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Connectivity of the Apalachicola River flow variability and the physical and bio-optical oceanic properties of the northern West Florida Shelf

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ABSTRACT

Maps of satellite-derived estimates of monthly averaged chlorophyll *a* concentration over the northern West Florida Shelf show interannual variations concentrated near the coastline, but also extending offshore over the shelf in a tongue-like pattern from the Apalachicola River during the late winter and early spring. These anomalies are significantly correlated with interannual variability in the flow rate of the Apalachicola River, which is linked to the precipitation anomalies over the watershed, over a region extending 150–200 km offshore out to roughly the 100 m isobath. This study examines the variability of the Apalachicola River and its impacts on the variability of water properties over the northern West Florida Shelf. A series of numerical model experiments show that episodic wind-driven offshore transport of the Apalachicola River plume is a likely physical mechanism for connecting the variability of the river discharge with oceanic variability over the middle and outer shelf.

1. Introduction

The Apalachicola River is an important source of freshwater and nutrients to the northern West Florida Shelf (WFS) in the northeastern Gulf of Mexico (GoM) (Fig. 1). The watershed, which includes the Chattahoochee and Flint Rivers, drains approximately 50,000 km^2 of southern Georgia, eastern Alabama and north Florida. The river empties onto the northern WFS through Apalachicola Bay, an estuary with great ecological diversity that supports finfish and shellfish populations of significant economic value. The annual mean discharge of the Apalachicola River (estimated from the flow rate at Sumatra, FL, about 42 km from the mouth) is 736 m^3/s, making it the largest source of freshwater to the GoM east of Mobile Bay. The river flow rate typically peaks in March with an average monthly discharge of approximately 50% above the annual mean and has a minimum in October of roughly half the annual mean. The historical river flow rate varies dramatically from its annual cycle. The daily-averaged flows measured at Sumatra, FL, from 1977 to 2000 range from a minimum of roughly 140 m^3/s to a maximum of over 5000 m^3/s.

Previous studies have linked precipitation variability over the southeastern United States, which encompasses the Apalachicola-Chattahoochee-Flint (ACF) river system watershed, with multiple climate modes (e.g., Gershunov and Barnett, 1998). A significant precipitation signal has been shown to be connected with the El Niño/Southern Oscillation (ENSO), which typically has higher rainfall during the warm (El Niño) phase (Ropelewski and Halpert, 1986) and reduced precipitation over the region during the cold (La Niña) phase (Smith et al., 1998). Enfield et al. (2001) also examined the interdecadal modulation of the ENSO teleconnections suggesting a greater correlation between rainfall over the southeastern United States and the Southern Oscillation during the cold phase of the Atlantic Multi-Decadal Oscillation (AMO).

The Apalachicola River is a major nutrient source for the northeastern GoM. It provides 92% of the total dissolved inorganic nitrogen to the Apalachicola Bay estuary and exports over 80 mg N/m^2 per day to the GoM in winter (Mortazavi et al., 2000). This nitrogen input enhances primary productivity in the near-shore waters. Offshore of Apalachicola Bay are habitats for commercially important reef fishes, including the Middle Grounds to the southeast and marine protected areas to the south and southwest. For example, commercially important gag grouper (*Mycteroperca microlepis*) typically spawn at locations concentrated roughly along a hard bottom region between the 70 and 90 m isobaths south of Apalachicola Bay in February and March (Hood and Schlieder, 1992), with the larvae settling in the sea grass beds of the coastal zone in March through May (Fitzhugh et al., 2005). Impacts of the Apalachicola River nutrient and freshwater inputs on the marine ecosystems supporting fish populations over the inner, middle, and outer shelf regions remain unclear.

The large variability of the Apalachicola River flow rate manifests in variability of the freshwater and nutrient budgets for the northeastern GoM. Variations in bio-optical properties, particularly satellite-derived chlorophyll concentrations indicative of phytoplankton abundance, offshore of the Apalachicola Bay

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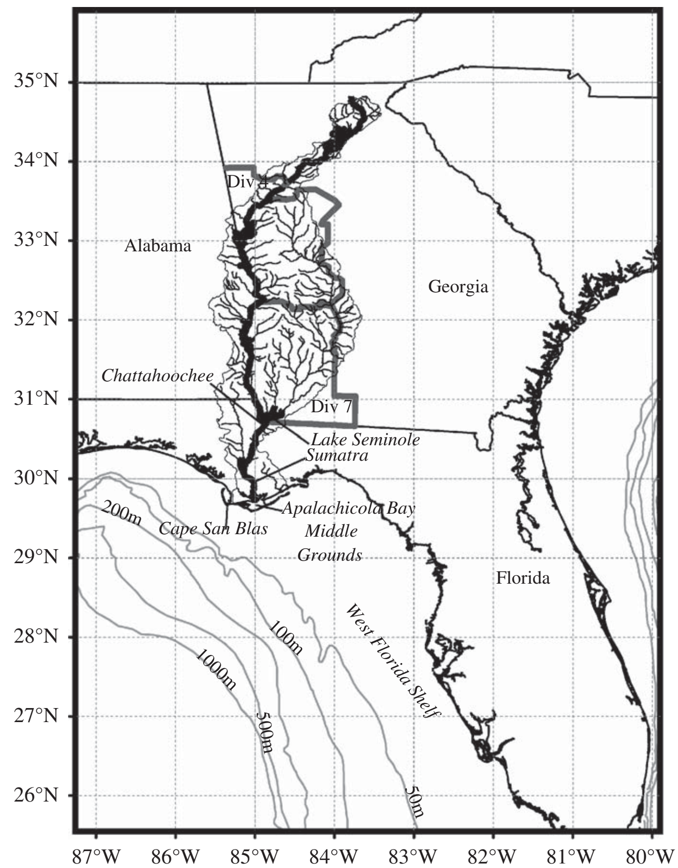

Fig. 1. Map of ACF river system and tributaries with its watershed outlined, and of the bathymetry of the northeastern Gulf of Mexico. Georgia Climate Divisions 4 and 7 are outlined in gray. Locations of river flow measurements at Chattahoochee, FL, and Sumatra, FL, are indicated.

and the precipitation anomalies inland over western Georgia appear correlated at interannual time scales, particularly during the spring months. This study seeks to explain the connectivity between precipitation variability over the watershed and variability of oceanic properties offshore. The time series of the Apalachicola River flow rate recorded over a 78-year period is examined. Analyses of satellite-observed ocean color data and numerical model experiments show the response of the ocean salinity field and chlorophyll concentration estimated from the ocean color data to variability in the Apalachicola River discharge, and are used to estimate the spatial extent of the river's influence in the northeastern Gulf. Numerical model simulations predict a region of low and high salinity anomalies extending out over the northern WFS during anomalous wet and dry years in the southeastern United States. The spatial patterns of chlorophyll concentration anomalies derived from satellite data are in good agreement with the model-predicted salinity anomaly patterns over the northern WFS induced by variations in the Apalachicola River discharge. Model experiments demonstrate that wind-driven transport of the buoyant low-salinity water by synoptic scale atmospheric forcing is critical for determining the spatial extent of the river's influence over the shelf, and providing the mechanism for connecting the variability of the river discharge with the variability in oceanic properties offshore.

2. Variability of the Apalachicola River

The Apalachicola River begins at Lake Seminole near the Alabama-Georgia-Florida border, formed by the construction of the Jim Woodruff Dam in 1957 at the confluence of the Chattahoochee and Flint Rivers (Fig. 1). Along the Chattahoochee River is a series of lakes formed by the construction of several dams, the last of which was completed in 1975. The 560 km long Flint River has two major impoundments upstream from Lake Seminole built in the 1920s and 1930s. Although some surface water from these reservoirs is used for public water supply and agricultural irrigation, the dammed reservoirs are currently primarily used for power generation and a greater portion of water consumption within the drainage basins is supplied from groundwater sources.

Daily-averaged flow rates for the Apalachicola River measured at Chattahoochee, FL (below the Jim Woodruff Dam at Lake Seminole–USGS station 2358000) are obtained from 1 October 1928 to 31 December 2007. Additional daily-averaged flow rates for the river are obtained from Sumatra, FL (USGS station 2359170) from 1 October 1977 to 30 September 2000. The Chattahoochee station is located approximately 180 km upriver from the bay and excludes a portion of the watershed in the Florida Panhandle that contributes to the total river discharge to the ocean. The Sumatra gauge is furthest downstream, 42 km from the mouth of the river, and is negligibly influenced by tides. The mean flow rate at Chattahoochee is about 18% less than measured at Sumatra, but the variability of the flow at Chattahoochee is highly correlated with the variability at Sumatra. Daily streamflow at Sumatra is significantly (at the 99% confidence interval) correlated with daily streamflow at Chattahoochee at lags from zero to seven days, peaking at a five-day lag (Appendix A). Monthly variations in the river flow measured at Chattahoochee explain 85% of the variability of the monthly flow rates measured at Sumatra. Because the flow time series obtained from the Chattahoochee gauge serves as a good proxy for the variability of the discharge rate of the Apalachicola River, this roughly 78-year data record is analyzed to study the river's influence on the northeastern GoM.

Distributions of the daily-averaged flow rates for each month show strong seasonal variability (Fig. 2). The median flow at Chattahoochee peaks in March at more than three times the median flow rate in October. The range of variability, indicated by the width of the middle 80% of the distributions, exhibits similar seasonal variability with a maximum range in March of 1506 m^3/s and a minimum of 326 m^3/s in September. Extreme daily flow rates are caused by drought and flood conditions occurring occasionally throughout the period.

The daily flow rates are averaged for each calendar month of the data record to compute the monthly flow anomalies. The resulting monthly anomalies are then filtered with a five-month running mean to highlight variability at interannual to interdecadal time scales (Fig. 3). To explore possible linkages between the Apalachicola River flow anomalies and ENSO phase, the monthly average discharge time series is conditionally sampled by an ENSO phase classification based on the Japan Meteorological Agency (JMA) index (Japan Meteorological Agency, 1991). This index has been computed by averaging sea surface temperature anomalies over the region 4–4°S, 150–90°W, and then applying a five-month running-average centered on each month. Although the JMA uses additional criteria for defining El Niño (warm phase) and La Niña (cold phase) events, for this study a month is classified as a warm (cold) phase if the JMA index value for that month exceeds (is less than) 0.5 °C (0.5 °C) and if the month lies within a period of at least six consecutive months during which the threshold criterion is met. Otherwise, the month is classified as "neutral". A cursory examination of the monthly flow anomalies based on this index does not immediately suggest any strong relationship (Fig. 3). However, the most significant ENSO-related climate variability in the southeast US precipitation

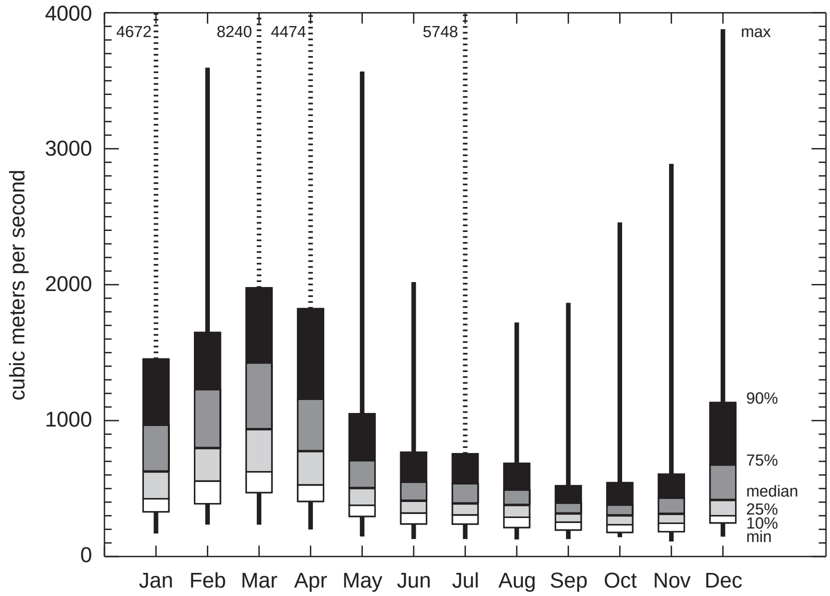

Fig. 2. Distributions of the Apalachicola River daily flow rates (measured at Chattahoochee, FL from 1929 to 2007) by month. The 10th, 25th, 50th (median), 75th, and 90th percentiles are shown with the recorded maximum and minimum. Dotted maxima lines extend beyond the plotting limits and their values are indicated.

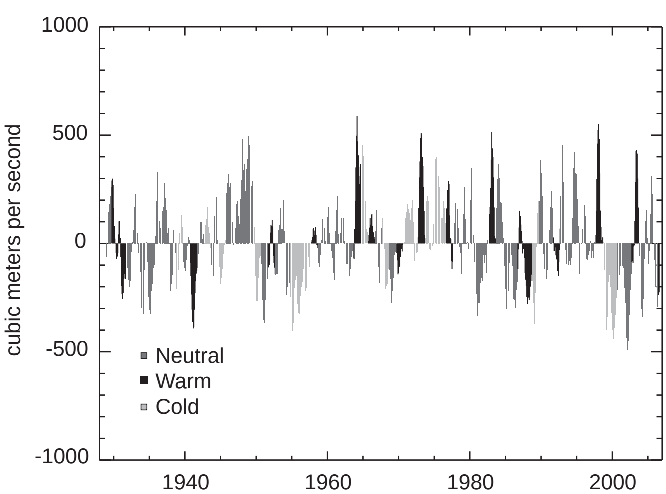

Fig. 3. Apalachicola River monthly flow rate anomalies measured at Chattahoochee, FL, filtered with a five-month running average. The anomalies are shaded by ENSO phase (black = warm phase, gray = cold phase, light gray = neutral phase). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

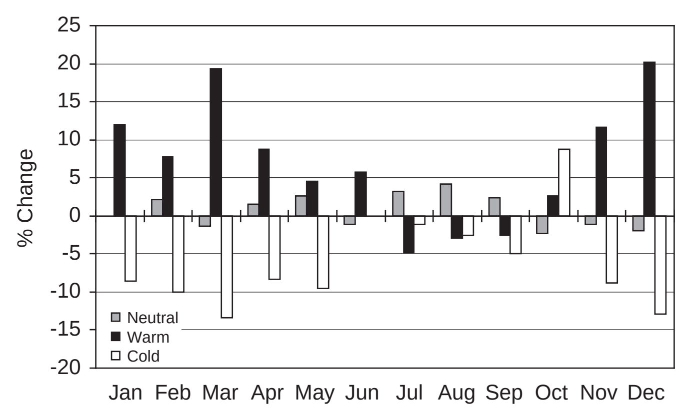

Fig. 4. Percent departure from monthly climatology of the Apalachicola River flow rate (measured at Chattahoochee, FL) averaged over each month and ENSO phase.

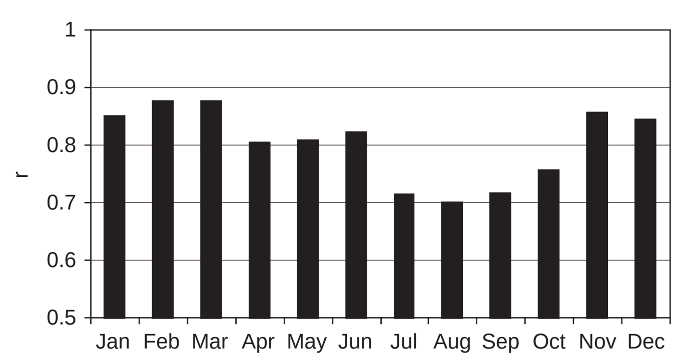

Fig. 5. Linear correlation coefficient computed between the Apalachicola River monthly flow rate anomalies (measured at Chattahoochee, FL, and filtered with a five-month running average) and monthly precipitation anomalies from Georgia Climate Divisions 4 and 7 (averaged together then filtered with a five-month running average) computed for each calendar month over the time period 1929–2006. The time axis corresponds to the filtered river flow anomaly time series, and the precipitation anomaly time series leads by one month.

is found in the fall through late winter months (Ropelewski and Halpert, 1986). If the monthly average discharge time series conditionally sampled by ENSO phase is examined for each calendar month, a striking signal is found in the late fall through early spring (Fig. 4). The monthly averaged river flow during a warm phase is nearly 20% above average (computed from all years) for some months, and 13% below average for others. Little signal is evident for the neutral ENSO phase.

River discharge is governed by the hydrological processes within the drainage basin. Georgia Climate Division 7 lies largely within the ACF watershed (Fig. 1). Monthly precipitation anomalies for this climate division are computed for January 1929–December 2006. After applying a five-month running-average to these anomalies and to the Apalachicola River flow anomalies, the two time series are correlated at $r = 0.75$ with the precipitation anomalies leading the river flow anomalies by one month. This correlation varies seasonally as can be seen when the time series are subsampled by month (Fig. 5). Maximum correlations are greater than 0.8 in late fall through early spring months and less than 0.6 in mid-summer. This is likely due to shifting precipitation patterns between the cold months, when large-scale extra-tropical weather systems govern rainfall distribution, and the warm months, when rainfall in the coastal region is dominated by local diurnal convective activity.

3. The influence of the Apalachicola River on ocean color

Monthly climatology maps are constructed from the Sea Viewing Wide Field-of-View Sensor (SeaWiFS) satellite chlorophyll *a* concentration standard mapped images (SMI) from 1997 through 2006. This 9 km resolution chlorophyll *a* SMI product is made available from the NASA Goddard Space Flight Center Distributed Active Archive Center and is computed from the Level 2 chlorophyll *a*.product. Monthly anomalies from this climatology are then computed from monthly SMI chlorophyll *a* maps. This satellite chlorophyll product can have errors, particularly in coastal regions with terrestrial runoff, due primarily to chromophoric (or colored) dissolved organic matter (CDOM) and possibly suspended particulate matter, with consequences further discussed later in this section. Nevertheless, data from this product will be referred to as chlorophyll throughout this text.

During this ten-year period for which the satellite chlorophyll *a* anomalies are computed, the southeastern US experienced extended periods of anomalously high and low precipitation with corresponding anomalously high and low river flow (Fig. 6), particularly during the 1997–1998 El Niño (anomalously high) and the 1999–2000 La Niña (anomalously low). Monthly anomalies from the late winter/early spring of 1998 and 2000 show widespread elevated and suppressed chlorophyll concentrations

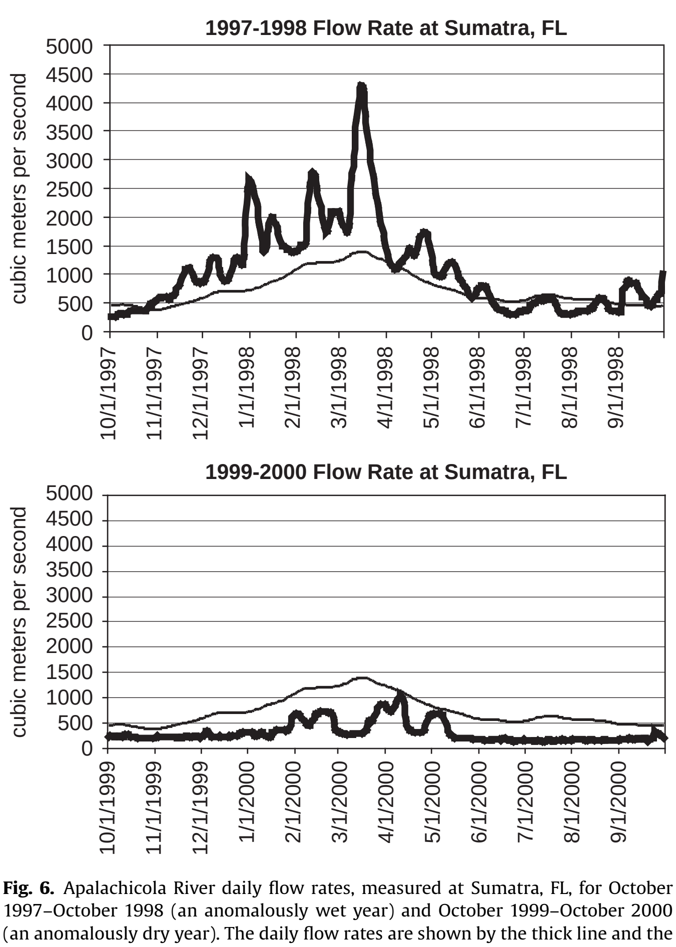

Fig. 6. Apalachicola River daily flow rates, measured at Sumatra, FL, for October 1997–October 1998 (an anomalously wet year) and October 1999–October 2000 (an anomalously dry year). The daily flow rates are shown by the thick line and the thin line is the daily climatology flow rate computed from the Sumatra, FL data.

throughout the region (Fig. 7). The anomaly magnitudes are largest ($>3\,\mathrm{mg\,m^{-3}}$) in coastal areas near the freshwater sources. Noticeable in both years are tongues of locally high ($>\sim 0.3\,\mathrm{mg\,m^{-3}}$) anomaly magnitudes extending southward from near the Apalachicola River to approximately 150 km offshore over the middle shelf. These anomalies can be compared to the March-averaged SeaWiFS-derived chlorophyll *a* concentrations of $0.825\,\mathrm{mg\,m^{-3}}$ over the boxed region in Fig. 7 (lower left panel).

Gilbes et al. (1996) documented a plume with elevated pigment concentrations in this region using data from Coastal Zone Color Scanner and confirmed its existence with *in situ* observations. These episodic plumes varied in intensity and duration from one week to one month and were identified from satellite imagery peaking in spring months. They were also coincident with reduced surface salinities suggesting a riverine origin, but the process responsible for their formation remained unclear. Subsequent observations reported by Gilbes et al. (2002) showed elevated primary production, chlorophyll concentrations, as well as CDOM and sediment levels within this plume, and implicated the Apalachicola River as its source. Optically significant ($>1\,\mathrm{mg\,m^{-3}}$) suspended particulate material concentrations are typically found only within a few kilometers of the coast in the eastern Gulf of Mexico (Manheim et al., 1972). However, Del Castillo et al. (2000) measured elevated absorption coefficients of CDOM at stations to the south of Apalachicola Bay. Thus, it is likely that the elevated satellite-derived chlorophyll within the plume is primarily due to riverine input of nutrients, but discharged sediment and CDOM concentrations probably affect the chlorophyll estimates, especially near the coast. Regardless of the composition of the water, the results still point to a riverine origin for the pigment anomalies. Further investigation involving *in situ* sampling and bio-optical validation of the satellite products is needed to confirm this.

The SeaWiFS SMI chlorophyll anomalies are averaged over a 0.5° longitude $\times\, 0.5^\circ$ latitude region centered south of Apalachicola Bay around 84.75°W, 29.25°N (Fig. 7). Since the largest anomalies are typically seen during the month of March, the chlorophyll anomaly time series from this month is compared to the Apalachicola River flow three-month averaged anomalies from January to March and to the five-month average precipitation anomalies over a large area of the watershed for November–March (Fig. 8). Thus, the chlorophyll time series lags the river discharge time series by zero to two months, and the precipitation time series by zero to four months. Over the ten-year record, the chlorophyll anomaly time series is correlated with the river discharge anomaly time series with $r = 0.91$, and with the precipitation anomaly time series with $r = 0.94$. This strongly suggests that particularly during the months of typically large river discharge and variability, elevated and suppressed chlorophyll concentrations are associated with variations in the river discharge linked with precipitation over the watershed.

The spatial pattern of the correlation between the March monthly averaged chlorophyll *a* anomalies and the January–March-averaged Apalachicola River flow rate is demonstrated by correlating the chlorophyll time series with the river flow time series as described above, but at each 9 km wide grid cell of the SeaWiFS-mapped product. Similar techniques have been applied for correlating suspended particulate matter estimated from SeaWiFS data with river discharge in the northern Gulf of Mexico (Salisbury et al., 2004). The map of the linear correlation coefficients that are significantly different from zero (with 99% confidence) again highlights the tongue-like pattern extending just over 200 km offshore from Apalachicola Bay roughly along the 50 m isobath to about 150 km offshore along the 100 m isobath (Fig. 9). Near the coast, correlation coefficients drop below the threshold for significance due to noise in the time series of

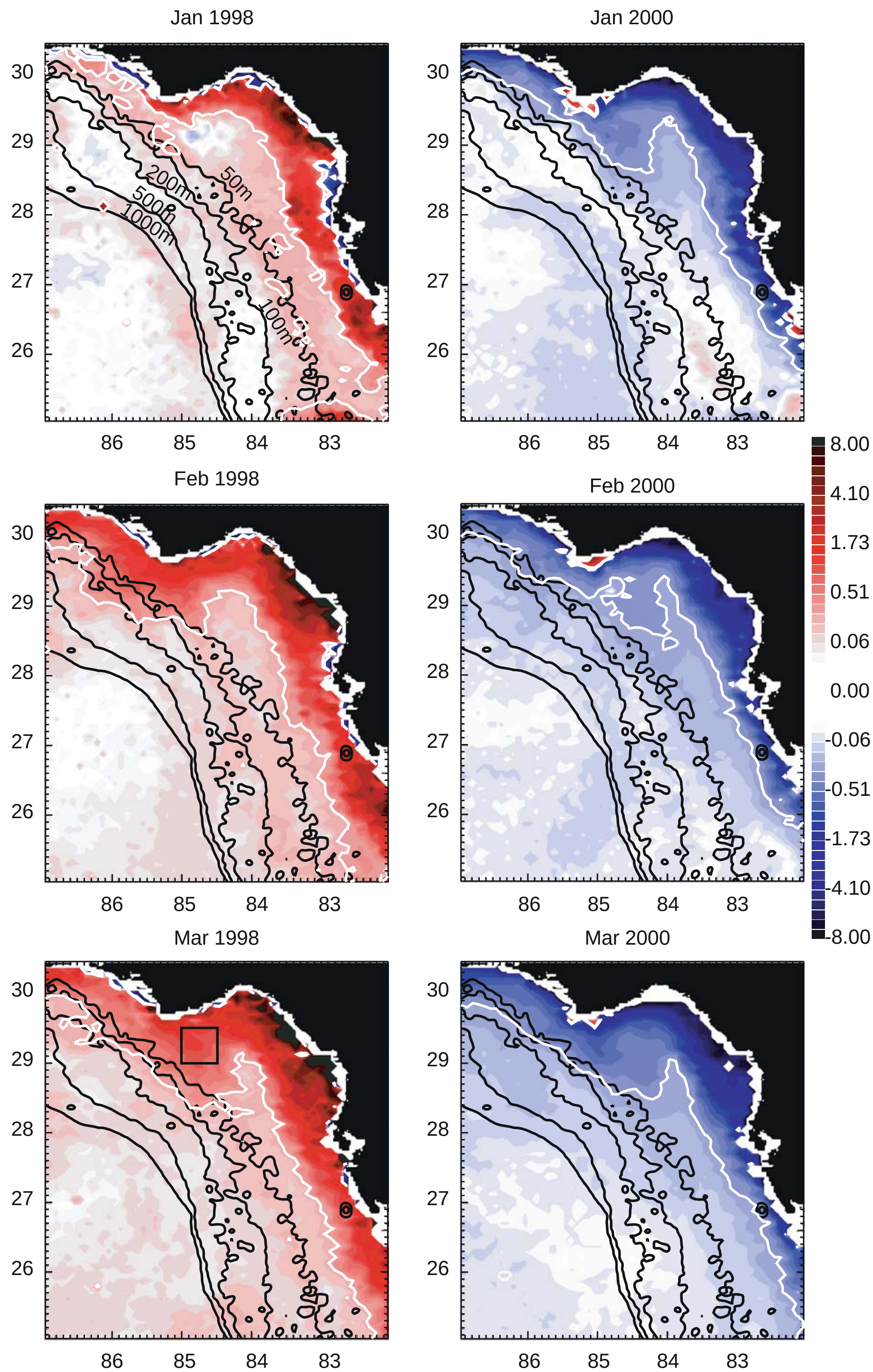

Fig. 7. Monthly chlorophyll *a* anomalies (mg m^{-3}) computed from SeaWiFS ocean color data for January through March of 1998 and 2000. A logarithmic scale is applied to the color map and the $\pm$0.262 mg m^{-3} anomalies contoured by white lines. The black square in the lower left panel indicates the region in which the anomalies are averaged for the time series displayed in Fig. 8.

chlorophyll estimates, which possibly arises due to localized nutrient input from other terrestrial sources or inaccuracies in the satellite-derived chlorophyll estimates caused by the presence of suspended particulate material, CDOM (Harding et al., 2005) or possibly reflectance from the sea floor in very shallow areas. Significant correlations over the inner shelf away from the Apalachicola River are likely due to other rivers in the region exhibiting similar interannual variability. The precipitation variability that affects the ACF watershed is coherent at interannual time scales over much of the southeastern United States, so other rivers in the region are likely to have similar interannual signals and affect coastal water in much the same way. For example, the next largest river discharging to the study domain is the Suwannee River, and indeed the February–March–April three-month running anomalies computed from the USGS 02323500 gauge are correlated with the Apalachicola River flow anomalies with $r = 0.65$ from 1942–2007. Such similar variability between regional rivers and likely overlapping regions of influence make

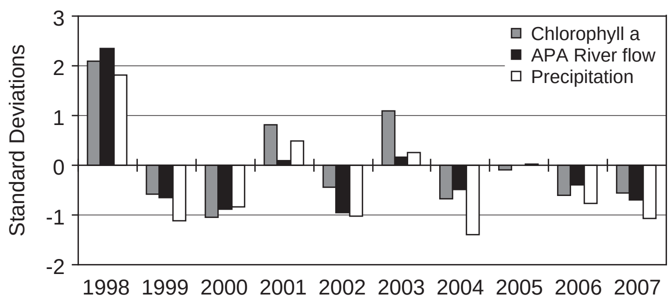

Fig. 8. Monthly anomalies of SeaWiFS-derived chlorophyll *a*, Apalachicola River flow rate (measured at Chattahoochee, FL), and precipitation over Georgia Climate Division 7. The chlorophyll anomalies are averaged over a $0.5^\circ \times 0.5^\circ$ region centered at 84.75°W, 29.25°N (Fig. 7) for March of each year. The Apalachicola River flow monthly anomalies are averaged over the time period January–March (leading the chlorophyll anomalies by zero to two months). The precipitation anomalies have been averaged over the period November–March (leading by zero to four months).

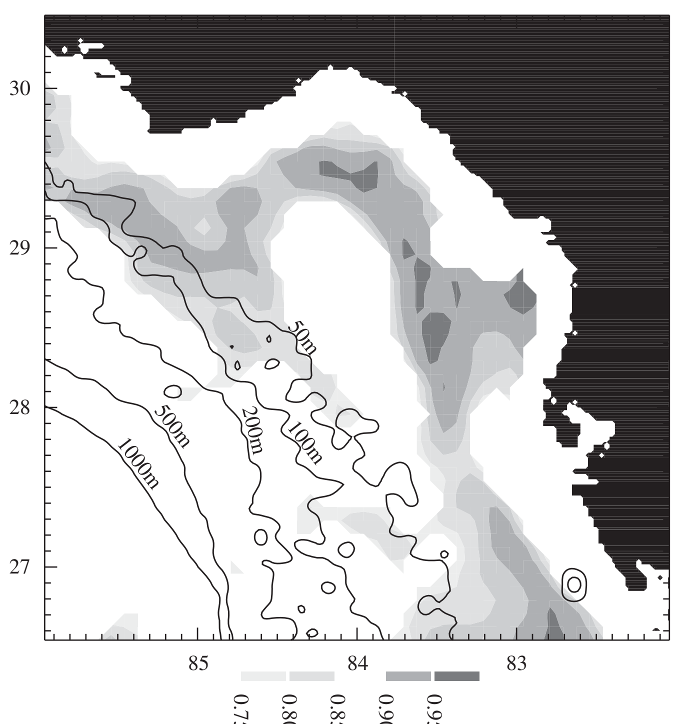

Fig. 9. Map of linear correlation coefficient computed from the time series of SeaWiFS-derived monthly averaged chlorophyll *a* anomalies for March of each year from 1998 to 2007 and the Apalachicola River flow anomalies averaged over January–March of each year. Shaded values indicate significant correlation (greater than 0.765) between the two time series at the 99% confidence interval (Emery and Thomson, 2001).

isolating the oceanic region of connectivity to the Apalachicola River problematic from analysis of observational data alone. Numerical model experiments are therefore used to further study the issue in Section 4 below.

4. Modeling the influence of the Apalachicola River on the ocean salinity field

4.1. Model configuration

A set of numerical model experiments is performed to better understand the scope of influence of the Apalachicola River's variability in the northeastern GoM, and to explain the mechanisms responsible for linking the terrestrial climate variability with the regional oceanic variability. The Navy Coastal Ocean Model (NCOM) (Martin, 2000) has been applied to the GoM and northwestern Caribbean Sea by Morey et al. (2003a, b) at 1/20° horizontal resolution to study the transport of low-salinity water formed by rivers along the coastal areas of the northern and western Gulf. The model configuration has been improved and the study has been extended over the entire GoM coastline by Morey et al. (2005a). This last model configuration is now used for the numerical experiments. The model specifics are detailed in the above-cited literature, but essentially this primitive equation three-dimensional model has been configured with a hybrid vertical coordinate system (20 evenly spaced terrain-following layers above 100 m and 40 geopotential-following levels below 100 m) over the region 98.15°W to 80.60°W, 15.55°N to 30.5°N. The simulations use the quasi-third-order horizontal advection scheme of Holland (1998) and the Mellor and Yamada (1982) Level 2 turbulence closure model. Thirty rivers are simulated in the model as volume fluxes at coastal grid cells with salinity of 5 (Practical Salinity Units, or PSU, are assumed throughout) and temperature equal to the 1998 World Ocean Atlas (Conkright et al., 1998) monthly climatology sea surface temperature nearest each source. Monthly climatology discharge rates for US rivers are derived from the United States Geological Survey streamflow statistics.

Two one-year periods (chosen to start and end in September, approximately the minimum of the annual cycle for river flow and variability) are selected for study and comparison to climatology. September, 1999 through September, 2000 was an anomalously dry year with corresponding anomalously low flow in the Apalachicola River (Fig. 6). This was a strong La Niña year as classified by the JMA. Conversely, the river flow during the year starting and ending in September of 1997–1998, a strong El Niño year, was anomalously high.

Four near-identical twin model "forecasts" are run for the period 22 September, 1999 through 21 September, 2000. Using the technique of assimilating Modular Ocean Data Assimilation System (MODAS) (Fox et al., 2002) synthetic temperature and salinity profiles described in Morey et al. (2006), an analysis run is conducted from 19 June, 1999 to 00 UTC 22 September, 1999. The model state at the end of the analysis run is used to initialize the model forecast runs, which have no data assimilation. Twelve-hourly wind fields for the analysis and forecast runs are constructed with an objective gridding technique applied to the SeaWinds satellite scatterometer-derived winds using the National Center for Environmental Prediction–Department of Energy Atmospheric Model Intercomparison Project Reanalysis 2 (NCEP-DOE AMIP-II Reanalysis) 10 m wind fields, as described in Morey et al. (2005b).

The numerical experiments are configured as follows. The first experiment is a realistic forecast of the 1999–2000 (dry year) period in which the daily Apalachicola River discharge (defined by the daily streamflow measured at the Sumatra, FL gauge) is applied with the high-frequency (12-hourly) winds for the same time period (termed experiment HFDRY). Note that all other rivers have their monthly climatology discharge rates prescribed. The next experiment is identical except that the 1997–1998 (wet year) daily Apalachicola River discharge values are substituted (termed experiment HFWET). A third experiment is run with monthly climatology Apalachicola River discharge, but still forced by the high-frequency winds (experiment HFCLIM). Finally, the model is forced from the same initial conditions, but monthly climatology winds (DaSilva et al., 1994) are applied along with the monthly climatology river discharge for all rivers (experiment CLIM, see Table 1).

4.2. Model results

Differences in monthly near-surface model salinity fields from the experiments with different Apalachicola River discharge rates (HFWET and HFDRY) highlight the spatial extent of the influence of the river's variability over the northeastern Gulf (Fig. 10a–c). Results for January through March are analyzed because the river discharge and variability are largest during these months, which coincide with the spawning of gag grouper (Fitzhugh et al., 2005).

Table 1
Numerical model experiments.

Experiment name	Wind stress	APA river discharge
CLIM	Monthly climatology	Monthly climatology
HFCLIM	1999–2000 12-hourly winds	Monthly climatology
HFDRY	1999–2000 12-hourly winds	1999–2000 daily discharge
HFWET	1999–2000 12-hourly winds	1997–1998 daily discharge

The maps show a reduction in salinity during the anomalously wet year compared to the anomalously dry year over a tongue-like region extending south and southeastward from the coast near the Apalachicola River with differences greater than 0.25 up to 200 km offshore. The spatial patterns of the salinity differences have similar characteristics to the spatial patterns of the monthly chlorophyll concentration anomalies. Localized differences in the model solutions along the Florida Peninsula and in deeper waters are the result of small positional changes in salinity fronts near other rivers and offshore eddies that are expected from a nonlinear model after several months of integration.

Since the HFWET and HFDRY experiments differ only in the prescribed freshwater discharge from the Apalachicola River, the differences in the model solutions isolate the impacts of that particular river from other influences in the region, such as other rivers and shelf-edge upwelling due to interannual variability in the winds. For example, from the analysis of SeaWiFS data (Figs. 7 and 9), large anomalies and correlations are found not only in the tongue region extending offshore of the Apalachicola River, but

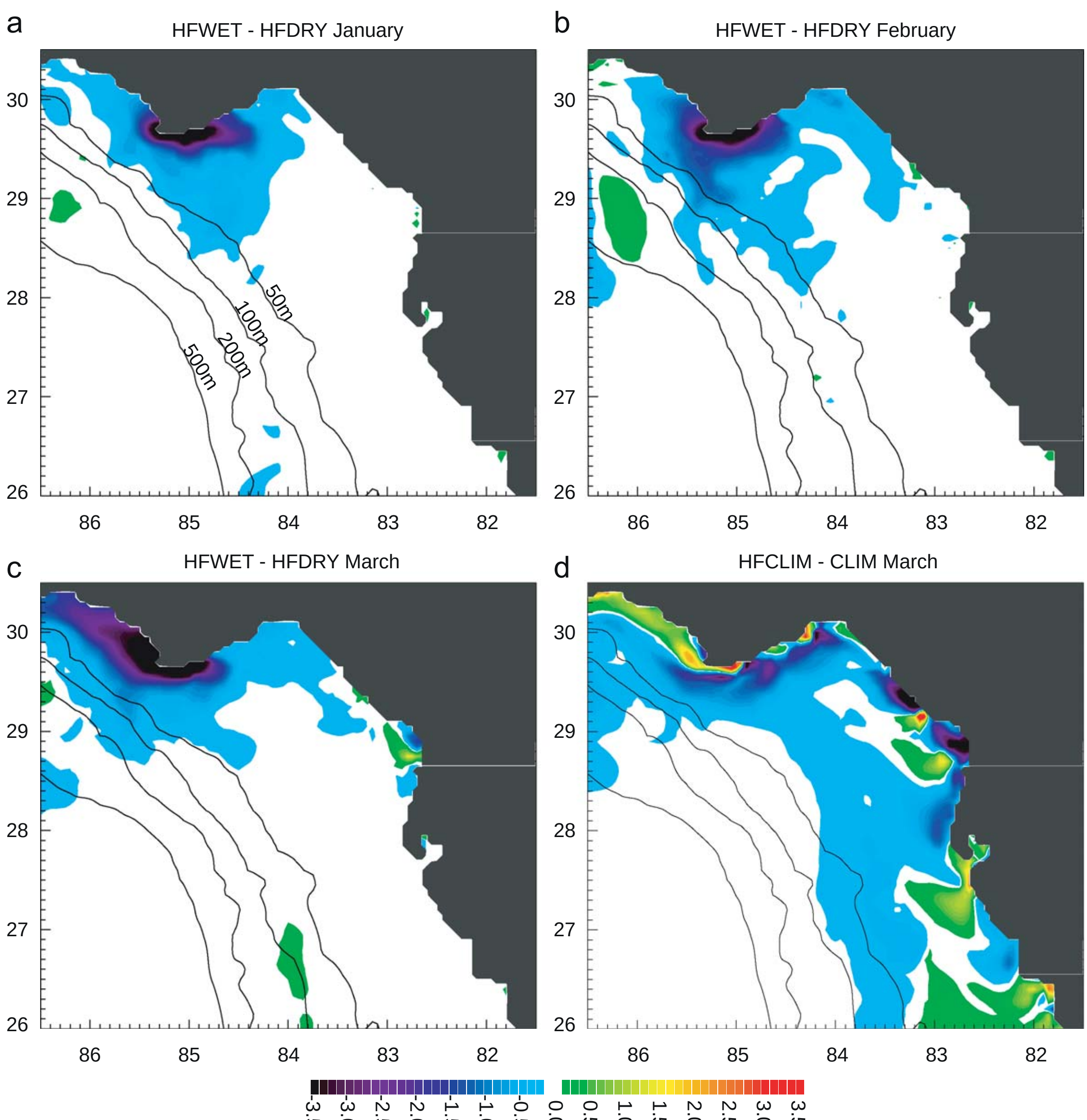

Fig. 10. Differences between the monthly averaged salinity of the HFWET and HFCLIM experiments for January–March (a–c), and for the HFCLIM and CLIM experiments for March (d). Salinity differences less than 0.125 in magnitude are not colored.

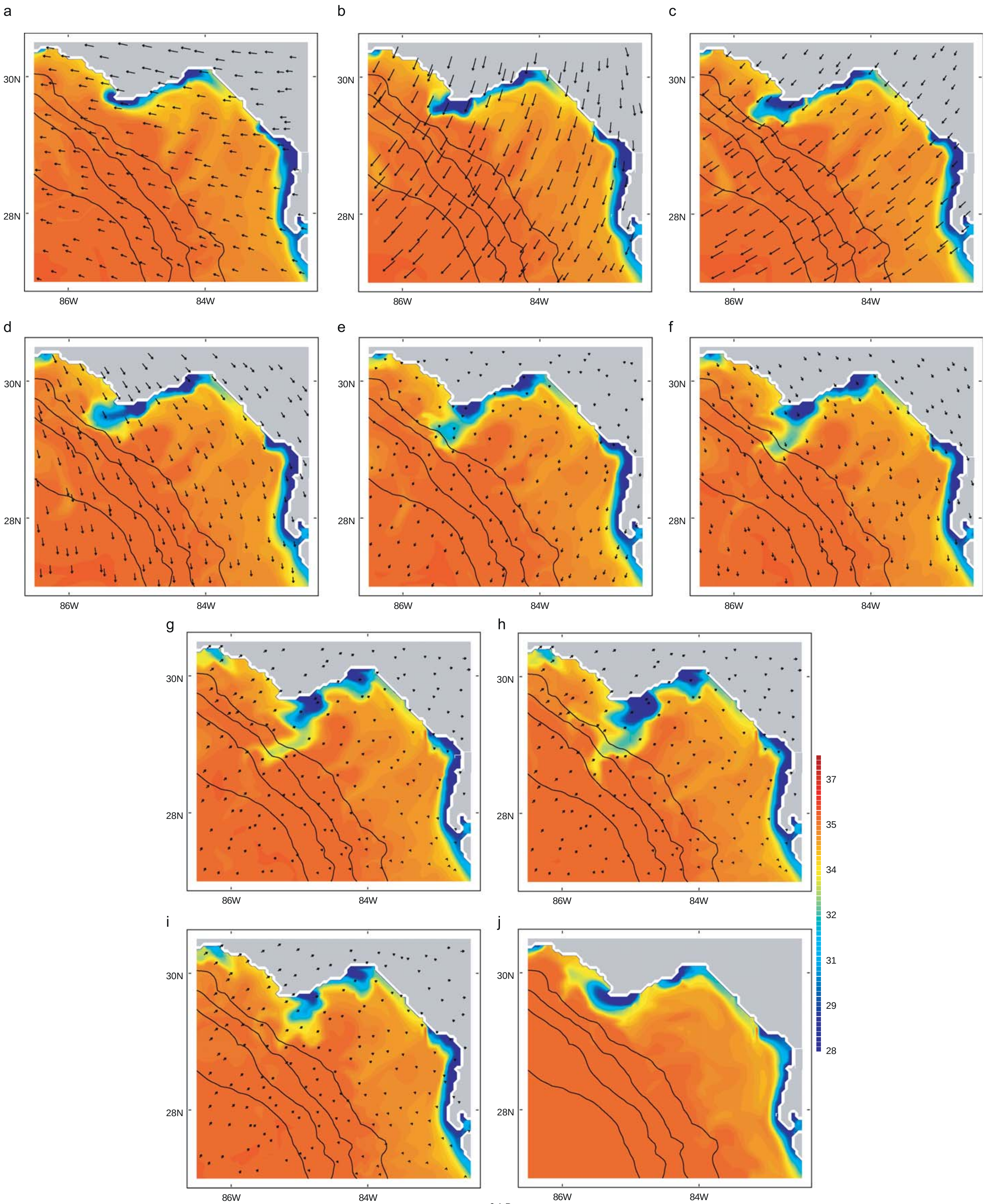

Fig. 11. Synoptic maps of model surface salinity and wind stress from the HFCLIM experiment showing the evolution of an offshore-directed plume of low-salinity water emanating from near the Apalachicola River (a–g). The fields from the HFWET (h), HFDRY (i), and CLIM (j) experiments are shown for 11 February for comparison. The intensity of the plume varies with the differing Apalachicola River discharge rates, and the plume remains confined to the coast in the CLIM experiment in which there is no episodic wind forcing. (a) Jan 30, 2000—clim flow; (b) Feb 1, 2000—clim flow; (c) Feb 3, 2000—clim flow; (d) Jan 5, 2000—clim flow; (e) Feb 7, 2000—clim flow; (f) Feb 9, 2000—clim flow; (g) Feb 11, 2000—clim flow; (h) Feb 11, 2000—high flow; (i) Feb 11, 2000—low flow and (j) Feb 11, climatology winds—clim flow.

also around the coastal areas. It is difficult to distinguish from these maps the domain of influence of the Apalachicola River from influences from other rivers precisely. The differences between the twin model experiments show that interannual variations in the Apalachicola River discharge alone can affect a large area of the northern WFS.

Inspection of the model salinity fields during January–March reveals a series of intermittent plumes of low-salinity water directed towards the south and southeast from near the Apalachicola River location (the evolution of one such event is shown in Fig. 11). The spatial patterns of these low-salinity plumes are very similar in the HFWET, HFDRY, and HFCLIM experiments (Fig. 11g–i), despite large differences in the experiments' Apalachicola River discharge rates. The intensity of the low-salinity anomalies within the plumes does vary with river discharge intensity. When monthly averages of the surface salinity fields are computed, the presence of these events manifests in the tongue-like spatial patterns observed in the monthly maps of salinity differences between the models (Fig. 10).

The southward-directed low-salinity plumes are noticeably lacking in the CLIM experiment (Fig. 11j), which is forced by the monthly averaged winds with no synoptic scale variability. Thus, it is apparent that high-frequency variability in the winds is critical for the formation of these plumes. An explanation for the presence of these offshore-directed plumes is found in prior studies of the behavior of river plumes under different wind-forcing scenarios. Under the light wind conditions of the CLIM experiment, the low-salinity water remains nearly trapped near the coastline with the coast to the right under the influence of the earth's rotation (Wiseman and Garvine, 1995). Kourafalou et al. (1996) and Otero et al. (2008) show that during upwelling winds, the plume will reverse direction along the coastline and penetrate offshore in a jet-like pattern similar to what is seen in the high-frequency wind-forced model experiments.

To relate the formation of the offshore-directed low-salinity plumes with the wind direction, time periods during which the offshore low-salinity jets develop are determined and compared with the wind stress direction (Fig. 12). Time periods during which these features develop in the model are objectively determined from the surface salinity field. A good indicator of when these events occur is either the minimum or average salinity within the region 29.5–30.0°N and 84.5–85.0°W decreasing by at least 0.2 PSU/day. In the model experiments forced by high-frequency winds, the plumes intensify and penetrate farther offshore during intermittent northerly or westerly wind events. These wind directions are associated with the passage of mid-latitude atmospheric cold fronts which commonly affect the weather in the region at the 3–7 day synoptic time scale during the late fall through early spring months. The Apalachicola River discharge location lies just to the east of a cape (Cape San Blas) where the coastline orientation changes from northwest–southeast to more zonal with a southwest–northeast orientation. Under light forcing conditions, the plume turns to the right and rounds the cape. Here, winds with a northerly or westerly

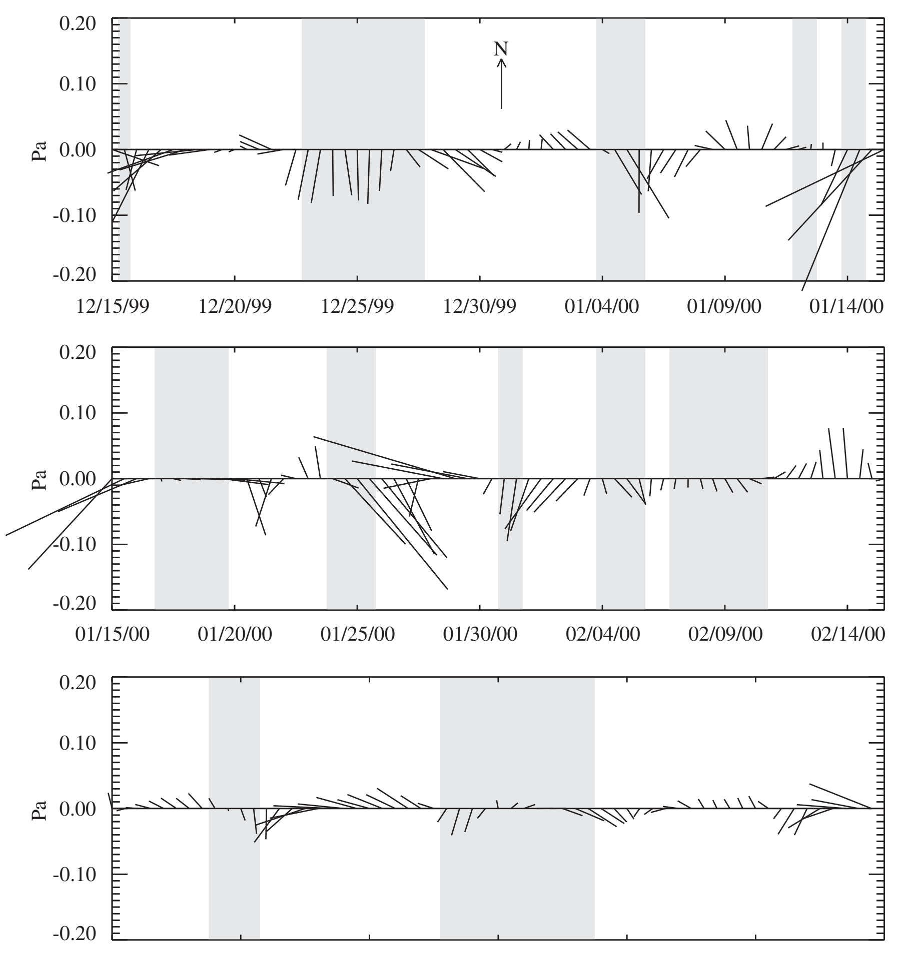

Fig. 12. Wind time series from 29.75°N, 84.75°W. Shaded areas denote times where the minimum salinity within the box defined by 29.5–30.0°N and 84.5–85.0°W is decreasing by at least 0.2 PSU/day or the mean salinity within the box is decreasing by at least 0.2 PSU/day.

component are upwelling-favorable and will direct the buoyant surface water offshore via the Ekman transport. Winds with a westerly component are upwelling-favorable just near the Apalachicola River mouth and will similarly direct the plume offshore. The climatology wind fields lack these episodic northerly or westerly wind events that force offshore transport of the low-salinity water and hence, these plumes do not exist over the shelf in the numerical model experiments forced by climatology winds.

A series of maps of the model salinity fields and wind stress fields show how the plume detaches from the coast and is directed offshore during one of these events (Fig. 11a–g) from 30 January to 11 February. The plume is initially attached to the coast and separates to the west of Cape San Blas under northerly winds around 1 February (Fig. 11b). Bursts of northerly and north-westerly winds around 5 February (Fig. 11d) and 9 February (Fig. 11f) promote further penetration of the low-salinity feature offshore. The February-averaged winds in the region are north-easterly, which is not an upwelling-favorable direction to either side of Cape San Blas. Hence, the river plume in the CLIM experiment does not extend offshore at this time (Fig. 11j). Additionally, since the CLIM experiment is initialized with an identical offshore Loop Current and mesoscale eddy field as the high-frequency wind-forced experiments, the lack of offshore penetration of the plume in the CLIM experiment verifies that the offshore eddy-induced circulation is not a controlling factor in the position of the Apalachicola River plume.

Further evidence of the role of the high-frequency winds in redistributing the low-salinity water offshore can be seen in differences between the monthly averaged near-surface salinity fields of the CLIM and HFCLIM experiments (Fig. 10). These experiments have identical river discharge rates but differ in that the former is forced by monthly climatology winds and the latter by wind fields that resolve synoptic scale atmospheric variability (from 1999 to 2000). The HFCLIM experiment has lower surface salinity over much of the WFS caused by the offshore wind-driven transport of low-salinity water (not just from the Apalachicola River, but also from the other river sources around the Florida coast). Under the light wind conditions of the CLIM experiment, the low-salinity water remains trapped near the coastline. Thus, this wind-driven transport of buoyant low-salinity water from near the coastline towards the deeper waters of the shelf by intermittent offshore winds provides a mechanism for connecting the salinity field over the middle and outer shelf regions with the coastal salinity variability formed by the riverine input.

5. Discussion and conclusions

In this paper, historical data have been analyzed to describe the variability of the freshwater discharge to the West Florida Shelf by the Apalachicola River at time scales from seasonal to inter-decadal. This river is of particular regional importance for a number of reasons. First, it feeds into one of the historically least polluted estuaries in the southeastern United States (Livingston and Kitchens, 1984). Second, it is the largest point source of freshwater along the Florida coastline and adjacent to the wide WFS. Third, it is proximate to important reef fish habitats, spawning grounds for commercially important fisheries, and ecologically diverse sea grass beds. And finally, the river's future management policies are uncertain. It is therefore useful to understand the natural variability of the river system and its impacts on the regional oceanography and marine ecosystems.

There is a large seasonal cycle in the flow rate and variability of the Apalachicola River, with both peaking in the late winter and early spring months. The flow during these months also exhibits marked interannual variability due to variations in precipitation over the watershed. The precipitation during these months over the southeastern United States has previously been shown to be linked with ENSO, with wetter than normal conditions during the warm phase and drier conditions expected during the cold phase. Indeed, analysis of the monthly river discharge anomalies by ENSO phase does show that approximately 20% greater flow is expected during some winter and spring months of a warm ENSO phase compared to up to 13% less flow than average during a cold phase. Interestingly, the early spring peak in the annual cycle of variability coincides with the time during which the most regionally important food fish, gag grouper, spawn over the middle and outer WFS and the larvae begin their transit to the coastal zone (Fitzhugh et al., 2005).

Satellite ocean color data show large positive and negative anomalies in the late winter/early spring monthly chlorophyll *a* concentration in a tongue-like pattern that extends southward and southeastward from near the Apalachicola River offshore as far as 200 km. These anomalies vary with the monthly river flow and precipitation anomalies over representative portions of the ACF watershed. This, in the context of previous analyses of *in situ* data by Gilbes et al. (2002), is highly suggestive of a link between the regional terrestrial climate variability and biological variability over the middle and outer northern WFS.

It is difficult to distinguish from ocean color data alone the region of influence of the Apalachicola River from other terrestrial sources of nutrients leading to enhanced chlorophyll concentrations in the region, yet understanding the impacts of this particular river this is a driving motivation for this study. Several smaller rivers in the region exhibit similar seasonal and interannual variability. Also, the region is not always isolated from influences from the Mississippi River, which inputs freshwater and nutrients to the Gulf of Mexico at a vastly higher rate; however, it has been demonstrated that during the fall and winter months its influence is dominantly toward the west and during the summer months its impacts are seen typically offshore of the WFS break (Morey et al., 2003a, 2003b, 2005a). Therefore, a suite of numerical model experiments is used to highlight the geographic scope of influence of the Apalachicola River on the ocean salinity field, and to provide insight into the physical mechanisms responsible for connecting the terrestrial precipitation and Apalachicola River discharge variability with interannual variations over the northern WFS.

The difference in monthly averaged salinity maps between two nearly identical experiments, differing only in their prescribed Apalachicola River daily discharge rates, shows that changes in the river flow affect a region with a similar spatial pattern as shown by the satellite-observed chlorophyll anomalies. Visualization of the model fields shows that this pattern is the result of time averaging that includes periods when the river plume is directed far offshore as an intermittent jet-like feature. Another nearly identical model experiment with slowly varying monthly climatology wind stress forcing does not exhibit these features, which are found in the model cases with 12-hourly satellite-derived winds. This indicates that high-frequency (resolving the atmosphere synoptic variability) wind forcing is likely responsible for the offshore penetration of the river plume.

Inspection of the wind stress time series in relation to the development of the offshore jets of low-salinity water from the Apalachicola River plume shows that these events occur during northerly and westerly winds, typically associated with the passages of atmospheric cold fronts during the winter and spring months. These wind directions are upwelling-favorable along the coastline on either side of the Cape San Blas. Previous studies have shown that under upwelling-favorable winds, a river plume will reverse direction along the coast, detach from the coast, and penetrate offshore, as is seen in the model experiments.

These wind-driven processes provide the physical link between the river discharge and the offshore marine environment.

In summary, interannual variability in precipitation, particularly during the fall through early spring months, over the ACF watershed produces variations in the rate at which nutrient-rich freshwater from the Apalachicola River is discharged to the northern WFS. During these seasons, intermittent northerly and westerly winds episodically direct the river plume offshore to the south and southeast over the shelf. Variations in the near-coastal salinity and concentration of nutrients near the Apalachicola River is connected to the variability of the salinity and remotely sensed chlorophyll concentrations offshore in the regions affected by the wind-driven river plume. This completes the mechanism for linking interannual variations in the regional climate over the southeastern US with variability in the hydrographic, bio-optical, and biological properties over the northern WFS.

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Appendix A. Cross-correlation and regression model for Apalachicola River flow rates measured at Chattahoochee, FL and Sumatra, FL

If an input series is autocorrelated, the direct cross-correlation function between the input and response series gives a misleading indication of their relation, and significance levels cannot be determined (Jenkins and Watts, 1968). In fact, calculating the cross-correlation between the daily streamflow time series measured at Chattahoochee and Sumatra yields very significant correlation over very long lags, both positive (Chattahoochee leading Sumatra) and negative (Sumatra leading Chattahoochee), which is physically implausible (Fig. A1). One solution to this problem is the Box-Jenkins approach (Box and Jenkins, 1976) sometimes called *prewhitening* (Chatfield, 1996). First, an autoregressive integrated moving average (ARIMA) model (Chatfield, 1996) of sufficient order is fit to the input series and used to filter the input series to reduce the residual series to white noise. Next, the response series is filtered with the same model. Since the time series are highly unstable, the time series are differenced twice prior to filtering with the ARIMA models. Finally, the cross-correlation between the filtered response and the filtered input time series can be computed (Fig. A1). The result in this case makes sense, as the two time series show significant correlation at lags of zero to seven days (with the upstream Chattahoochee time series leading the downstream Sumatra time series), and no relation at negative lags to three days. (The seemingly significant correlation at negative lags beyond three days is leftover from autocorrelation which has not been explained by the ARIMA model.)

Now that it has been determined that the two time series are significantly correlated at lags of zero to seven days, a regression model can be applied to determine the percentage of variance of the Sumatra time series explained by variations in the Chattahoochee time series. The regression model is

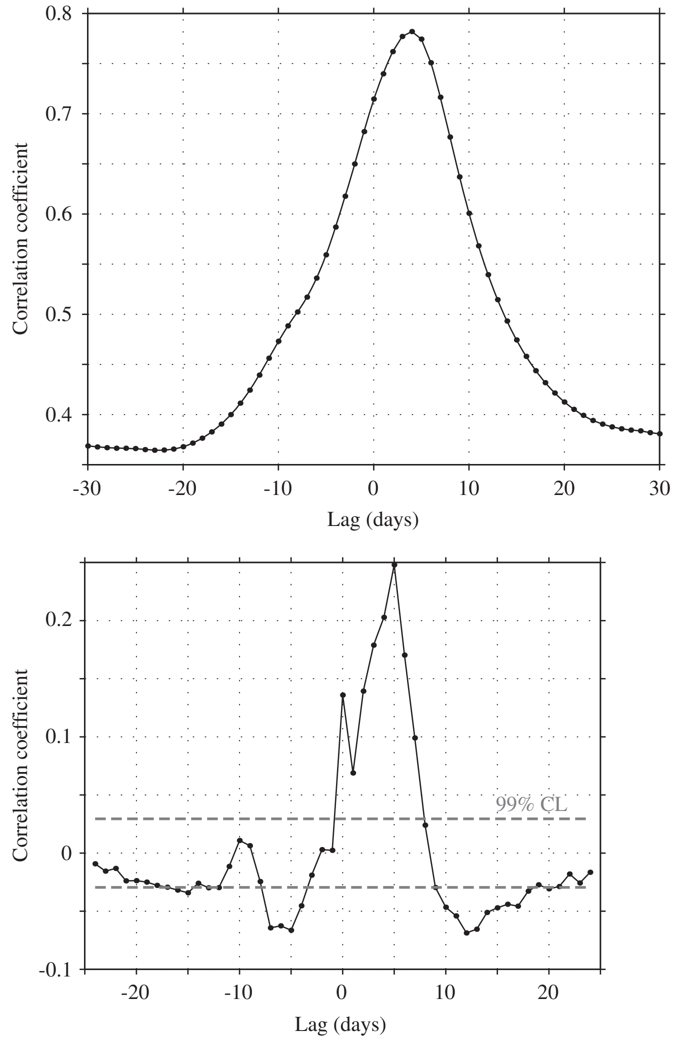

Fig. A1. Top: cross-correlation between daily flow rates measured at Sumatra, FL, and Chattahoochee, FL (positive lag indicates the Chattahoochee time series leads Sumatra time series). Bottom: same as *Top*, but after prewhitening of the time series to remove autocorrelation. The 99% confidence interval is indicated.

$$Q_S^i = \alpha_0 + \sum_{j=0}^{7} \alpha_{j+1} Q_C^{i-j} + \varepsilon_i \quad \text{(A1)}$$

where Q_S is the daily streamflow time series measured at Sumatra and Q_C is the time series from Chattahoochee. Using this model, the daily river flow rate measured at Chattahoochee explains 77% of the variability of the daily flow rate measured downstream at Sumatra. A similar regression model with no lags applied to the monthly flow rates measured at Chattahoochee explains 85% of the variability of the monthly flow rates at Sumatra.

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