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Variability and Prediction of Freshwater and Nitrate Fluxes for the Louisiana-Texas Shelf: Mississippi and Atchafalaya River Source Functions

A. BRATKOVICH[1]
National Oceanic and Atmospheric Administration
Great Lakes Environmental Research Laboratory
2205 Commonwealth Boulevard
Ann Arbor, Michigan 48105

S. P. DINNEL
Center for Marine Science
University of Southern Mississippi
Stennis Space Center, Mississippi 39529

D. A. GOOLSBY
United States Geological Survey
Denver Federal Center, MS 406
Box 25046
Building 25
Lakewood, California 80225

ABSTRACT: Time histories of riverine water discharge, nitrate concentration, and nitrate flux have been analyzed for the Mississippi and Atchafalaya rivers. Results indicate that water discharge variability is dominated by the annual cycle and shorter-time-scale episodic events presumably associated with snowmelt runoff and spring or summer rains. Interannual variability in water discharge is relatively small compared to the above. In contrast, nitrate concentration exhibits strongest variability at decadal time scales. The interannual variability is not monotonic but more complicated in structure. Weak covariability between water discharge and nitrate concentration leads to a relatively "noisy" nitrate flux signal. Nitrate flux variations exhibit a low-amplitude, long-term modulation of a dominant annual cycle. Predictor-hindcastor analyses indicate that skilled forecasts of nitrate concentration and nitrate flux fields are feasible. Water discharge was the most reliably hindcast (on seasonal to interannual time scales) due to the fundamental strength of the annual hydrologic cycle. However, the forecasting effort for this variable was less successful than the hindcasting effort, mostly due to a phase shift in the annual cycle during our relatively short test period (18 mo). Nitrate concentration was more skillfully predicted (seasonal to interannual time scales) due to the relative dominance of the decadal-scale portion of the signal. Nitrate flux was also skillfully forecast even though historical analyses seemed to indicate that it should be more difficult to predict than either water discharge or nitrate concentration.

Introduction

Recent analyses of water discharge and nitrate concentration data (Dinnel and Bratkovich 1993) from the lower Mississippi River have shown that the dominant characteristics of associated riverine source functions can be effectively portrayed in a simplified form amenable to optimal estimator analysis. Optimal estimator analysis is a generalized estimation approach that employs a set of basis functions or model components subject to physical, numerical, or conceptual constraints to maximize or minimize a performance index (e.g., least-squared error between a model and pertinent observations is one possibility).

This work explores the capabilities and limits of such an approach considering the irresolvable restrictions, errors, or ambiguities imposed by the historical database and observational regimen. The goals of this work are to quantitatively specify, and ultimately predict, riverine forcing functions that

[1] Corresponding author.

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have a significant impact upon various aspects of ecosystem function for the receiving shelf waters of Louisiana and Texas (e.g., Lohrenz et al. 1990; Dagg et al. 1991) and have more global impacts (e.g., Walsh et al. 1981).

Riverine water discharge and nitrate flux are related quantities that have very different evolutionary pathways on the shelf since nutrient transformations tend to occur about an order of magnitude faster than the ultimate mixing of the freshwater component of the plume. The light field, mediated by water-column particle fields and initial plume mixing and subsequent dilution, is also a fast-time-scale factor in the evolution of nutrient and phytoplankton fields (Lohrenz et al. 1994). In short, the interaction of river plumes with shelf waters is quite complicated, involving multiple space and time scales.

The Mississippi and Atchafalaya rivers are the dominant sources of freshwater (buoyancy) flux and nitrate flux for the inner portion of the Louisiana-Texas shelf. One notable impact of the combined effects of the resultant intense, near-surface, density stratification and nutrient enhancement is that inner shelf waters west of the Mississippi Delta routinely experience hypoxia during summer. Improving estimates of the overall duration and spatial extent of the hypoxia is a current research and resource management issue.

There is some scientific consensus that two important factors contributing to shelf hypoxia are directly attributable to riverine source behavior. The first factor is riverine nutrient loading, which can lead to exceptionally high oxygen consumption rates resulting from the decomposition of planktonic matter ultimately derived from riverine nutrient sources. The second factor is persistent, intense, near-surface density stratification, which inhibits the vertical exchange of oxygen in the upper water-column. Other factors include the balance between near-bottom oxygen consumption due to organic matter decomposition and oxygen production due to photosynthetic respiration. While other mechanisms may contribute to hypoxia production or maintenance, these are the most often cited (see Bierman et al. 1994; Dortch et al. 1994; Rabalais et al. 1994).

Recently, the National Oceanic and Atmospheric Administration's (NOAA) Coastal Ocean Program has initiated studies of the hypoxia problem in these waters through its Nutrient Enhanced Coastal Ocean Productivity (NECOP) program (see introduction to this volume). The ultimate goal of this program component is to examine, understand, and predict ecosystem impacts such as shelf hypoxia resulting from riverine fluxes. An obvious first step in this sequence is to evaluate the characteristics and predictability of presumed riverine forcing functions. If these basic forcing factors are poorly behaved or relatively unpredictable, then the odds of actually predicting the characteristics or impacts of higher-order ecological processes in riverine-influenced shelf waters are significantly diminished.

Truly skilled predictions (i.e., accurate estimates forward in time) of any environmental phenomena are rare. Niels Bohr summed it up by saying (with a touch of humor, insight, and irony) "Prediction is hard . . . especially about the future." Most successful predictions of environmental phenomena have been based upon a thorough understanding of forcing mechanisms and the identification of reliable response patterns rather than a detailed understanding of associated response dynamics. That is, given a somewhat consistent environmental response, the prediction problem comes down to quantitative anticipation or forecasting of system forcing functions. This can be very difficult, as in the case of synoptic-scale meteorological variability (Lorenz 1973), or relatively straightforward (after sufficient observation and study), as in the case of gravitationally-forced tidal sea-surface elevation changes at a specific coastal location (Munk and Cartwright 1966).

In prior work (Dinnel and Bratkovich 1993), we have investigated the variability of riverine forcing functions for the coastal receiving waters of the Mississippi Delta region and presented a very preliminary evaluation of their potential predictability. In this work, we further examine various aspects of the associated prediction problem both with regard to forcing characteristics and observational aspects.

We make actual predictions of riverine forcing functions, based on estimators that exhibit significant skill (in two of three variable fields), later in this work and analyze the relative strengths and weaknesses of our approach. From our analysis, we conclude that this environmental prediction problem is one that is tractable for the forcing functions but not necessarily for shelf responses.

Database and Methods

The database used in the following analysis is composed of three components: 1) 37-yr-long time series of water discharge rate and nitrate concentration data from the lower Mississippi River (taken downstream from the diversion of Mississippi River water into the Atchafalaya River), 2) 92-yr-long time series of annually averaged water discharge from both the Atchafalaya River (a distributary of the Mississippi River) and the lower Mississippi River, and 3) an 18-mo-long time series of "weekly" sampled nitrate concentration data from the lower

Mississippi River. Only the first component was treated in Dinnel and Bratkovich (1993).

The 37-yr-long time series are shown in Fig. 1. The water discharge data are from a monitoring station at Tarbert Landing, Mississippi. Individual values are monthly averages of daily-averaged values. The daily-averaged values are inferred from data-adaptive models of discharge versus water level, which are checked on a weekly basis. The resulting computed discharge rates are normally accurate to within 10% of actual measured rates. The computed monthly-averaged discharge values should be well within 1% of actual measured values given no bias in the overall measurement or calibration procedure.

The nitrate concentration data are from St. Francisville, Louisiana. Individual values are single day "grab samples" based on cross-sectional averages of in situ sample data. Nitrate flux was computed as a simple product of water discharge and nitrate concentration. Later in this work, we examine the potential error variance associated with this sampling regimen. Respective stations are 450 km and 480 km upstream from the delta. The Atchafalaya River branchpoint is ~50 km upstream from St. Francisville. There are no major distributaries downstream of these monitoring stations. However, the city of New Orleans and the riverbank industrial corridor between New Orleans and Baton Rouge does add to the nutrient loading downstream of the nitrate sampling site.

The second component (92-yr-long time series) is extracted from data reports (United States Army 1954–1992). Water discharge values are annual means ultimately formed from daily-average values for both the lower Mississippi and Atchafalaya rivers. The United States Army Corps of Engineers water-discharge monitoring site for the Atchafalaya River is Simmesport, Louisiana. Simmesport is ~13 km downstream of the branchpoint with the Mississippi River and ~5 km downstream from the confluence with the Red River.

We know of no long-term, continuous nitrate concentration data for the Atchafalaya River. However, given the flow rates and nitrate concentration variation rates for the lower Mississippi River, we expect that the Atchafalaya River nitrate concentration values would be very comparable to lower Mississippi River values. The Red River joins the Atchafalaya River below its branch point with the Mississippi River. This tributary can be a major source of water discharge and various nutrient constituents. On an annual average basis, the Red River contributes an additional ~33% to the Atchafalaya River water discharge (Van der Leeden et al. 1990). The Red River contribution to water discharge is accounted for in our analyses, but its impact on nitrate fields is not.

The third component is reported (in part) in Goolsby et al. (1991) and in Goolsby and Battaglin (1993) and consists of higher frequency (once to twice weekly) nitrate samples taken over an 18-mo period spanning April 1991 through September 1992. We shall refer to this series as the "high frequency" dataset in the remainder of the text. The sampling site was Baton Rouge, Louisiana. The sampling regimen was that described by Goolsby et al. (1991). Samples for dissolved nitrate and several other forms of nitrogen and phosphorus were collected, using an integrating water sampler, from the upper 7 m of the water column. The samples were filtered, chilled, and subsequently analyzed at the United States Geological Survey's Nutrient Water Quality Laboratory in Denver, Colorado, using methods described in Fishman and Friedman (1989). Nitrate concentration values from these samples were comparable to monthly, cross-sectionally-averaged samples collected upstream at St. Francisville (standard error of ~20%).

To examine this data in a comparative way, we used a water-discharge time series (subsampled from daily-averaged estimates) with precisely the same sample dates as the nitrate data. This allowed for the formation of high frequency sampled nitrate flux estimates and related statistical quantities. The daily-averaged estimates of water discharge are derived from a data-adaptive calibration between discharge and water level which is checked twice a week and updated on a seasonal basis. This procedure introduces a standard estimation error of less than 10%. Again, nitrate flux was computed as a simple product of water discharge and nitrate concentration for each specific sample date.

The methods employed in the basic statistical analysis are described in Bendat and Piersol (1986). In particular, we use their definitions of the probability density function and autocorrelation function as working standards. Taken together, these two functions completely describe a Gaussian random variable field; otherwise higher-order statistics are required.

We follow the approach of Davis (1976, 1977) in the predictor-hindcastor analyses. A predictor-hindcastor, P′, is constructed for the target field, P, called the predictand. In the following development, it is assumed that the long-term mean value has been estimated and removed from quantities of interest (i.e., only variability about the mean is considered). Various estimators are formed from a dot product of two vectors,

$$P' = \bar{a} \cdot \bar{d} \quad (1)$$

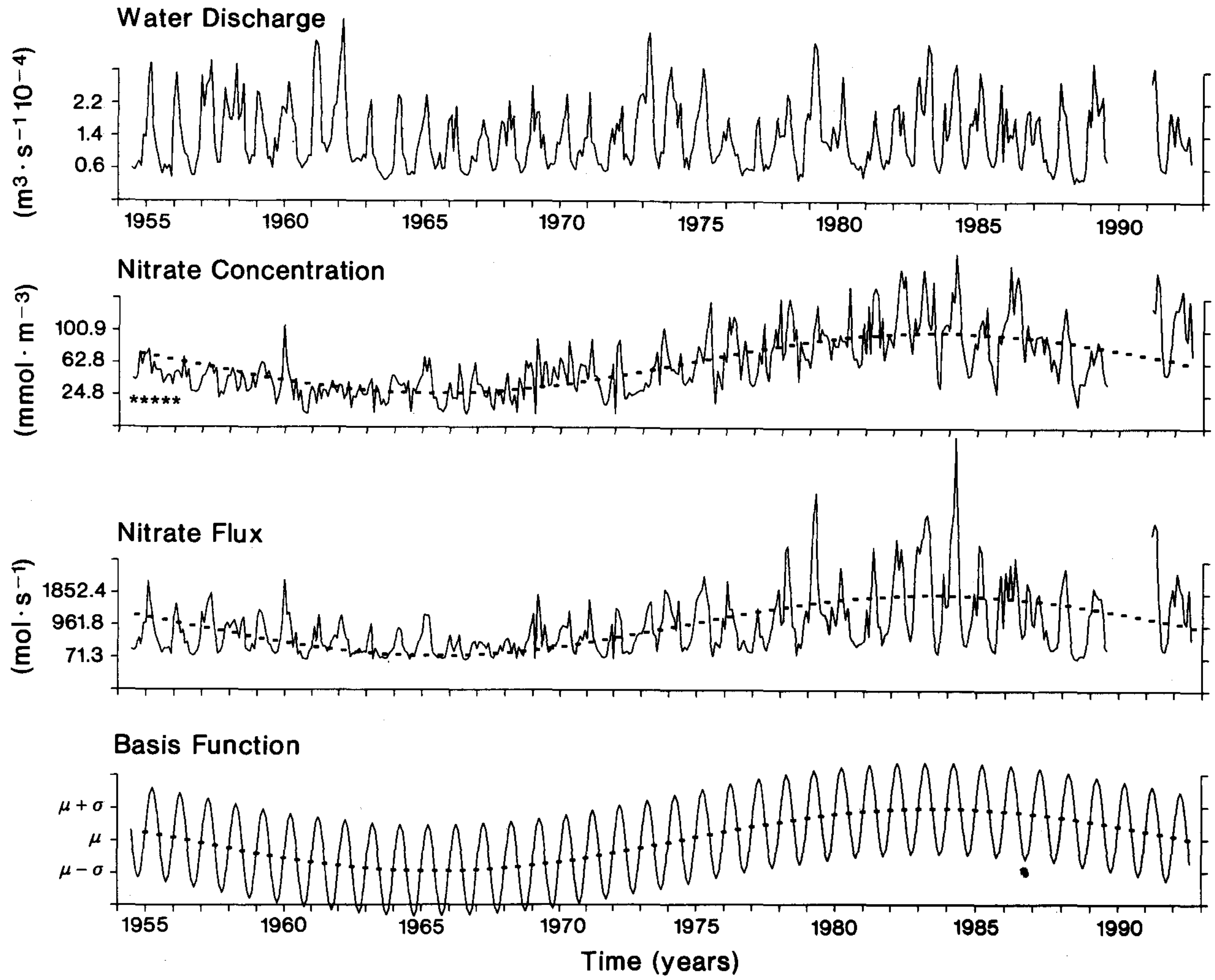

Fig. 1. Long-term monthly time-series data from the lower Mississippi River that were employed in this study. All vertical coordinates are scaled such that the middle tick corresponds to the 37-yr-mean and adjacent ticks are separated by one standard deviation. Water discharge, nitrate concentration, and nitrate flux are shown respectively in frames A, B, and C. Dotted lines in frames B and C are decadal running-mean-averages of the monthly data series (first and last 5 yr are extrapolated). Frame D shows the near-optimal hindcastor for nitrate flux (mean added) composed of an annual cycle and lower frequency 36-yr cycle. Estimated historical reference values for nitrate concentration are show to left as ****; based on data from Riley (1937) and Turner and Rabalais (1991).

where $\bar{a}$ is a vector of weighting coefficients and $\bar{d}$ is a data vector. Individual components of these vectors are denoted by a_i and d_i. One type of optimal predictor minimizes the mean square error between the predictand and predictor for future realizations of P. The same statement holds true regarding optimal hindcastors, but for past realizations of P.

The conventional definition of estimator skill, S, associated with P′ is

$$S = 1 - \langle(P - P')^2\rangle/\langle P^2\rangle \quad (2)$$

and generally varies between zero and unity. Here, the brackets denote ensemble or time-averaged estimated quantities. Component values for $\bar{a}$ can be estimated using the following expression

$$a_i = \langle Pd_i\rangle/\langle d_i^2\rangle \quad (3)$$

which yields near-optimal values for $\bar{a}$ given that the P and $\bar{d}$ fields have certain properties (cf. Davis 1976). One important prerequisite is that the components of $\bar{d}$ must have Gaussian distributions for Eq. (3) to produce near-optimal skill levels. Another desirable characteristic is that various components of $\bar{d}$ be orthogonal to minimize redundant information content for various input data components.

TABLE 1. Means, standard deviations (SD), skewness, flatness (kurtosis), coefficients of variation (CV), and hindcastor skills for monthly time series of water discharge (Tarbert Landing, Mississippi), nitrate concentration (St. Francisville, Louisiana) and associated nitrate flux. Hindcastor skills are presented for predictions using the annual (A), very-low-frequency (VLF), and both the annual and the VLF cycles. Estimated skills below the threshold (~0.2) associated with random correspondence or artificial skill are indicated by **** (adapted from Dinnel and Bratkovich 1993).[a]

						Hindcastor Skill		
	Mean	SD	Skew	Flat	CV	A	VLF	A + VLF
Water discharge ($m^3\ s^{-1}$)	14,100	7,800	0.93	3.29	0.55	0.44	****	0.46
Nitrate concentration ($mmol\ m^{-3}$)	63	38	0.90	3.51	0.60	****	0.50	0.48
Nitrate flux ($mol\ s^{-1}$)	962	891	1.84	7.60	0.93	0.27	0.26	0.49

[a] Perfect estimators have skill ~1.0. Poor estimators have skill ~0.0. For these particular estimators, the artificial skill level is estimated to be ~0.2.

Most generally, S is maximized for $\bar{a}$ corresponding to

$$\partial S/\partial a_i = 0 \text{ and } \partial^2 S/\partial a_i^2 < 0. \quad (4)$$

Therefore, estimates of the near-optimal $\bar{a}$ can be formulated on a computational or trial-and-error basis regardless of the specific statistical properties of the predictand, the input data vector, or the exact definition of skill utilized. Our results are based upon this latter optimization method.

P′ can be arbitrarily elaborate or complex. Generally speaking, an N-degree-of-freedom (N-DOF) model can always be constructed to perfectly fit an N-DOF dataset. Therefore, some effort must be made a priori to determine a suitably simple (low DOF), or dynamically motivated, form for P′ and to identify reasonably limited input data vectors.

Very complex, data-intensive constructions of P′ tend to have relatively high hindcasting skill, when applied to the datasets they were constructed from, and relatively low prediction skill, when applied to new datasets or real forecasting situations. The artificial skill (the fraction of the skill due to fortuitous agreement) associated with an unnecessarily complex or data-intensive estimator can be very large. One expects the artificial skill to be proportional to M/N, where M is the number of free model parameters and N is the effective number of degrees of freedom associated with the test data. Therefore, it is very important, regarding the a priori design of P′, to carefully characterize the properties or behavior of predictand and input data fields to help sort out random complexity from underlying behavior consistent with basic physical principles.

At the outset, we know that aspects of this problem (i.e., describing or predicting basinwide precipitation and other factors contributing to runoff such as soil moisture or changes in land-use practices) are far beyond our intent or capacity. Therefore, the river outflows are viewed as viable source or forcing functions for the shelf ecosystem. As such, we focus upon their variability and possible impacts, not on upstream processes or mechanisms. Also, we seek to invoke the full averaging power of this extensive drainage basin system. Considering individual sub-basins, hydrologic fields, or land-use practices defeats our purpose or specific intent in this particular work. Therefore, we focus on aspects of riverine source function variability directly adjacent to the shelf receiving waters.

Results

Before proceeding with the presentation of new results, it is useful to summarize a few fundamental findings from Dinnel and Bratkovich (1993). Mean values, variances, skewness, and kurtosis (flatness) values are given in Table 1 for riverine forcing fields (lower Mississippi River). Note that the estimated skewness and kurtosis values for all fields are much higher than expected for a normally distributed random variable.

Variance distributions are given in Table 2 for these same fields. Variability in water discharge (volumetric flow rate), Q, is greatest for annual time scales, while variability in nitrate concentration, N, is greatest for decadal time scales. Nitrate flux, Q_N, which is a simple product of water discharge and nitrate concentration, logically shows a hybrid behavior. However, a regression analysis between Q and N (from Dinnel and Bratkovich 1993) showed that covariability was weak ($R^2 < 0.2$) leading to more sporadic behavior for Q_N than might be intuitively expected. The band-averaged squared-coherence was also weak (<0.4) at most periods other than annual.

The Atchafalaya River average discharge rate has been regulated at approximately 30% of the total Mississippi River average discharge for the last 17 yr. Prior to 1977, the Atchafalaya River was not consistently regulated as illustrated in Fig. 2. This fact is significant because it has bearing upon the in-

TABLE 2. Variance distributions of monthly mean Mississippi River water discharge (Tarbert Landing, Mississippi), monthly sampled nitrate concentration (St. Francisville, Louisiana), and derived monthly nitrate flux from August 1954 through December 1990 (adapted from Dinnel and Bratkovich 1993).

	Water Discharge (10^7 m^6 s^{-2})		Nitrate (10^{-7} mol^2 m^{-6})		Nitrate Flux (10^5 mol^2 s^{-2})	
	Variance	% Total	Variance	% Total	Variance	% Total
Total	6.084	100.0	146.228	100.0	7.937	100.0
Sub-annual band[a] (<0.9 cpy)	1.521	25.0	98.190	67.1	3.517	44.3
Annual band (0.9–2.25 cpy)	3.663	60.6	29.020	19.8	3.568	45.0
Supra-annual band (>2.25 cpy)	0.864	14.4	19.014	13.0	0.852	10.7

[a] Frequency bandwidth units are cycles yr^{-1} (cpy).

terpretation of riverine source function data and statistics predating 1977.

The 1900–present average discharge rate (decadal time scale) for the lower Mississippi River is remarkably stable near 14,000 m^3 s^{-1}, but it does show a decrease during the 1950s and 1960s. The riverine flow delivered to the shelf waters adjacent to Atchafalaya Bay has slowly increased, and the combined flow delivered to the shelf region has also increased, more notably over the last two de-

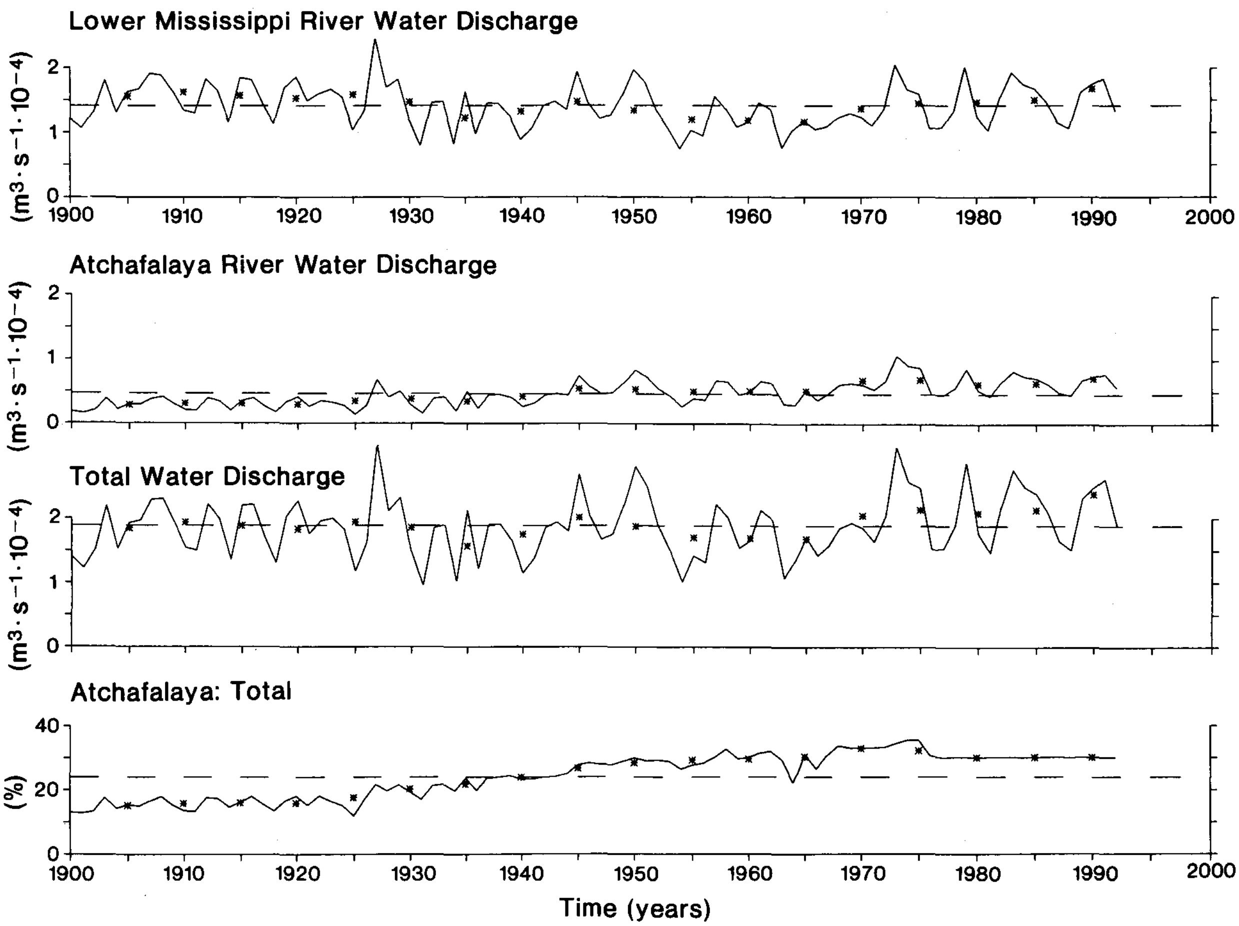

Fig. 2. The 92 yr of annual average water-discharge time-series data for the lower Mississippi River (A), Atchafalaya River (B), and combined flow (C). (D) shows the flow ratio for the same time period; Atchafalaya River to total flow. *'s are centered, decadal running-mean-averaged values (last values are partially extrapolated). Dashed horizontal lines are 92-yr average values. The Atchafalaya River to total flow ratio has been strictly regulated at ~30% since 1977.

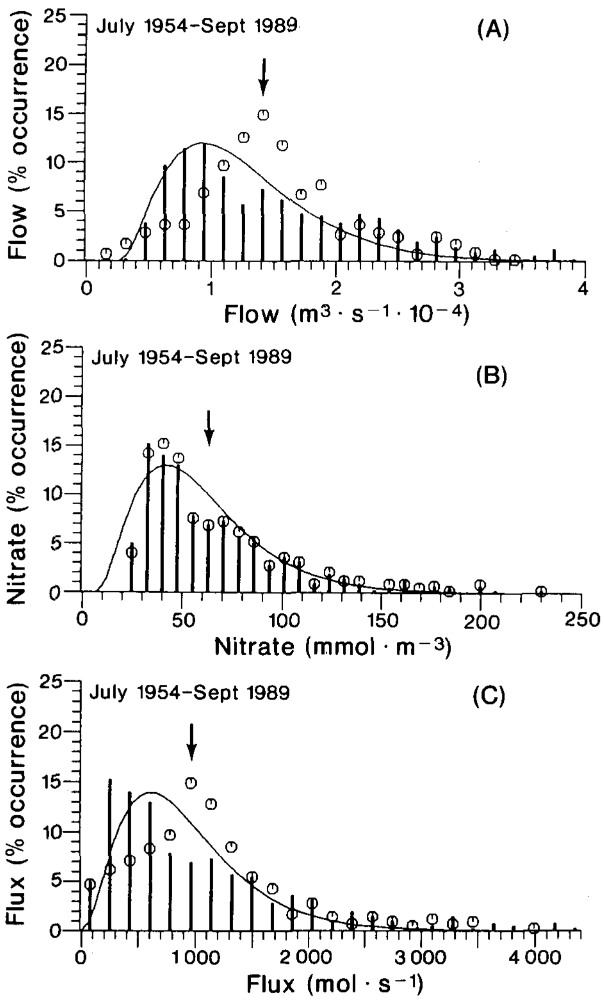

Fig. 3. Probability density functions for monthly time-series data. Water discharge, nitrate concentration, and nitrate flux are shown in frames A, B, and C, respectively. Arrows mark the long-term average values for the respective fields. Superimposed upon these estimates are Poisson distributions renormalized to the axes used. Plotted symbols are residual (best-fit annual cycle removed) distributions relevant to discussion later in the text. Approximately 5% of the nitrate flux residuals were negative and therefore not physically realistic but arithmetically possible. To avoid confusion, these points were not plotted.

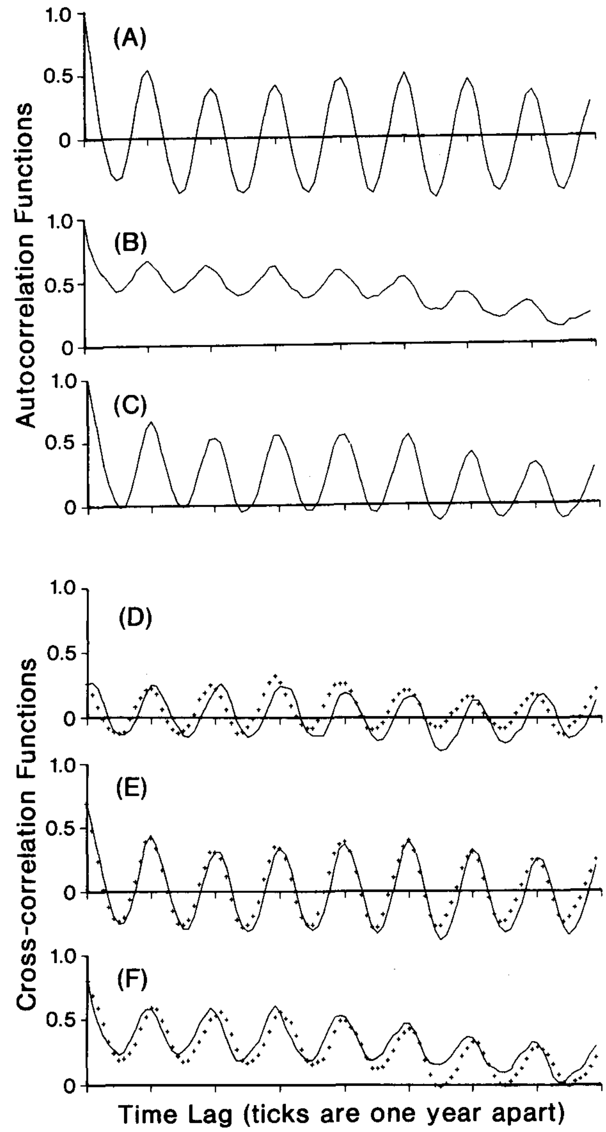

Fig. 4. Correlation functions for monthly time-series data. Frames A, B, and C are autocorrelation functions for water discharge, nitrate concentration, and nitrate flux, respectively. Frames D, E, and F show time-lagged cross-correlation functions for discharge-concentration, discharge-flux, and concentration-flux pairs, respectively. Solid lines are for the first variable leading the second variable. +'s are for the first variable lagging the second. All frames are comparably scaled. Functional definitions are those employed by Bendat and Piersol (1986).

cades. The 1900–present average percentage discharge (Atchafalaya River to total) for these data is ~25%. This percentage increases more or less linearly from less than 15% in 1900 to greater than 35% in 1970. This percentage was reduced to 30% in the mid-1970s by means of regulatory structures. Although it is not obvious from Fig. 2, the historical coefficient of variability (ratio of the mean to the standard deviation for 1900–1992) for the Atchafalaya River (0.42) is considerably greater than that for the lower Mississippi River (0.24). Therefore, the Atchafalaya River (including Red River contribution) has been prone to much wider swings in water discharge over the last century.

Figures 3 and 4 show the probability density function (PDF) estimates (frequency of occurrence histograms) and the correlation function estimates for the 37-yr-long monthly-average time-series components under consideration. As mentioned above, the skewness and kurtosis values associated with these time series reflect non-Gaussian behavior and are better fit by skewed density functions. These skewed distributions allow for the higher relative percentage of episodic, large-amplitude events observed in the time series. Approximate best-fit Poisson density functions are shown superimposed on the estimated PDFs. Also shown are PDFs for residual time-series (average annual cycle subtracted) associated with the hindcastor analyses (see Discussion).

The autocorrelation and cross-correlation estimates (Fig. 4) contain information equivalent to autospectra and cross-spectra, but are better suited to the consideration of hindcastor-predictor results since they quantitatively illustrate a given field's self-similarity with elapsed time. The time scale associated with the fastest-acting process impacting a field is given by the time lag to the first local minimum, important intermediate time scales are given by the elapsed time between rebound peaks, and an estimate of the time scale of the slowest-acting energetic process is given by the e^{-1} decay scale time for the functional envelope.

Autocorrelation estimates (Fig. 4A,B,C) indicate that seasonal and annual time scales are important since the first zero crossing tends to occur at about 3 mo, and major rebound maxima occur at 1-yr-lag intervals. The shape of the functional envelope for water discharge and nutrient concentration time series is significantly different, which is a manifestation of the relative importance of interannual variability in each of these fields. Nutrient flux is an algebraic product and its autocorrelation function reflects that fact. The long-time-lag local maxima for nutrient flux are comparable to those for nitrate concentration.

The cross-correlation functions shown in Fig. 4 (D,E,F) help explain the lack of persistance in nitrate flux. The cross-correlation between water discharge and nitrate concentration is weak for all lags but shows some rebound at annual time scales. Also, the cross-correlations shown are approximately symmetric about the zero-time-lag origin. Roughly characterized, the correlation between these two fields is no better at zero time lag than it is for time lags of 12 mo, 24 mo, or 36 mo earlier or later. One expects relatively high correlation values between water discharge and nitrate flux or between nitrate concentration and nitrate flux since the variable pairs in these two sets of fields are algebraically related to each other.

In Dinnel and Bratkovich (1993), we did a preliminary hindcastor analysis of monthly water discharge, nitrate concentration, and nitrate flux variability (mean values subtracted) and found that associated hindcastor skills were 0.44, 0.50, and 0.49, respectively. The "artificial" skill was estimated to be 0.1–0.2 depending upon the sophistication of the estimator employed.

The form of the hindcastor used was

$$P' = a_1 \times \sin(f_1 t + \phi_1) + a_2 \times \sin(f_2 t + \phi_2)$$

Note that up-to-date input data are not actually required to forecast with this particular model. Based upon the results of prior analyses in Dinnel and Bratkovich (1993), one of the frequencies chosen corresponded to the annual cycle; the other was a 36-yr period sinusoid. The subscripts on the model parameters (an amplitude, frequency, and phase) refer to separate frequency components. Note that the input data functions chosen are orthogonal. This is an important feature that helps eliminate "cross-talk" or redundant information content between various input functions. Also, these functions are physically or observationally motivated and they fit the interpretive context set by spectral analyses.

Since adding model parameters or components can deteriorate actual skill levels, we found that the best hindcastor for water discharge only had an annual component. The best nitrate concentration model was based upon a single 36-yr sinusoid. The best nitrate flux model utilized both components and thus had six, rather than three, parameters. Despite the extra complexity, the nitrate flux model had about the same numerical skill score as that of the best hindcastors of water discharge and nitrate concentration.

The degrees of freedom (DOF) associated with these results were estimated by dividing the total record length by approximately 1 yr, a natural time scale indicated by the structure of the correlation functions shown in Fig. 4. The natural time scale employed (and associated DOF) is to some degree a matter of mechanistic focus. Many environmental fields have multiple time scales associated with them, as well as a number of diverse mechanisms or input-response relationships with other fields or phenomena. The annual cycle and seasonal time scale are important or dominant in all the fields we consider. Our forecasting efforts will also focus on this scale range.

This brings us to matters of prediction. Shown in Fig. 5 are high-frequency data series (bin-averaged within each month) for the lower Mississippi River with several different "predicted" sequences superimposed. All predictions have been adjusted by offsets equal to the shorter term mean values (last 10 yr of available data preceding the prediction time window). Although data from the 18-mo-long test window is not used, this is an accommodation that helps match local means (and therefore variance levels) with historical levels. It

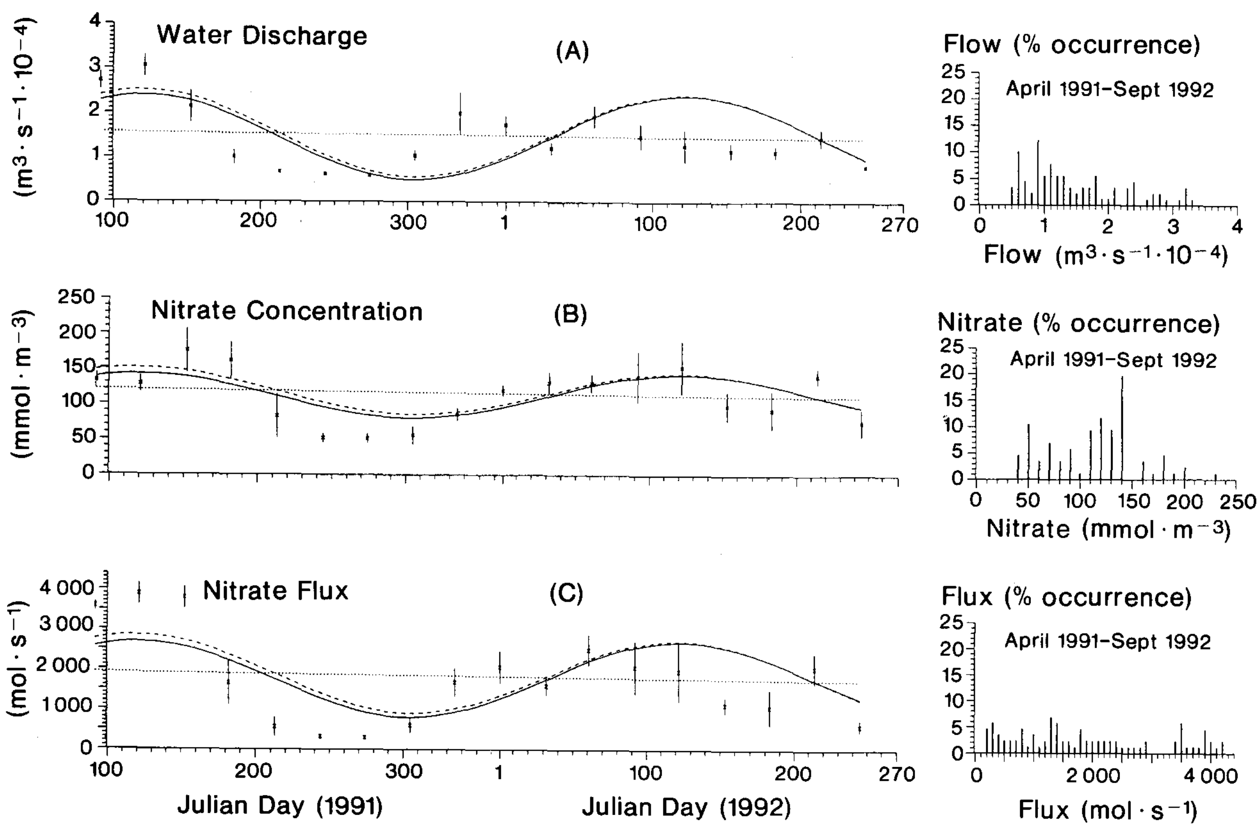

Fig. 5. Time series for high-frequency dataset. Frames A, B, and C show water discharge, nitrate concentration, and nitrate flux, respectively. Plotted *'s are monthly averages; vertical bars indicate variability about the monthly mean. Probability density function estimates are shown to the right of each frame. Variability "predictions" (with long-term means added) are also shown in each frame. The dashed line is the prediction based upon both very-low-frequency (VLF) and annual components. The solid line is the prediction based upon the annual component alone. The dotted line is prediction based only upon the VLF component.

introduces another DOF into each forecastor. Related statistics and prediction skill estimates are presented in Table 3.

The skill levels for water discharge predictors are all low and indistinguishable from zero. These skill levels generally imply that using the local mean discharge value (say a running-mean average over the last several years) is a viable prediction scheme and that the phasing or persistence of annual or interannual cycles may not be sufficiently stable to warrant their inclusion in a skillful predictor (at least for interannual time scales). This point is revisited in the Discussion.

Prediction skills for nitrate concentration esti-

TABLE 3. Means, standard deviations (SD), skewness, flatness (kurtosis), coefficients of variation (CV), and forecasting skills for monthly-averaged high-frequency data series of water discharge (Tarbert Landing, Mississippi), nitrate concentration (Baton Rouge, Louisiana), and associated nitrate flux. Values in parentheses are for full resolution data with no averaging. Forecastor skills are presented for predictions using the annual (A), very-low-frequency (VLF), and both the annual and the VLF cycles. Estimated skills below the threshold (~0.2) associated with random correspondence or artificial skill are indicated by ****.[a]

						Forecastor Skill		
	Mean	SD	Skew	Flat	CV	A	VLF	A + VLF
Water discharge	14,446	6,797	0.83	2.93	0.47	****	****	****
(m^3 s^{-1})	(15,155)	(7,648)	(0.79)	(2.59)	(0.50)			
Nitrate conc.	111	43	−0.17	1.87	0.33	0.61	0.20	0.57
(mmol m^{-3})	(118)	(37)	(0.11)	(2.61)	(0.36)			
Nitrate flux	1,744	1,108	0.58	2.39	0.64	0.79	0.66	0.80
(mol s^{-1})	(1,918)	(1,220)	(0.45)	(1.98)	(0.63)			

[a] Perfect estimators have skill ~1.0; Poor estimators have skill ~0.0. For these particular estimators, the artificial skill level is estimated to be ~0.2.

mators are much better than those for water discharge. They are significantly nonzero and fall in the range 0.2–0.6 depending upon which model is used and the exact methodology used to form the skill estimates. These higher skill levels are probably due to two factors: the dominance of the interannual to decadal portion of the signal and the relative phasing of the annual cycle in this variable for this specific prediction time window.

The nitrate flux predictors show significantly nonzero skill levels in the same range as those for nitrate concentration. These same two factors (signal persistence and favorable phasing of the annual cycle) contribute to higher skill levels.

Table 3 gives statistics for the high frequency dataset. The important points illustrated here are that the percentage variance at frequencies greater than 12 cycles yr^{-1} (cpy) is ~20% for all three variable fields (i.e., high-frequency "noise" is small). The ratio of the associated high-frequency variation amplitude to that of the annual and interannual components of the signal is generally less than one. The high-frequency "noise level" at 6 cpy and greater is comparable to the supra-annual component of variance based on historical estimates (i.e., our specific 18-mo time frame is not atypical). All three of these points indicate that the errors due to the nitrate concentration sampling regimen (i.e., monthly interval grab sampling), while significant, still allow constructive use of these data for the purposes of heuristic time series analyses at seasonal to interannual time scales.

This last point is examined a bit further in Fig. 6, which shows estimated autocorrelation functions for water discharge (top), nitrate concentration (middle), and nitrate flux (bottom) for the high frequency dataset. All three autocorrelations have their first zero crossing at time lags greater than 60 d, all exhibit relatively high values (0.6–0.8) at time lags of 30 d or less, and all three rebound to values of 0.5 or greater for time lags around 1 yr. The weak covariability between water discharge and nitrate concentration is also manifest in the character of the associated cross-correlation function (not shown), which never exceeds an absolute value of ~0.3, even at zero time lag.

The skill values presented in Table 3 are directly comparable to those related to the historical database (37-yr time series) for these variable fields (shown in Table 1). In the historical case, the estimators involved were hindcastors. In Table 3, they are forecastors; estimators are compared to new data (forward in time) that were not used to construct the estimation scheme. The simple difference between hindcast and forecast skills for each specific case gives a preliminary estimate of the artificial skill associated with fortuitous agreement between estimator and data fields. The hindcastor-forecastor skill difference is greatest (~0.4) for water discharge estimators and less (~0.2) for both nitrate concentration and nitrate flux estimators.

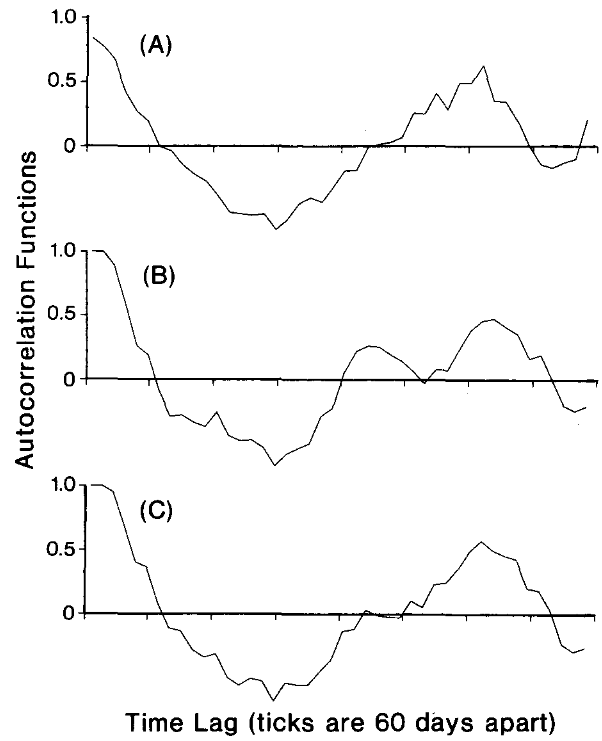

Fig. 6. Autocorrelation function estimates for the high frequency sampled dataset. Frames A, B, and C are the autocorrelation functions for water discharge, nitrate concentration, and nitrate flux, respectively. All frames are scaled the same. Note that the time-lag axes (horizontal coordinate) are stretched compared to Fig. 4.

Discussion and Summary

Our results focused upon two areas of inquiry: advanced statistical characterization of riverine forcing functions and the testing of effective hindcastors-forecastors for these functions. Here these results are discussed in the contexts of the general problem of formulating accurate environmental predictions and of the potential impacts or responses of shelf waters to these riverine forcing functions.

Genuinely skilled predictions of natural phenomena are rare. The infrequent success stories usually involve deterministic dynamical systems and well-known forcing functions such as the motion of celestial bodies under the mutual influence of their gravitational fields. In this work, we addressed aspects of an environmental prediction problem that was considerably less tractable than a simple dynamic trajectory problem.

The supply of water and nutrients delivered to the lower Mississippi and Atchafalaya rivers is the result of many environmental processes interacting over an area that includes ~40% of the coterminous United States, acting over a range of time scales but dominated by seasonal to annual time scales (annual to interannual cycles). The time-space averaging of land-based processes acts as a low-pass filter as does the riverine advection and subsequent mixing of various tributary inputs and associated water mass properties. The behavior of this very complicated natural system is somewhat less erratic in its lower reaches due to this natural, noise-averaging filter. This last point relates to the associated environmental prediction problem in that there is some hope of characterizing persistent aspects of the average or low-pass-filtered output of the system and subsequently predicting its behavior. We have made some progress in that area here.

The probability density functions (PDFs) that best characterize the amplitude variability of riverine water discharge, nitrate concentration, and nitrate flux appear to be skewed and flattened beyond values one would expect for Gaussian random fields. This is significant since the Central Limit Theorem indicates that outputs that are the result of a sum of somewhat equivalently weighted random processes will tend to be Gaussian regardless of the character of the individual processes involved. One must conclude that the riverine forcing functions treated here are the result of one or two dominant processes characterized by skewed and flattened amplitude distributions. Mississippi River drainage basin states are well-known for episodic wet weather in spring and early summer as well as snowmelt runoff events in the upper drainage basin. The PDF characteristics mentioned above also describe this class of behavior. Precipitation in its various forms dominates the overall hydrologic regime, and mediating processes seem to be washed out of the signal. Otherwise, associated PDFs would be more symmetric or near-normal.

We investigated this point a bit further by subtracting the best-fit annual-average signal from each 37-yr historical time series. The residuals were then used to construct new PDF estimates that are seasonally adjusted to some extent. The result is presented in Fig. 3 overlaid upon PDFs associated with the original data. The residual PDFs for water discharge and nitrate flux show considerably more symmetry than those for the original data. The same cannot be said for the nitrate concentration PDF.

The autocorrelation functions for these riverine forcing functions show their time-lagged self-similarity or memory. The shape of these functions implies that month-to-month self-similarity is relatively strong and comparable to the year-to-year (in a given month), longer term memory. There are several factors at play here. First, week-to-week atmospheric weather conditions are generally erratic in comparison to the strength and persistence of the annual cycle. The latter is largely due to planetary-scale, repeatable solar-forcing. The former is an unstable, continental-scale fluid mechanical and thermodynamical process, which is highly unpredictable on synoptic time and space scales. The physical size and effective averaging time scale of the Mississippi drainage basin is considerably greater than that of synoptic-scale weather systems and, therefore, the basin acts as an effective low-pass filter for noisy, weather-scale processes.

The second point regards the nitrate data and associated sampling regimen. We found that week-by-week or month-by-month grab sampling (vertically or cross-sectionally averaged) did a reasonably good job of describing the annual cycle or larger interannual trends in the data; however, the noise level (standard error) associated with the month-to-month grab sampling was ~20%. This sampling-regimen-induced noise is obscured by the uncertainty associated with regional-scale precipitation patterns over subdrainage-basin regions at weekly-to-monthly time scales. Compounded superposition effects can shift or blur the exact timing or amplitude of subseasonal time-scale features making it difficult to consistently hindcast or predict seasonal transitions.

Our ability to actually predict future realizations of riverine forcing function fields was somewhat limited. Nitrate-related fields were predicted over an 18-mo period with some success. We were unsuccessful at predicting water discharge over the same period. However, given the time scales involved in this particular environmental prediction problem, we were essentially presenting the outcome of a single experiment rather than an ensemble averaged result.

The water-discharge predictor performance is very sensitive to the exact phasing of the annual cycle. In this particular time period, peak discharge appeared to arrive somewhat early and a phase shift of a month or two was enough to degrade the effective skill of the estimate. We followed up on our original calculations and found that a forward shift of 1 mo brought the skill above the estimated nonzero significance threshold to ~0.3.

The prediction skill for the nitrate-related fields was considerably better than that for water discharge. The difference between water discharge and nitrate concentration skill is somewhat surprising, but there are several explanations for this outcome. First, considering the variance distributions presented in Table 2, interannual variability is obviously more dominant in the nitrate concentration field. If an estimator represents the interannual or decadal scale signal well, it is likely to portray the near future (the next few years) pretty effectively. Second, the annual cycle in nitrate concentration is less dominant and phase-stable on a historical basis. Therefore, in this particular case the phase shift in the annual cycle had less impact on overall prediction skill than for water discharge. Third, in nitrate concentration and nitrate flux fields, there can be a dilution effect in that higher runoff rates can tend to dilute dissolved constituents. This same mechanism can reconcentrate dissolved constituents during low flow periods. Finally, the last explanation is random chance. Remember that the case examined is essentially the outcome of a single, annual-time-scale experiment and we may be reporting the result of fortuitous or anomalous circumstances. We presented comparative statistics (Table 3) that indicated the test period was fairly representative of historical circumstances.

The freshwater discharge from the Mississippi and Atchafalaya rivers is a time-varying source of suspended and dissolved constituents as well as a dominant factor determining related vertical and horizontal fluxes and rate processes. River waters distribute themselves on the shelf in response to a variety of factors. They move offshore or alongshore due to their own momentum, and that of their receiving waters, and flow downhill in response to gravitational body forces. Within a few hours or tens of kilometers, river waters are mixed ~5:1 with saltier (but less optically dense) coastal receiving waters as described by Wright and Coleman (1971). Remarkably, integral mass conservation considerations dictate that the subsurface flow of denser coastal mixing water toward initial dilution sites must be ~5 times the riverine freshwater flux. Therefore, the dynamical history of the coastal receiving waters is crucial to the evolution and fate of recently introduced river water. Initial dilution leads to significant changes in optical properties, the quality of the light field, relative nutrient partitioning, and finally, phytoplankton growth potential.

After this initial dilution phase, a very persistent buoyant surface layer caps the water column, diminishing vertical fluxes of mass, momentum, energy, and other important constituents such as dissolved oxygen. The associated density difference is unusually large for shelf waters (~5 kg m^{-3}) and, consequently, the vertical fluxes through the surface mixed-layer are relatively small compared to typical shelf conditions.

One goal of this work is to help evaluate environmental impacts such as near-bottom oxygen depletion and related amelioration strategies. Consumption of oxygen is promoted by the decay of organic material ultimately associated with riverine nutrient inputs, mediated by phytoplankton production. The linkages between nutrient inputs and oxygen depletion are treated in various works in this volume and in the literature (e.g., Lohrenz et al. 1994; Rabalais et al. 1994). We note here that the entire sequence of events from initial nutrient input to phytoplankton growth, settlement, and decay is likely to be several times shorter than the average freshwater shelf-residence time (estimated by Dinnel and Wiseman 1986 to be 1–2 mo). Therefore, the phytoplankton biomass resulting from large riverine nutrient flux levels will tend to stay trapped on the shelf to the extent it avoids grazing pressure and subsequent mobilization through the foodweb. The aforementioned physical controls associated with riverine buoyancy flux and related secondary circulation tend to help capture and contain decaying organic matter and resultant hypoxic water beneath the surface mixed-layer. Eadie et al. (1994) show that there is good correspondence between decadal scale variability in United States fertilizer use, riverine nitrate flux delivered to shelf waters, and the sedimentary accumulation rate for organic carbon near the delta.

The primary findings of this study can be summarized as follows. Riverine forcing functions for freshwater discharge, nitrate concentration, and nitrate flux can be hindcast or forecast at significant skill levels on seasonal to annual time scales. Forecast success was due in large part to the innate persistence of the nitrate concentration signal at interannual time scales. Forecast failure (in water discharge) was primarily due to a phase shift in the annual cycle.

The probability density functions for the above fields are non-Gaussian and are better fit by asymmetric distributions. In Fig. 3, we showed Poisson distributions that were reasonably good fits to those observed. The overall riverine source problem can be put in a Poisson framework by asking the following question. "How many integral units of riverine constituent (above a long-term threshold) will be delivered to the shelf over some interval given a specified average arrival rate?"

The structure of the autocorrelation functions indicates that multiple time scales play a role in this forcing function problem. The annual cycle of water discharge combines with decadal-scale variability in nitrate concentration to produce a more complicated nitrate flux signal. Primitive mean-value-based forecastors for these fields might perform as well as more complicated estimation schemes at decadal time-lag horizons. The observational uncertainty induced by an instantaneous monthly transect-averaged nitrate sampling regimen appears to set a noise floor on nitrate flux estimation schemes that is 10–20% of the natural variability at time scales less than the seasonal scale. The month-to-month variability is about the same as that observed from year-to-year during the same month.

Although the variability of riverine source functions is somewhat understandable or predictable, conditions related to coastal receiving waters are subject to a wide range of environmental forcing functions. The riverine, coastal nutrient enhancement, stratification intensification, and primary productivity levels on the inner portion of the Louisiana-Texas shelf are very high by conventional shelf ecosystem standards at most time-space scales. First-order shelf-scale processes such as dominant, persistent circulation patterns, average temperature and salinity conditions in coastal waters, or surface wind-mixing probably control the degree to which hypoxia develops in inner shelf waters at weekly-to-monthly time scales.

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