RED TIDE BLOOM DYNAMICS WITH RESPECT TO RAINFALL AND RIVERINE FLOW

FINAL REPORT

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ACKNOWLEDGMENTS

Without whom, none of this would be possible; Peter Howd, Jon Perry, Pat Minotti, Ari Nissanka, Jay Law, and Kim Churchill.

INTRODUCTION:

Worldwide, the incidence of harmful algal blooms is reported to be increasing in both frequency and duration. In the Gulf of Mexico, the dominant organism responsible for red tides is *Karenia brevis* and its presence has been inferred as early as 1844 (Feinstein, 1956). A number of mechanisms for the perceived increases in blooms have been proposed, including the increase in nitrogen loadings to coastal waters by both anthropogenic activities and long term climatic cycles. This report documents the procedures and results of an examination of blooms of *K. brevis* in the Gulf of Mexico for relationships to rainfall and riverine flows as surrogates for nutrient loadings, to hurricanes as a potential source of nutrients by water overturn, to selected climatological indices as surrogates for temperature or rainfall-related forcing functions, and to the atmospheric deposition of inorganic nitrogen.

DATA SOURCES/PROCESSING:

The core of the data to be examined was a recent compilation of data on *K. brevis* prepared by the Florida Marine Research Institute. The compilation (FFWCC-FMRI, 2001) consisted of any red tide organism counts in Florida waters from 1953 through 1998, together with associated physical (temperature, salinity), nutrient, and trace metal concentrations and represented data collected by over 50 organizations or agencies. These data from all coastal Florida waters were truncated to the Gulf of Mexico for analysis, maintaining over 44,000 samples. Since it was likely that processes which induce or maintain a bloom may vary geographically, and since red tide initiations more frequently been observed off of the southwest Florida coast (Feinstein, 1956), red tide data sets were spatially binned into three geographic regions **(Figure 1).** Data reduction included a quality assurance review for missing or inconsistent units. Additional categories of presence/absence of *K. brevis*, and nutrient ratios were computed. In some instance, soluble and total inorganic parameters were combined to provide a longer term data set. [There are other data sets (some quite substantial) with records of nutrients or physical parameters, but they were not included in the compilation unless cell counts for *K. brevis* were conducted.]

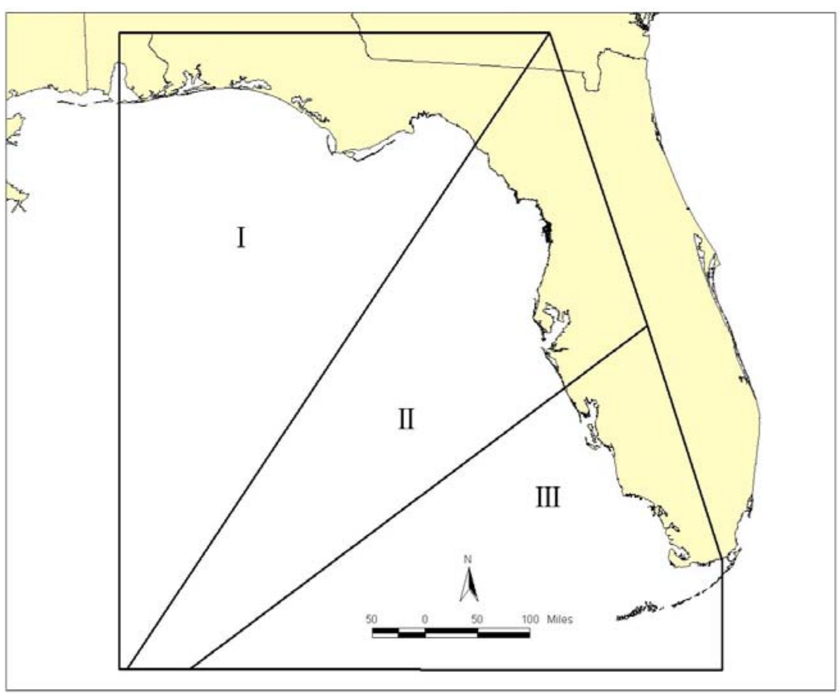

Figure 1. Study regions within the Gulf Of Mexico.

The distribution of *K. brevis* cell count data was highly skewed with both a large number of zero observations and a few extreme concentrations (**Figure 2**). (Extremely high concentrations were considered to be real data and were not removed from the data set.) For the cell count or concentration data, however, both the number of observations and magnitude of concentrations by region was undoubtedly a function of whether a bloom was detected, subsequent sampling effort, level of financial support for sampling, and whether the most intense portion of the bloom was close to available sampling resources. Bloom 'detectablility' and response have undoubtedly increased

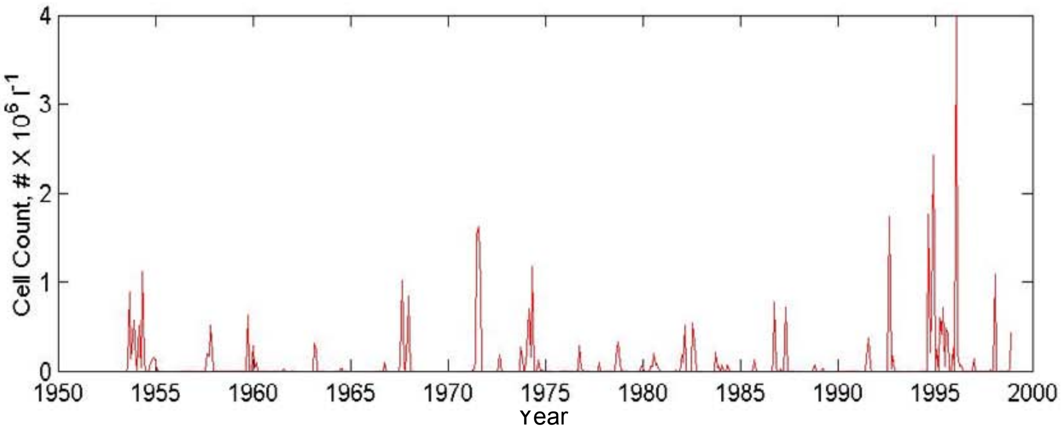

Figure 2. Time series of *K. brevis* cell count concentrations for the study area as a whole.

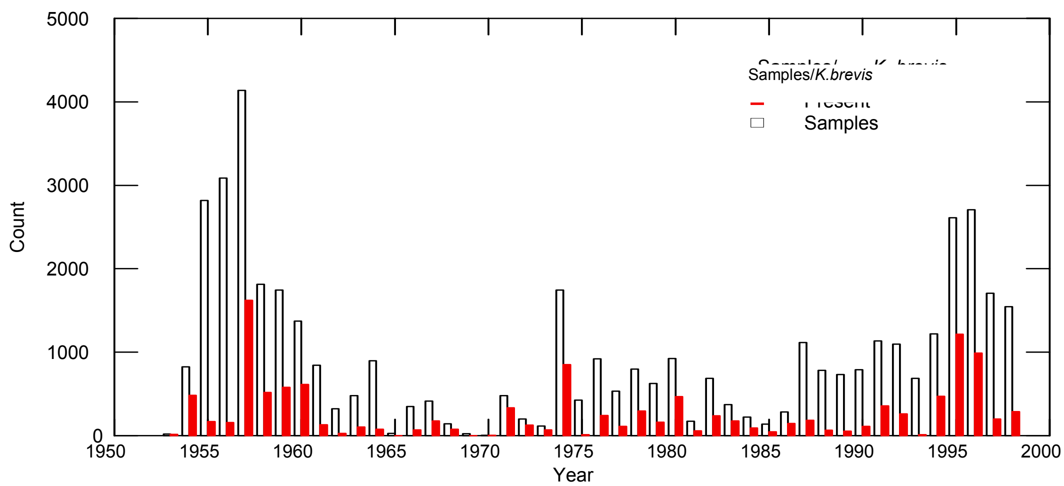

Figure 3. Number of samples (white bars) and samples with *K. brevis* present (red bars) as annual totals, for the entire study area.

over the years, especially with the advent of remote sensing methods. **Figure 3** illustrates high levels of sampling effort both during the 1950's and the 1990's with relatively lower levels in the intervening years. **Figure 4** illustrates the increasing spatial distribution and increasing density of samples over the study period. Additionally, the number of ancillary measurements made in addition to cell counts has also increased. Data analysis techniques which involve spatial and temporal binning have the opportunity to seriously bias mean values to the area or period with the most number of samples. This does not affect simple parameter:parameter correlation analyses on unbinned data, but makes problematic any time series analysis of numeric cell concentration data.

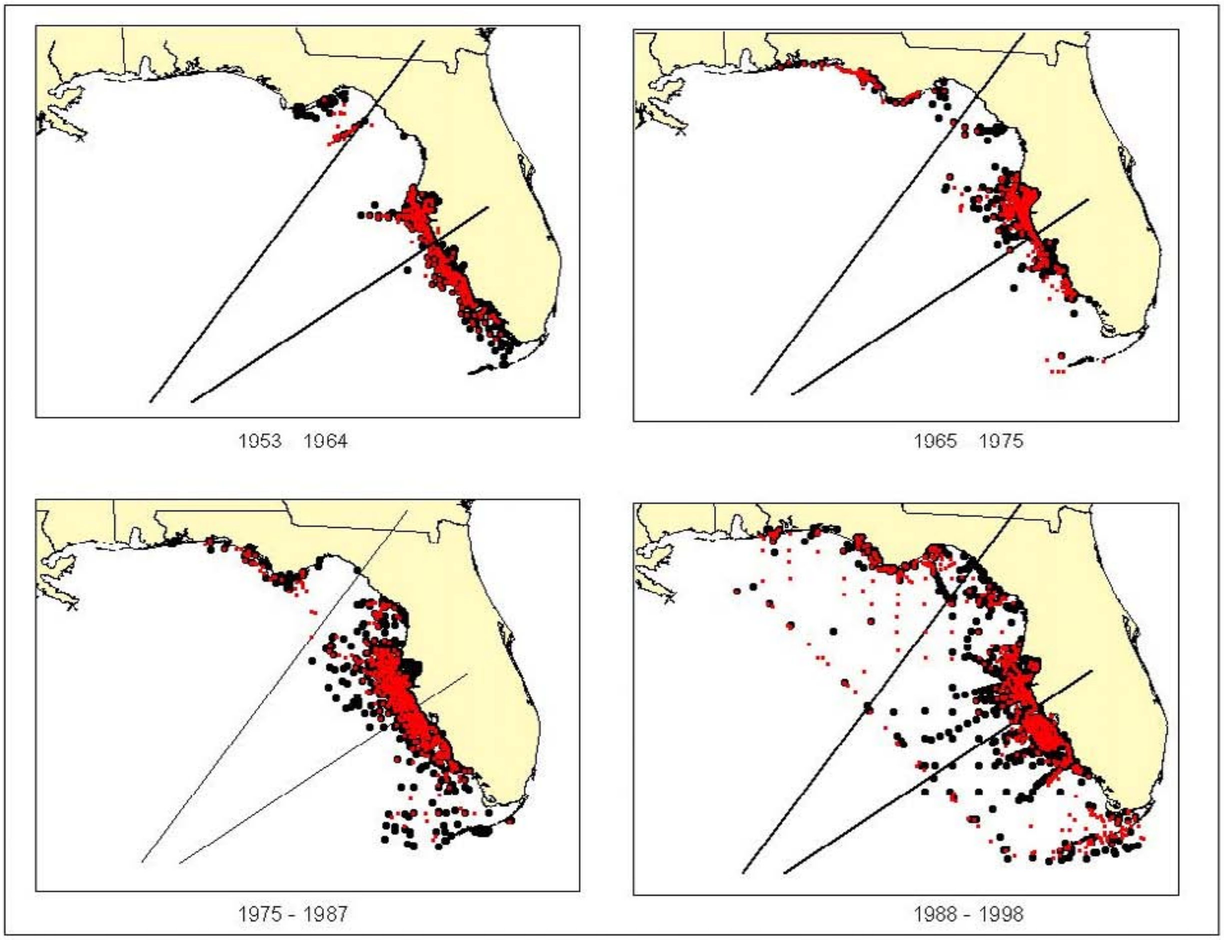

Figure 4. Spatial distribution of sampling effort over the roughly four quarters of the study period. Black dots are sampling locations. Red indicate where *K. brevis* was present.

In order to perform a time series analysis with sufficient regional and seasonal detail, the data were binned by region (I, II, and III; **Figure 1**, above) and by month. For the region as a whole, 80% of the 552 months covered by the study had at least one observation. These observations were very unevenly divided by regions, however, with data in only 10% of the months for Region 1, 75% for Region 2, and 52% for Region 3. Where no observations were available for the month, they were replaced with absence or zero data. This was an implicit assumption that all major blooms were detected, and that cell counts were at some level near zero when no samplings were conducted. The effect of this data treatment is conservative in that it will reduce the ability to detect significant correlations (if present) with independent variables, but will not determine potentially spurious correlations. Consideration of results obtained should also recall the minimal amounts of data in Region 1 in particular. Larger geographic bins, however, which would reduce the number of missing data for a given month, would reduce the ability to detect regional differences.

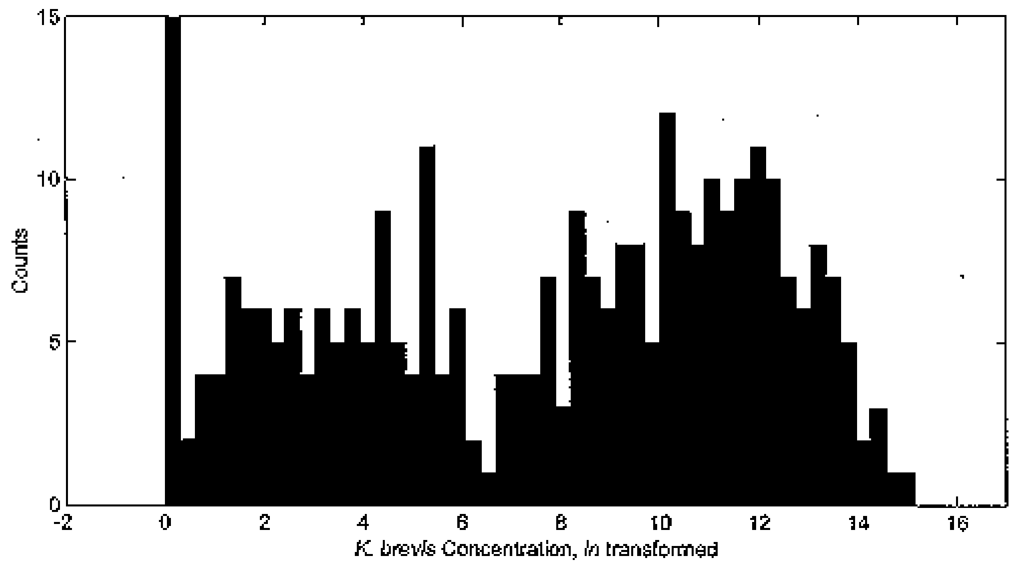

Figure 5. Frequency distribution of *In* transformed *K. brevis* cell counts.

To avoid the use of effort-skewed concentration data and minimize bias introduced by spatial binning, more suitable *K. brevis* parameters for time series analyses were presence/absence and the duration of the organism's presence. Presence/absence also avoided uncertainties associated with reporting units (cell/liter, 1000's cells/liter) which was suspected based on the bi-modal distribution of log transformed cell concentration data **(Figure 5)**. Due to reporting uncertainties, presence/absence data were set to 1 for any value greater than zero rather than using an arbitrary threshold value to differentiate a bloom from 'background' organism concentrations.

From presence/absence, a duration parameter was computed as the number of months of the following *n* months in which red tides were observed. Periods chosen included 3, 6, 9, 12, 18, and 24 months (**Figure 6**). A weighted duration was also computed over the same intervals, with a linear decrease in weight given to months at greater temporal distances (i.e. for a 3 month weighted duration, a value of 3 for presence this month, plus a value of 2 for presence next month plus 1 if present the following month). All duration parameters were separately computed for each of the three regions. Another advantage of the duration parameter was that the data for *K. brevis* became more nearly normal (**Figure 7)** with increasing periods. *Karenia brevis* data were not deseasonalized since an annual cycle is not always clear.

One artifact of the duration parameter is that 3 month and longer durations become progressively more phase shifted ahead of the occurrence of the *K. brevis*. An example of this is presented in **Figure 8** in which a single occurrence of *K. brevis* in an arbitrary month 26 is plotted together with the 3 month, 6 month, 12 month, and 24 month duration parameters. This is a consequence of 'looking ahead' to compute the duration parameter (i.e., "How many times in the next *n* months does *K. brevis* occur?") and a desire to link *K. brevis* occurrence in the future with climatic or other conditions that have occurred in the past. The midpoint of the duration parameter is phase shifted ahead by approximately one half of the duration period which should be kept in mind when interpreting the various correlation analyses to be performed.

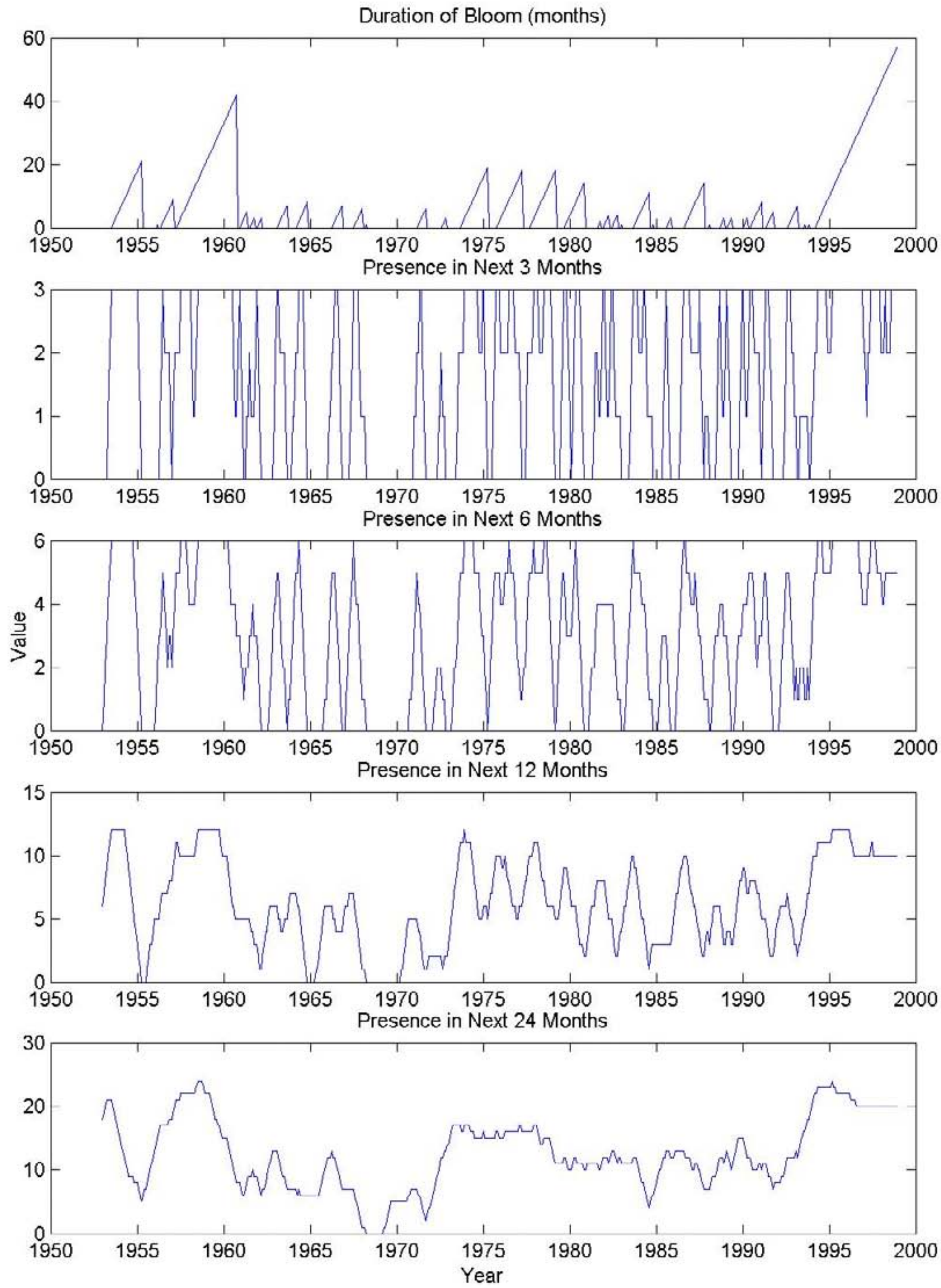

Figure 6. *Karenia brevis* duration parameters for the study area as a whole. Values are the number of months in the next *n* months in which *K. brevis* was present for *n* = 3, 6, 12, and 24 months.

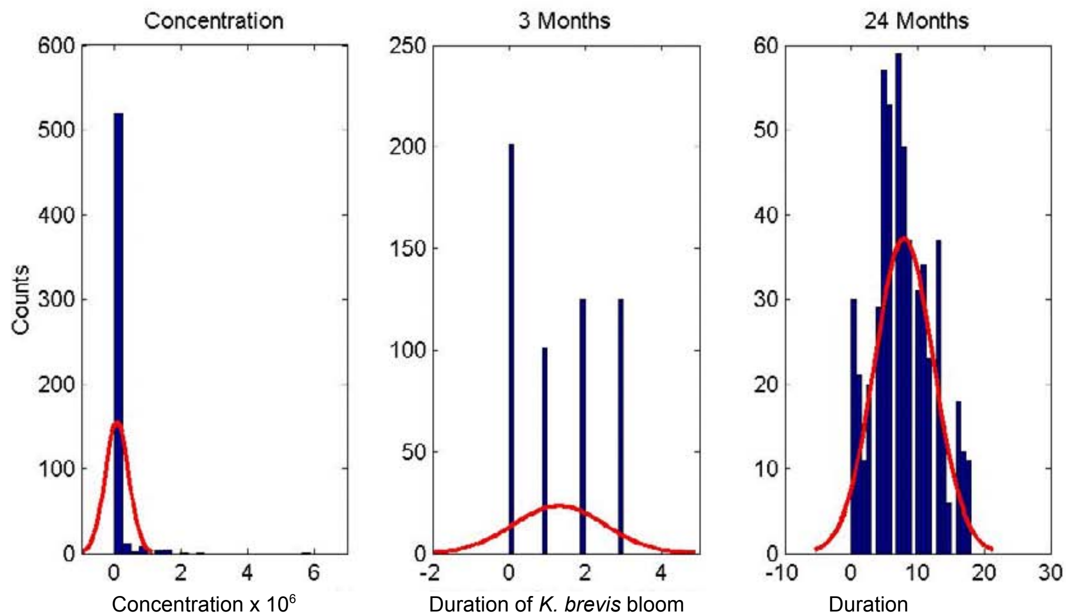

Figure 7. Increasing normality of the distribution of *K. brevis* durations with increasing duration period.

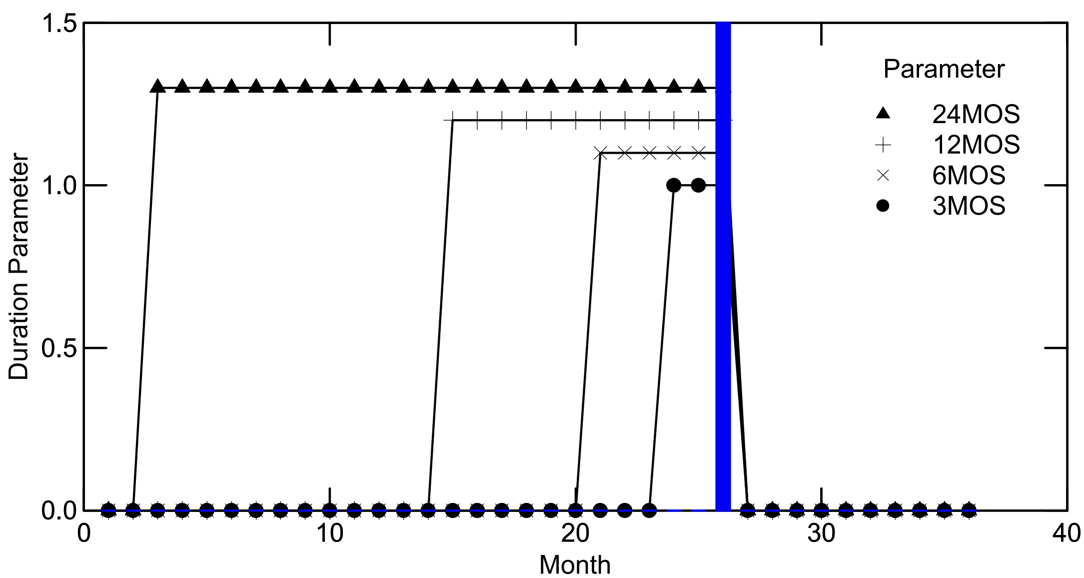

Figure 8. Phase shift in *K. brevis* duration parameters within increasing period. Bar indicates the single month when *K. brevis* was observed. Duration values are slightly offset from 1.0 for clarity.

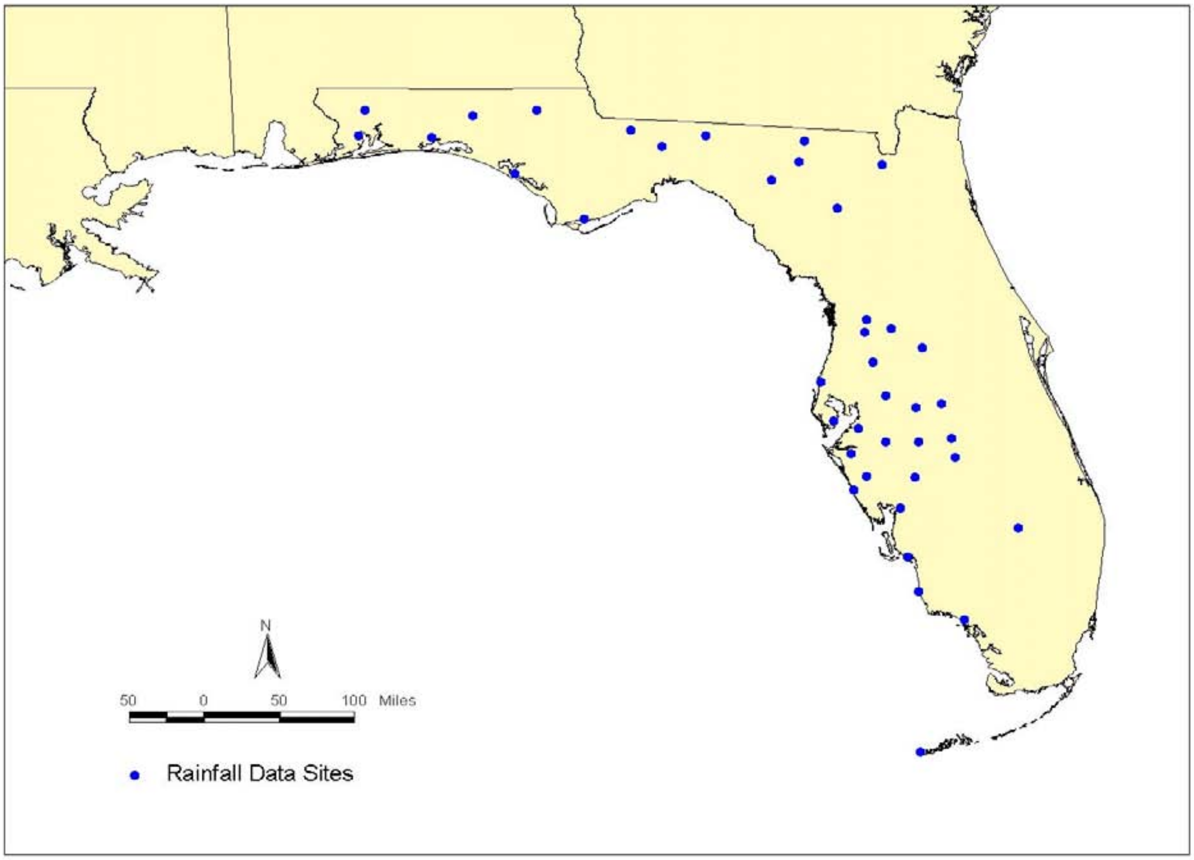

Figure 9. Florida COOP-NWS rainfall stations used for analysis.

Monthly rainfall data at 41 locations **(Figure 9, Table 1)** were obtained from the Northwest, Suwannee, Southwest, and South Florida Water Management Districts and the National Climatic Data Center. Sites were part of the Cooperative and National Weather Service (COOP-NWS) network of stations and were selected based on location within watersheds to the Gulf of Mexico, concurrence of period of record with the *K. brevis* data set and a minimum of missing observations. The episodic nature of rainfall data frequently resulted in statistical outlier data which, nevertheless, represent true conditions such as during hurricanes. Extreme monthly values were not removed, therefore. Due to the episodic nature of rainfall, replacing missing data with interpolated values was not appropriate. Missing data in a given month were, instead, replaced with a randomly selected value of the other observations in that month. Data were transformed to the 0.41 power to improve normality, and statistically significant normality at the 95% level was achieved for 27 of the 41 stations. Non-normal station data, (with a representative station illustrated in **Figure 10**), however, appeared to be distributed in an approximately normal fashion and justified use of the statistical techniques which are resilient to minor violations of the assumptions of normality (Bendat and Piersol, 1993)**.** Rainfall data were also generally stationary as to means and variances (invariant with time), although some stations had minor violations as evidenced in the above figure.

Table 1. FLCOOP-NWS Rainfall Stations.

Site Number	Station	Latitude	Longitude
41	PENSACOLA	30.5303	-87.1994
40	MILTON EXPERIMENT STATION	30.7812	-87.1398
39	NICEVILLE	30.5196	-86.4984
38	DE FUNIAK SPRINGS	30.7292	-86.1042
37	PANAMA CITY	30.1667	-85.7000
36	CHIPLEY	30.7833	-85.4833
35	APALACHICOLA	29.7307	-85.0299
34	QUINCY EXPERIMENT STATION	30.5833	-84.5833
33	TALLAHASSEE	30.4333	-84.2833
32	MONTICELLO	30.5333	-83.8667
31	MAYO	30.1000	-83.2333
30	LIVE OAK	30.2833	-82.9667
29	JASPER	30.4833	-82.9167
28	GLEN ST MARY NURSERIES	30.2500	-82.1667
27	HIGH SPRINGS	29.8324	-82.5994
26	TARPON SPRINGS	28.1444	-82.7611
25	ST PETERSBURG	27.7679	-82.6320
24	TAMPA BAY AREA WSO	27.7000	-82.4000
23	BRADENTON	27.4502	-82.4721
22	INVERNESS	28.7566	-82.3153
21	BUSHNELL	28.6651	-82.0831
20	BROOKSVILLE	28.6333	-82.3333
19	CLERMONT	28.4833	-81.7833
18	SAINT LEO	28.3379	-82.2600
17	PLANT CITY	28.0180	-82.1349
16	WINTER HAVEN	28.0160	-81.7430
15	FORT GREEN	27.5682	-82.1351
14	MOUNTAIN LAKE	27.9333	-81.6000
13	BARTOW	27.8997	-81.8453
12	AVON PARK	27.6000	-81.5000
11	WAUCHULA	27.5700	-81.8167
10	DESOTO CITY	27.4167	-81.4667
9	MYAKKA RIVER STATE PARK	27.2389	-82.3167
8	ARCADIA	27.2283	-81.8567
7	VENICE	27.1001	-82.4394
6	PUNTA GORDA	26.9291	-81.9913
5	FORT MYERS BEACH	26.4500	-81.9278
4	NAPLES	26.1167	-81.8167
3	CLEWISTON	26.7350	-80.8593
2	EVERGLADES	25.8491	-81.3841
1	KEY WEST	24.5667	-81.8000

Rainfall anomalies were computed for the 41 individual stations by removing the long term monthly mean value of transformed data and a total of 33 of the 41 stations were then normally distributed. Again, even the non-normal stations were approximately normal. Both rainfall and rainfall anomalies were also compiled as 3, 6, 12, and 24 month accumulations. More stations achieved statistical normality with increasing accumulation periods and data also became more stationary.

Daily and monthly flow data from United States Geological Survey (USGS) gages were obtained for major riverine systems along Florida's west coast **(Figure 11, Table 2)**. Stations were selected with an emphasis on a complete (>90%) record over the period of interest, with mean monthly flows greater than 100 cfs, and on stations with a substantial number of nitrogen analyses. A total of 21 stations met criteria. In some instances, several stations within a single watershed were included to permit potential contributing regions of a watershed to be evaluated. Unfortunately, flows from the Caloosahatchee River in south Florida were only available since 1963. Given the nutrient loadings to Lake Okeechobee (the Caloosahatchee headwaters), all time series analyses were repeated using a reduced period of record in order to evaluate any potential effects of the Caloosahatchee River.

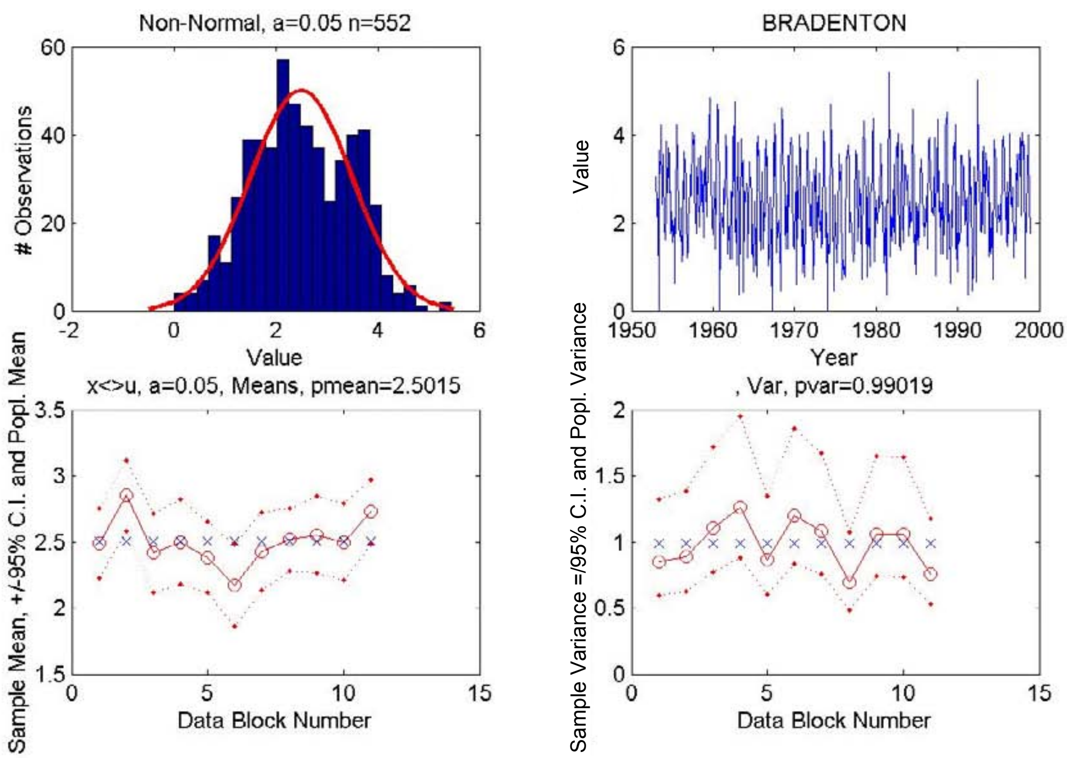

Figure 10. Approximate normality and time series of transformed monthly rainfall at a selected station. Also illustrated are the means and variances of 11 data blocks over the period of record illustrating non-stationarity.

Table 2. Riverine Flow Stations

Site Number	Site ID	Name	Latitude	Longitude	Start	End	Mean Annual Flow (cfs)	# of Total Nitrogen Data
21	2375500	Escambia River near Century	30.965	-87.2342	1935	1998	6358	136
20	2370000	Blackwater River near Baker	30.83333	-86.7347	1951	1998	359	9
19	2368000	Yellow River near Milligan	30.75278	-86.6292	1939	1997	1169	128
18	2369000	Shoal River near Crestview	30.69722	-86.5708	1939	1998	1133	-
17	2366500	Choctawhatchee River near Bruce	30.45083	-85.8983	1931	1998	7202	122
16	2359000	Chipola River near Altha	30.53389	-85.1653	1913	1998	1529	128
15	2358000	Apalachicola River at Chattahoochee	30.70083	-84.8592	1929	1998	22435	150
14	2329000	Ochlockonee River near Havana	30.55389	-84.3842	1927	1998	1070	152
13	2330000	Ochlockonee River near Bloxham	30.38306	-84.655	1927	1998	1739	3
12	2320500	Suwannee River at Branford	29.95556	-82.9278	1932	1998	7118	162
11	2323500	Suwannee River Wilcox	29.58945	-82.9367	1942	1996	10492	80
10	2313000	Withlacoochee River near Holder	28.98861	-82.3497	1932	1998	1025	180
9	2304500	Hillsborough River near Tampa	28.02361	-82.4281	1939	1997	460	8
8	2301500	Alafia River at Lithia	27.87194	-82.2114	1933	1997	339	168
7	2300500	Little Manatee River near Wimauma	27.67083	-82.3528	1940	1997	169	108
6	2298830	Myakka River near Sarasota	27.24028	-82.3139	1937	1997	251	124
5	2294650	Peace River at Bartow	27.90195	-81.8175	1940	1997	226	146
4	2295637	Peace River at Zolfo Springs	27.50417	-81.8011	1934	1997	627	145
3	2296750	Peace River at Arcadia	27.22195	-81.8761	1932	1997	1075	202
2	2297310	Horse Creek near Arcadia	27.19917	-81.9886	1951	1997	188	109
1	2297100	Joshua Creek at Nocatee	27.16639	-81.8797	1951	1997	106	61
0	S79	Caloosahatchee River at Franklin Lock	26.724	-81.698	1963	1998	1596	-

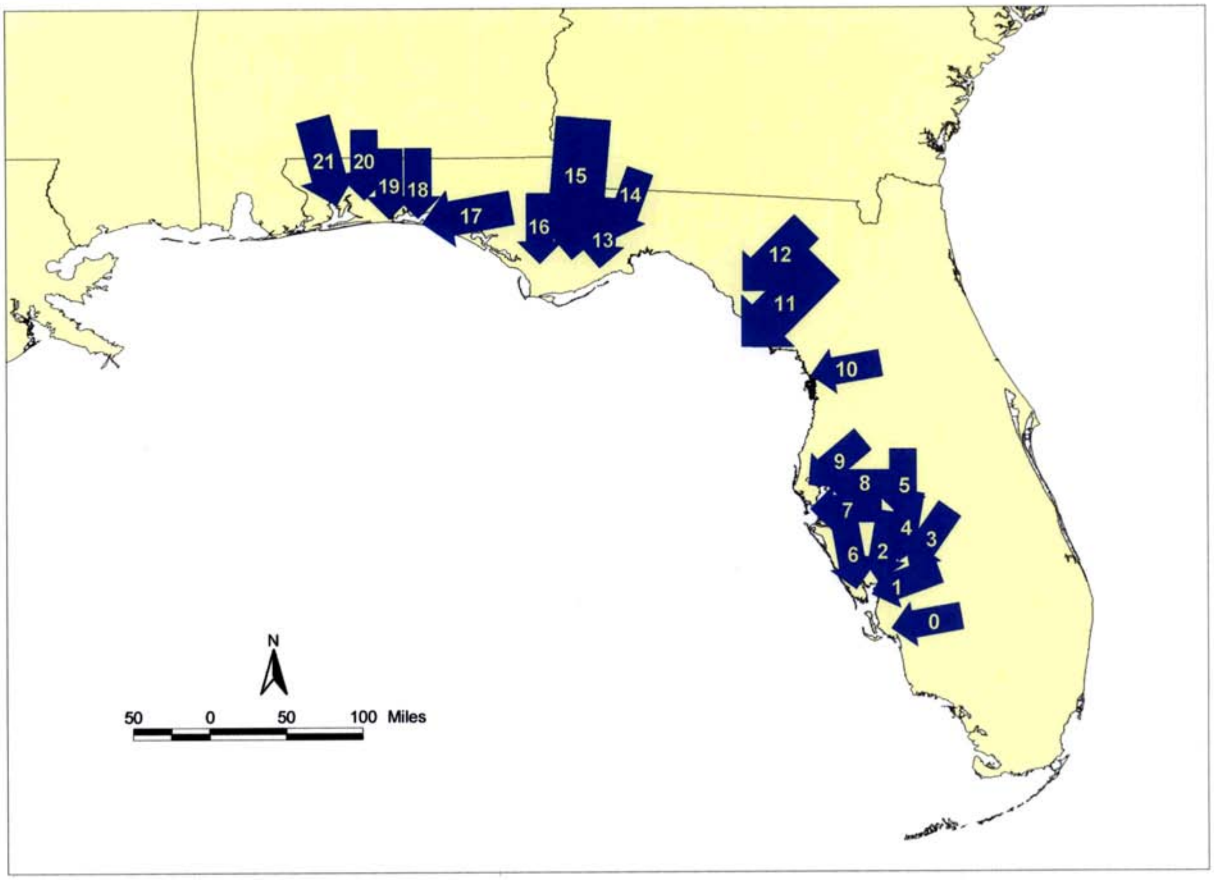

Figure 11. U.S. Geological Survey and South Florida Water Management District riverine discharge stations used for analysis.

Flow data, for all but the most recent, have been subjected to USGS quality assurance procedures which should capture gross outliers from instrumental failures. Extreme values in daily data and monthly data are considered typical of riverine flow, provided they follow the expected pattern of more or less rapid increase, followed by more gradual declines (for unmanaged rivers). Extreme values in flow data were, therefore, not removed. Missing data were replaced with interpolated means between adjacent months. Data normality was improved by a power transformation of 0.17, although all stations remained non-normal at the 95% level. Similarly to rainfall, monthly anomalies were computed for each station by deseasonalizing, removing the long term mean monthly flow from each monthly value. Again non-normal stations were approximately so **(Figure 12)**. In addition, cumulative flows and flow anomalies were computed for the prior 3, 6, 12 and 24 months **(Figure 13**) and evaluated as independent variables together with the monthly data. More of the cumulative flows and flow anomalies were normally distributed at the 95% level.

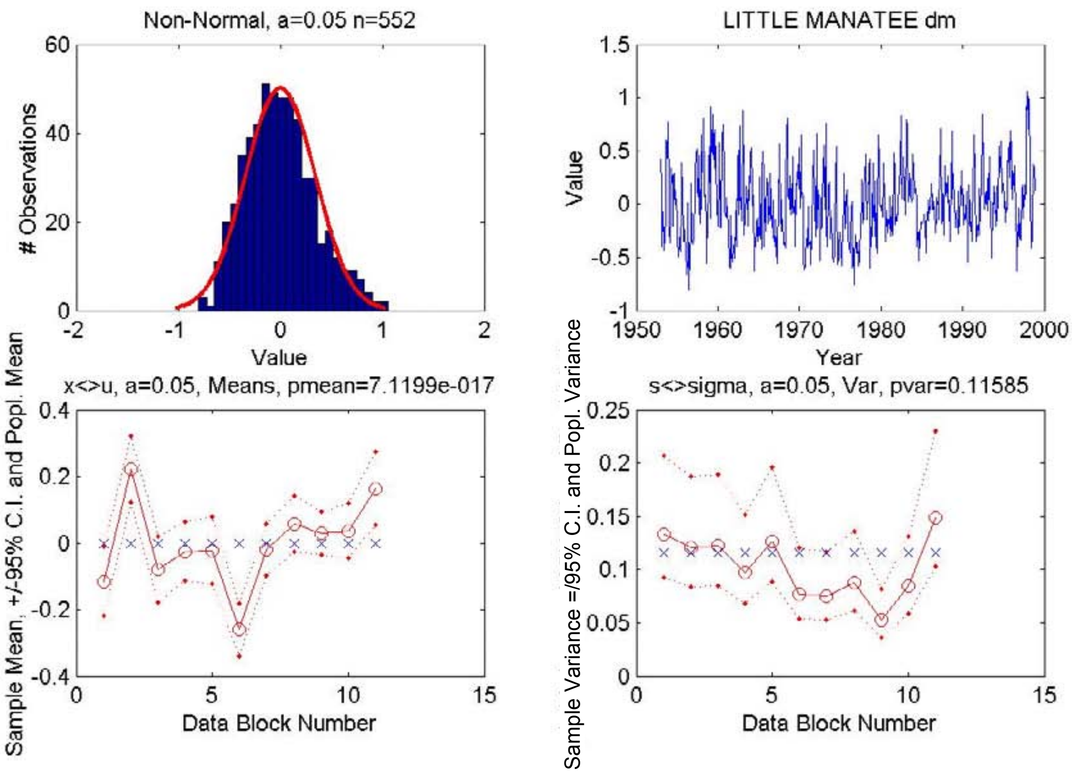

Figure 12. Approximate normality and time series of transformed and deseasonalized discharge data at a selected station. Also illustrated are the means and variances of 11 data blocks over the period of record illustrating non-stationarity.

The most downstream discharge stations do not capture 100% of a watershed's yield, but miss some unknown fraction that is often estimated (with increasing complexity and uncertainty) by ratioing the relative areas, ratios of spatially weighted rainfall within the gaged and ungaged portions, and modeling rainfall:runoff relationships as a function of land use and literature coefficients. The variation in the partial (gaged) flows from a watershed, however, can be generally considered to be representative of the total basin discharge and so should be a useful surrogate for total discharge. As the intent of this project was not a mechanistic or water-balance modeling effort, augmenting gaged flows by one of the above methods would not substantively add to the information that could be gained (i.e. if correlation between *K. brevis* and flow were significant, then correlation between *K. brevis* and flow times a factor provides no new information.) Accordingly flows were used in the analysis as reported by U.S.G.S., and no attempt was made to augment them for the ungaged portions of the respective watersheds.

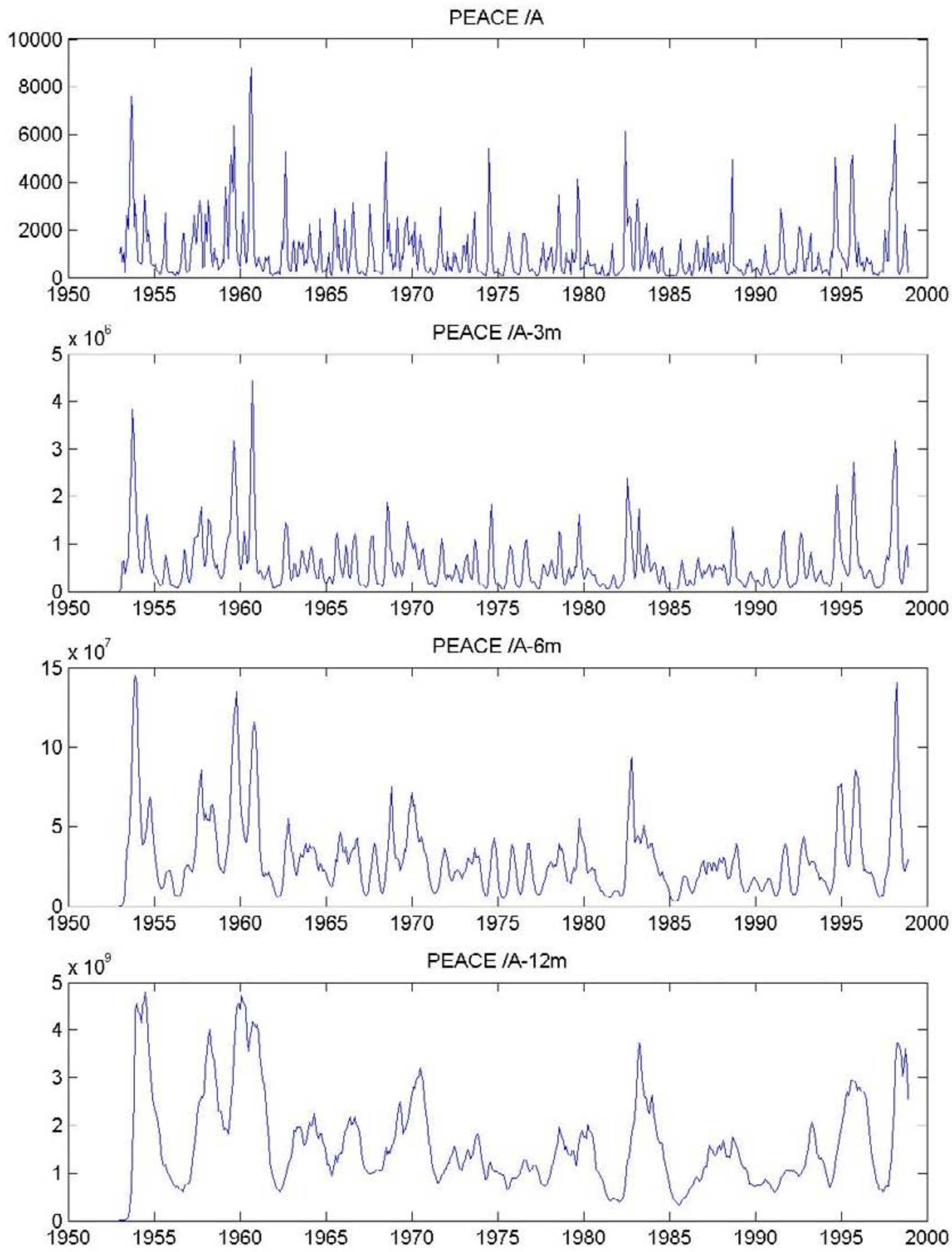

Figure 13. Monthly and cumulative flows (cfs) over increasing periods (3, 6, 12 months) of the Peace River at Arcadia.

Riverine loads of nitrogen were initially of interest, as well. Nutrient data were retrieved for all river stations except for the Caloosahatchee River from the USGS' "Water Resources of the United States" Website (water.usgs.gov). Parameters of interest included: total nitrogen (TN), nitrate-nitrite (NO_{23}-N), nitrate (NO_3-N), ammonia (NH_4-N) and total Kjeldahl nitrogen (TKN). All data were converted as necessary to mg l^{-1} as nitrogen. Data reported as "less than reported" were divided by 2 for incorporation into the database. Phosphorous data were also obtained for the following parameters, total phosphorous (TP), total and dissolved orthophosphate (PO_4-P, D-PO_4-P). All were converted to mg l^{-1} phosphorous. The resulting database was further reduced to TN and inorganic nitrogen (IN), TP and orthophosphorous (PO_4-P). Parameters were combined in an hierarchical order per sampling date. In order to arrive at TN for a station for a given sampling date, the TN value was used if reported, otherwise a calculation of TKN + NO_{23}-N was used to approximate TN. Inorganic nitrogen calculated as NO_{23}-N + NH_4-N was used. Total phosphorous and orthophosphorous (PO_4-P) were similarly reduced.

The resultant data set (1242 values for TN, and 4394 values of IN), however, provided data during only 32% of the months of the study period. Coverage by river ranged from data available in 333 of the 552 months to only 9 of 552 months. While inorganic nitrogen data were available from 1953-1998, total nitrogen data were generally restricted to the period 1970-1984. The inorganic nitrogen fraction ranged between 5% to ~100% of all total nitrogen and varied substantially over time within a given river. Flow parameters were investigated to determine if a consistent relationship existed with in-stream concentrations of either total or inorganic nitrogen. Parameters used included the daily flow value for the sample in question, the 7 day cumulative flow, and the 30 day cumulative flow. Flow:nitrogen (both total and inorganic) relationships by station were not highly correlated as a rule. While a general exponential decrease with increasing flow was commonly observed **(Figure 14)**, the relationships were also quite variable **(Figure 15** and **Figure 16)**, with concentrations for a given flow ranging over several orders of magnitude. Additionally, some riverine systems appear to have experienced changes in nutrient loadings over time **(Figure 17)** (Turner, 2001). Determination of trends in loads become problematic for systems with small data sets and was well beyond the scope of this project. Given the density of data, uncertainty of flow:concentration relationships, and potential for trends in loading unrelated to flows, the computation of nitrogen loadings from flow data and flow:concentration relationships was considered to be capable of producing spurious results and was not pursued.

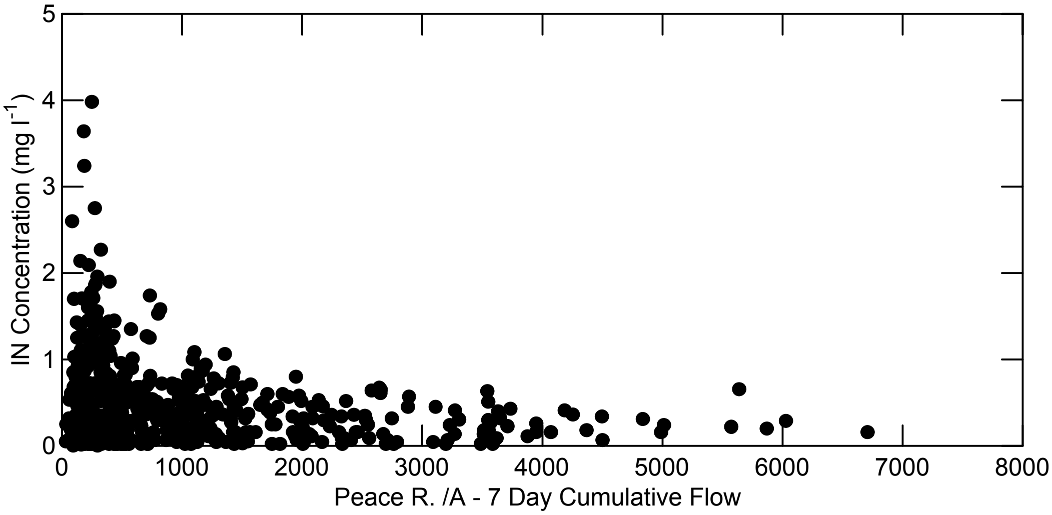

Figure 14. Inorganic nitrogen concentrations as a function of 7 day cumulative flows of the Peace River at Arcadia.

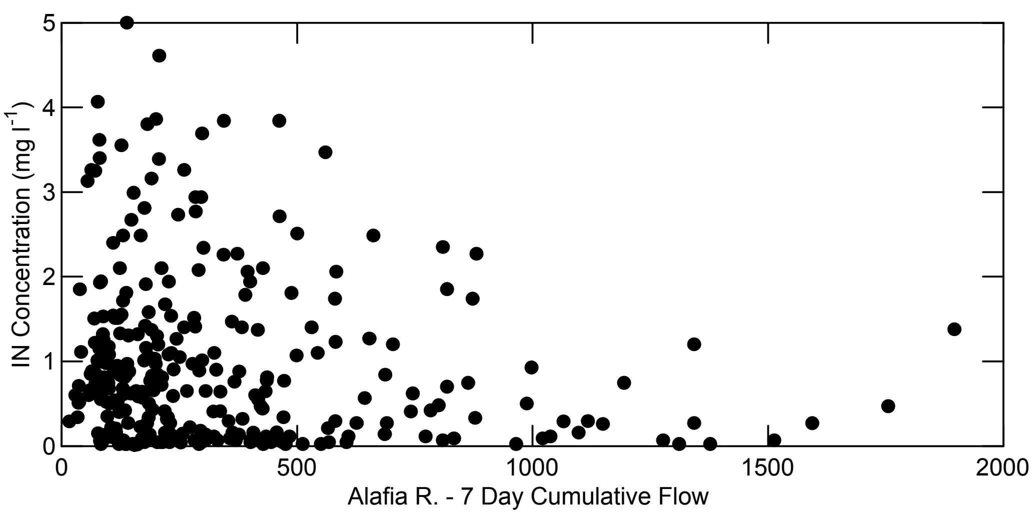

Figure 15. Inorganic nitrogen concentrations as a function of 7 day cumulative flows of the Alafia River

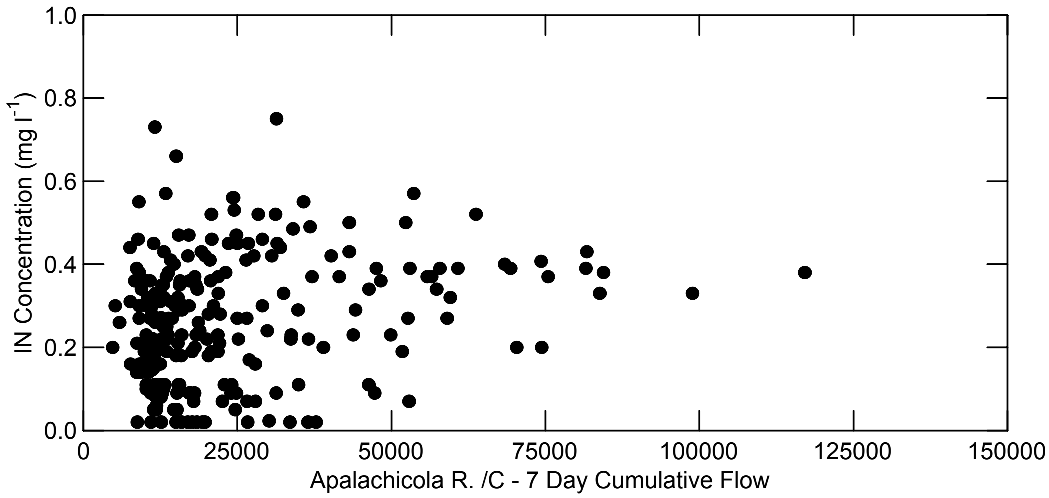

Figure 16. Inorganic nitrogen concentrations as a function of 7 day cumulative flows of the Apalachicola River at Chattahoochee, FL.

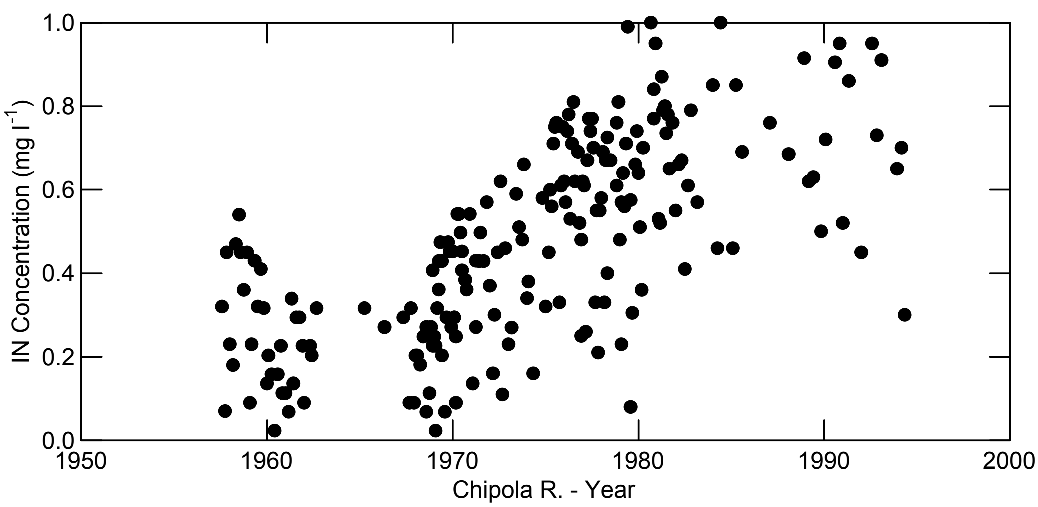

Figure 17. Trends in inorganic nitrogen concentration of the Chipola River between 1958 and 1995.

Atmospheric deposition data were obtained from nine National Atmospheric Deposition Program/National Trends Network sites **(Figure 18, Table 3)** from Mississippi through Florida (http://nadp.sws.uiuc.edu/) . Monthly loadings were computed as the sum of weekly loadings of inorganic nitrogen (ammonium and nitrate as N). Sampling effort for atmospheric loadings was generally temporally uniform, once stations began to operate. These data are subjected to intensive quality assurance measures that should be effective at removing instrumental or analytical errors. Similar to rainfall data, extreme values of loadings were retained for analysis, and any missing data replaced with a random selection of data from the same month in other years. Data normality was improved by a power transformation of 0.34. Some month to month variation was artificially introduced by computing calendar monthly totals from weekly data (i.e. some months with 4 weeks, some months with 5). The episodic nature of atmospheric deposition is expected to introduce much more variation than this summation effect. Two sites (FL03 and GA41) have the longest period of record, beginning collections in October, 1978. The remaining sites evaluated were operational by 1983. In order to include atmospheric deposition as an explanatory variable, time series analyses were repeated for both the 1979-1998 and 1983-1998 time periods.

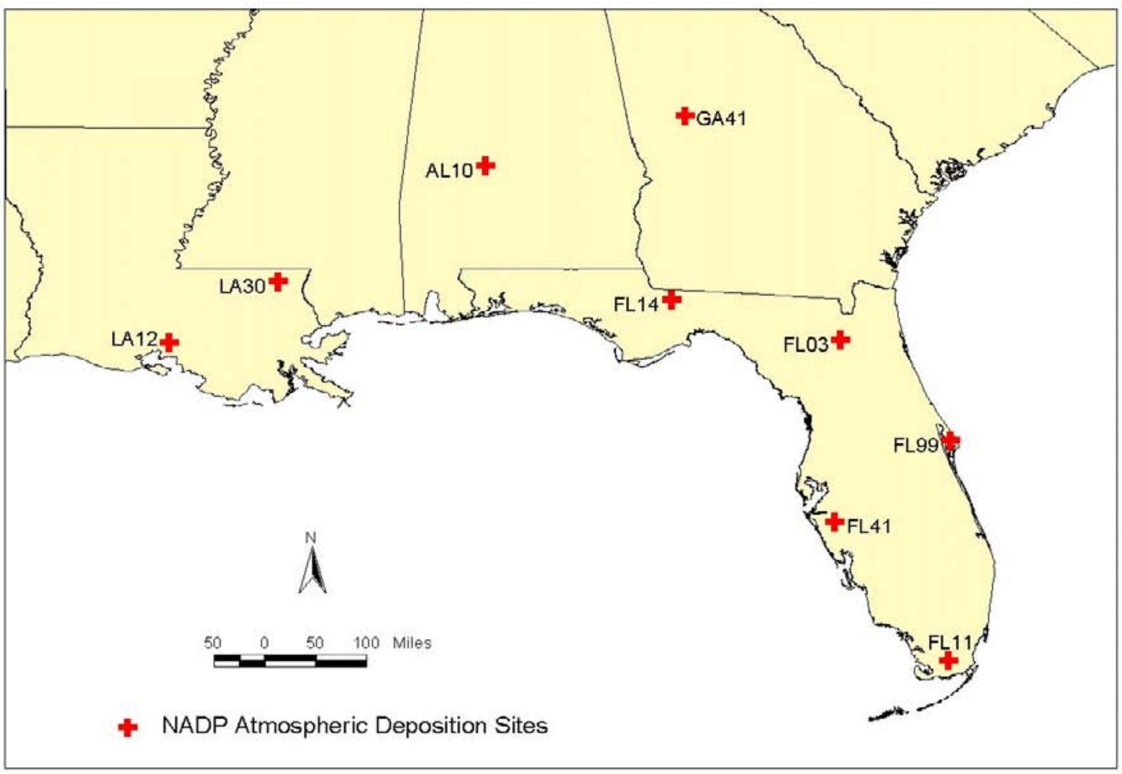

Figure 18. National Atmospheric Deposition/National Trend Network sites used for analysis.

Table 3. NADP Atmospheric Deposition Stations.

Site Number	Site ID	Name	County	Latitude	Longitude	Start Date	End Date
9	LA12	Iberia Research Station	Iberia	29.9297	-91.7153	11/16/82	Active
8	LA30	Southeast Research Station	Washington	30.8114	-90.1808	01/18/83	Active
7	AL10	Black Belt Substation	Dallas	32.4583	-87.2422	08/31/83	Active
6	GA41	Georgia Station	Pike	33.1778	-84.4061	10/03/78	Active
5	FL14	Quincy	Gadsden	30.5481	-84.6008	03/13/84	Active
4	FL99	Kennedy Space Center	Brevard	28.5428	-80.6444	08/02/83	Active
3	FL03	Bradford Forest	Bradford	29.9747	-82.1981	10/10/78	Active
2	FL41	Verna Well Field	Sarasota	27.3800	-82.2839	08/25/83	Active
1	FL11	Everglades National Park	Dade	25.3900	-80.6800	06/17/80	Active

Climatological indices were obtained from the Climate Prediction Center of NOAA (http://www.cpc.ncep.noaa.gov/data/indices). Indices represented a temporally uniform 'effort', with uncertainties incorporated from the data processing used to compute them. Depending on the degree of smoothing in the index, the records have a greater or lesser degree of month to month variation. The significance of a correlation analysis between monthly values and the mean of the adjacent months was used to select whether occasional missing data were replaced with interpolated means or with randomly selected monthly values. Indices were limited to those with at least monthly values and included the Pacific Decadal Oscillation with the sea surface temperature anomalies removed (PDO w/o SST anomaly), North Atlantic Oscillation (NAO), west Pacific pattern (WP), tropical SST anomalies, global mean SST anomalies, a global SST El Nino-Southern Oscillation (ENSO) index, Southern Oscillation Index (SOI) pressure differentials (Tahiti minus Darwin) and anomalies, and the Tropical Land Temperature Anomaly. Indices are illustrated in **Figures 19 and 20**.

Hurricane data as locations, wind speeds, and storm durations for 1998 were obtained from the National Hurricane Center (ftp://ftp.nhc.noaa.gov/pub/tracks) (Jarvinen, *et al.*, 1984) and added to data compiled from the same source by Dr.Todd Mitchell (http://tao.atmos.washington.edu/data_sets/tropical_cyclones). Position locations were reduced to one per day (at 0000 hours) with associated wind speeds **(Figure 21)**. Observations were truncated to the study area plus 1° of latitude or longitude on all boundaries. Daily hurricane position was used to assign a storm to one of the three geographic regions identified above for *K. brevis* counts. Boundaries for each region were expanded by 1° of latitude to the north and the south to capture edge effects of storms. Hurricane data since 1953 represented a relatively uniform effort with the advent of airborne reconnaissance and tracking in 1944. Hurricane parameters were collapsed by month and parameters computed included number of days of hurricane presence per month, and the mean and the sum of wind speed during those days, the square of wind speed, and duration of storm times the square of wind speed **(Figure 22).** In months with no data, parameters were set equal to zero. Similar to the *K. brevis* data, hurricane data were highly skewed and distributions were further distorted by large numbers of zero data. A duration parameter for the wind speed squared was computed, analogous to *K. brevis* durations, over 3, 6, 12, and 24 months, to improve normality of data distributions.

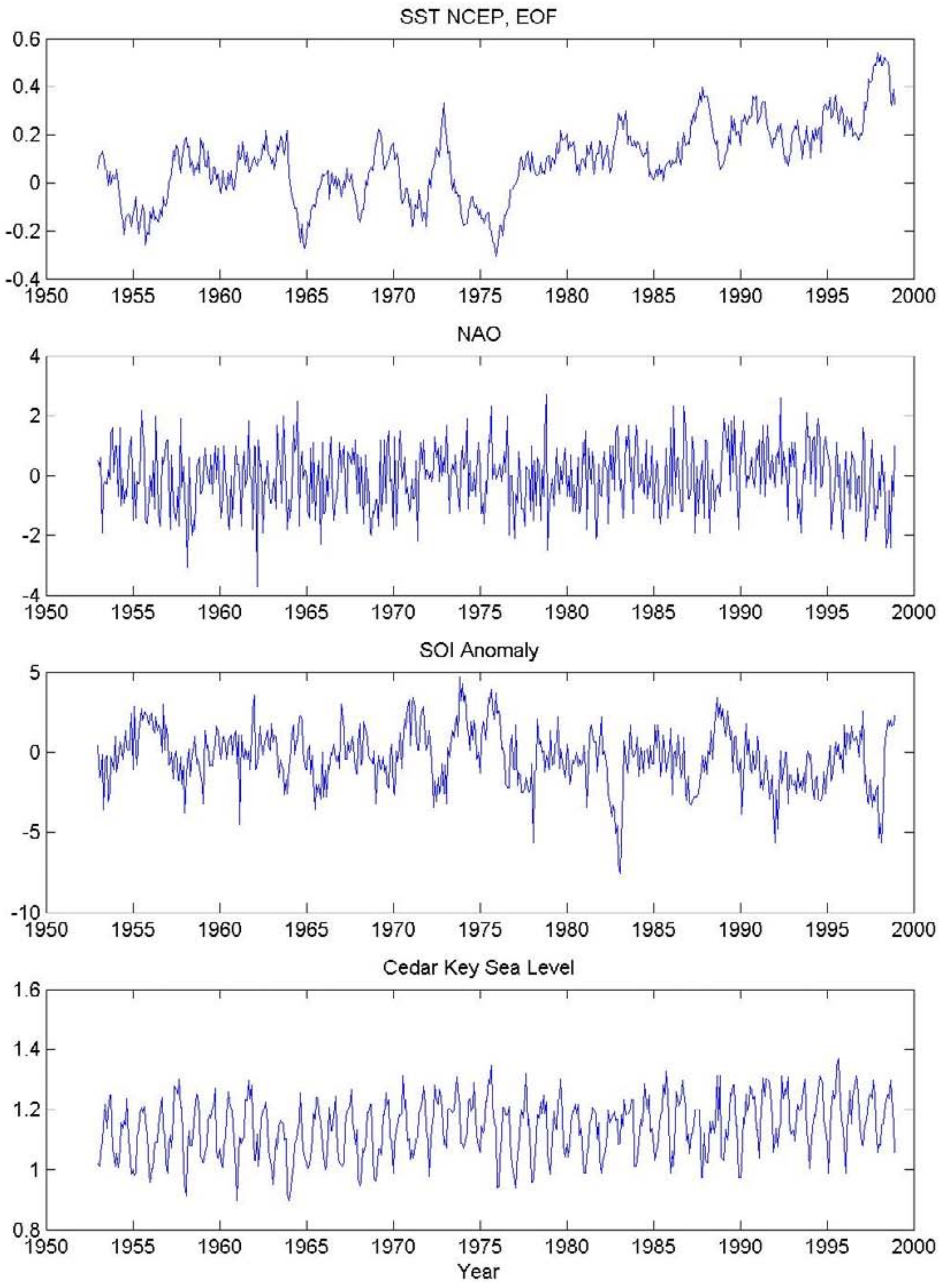

Figure 19. Selected climate indices evaluated with respect to *K. brevis* blooms.

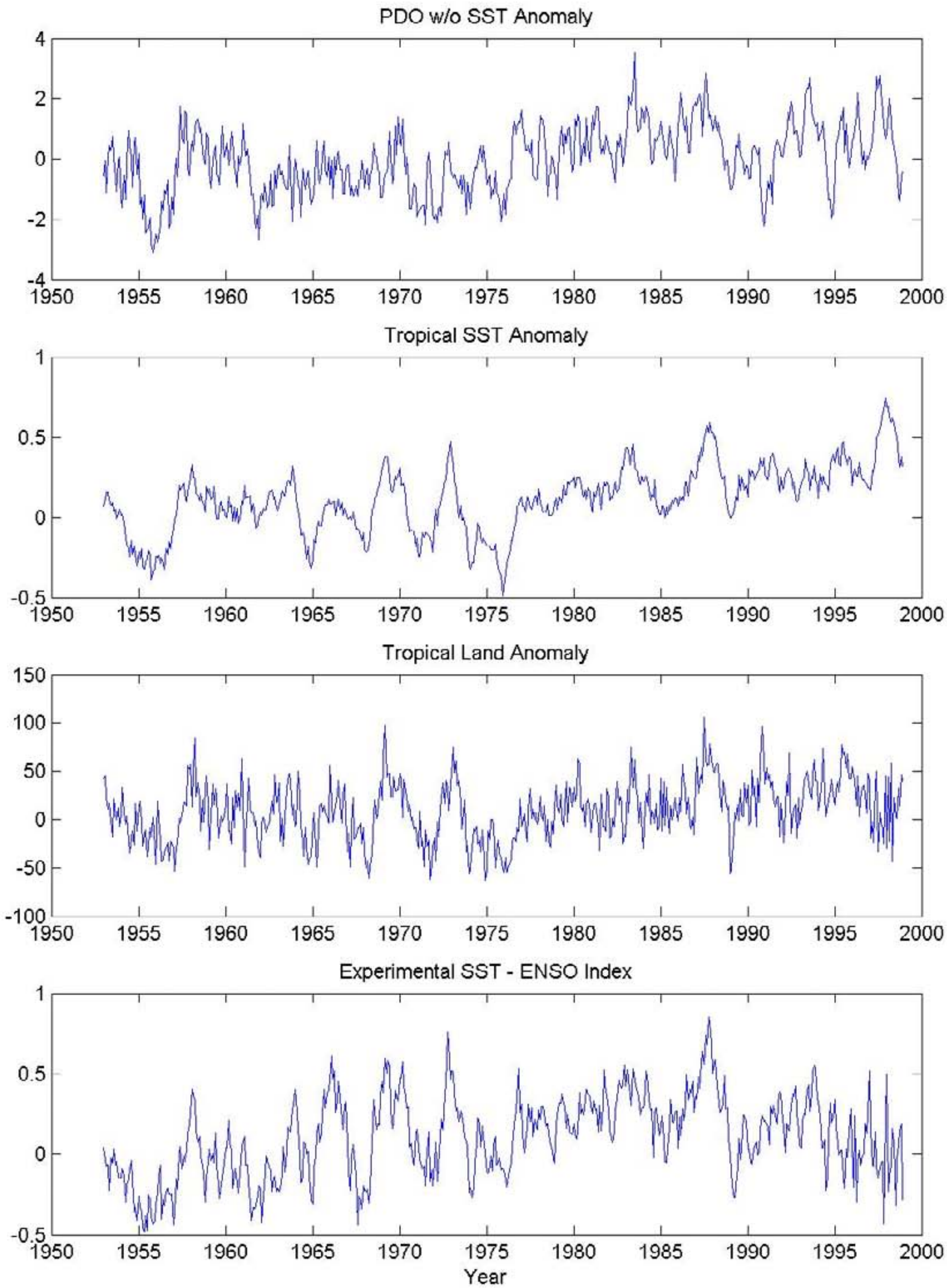

Figure 20. Additional climate indices and sea level record evaluated with respect to *K. brevis* blooms.

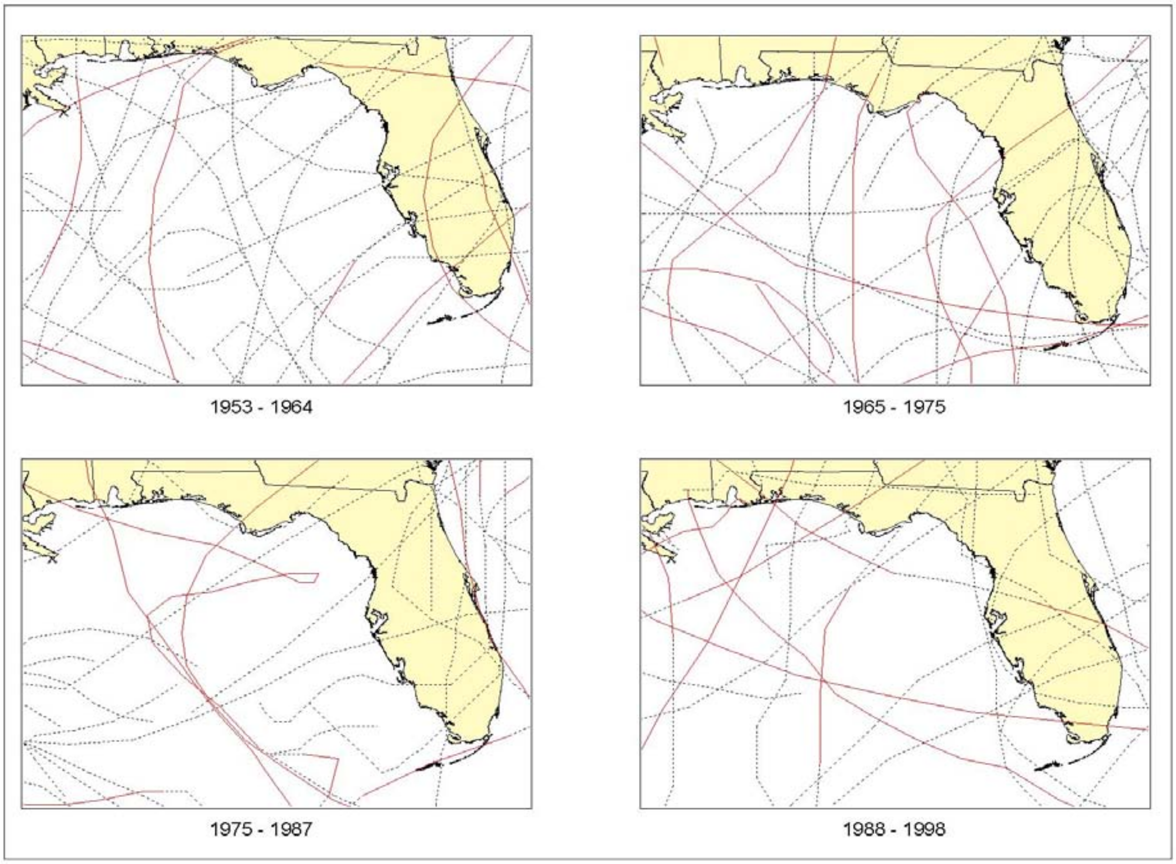

Figure 21. Tracks of named storms over the roughly four quarters of the study period. Solid red lines indicate winds of hurricane strength (>119 km hr^{-1}).

Auto- and cross-correlation analyses were used to examine relationships between *K. brevis* parameters and the preceding independent variables. The analysis compares *n* pairs of data from two time series [x(t) and y(t) at all t (time) values] and computes a correlation parameter analogous to the *r* value obtained from standard linear correlation between two variables. The parameters are then lagged relative to one another [x(t) and y(t+1) at all t where there is still an overlap] and the correlation parameter computed again. This process is repeated for all lags from t-(n-1) to t+(n-1) and the resulting group of correlations plotted as a function of lag period. The analysis provides information on the co-occurrence of two variables (cross-correlation), if they are in or out of phase with one another, whether the two variables have a common periodicity, whether increases in one parameter occurs prior to another, and whether a single variable has an underlying periodicity (auto-correlation).

The significance of the resulting auto- and cross-correlation values employed the use of N* (Chelton, 1983) to correct for the effects of serial correlation in the time series data sets. The value of N* is the effective degrees of freedom, and for cross-correlations, the method of cross-correlation at long lags indicating spurious or artificial correlation was used. In comparison to typical presentations of time series analyses, this represents a very conservative approach requiring a much higher correlation value before relationships are considered significant. This is demonstrated with a comparison between critical values computed with N* or with sample number, N. Both critical values are illustrated in subsequent graphs, with the smaller confidence intervals based on N, and the larger intervals based on N*.

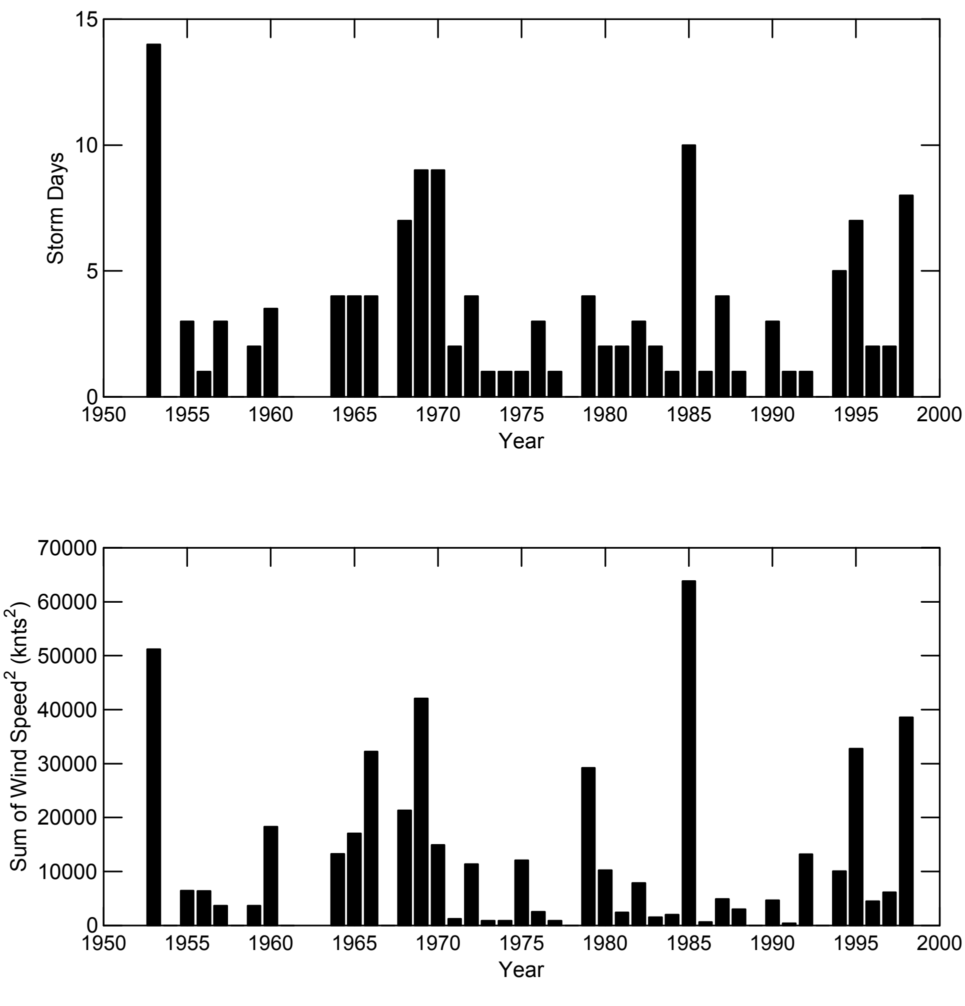

Figure 22. Annual totals of storm days and the sums of the squares of wind speeds for the entire study region.

RESULTS AND DISCUSSION:

Karenia brevis

Occurrences of red tides and sampling efforts were quite different between the three geographic regions (panhandle, central, and southwest). (When examining results, the presence of data as opposed to zero-padding for missing data should be kept in mind. Samples collected are indicated on **Figure 23**.

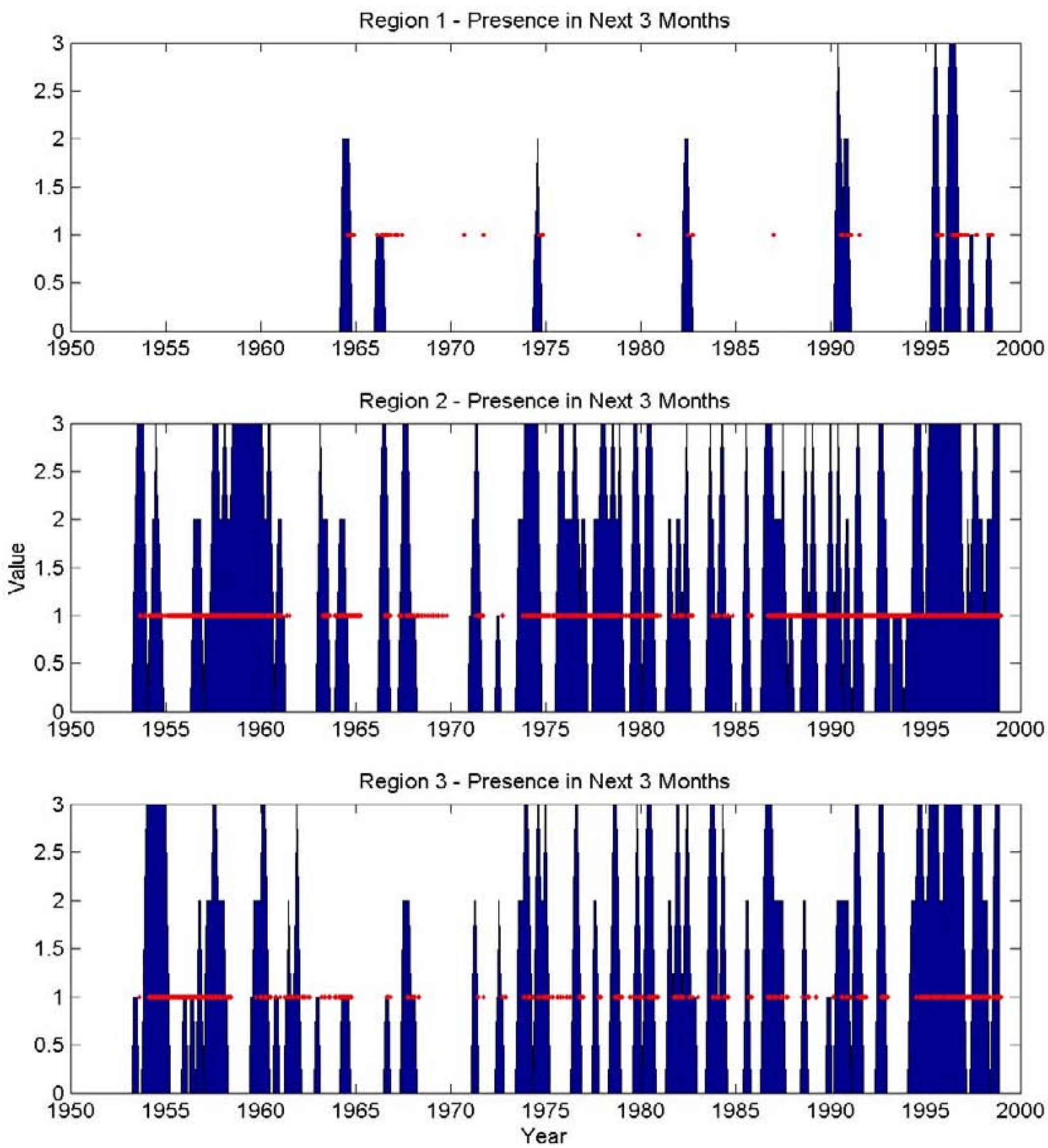

Figure 23. Regional distribution of the 3 month *K. brevis* duration parameter (see text). Red indicates months in which samples were collected.

It appears that sampling did not take place in Region 1 unless a bloom was identified. Frequency and durations were much higher in Region 2, followed by Region 3, and lastly by Region 1. The periods of 1956-1960 and 1994-1998 were marked by extended red tides in Region 2 and to a lesser extent in Region 3. The years of 1955, 1962, 1965, and 1969-70, were periods when *K. brevis* was absent for extended periods. In all but one case in 1966 (when blooms co-occurred), blooms in Region 1 have been preceded by blooms in Region 2 by a number of months, and may well represent advection of an existing bloom into an area, rather than a separate initiation event. Blooms in Region 3 either co-occur or lag blooms in Region 2 by a 1 month period, and argue for some combination of simultaneous initiation and advection. Use of the 24 month duration parameter smooths the potential effects of missing samples. The maximum duration in Region 1 was 11 months out of 24 months which occurred in 1995 (**Figure 24**).

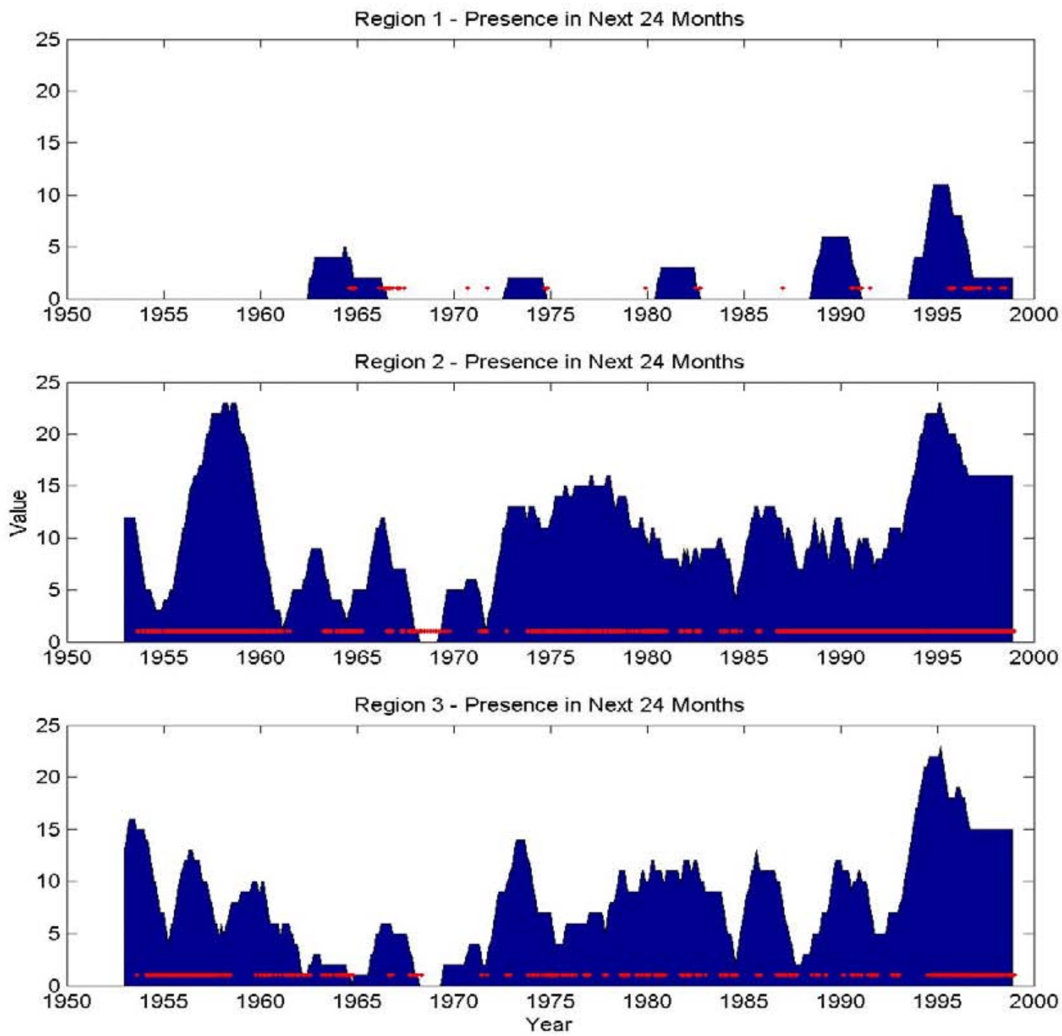

Figure 24. Regional distribution of the 24 month *K. brevis* duration parameter (see text). Red indicates months in which samples were collected.

In contrast in Region 2, there have been very few periods when *K. brevis* was not present during a given 24 month window. There have also been periods in 1958 and 1995 when *K. brevis* was present for a 24 month period. While 1969-1970 is noted as a period of low *K. brevis* occurrence for all regions, the only samples collected were in Region 2. The validity of the assumption that 'no sample' is equivalent to zero concentration of *K. brevis* can certainly be challenged, but other non-zero replacement techniques will produce spurious (false positive) results.

For each region, the *K. brevis* parameter which most approached normality proved to be the 24 month frequency, the number of months of the next 24 in which red tide was present. None of the *K. brevis* parameters, however, were stationary as to means or variances. In the last ~50 years, there have been three general periods when red tides were frequent, centered on 1956-60, 1974-1980, and 1994-1998. The presence of these periods, and transitions between, result in non-stationary parameters. Since the *K. brevis* presence was the dependent variable under investigation, it was felt inappropriate to detrend with breakpoints, although any monotonic trends were removed. The presence of non-monotonic trends will degrade the values of the auto- and cross-correlation functions, and reduce any ability to detect periodicity. Even without significance, however, the functions will be useful for indicating parameter relationships.

Auto-correlation analysis of breve durations resulted in slight, but non-significant (adjusted for N*) auto-correlation coefficients in Region 2 at approximately 12 and 24 months with declining values at greater lags (**Figure 25**). Region 3 observed non-significant local maxima in the correlation function at 24, 38, and 46-47 months, with an even smaller feature at 13 months (**Figures 26**). These features were less prevalent in the longer duration parameters. The longer lags indicates that the *K. brevis* blooms are a recurrent phenomenon, but one for which the annual signal varies from year to year. Annual cycles are more prevalent in Region 2 than in Region 3. The duration parameters all had a very low N* (between 4 and 41, compared to 552 data points), a result of increasing serial correlation by performing what is in essence a running average.

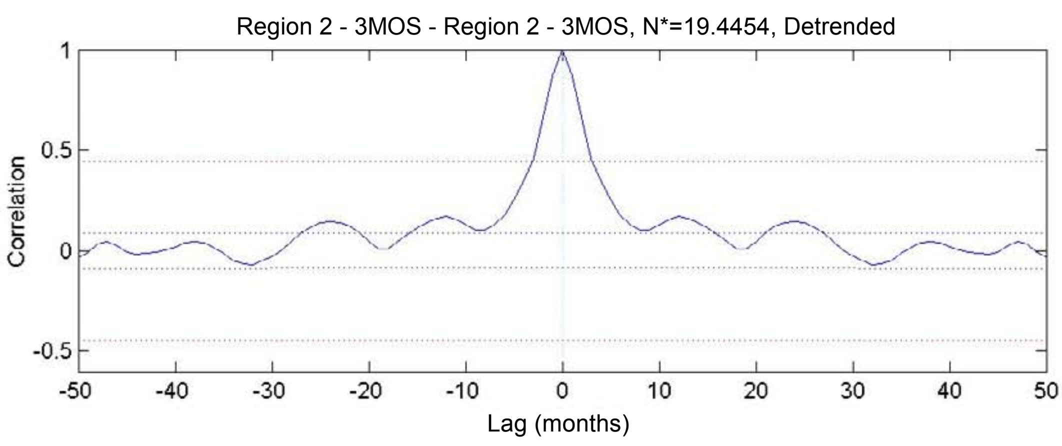

Figure 25. Auto-correlation of the 3 month *K. brevis* duration parameter in Region 2 demonstrating imperfect seasonality. Monotonic trend has been removed. Confidence intervals are based on N (blue, inner) and N* (red, outer) after adjusting for serial correlation.

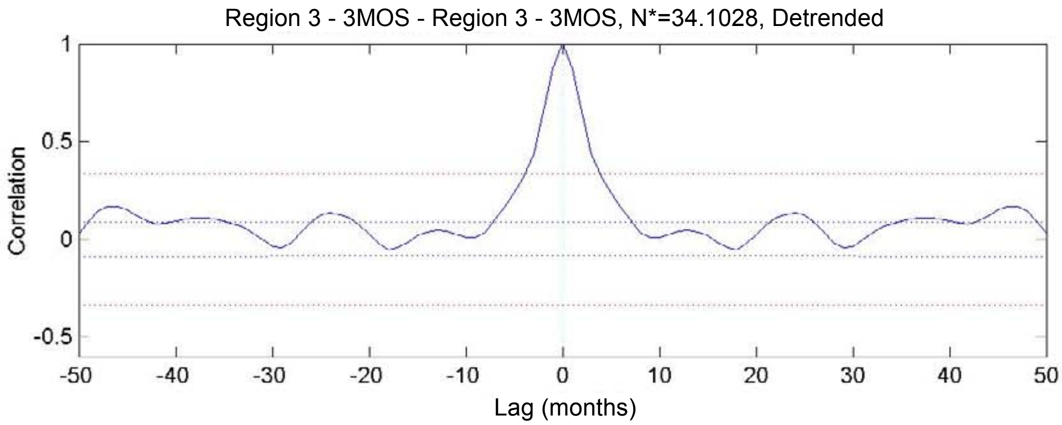

Figure 26. Auto-correlation of the 3 month *K. brevis* duration parameter in Region 3 demonstrating imperfect seasonality. Monotonic trend has been removed. Confidence intervals are based on N (blue, inner) and N* (red, outer) after adjusting for serial correlation.

Rainfall

Transformed rainfall data as well as deseasonalized data were generally stationary for both means and variances. Of the 41 stations, a climatological boundary in the middle of the state separated panhandle stations from the southern Florida stations. Based on auto- and cross-correlations, northern sites experience a roughly semi-annual cycle of rainfall, with precipitation originating from winter cold fronts and summer convective rainfall. While not significant once serial correlation is accounted for, lags of 6, 12, 18, etc. months display positive correlations of northern stations with themselves and with other northern stations. The only significant relationships between the northern stations are at lag=0, i.e. annual cycles of rainfall have neither the amplitude nor the reproducibility to generate significant relationships at alternate lag periods **(Figure 27**). This is a demonstration of the highly conservative approach of adjusting for serial correlation. Southern sites express a dominant 12 month cycle in which significant correlations both between and within sites appears at 0, 12, 24, and 36 month lags **(Figure 28).** Cross-correlations are significant from Pensacola to all but Key West at lag=0, indicating that periods of maximum rainfall are in phase throughout most of the state, despite the differing rainfall provinces.

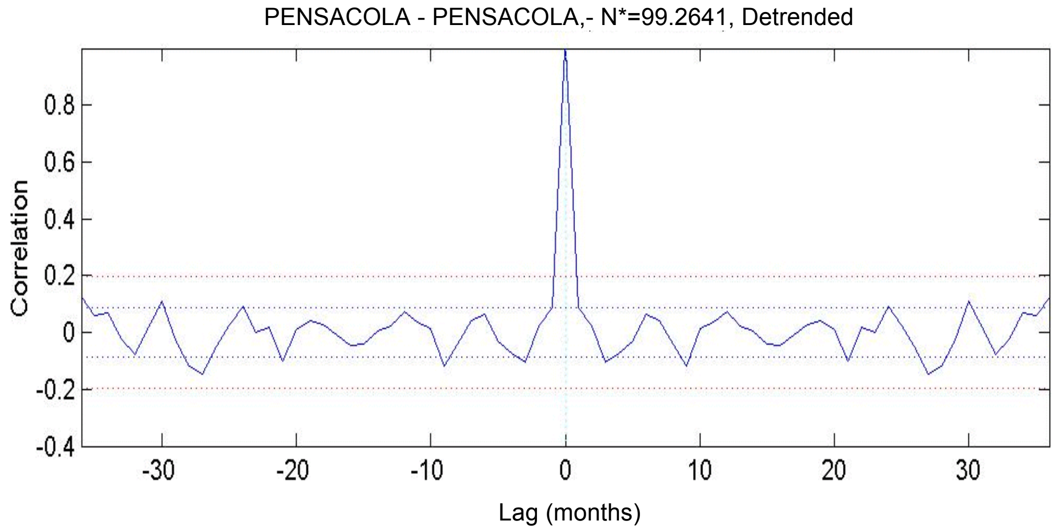

Figure 27. Auto-correlation of rainfall at Pensacola demonstrating the 6 month cycle of rainfall for stations in the northern portion of the state. Confidence intervals are based on N (blue, inner) and N* (red, outer) after adjusting for serial correlation.

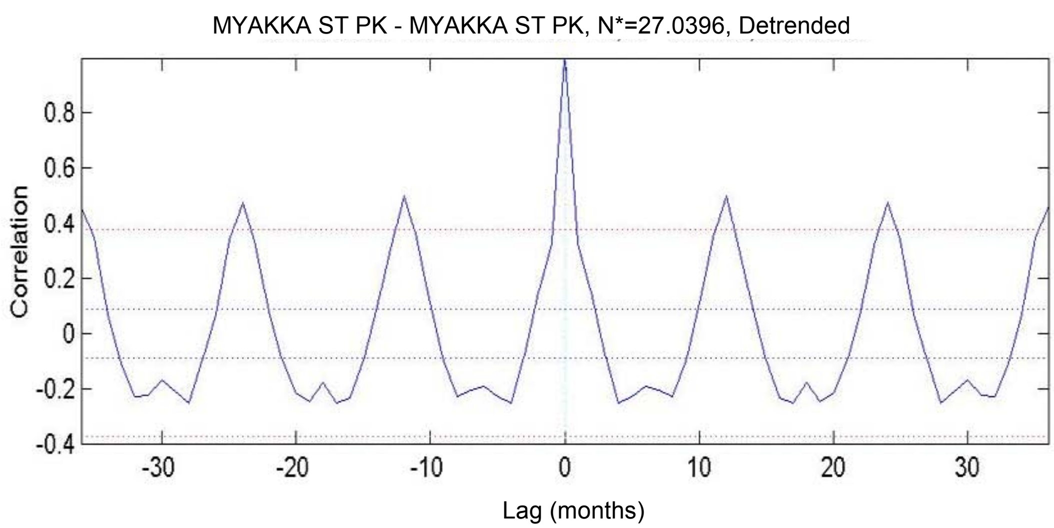

Figure 28. Auto-correlation of rainfall at Myakka River State Park demonstrating the 12 month cycle of rainfall for stations in the central and southern portion of the state. Confidence intervals are based on N (blue, inner) and N* (red, outer) after adjusting for serial correlation.

Auto- and cross-correlation of the deseasonalized rainfall (rainfall anomalies), were significantly correlated at lag=0, with the level of significance declining with increasing distance between stations. Anomalies persisted roughly state-wide, however, with the excess rainfall in Pensacola significantly correlated with the anomalies at all other rainfall stations with the exception of Arcadia, Naples, Everglades, and Key West. The anomaly at Bradenton was significantly correlated with anomalies at all other stations, from Pensacola to Key West. While there is regional coherence in rainfall patterns, the climatic factors which produce rainfall anomalies tend to affect the entire state. As evidenced by this data set, however, the anomalies have no dominant periodicity in any region of the state, and correlations rapidly decay to non-significance at lags other than zero.

To investigate the linkages between *K. brevis* occurrence and rainfall, cross-correlations of the various duration parameters with all rainfall stations were performed. Two of the individual results appear in **Figure 29** for Region 2. Confidence intervals based on N and N* (adjusted for serial correlation) are also plotted. The cross-correlation function was then normalized to the upper confidence interval based on N*, such that significant values were then greater than or equal to one. Rainfall stations were then 'stacked' or ordered from the north, down the coastal watersheds to Bradenton, then to the interior of the state (Inverness), and south through the Peace River watershed, through Venice, and south to the Keys. The normalized significance results were color coded, with black for values greater than or equal to 1.0 (significant), and plotted as in **Figure 30.**

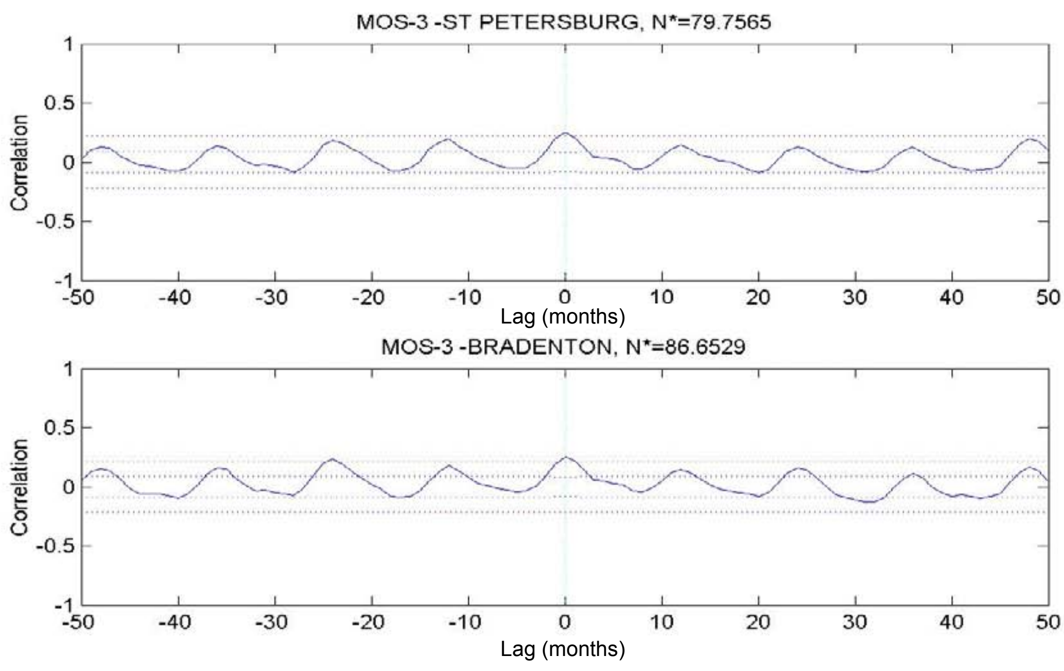

Figure 29. Two examples of cross-correlation functions between the 3 month *K. brevis* duration parameter and rainfall. Confidence intervals are based on N (blue, inner) and N* (red, outer) after adjusting for serial correlation.

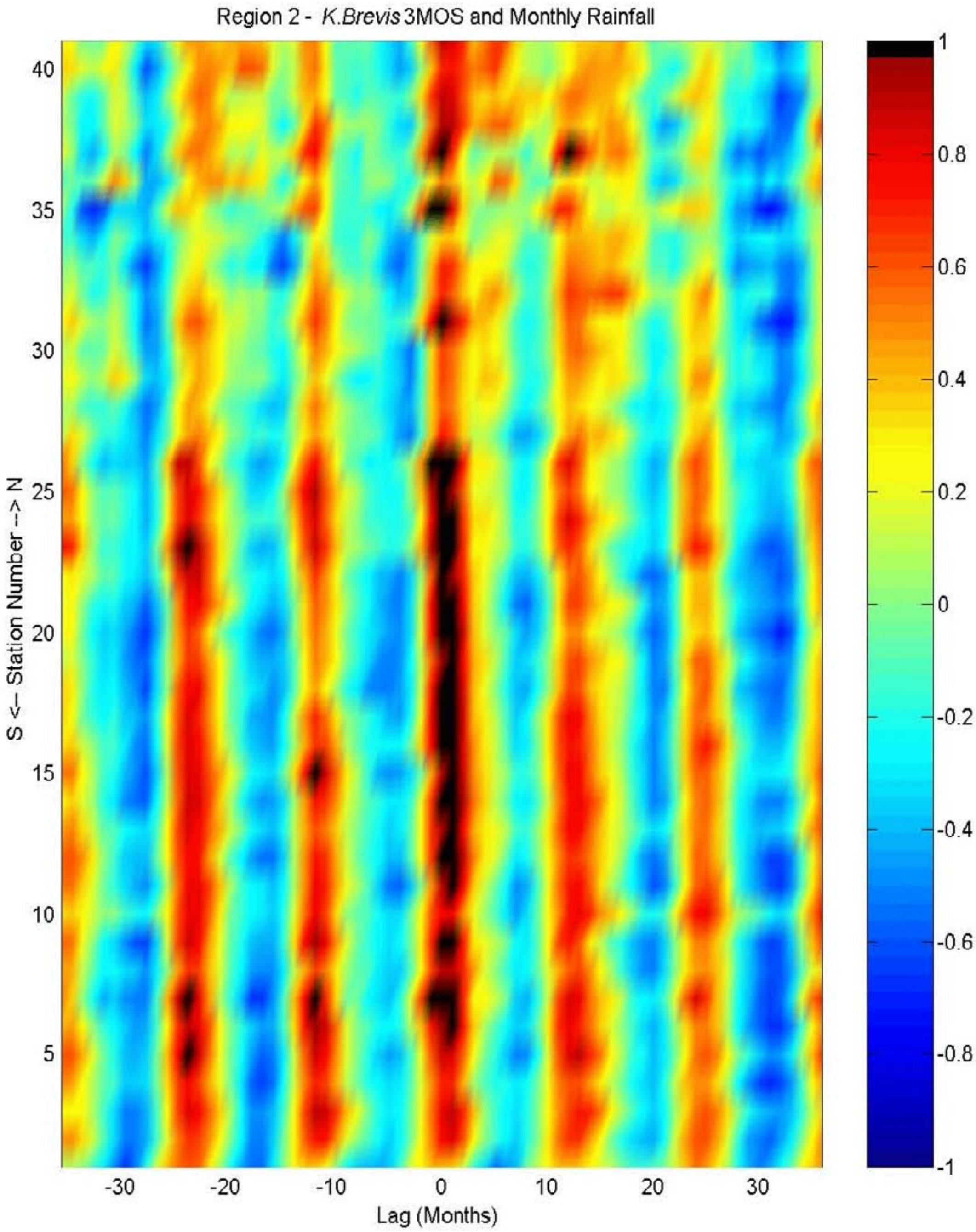

Figure 30. Compilation of normalized cross-correlation functions of the 3 month *K. brevis* duration parameter in Region 2 against all rainfall stations. Stations are roughly ordered from north (41) to south (1). Significant positive correlations appear in black.

The figure is interpreted to mean that the presence of *K. brevis* over the next three months in Region 2 is significantly correlated with rainfall amounts received in a given month, with the best agreement between *K. brevis* and rainfall at stations between Tarpon Springs (Station 26) and Punta Gorda (Station 6; **Figure 31**). When rainfall data are offset from *K. brevis* data by +12 or -12 months, then the two variables are again positively correlated, but generally not significantly so, reflecting the imperfect seasonality of red tide occurrences and, to a lesser extent, rainfall. Looking at the lags, significance was present in any from -1 to +2 months. Recalling the phase offset induced by computation of the *K. brevis* duration parameter, this result is equivalent to the monthly rainfall leading the actual incidence of *K. brevis* by 0 to 3 months. A similar plot using the 6 month and longer duration parameters reveals little additional insight, except to note that lags are somewhat longer and correspond to a relatively rapid response (or strong connection via a third parameter) between rainfall and *K. brevis* occurrences.

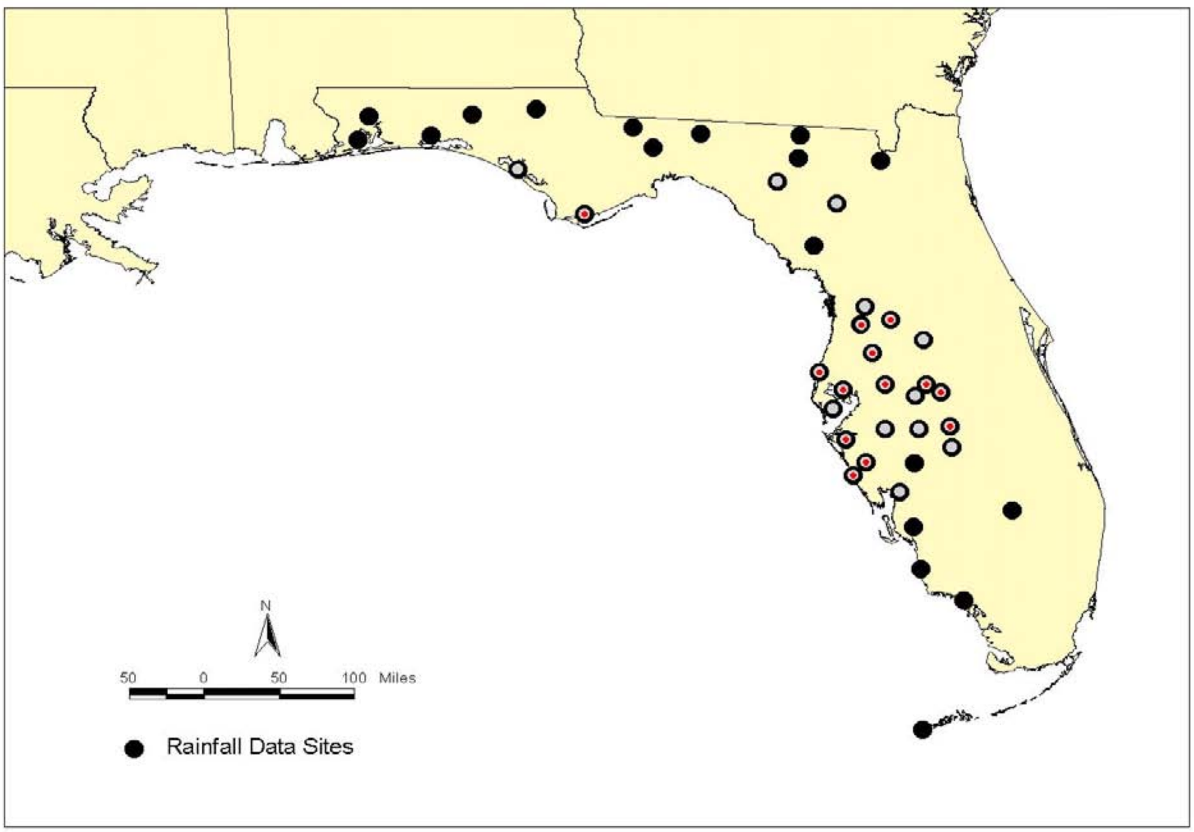

Figure 31. Rainfall stations which exhibited significant correlations with the 3 month *K. brevis* duration parameter in Region 2. Black dot - no significance. Black/grey dots - significant for a one month period. Black/grey/red dots - significant for a two month period.

A similar analysis of 3 month duration of *K. brevis* against rainfall anomalies **(Figure 32)** resulted in few significant results (Tarpon Springs rainfall at lag=0) but very suggestive patterns. *K. brevis* durations in Region 2 were positively correlated (although not significantly) with rainfall anomalies in the central portion of the state and with a few of the panhandle stations. Positive correlations for *K. brevis* durations also extended for lag periods of up to 10 months. Re-stated: following a rainfall anomaly, *K. brevis* persisted for up to 10 months.

The behavior of *K. brevis* with respect to rainfall and rainfall anomalies in all three regions appears in **Figure 33** and **Figure 34,** respectively, where the central panel of each duplicates that shown in **Figures 30** and **32** above. There were no significant results for Region 1. The slight seasonal pattern of correlation with rainfall at southern stations was not apparent for the northern stations, despite their proximity, indicating that rainfall alone does not control the incidence of red tides in the panhandle region. In Region 3 to the south, correlation with northern rainfall stations was poor, as might be expected. Significant correlations were present at lag=0 for both Venice and Avon Park rainfall. Positive, although non-significant, correlations with rainfall were present from the Tampa Bay area to the south. It would appear that *K. brevis* occurrence in Region 2 is strongly linked to rainfall in the central and southern portions of the state. Region 3 occurrences are generally not significantly linked to rainfall, but follow a similar pattern to Region 2. Region 1 red tides are not correlated with rainfall from nearby stations, but have a non-significant positive correlation with southern rainfall stations. Given the typical direction of Loop Current flow in the Gulf of Mexico, one would clearly not expect rainfall in south Florida to generate red tides in north Florida waters, but some third factor may well control both phenomena.

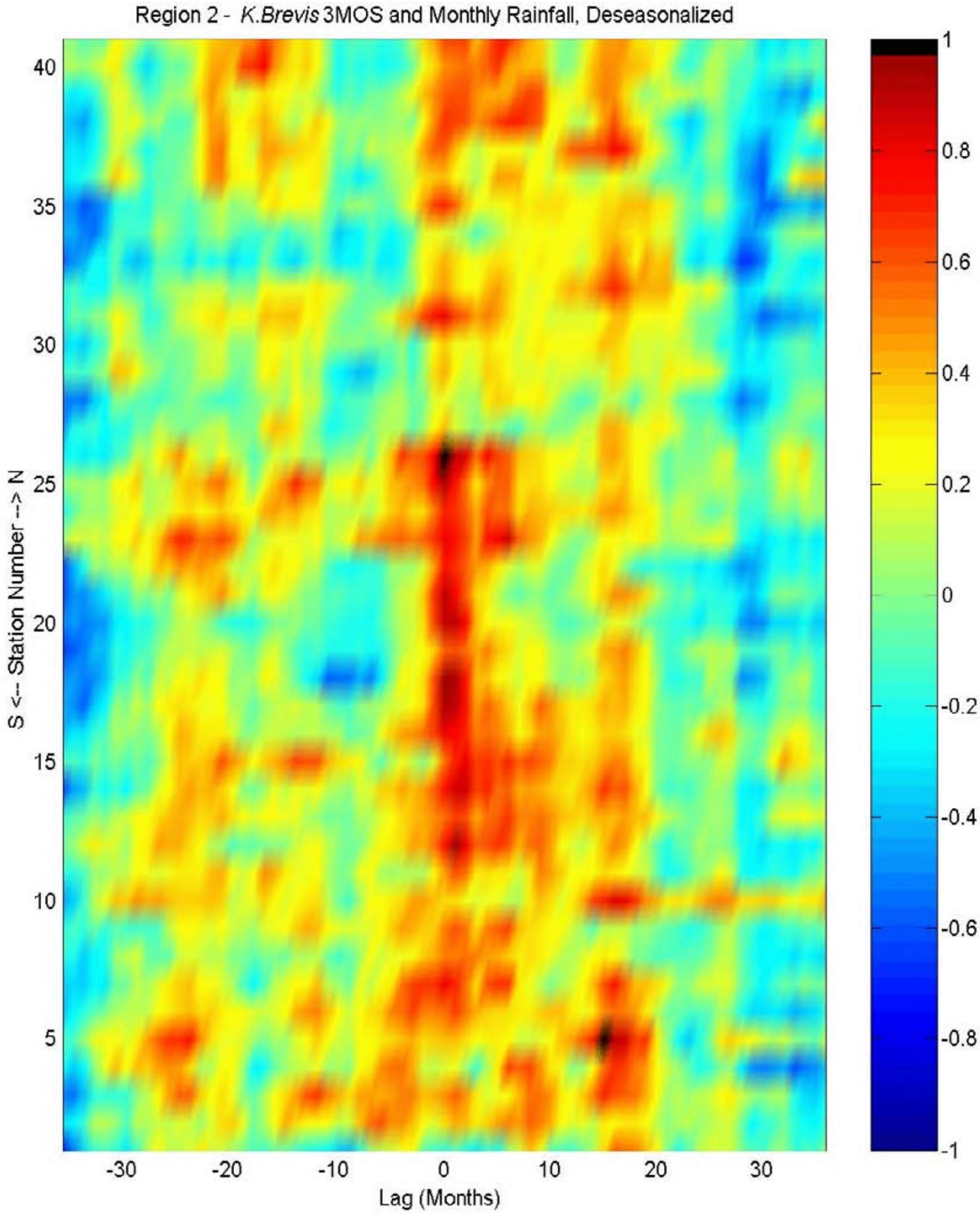

Figure 32. Compilation of normalized cross-correlation functions of the 3 month *K. brevis* duration parameter in Region 2 against rainfall anomalies of all stations. Stations are roughly ordered from north (41) to south (1). Significant positive correlations appear in black.

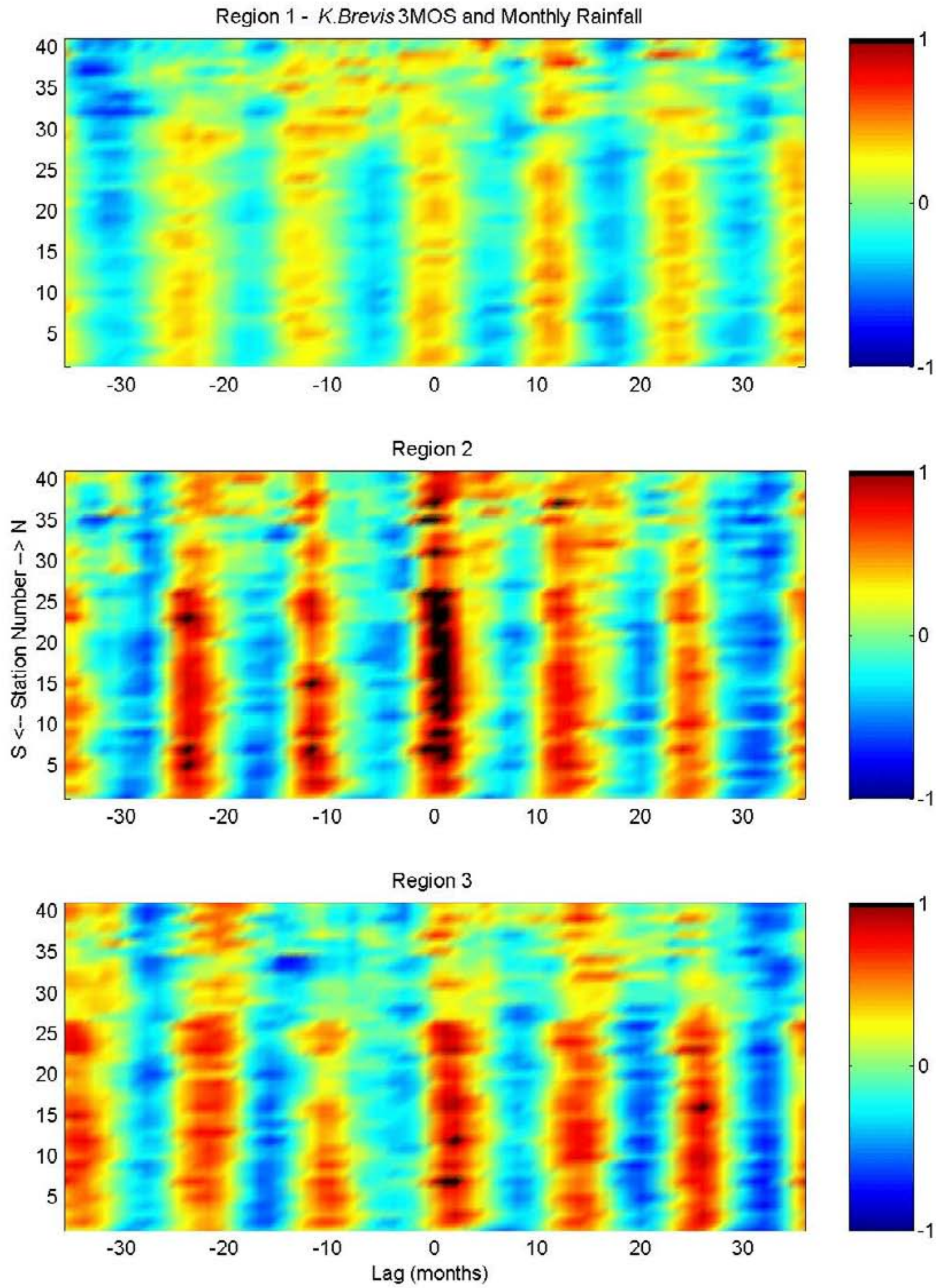

Figure 33. Compiled normalized cross-correlations of the 3 month *K. brevis* duration parameter in Regions 1, 2, and 3 against rainfall.

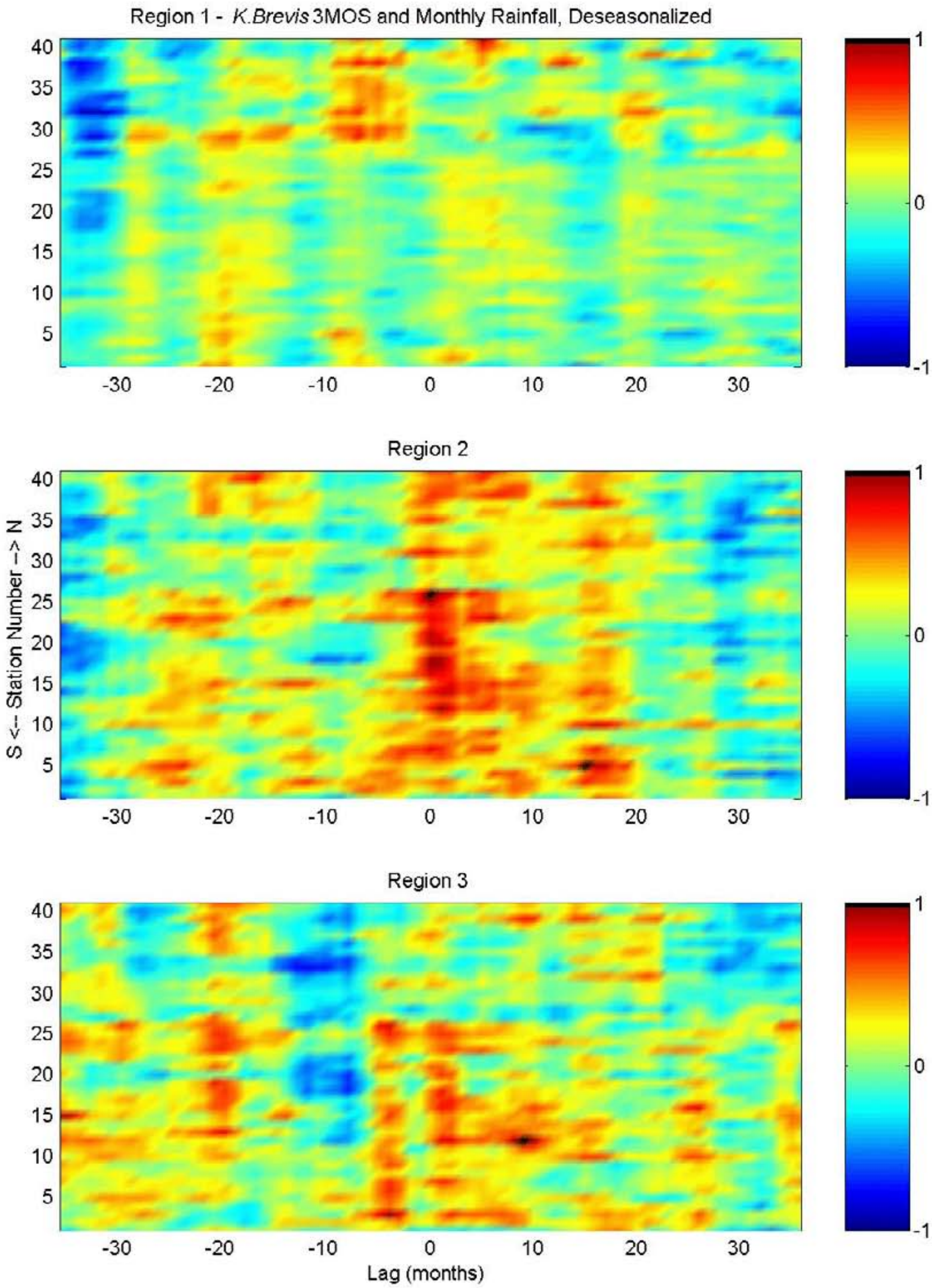

Figure 34. Compiled normalized cross-correlations of the 3 month *K. brevis* duration parameter in Regions 1, 2, and 3 against rainfall anomalies.

Rainfall anomalies display a less clear pattern and with the exception of rainfall at Tarpon Springs at lag=0, there are no other significant correlations with *K. brevis* occurrence. The most positive (although non-significant) correlation, however, is still for rainfall anomalies received in the interior and coastal portions of central Florida.. If causal, the effects are relatively immediate in that the highest correlation is generally at lag=0. (Or recalling the phase shift induced by the *K. brevis* parameter, approximately one month following the rainfall anomaly.) For Region 3, there are again few significant results, but higher positive correlations occur at one to two month lags (*K. brevis* occurring after the rainfall anomaly) and may indicate advection of a bloom which initiates in Region 3. There is also a positive, although again non-significant, correlation in which *K. brevis* leads the rainfall anomaly at central and southern stations by approximately four months. There is presently no rational, mechanistic explanation for this pattern and it may be simply an artifact of the distribution of *K. brevis* occurrences in Region 3.

Little additional information arose from examining either the *K. brevis* parameters of increasing duration, or as a function of increasing accumulation periods of rainfall **(Figure 35)**. One point to note would be that as the rainfall accumulations increase (monthly rainfall, 3, 6, 12, and 24 months), the area of significance or highest non-significant correlation phase shifts to the left, i.e. at first glance, *K. brevis* occurrences appear to be leading the rainfall. The rainfall parameter, however, is computed from the rainfall for the prior *n* months, and if *K. brevis* is responding relatively immediately to rainfall amounts then it will appear to lead the longer cumulative rainfall parameters. The longer periods of rainfall accumulation act to remove seasonality from rainfall records and by reducing the variance, produce lower correlation values.

Riverine Flow

Transformed flow data, like rainfall, were approximately normal, with deseasonalized flow data or flow anomalies even more so. Few stations, however, could be considered stationary as long term climatic cycles, hydrological alterations, and land use changes interact to affect watershed yields. The 1950's represented a period of very low flow in the panhandle rivers, with low flows again observed in the late 1960's. Following high discharges in ~ 1975, flows were more stable between 1980-1998, with some stations reporting increases in the late 1990's. The Apalachicola and Suwannee systems, with similar low flows in the 1950's, have been more variable over time. For some central Florida rivers (the Withlacoochee, Hillsborough, Alafia, and Peace) high flows near 1960 have declined until the early 1990's, then have increased rapidly. The Little Manatee, Myakka River, and Horse Creek have also declined, with a steady reduction in variance as well, until approximately 1975, then have increased steadily. Variation in flows has been such that while auto- and cross-correlations of flows show regular fluctuations at lags of 12 month intervals, few other than at lag=0 are significant.

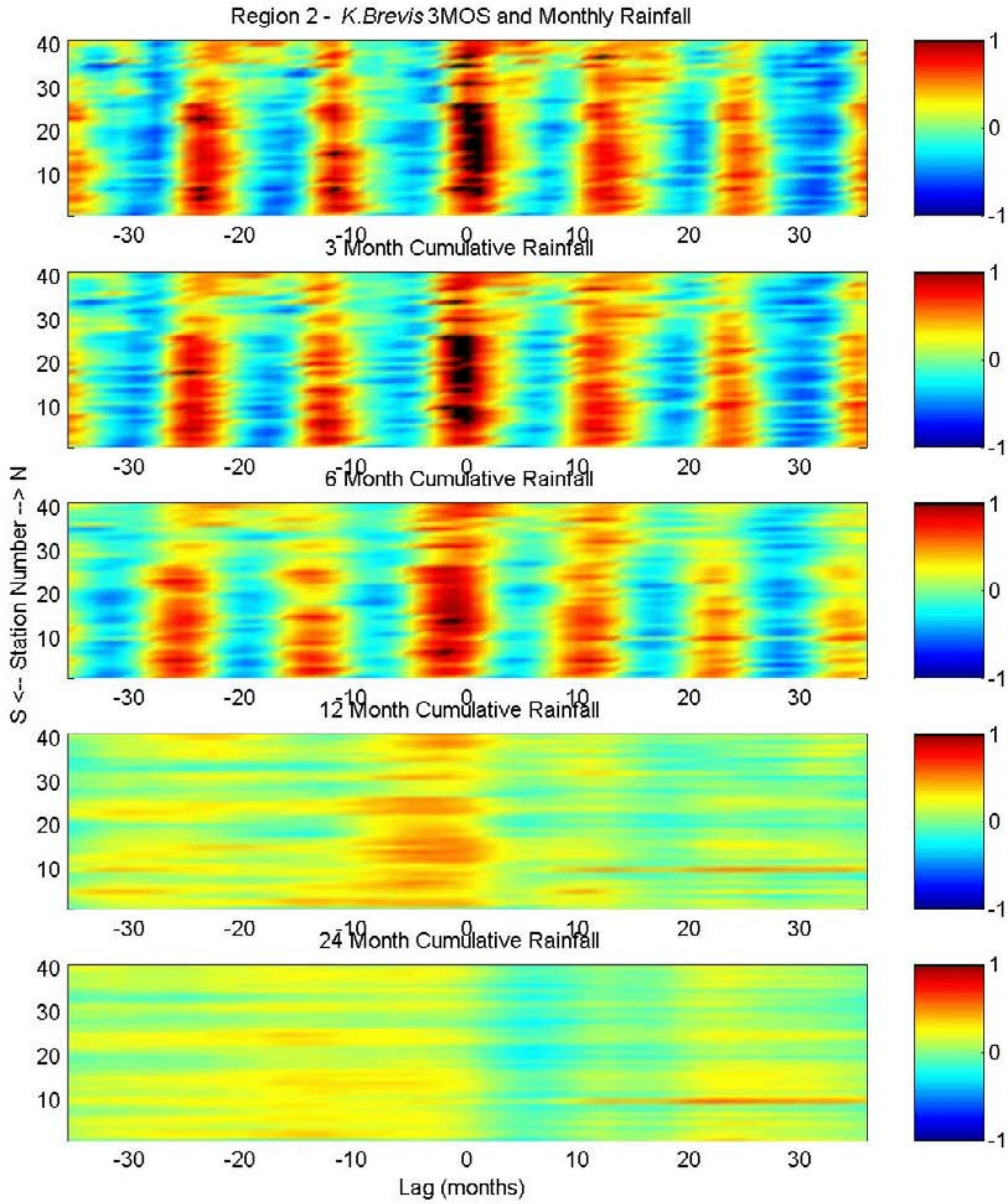

Figure 35. Results of cross-correlations between *K. brevis* duration and increasing periods of cumulative rainfall.

The Florida rivers examined in this study, like rainfall stations, can be placed into two climatological provinces. The northern rivers experience maximum flows in March-April and flow minima in September-October. Much of the flow from these systems originates from outside Florida and total flows are up to an order of magnitude larger in total discharge than many of the central and southern rivers (**Figure 36**). At the Withlacoochee and to the south, however, the pattern of flows alter such that the southern rivers experience flow minima in the Spring dry season (April-May) and maxima during the late summer wet season (August-October). As a result, flow maxima of the two groups of rivers are approximately 6 months offset.

In a similar investigation to that described above for rainfall, cross-correlations of the various *K. brevis* duration parameters were performed against riverine flow both using monthly flow values and increasing periods of flow accumulation (3, 6, 12, and 24 months). As for rainfall, either increased duration parameters or increased flow accumulation periods smoothed the record such that no correlations of significance emerged. The 3 month *K. brevis* duration against monthly flows appears in **Figure 37)**. Examining Region 2 first, flows in a number of rivers are significantly correlated with *K. brevis* 3 month durations. In general, *K. brevis* maxima lag flow maxima in the northern rivers by approximately 6 months and are correlated at lag=0 for the central and southern rivers. Rivers with significant correlations include the Yellow, Choctawhatchee, Chipola, Hillsborough, Little Manatee, Myakka, Peace River at Zolfo Springs and at Arcadia, Horse Creek and Joshua Creek.

The meaning of the long lags for flow from northern rivers, can initially be rationalized as a product of the differing flow regimes between north and south and a lack of direct causality between flows and *K. brevis*. The significance, however, is not symmetrical about lag=0, and higher values are obtained when *K. brevis* lags flow (rather than when *K. brevis* leads flow). Estimated net travel times between the mouths of northern rivers and Region 2 would be less than 0.03 m sec^{-1} if flows were directly influencing *K. brevis* in Region 2. Additionally, although results are not significant, Region 1 *K. brevis* lags flows by northern rivers by approximately 3 months, a result which can be rationalized as flows (and nutrient loads) during the winter occur at non-optimum temperatures, and that coastal waters need to warm before blooms can progress. As might be expected, flows in southern rivers have low correlations with *K. brevis* in Region 1. Region 3 displays a complementary pattern in that *K. brevis* is significantly correlated only with the southern rivers (Hillsborough, and Peace River at Zolfo Springs and Arcadia). Relationships with the northern rivers are non-significant, with local maxima at lags of *K. brevis* of approximately 6 months.

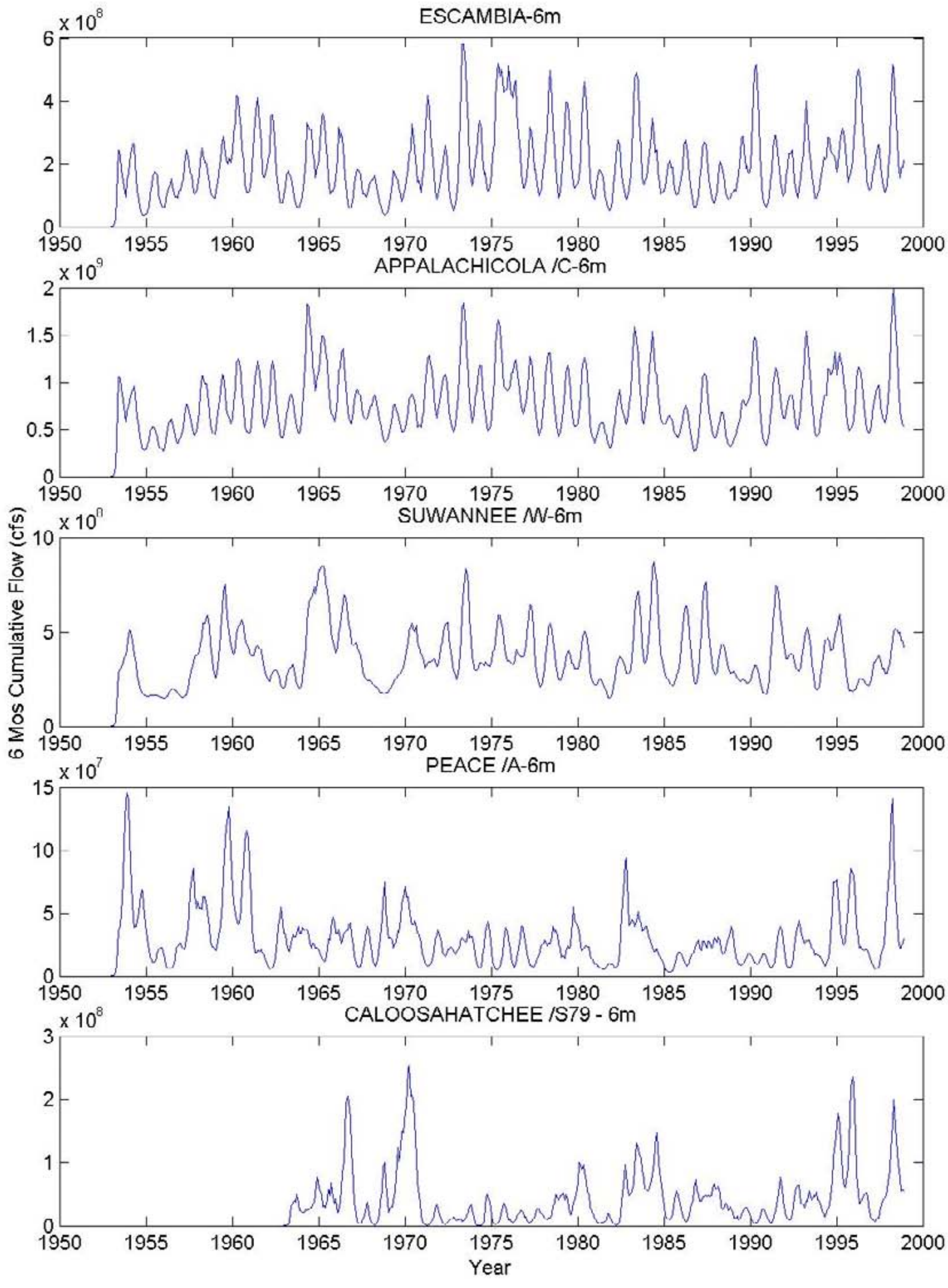

Figure 36. Flows (as 6 month cumulative values) of selected rivers in Florida.

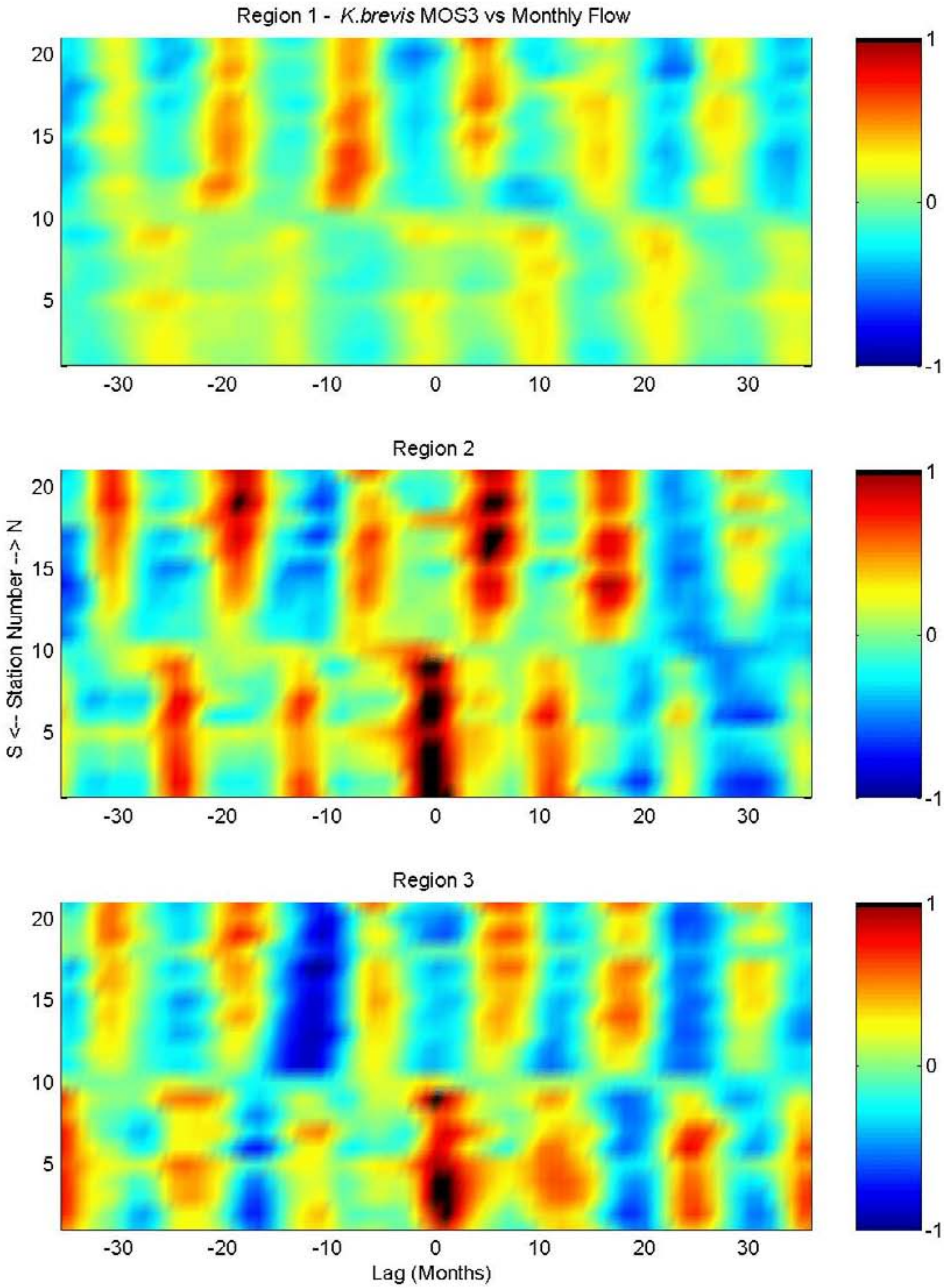

Figure 37. Compiled normalized cross-correlations of the 3 month *K. brevis* parameter in Regions 1, 2, and 3 against monthly mean riverine flows. Rivers are roughly ordered from north (21) to south (1), and do not include the Caloosahatchee River.

Cross-correlation of *K. brevis* with flow anomalies **(Figure 38**) present a more coherent pattern, although with no results of statistical significance. In Region 1, *K. brevis* lags selected northern rivers (Apalachicola and Choctawhatchee Rivers) by 3 to 10 months, with little relationship to any rivers further south. In Region 2, *K. brevis* lags selected northern rivers by 0 to 10 months, and has positive correlations at lag=0 with flow in all rivers to the south of the Withlacoochee River. For Region 3, *K. brevis* has little relationship to northen river flow, and was positively correlated at lags from 0 to 10 months with most of the southern rivers.

The Caloosahatchee River was also of interest with regard to riverine flows and *K. brevis*. Data from this system were only available since 1963, and so cross-correlation analyses were repeated with a subset of the *K. brevis* duration parameters. No significant results were obtained for any of the cumulative flows, deseasonalized flows, or any of the duration parameters. Positive (although non-significant) correlations were present for Regions II and III at lags of 0 and 12 months. Patterns did not contradict any flow relationships discussed above, but did not provide substantive new information.

Atmospheric Deposition

Data for atmospheric deposition of inorganic nitrogen in rainfall were available from 1978-1998 for two stations (north central Florida and Georgia). The period of record for the remaining stations in the region began in 1983 **(Figure 39)**.

Monthly and deseasonalized data were generally normal and stationary as to means and variances. Atmospheric loadings were, on average, greater in Georgia than in Florida **(Figure 40)**. Cross-correlations analyses were conducted on two subsets of the *K. brevis* duration parameters, matching the appropriate time periods. Perhaps due in part to the abbreviated record, no significant correlations were observed between the *K. brevis* parameters and the 1978–1998 data set. The only instructive pattern was for *K. brevis* in Region 2, in that more positive (although non-significant) relationships at lag=0 were present for the long term Florida site than the Georgia site.

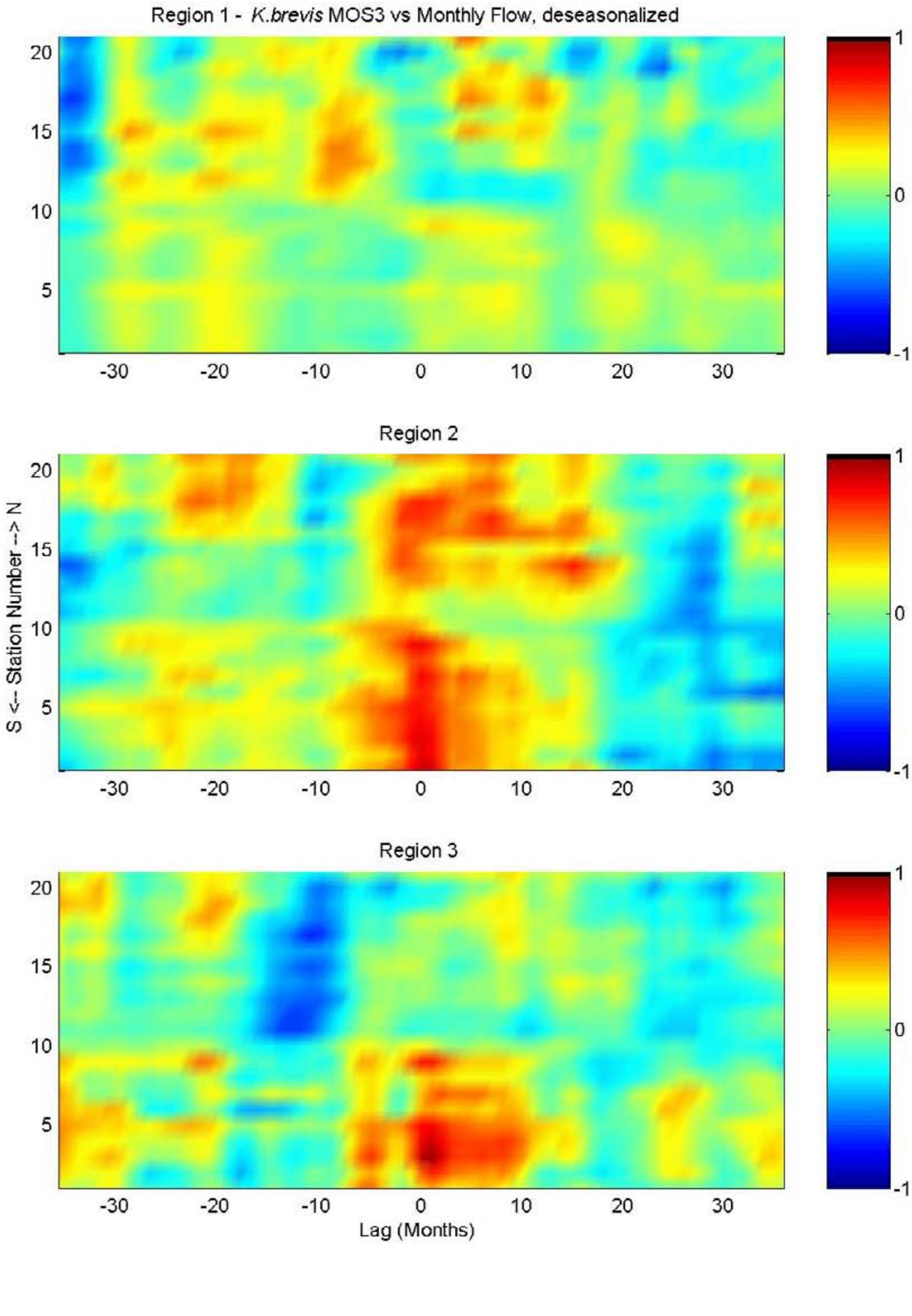

Figure 38. Compiled normalized cross-correlations of the 3 month *K. brevis* parameter in Regions 1, 2, and 3 against monthly riverine flow anomalies. Rivers are roughly ordered from north (21) to south (1), and do not include the Caloosahatchee River.

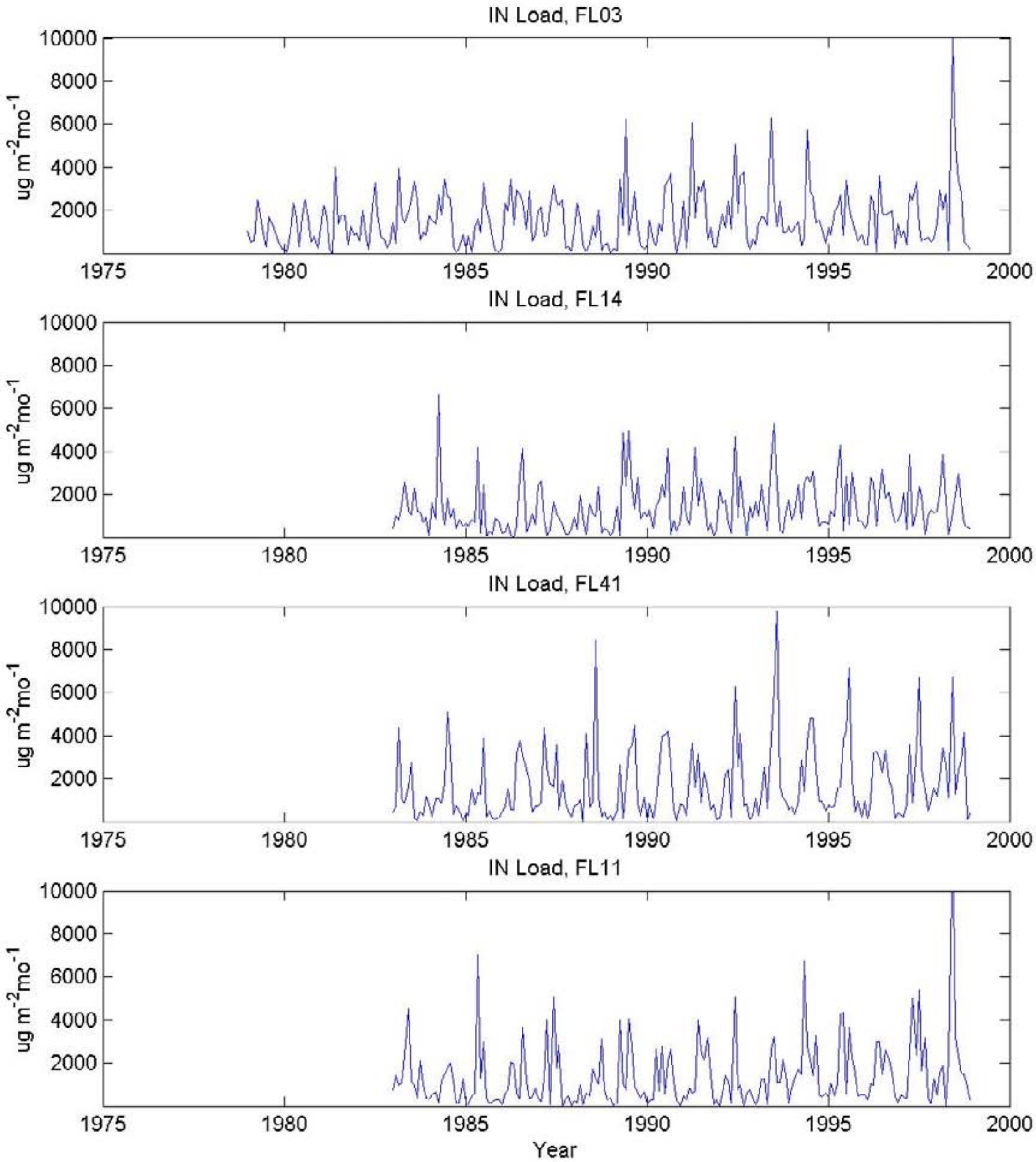

Figure 39. Atmospheric deposition loads (in rainfall) of inorganic nitrogen at selected stations.

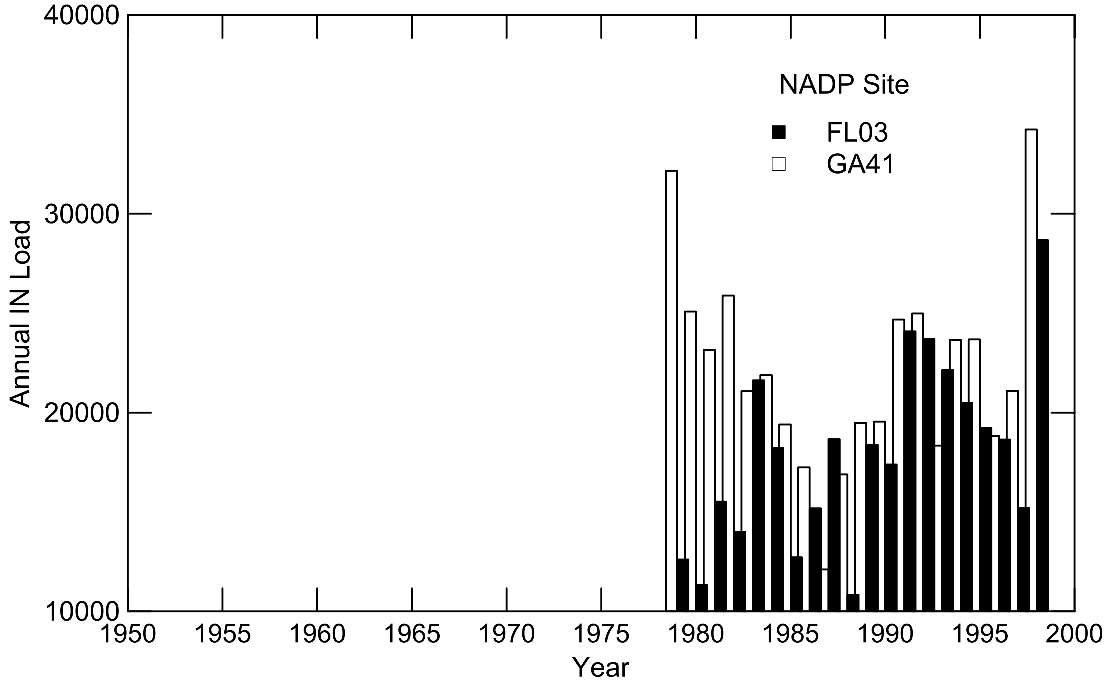

Figure 40. Annual atmospheric deposition loads at the sites with the longest period of record in Florida and Georgia.

For the 1983-1998 deposition data, the only result of significance was that *K. brevis* durations in Region 2 lagged atmospheric deposition in Alabama by approximately 2 months **(Figure 41).** Other deposition sites had positive, although non-significant, correlations at similar lags. Region 3 had similar non-significant, positive correlations, while Region 1, at a closer proximity to more of the deposition sites, had lower correlations than the other regions. No additional information was obtained by examining deseasonalized loadings.

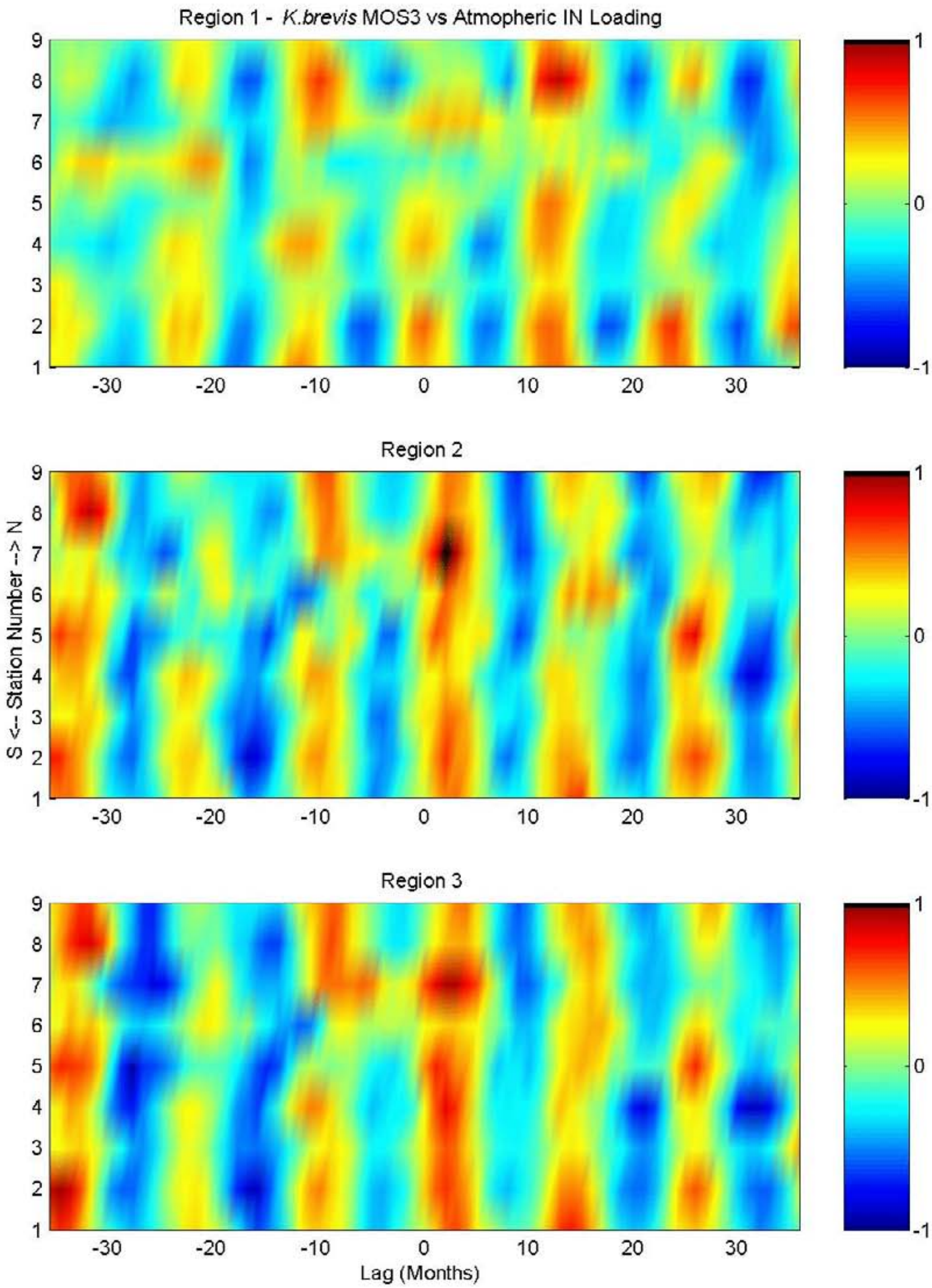

Figure 41. Compiled normalized cross-correlations of the 3 month *K. brevis* parameter in Regions 1, 2, and 3 against monthly atmospheric loads of inorganic nitrogen. Sites are roughly ordered from north (9) to south (1).

Hurricanes

The hurricane parameters of squared and summed wind speeds were also accumulated over varying periods, as were flow data. All of the resulting hurricane parameters, however, were extremely non-normal due to the high numbers of zero data. Transformations were not helpful in improving the distributions. Auto-correlations by regions indicated broad maxima (although non-significant) at lags between 9 and 15 months, consistent with the more-or-less annual appearances of storms during the hurricane season. Regions 2 and 3 displayed little correspondences between *K. brevis* parameters and wind speeds. In Region 1, however, positive, although non-significant, correlations were observed at lags of -1 and +11 months **(Figure 42)**. Adjusting for phase shift, *K. brevis* occurred at lags of 0 and 12 months following months with high winds. This result was attributed primarily to the rough annual cycle of both hurricane and red tide occurrence, neither of which is strong in Region 1.

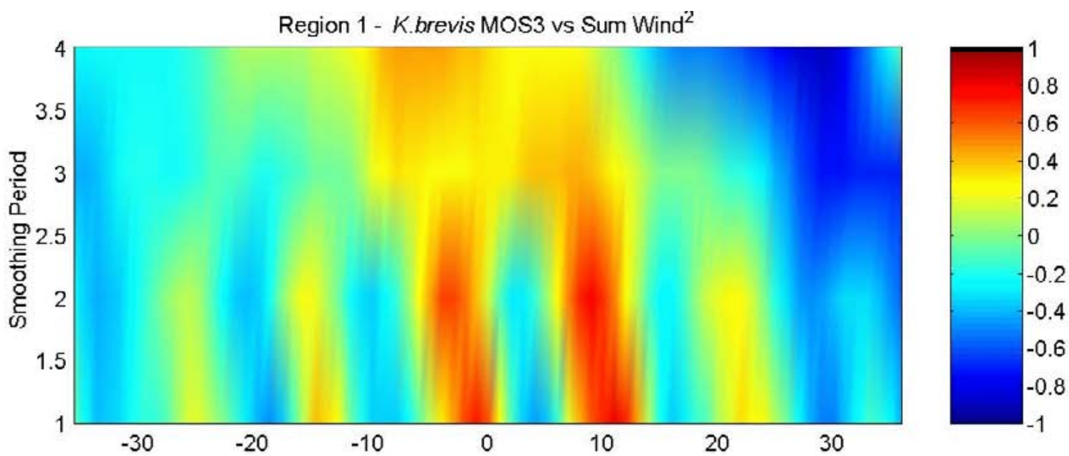

Figure 42. Compiled normalized cross-correlations of the 3 month *K. brevis* parameter against the sum of squares of wind speed . The y-axis represents increased smoothing periods of the wind speed^2 parameter (1, 3, 6, 12, and 24 months).

Climate Indices

Of the climate indices examined, including sea level at Cedar Key and at Key West, all were normal or approximately so, and none were stationary, with increasing trends present in many over the period of interest. The lag scales of auto-correlations of the indices were typically large with broad maxima and minima, indicating underlying long term repetitive oscillations over extended periods. Of interest was that at lags near zero, the Tropical SST Anomaly was inversely correlated with and lagged the SOI anomaly by 3-4 months and leads the Tropical Land Anomaly by approximately the same amount. Similarly the global mean SST anomalies lead the Tropical Land Anomaly by 3-4 months as well.

Climate indices were linearly detrended prior to analysis, but none of the *K. brevis* parameters were significantly correlated with either the climate indices investigated or with smoothed versions (3, 6, 12, and 24 month means). The same was true of sea level. In addition, patterns of positive and negative correlation varied substantially between regions for most of the indices. The relationship of 3 month *K. brevis* durations with the Tropical SST anomaly **(Figure 43)** is illustrated with only a slight positive correlation at a 10 month lag for Region 2. This is somewhat surprising given the high correspondence of rainfall at stations south of Tarpon Springs with the Tropical SST anomaly **(Figure 44)** and the previously demonstrated correspondence of rainfall at central and southern stations with *K. brevis* durations in Region 2 **(Figure 30, above).**

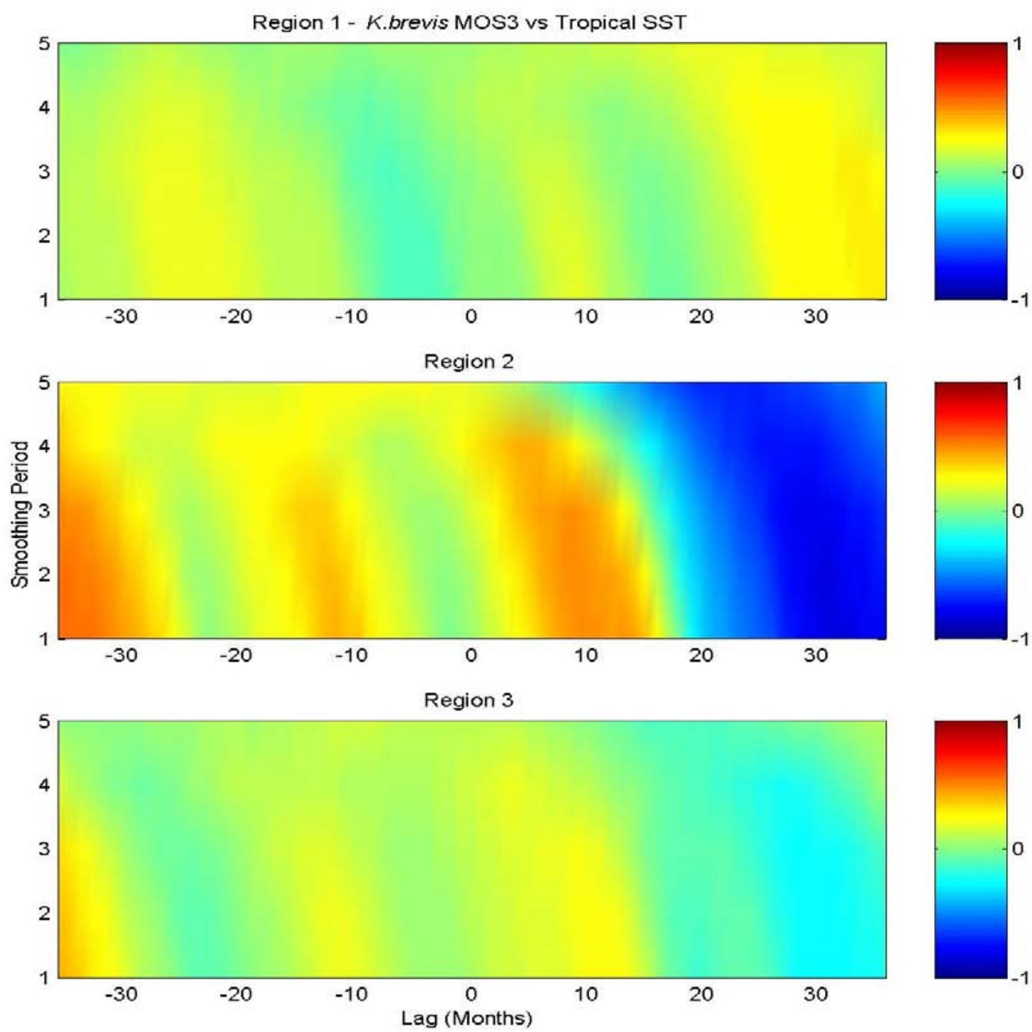

Figure 43. Compiled normalized cross-correlations of the 3 month *K. brevis* parameter in Regions 1, 2, and 3 against the Tropical SST Anomaly. The y-axis represents increased smoothing periods of the SST parameter (1, 3, 6, 12, and 24 months).

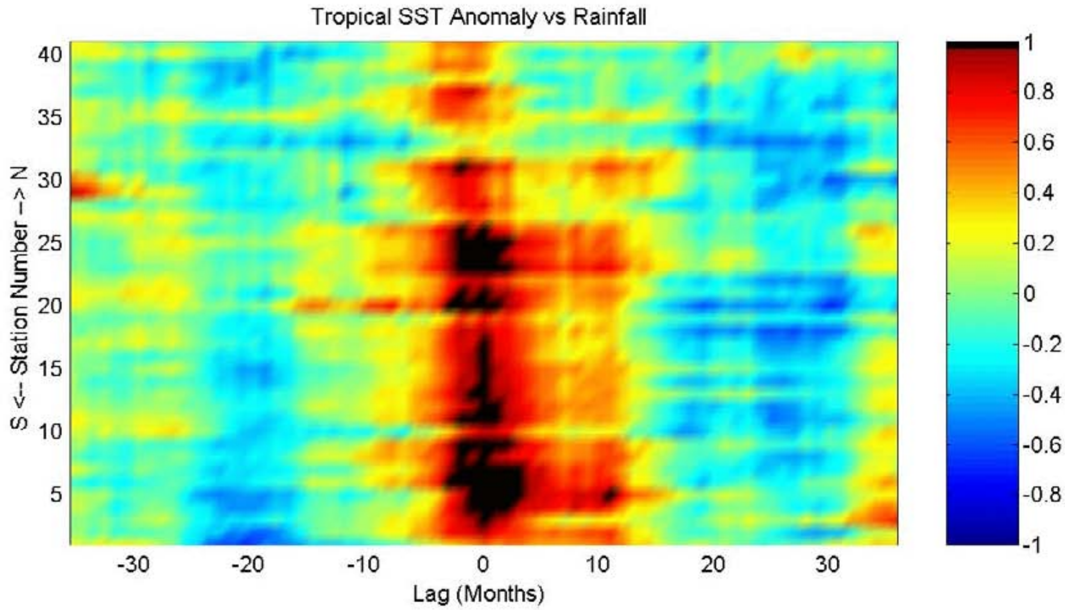

Figure 44. Compiled normalized cross-correlations of the Tropical SST Anomaly against rainfall. Stations are roughly ordered from north (41) to south (1).

SUMMARY:

Karenia brevis concentration data in the Gulf of Mexico between 1953 and 1998 were obtained from a recent FMRI data rescue project and analyzed for correlation with rainfall and flow records as surrogates for nutrient loadings, and against atmospheric deposition of nitrogen, hurricane and tropical storm incidence, and a variety of climate indices. The study area was divided into three sub-areas and each was analyzed separately since the incidence of red tides in Florida waters, and possible forcing factors, varies regionally. Available data (>44,000 records) were binned into monthly time steps by region. As *K. breve* data originated from a variety of sources, and as sampling effort clearly varied over the study period, cell concentration data were reduced to presence/absence. Of the 552 months addressed, data were available by region and month in 756 of the total of 1656 region-month bins. *Karenia brevis* was assumed to be absent in those instances where data were missing. Region 1, to the north, was minimally sampled, apparently only in response to detected blooms, while Region 2 was sampled the most. From presence/absence, duration parameters were computed for *K. brevis*, i.e. in how many of the next *n* months was *K. brevis* reported within the region. Durations were computed for n=3, 6, 12, and 24 months. All analyses determined significance levels after adjusting for serial correlation within the various data sets.

Region 1 blooms typically followed the presence of *K. brevis* in Region 2, while Region 3 blooms either developed simultaneously or lagged blooms in Region 2 by a month. Occurrences in Region 1 were relatively minimal, while *K. brevis* was most frequently observed in Region 2, with almost as many positive observations in Region 3. Periods of low *K. brevis* occurrence in Regions1 and 3 were also periods of low sampling effort. Fortunately, sampling effort in Region 2 has been high and samples confirmed a period of generally low *K. brevis* occurrence in 1969. In general, 1956-1960 and 1994-1998 represent periods of extended red tides.

The state could be separated into two rainfall provinces, with semi-annual cycles in the north and an annual cycle for the central and southern stations. Periods of maximum rainfall were coherent across the state, as were rainfall anomalies (monthly means removed), although correlations declined with increasing distance between stations. For anomalies, lack of significance in cross-correlations at lag other than 0 months indicated no dominant short term periodicity. Rainfall data were approximately stationary over the study period.

Karenia brevis duration over the next three months in Region 2 was significantly correlated with rainfall at a number of stations from Tarpon Springs to Punta Gorda. If causal, the effects were relatively immediate, with highest correlations between a 0 and 3 months lag of *K. brevis* from rainfall. Relationships were not as pronounced between *K. brevis* in Region 2 and northern rainfall but were similar in phase. The analysis of rainfall anomalies, while with no significant results, also indicated that *K. brevis* persists as long as 10 months beyond a rainfall anomaly. There were no significant results for Region 1, and it should be noted that correlations were higher (although again not significant) for southern rainfall stations than for northern stations in close proximity. *Karenia brevis* in Region 1 also lagged rainfall at southern stations by a number of months and may argue for advection rather than initiation of the bloom within Region 1. In Region 3, correlations of *K. brevis* with northern rainfall were poor, and were higher with the southern rainfall stations, although few were statistically significant.

Flow data could also be separated into two hydrological provinces. Northern rivers recorded flow maxima in March and April, while rivers including and south of the Withlacoochee River typically received flow maxima in August-October (approximately 6 months out of phase from one another). Flow data were also highly non-stationary, with rivers within a region having roughly similar behaviors. Again a number of significant correlations existed for Region 2 *K. brevis* duration and riverine flow. *Karenia brevis* duration lags flows in northern rivers by approximately 6 months and is significantly correlated with flows in a number of southern rivers at lag=0 months. The relationship between flow and *K. brevis* seemed somewhat disconnected based on potential travel times between northern rivers and Region 2. Temperatures may be inadequate to support blooms during the periods of high discharge from northern rivers, however, and the delay may reflect time for coastal waters to warm. Region 1 *K. brevis* durations had little relationship to southern rivers and only slight (non-significant) correlation with northern rivers. Similarly, Region 3 *K. brevis* durations experience the highest correlations with flow from southern rivers, including some of statistical significance, while correlations were reduced with northern rivers. No results of significance were obtained from deseasonalized flows or when the data set was reanalyzed for the period for which Caloosahatchee River flows were available.

The data set was also reanalyzed for the periods for which atmospheric deposition data were available (1978-1998 and 1983-1998). The only significant results were for *K. brevis* in Region 2 and a deposition site in Alabama. The lack of geographical coherence between *K. brevis* and sites in closer proximity argues that atmospheric deposition of nitrogen is not a direct or dominant factor in *K. brevis* blooms. Hurricane and tropical storm incidence, measured as the sum of the wind speed squared within the month, were generally uninformative, as were correlations of *K. brevis* with a variety of climate indices. Interestingly, the Tropical SST Anomaly was significantly correlated with almost all rainfall sites south of Tarpon Springs, at zero and longer lags. Despite this result and the correspondence of *K. brevis* with rainfall at southern sites, *K. brevis* was not significantly correlated with the Tropical SST Anomaly.

The results of these analyses cannot be considered conclusive. While every effort was made to normalize data by transformations or by computation of duration parameters, not all transformations were successful. In addition, the most normal of the duration parameters for *K. brevis,* were also the parameters for which no significant results were obtained. The parameter which recorded the most significant results was the 3 month *K. brevis* duration parameter, the most non-normal of all. In an effort to compensate for these violations of normality and any impact on computed significance, confidence intervals were conservatively determined by adjusting for serial correlation in the data. Assumptions of *K. brevis* absence when no data were available can also be criticized, but no more conservative assumption was immediately apparent. These analyses are most valuable for the indications of linkages that they provide, fully realizing that the occurrence of *K. brevis* is undoubtedly a multi-variate response of a living organism and one which is unlikely to be neatly reduced to a few physical or chemical forcing factors.

Despite these caveats, a number of useful observations or generalities emerge. The occurrence and duration of *K. brevis* was highly regionalized, as were the apparent linkages to rainfall and flow. Region 2 recorded the most significant correlations with potential forcing functions and was clearly the area (within this study) of highest activity. Those factors which were significant were, in general, geographically coherent, i.e. southern regions responding more positively to southern rivers and rainfall, less so to northern rivers and rainfall. *Karenia brevis* in Region 2 was significantly correlated with rainfall and flows from central and southern regions of Florida. Lags were short if any, indicating relatively immediate effects, provided the link is causal and not the result of some controlling, but unknown third factor. Patterns of *K. brevis* in Region 1 can be explained by a combination of advection from Region 2 and flows to the region occurring when temperatures are inhospitable to *K. brevis*, although this is admittedly speculative. *Karenia brevis* in Region 3 was similar in occurrence and linkages to that in Region 2, with some shifting of the rivers and stations for which higher correlations were obtained to those closer to the region. Direct deposition of inorganic nitrogen in rainfall did not appear to play a primary role in fostering and maintaining blooms, although this result makes no statement about other components of atmospheric deposition. Climate indices, while demonstrated to be influential on rainfall patterns in the central and southern regions of the state, were not significantly correlated with long term patterns of *K. brevis* duration.

LITERATURE CITED:

Bendat, J.S. and A.G. Piersol. 1993. Random data analysis and measurement procedures. 2nd Edition.

Chelton, D.B. 1983. Effect of sampling errors in statistical estimation. Deep Sea Research 30(10A):1083-1103.

FFWCC-FMRI. 2001. Red Tides in Florida 1954-1998. FL_HAB_Historical_Data.mdb.

Feinstein, A. 1956. Correlation of various ... phenomena with red tide outbreaks on the Florida west coast. Bulletin of Marine Science of the Gulf and Carribean 6(3):209-232.

Jarvinen, B.R., C.J. Neumann, and M.A.S. Davis. 1984. A tropical cyclone data tape for the North Atlantic basin, 1886-1983: Contents, limitations, and uses. NOAA Technical Memorandum NWS NHC 22.

Turner, R.E., N.N. Rabalais. 2001. Report to the Southwest Florida Water Management District. A Paleo-Reconstruction of Water Quality in the Charlotte Harbor Estuary Florida.