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The position of the Gulf Stream influences waterbird brood numbers in a Mediterranean wetland (Albuferas de Adra, Spain)

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ABSTRACT

The position of the Gulf Stream influences waterbird brood numbers in a Mediterranean wetland (Albuferas de Adra, Spain)

Wetlands constitute complex ecosystems where different stable states alternate through catastrophic regime shifts. It is known that the inter-annual variation in the spring weather conditions constitutes a key factor for catastrophic shifts between phytoplankton-dominated turbid states and clear water phases in Albuferas de Adra, a Mediterranean coastal wetland. In previous studies we demonstrated that this alternation of equilibrium states has an effect on waterbirds, which show higher abundance and brood production in years characterised by the occurrence of clear water phases. In this paper we examine the teleconnection between the Gulf Stream position, a large-scale oscillating phenomena influencing weather conditions in West Europe, the weather variability in Albuferas de Adra and waterbird brood numbers in such an ecosystem. Our results suggest that when the Gulf Stream moves towards the south unstable meteorological conditions prevail in the region, favouring the productivity of waterbirds within the wetland through the occurrence of clear water phases. By contrast, northern displacements of the oceanic current are associated with stable weather, turbid water phases and lower numbers of broods. The Gulf Stream position significantly influenced the reproduction of the specialist coots, grebes and diving ducks, while no relation with the generalist and ubiquitous dabbling ducks was found. Potential implications for wetland management and waterfowl conservation are noted.

Key words: Gulf Stream position, teleconnections, wetlands, waterbirds, clear water phase, Albuferas de Adra.

RESUMEN

La posición de la Corriente del Golfo influye sobre el número de nidadas de aves acuáticas en un humedal mediterráneo (Albuferas de Adra, España)

Los humedales son ecosistemas complejos caracterizados por la alternancia de estados estables a través de cambios catastróficos. En Albuferas de Adra (Almería, España) la variabilidad interanual en las condiciones meteorológicas primaverales constituye un factor clave en el control de la alternancia entre estados estables caracterizados por aguas turbias y elevada biomasa fitoplanctónica y fases de aguas claras. En estudios previos demostramos que esta alternancia de estados tiene efectos sobre la comunidad de aves acuáticas del humedal, que desarrolla mayor abundancia y número de nidadas en los años en que ocurren fases de aguas claras. En este artículo se analiza la teleconexión entre la posición de la Corriente del Golfo, un fenómeno oceánico oscilatorio de gran escala que afecta las condiciones meteorológicas en la fachada atlántica europea, la variabilidad meteorológica en Albuferas de Adra y el número de nidadas de aves acuáticas en dicho ecosistema. Los resultados sugieren que el desplazamiento hacia el Sur de la Corriente del Golfo induce inestabilidad meteorológica en la zona de estudio, lo que favorece la ocurrencia de fases de aguas claras y la reproducción de las aves acuáticas. Por el contrario, los desplazamientos hacia el Norte de la corriente oceánica se asocian con condiciones meteorológicas estables, fases de aguas turbias y menor número de nidadas en el humedal. La posición latitudinal de la Corriente del Golfo afecta significativamente al número de nidadas de los grupos de aves especialistas como fochas, somormujos y patos buceadores, mientras que no se encontró relación significativa con el grupo generalista y ubiquista de patos nadadores. Finalmente, se discuten posibles implicaciones para la gestión de humedales y conservación de la avifauna acuática.

Palabras clave: *Posición de la corriente del golfo, teleconexiones, humedales, aves acuáticas, fase de aguas claras, Albuferas de Adra.*

INTRODUCTION

Climate is a critical factor influencing organism and ecosystem dynamics, and one of the central challenges of contemporary ecology is to understand how climate variability affects ecosystem structure and function. In the present context of climate change, achieving this knowledge is especially relevant to design and implement appropriate ecosystem conservation and management strategies.

Early studies typically focused on the influence of local weather variables on ecosystems, overlooking the holistic nature of the climate system (Stenseth *et al.*, 2002). Nevertheless, the increasing interest in studies on the response of ecosystems to climate variability has highlighted the influence of large-scale climatic oscillators on the local weather conditions that, in turn, drive the ecosystems fate. Large-scale phenomena influencing the weather in western Europe include the latitudinal position of the Gulf Stream current, a complex oceanic feature that seems itself to be a response to large-scale atmospheric changes, in particular to the North Atlantic Oscillation (NAO) two years previously and, to a lesser extent, to the El Niño Southern Oscillation (ENSO) (Taylor & Stephens, 1998; Taylor & Gangopadhyay, 2001; Jennings & Allott, 2006). Currently, it is well-known that the weather conditions in northern and western Europe are strongly determined by the latitudinal position of the North-wall of the Gulf Stream (Taylor *et al.*,1992, 2002; Taylor & Stephens, 1998; Taylor, 2011). The position of this oceanic current is characterised by a marked annual variability (Taylor, 2011) and is frequently measured using the Gulf Stream Index (GSI). Taylor (2002, 2011) demonstrated that the sea-level pressure and distribution of storm tracks over North and West Europe in spring significantly differed in extreme positive and negative GSI years. Thus, when the Gulf Stream moves toward the south (low GSI values) unstable spring weather conditions prevail, while northward displacements of the current (high GSI values) are typically associated with stable and calm weather.

Year-to year changes in the weather have a profound effect on ecosystems dynamics, which integrate subtle climatic signals (Taylor, 2011; Taylor *et al.*, 2002). In agreement, several studies have demonstrated that the latitudinal position of the Gulf Stream has an effect through meteorological variations on very diverse biological communities, such as terrestrial plants (Willis *et al.*, 1995), marine plankton (Taylor & Stephens, 1980; Taylor *et al.*, 1992; Taylor, 1995; Planque & Taylor, 1998; Borkman & Smayda, 2009), marine fish (Lavín *et al.*, 2007) and freshwater plankton (George & Taylor, 1995; Planque & Taylor, 1998; George, 2000, George *et al.*, 2010; Moreno-Ostos *et al.*, 2012). The position of the oceanic current also influences the physical regime of freshwater ecosystems (George & Taylor, 1995; George, 2000) and the hydrological (Noges, 2004; Jennings & Allott, 2006) and biogeochemical (Jennings & Allott, 2006) properties of watersheds.

In relation to the waterbird community, a few previous studies have explored the links between other planetary sources of inter-annual climatic variability (such as NAO and ENSO) and the ecological dynamics of waterbirds in the Mediterranean region (i.e., Almaraz & Amat, 2004; Figuerola, 2007; Bechet & Johnson, 2008; Gordo *et al.*, 2011), but there is still a lack of research on the effects of variations in the Gulf Stream latitudinal position on waterbirds communities in Mediterranean wetlands.

Nevertheless, it is now clear that the dynamics of waterbirds is strongly influenced by annual variations in local weather, which in turn induce catastrophic shifts between different alternative stable states in wetlands. In this sense, Moreno-Ostos *et al*. (2007) demonstrated that the occurrence of spring clear or turbid water phases in a Mediterranean wetland (Albuferas de Adra, Southern Spain) was strongly influenced by meteorological forcing at the early spring, which determined the structure of phytoplankton and zooplankton communities. Thus, spring clear water phases were linked with unstable weather conditions and low water column thermal stability, which favoured the dominance of small-edible phytoplankton species (i.e., *Chlorella vulgaris*, *Coelastrum* sp., *Ankyra* sp., *Scenedesmus* sp., *Cryptomonas* sp. and *Cyclotella* sp.) and the development of dense *Daphnia magna* populations, an efficient grazer that induced the microalgae populations collapse, the dramatic increase in water transparency and the subsequent proliferation of dense submersed macrophyte populations *(Najas marina* and *Potamogeton pectinatus*). By contrast, when stable and calm meteorological conditions prevailed during the early spring in the wetland and when thermal stability was relatively high, the early bloom of filamentous cyanobacteria (*Anabaena* sp., *Oscillatoria* sp., *Pseudoanabaena* sp., *Anabaenopsis* sp. and *Spirullina* sp.) and the low relative abundance of small edible microalgae strongly reduced the success of the cladocera populations, finally resulting in the suppression of the clear water phase and the absence of submerged macrophyte populations. These observations were in agreement with Scheffer *et al*. (2001) and Scheffer & Carpenter (2003), who demonstrated that the alternation of clear and turbid water phases in shallow lakes constitutes a catastrophic process strongly influenced by annual differences in the early-spring weather.

Subsequently, Moreno-Ostos *et al*. (2008) demonstrated the impact of such an alternation of stable states on the Albuferas de Adra waterbird

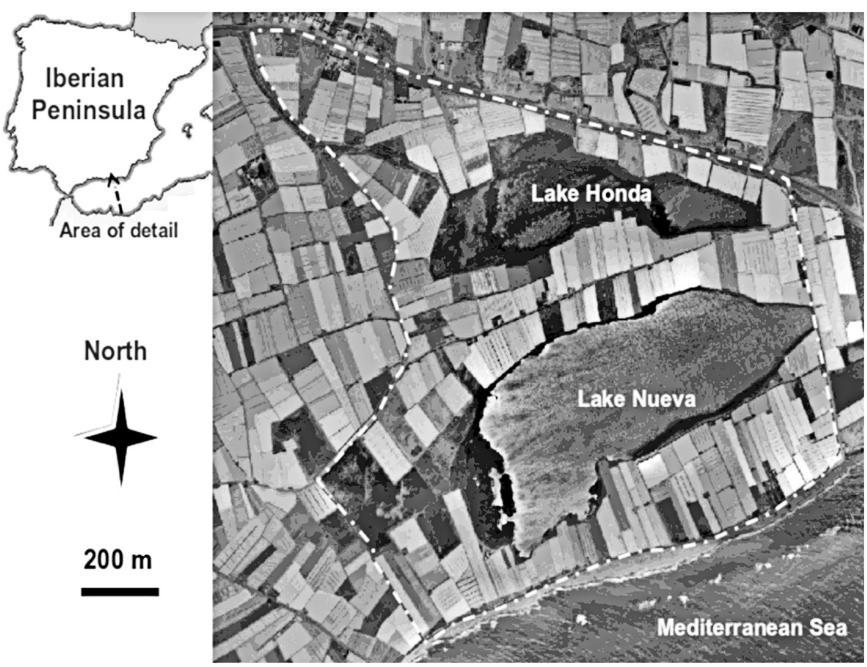

Figure 1. Geographical location of the Albuferas de Adra wetland within the Iberian Peninsula. The aerial photograph shows the two shallow lakes constituting the coastal wetland (Lake Honda and Lake Nueva). The lakes are surrounded by a narrow belt (few meters) of *Phragmites australis*, and the wetland is located between greenhouses in a flattish landscape. The white dotted line depicts the Ramsar site limits. *Localización geográfica de Albuferas de Adra en la Península Ibérica. La fotografía aérea muestra las dos lagunas someras que constituyen el humedal (Laguna Honda y Laguna Nueva). Las lagunas están circundadas por un estrecho cinturón perilagunar de* Phragmites australis*, y el humedal se encuentra en un terreno llano rodeado de invernaderos. La línea blanca punteada representa los límites de la zona Ramsar.*

community. They found significant increments in the abundance and brood production of aquatic birds during the clear water phase periods in contrast with the turbid water phases, as the increase of macrophytes coverage associated with the increased water transparency attracted waterbirds for available food and shelter.

In this article, we report for the first time that the number of waterbird broods in Albuferas de Adra is closely related with North-South displacements of the Gulf Stream in the Atlantic Ocean, a large-scale process inducing subtle changes in the local spring weather.

STUDY SITE

Albuferas de Adra is one of the most important coastal wetlands in Mediterranean Southern Spain (Fig. 1). It is composed of two adjacent small, shallow and eutrophic lakes (Lake Honda and Lake Nueva) and constitutes an internationally recognised marsh for waterbirds. Due to its ecological importance as a permanent wetland in a semiarid region, Albuferas de Adra was declared a Natural Reserve in 1989. Since 1994, the site is also included in the list of Protected Areas of the Ramsar Convention of Wetlands of International Importance and, since 2002, constitutes a European Special Protection Area for Wild Birds. Populations of globally endangered species, such as the White-headed duck (*Oxyura leucocephala*), overwinter and breed in these lakes, forming one of its most relevant populations in Europe (Paracuellos *et al.*, 1994; IUCN, 2012). In spite of its relevance for biological conservation steady land and water reclamation processes for intensive agriculture have significantly reduced the size of the wetland (Paracuellos, 2006) and have induced an accelerated eutrophication process (Cruz-Pizarro *et al.*, 2003) increasing the wetland conservation challenges and making ecological research essential. Extended limnological descriptions and detailed descriptions of the processes in the wetland can be found elsewhere (Cruz-Pizarro *et al.*, 2003; de Vicente *et al.*, 2003, 2006; Moreno-Ostos *et al.*, 2007, 2008).

METHODS

Gulf Stream position and local weather variables

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 is 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.

The sea-level pressure plots of Western Europe (composite anomaly of the season, referred to the new climate normal time period 1981-2010) were obtained from the NCEP Reanalysis Derived data (Kalnay *et al.*, 1996) provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their web site (http://www.esrl.noaa.gov/psd/).

To analyse the impact of GSI on local weather conditions we have studied a 10-year (2001-2010) daily meteorological dataset recorded by a weather station deployed near the Albuferas de Adra wetland complex. As GSI is known to influence Western European weather patterns through changes in the spring meteorological conditions (Taylor, 2002, 2011), for each studied year, we have computed the spring (March to May) mean wind speed, the number of wind events and the accumulated rainfall. For each considered year, spring wind events were defined as the number of spring days in which the wind speed was above the spring mean value of the complete time series.

Waterbird broods

Waterbird brood numbers were obtained from an 18-year (1993-2010) annual waterbird reproductive census provided by the Consejería de Medio

Ambiente y Ordenación del Territorio (since 2003 from the Emergencies, Epidemiological Control and Wild Fauna Survey Program, Junta de Andalucía, Spain). For these censuses, the number of broods of each waterbird species was obtained from direct observation using binoculars and a telescope at selected points along the edges of Albuferas de Adra wetland during the breeding season (at least one complete monthly control per year, mainly from March to September). Following Moreno-Ostos *et al.* (2008) we considered only the dabbling and diving breeding birds more related to the aquatic habitat because these constitute the dominant guild in the study area (Paracuellos *et al.*, 1994) and are characterised by certain homogeneity in the use of the wetland resources (Nilsson & Nilsson, 1978). These waterbird species were then grouped into the following feeding guilds: coots (*Fulica atra*), grebes (*Podiceps cristatus*, *Podiceps nigricolis* and *Tachybaptus ruficollis*), diving ducks (*Netta rufina*, *Aythya ferina* and *Oxyura leucocephala*) and dabbling ducks (*Anas platyrhynchos* and *Anas clypeata*). Because all of the waterbirds included in this study were large and easily detectable, and all of the counts were replicated at least seven times in a year, we assume that there are few detection errors and that the direct counts showed a high level of accuracy (Tellería, 1986; Bibby *et al*., 2000).

Statistical methods

Correlations between variables were analysed by Pearson's method (Sokal & Rohlf, 1995). To detect spurious correlations, the absence of autocorrelation within biological time-series was checked with a Durbin-Watson test (Neter *et al.*, 1996); none of the values were related with previous years in any species.

RESULTS

The influence of the Gulf Stream latitudinal position on the wetland weather conditions

During the whole study period (1993-2010) mean annual GSI ranged between −0.86 (South mode, 2004) and 2.15 (North mode, 1995). A large-scale picture of April-May averaged sea-level pressure anomaly (mbar) obtained from

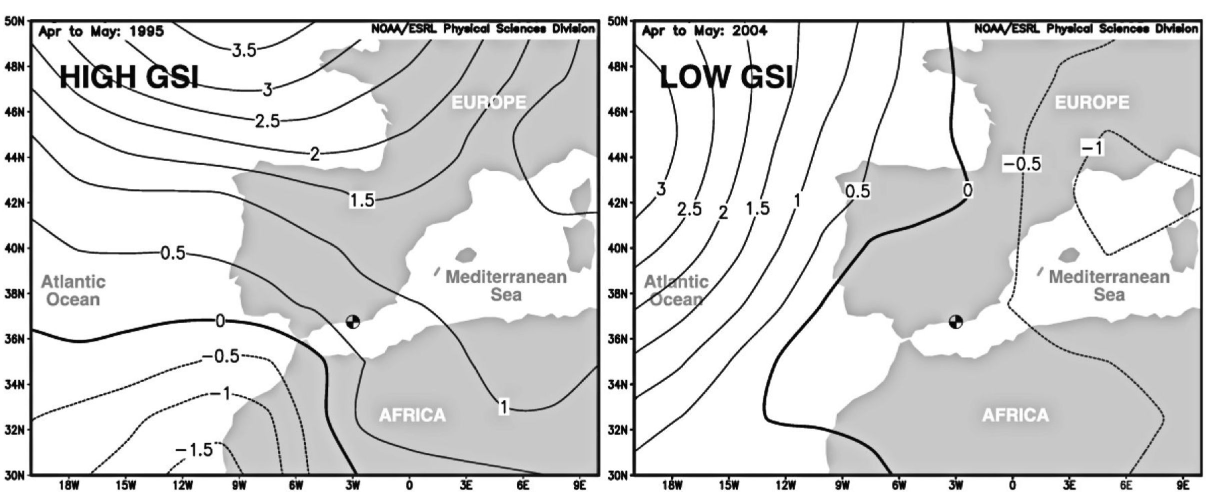

Figure 2. A large-scale picture showing the April-May anomaly on sea-level pressure (mbar) obtained from the Earth System Research Laboratory of NOAA (http://www.esrl.noaa.gov). The left panel corresponds with the high GSI year 1995. The right panel corresponds with the low GSI year 2004. The black and white circle depicts the study site. *Imagen de gran escala que muestra la anomalía primaveral (Abril-Mayo) en la presión atmosférica a nivel del mar (mbar) obtenida de Earth System Research Laboratory of NOAA (http://www.esrl.noaa.gov). El panel izquierdo corresponde al año 1995 (alto valor de GSI). El panel derecho corresponde al año 2004 (bajo valor de GSI). El círculo blanco y negro representa el lugar de estudio.*

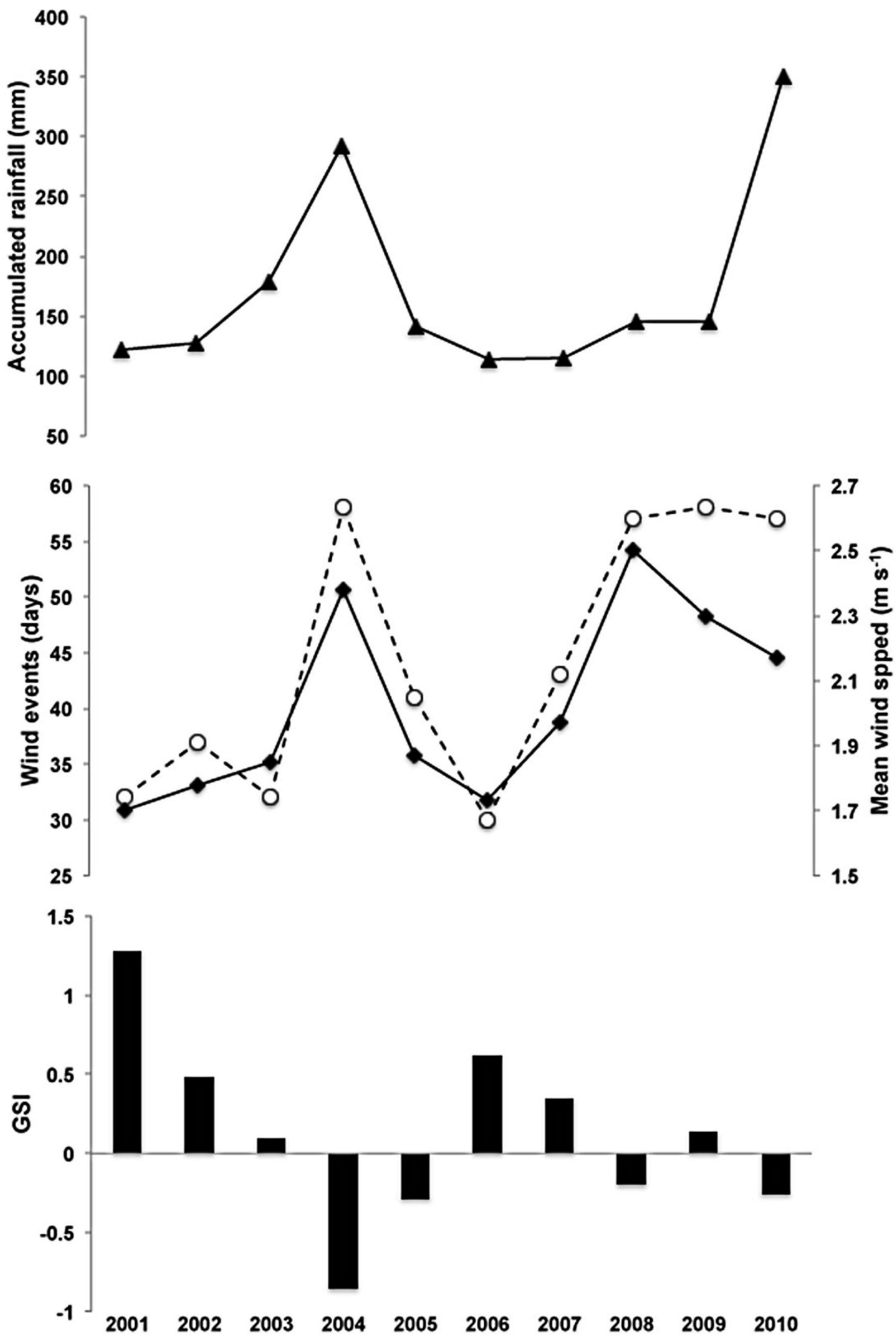

Figure 3. Annual changes in GSI (bars) and local spring weather variables (black circles: mean wind speed; white circles: number of wind events; triangles: accumulated rainfall) in the Albuferas de Adra wetland. Regression parameters are described in the text. *Cambios anuales en el valor de GSI (barras) y en las variables meteorológicas locales (círculos negros: velocidad media del viento; círculos blancos: número de eventos de viento; triángulos: precipitación acumulada) en Albuferas de Adra. Los parámetros de las regresiones se describen en el texto.*

the Earth System Research Laboratory of NOAA showed that the North mode of the Gulf Stream was related to positive sea-level pressure anomaly conditions on the West and South coast of Spain, whilst South displacements of the oceanic current coincided with negative sea-level pressure anomaly values in the region (Fig. 2). In agreement, our 10-year (2001-2010) meteorological dataset recorded in the vicinities of Albuferas de Adra demonstrated that the Gulf Stream position significantly influenced the local weather conditions (Fig. 3). Thus, GSI was negatively correlated with mean spring wind speed ($R^2 = 0.51$; $p < 0.02$; $n = 10$), with the number of spring wind events ($R^2 = 0.41$; $p < 0.025$; $n = 10$) and with the spring accumulated rainfall ($R^2 = 0.42$; $p < 0.05$; $n = 10$).

Implications for waterbird brood numbers

As a general trend, the number of waterbird broods in the wetland increased markedly during low GSI years and decreased when GSI was higher (Fig. 4). This inverse relationship was more intense in the case of grebes ($R^2 = 0.46$; $p < 0.005$; $n = 18$) and coots ($R^2 = 0.34$; $p < 0.015$; $n = 18$) and was slightly weaker (although still significant) for diving ducks ($R^2 = 0.25$; $p < 0.050$; $n = 18$). By contrast, this regression was not significant at all for the dabbling ducks.

DISCUSSION

Limnological characteristics and the abundance of macrophytes have previously been suggested as central factors affecting waterfowl distributions and densities (Nilsson & Nilsson, 1978; Amat & Sánchez, 1982; Johnson & Montalbano, 1984; Green, 1998; Moreno-Ostos *et al.*, 2008; Atiénzar *et al.*, 2012). In the Albuferas de Adra wetland these limnological features are known to depict marked inter-annual variability and to be closely related to the spring weather conditions (Moreno-Ostos *et al.*, 2007, 2008). The results presented in this paper advance the understanding of this topic, showing that the long-term variability in the weather conditions prevailing in the wetland area are linked to the Gulf Stream position in the Atlantic Ocean. These findings are in agreement with Taylor's conclusions (2002, 2011) on the influence of the oceanic current on western European weather, and Moreno-Ostos *et al.* (2012) have reported similar relationships between the Gulf Stream position and the spring weather conditions in a water-supply reservoir located in south-west Spain. Nevertheless, this is the first study reporting a significant effect of GSI on the weather of the south-east Iberian Mediterranean coast.

As Albuferas de Adra is a permanent wetland complex with a rather constant water depth and is artificially constrained by the extent of intensive agriculture in the vicinity, the effect of inter-annual weather variations on the flooded area is negligible. Nevertheless, spring weather conditions constitute the key factors responsible for the alternation between clear and turbid water phases, a catastrophic dynamics that induces dramatic inter-annual changes in the ecosystem characteristics (Moreno-Ostos *et al.*, 2008). In a recent paper, Moreno-Ostos *et al.* (2012) have shown that the phytoplankton community in a deep Mediterranean reservoir was significantly influenced by the annual GSI through its control on the local spring weather. Interestingly, they also found that shifts in the phytoplankton community followed catastrophic dynamics.

In the present study, we note that the number of broods of specialist birds are significantly related to the Gulf Stream position through its influence on the local spring weather conditions. Thus, when the Gulf Stream moves toward the south, the induced spring meteorological instability favours the occurrence of clear water phases and the development of submerged macrophytes (Moreno-Ostos *et al.*, 2007), which provide abundant food for herbivorous birds such as coots and significantly enhance their brood production (Amat, 1981; Kerekes, 1994; Perrow *et al.*, 1997; Brinkhof & Cavé, 1997; Moreno-Ostos *et al.*, 2008). Grebe brood numbers are also favoured during low GSI years. Those visual predators demonstrate better hunting capacities when the water is clear, and their prey abundance

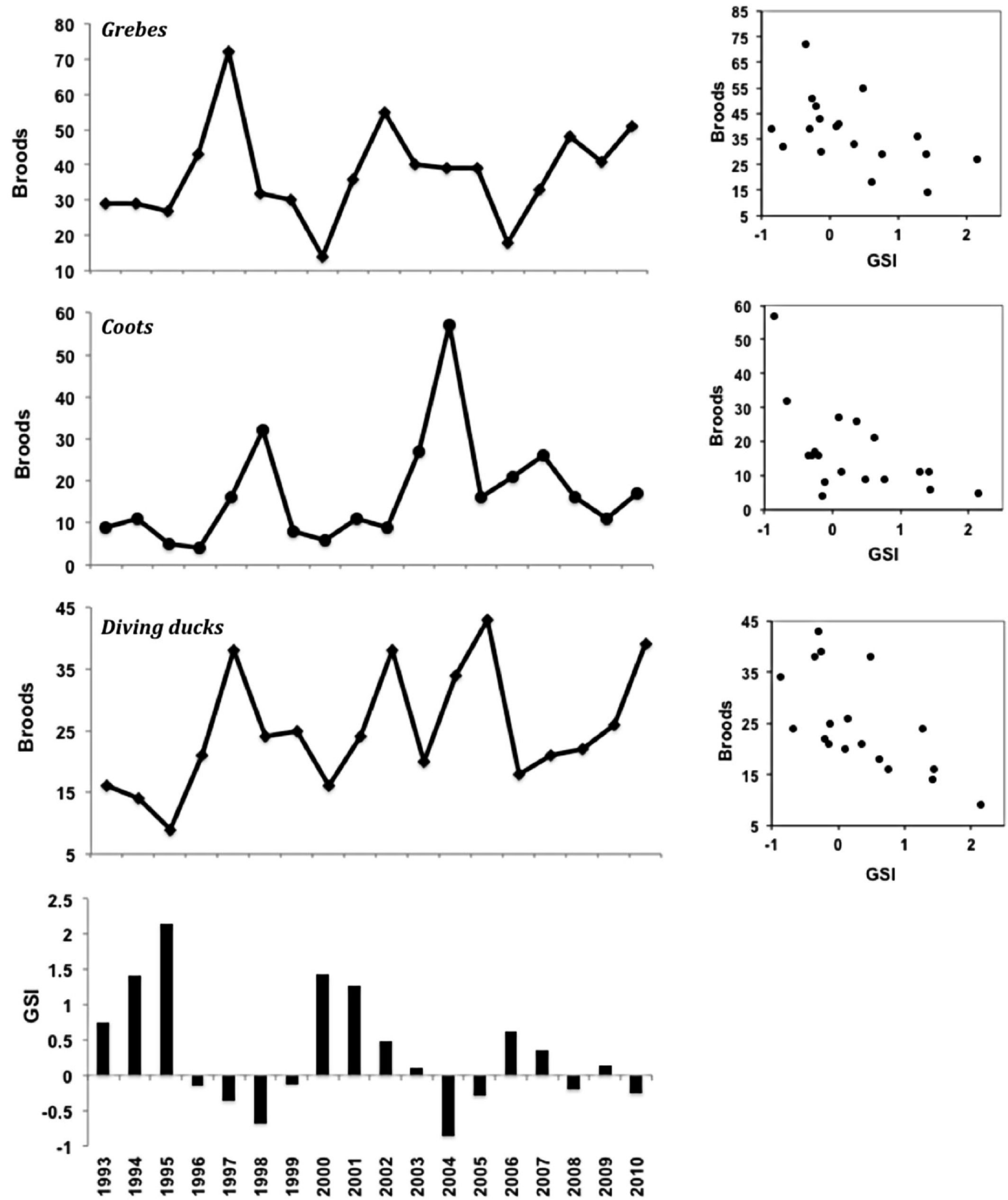

Figure 4. Annual variability in GSI values and in waterbird brood numbers in the Albuferas de Adra wetland. Scatter plots depict the relationship between GSI and brood numbers for the different feeding guilds considered. Regression parameters are described in the text. *Variabilidad anual en los valores de GSI y el número de nidadas en Albuferas de Adra. Los gráficos de dispersión muestran las relaciones entre GSI y el número de nidadas para los diferentes grupos funcionales de aves acuáticas considerados. Los parámetros de las regresiones se describen en el texto.*

also increases with the increase in submerged plant coverage (Gregg & Rose, 1985). A similar inverse (although slightly less significant) response to changes in GSI was observed for diving duck broods. In agreement, Moreno-Ostos *et al*. (2008) found that the abundance of this feeding guild in the wetland depicted a weaker but still significant relationship with the occurrence of the spring clear water phase and hypothesised that their more omnivorous diet (Sánchez *et al*., 2000) should be in the base of this relatively lower dependence on regime shift in the wetland. Moreover, it has been suggested that the globally endangered diving White-headed duck depicts broader habitat requirements during the breeding season than during the winter (Amat & Sánchez, 1982; Moreno-Ostos *et al*., 2008; Atiénzar *et al*., 2012). As a contrast, the brood number of the generalist, ubiquitous and highly adaptable dabbling ducks was not affected at all by changes in GSI throughout the study period.

The present study clarifies that waterfowl brood production in Albuferas de Adra depends largely on a complex ecological sequence of related factors propagating from local weather to the alternation of different ecosystem states. This sequence is initiated by the latitudinal position of the Gulf Stream in the Atlantic, which significantly influences the spring meteorological conditions prevailing in the wetland and the subsequent alternative stable state. The correlation found between GSI and numeric response of broods of the same year implies a proportional (linear) and instantaneous (no time-lag) response of organisms to a regional climate index. This is an extreme case of synchronisation between climate and biology that could be explained by non-interactive (or additive, sensu Stenseth *et al*., 2002) effects of climate on Albuferas de Adra's waterbirds. However, the clear/turbid water phases seem to be an ecological on/off switch driven by catastrophic jumps along a non-linear mechanism linking climate and phytoplankton behaviour in these lakes. Such catastrophic changes may not be revealed by covariance analysis if responses are not proportional to signals, as is usual in non-linear systems (see Barnosky *et al*., 2012, for a review of abrupt ecological shifts across critical thresholds).

In agreement with George & Taylor (1995) and Taylor *et al*. (2002), our results support that organisms act as integrators of complex weather signals; therefore, they show a more significant correlation to the Gulf Stream position than local meteorological observations and may provide a sensitive sensor of regional climate change. Although more research is needed, our findings are likely to apply to other wetlands and lakes in Western Europe.

Appropriate knowledge of waterbird habitat use and selection has become a useful tool for monitoring and managing aquatic bird populations (Løfaldli *et al*., 1992; Quevedo *et al*., 2006; Smart *et al*., 2006; Liordos, 2010; Atiénzar *et al*., 2012). The reported inter-annual catastrophic and complex variability contributes to this knowledge and should be taken into account for adequate waterbird and wetland conservation and management programs. Although climate variability is naturally imposed and not manageable, GSI can be successfully predicted by relatively simple multiple regression empirical models (Taylor & Stephens, 1998; Taylor & Gangopadhyay, 2001). We encourage ecosystem managers to use these predictions to roughly anticipate annual waterbird brood production in the wetland and to, accordingly, formulate the most convenient management strategies for waterfowl conservation.

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