Journal of Coastal Research	18	2	267–273	West Palm Beach, Florida	Spring 2002

The Use of AVHRR Satellite Data for Estimating Spatially Varying Critical Wind Stress in Florida Bay

Varis Ransibrahmanakul† and Richard P. Stumpf‡

†Technology Planning and Management Corporation
Office at: NOAA National Ocean Service
Center for Coastal Monitoring and Assessment
1305 East-West Highway, N/SCI1 rm 9110
Silver Spring, MD 20910, U.S.A.

‡NOAA National Ocean Service
Center for Coastal Monitoring and Assessment
1305 East-West Highway, N/SCI1 rm 9109
Silver Spring, MD 20910, U.S.A.

ABSTRACT

RANSIBRAHMANAKUL, V. and STUMPF, R.P., 2002. The use of AVHRR satellite data for estimating spatially varying critical wind stress in Florida Bay. *Journal of Coastal Research,* 18(2), 267–273. West Palm Beach (Florida), ISSN 0749-0208.

Critical bottom stress for resuspension and sediment settling are essential parameters in determining and modeling sediment transport in shallow water. However, these parameters are often assumed spatially uniform due to the problem of obtaining the necessary data. This paper presents a method for obtaining spatially varying critical wind stress and spatially varying change in concentration by settling in Florida Bay. As a means to get critical wind stress, a simple model for estimating suspended sediment concentration was implemented. The model has one time-dependent input, wind stress; and four time-independent inputs: maximum concentration, minimum concentration, temporal scale of sediment settling decay, and critical wind stress. Maximum concentration, minimum concentration, and temporal scale of sediment concentration settling decay were derived from time series of Advanced Very High Resolution Radiometer (AVHRR). Temporal scale of settling was determined using a simple model of concentration change with wind mixing of the water column. The critical wind stress for resuspension was obtained by optimizing the error between the model's results and the observed concentrations. The modeled sediment concentration performed best in areas where wind was the only dominant forcing agent rather than in areas where advection may also play a significant role. Incorporating this approach into standard modeling of sediment circulation can provide better information on the occurrence and potential for resuspension.

ADDITIONAL INDEX WORDS: *Remote sensing, wind stress, AVHRR, sediment resuspension, Florida Bay.*

INTRODUCTION

Resuspension of bottom sediments can enhance nutrient cycling (GRANT and BATHMANN, 1987; SIMON, 1989) but also can attenuate light in the water (BLOM *et al.*, 1994; STUMPF *et al.*, 1999), and inhibit seagrass growth. Several studies have shown dramatic changes in suspended sediment concentration when wind speed exceeded a threshold. A suspended sediment concentration increase of ten-fold in Chesapeake Bay (WARD, 1985), ten-fold in a prairie lake (CARPER and BACHMANN, 1984), and four-fold in Tamaren Lake, Sweden (BENGTSSON and HELLSTROM, 1992) were observed when winds exceeded 7, 5, and 5 m s^{-1}, respectively. Bottom resuspension is activated when bottom shear stress exceeds a critical bottom stress. Consequently, many models are step functions. PARCHURE and METHA (1985) and VLAG (1992) set the upward flux of suspended silt to zero when bottom shear stress is less than critical bottom stress, and the flux approaches a predefined maximum when bottom shear stress becomes greater than critical bottom stress.

00122 received 26 August 2000; accepted in revision 29 August 2001.

Although critical bottom stress is an important parameter in resuspension models, few critical bottom stresses are derived from observed data. Time series of suspended sediment measurements required to properly estimate critical bottom stress are rare because sampling frequency is problematic in field efforts. Generally only short time periods can be handled. For example, WARD *et al.* (1984) sampled daily for 10 days; CARPER and BACHMANN (1984) had biweekly sampling for 41 days. The alternative approach of using laboratory measurements requires extensive sample, labor, and modeling to determine critical wind stress from critical bottom stress. As an example, PRAGER and HALLEY (1997) spent months of diving observations, summer 1996 through January 1997, to construct a map of Florida Bay bottom types.

Due to the lack of observations, critical bottom stress is often assumed constant although it is known to vary temporally and spatially even in small lakes (EVANS, 1994). In an alternate approach, CARPER and BACHMANN (1984) solved for critical shear stress empirically when the wavelength exceeds twice the water depth. Except for depth, their empirical solution did not (and could not readily) account for other de-

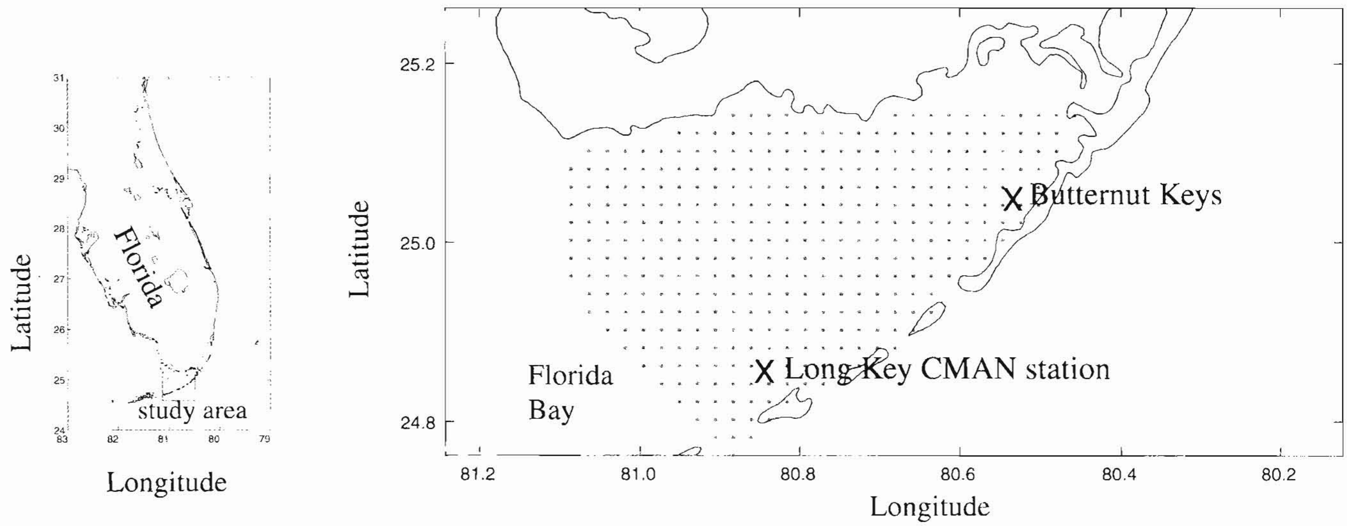

Figure 1. The study area Florida Bay. For each grid element (gray dots), critical wind stress was obtained. Monthly mean concentration in Figure 2 was obtained at Butternut Keys. Wind stress in Figure 4.1 was obtained from a CMAN station at Long Key.

pendent variables, such as size and type of sediments, sediment compaction, and water content.

In this paper, we propose an approach for estimating spatially varying critical wind stress from time series of Advanced Very High Resolution Radiometer (AVHRR) satellite data. The AVHRR sensor is sensitive to the red, near-infrared, and thermal wavelengths with a spatial sampling of 1.1 km at nadir. The combination of the red and near-infrared bands can be used to derive water reflectance, a turbidity indicator, using standard corrections for atmosphere and sun angle (STUMPF and FRAYER, 1997). The sampling frequency is near daily. Although, clouds could introduce severe data discontinuity, selective AVHRR data can be used to monitor turbidity and suspended sediments in Delaware Bay (STUMPF and PENNOCK, 1989), Mobile Bay (STUMPF *et al.*, 1993), and the Mississippi River plume (WALKER, 1996). In this study, we used the data between January and March 1995 to estimate critical wind stress because (1) there were many resuspension events; (2) approximately 50% of all the pixels in Florida Bay were useful as compared to ~16–40% between 1994 and 1995; and (3) collections were fairly continuous over time between January and March 1995 (The observations are marked as dark dots in Figures 4.2–4.5).

Florida Bay is a semi-enclosed estuary, about 500 km^2, off the Gulf of Mexico, between the Florida Keys and mainland Florida (Figure 1). A combination of seagrass die-offs and reported increases in turbidity have lead to an extensive study of the estuary (FOURQUREAN and ROBBLEE, 1999). Even with the seagrass die-offs, seagrass beds are still extensive in the bay; although they vary considerably in density and size (HALL *et al.*, 1999). These beds play a significant role in controlling resuspension (STUMPF *et al.*, 1999) as they can attenuate mixing and, hence, increase the critical stress required for resuspension.

The tidal energy is relatively weak, the highest tidal amplitude of 0.3 m occurs in the western bay (WANG, 1994). Wind is the dominant agent controlling resuspension. In the summer, southeasterly trade winds are most frequent. In the winter, strong northerly winds associated with cold front passages occurs about every week (LEE, 1986). Sediment resuspension is a key aspect of the turbidity problem, particularly during winter when recurrent cold fronts bring strong winds (STUMPF *et al.*, 1999).

The mudbanks divide the Bay into a complex of basins, each having depths of 1–2m. These limit advection so the basins can be considered similar to shallow turbid lakes for resuspension. BAILEY and HAMILTON (1997) used the following exponential function to describe deposited concentration, C_{dep}, due to settling in turbid Lake Thomasons, Western Australia.

$$C_{dep} = C_0 \exp(-\beta h^{-1} t^{-1})$$

Where β is a deposition parameter, C_0 is the initial concentration, h is depth, and t is time. BAILEY and HAMILTON (1997) compared the model to laboratory observed concentrations and found the function's r^2 to be 0.85. LICK (1982), SONDERGRAD *et al.* (1992), and HAMILTON and MITCHELL (1996) also suggested that sediment settling takes an exponential form. CARTER and ROBINSON (1987) and MARIANO and BROWN (1992) used the term $\exp(-[dt/T]^2)$ to describe several dynamic regimes; where *dt* is temporal lag and T is a temporal decay scale.

SATELLITE IMAGE AND WIND MEASUREMENTS

The satellite data used in this study have been previously processed and validated by STUMPF *et al.* (1999) to describe variations in water clarity and bottom albedo in Florida Bay from 1985 to 1997. STUMPF *et al.* (1999) disregarded AVHRR data with solar zenith angles greater than 65 degrees then removed the cloud contaminated pixels. The remaining pixels were corrected for atmospheric path radiance and sun angle

(STUMPF and PENNOCK, 1989; STUMPF and FRAYER, 1997; STUMPF *et al.*, 1999) to obtain total percent reflectance of the water, R. However, Florida Bay is optically shallow, meaning the obtained reflectance could include bottom (*e.g.*, mud, sand, seagrass) refelctance, backscatter from suspended sediments in the water column and reflectance from the sea surface. To correct for bottom reflectance, STUMPF *et al.* (1999) used the minimum monthly mean reflectance for each year at each pixel, R_{min}, to represent the reflectance due to bare bottom or seagrass background for that year. The reflectance of the water alone at each pixel becomes $R_w = R - R_{min}$. The variability of sea state was negligible because Florida Bay is depth and fetch limited; also, waves and flat seas cannot be separated at 1 km pixel resolution. Generation of corrected water reflectance (for the sun angle, atmospheric radiance, and bottom reflectance) allowed direct comparison of AVHRR image data from different time periods. A more detailed description of the correction procedure may be found in STUMPF *et al.* (1999). The relationship $C_{obs} = 6.9\ R_w - 20.1$ was applied to convert R_w to "observed" concentrations, C_{obs}, in mg L^{-1}. The relationship was based on unpublished data from field measurements and satellite images. The validation of this relationship is not critical because only relative, rather than actual, concentration is required to estimate critical wind stress.

In addition to the satellite data, wind stress was obtained from the CMAN station (NOAA National Oceanographic Data Center) at Long Key, Florida (Figure 1). We assumed that the spatial variability of wind stress (using squared wind speed) is negligible in the bay, although this is not always the case. The scattered plot of the monthly mean wind stress and monthly mean suspended sediment concentration from Butternut Keys (Figure 1) suggests that wind is an important driving agent in the bay. Excluding October, November, and December, the r^2 between monthly mean wind stress and monthly mean suspended sediment concentrations for northeastern bay, between 1995 and1996, is 0.70 (Figure 2). In the fall, resuspension may require higher wind stress because bottom is bounded by algal mats that die in the winter (PRAGER, 1998).

METHODS

As a means to get spatially varying critical wind stress, we implemented a model to estimate suspended sediment concentrations with critical wind stress as one of the parameters. We obtained critical wind stress by optimizing the model results to the observed suspended sediment concentrations from satellite.

A step model was used because previous studies (CARPER and BACHMANN, 1984; WARD, 1985; BENGTSSON and HELLSTROM, 1992) observed resuspension to occur when wind speed exceeds a certain threshold. The model requires one time dependent input, wind stress τ. It also requires four time independent inputs: maximum concentration C_{max}, minimum concentration C_{min}, temporal decay scale of sediment settling T, and critical wind stress τ_{cr}. When $\tau > \tau_{cr}$, we assume resuspension occurs and the estimated suspended sediment concentrations C_{est} is constrained to C_{max} (*e.g.*, PARCHURE and METHA, 1985; VLAG, 1992). When $\tau < \tau_{cr}$, we assume settling occurs and C_{est} becomes the product of C_{max} and an exponential term (*e.g.*, BAILEY and HAMILTON, 1997). The exponential term $\exp[-[t - t^*]^2 T^{-2} [\tau_{cr} - \tau]\tau_{cr}^{-1}]$ describes settling where t is the current time, t^* is the time of last resuspension, and T is the temporal decay scale of observed suspended sediment concentration, C_{obs}. One difference between our exponential term and that of CARTER and ROBINSON (1987) and MARIANO and BROWN (1992) is the presence of $[\tau_{cr} - \tau]\tau_{cr}^{-1}$ which was introduced to scale settling rate to stress-induced mixing. As τ approaches τ_{cr}, the exponential term approaches 1 and C_{est} approaches C_{max}. As τ approaches 0, C_{est} approaches $C_{max} \exp[-[t - t^*]^2 T^{-2}]$. If C_{est} falls below the minimum concentration, C_{min}, C_{est} is constrained to C_{min}. The constraints and model may be expressed as follows:

if $\tau > \tau_{cr}$, then

$$t^* = t \qquad C_{est} = C_{max}$$

if $\tau < \tau_{cr}$, then

$$C_{est} = C_{max} \exp[-[t - t^*]^2 T^{-2} [\tau_{cr} - \tau]\tau_{cr}^{-1}]$$

if $C_{est} < C_{min}$, then

$$C_{est} = C_{min}$$

For each grid element shown in Figure 1, C_{min}, C_{max}, T, and τ_{cr} were obtained in this study and shown in Figure 3. Their spatial variability will be discussed in the next section. The term C_{max} was computed as the mean of C_{obs} following selected strong winter wind events in 1995 and 1996. Similarly, C_{min} was the mean of C_{obs} between July and September 1995 and 1996, when winds were weak (winds are weak in tropical summer). The term T was obtained from the autocorrelation function, $r(\Delta t)$. Following BRINK *et al.* (1991), an autocorrelation function may be defined as:

$$r(\Delta t) = \frac{\sum^{N} [C_{obs}(t) - \bar{C}_{obs}(t)][C_{obs}(t + \Delta t) - \bar{C}_{obs}(t + \Delta t)]}{N\sigma_{obs}(t)\sigma_{obs}(t + \Delta t)}$$

where $C_{obs}(t)$ is observed concentration at time t, Δt is time lag, $\bar{C}_{obs}(t)$ is mean observed concentration at time t, N is the number of observations, and σ_{obs} is the standard deviation of C_{obs}. In this study, we assumed $\sigma_{obs}(t) = \sigma_{obs}(t + \Delta t)$ and $\bar{C}_{obs}(t) = \bar{C}_{obs}(t + \Delta t)$. When $r(\Delta t)$ equals to e^{-1}, the resulting Δt is the e-folding decay scale of C_{obs}. This e-folding time will be denoted by T. Once C_{min}, C_{max}, and T were estimated, τ_{cr} and C_{est} remained unknown. We estimate critical wind stress as one that produced the minimum squared error between C_{obs} and C_{est} from January 1 through March 31, 1995. This semi-empirical based model allows us to bypass variables that are unknown or difficult to measure such as the translation of wind stress into bottom stress and the resuspension critical stress for bottom with spatially variable seagrass cover, grain size, water contents, *etc.*

RESULTS AND DISCUSSION

Four hundred and ninety AVHRR scenes between January 1995 and December 1996 were used to produce observed suspended sediment concentrations time series. Figure 4.1

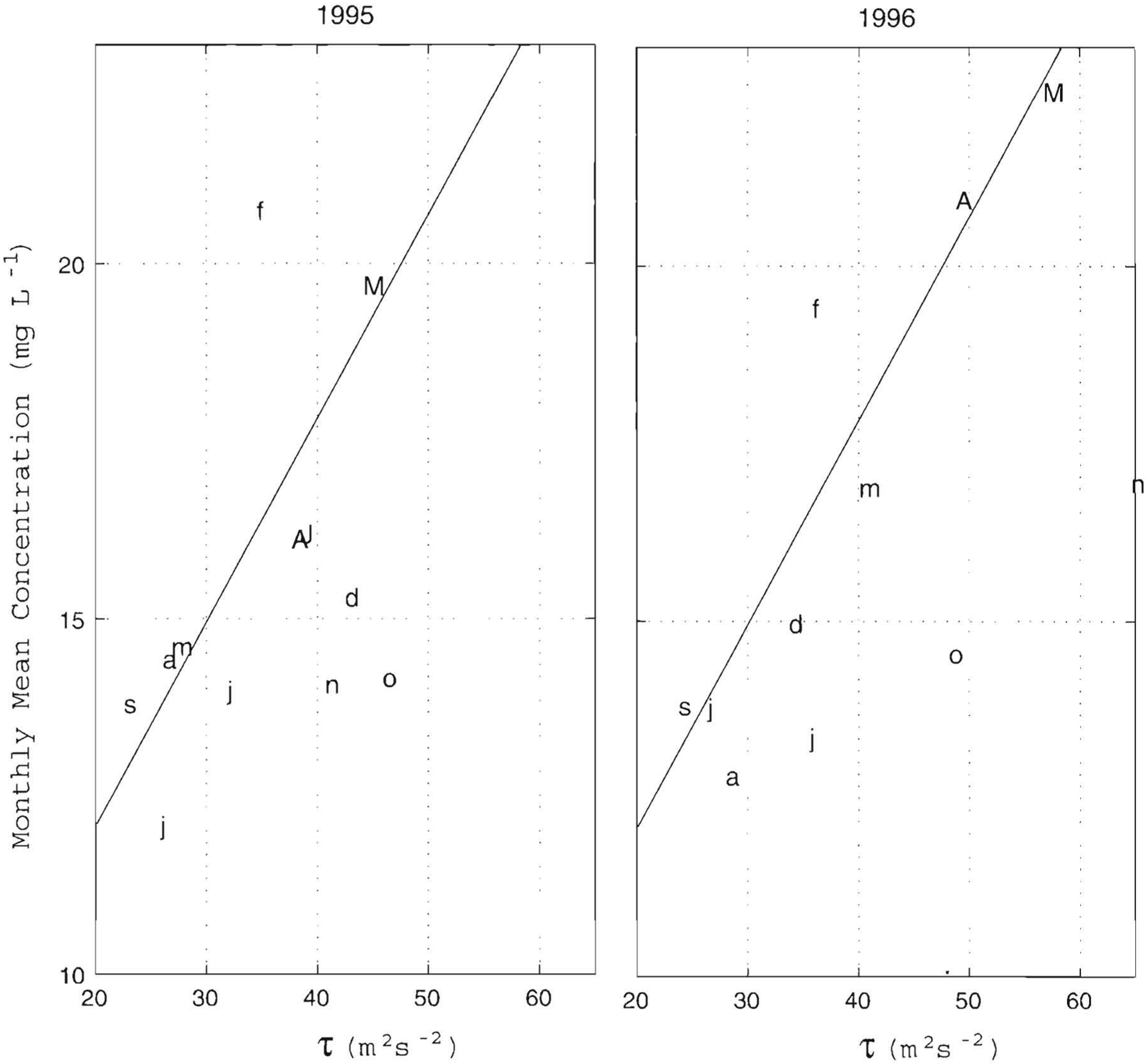

Figure 2. Scattered diagram of monthly mean suspended sediment concentration form Butternut Key and wind stress. The legends are J January, F February, M March, A April, m May, j June, j July, a August, s September, o October, n November, and d December. The ensemble best fit line for all months but October, November, and December is overlain; its r^2 is 0.70.

shows the observed wind stress obtained from a CMAN station at Long Key, Florida. The spikes in the wind stress indicate short but strong wind events, usually greater than 100 m^2s^{-2}. Disregarding the model results (dark lines in Figures 4.2–4.5), the observed wind stress and observed suspended sediment concentrations can provide some insights into the resuspension process of Florida Bay. During and/or shortly after strong wind events, observed suspended sediment concentrations in northeastern bay (dark dots in Figures 4.2–4.3) often increased from its normal condition of ~5 mg L^{-1} to 60 mg L^{-1}. Between August and December of 1995 and 1996, when wind stress was below 100 m^2s^{-2}, the observed concentrations remained stable at 5–10 mg L^{-1}.

Except for the difference in magnitudes of the concentrations, the observed suspended sediment concentrations in the western bay also increased during and/or shortly after strong wind events (Figures 4.4–4.5). Their normal suspended sediment concentrations are ~10 mg L^{-1} and they approach 40–50 mg L^{-1}. The differences in magnitudes between the northeastern and western bays (Figures 4.2 and 4.3 vs Figure 4.5) could be associated with the differences in sea grass density and/or vegetated bottom type. In Figure 4.4, the period between September and November 1995 should be noted because the observed suspended sediment concentrations increased multiple folds but wind stress was relatively low. This area had extensive seagrass deaths and is near many mud banks (STUMPF *et al.*, 1999) with tidal flow causing chronic turbidity. Advection of mud caused the observed resuspension.

The primary objective of this paper is to introduce an approach to estimate spatially varying critical wind stress using AVHRR data. The estimated critical wind stress, along with

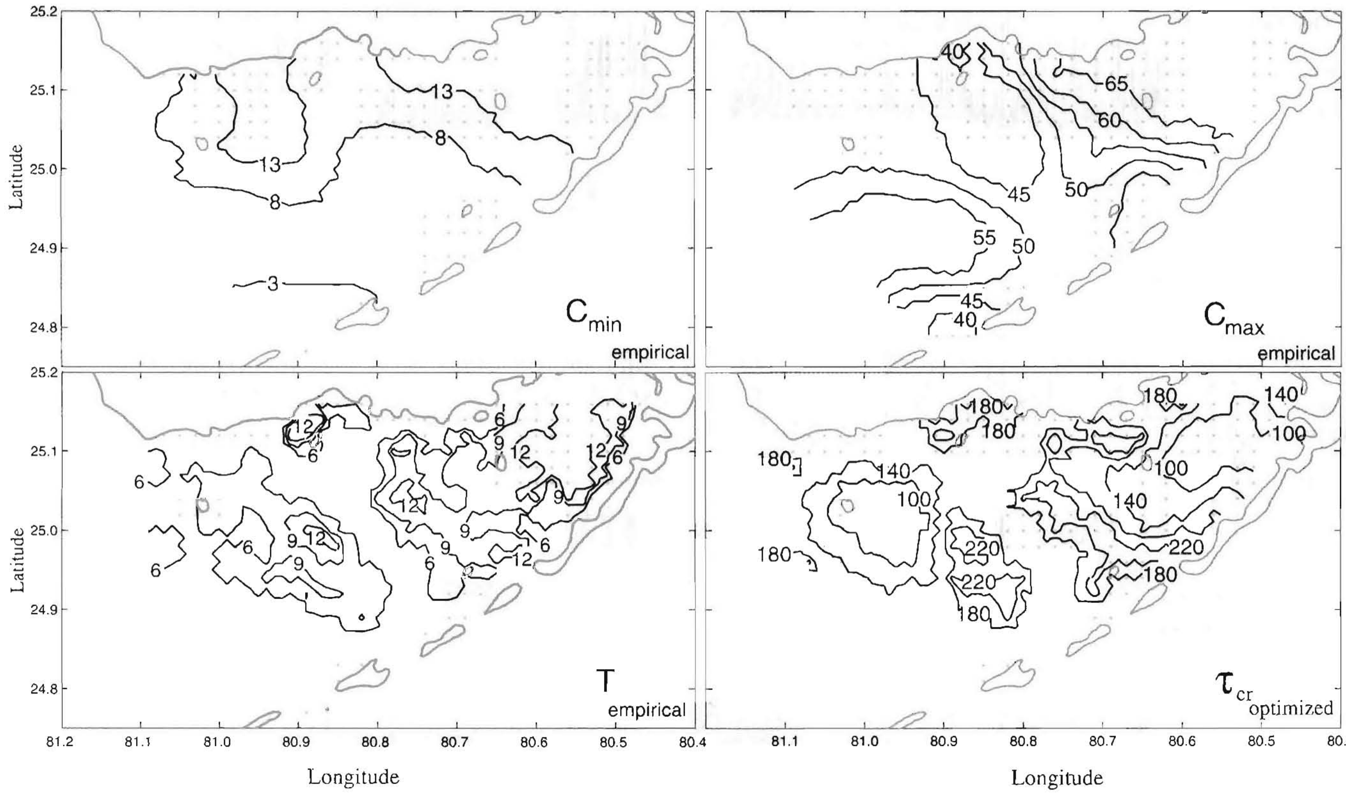

Figure 3. Maps of minimum concentration C_{min} (mg L^{-1}), maximum concentration C_{max} (mg L^{-1}), sediment settling decay scale T (days), maximum critical wind stress τ_{cr} (m^2 s^{-2}). Concentration related parameters (C_{min}, C_{max}, T) were estimated empirically with physical justifications from satellite data. The term τ_{cr} was obtained from model optimization using observed wind stress and concentrations between January 1 and March 31, 1995. The four parameters were used in the model to estimate wind-induced suspended sediment concentration in Florida Bay.

maximum concentration, minimum concentration, and temporal decay for Florida Bay suspended sediments are shown Figure 3. The generated critical wind stress is low in the northeastern bay (100 m^2s^{-2} contour) where HALL *et al.* (1999) observed relatively low seagrass density. PRAGER (1998) determined that 100 m^2s^{-2} would lead to wind speed resuspension in areas with no seagrass. The general critical wind stress is higher in parts of the western bay (180 and 220 m^2s^{-2} contours) where HALL *et al.* (1999) observed seagrass abundance. PRAGER (1998) suggests that 200 m^2s^{-2} is required for resuspension in the presence of algal mats. The spatial variability in Figure 3 also supports EVANS' (1994) note that critical shear stress varies spatially and temporally even in small lakes and estuaries.

In this study, a model was implemented as a means to get critical wind stress. Thus, some model validations will be discussed. The model results are shown as dark lines in Figures 4.2 through 4.5. Qualitatively, the model estimated high suspended sediment concentrations when the observed concentrations were high (*e.g.*, February, March, October, and December 1996); the model also estimated low suspended sediment concentrations when the observed concentrations were low (*e.g.*, June through September 1996). The observed concentrations were occasionally above the model's maximum concentrations and below the model's minimum concentrations because the model's maximum and minimum concentrations were the means of selected images (where means would eliminate outliers from skewing the values).

The χ^2 test was applied to determine the model's goodness of fit (Figure 5), with the null hypothesis H_o being: model − observed = 0. Our statistics show that the model performed better than random noise at significant level of 0.80, the better results here suggest what we would expect, that most variation in sediment concentration is locally induced by wind. The model performed poorly in the western bay that is affected by the Gulf currents, indicating the importance of advection in determining sediment concentrations (*e.g.*, in Figure 4.4, the model failed to hindcast high concentrations events between September and November 1995). Although the χ^2 test in Figure 5 shows the model's performance is not statistically significant at the 10% criteria, it should be noted that (1) χ^2 is the accumulative error of all 429 scenes and that the model was only designed to estimate strong wind-induced suspended sediment concentrations. For example, C_{est} was simply constrained to C_{min} after settling from resuspension, and the model did not attempt to resolve tidal-induced variability. Also, (2) areas of potential applicability can be identified and the approach of using satellite data to obtain critical wind stress is still applicable to many shallow lakes and estuaries.

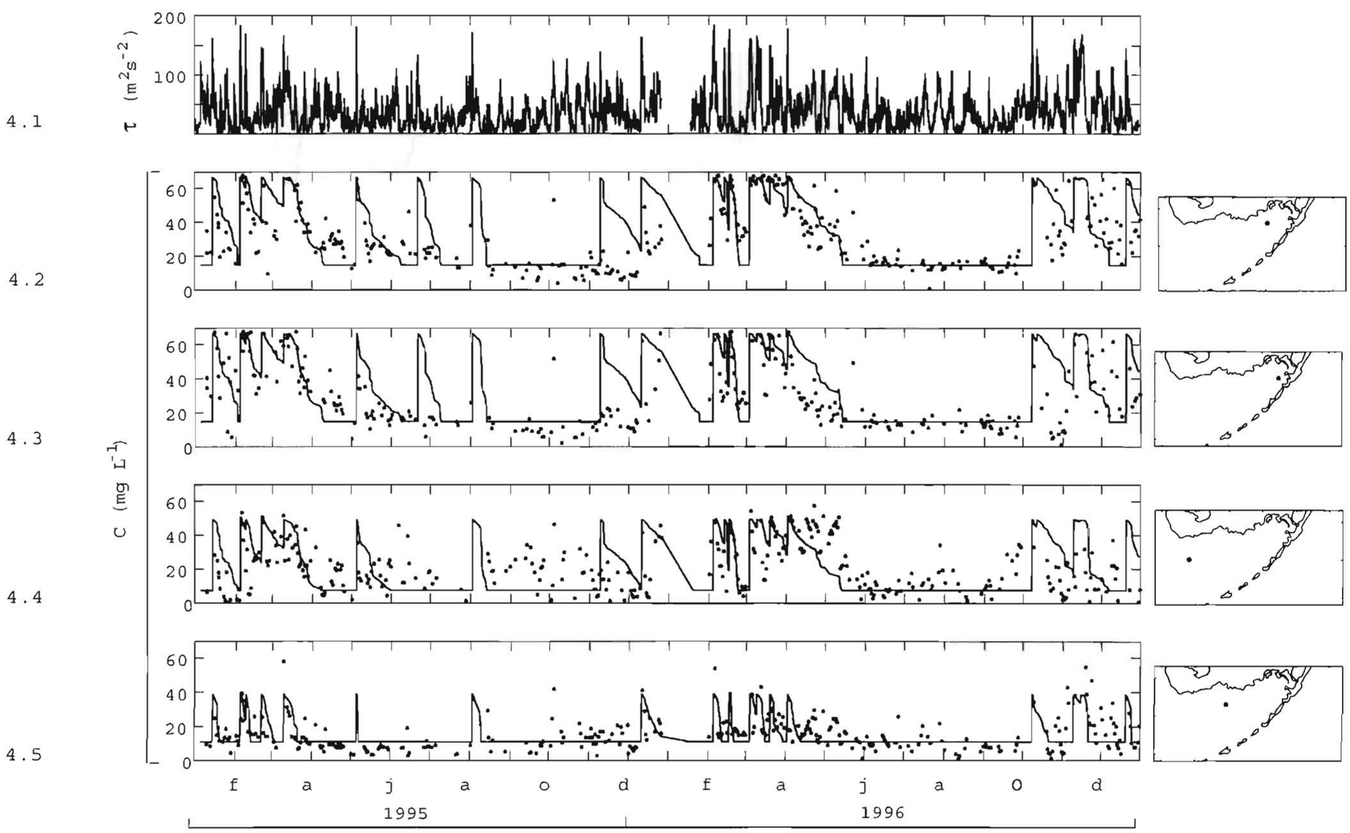

Figure 4.1. The wind stress from the Long Key, Florida, CMAN station.
Figures 4.2–4.5. The observed (dots) and predicted (line) suspended sediment concentrations for the stations shown on the right hand side.

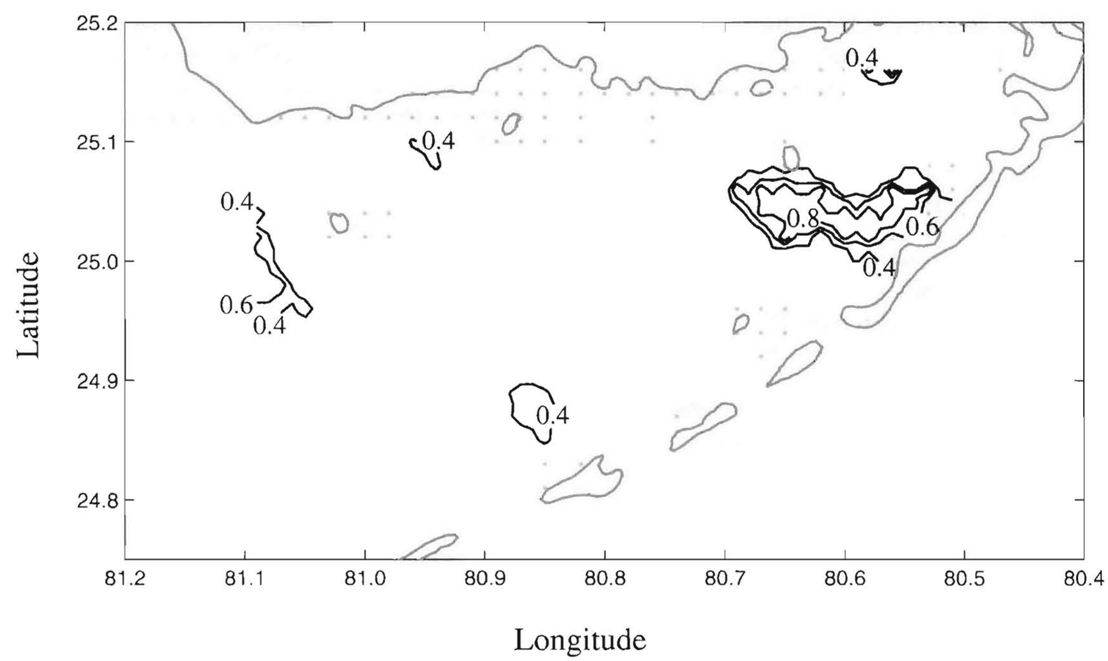

Figure 5. Evaluation of the model using χ^2 test. The 0.8 contour indicates the model performs better than random noise at significant level 0.8.

In addition to an advection term, an inclusion of a time dependent critical stress would also improve the model in this environment. The rapid succession of strong wind events in the winter attenuate consolidation and remove organic binding agents such as mats; while, the development of algal mats in the summer reduce resuspension (PRAGER, 1998). Prager's analysis suggests that 200 m^2s^{-2} is required for resuspension in the presence of algal mats, but only 100 m^2s^{-2} is needed when the mats have been removed. In another study, BENGTSSON *et al.* (1990) suggests that critical wind stress for unconsolidated materials (absence of mats) can be one-sixth that of the consolidated materials (presence of mats). We did not attempt to construct space-time dependent τ_{cr} because our data set of two-year time series is not sufficient to resolve seasonal variability. Furthermore, another set of independent time series would be needed to validate the model.

This paper introduces an alternate approach to intensive field sampling in obtaining spatially varying critical wind stress. Determination of critical shear stress can involve time-intensive field and laboratory analysis. The approach may improve and allow for better assessment of the theoretical aspects of determining critical stress. Modelers using wave hindcasting techniques will find the satellite-derived maps of critical wind stress useful for validating theoretically-derived critical bottom stresses.

ACKNOWLEDGEMENTS

The authors thank Megan Frayer for satellite data organization and registration. The authors also thank Jeff List, Rich Signell, and Ellen Prager for their technical comments. This project was supported by NOAA Coastal Ocean Program (Remote Sensing of Coastal Waters) and U.S. Geological Survey South Florida Ecosystem Program.

LITERATURE CITED

BAILEY, M., and HAMILTON, D., 1997. Wind induced sediment resuspension: a lake-wide model. *Ecological Modeling,* 99, 217–228.

BENGTSSON, L.; HELLSTROM, T., and RAKOCZI, L., 1990. Redistribution of sediments in three Swedish lakes. *Hydrobiologia,* 1992, 167–181.

BENGTSSON, L. and HELLSTROM, T. 1992. Wind-induced resuspension in a small shallow lake. *Hydrobiologia,* 241, 163–172.

BLOM, G.; VAN DUIN, E.H.S., and LIJKLEMA, L., 1994. Sediment resuspension and light conditions in some shallow Dutch lakes. *Water Science and Technology,* 30, 243–252.

BRINK, K.H.; BEARDSLEY, R.C.; NIILER, P.P.; ABBOTT, M.; HUYER, A.; RAMP, S.; STANTON, T., and STUART, D. 1991. Statistical properties of near-surface flow in the California Coastal Transition Zone. *Journal of Geophysical Research,* 96, 14693–14706.

CARPER, G.L. and BACHMANN, 1984. Wind resuspension of sediments in prairie lake. *Can. J. Fish. Aquat. Sci.,* 41, 1763–1767.

CARTER, E.F. and ROBINSON, A.R., 1987. Analysis models for the estimation of oceanic fields. *Journal of Atmospheric and Oceanic Technology,* 4, 49–74.

EVANS, R.D., 1994. Empirical evidence of the importance of sediment resuspension in lakes. *Hydrobiologia,* 284, 5–12.

FOURQUREAN, J.W. and ROBBLEE, M.B., 1999. Florida Bay: a brief history of recent ecological changes. *Estuaries,* 22, 345–357.

GRANT, J. and BATHMANN, U.V., 1987. Swept away: resuspension of bacterial mats regulates benthic-pelagic exchange of sulfur. *Science,* 236, 1472–1474.

HALL, M.O.; DURAKO, M.J.; FOURQUREAN, J.W., and ZIEMAN, J.C., 1999. Decadal changes in seagrass distribution and abundance in Florida Bay, *Estuaries,* 22, 445–459.

HAMILTON, D.P. and MITCHELL, S.F., 1996. An empirical model for sediment resuspension in shallow lakes. *Hydrobiologia,* 317: 209–220.

LEE, T.N., 1986. Coastal circulation in the Key Largo Coral Reef Marine Sanctuary. *In:* VAN DE. KREEKE, J. (ed.) *Physics of Shallow Estuaries and Bays* New York: Springer-Verlag, pp. 178–198.

LICK, W., 1982. Entrainment, deposition and transport of fine-grained sediments in lakes. *Hydrobiologia,* 91, 31–40.

MARIANO, A.J. and BROWN, O.B., 1992. Efficient objective analysis of dynamically heterogeneous and nonstationary fields via the parameter matrix. *Deep-Sea Research,* 39, 1255–1271.

PARCHURE, T.M. and METHA, A.J., 1985. Erosion of soft cohesive deposits. *Journal Hydrological Engineering,*, 10, 1308–1326.

PRAGER, E., 1998. Sediment Resuspension in Florida Bay. *Proceedings 1998 Florida Bay Science Conference,* May 12–14, 1998, University of Miami.

PRAGER, E.J. and HALLEY, R., 1997. *Florida Bay Bottom Types,* U.S. Geological Survey Open File 97–0526, Reston, Virginia.

SIMON, N.S., 1989. Nitrogen cycling between sediment and the shallow-water column in the transition zone of the Potomac River and Estuary. II. The role of wind-driven resuspension and adsorbed ammonium. *Estuarine, Coastal and Shelf Science,* 28, 531–547.

SONDERGAARD, M.; KRISTENSEN, P., and JEPPENSEN, E., 1992. Phosphorus release from resuspended sediment in the shallow and wind exposed Lake Arreso, Denmark. *Hydrobiologia,* 228, 91–99.

STUMPF, R.P.; GELFENBAUM, G., and PENNOCK, J.R., 1993. Wind and tidal forcing of a buoyant plume, Mobile Bay, Alabama. *Continental Shelf Research,* 13, 1281–1301.

STUMPF, R.P. and PENNOCK, J. R., 1989.Calibration of general optical equation for remote sensing of suspended sediments in a moderately turbid estuary. *Journal of Geophysical Research,* 94, 14363–14377.

STUMPF, R.P. and FRAYER, M.L.,1997. Application of AVHRR for examination of water clarity in time series in Florida Bay. *In:* KAHRU, M. and BROWN, C.W. (eds.) *Monitoring Algal Blooms: New Techniques for Detecting Large-Scale Environmental Change.* Landes Bioscience, chapter 1, 1–23.

STUMPF, R.P.; FRAYER, M.L.; DURAKO, M.J., and BROCK, J.C., 1999. Variations in Water Clarity and Bottom Albedo in Florida Bay from 1985 to 1997, *Estuaries,* 22, 431–444.

VLAG, D.P., 1992. A model for predicting waves and suspended silt concentration in a shallow lake. *Hydrobiolgia,* 235/236, 119–131.

WALKER, N.D., 1996. Satellite assessment of Mississippi River plume variability: causes and predictability, *Remote Sensing of Environment,* 58, 21–35.

WANG, J.D.; KREEKE, J.; KRISHMAN, N., and SMITH, D., 1994. Wind and tide response in Florida Bay, *Bulletin of Marine Science,* 54, 579–601.

WARD, L.G.; KEMP, W., and BOYNTON, W., 1984. The influence of waves and seagrass communities on suspended particulates in an estuarine embayment, *Marine Geology,* 59, 83–103.

WARD, L.G., 1985. The influence of wind waves and tidal currents on sediment resuspension in middle Chesapeake Bay, *Geo-Marine Letters,* 5, 71–75.