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Salinity patterns of Florida Bay

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Abstract

The salinity of Florida Bay has undergone dramatic changes over the past century. Salinity values reached their most extreme, up to 70, in the late 1980s, concurrent with ecological changes in Florida Bay including a mass seagrass die-off. In this study, surface salinity was measured at approximately monthly intervals between 1998 and 2004. The 7-year data set was analyzed to quantify the effects of precipitation, runoff, evaporation, and climatic variability on salinity in Florida Bay. Overall mean Bay-wide salinity varied from a low of 24.2 just after the passing of Hurricane Irene in October 1999 to a high of 41.8 near the end of a drought period in July 2001. Bay-wide mean salinity exhibited dramatic decreases, up to −0.5 per day, whereas increases were slower, with a maximum rate of 0.1 per day. The freshwater budget for Florida Bay was slightly negative on an annual basis with significant positive monthly values observed during the peak of the rainy season (August through October) and significant negative monthly values observed during the peak of the dry season (March through May). This resulted in a minimum mean monthly Bay-wide salinity in January and a maximum monthly mean in July. Mean salinity for the overall Bay and for each of its four subregions could be predicted with reasonable accuracy utilizing a mass balance box model. There was no monotonic trend in salinity over this 7-year study; however, meteorological phenomena, such as tropical cyclones and El Nino-Southern Oscillation, dramatically altered the salinity patterns of Florida Bay on interannual time scales.

Keywords: USA; Florida; Florida Bay; salinity gradient; environmental monitoring; spatial distribution; seasonal variability

1. Introduction

Florida Bay is a triangular-shaped shallow marine embayment located in a subtropical region. Morphologically, the Bay is dominated by an extensive system of shallow mud-banks and adjacent basins of relatively shallow depths (Fig. 1). This mud-bank/shallow basin system results in a mean water depth of 1.4 m with long residence times for the basins (over 6 months in the north-central Bay) (Lee et al., in press). Florida Bay is bound to the north by the Everglades and receives freshwater input via several streams, nearly all located in the northeastern corner of Florida Bay (McIvor et al., 1994). To the west is a relatively open connection with the southwest Florida shelf, through which a large amount of physical forcing (e.g. wind and tidal) exchanges into Florida Bay (Wang et al., 1994). To the south, Florida Bay is bound by the Florida Keys; however, there is a limited exchange with the coastal Atlantic Ocean through tidal channels between the Keys (Smith, 1998).

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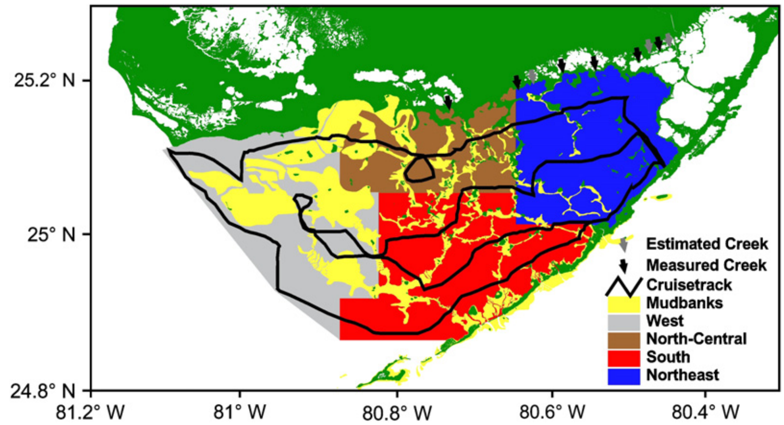

Fig. 1. Map of Florida Bay depicting the vast system of mangrove islands and shallow mud-banks (shown in green and yellow, respectively), as well as the sub-regional delineations.

Florida Bay is a unique ecosystem that has undergone numerous changes over the past century due to upstream water management and land use changes. The first such activity that may have had an influence on circulation and therefore salinity in Florida Bay was the building of spoil islands along the Florida Keys tract for the construction of the Florida Overseas Railway, 1907–1912 (Swart et al., 1996). The likely more significant activities were the upstream drainage and water management projects associated with Everglades land reclamation that began in 1952. These water management projects included the construction of a south Florida canal system, which diverted freshwater from its natural pathway directly into either the Gulf of Mexico or the Atlantic Ocean (Light and Dineen, 1994). As a result, freshwater delivery was greatly reduced to downstream ecosystems including Florida Bay and the southwest Florida shelf. The exact magnitude of this reduction is not known, but it has been estimated that canal construction and subsequent water management practices, intended to control flooding and make more of the land useful for habitation or agriculture, may have resulted in a nearly 60% decrease in freshwater reaching Florida Bay (Smith et al., 1989). The shallow bathymetry of Florida Bay amplifies the effects of water management, resulting in highly variable temporal and spatial salinity distributions (Nuttle et al., 2000). In fact, it is not uncommon to simultaneously observe hypersaline and estuarine salinities within different sub-regions of Florida Bay (Nuttle et al., 2000).

The three primary sources of salinity variation in Florida Bay are precipitation and freshwater runoff (which decrease salinity) and evaporation (which increases salinity). The sum of these three components, runoff plus precipitation minus evaporation, is referred to as the net freshwater supply. There are three classifications of estuaries based upon the net freshwater supply. ‘‘Classical estuaries’’ have lower salinity than the adjacent coastal ocean, because the net freshwater supply is overwhelmingly positive, most often due to large quantities of runoff. ‘‘Inverse estuaries’’ have higher salinity than the adjacent coastal ocean as a result of overwhelmingly negative net freshwater supply. i.e. evaporation is dominant. The third type of estuary is a ‘‘seasonally hypersaline estuary’’ where episodic hypersalinity and estuarine conditions occur at different times of the year. In ‘‘seasonally hypersaline estuaries’’ the net freshwater supply fluctuates widely throughout the year, but is near zero on an annual basis. This pattern is typical of Florida Bay, where hypersaline conditions prevail during early summer at the end of the dry season and estuarine conditions prevail in early winter at the end of the wet season.

Scientific and public interest in Florida Bay accelerated in 1987, when a multi-year drought resulted in observed mid-Bay salinities as high as 70 (all salinities reported herein were measured using the Practical Salinity Scale) that were followed by deleterious changes in the ecosystem (Fourqurean and Robblee, 1999; Hunt and Nuttle, in press). Beginning in 1987, Florida Bay experienced a massive seagrass die-off in the central and western sub-regions, the proximate cause of which has yet to be indisputably determined (Zieman et al., 1988; Robblee et al., 1991). The high salinity and reduced seagrass coverage coincided with a historic decline in the pink shrimp (*Farfantepenaeus duorarum*) fishery in the Dry Tortugas which use Florida Bay as a nursery (Nance, 1994), and preceded a decline in water quality and a series of algal blooms (Boyer et al., 1999). Federal public trust responsibilities were implicated due to the Bay's importance as a nursery for many of the adjacent commercial and recreational fisheries (Tilmant, 1989), as a primary habitat for several endangered species including the American crocodile (*Crocodylus acutus*) and Florida manatee (*Trichechus manatus latirostris*), and because the majority of the Bay is within Everglades National Park boundaries (McIvor et al., 1994). Threats to Florida Bay's ecosystem, along with growing recognition that the overall Everglades ecosystem was endangered, lead to the passage of Federal and State legislation (WRDA, 2000 and FFA, 2000, respectively) aimed at implementing the Comprehensive Everglades Restoration Plan (CERP). CERP's primary goal is to restore the quantity, quality, timing, and distribution of freshwater flow to the Everglades and adjacent ecosystems, including Florida Bay. This will, by design, influence salinity patterns in Florida Bay; as such, it is vital to understand the variability of salinity in Florida Bay prior to the implementation of CERP.

In this study we examine a 7-year record of salinity in Florida Bay, collected via approximately monthly survey cruises.

We also analyze ancillary data related to components of the freshwater budget to quantify the effects of runoff, precipitation, and evaporation on Florida Bay salinity. Further, we examine the influence of specific large-scale phenomena, such as the passage of tropical cyclones and the El Nino Southern Oscillation (ENSO). This analysis describes the principal salinity characteristics of the sub-regions in Florida Bay and the role of regional hydrology in maintaining these characteristics.

2. Methods

To monitor Florida Bay water quality, the National Oceanic and Atmospheric Administration's (NOAA) South Florida Program conducted a total of 76 survey cruises between January 1998 and December 2004. The surveys were nominally conducted at monthly intervals; however, the exact timing varied slightly. Surveys were carried out using the *R/V Virginia K*, a special purpose shallow draft power catamaran. The vessel's underway flow-through system incorporates a Seabird Model 21 thermosalinograph with a global positioning system (GPS) receiver (initially a JRC model DGPS200, upgraded in June 2003 to a Wide Area Augmentation System (WAAS) Garmin model 2010C GPS) to record temperature, salinity, and position at 7-s intervals along the cruise track, resulting in approximately 6000 data points per survey.

For data comparison between surveys, the raw data were normalized by estimating salinity every hundredth of a decimal degree in latitude and longitude using a kriging gridding procedure (Delhomme, 1978). This interpolation procedure produces a grid of equally distributed data points throughout Florida Bay (although the estimations are of course more accurate near the actual data points), minimizing biases that may occur as a result of over-sampling any one area during a particular survey.

Mean monthly precipitation values were obtained from NOAA's National Climatic Data Center (NCDC) for the three domains of Florida south of Lake Okeechobee (5, 6, and 7), from January 1997 through December 2004. These data are available via the climate visualization project (Climvis) (http://www.ncdc.noaa.gov/oa/climate/onlineprod/drought/xmgrg3.html). NCDC's Division 7 consists of Flamingo and the Florida Keys; thus, mean monthly precipitation values recorded for Division 7 were used as the measurements of direct precipitation, and were assumed for our purposes to be uniformly distributed over Florida Bay.

The runoff data for six estuarine creeks (McCormick Creek, Taylor River, Mud Creek, Trout Creek, Stillwater Creek, and West Highway Creek) that discharge freshwater directly into Florida Bay were obtained from the United States Geological Survey (USGS). The discharge values at these creeks were calculated at 15-min intervals using an Acoustic Doppler Velocity Meter (ADVM), which measures velocity at a single point in the creeks. These velocity measurements were calibrated to produce discharge measurements for each creek using 24-h shipboard acoustic Doppler current profiler (ADCP) transects along the mouth of the creek following the methodology of Lee and Smith (2002). The data from West Highway Creek were also used to estimate freshwater discharge from three other creeks in the area (East Creek, East Highway Creek, and Oregon Creek), according to a relationship previously reported (Hittle and Zucker, 2004). The sum of these nine creeks is thought to approximate total freshwater runoff into Florida Bay, except during exceptional precipitation events when runoff may occur through the Buttonwood Embankment, located along the northern shore to the west of the creeks. Runoff values in $m^3\ s^{-1}$ were transformed to cm per month to bring runoff into agreement with the precipitation and evaporation data units. Specifically, mean monthly runoff was multiplied by the length of the month in seconds to convert runoff to m^3 per month, which was then divided by the area of Florida Bay (2000 km^2) resulting in runoff units of cm per month.

Evaporation was also assumed to be uniform over the Bay, and was estimated from a bulk aerodynamic flux equation derived by Pond et al. (1974) and previously used to estimate evaporation over Florida Bay (Smith, 2000).

$$E = \rho_a C_E V_{10} \Delta q \quad (1)$$

In this equation, ρ_a is the density of air in kg m^{-3}, C_E is the non-dimensional evaporation coefficient for bulk aerodynamic fluxes which varies with wind speed and the difference between the measured and potential temperature (Smith, 1988), V_{10} is the wind speed at 10 m above sea-level, and Δq is the specific humidity difference between 10 m above sea-level and the water's surface. The density of air was calculated from the pressure and virtual temperature (List, 1963). The wind speed was adjusted to a 10 m height from the 7-m collection height assuming a power law profile with an exponent of 0.1 (Kourafalou et al., 1996). All of the observational data used for this calculation were collected by a National Data Buoy Center (NDBC) Coastal-Meteorological Automated Network (C-MAN) station located in southern Florida Bay just north of Long Key (http://www.ndbc.noaa.gov/station_page.php?station=lonf1), except for specific humidity which was calculated from measurements collected by the National Weather Service (NWS) Marathon Airport station (http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwDI~StnSrch~StnID~20004208), located approximately 35 km southwest of Florida Bay.

A dynamic mass balance model was implemented for Florida Bay following the approach of Hornberger and Spear (1980). This is an extension of the steady-state four-box model previously applied to Florida Bay by Nuttle et al. (2000). The model calculates salinity values for each of the four connected sub-regions (Fig. 1) at the beginning of each month, utilizing weekly time steps to reduce the possibility of numerical instabilities. The salinity values are simulated for each sub-region from the salinity at the beginning of the previous month along with precipitation, runoff, salinity at the Bay's western boundary, and evaporation in the preceding month, the area, and average depth of the sub-region, and parameters that characterize the magnitude of exchange between adjacent sub-regions and the western boundary, $X1$–$X7$ (Fig. 2). The model incorporates exchange with the southwest Florida shelf ($X6$ and $X7$ in

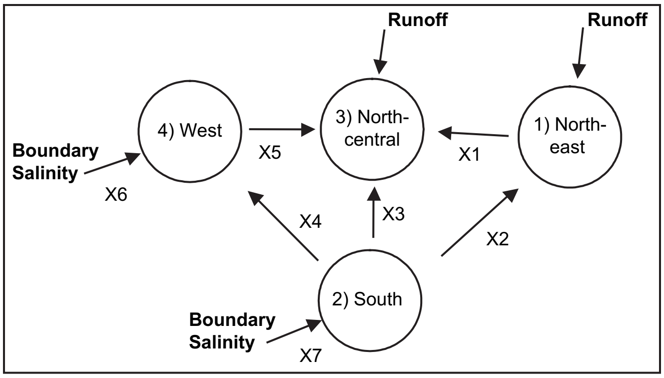

Fig. 2. Structure of the monthly time-step model showing the location of inflows from the Everglades and defining the exchange parameters. The arrows that represent the fluxes connecting the sub-regions establish the direction of "positive" values of the average discharge and exchange fluxes.

Fig. 2). However, exchange with the Atlantic Ocean via tidal passages in the Florida Keys is ignored, because the net long term transport is out of Florida Bay and tidal exchanges affect only local salinities very near the tidal passages (Lee and Rooth, 1972; Smith, 1998). Salinity time series data along the western boundary with the southwest Florida shelf are from the data set described in Boyer et al. (1997, 1999). The model does not use directly measured evaporation, and instead calculates monthly evaporation based on an assumed sinusoidal seasonal distribution derived by Nuttle et al. (2000). We estimate sub-region depths from bathymetric data collected in a recent high-resolution bathymetric survey (Hansen and DeWitt, 2000), which covered about 80% of Florida Bay, and fill the gaps with older bathymetric data compiled by Nuttle et al. (2000).

The model calculates the volume-averaged salinity for each sub-region at the beginning of a month from the salinity at the beginning of the previous month and the effect of advection and dispersive exchange with adjacent sub-regions during the course of the previous month, eq. (2).

$$S^i_{j+1} = S^i_j + \frac{1}{V^i}\sum_{k(\neq i)}\left[S^k_j - S^i_j\right]X^{i,k}\Delta t - \frac{1}{V^i}\sum_{k(\neq i)} S_\Delta Q^{i,k}_j \Delta t \qquad (2)$$

where S^i_j is the average salinity in sub-region i at the beginning of month j; V^i is the volume (assumed constant) of sub-region i; and Δt is the length of the time step, 1 month. The second term on the right-hand-side of eq. (2) calculates the effect of dispersive exchange with adjacent sub-regions and the coastal ocean, where $X^{i,k}$ refers to one of the calibrated exchange parameters $X1$–$X7$ (units of volume per month) that describes the exchange flux between sub-regions i and k (Fig. 2). The third term on the right-hand-side of eq. (2) calculates the effect of advection by the net flow for the month between sub-regions, where $Q^{i,k}_j$ refers to the net flow between sub-regions i and k calculated for month j. In the calculation of the advective flux, S_Δ is the salinity of the "upstream" sub-region. If $Q^{i,k}_j$ is directed out of sub-region i and into sub-region k, then $S_\Delta = S^i_j$ otherwise $S_\Delta = S^k_j$.

Net freshwater supply, i.e. the balance of precipitation plus runoff minus evaporation, influences salinity through the net flows, $Q^{i,k}_j$. The flows $Q^{i,k}_j$ are calculated at each time step by solving simultaneous equations that describe the mass balance for water in the network of sub-regions for the month (Fig. 2). In this implementation of the model, the volumes of the sub-regions are assumed to be constant; therefore the net flows into and out of each sub-region, including the net supply of freshwater to the sub-region, must sum to zero for each time step. If precipitation plus runoff exceed evaporation in a month, then the values of $Q^{i,k}_j$ will be positive, and their effect will be to decrease salinity, eq. (2). And conversely, if evaporation exceeds precipitation plus runoff, then the values of $Q^{i,k}_j$ will be negative, and their effect will be to increase salinity.

Where necessary in order to solve the equations, it is assumed that the relative magnitudes of net flows between sub-regions follow the relative magnitudes of the exchange flows including the freshwater supply. For example, in a month when the net freshwater supply to the north-central sub-region is Q_{NET} the net flows from the north-central sub-region into each of the other sub-regions are given by

$$Q^{3,1}_j = \frac{Q_{NET}X1}{X1+X3+X5}$$
$$Q^{3,2}_j = \frac{Q_{NET}X3}{X1+X3+X5} \qquad (3)$$
$$Q^{3,4}_j = \frac{Q_{NET}X5}{X1+X3+X5}$$

Thus, the net exchange between basins is derived from the exchange between all connected basins, as well as precipitation, runoff, and evaporation. The net exchange then influences the salinity based on the salinity of the water being exchanged and the amount of net exchange relative to the sub-region's volume.

3. Results

3.1. Time series

The mean Bay-wide salinity of Florida Bay for each cruise is depicted in Fig. 3. The most noticeable feature in this time series is the annual oscillation between high salinity in the early summer and low salinity in the early winter. The annual cycle in salinity computed from monthly averages lags the annual cycle of precipitation in south Florida depicted in Fig. 4a by approximately 4 months, with salinity values steadily dropping after the wet season commences (from May to November) and rising after the dry season commences (from December to April). The mean Florida Bay salinity varied from a minimum of 24.2 in November of 1999 to a maximum of 41.8 in July of 2001 and 2004 (Fig. 4b). The single most dramatic decrease in mean Bay-wide salinity for Florida Bay was 6.1 between two surveys taken on October 5–6, 1999 and October 18–19, 1999, representing a mean decline of nearly 0.5 per day. Increases in mean salinity were significantly more gradual than decreases ($F_{1,72} = 4.63$, $p = 0.035$,

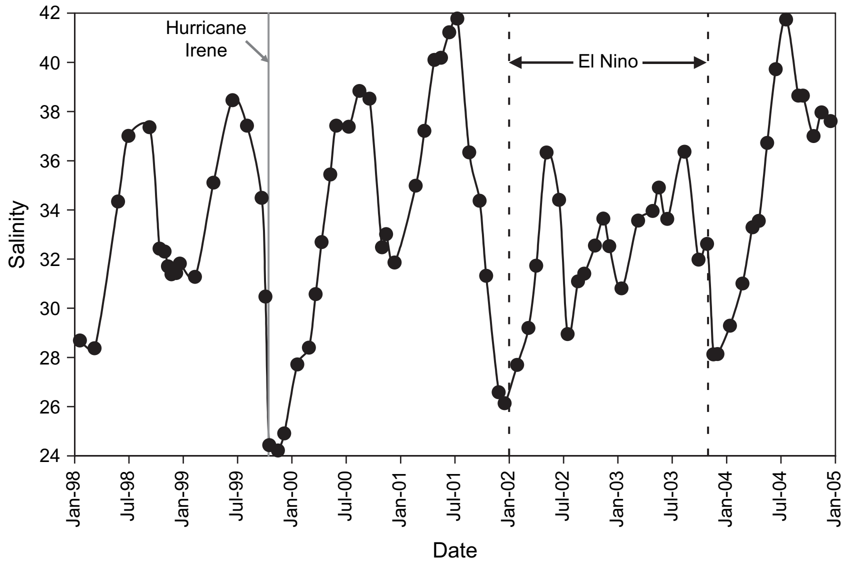

Fig. 3. Time series of mean salinity throughout Florida Bay for the 7-year study period.

F-test of the mean daily change in salinity between surveys for which salinity increased versus those that decreased) and the most rapid salinity escalation was an increase of just 4.6 over the 35-day period from April 2, 2002 to May 7, 2002, representing a mean increase of about 0.1 per day.

The monthly means for salinity, precipitation, runoff, and evaporation were calculated and plotted to depict the typical annual cycle observed during the study period (Fig. 4a). The lowest monthly mean salinities occurred from October to January at the end of the rainy season or shortly thereafter, as precipitation and subsequent runoff dilute the salinity of Florida Bay (Figs. 3 and 4). The highest salinities were recorded in the beginning of the summer, May through July, just after the beginning of the rainy season, which corresponds to the highest rate of evaporation (Figs. 3 and 4).

Fig. 4b depicts monthly means of runoff, precipitation, and evaporation for each month during the study period, together with average Bay-wide salinity values. The variability in evaporation was moderate, displaying a mean range slightly greater than a factor of two, with a maximum rate of approximately 15 cm per month during the summer and a minimum rate of approximately 6 cm per month during the winter. Precipitation was more variable; however, a wet season from May to November and a dry season from December to April were typically observed. Runoff displayed some interannual variation, but typically peaked during the last six months of each year (July to December) and fell to near zero sometime during the first six months of each year (January to June).

Contour maps of the mean seasonal salinity of Florida Bay reveal great differences in the spatial salinity pattern throughout the year (Fig. 5). In fact, the one constant is that the lowest salinity water was always observed in the northeast corner of the Bay. This is not surprising since direct freshwater runoff is concentrated in this sub-region (Swart and Price, 2002), and this sub-region also is largely isolated from the Atlantic Ocean by the upper Florida Keys. During the freshest months, November to January (Fig. 5a), the highest salinity, although still below oceanic values, was in the southern Bay where there is no direct runoff and where there is greater exchange with the coastal Atlantic Ocean through the tidal passages of the Florida Keys (Lee and Smith, 2002). The minimum salinity value of 18 is located in the northeast sub-region near the mouth of Taylor Slough, with rapidly increasing salinity (up to approximately 26) away from the northeast region towards the boundaries with the north-central and south sub-regions. Outside of the northeast sub-region, there is a general trend of gradually increasing salinity along the northeast to southwest axis of the Bay.

The mean seasonal salinity contour maps from February to April (Fig. 5b) and May to July (Fig. 5c), together with the data shown in Fig. 4b, indicate that there are steady salinity increases in Florida Bay from January to June. In the mean contour map for February to April the northeast corner, again, had the lowest salinity, but it has risen to approximately 23 from the previous season due to decreased precipitation and freshwater runoff (Fig. 4b). The maximum salinities of 36 are in the north-central and south sub-regions of Florida Bay as a result of the beginning stages of evaporative salinization. Further west, salinity decreases due to interactions along the open boundary with the southwest Florida shelf where freshwater runoff has lowered the near-shore salinity of the shelf waters, which in turn via exchange lowers the salinity along the western boundary of Florida Bay.

The highest salinities in Florida Bay occurred annually in the early summer from May through July. The mean salinity distribution during this time period is shown in Fig. 5c. As in the preceding months, the salinity maximum is located in the central Bay with values now reaching over 40, and gradually decreasing in a roughly radial pattern away from the maximum. Again, Florida Bay's northeast corner had the lowest mean salinity at about 26. Similar to the previous map, the west sub-region had a slightly lower salinity than the central Bay as a

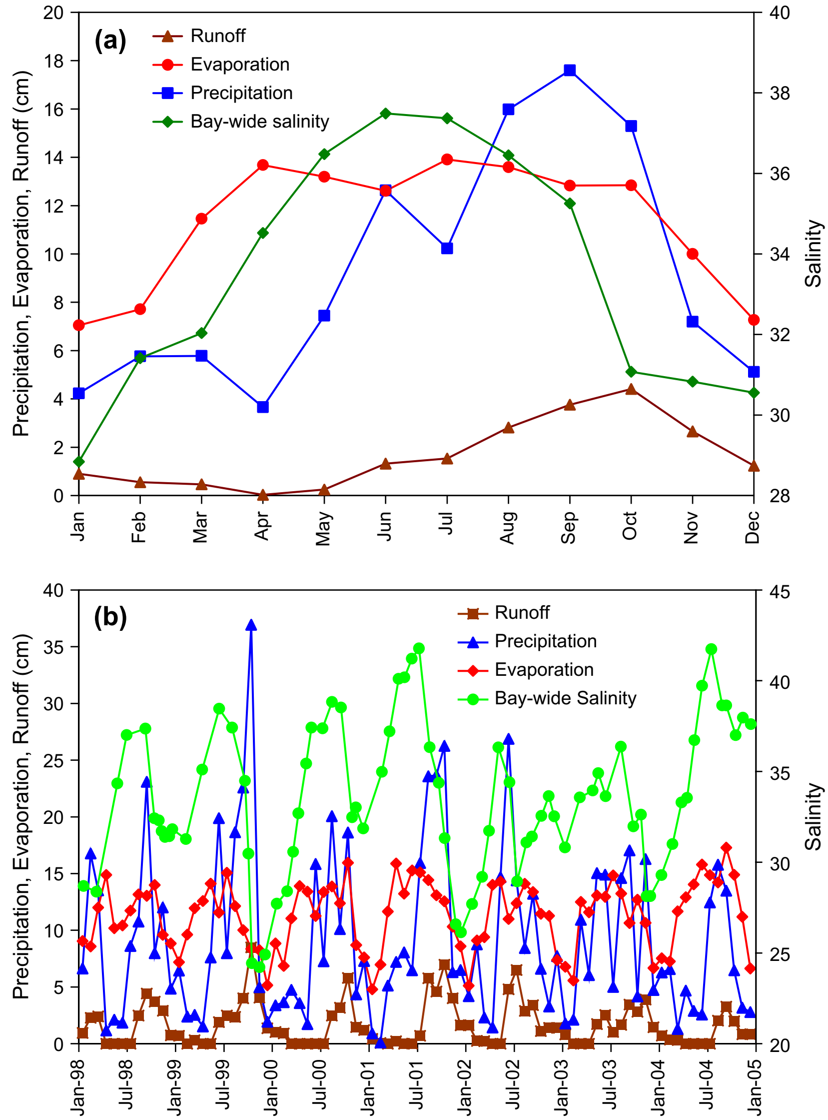

Fig. 4. (a) Monthly means for runoff, precipitation, evaporation, and mean Bay-wide salinity. (b) Time series of runoff, precipitation, evaporation and mean Bay-wide salinity from 1998 through 2004.

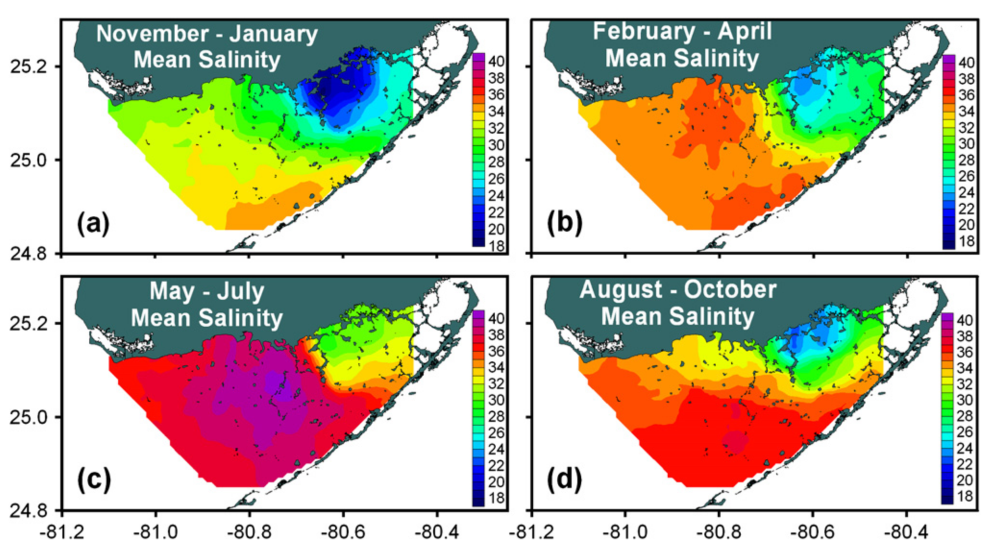

Fig. 5. Seasonal contour maps of salinity in Florida Bay.

result of exchange with the southwest Florida shelf waters. However, the salinities in west Florida Bay were still greater than those found in the adjacent coastal ocean, due to their proximity to the salinity maximum in the north-central Bay.

In the middle of the wet season, from August through October (Fig. 5d), salinity throughout Florida Bay shows an overall decrease. The highest salinities, approximately 38, are located in the south-central Bay. The north-central Bay shows a dramatic drop in salinity from greater than 40 down to 32, while in the northeast Bay salinities were reduced to 24 and in the west salinity values show a slight decrease from those in the nearby north-central sub-region.

3.2. Regional partitioning

All of the seasonal plots of Florida Bay salinity display a high degree of spatial heterogeneity among the four sub-regions of Fig. 1, indicating differing degrees of influence by the various forcing factors (exchange with the Atlantic Ocean, exchange with the southwest Florida shelf, runoff, precipitation, evaporation, etc.) on salinity (Fig. 5). This spatial heterogeneity is likely due to the topographical separation between the basins created by the shallow mud-banks characteristic of Florida Bay (Fig. 1). Many other parameters previously measured in Florida Bay exhibited a similar spatial heterogeneity, including light attenuation (Kelble et al., 2005), water quality (Boyer et al., 1997), sediments (Wanless and Tagett, 1989), seagrass (Zieman et al., 1989), fisheries (Tilmant, 1989), and benthic mollusks (Turney and Perkins, 1972). Previous work evaluating the freshwater influence in Florida Bay determined that the effect of freshwater input varied greatly among sub-regions in a similar manner as was observed in this study (Nuttle et al., 2000). Thus, it was decided to partition the Bay into four sub-regions (Fig. 1) roughly following the boundaries used by Nuttle et al. (2000).

Fig. 6a shows that the time series of mean salinity for each of the four sub-regions differ markedly. The northeast sub-region, as can be inferred by the seasonal contour plots

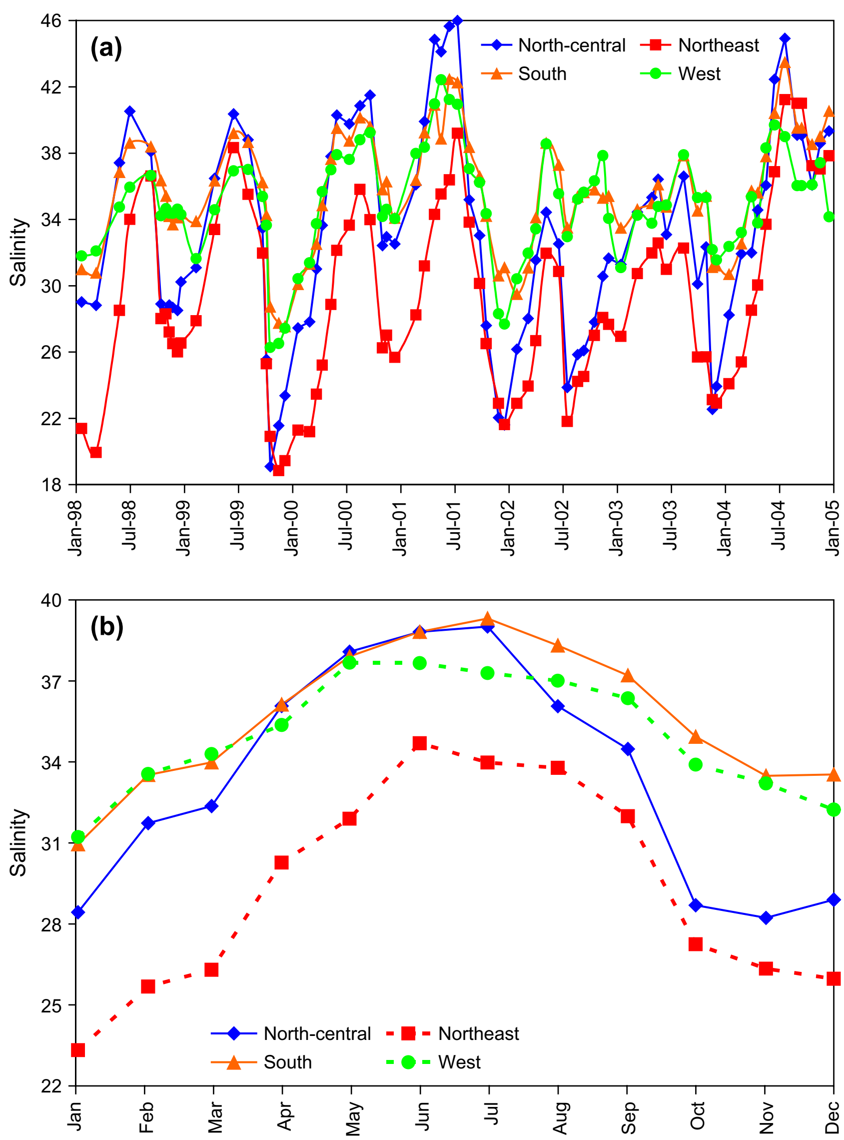

Fig. 6. (a) Time series of mean salinity for each of the four sub-regions in Florida Bay. (b) Mean monthly salinity for each of the four sub-regions.

(Fig. 5), was nearly always the freshest sub-region of Florida Bay. However, there were several occasions when the mean salinity of the north-central Bay was slightly lower for a single survey conducted at the peak of the wet seasons of 1999, 2001, and 2003. Furthermore, the north-central sub-region exhibited the most extreme salinity variations. The most dramatic salinity reduction in north-central Florida Bay for the period of record was a drop of over 14 in the 26 days from September 22–23, 1999 to October 18–19, 1999, equivalent to a reduction of greater than 0.5 per day. The greatest rate of increase in salinity was less dramatic, with an increase in salinity of over 6 in the 29 days from May 18–19, 2004 to June 16–17, 2004 representing a mean increase of about 0.2 per day. These rates of decrease and increase in salinity in the north-central sub-region surpass those for any of the other sub-regions. The south and west sub-regions of Florida Bay displayed more moderate salinity fluctuations than the north-central sub-region and tended to have more oceanic salinities than the northeast sub-region (Fig. 6a). The south and west sub-regions also tended to be more similar than any other sub-region pair.

Mean monthly salinities for each sub-region are depicted in Fig. 6b. The northeast sub-region exhibited the lowest mean salinity every month, with the greatest contrast from the other sub-regions (greater than 5) observed during the period of increasing salinity from January to May. The difference was not as significant during the wet season, with the mean salinity for the northeast sub-region only 1.5 less than the north-central sub-region. Furthermore, the largest range in mean monthly salinity (23.3–34.7) was observed in the northeast sub-region, although the range for the north-central sub-region was only slightly less (28.2–39.0). The north-central sub-region exhibited its lowest mean salinity in November, whereas all the other sub-regions had their lowest salinities in January. Also, the north-central sub-region featured the largest single month change in salinity for both increasing and decreasing salinity, with an increase of 3.7 from March to April and a decrease of 5.8 from September to October. The west and south sub-regions had similar mean monthly salinities, with a much smaller range than either the north-central or northeast sub-regions. The south sub-region showed the highest mean monthly salinity (39.3 in July), although it was only slightly higher than the mean monthly salinity of the north-central sub-region (39.0 in July). The slightly lower mean monthly salinity for the north-central region was largely influenced by the 2002–2003 anomalous salinity distributions attributed to El Nino, because in both years the north-central salinity was much less than the south sub-region (Fig. 6a). The major difference between the west and south mean monthly salinity time series shown in Fig. 6b is that the west sub-region maintains a lower salinity during and just after the wet season.

3.3. Mass balance model

Calibration of the mass balance model identifies a set of values for the model parameters that minimizes the sum of squared errors. The model parameters comprise the set of seven exchange fluxes (Fig. 2) and three parameters that define the variation in evaporation within a year. The errors are calculated as the difference between the salinity calculated by the model and the mean salinity values estimated from the survey data in each sub-region. The calibrated model estimates salinity quite accurately with a root mean square error (RMSE) of 2.1 for the Bay as a whole. Furthermore, the model performed reasonably well in each of the sub-regions (Fig. 7). The errors were slightly larger in the north-central and northeast sub-regions (RMSE 2.4 and 2.2, respectively), which also displayed larger ranges of variation in salinity (Fig. 6). Evaporation, estimated by model calibration, has an annual average of 134 cm per year, and the highest evaporation is estimated to occur just before the onset of the summer wet season. This is about 10% higher than the evaporation estimated by Nuttle et al. (2000), which was based on a steady-state salinity mass balance model, but both are within the range of all previous evaporation estimates. The model estimated mean evaporation value was nearly identical to the mean annual evaporation calculated from the C-MAN station for this 7-year study period (136 cm).

The Nash–Sutcliffe model efficiency statistic provides a better measure of the model's accuracy at predicting mean salinity both Bay-wide and for each of the four sub-regions (Nash and Sutcliffe, 1970). Model efficiency, *Eff*, is calculated from the mean square error normalized to the variance of the

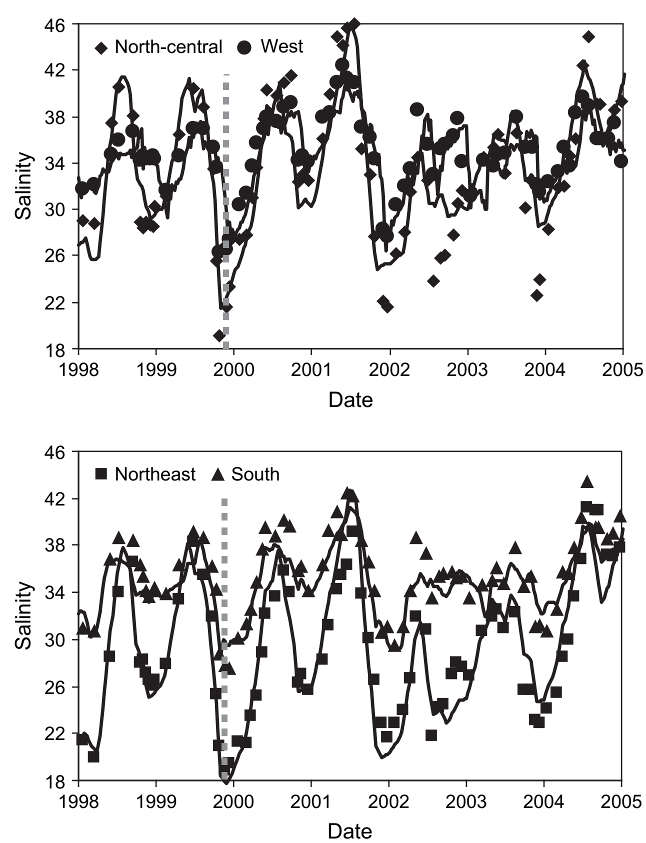

Fig. 7. Times series of mean salinity from observations (circles, triangles, squares, diamonds) and salinity calculated by the mass balance model (solid lines) for each of four sub-regions in Florida Bay. The vertical dashed line indicates the occurrence of tropical storm Irene, which delivered over 20 cm of freshwater to the Bay.

observed salinity and is similar to the coefficient of determination statistic in regression models.

$$\text{Eff} = 100(1 - \text{MSE}/\text{Var(observed)}) \tag{4}$$

where MSE is the mean of the squared residual errors and Var(observed) is the variance of the observed salinity data. The calibrated mass balance model achieves a model efficiency of 86 for all four sub-regions taken together; model efficiency values for each of the sub-regions taken separately are 85, 85, 79 and 64 for the north-central, northeast, south and west sub-regions, respectively. Model efficiency for the whole Bay is higher than the average of sub-region results because the variance of the observed salinity for the entire Bay includes the effect of spatial variation between sub-regions that is not present in the variance within sub-regions.

3.4. Correlation analyses

To attempt to understand exactly how precipitation and runoff into Florida Bay affect Bay-wide, as well as sub-regional, mean salinities we examined the Pearson correlation coefficients between precipitation, runoff, evaporation, and salinity. The correlation between monthly mean precipitation and salinity Bay-wide and for each of the four sub-regions is given in Table 1, with lags from zero to 6 months. Correlation coefficients were highest at a lag of four months for all analyses except the north-central. The 4-month lag for Bay-wide salinity is clear in Fig. 4b, in that maximum mean monthly precipitation occurs in September and the minimum salinity is in January. The minimum mean monthly salinities were also observed in January for the northeast, south, and west sub-regions, further evidencing their 4-month lag. The lone exception, the north-central sub-region, had the highest correlation coefficient for a two month lag and its minimum mean monthly salinity was observed in November, 2 months after the peak precipitation.

To investigate the relationship between precipitation and runoff, correlation analysis was performed between runoff into Florida Bay and precipitation over the Florida peninsula south of Lake Okeechobee (Divisions 5 and 6 from NCDC CLIMVIS) and indicated a lag time of 1 month (Table 2). The lag between precipitation and runoff can also be seen in Fig. 4b, where peak precipitation is observed in September and peak runoff 1 month later in October. The correlation and lag between runoff and salinity (Table 1) are intermediate in character with a lag between runoff and mean Bay-wide salinity of 2 months. All of the sub-regions displayed slightly different lagged correlations between runoff and salinity. A 1-month lag was observed in the north-central sub-region, a 2-month lag occurred in the northeast, in the west the lag was 2–3 months and in the south it was 3 months. These lags are partially a reflection of the mixing time it takes for runoff to decrease salinities throughout a large portion of Florida Bay, but they also may be the cumulative effect of runoff on salinity. Furthermore, the relationship between runoff and salinity is complicated by upstream water management decisions taken to avoid flooding and manage the water supply. The correlation between evaporation and salinity was similar throughout Florida Bay (Table 1), with no lag in any of sub-regions. Therefore, differences in evaporation rates between sub-regions, although not calculated herein, are unlikely to contribute to temporal salinity variability among sub-regions.

3.5. Net freshwater supply

The typical annual cycle of net freshwater supply for Florida Bay is shown in Fig. 8 based upon monthly means of precipitation, runoff, and evaporation. Net freshwater supply was positive toward the peak of the wet season (August to October) and significantly negative toward the end of the dry season (March to May). During the rest of the year the net freshwater supply was near zero. It is important to realize that the net freshwater supply calculated here is an underestimate, because runoff into Florida Bay has been assumed to be limited exclusively to the nine creeks quantified in this study. These nine creeks cannot be expected to contain all of the freshwater discharged into Florida Bay from the Everglades, especially during significant rain events where runoff through the Buttonwood Embankment can be significant. Moreover, fresh groundwater flux is assumed to be zero, primarily because groundwater entering Florida Bay is typically saline to hypersaline (Corbett et al., 1999).

The lag between the net freshwater supply and the wet season/dry season cycle of 2–3 months is the result of several factors. First, at the commencement of the rainy season in May or June, much of the potential runoff has not yet reached Florida Bay (Fig. 4); therefore, only direct precipitation is lowering salinity. The first rains are required to saturate the Everglades and initiate sheet-flow; accordingly, little early runoff reaches Florida Bay. Evaporation exceeds precipitation over Florida Bay while runoff is still negligible, resulting in negative net freshwater until June (Fig. 8). The same relationships are seen in the 3-month lagged correlation between gross freshwater supply (runoff plus precipitation) to Florida Bay and mean Bay-wide salinity (Table 1).

The dominant feature in the mean Bay-wide salinity time series (Fig. 3) is an annual oscillation. In general, negative net freshwater supply from March through May increases salinity while net positive freshwater supply from August to October decreases salinity (Fig. 4). The lowest Bay-wide salinities often occur in January (Fig. 4), several months after the net freshwater supply decreases to near zero. There are several underlying reasons for this lag. First, the cumulative effect of net freshwater supply only requires net freshwater supply (in Eq. (2)) to be greater than zero to decrease salinity. Second, the west sub-region of Florida Bay is affected by indirect runoff which has an inherent delay, as the rivers along the southwest Florida shelf decrease near-shore salinities, which over time exchange with the western sub-region of Florida Bay, ultimately lowering its salinity. Lastly, this could result from runoff into Florida Bay being somewhat underestimated by the nine creeks we quantified, resulting in an underestimate of net freshwater supply in this study.

Table 1
Lagged Pearson correlation coefficients for mean Bay-wide salinity and in each of the four sub-regions with precipitation, runoff, evaporation, and gross freshwater supply (precipitation plus runoff), from top to bottom respectively. The *p* value is the probability of a type I error with the statistically significant values highlighted in bold

			No lag	1 month	2 months	3 months	4 months	5 months	6 months
Precipitation vs. salinity	Entire Bay	Pearson *r*	−0.07	**−0.31**	**−0.45**	**−0.49**	**−0.52**	**−0.46**	−0.17
		p value	0.57	**<0.01**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.17
	North-central	Pearson *r*	−0.17	**−0.41**	**−0.53**	**−0.49**	**−0.46**	**−0.33**	−0.08
		p value	0.16	**<0.01**	**<0.001**	**<0.001**	**<0.001**	**0.01**	0.50
	Northeast	Pearson *r*	0.00	−0.24	**−0.40**	**−0.44**	**−0.50**	**−0.48**	−0.23
		p value	0.98	0.05	**<0.01**	**<0.001**	**<0.001**	**<0.001**	0.05
	South	Pearson *r*	−0.03	−0.28	**−0.36**	**−0.46**	**−0.53**	**−0.50**	−0.20
		p value	0.83	0.02	**<0.01**	**<0.001**	**<0.001**	**0.001**	0.10
	West	Pearson *r*	−0.08	−0.28	**−0.40**	**−0.46**	**−0.49**	**−0.44**	−0.11
		p value	0.53	0.02	**<0.01**	**<0.001**	**<0.001**	**<0.001**	0.36
Runoff vs. salinity	Entire Bay	Pearson *r*	**−0.39**	**−0.58**	**−0.62**	**−0.58**	**−0.46**	−0.22	
		p value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.08	
	North-central	Pearson *r*	**−0.52**	**−0.66**	**−0.65**	**−0.52**	**−0.35**	−0.08	
		p value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.01**	0.50	
	Northeast	Pearson *r*	−0.30	**−0.53**	**−0.59**	**−0.55**	**−0.44**	−0.27	
		p value	0.02	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.03	
	South	Pearson *r*	−0.30	**−0.51**	**−0.56**	**−0.59**	**−0.50**	−0.27	
		p value	0.02	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.03	
	West	Pearson *r*	**−0.35**	**−0.49**	**−0.54**	**−0.55**	**−0.43**	−0.20	
		p value	**<0.01**	**<0.001**	**<0.001**	**<0.001**	**<0.01**	0.11	
Evaporation vs. salinity	Entire Bay	Pearson *r*	**0.63**	**0.49**	0.21				
		p value	**<0.001**	**<0.001**	0.08				
	North-central	Pearson *r*	**0.50**	**0.35**	0.09				
		p value	**<0.001**	**<0.001**	0.49				
	Northeast	Pearson *r*	**0.59**	**0.53**	0.28				
		p value	**<0.001**	**<0.001**	0.020				
	South	Pearson *r*	**0.67**	**0.54**	0.27				
		p value	**0.001**	**<0.001**	0.03				
	West	Pearson *r*	**0.65**	**0.44**	0.16				
		p value	**0.001**	**<0.001**	0.20				
Gross freshwater supply vs. salinity	Entire Bay	Pearson *r*	−0.14	**−0.38**	**−0.51**	**−0.53**	**−0.52**	**−0.42**	−0.12
		p value	0.26	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.34
	North-central	Pearson *r*	−0.25	**−0.48**	**−0.59**	**−0.52**	**−0.45**	−0.28	−0.03
		p value	0.04	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.02	0.80
	Northeast	Pearson *r*	−0.06	**−0.31**	**−0.46**	**−0.49**	**−0.51**	**−0.44**	−0.19
		p value	0.62	**<0.01**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.12
	South	Pearson *r*	−0.09	**−0.34**	**−0.42**	**−0.51**	**−0.53**	**−0.46**	−0.15
		p value	0.48	**<0.01**	**<0.001**	**<0.001**	**<0.001**	**0.001**	0.22
	West	Pearson *r*	−0.14	**−0.33**	**−0.45**	**−0.50**	**−0.49**	**−0.40**	−0.06
		p value	0.25	**<0.01**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.64

To examine interannual variability in net freshwater supply we calculated the budget for each year of the study period (Table 3, Fig. 9). This highlighted the large degree of variability that was measured in each of the components on an annual basis. Annual runoff varied by greater than a factor of two (10.4 cm to 25.7 cm), precipitation had slightly lower variation, and evaporation was much more stable varying over a range that was less than 17% of the mean. These variations combined to produce variations in the net freshwater supply of over 92 cm from the peak in 1999 to the minimum in 2004; however, the mean salinity remained significantly more stable varying from 31.2 to 36.3 (less than 16% of the mean). The stability in annual average Bay-wide salinity is likely due to the fact that historical conditions affect the salinity and thus a unidirectional long-term trend is required to significantly alter the mean salinity value.

Table 2
Pearson correlation between precipitation over the Florida Peninsula south of Lake Okeechobee (NCDC Climvis divisions 5 and 6) and runoff into northeast Florida Bay. The time value corresponds to the lag from precipitation to runoff and bold values represent statistically significant correlations

	No lag	1 month	2 months	3 months	4 months
Pearson *r*	**0.52**	**0.68**	**0.51**	**0.37**	0.19
p value	**<0.001**	**<0.001**	**<0.001**	**<0.01**	0.10

The observed rates of precipitation, runoff, and net freshwater supply to Florida Bay for this detailed 7-year period of study are similar to those calculated in a study summarizing freshwater influence on Florida Bay (Nuttle et al., 2000),

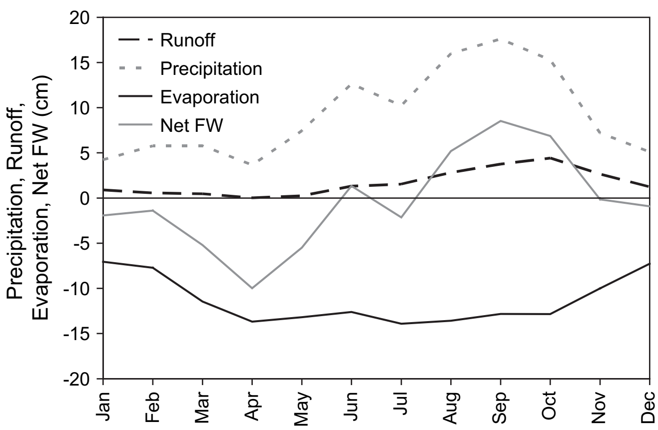

Fig. 8. The mean annual freshwater budget for Florida Bay, 1998–2004.

despite the fact that the two studies employed very different methods for calculating runoff and precipitation. The precipitation values in the present study were obtained from the Climvis program at NCDC for Division 7 of Florida, which corresponds to the Florida Keys and Flamingo, whereas Nuttle et al. (2000) used longer records of precipitation from land stations calibrated against shorter records for stations in the Bay to produce estimates of precipitation directly over Florida Bay. There was a difference in mean annual precipitation of 13 cm between the two studies, from 98 cm in the prior study to 111 cm in the present study, which is within one standard deviation of the mean annual precipitation ($\sigma = 18.5$). Methodologies for estimating runoff were also very different. Nuttle et al. (2000) defined runoff as the upstream monthly discharges into Taylor Slough and the C111 canal. The present study used runoff measurements made directly at the mouth of six major discharge sites into northern Florida Bay and estimated discharge at three other sites. Runoff in the present study was more than double that of the previous study, 20 cm vs. 9 cm; however, as the magnitude of overall runoff is small compared to precipitation, the effect of this difference on the overall freshwater supply to Florida Bay is relatively minor. Our study found a slightly negative mean annual net freshwater supply of −5.3 cm, though there were significant interannual differences ranging from −59.2 in 2004 to 33.1 cm in 1999 (Table 3). The annual net freshwater supply for this study (−5.3 cm) is similar to that calculated by Nuttle et al., 2000 (−3.0 cm) and both values are well within one standard deviation ($\sigma = 28.9$) of the large interannual variation in net freshwater supply we observed. If the lower evaporation estimate calculated from the mass balance model, −134 cm per year, were used in calculating net freshwater supply, the mean net annual freshwater supply for the present study would increase to −3.3 cm.

Table 3
Annual mean Bay-wide salinity, precipitation, runoff, evaporation, and net freshwater supply

Year	Salinity	Precipitation (cm)	Runoff (cm)	Evaporation (cm)	Net
1998	32.4	109	19.1	135	−6.6
1999	31.2	133	25.7	126	33.1
2000	33.7	101	16.1	137	−20.3
2001	35.5	130	24.4	142	12.5
2002	31.8	112	23.6	133	2.5
2003	32.4	113	19.4	131	1.0
2004	36.3	78	10.4	148	−59.2
Mean	33	111	19.8	136	−5.3

4. Discussion

4.1. Spatial salinity distribution

Salinity differences for each of the four sub-regions arise from differing influences of direct and indirect runoff and advection. The northeast had the lowest salinity throughout the study with only a few exceptions (Fig. 6a). This sub-region receives the vast majority of the direct freshwater runoff from the Everglades. Five of the six major runoff points into Florida Bay measured in this study were located along the northern boundary of the northeast sub-region, and these five accounted for over 94% of estimated runoff. In the beginning of the dry season, from January to May, the salinity in the northeast remained much lower then the other three sub-regions (Fig. 6), due to continued runoff from January through March, while very little direct precipitation occurred over Florida Bay (Fig. 4).

The large range in salinity observed in the northeast is the combined result of the seasonally variable direct freshwater supply with shallow bathymetry. The northeast sub-region is the second shallowest in the Bay (after the north-central sub-region). In fact, when freshwater input is minimal, evaporation can become the dominant factor, elevating the salinity dramatically due to the sub-region's shallow depth. Thus, hypersaline conditions are often observed in this sub-region during drought periods such as the summer of 2004 (Fig. 6a).

Salinity in the north-central sub-region varies primarily as a result of local precipitation and evaporation. The shallow depth of this sub-region enhances salinity sensitivity to the effects of these two forcing factors by simple dilution and evaporative concentration (cf. eq. (2)). There is minimal direct freshwater runoff into this sub-region (less than 6% of the measured total) and exchange with other sub-regions is also minimal with an approximate residence time of over 6.6 months, due to the large expanse of shallow mud-banks which surround and are contained within this sub-region (Fig. 1) (Lee et al., in press). The quick responses in this sub-region's salinity time series forced primarily by local precipitation and evaporation are shown in the relatively short lagged correlations between precipitation and runoff to salinity (Table 1). The lag between precipitation and salinity in the north-central sub-region is only 2 months, roughly half the lag period observed in the other three sub-regions where salinity is more affected by direct and/or indirect runoff.

The relatively quick response of salinity in the north-central sub-region to direct precipitation was evidenced by salinity in this sub-region being as low as or lower than that observed in the northeast following large precipitation events (during three years 1999, 2001, and 2003). Additionally, for all years except 2002 and 2003, the highest annual salinities were also located

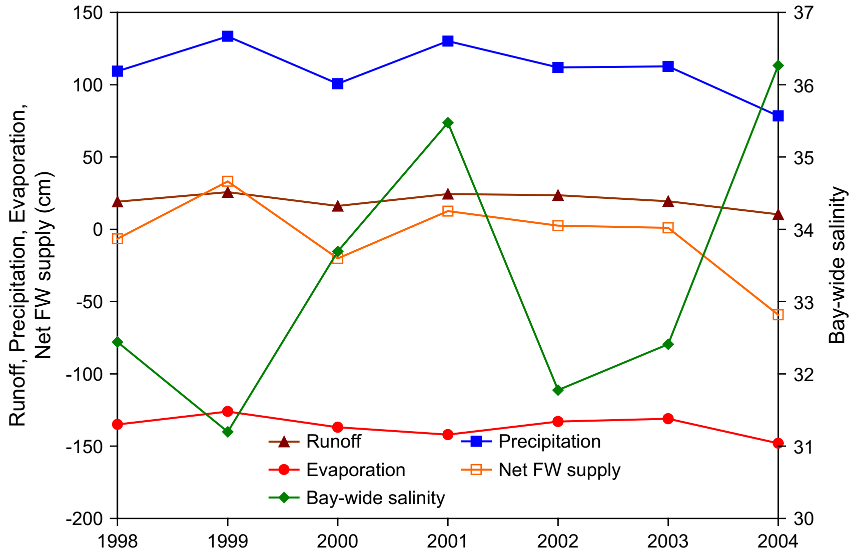

Fig. 9. Plot of the mean annual values for runoff, precipitation, evaporation, net freshwater supply, and Bay-wide salinity.

in the north-central sub-region (Fig. 6a). The north-central sub-region exhibited the greatest rates of both salinity increase and decrease. A reduction of over 14 in 26 days coincided with the passing of Tropical Storm Harvey and Hurricane Irene near Florida Bay in September and October 1999. In contrast, a salinity increase of over 6 in 28 days was observed between May and June of 2004, due to anomalously low precipitation (only 2 cm, about 20% of the monthly mean precipitation for this period) during a period of high evaporation (Fig. 4).

The salinities in the south and west sub-regions of Florida Bay were typically similar to one another (Fig. 6) indicating that these sub-regions are subject to similar forcing and are more closely coupled by advection than the other sub-regions. Both the south and west sub-regions are affected by the nearshore waters of the southwest Florida shelf, though exchange in the south is somewhat limited by mud-banks in this region (Wang et al., 1994). These shelf waters are seasonally less saline than waters found further offshore in the Gulf of Mexico or Florida Straits due to freshwater runoff along the coast of southwest Florida. In addition to these nearshore shelf waters, the south sub-region is also influenced by exchange with the coastal waters of the Florida Keys through tidal passages (Lee and Smith, 2002). The exchange with the Keys waters, which do not display the same seasonal salinity patterns as the southwest Florida shelf and are typically stable at about 36.3 (Johns et al., 2005), takes place on both tidal and long-term time scales as a result of regional wind forcing and horizontal pressure gradients. In both cases, exchange with adjacent coastal waters has a stabilizing effect upon interior Bay salinity. Therefore, both the south and west sub-regions display much smaller salinity fluctuations than observed in the northeast and north-central sub-regions. Nonetheless, the west and south sub-regions still exhibit the annual salinity oscillation typical for Florida Bay (Fig. 6), indicating that the annual cycle in net freshwater supply is the dominant force driving the temporal salinity distributions of both regions.

There were significant differences between the salinity of the west and south sub-regions. Most notably, the south typically had higher salinities in summer months than the west. Several factors contributed to this difference. First, as depicted in Fig. 1, a significant area of the south sub-region is covered by mud-banks and is on average shallower than the west sub-region, resulting in greater salinity sensitivity to evaporation. Second, exchange between the west sub-region and the southwest Florida shelf is less restricted than exchange between the south sub-region and either the southwest Florida shelf or Atlantic Ocean (Wang et al., 1994), thus salinity remains more stable in the west sub-region. Third, there is some direct connection between the north-central and south sub-regions, which allows the hypersaline waters of the north-central sub-region to exchange into the south sub-region (Lee et al., in press). Moreover, Atlantic coastal waters off the Keys are on average more saline than southwest Florida shelf waters, because there is a large amount of freshwater runoff from rivers along the southwest Florida coast. This lower salinity water on the southwest Florida shelf then exchanges with west Florida Bay and decreases its salinity whereas in the south, the indirect runoff, which can come from two sources (northeast Florida Bay and the southwest Florida shelf), must first mix throughout the northeast or west sub-region and decrease its salinity before exchanging with and decreasing the salinity in the south. This is evidenced by the lagged correlation from runoff to mean salinity in the south being the longest (3 months), while in the west the correlation was slightly less (2–3 months) (Table 1). However, this last explanation assumes that runoff from rivers on the southwest Florida shelf has a similar temporal distribution to runoff directly into Florida Bay.

4.2. Salinity anomalies

There were several cases where the observed salinity values seemed anomalous, but upon closer examination were found to be in concert with meteorological events. For example, the lowest mean Bay-wide salinity observed, 24.2, was measured on November 16, 1999. Furthermore, October, November, and December of 1999 were the only months for the entire 7-year record that mean Bay-wide salinity was less than 26. The likely proximate cause of these anomalously low salinities was the passing of Hurricane Irene just to the west and north of Florida Bay on October 15, 1999 (Fig. 10). Precipitation was intense during this event, with a recording station in Tavernier on the eastern edge of Florida Bay reporting precipitation of 20.8 cm in one day.

This amount of precipitation had a large and immediate impact on the salinity of Florida Bay due to the Bay's shallow depth. Assuming the precipitation value at Tavernier is representative of the entire Bay, and using the estimated mean water depth of 1.4 m in the Bay derived from the recent bathymetric survey (Hansen and DeWitt, 2000), the quantity of direct precipitation associated with Irene equaled an astonishing 15.3% of Florida Bay's total volume. There was a regularly scheduled survey run on October 5–6, 1999, approximately 10 days before Hurricane Irene, and an additional survey was conducted on October 18–19, just a few days after Hurricane Irene, specifically to measure any hurricane-related changes. The pre-Irene survey had a mean Bay-wide salinity of 30.5. Three days after Irene, the mean salinity had dropped 20% to 24.4 (Fig. 11). This was the most rapid Bay-wide decrease in salinity observed during our 7 yr record (nearly 0.5 per day).

Furthermore, the survey conducted just after Hurricane Irene revealed a unique spatial salinity distribution (Fig. 11). It was the only survey that showed direct freshwater outflow from the Everglades along the northern boundary of central and western Florida Bay. Sheetflow runoff into these areas of Florida Bay has been hypothesized to have occurred frequently prior to the drainage of the Everglades and the dramatic reduction in freshwater runoff to Florida Bay (Hunt and Nuttle, in press). It is hypothesized that only when water levels in the Shark River Slough are sufficiently high, can runoff enter central Florida Bay from the north through the Buttonwood Embankment and out of McCormick Creek. Thus, if such historical water levels were restored by CERP, runoff through these areas might occur more frequently, and perhaps not just in response to major events such as tropical cyclones, possibly reducing the frequency and magnitude of hypersalinity events in north-central Florida Bay.

Salinity values calculated with the mass balance model failed to adequately capture the response of salinity in the north-central sub-region to the freshwater delivered by Hurricane Irene (Fig. 7). Similarly, the mass balance model failed to capture the low-salinity extremes in 2002 and 2004. Two aspects of the model might account for these deficiencies. First is the assumption that precipitation is uniform over the Bay and is equal to the Climvis Division 7 values. Hurricane Irene passed to the west of Florida Bay (Fig. 9) which may have subjected the north-central and west sub-regions to greater precipitation than the Florida Keys where the precipitation stations included in the Division 7 data set are located. Second, as noted above, direct freshwater runoff into the north-central sub-region was anomalously high immediately following Irene's passage. This anomaly is not reflected in the flow data estimated from the discrete estuarine creeks. Therefore, model estimates of net freshwater supply into the north-central

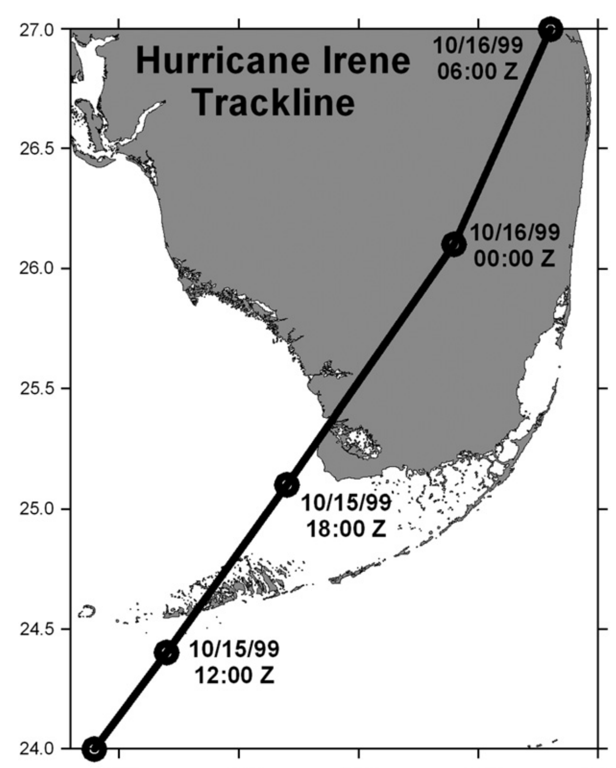

Fig. 10. The track of the center of Hurricane Irene as it passed just to the west of Florida Bay in October 1999.

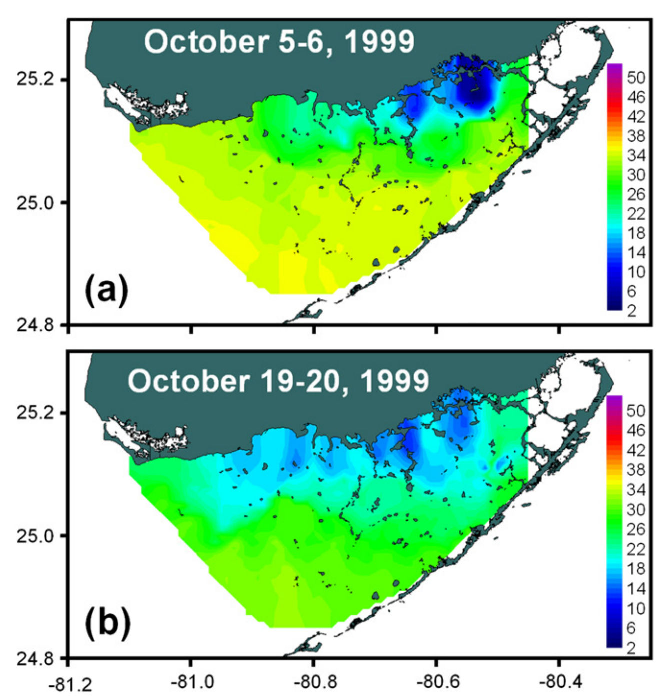

Fig. 11. Salinity contour maps for surveys conducted (a) 10 days prior to Hurricane Irene and (b) 4 days after Hurricane Irene.

sub-region likely underestimate the supply of freshwater into this region under these unusual conditions.

The highest mean Bay-wide salinities were measured in July of 2001 (41.8) and 2004 (41.7). They were the result of precipitation deficiencies in the preceding years, 2000 and 2003, followed by a delayed onset of the subsequent rainy season. In 2000, precipitation was far below normal resulting in an annual net freshwater supply of −20 cm (Table 3). In 2003, annual net freshwater supply was higher at 1 cm, but precipitation and runoff were temporally more uniform than usual, resulting in higher than typical salinities at the end of 2003. Subsequently, in both 2001 and 2004, precipitation was unimodal and did not peak until late summer, whereas typically precipitation is bi-modal, peaking in early summer (May or June) and again in late summer (August or September). The delayed onset of the rainy season during 2001 and 2004 resulted in anomalous negative freshwater supply numbers in the summer when evaporation is at its highest (but is typically offset by precipitation), and led to the maximum salinities observed in July of both 2001 and 2004.

We examined the hypersalinity distribution sequence for 2004 to describe the typical development and evolution of hypersaline events in north-central Florida Bay (Fig. 12). High salinities were first observed in the western half of the north-central sub-region (Fig. 12a), an area with the largest concentration of shallow mud-banks (Fig. 1). This hypersaline water then moved to the east and intensified (Fig. 12b), due to increased temperatures in mid-summer, which resulted in increased evaporation (Fig. 4). Eventually, the hypersaline water decreased in magnitude and its center shifted to the southeast as precipitation and runoff began to increase and western Florida Bay freshened via exchange from the southwest Florida shelf (Fig. 12c). In contrast to the model's performance during periods of anomalously low salinity values, the mass balance model matched observed salinity behavior during these periods of anomalously high salinity values quite well (Fig. 7). Presumably, the effects of underestimates in net freshwater supply are minimized when runoff is so markedly decreased.

The maximum rate of salinity increase Bay-wide (over 0.1 per day) was observed from April 2–3, 2002 to May 7–8, 2002 (Fig. 13a). However, the second and third highest increases, both slightly greater than 0.1 per day, were observed from April 20–21, 2004 to May 18–19, 2004 and May 18–19, 2004 to June 16–17, 2004, several months before the second highest mean Bay-wide salinity of 41.7 was recorded on July 21, 2004. Note that the maximum rate of salinity decrease (nearly 0.5 per day) was more than fourfold greater than the maximum rate of salinity increase. Accordingly, it can be concluded that Florida Bay requires a significantly prolonged drought to produce the historically documented extreme hypersaline conditions.

Another anomalous salinity pattern was observed in the last six months of 2004, with the usually estuarine northeast sub-region having much higher salinity than typical and in fact displaying the highest salinity of all four sub-regions during August and September 2004 (Fig. 6a). The cause of this anomalous salinity pattern is likely the unusual distribution

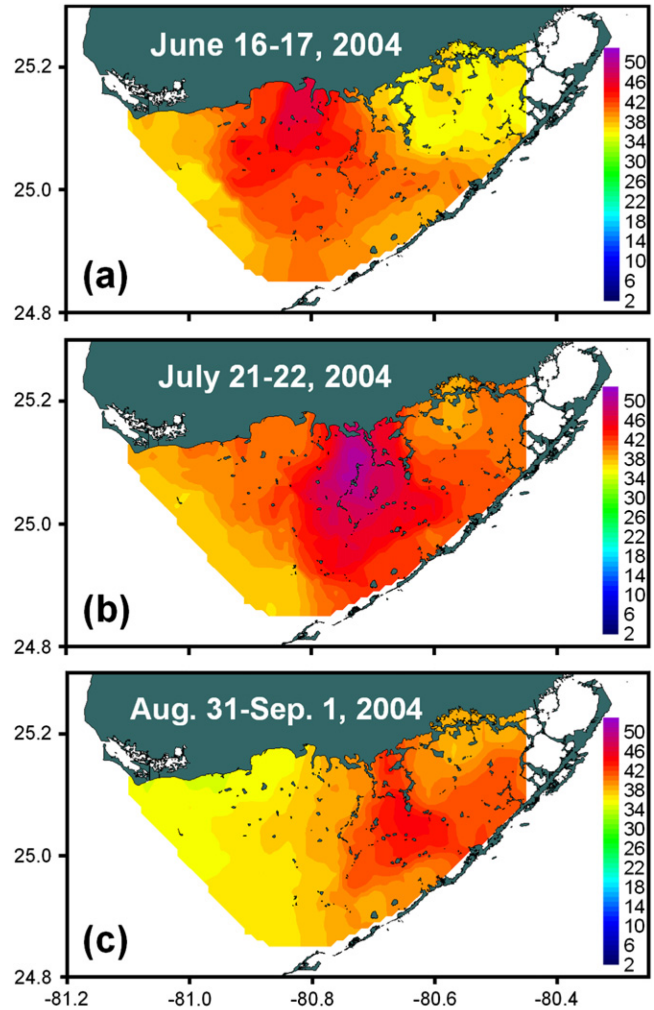

Fig. 12. Series of salinity contour maps showing the formation and movement of a typical hypersalinity event from (a) June 2004, (b) July 2004, and (c) August 2004.

of regional precipitation during the 2004 wet season. Precipitation was dramatically lower than any other year during this study, which resulted in by far the lowest observed direct runoff to northeast Florida Bay, Table 3. Moreover, Hurricanes Charlie, Frances, and Jean all passed just to the north of Lake Okeechobee in the late summer to early fall of 2004. Although these hurricanes had minimal direct effects upon Florida Bay in either precipitation or runoff, nevertheless they indirectly affected the salinity patterns in the Bay by markedly reducing the salinity along the southwest Florida shelf, and these waters subsequently advected into the western Bay (Johns et al., 2005). This exchange was sufficient to reverse the typical difference observed between salinity in the northeast sub-region and the other three sub-regions, resulting in the northeast sub-region displaying the highest salinity for several months during the wet season of 2004.

4.3. Interannual variation

To examine the variation between years and attempt to uncover any long term and/or anomalous trends, annual values

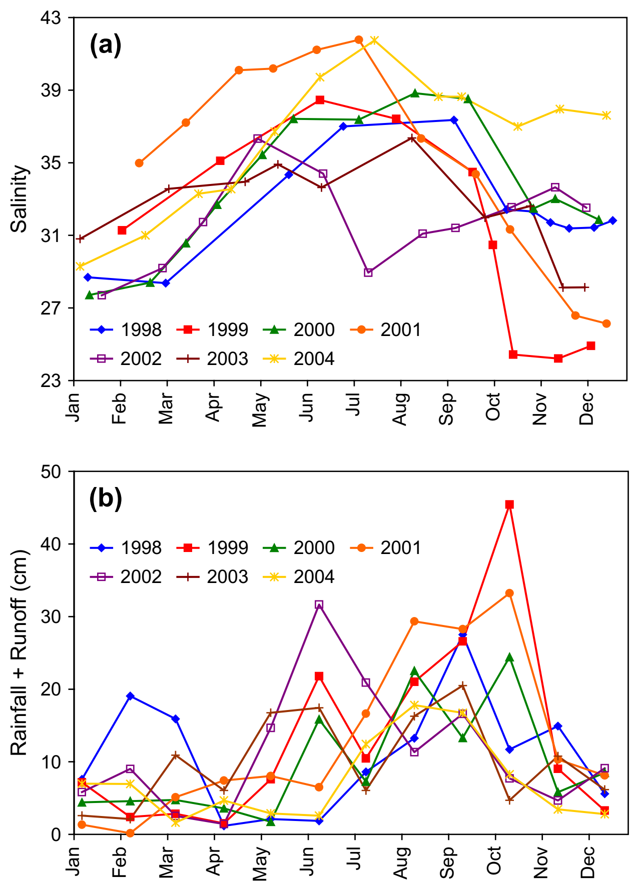

Fig. 13. Annual time series of (a) salinity and (b) precipitation plus runoff for each of the seven years during the study.

of mean salinity, precipitation, runoff, and net freshwater supply were calculated (Table 3 and Fig. 9). Annual runoff was significantly less than annual precipitation, ranging from 13.3% to 21.1% of precipitation with a mean annual runoff value that was 17.9% of the mean annual precipitation. While 17.9% is significantly higher than the less than 10% calculated if runoff values were assumed to be equal to upstream values at C-111 and Taylor Slough (Nuttle et al., 2000), the true percentage may be even higher as our runoff measurements do not include all of the direct freshwater runoff pathways into Florida Bay, and must therefore be assumed to be a conservative estimate of total runoff.

Although both the maximum and minimum annual salinity coincided with the minimum and maximum precipitation and runoff, respectively, annual salinity was not consistently correlated with annual precipitation and runoff. In 2001, the second highest mean annual salinity observed coincided with the second highest annual precipitation and runoff values. To examine such apparent incongruities, the annual temporal distribution of salinity and precipitation plus runoff were plotted for each year (Fig. 13). In 2000, the preceding year, precipitation and runoff were the second lowest during the survey period (Table 3 and Fig. 13). Thus, at the beginning of the ensuing year the salinity remained high. The onset of the rainy season in 2001 was delayed until July, resulting in the high salinities during the first six months of the year. Subsequently, August and September 2001 were the wettest in the 7-year data set, and July and October were the second wettest (Fig. 13b). As a result, 2001 was a year of unusual salinity extremes, varying from the highest value measured, 41.8 in July, to the second freshest values for October, November, and December (Fig. 13a).

These plots of each individual year's temporal salinity and precipitation plus runoff cycle were also utilized to examine interannual variation (Fig. 13). This revealed another salinity anomaly in 2002, in that July had the lowest salinity for the year, rather than December or January. In 2002, precipitation and runoff peaked much earlier than usual (Fig. 13b), from May through July, causing decreased salinity earlier in the summer and subsequent increases in salinity through the end of the year. Overall, in 1998, as well as in 2002 and 2003, the annual oscillation in salinity as well as runoff and precipitation was dampened (Fig. 13). Precipitation patterns of 1998, 2002, and 2003, were more evenly distributed throughout the seasons (Figs. 4b and 13b). As a result, salinities became more uniformly distributed temporally, remaining between 28 and 36, and lacked the typical seasonal patterns (Figs. 4a and 13a). The cause of the anomalous precipitation pattern is thought to be ENSO, which was observed in Pacific Ocean sea surface temperature anomalies during 1997–1998 and again in 2002–2003 (Wang and Fiedler, in press). ENSO has been shown to affect precipitation throughout the Florida peninsula by increasing the amount of precipitation during the dry season (Sun and Furbish, 1997). The 1997–1998 ENSO caused a reversal of the typical dry and wet seasons of south Florida with a dry summer/fall in 1997 and a wet winter/spring in 1998 (Johns et al., 1999; Lee et al., 2002). Others have hypothesized that ENSO has a strong effect on salinity in Florida Bay based upon carbon isotopic analysis of coral skeletons (Swart et al., 1996, 1999).

5. Conclusions

Florida Bay is a seasonally hypersaline estuary with a slightly negative mean annual net freshwater supply of −5.3 cm. On average, direct runoff into Florida Bay accounts for greater than 15% of all freshwater entering the Bay, indicating that although the freshwater supply is dominated by precipitation, runoff cannot be neglected especially in the northeast sub-region. Salinity patterns in Florida Bay are directly related to the seasonal climate of south Florida. The net freshwater supply during the peak of the wet season is generally positive, decreasing salinity through a minimum in January. From March to June the net freshwater supply is typically negative, causing salinity values to increase until hypersaline conditions prevail throughout a large portion of Florida Bay.

The salinity of Florida Bay is also affected by extreme meteorological and climatic variability. Lowest overall mean salinities in Florida Bay were measured after the passing of Hurricane Irene, the only tropical storm or hurricane to have a significant direct effect upon Florida Bay during this study. The ENSO events of 1997–1998 and 2002–2003 resulted in a significant dampening of the wet season/dry season annual precipitation cycle, reducing temporal salinity variability during these periods.

Comparisons of direct observations and a mass balance model demonstrate that it is possible to reasonably estimate mean salinity for Florida Bay and each of the four sub-regions from runoff and precipitation alone ($Eff > 63$ in all regions), except after major precipitation events. Because net freshwater supply in Florida Bay is near zero on average, large reductions or increases in runoff can cause significant changes in the salinity patterns. For example, a significant change in the salinity pattern of Florida Bay could occur by shifting to the west sources of runoff along the northern boundary of Florida Bay, causing more frequent and a greater amount of runoff to discharge directly into the north-central or western sub-regions during the wet season. This runoff pattern was only observed once during our 7-year study period, just after the passing of Hurricane Irene, but has been hypothesized to have been a typical occurrence in the past when water levels in the southern Everglades were higher.

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