Time series analysis of the *Karenia brevis* blooms on the West Florida Shelf: relationships with El Niño – Southern Oscillation (ENSO) and its rate of change

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Abstract

Blooms of the toxigenic dinoflagellate *Karenia brevis* occur regularly in the Gulf of Mexico, especially along the coast of western Florida, U.S.A. Here, time-series data from 1998 to 2020 were used to examine relationships between *K. brevis* abundance and the El Niño – Southern Oscillation (ENSO) and its rate of change, as well as temperature, precipitation, river flow, and salinity. This time series includes periods of substantial blooms ($\sim 1.4 \times 10^6$ cells L^{-1}) and times characterized by background cell concentrations ($\sim 1.0 \times 10^3$ cells L^{-1}). El Niño brings wet and cool weather to South Florida, including a greater frequency of storms, while La Niña brings dry and warm weather. However, mild La Niña and periods of ENSO transitions bring a higher frequency of hurricanes that directly impact Florida. Excluding the large bloom of 2020–2021 (not included herein), the highest *K. brevis* abundances observed were associated with blooms in 2004–2005 and 2017–2018, both of which occurred when hurricanes followed drought periods. High correspondences between cell concentrations, Peace River discharge and ENSO index indicated that freshwater flow, and climate oscillations may play important roles–both direct and indirect–on *K. brevis* blooms on the West Florida Shelf. These time-series analyses will help to inform new models of bloom formation and termination in western Florida waters and may help to guide nutrient reduction targets from river discharge.

Keywords: Karenia brevis, West Florida Shelf, ENSO, time series analysis

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Introduction

Blooms of the toxigenic dinoflagellate *Karenia brevis* occur annually in the eastern Gulf of Mexico (Steidinger, 2009). Bloom duration can vary from months to years, and blooms can extend up to 1000 km along the coastline. Blooms initiate offshore (20–65 km) and the transportation of the cells nearshore occurs via the bottom Ekman layer driven by wind-driven and upwelling-related transport (Steidinger, 1975; Weisberg *et al*., 2016). Both physical drivers and nutrient supply are important to the initiation, development, and maintenance of *K. brevis* blooms (reviewed in Heil and Muni-Morgan, 2021; Li *et al*., 2021).

Oscillations of El Niño and La Niña, the El Niño - Southern Oscillation (ENSO), affect southwest Florida in complex ways. El Niño brings wet and cool weather to South Florida, including a greater frequency of storms, while La Niña brings dry and warm weather. However, both mild La Niña periods and transitions in ENSO periods may bring a higher frequency of hurricanes, which increase both freshwater flows and associated nutrient delivery to coasts. This study investigated the relationship between environmental conditions (temperature, salinity, river discharge and the ENSO) and the *K. brevis* concentration along the southwestern coast of Florida, using available long-term data.

Materials and Methods

Overview of Florida HAB database

Geo-referenced *K. brevis* surface cell concentration data (cells L^{-1}) with associated temperature (˚C), and salinity data for southwest Florida from 1998 to 2020 were obtained by request from the Florida Fish and Wildlife Research Institute (FWRI). This *K. brevis* cell concentration database (the Florida HAB Historical Database) contains data collected by state and county agencies, private research institutions and university researchers and represents samples collected during research, routine monitoring, and event response sampling of suspected or confirmed *K. brevis* events. This analysis is limited to data post-1998 when routine sampling intensified, but the database contains records dating back to 1953. This analysis also does not include the large bloom that began in late 2020.

Monthly ENSO status was derived from the US National Oceanic and Atmospheric Administration (NOAA; https://ggweather.com/enso/oni.htm). These data are reported as running three-month averages. Precipitation data (mm) and the discharge of the Peace and Caloosahatchee Rivers (cubic feet s^{-1}) data were from the United States Geological Survey (sites USGS 2296750 and USGS 2292000, respectively; https://waterdata.usgs.gov/nwis). The Peace River is one of the largest rivers in Florida with a natural flow. The Caloosahatchee River is significantly larger; however, its flow is actively managed and thus does not necessarily parallel precipitation trends.

Statistical analysis

Monthly *K. brevis* cell concentration averages were calculated for the whole southwest Florida to compare all variables during the study period of 22 years. To determine relationships, correlations were estimated using Pearson's correlations between these monthly averaged *K. brevis* (log-transformed) abundances and environmental variables were calculated. As there is a possibility of a lag response in *K. brevis* concentration in relation to environmental conditions (Dixon and Steidinger, 2004), cross-correlation analysis with lags from 0 to 12 months was performed. Multi-co-linearity was assessed before estimating a model with a combination of predictors. A generalized additive mixed model (GAMM) representing the relationship between Peace River discharge and environmental parameters (ENSO index and precipitation) was also developed. In both approaches, normality, variance homogeneity, and uncorrelatedness of model residuals were assessed using residual time series and Q–Q plots, Shapiro–Wilk normality tests, and plots of the autocorrelation function. As the residuals of the models presented non-normal distribution, the sieve bootstrap approach was used to obtain sample distributions of the model coefficients and assess their statistical significance. All analyses were performed using R language (R Core Team, 2021).

Results and Discussion

Blooms of *K. brevis* typically originate in late summer, following the wet season (e.g., Lenes and Heil, 2010). However, annual variations in bloom duration and intensity are large. In years of substantial La Niña, when dry conditions develop, blooms are typically short lived, as exemplified by the 2000 bloom (Fig. 1a). The spring accumulations of *K. brevis* during 2000 represented the prolonged bloom that was initiated the previous year. In contrast, during El Niño years (e.g., 2015), blooms may be sustained at high cell abundances for a longer period throughout the fall months, following the more significant flows of the summer wet season (Fig. 1b). The annual timing of blooms implies that nutrients delivered during the summer wet season help to sustain nearshore blooms into the fall months and may help to regulate the magnitude of blooms that develop.

Extreme bloom conditions are witnessed only occasionally, as exemplified in 2005, when high cell abundances were observed throughout the year (Fig. 1c), including throughout the summer months. That blooms can be sustained throughout the summer months, at least during some years, implies that higher summer temperatures are not an obstacle to sustaining blooms. While summer temperatures may exceed the temperature optimum for growth (Steidinger, 2009; Vargo, 2009), they are not necessarily inhibiting for growth, especially if sufficient nutrients are available. In 2005, when the bloom was sustained through the summer months, flow from the Caloosahatchee River was three times its long-term average during the months of April and May, thus potentially delivering above average nutrient loads early in that year.

Positive significant correlations between Peace River discharge, ENSO, and *K. brevis* were observed with zero lag (Table 1). Dixon and Steidinger (2004) observed a similar relationship between *K. brevis* concentration and Peace River flows for the 1953-1998 period. Moreover, the GAMM indicated a statistically significant relationship between the Peace River discharge and ENSO at both lag 0 and 1 month. Although cross-correlation analysis showed a lag response of two months between ENSO and *K. brevis*, it was not statistically significant in the model. Also, significant negative relationships were

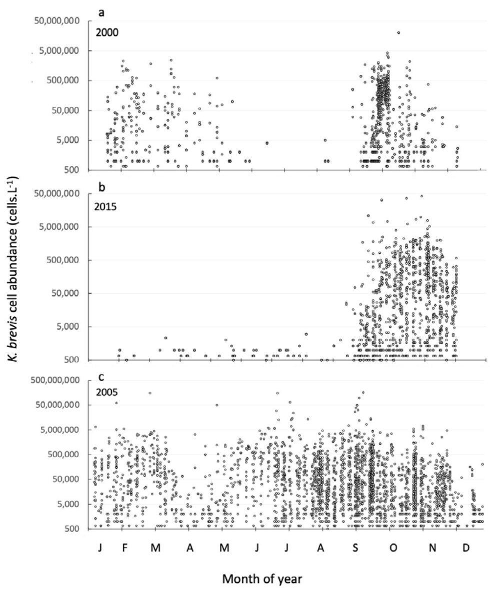

Fig. 1. Examples of the variation in annual *K. brevis* bloom intensity and timing. The year 2000 was a year of La Niña, 2015 was a year of substantial El Niño, and 2005 was a year of transition from El Niño to La Niña. Note difference in scales between years.

observed between precipitation, salinity, temperature, and *K. brevis* (Table 1). No significant relationships were observed with flow from the Caloosahatchee River, as was observed by Dixon and Steidinger (2004) for 1953-1998. While overall flows from the Caloosahatchee River are higher than those of the Peace River, flows are more irregular, as they are actively managed to avoid inland flooding, which leads to a lack of long-term correlations across years.

Blooms in 2000, 2010 and 2020, were associated with intensive La Niña conditions (ENSO <1), while bloom years such as 2015 had intensive El Niño conditions (ENSO >1). More common, however, are bloom years that are neutral with respect to La Niña or El Niño (i.e. mild ENSO conditions). Intensive La

Table 1. Statistically significant cross-correlation between time series of log-transformed *K. brevis* abundance and the environmental variables with lags ranging from 0 to 12 months. P-values are in parentheses.

Variables	**Lag**	**Correlation (*p*-value)**
ENSO	0	0.15 (0.01)
Peace River discharge	0	0.14 (0.01)
Precipitation	0	-0.13 (0.02)
Salinity	0	-0.13 (0.03)
Temperature	0	-0.15 (0.01)

Niña years bring drought and few hurricanes, but milder La Niña conditions and ENSO transition periods can yield hurricanes that directly impact the Florida coast (Fig. 2). Excluding the large bloom that is currently ongoing (2020–2021), the highest annual abundances of *K. brevis* observed in this study were during the 2004–2005 and 2017–2018 blooms, which occurred when hurricane events followed drought periods (Fig. 2). When combining these data, the periods of largest blooms occurred during transition periods in the ENSO index (Fig. 2).

Nutrient loads were not directly addressed herein, however Li *et al*. (2021) demonstrated that the probability of *K. brevis* increased with increasing river flows across all discharge levels, suggesting that the composition of nutrients discharged by different rivers impacts localized coastal *K. brevis* blooms. Medina *et al*. (2020) observed NO_{3+2} levels at lock S79 upriver of the Caloosahatchee River mouth were related to localized *K. brevis* concentrations at the river mouth from 2012-2018, although it was unclear if this effect was the result of river or estuarine nutrient sources. Effects of nutrient loads on HABs associated

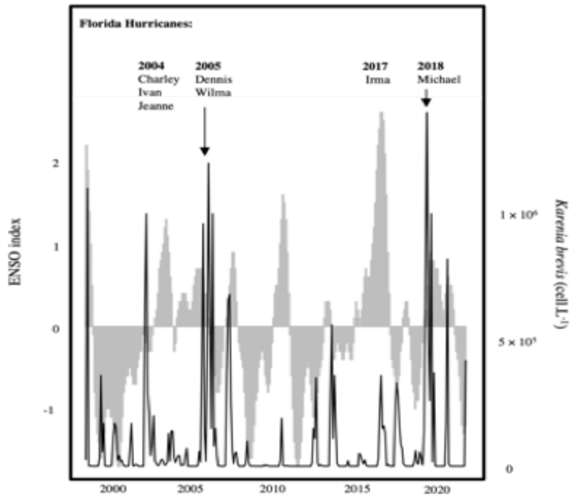

Fig. 2. ENSO index and *K. brevis* abundance (cells L^{-1}) between the years 1998 and 2020 in West Florida Shelf.

with hurricanes and ENSO have also been documented for Lake Okeechobee, the Indian River Lagoon and Florida Bay (Phlips *et al*., 2020; Glibert *et al*., 2021). A study using a three-dimensional ocean-biogeochemical model has also identified ENSO as the main driver of the variability of plankton biomass in the northern Gulf of Mexico during winter and spring (Gomez *et al*., 2019).

In summary, as the river drainages impacting the West Florida Shelf are large, changes in precipitation can translate to large changes in discharges and associated nutrients. Changes in discharge arising from ENSO oscillations as well as active management have the potential to affect *K. brevis* bloom timing, duration, and intensity through changes in nutrient delivery and salinity and temperature. These relationships may also help to inform potential nutrient reduction strategies to mitigate blooms.

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