográfica del embalse de El Gergal y valores medios de presión atmosférica a nivel del mar (mbar) en Abril-Mayo obtenidos del International Comprehensive Ocean-Atmosphere Data Set (ICOADS), disponible en el Earth System Research Laboratory de NOAA (http://www.esrl.noaa.gov). El panel izquierdo corresponde al año 2001 (alto valor de GSI). El panel derecho corresponde al año 2004 (bajo valor de GSI).*

above the water surface (u_{10}) was calculated from the wind speed at 2 m (u_2) using equation 2,

$$u_{10} = u_2 \, \ln(10/Z_0)/\ln(2/Z_0) \qquad (2)$$

where Z_0 is a dimensionless constant equal to 0.000115 (Brookes *et al.*, 2003)

Phytoplankton community composition and biovolume

During the studied period (2000-2006) water samples for phytoplankton analysis were collected every two weeks from the same sampling station. On each occasion, water samples were collected from discrete depths of 0, 2, 5, 10, 15, 20, 25 and 30 m using a 5 L Van-Dorn water sampler. The samples were preserved in lugol's iodine solution and the cells indentified and counted under inverted microscope following Utermöhl's method (1958).

Morphological measurements were carried out using an inverted Leica DMIL microscope attached to an Allied Pike F145C-IRF16 digital camera and a Sanyo B/W CCD VC-2512 video camera. Images were processed using the Fotomaton II software (University of Málaga). At least 100 microscope measurements of cells/colonies length and width were made for each phytoplankton species at every sample. Cell volumes were calculated from the obtained morphological data following Hillebrant *et al.* (1999).

The species encountered in the samples were classified into functional groups following Reynolds(1997; 2002), a well-known and widely-recognised methodology previously applied to El Gergal phytoplankton (Moreno-Ostos *et al.* 2009b, Hoyer *et al.* 2009). Group biovolume were estimated by adding the biovolume corresponding to the member species at each depth and then averaging the biovolume encountered at all depths. Finally, year-to-year variations in mean annual group biovolume were calculated.

Gulf Stream Position

The annual mean latitude of the north wall of the Gulf Stream was studied using the Gulf Stream Index (GSI) described by Taylor & Stephens (1980). In this procedure, the latitude of the north wall is read from each chart at six longitudes (79° W, 75° W, 72° W, 70° W, 67° W and 65° W) and an index of position constructed using principal component analysis. The first principal component typically accounts for a high proportion of the variance and constitutes the best estimate of the latitudinal displacement of the Gulf Stream (George, 2000). Annual GSI data were obtained from the Plymouth Marine Laboratory (PML) at http://www.pml.ac.uk/gulfstream.

RESULTS

The Gulf Stream position influences the long-term local weather conditions

During the studied period mean annual GSI ranged between 1.467 in 2001 (north mode of the Gulf Stream) and –0.847 in 2004 (south mode of the Gulf Stream) (Fig. 2a), a range of

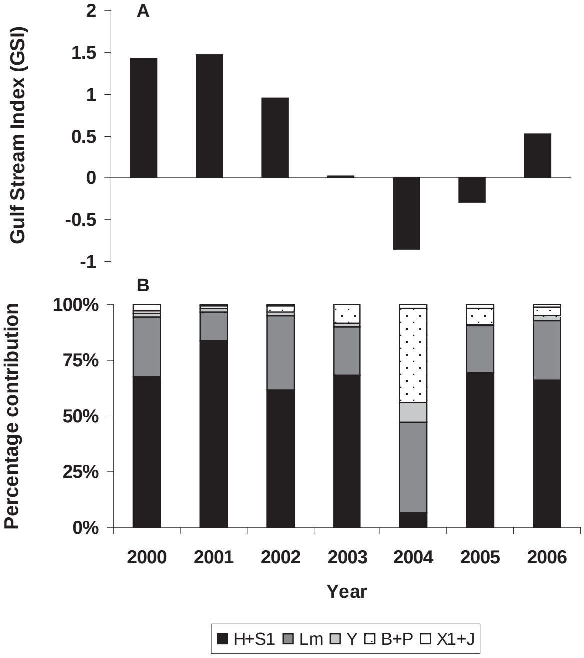

Figure 2. A) Annual average GSI values. B) The relative contribution of each considered phytoplankton functional group to total phytoplankton biovolume. *A) Valores medios anuales de GSI. B) Contribución relativa de cada grupo funcional considerado al biovolumen fitoplanctónico total.*

GSI values consistent with those previously considered in the literature (i.e. George 1995, 2000; Taylor & Stephens, 1998; Taylor, 2011). A large-scale picture of April-May averaged Sea Level Pressure (mbar) obtained from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) available at the Earth System Research Laboratory of NOAA revealed that north mode of the Gulf Stream was related to high pressure conditions in the Atlantic coast of the Iberian Peninsula, whilst south displacements of the oceanic current coincided with lower pressure and higher pressure gradient in this area (Fig. 1). Accordingly, meteorological and physical records in El Gergal suggest that the Gulf Stream position significantly influenced the local weather and mixing conditions. Again, north mode of the Gulf Stream was related with stable conditions in El Gergal, while south displacements of the Gulf Stream induced a more unstable environment. Thus, GSI was positively correlated with mean annual atmospheric pressure ($r = 0.91$; $p < 0.005$) and mean annual air temperature ($r = 0.93$; $p < 0.001$), and negatively correlated with mean annual shear velocity ($r = -0.90$; $p < 0.001$) and with the number of wind events (wind speed >4 ms^{-1}) per year ($r = -0.89$; $p < 0.05$).

The influence of the Gulf Stream position on the functional composition of phytoplankton

Long-term changes in meteorological forcing initiated by the Gulf Stream latitude influenced the relative biovolume of components of the phytoplankton community in El Gergal reservoir (Fig. 2b). Thus, during high GSI years the warm and calm conditions favoured the development of a phytoplankton community governed by functional groups $H + S_1$ (positively buoyant filamentous cyanobacteria) and L_m (swimming dinoflagellates). However, during

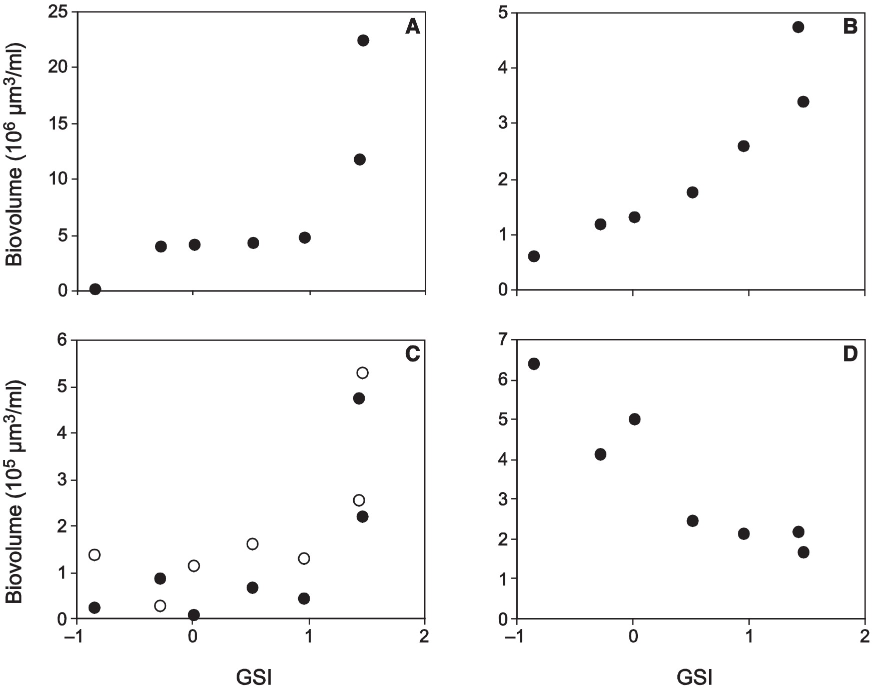

Figure 3. The influence of GSI on different phytoplankton functional groups (Reynolds 2002) biovolume in El Gergal reservoir. A) groups $H + S_1$ cyanobacteria; B) group L_m dinoflagellates ; C) groups $X_1 + J$ chlorophytes (black circles) and Y cryptophytes (white circles); D) groups B + P diatoms. *Influencia del valor del GSI en el biovolumen diferentes grupos funcionales de fitoplancton en el embalse de El Gergal. A) Cianobacterias de los grupos $H + S_1$; B) dinoflagelados del grupo L_m; C) clorofilas de los grupos $X_1 + J$ (círculos negros) y criptofitas del grupo Y (círculos blancos); D) diatomeas de los grupos B + P.*

the unstable low GSI years these functional groups were less abundant and functional groups B+P (negatively buoyant diatoms) increased their percentage contribution to total biovolume. The percentage contribution of groups X_1+J (neutrally buoyant chlorophytes) and Y (cryptophytes) remained always low although it slightly increased during high GSI years.

The response of different phytoplankton functional groups to variations in the Gulf Stream position

Each different phytoplankton functional group considered in this study developed a particular response in terms of biovolume to the long-term changes in the weather conditions induced by annual variations in GSI (Fig. 3). In this sense, the response of functional groups H+S_1 to changes in GSI was characterized by a typical catastrophic (*sensu* Scheffer *et al.* 2001) non-linear function with rapid state transitions through two marked GSI thresholds (Fig. 3a). When the Gulf Stream moves to the south (GSI < −0.3) the enhanced wind-induced turbulent mixing prevents the development of filamentous cyanobacteria, while their abundance dramatically increased when the oceanic current is located well to the north (GSI > 1) and shear stress decreases. During years when GSI was within these two thresholds values the cyanobacteria biovolume remained nearly constant around $4.3 \cdot 10^6$ μm^3/ml and coexistence with other phytoplankton groups occurred.

Dinoflagellates abundance depicted a similar response to long-term changes in GSI, with the highest abundances recorded during the low turbulent mixing and stable weather conditions prevailing in the reservoir during high GSI years and the lowest during the unstable low GSI years. Interestingly, GSI threshold levels were in agreement with those described for cyanobacteria, although the character of the dinoflagellates response was smoother and the critical GSI levels for transitions between states were fuzzier (Fig. 3b).

The response of groups Y and X_1+J abundance to changes in GSI was also catastrophic, although just one GSI “breakpoint” around GSI 1.4 was identified. Thus, cryptophytes and chlorophytes abundance remained low and roughly constant in those years when GSI < 1.4, while it sharply increased above this threshold value (Fig. 3c).

By contrast, a significant continuous (rather than catastrophic) negative linear correlation was found between GSI and functional groups B+P biovolume ($r = 0.93$; $p < 0.0001$; $n = 7$) (Fig. 3d) thus revealing that the turbulent conditions prevailing during low GSI years enhanced the development of negatively-buoyant diatoms.

DISCUSSION

Long-term changes in the existing meteorological conditions (i.e. temperature, wind speed, turbulent mixing) have a profound effect on the freshwater plankton communities development (Margalef, 1980; Catalan & Fee, 1994; George *et al.*, 1998, George, 2000). In this context, it has been suggested that the position of the Gulf Stream should be considered as a relevant factor influencing phytoplankton dynamics in the lakes located in the Atlantic coast of Western Europe (Taylor *et al.*, 1992; Taylor, 2002; Taylor *et al.*, 2002; Taylor, 2011; Jennings & Allott, 2006; George *et al.*, 2010). Previous studies (George & Taylor, 1995; Taylor, 2002) have reported that the mediating factor seems to be the subtle changes in the spring and early summer weather induced by the Gulf Stream position, especially in the wind speed dynamics (Noges, 2004, see also George & Hewitt, 1998).

Our results suggest that the phytoplankton community composition and the success of certain functional groups are indirectly linked to the Gulf Stream position, which significantly influences the local meteorological forcing over the reservoir. As far as we know from the literature, this is the first study revealing the interaction between the Gulf Stream position and the phytoplankton community dynamic in a freshwater ecosystem in SW Europe. Previous results reported by Moreno-Ostos *et al.* (2009b) using a high-resolution autonomous monitoring device highlighted the influence of wind mixing on the cyanobacteria and diatoms dynamics in El Gergal reservoir. Now we show that the South displacements of the Gulf Stream were associated with stronger turbulent mixing in El Gergal and favoured the development of negatively buoyant diatoms, while a North position of the Gulf Stream influenced a less intense wind-induced mixing and, consequently, the growth of positively buoyant cyanobacteria and swimming dinoflagellates populations in the reservoir. In this context, George (2000) reported the occurrence of intense *Aphanizomenon* sp. blooms during high GSI years in Esthwaite Water (England, UK), while during low GSI years the phytoplankton community was mainly governed by microalgae. These climate-induced changes in phytoplankton community could also propagate through the trophic web influencing zooplankton composition. Thus, George (2000) demonstrated that during low GSI years the enhanced small edible algae populations sustained higher abundances of *Daphnia* during the early summer in Esthwaite Water, while the increased cyanobacteria populations during high GSI years avoided the large-sized cladocera growth. A comparable effect was reported in the North Basin of Windermere Lake by George & Taylor (1995).

Our study reveals that the abundance of many phytoplankton functional groups in El Gergal reservoir (i.e. cyanobacteria, dinoflagellates, cryptophytes and chlorophytes) responds catastrophically to gradual changes in GSI. From a reservoir management scope this is especially relevant in the case of cyanobacteria, a harmful phytoplankton group which develops sudden and persistent surface blooms with deleterious effects on the stored water quality. Although more research is needed, in this study we have delimited the GSI threshold value for the occurrence of dense cyanobacteria blooms. On the basis of this knowledge, reservoir managers should forecast GSI as an early-warning signal of approaching catastrophic shift to cyanobacteria dominance and implement water management strategies to avoid the development of surface blooms during high GSI years. In this context, Taylor & Stephens (1998) obtained a multiple regression empirical model to predict GSI from the NAO index recorded two years previously and the previous year's Gulf Stream position.

Ecosystem state shifts can cause large losses of ecological and economical resources, and restoring a desired state may require drastic and expensive intervention (Scheffer *et al.*, 2001; Scheffer & Carpenter, 2003). As perturbations are difficult to control, the most pragmatic and effective way to manage ecosystems is to build and maintain resilience of desired ecosystem state (Scheffer *et al.*, 2001). In El Gergal reservoir case, while meteorological forcing (i.e. wind mixing) is naturally imposed, not manageable and strongly linked to annual changes in the Gulf Stream position, selective water withdrawal constitutes a valuable tool for reservoir managers to influence the phytoplankton community composition in the reservoir (Hoyer *et al.*, 2009) and sustain a low cyanobacteria abundance stability domain. As the mixed layer depth of reservoirs submitted to selective withdrawal operations is strongly influenced by the water withdrawal depth (Moreno-Ostos *et al.*, 2008), during the thermally-stratified period of high GSI years hypolimnetic withdrawal could disband the positive-buoyant cyanobacteria patches throughout the enlarged mixed layer, promoting the shift to a phytoplankton community governed by innocuous chlorophytes and diatoms.

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