Dynamics of Carbon Export to the Atmosphere and Oceans from Fluvial Systems of the Humid Tropics: Southeast Asia

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

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TITLE OF PROPOSED PROJECT **Dynamics of Carbon Export to the Atmosphere and Oceans from Fluvial Systems of the Humid Tropics: Southeast Asia**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PREPROPOSAL NO., IF APPLICABLE
$	48 months	10/01/02	

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- ☐ HISTORIC PLACES (GPG II.C.9)
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Page 1 of 2 Electronic Signature

A. PROJECT SUMMARY

The overall question we are addressing in this proposal is, *"What role does the evasion (outgassing) of CO_2 from the river system to the atmosphere play relative to fluvial carbon export to the ocean in the carbon cycle of the humid tropics?"* We have recently demonstrated that outgassing of CO_2 from rivers and wetlands of the central Amazonian basin is 1.2 ± 0.3 Mg C ha^{-1} y^{-1}, or, when extrapolated across the entire basin, an order of magnitude greater than fluvial export of organic carbon to the oceans. Such a flux would be an important loss, as it is approximately equal to lower estimates of carbon sequestration in the Amazon. These conclusions lead to the working hypothesis for this proposal, that *Surface water CO_2 evasion is the dominant source of carbon loss (exceeding export to the oceans by a factor of 10) in fluvial systems of the humid tropics, and in the aggregate reconciles the tropics in the global carbon budget. Evasion is driven primarily by in-stream respiration of organic carbon translocated in space and time from its terrestrial and riparian origins*. While estimates are becoming better constrained in the Amazon, they are not elsewhere in the tropics, particularly in regions of much greater anthropogenic impact.

With this proposal we intend to extend and test our Amazon-based working hypothesis to another significant region, Southeast Asia. We propose to (1) enhance an existing model with improved water routing and inundation, sediments, and carbon modules as a function of landscape condition, (2) conduct a field sampling campaign to determine region-specific processes and provide data for model validation, and (3) use the resulting improved model to analyze questions concerning the dynamics of carbon in the fluvial environments of Southeast Asia which will test our working hypothesis.

The most significant intellectual merit of our proposal is (1) that a significant anomaly in the global carbon cycle is being addressed, and (2) the work represents a convergence of historically separate lines of earth science into a significant "new" view of the global importance of the processes and magnitudes of land-water-atmosphere coupling. The most important broader impact of the work will most likely come via improved tools and information networks for "sustainability" in a region of multiple transboundary environmental pressures.

TABLE OF CONTENTS

For font size and page formatting specifications, see GPG section II.C.

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

C. PROJECT DESCRIPTION

C.1. The Role of Tropical Riverine Environments in the Global Carbon Cycle

The overall question we are addressing in this proposal is, *"What role does the evasion (outgassing) of CO_2 from the river system to the atmosphere play in the carbon cycle of the humid tropics relative to fluvial carbon export to the ocean?"* The context is the following.

The major biogeochemical role of river systems in the global carbon cycle is typically considered to be the fluvial export of total organic carbon (TOC) and dissolved inorganic carbon (DIC) to the ocean (0.4 - 0.8 and 0.4 Gt C yr^{-1}, respectively)(Degens *et al.* 1991). While these fluxes are small components of the global C cycle, they are significant compared to the net oceanic uptake of anthropogenic CO_2 (Sarmiento and Sundquist 1992). Aquatic carbon exports from terrestrial ecosystems, however, are not limited to fluvial discharge. Early measurements in the Amazon suggested that global CO_2 efflux (fluvial export plus respiration) from the world's rivers could be on the order of a Gt C yr^{-1} (Richey *et al.* 1980). Recent measurements of temperate rivers lead to estimates of global river-to-atmosphere fluxes of ~0.3 Gt C yr^{-1}, with evasion nearly equivalent to riverine TOC or DIC export (Cole and Caraco 2001). Hope *et al* (2001) cautioned that direct measurements of land-atmosphere CO_2 gas exchange that ignore water-borne fluxes might significantly overestimate terrestrial carbon accumulation. There is new evidence that outgassing of CO_2 may be an emerging issue in the carbon cycle of the tropics.

Terrestrial ecosystems in the humid tropics play a potentially important but presently ambiguous role in the global carbon cycle. Global estimates of atmospheric CO_2 exchange based on inverse modeling, while poorly-constrained, indicate that the tropics are near equilibrium or are a source with respect to carbon (Schimel *et al* 2001; Gurney *et al.* 2002). But ground based measurements in the Amazon indicate that mature rainforests are absorbing carbon at a rate similar to or greater than the ~1.6 Gt C y^{-1} that is being released by tropical deforestation. Estimates of the magnitude of carbon sequestration are uncertain, however, depending on whether they are derived from measurements of gas fluxes above forests (Grace *et al*. 1995, Mahli e*t al.* 1998) or of biomass accumulation in vegetation and soils (Phillips *et al.* 1998; Mahli and Grace 2000). It is also possible that methodological errors may overestimate rates of carbon uptake. Another explanation from Malhi and Grace (2000) involves carbon "…that leaks out of the forest in forms that are not usually measured, such as gaseous emissions of hydrocarbons or dissolved C in groundwater flows. Although this carbon leakage is thought to be relatively small, surprises cannot be ruled out."

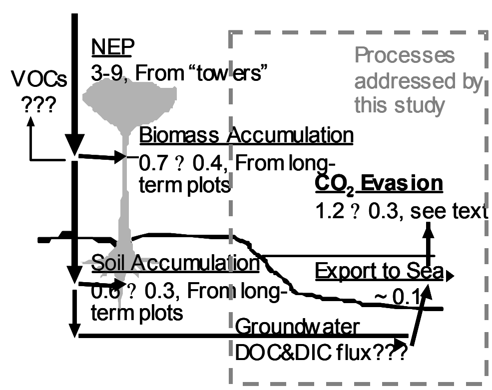

Fig. 1. Estimated C fluxes in the Amazon, Mg C ha^{-1} y^{-1} (adapted from Mahli and Grace 2000, Richey et al. in press)

We have recently demonstrated that outgassing of CO_2 from rivers and wetlands of the Amazonian basin constitutes an important carbon loss process, equal to 1.2 ± 0.3 Mg C ha^{-1} y^{-1} (Richey *et al* in press; Section C.2). This carbon likely originates from organic matter transported from upland and flooded forests, which is then respired and outgassed downstream. Extrapolated across the entire basin, the resulting flux of about 0.5 Gt C y^{-1} is an order of magnitude greater than the fluvial export of organic carbon to the ocean (Richey *et al.* 1990). Assuming that the fluxes computed for the Amazon are representative of fluvial environments of lowland humid tropical forests in general, surface water CO_2 evasion in the tropics may help explain the anomaly in the current balance of the global carbon cycle. Extrapolating over the global area covered by humid tropical forests with our estimate of areal evasion rates for the Amazon basin yields a flux of roughly 0.9 Gt C y^{-1}, or three times larger than previous estimates of global evasion. A return flux from water to the atmosphere of this magnitude comes closer to reconciling the independent carbon budgets for the tropics.

These conclusions lead to the working hypothesis for the work we are proposing here:

Surface water CO_2 evasion is the dominant source of carbon loss (exceeding export to the oceans by a factor of 10) in fluvial systems of the humid tropics, and in the aggregate reconciles the tropics in the global carbon budget. Evasion is driven primarily by in-stream respiration of organic carbon translocated in space and time from its terrestrial origins.

While the computations of fluvial and evasion flux are becoming progressively better constrained for the Amazon, they are not elsewhere in the humid tropics. With this proposal we intend to extend and test our Amazon-based working hypothesis to another significant region, Southeast Asia. The region is an area comparable to the Amazon basin, covering more than 4.5 million km^2 of land area (Fig. 2). But at the other end of the development spectrum from the Amazon, the extraordinary pace of development and population growth in Southeast Asia has placed dramatically increasing pressure on its river basins and downstream coastal ecosystems. Impacts occur through erosion of the land surface, changes in the nature of the sediment and its associated organic matter, and nutrient content from agricultural and urban sources. Changes in hydrology are an immediate consequence of dam construction and large-scale water diversion for irrigation. Longer-term changes in regional weather patterns and climate would result in altered flow regimes. These changes have major consequences for water resources.

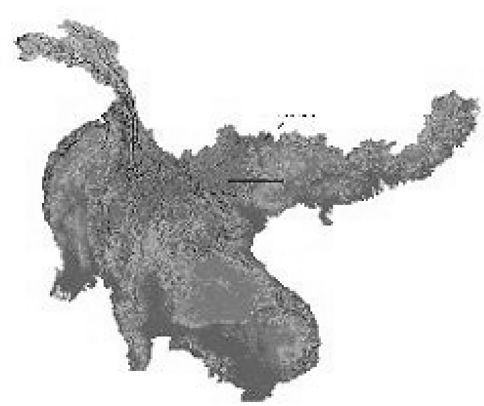

Fig. 2. Relief map of internally-consistent DEM and river networks (and landcover, Soils, and population) of SE Asia, from *SEA/BASINS* project (see text).

To test our hypothesis, we propose three primary objectives: (1) enhance an existing geospatial model to provide the template for analysis of the biogeochemical dynamics of Southeast Asia river basins, (2) conduct a field-sampling campaign to provide the patterns and processes and subsequent validation data for the model, and (3) use the resulting model to assess a set of questions which will test and resolve the hypothesis. This work will entail numerical models and quantitative techniques, remote sensing, and field data. Fieldwork will use combined measurements of the direct CO_2 flux, isotopic and molecular tracers of organic matter sources and fates, sediment transport, and within river remineralization rates to yield rates of CO_2 production and evasion. Coupled hydrologic and biogeochemical models will extrapolate this measurement–based understanding of carbon dynamics to the broader humid tropical ecosystems, from terrestrial to marine.

The work will be done as a partnership between colleagues at the University of Washington (Seattle, USA), and the, and Southeast Asia START Regional Center (SEA START RC, Chulalongkorn University, Bangkok, Thailand). The project is made feasible by leveraging a series of existing programs and sampling networks.

C.2. Results from Previous NSF Support

The research proposed here is based on our long-term CAMREX (Carbon in the Amazon River Experiment) project. Starting in 1982, our goal has been to determine the sequence of processes that controls the distributions and transformations of water and bioactive elements in large-scale river systems. As documented in over 120 publications, the CAMREX dataset represents a time series unique in its length and detail for very large river systems. Our overall perspective in CAMREX is that the Amazon is a test case for developing extendable models of how hydrologic and biogeochemical cycles are coupled at regional to continental scales in the humid tropics. Our studies serve the dual purposes of gaining a broad mechanistic understanding, and of establishing data baselines needed to assess anthropogenic perturbations to these globally critical and ecologically complex systems.

NSF DEB-98-15912, $275,000, 1999- 2000. (J.E. Richey, P.I.; J. Hedges, A. Devol, P. Quay, R. Victoria, co-I's), Towards a model of the biogeochemistry of continental-scale river basins: an Amazon case study.

Within the immediate past funding period, we focused on model-based synthesis of previous field measurements.

Carbon Dioxide Evasion from Amazon River Corridors to the Atmosphere. We evaluated the evasion of CO_2 from the fluvial environments of a 1.77 million-km^2 quadrant (Fig. 3) of the low-gradient central Amazon basin Richey *et al*. (in press). The problem was to determine the spatial extent of inundated areas across the full scale of Amazonian environments, from first order streams to the mainstem and its floodplain, and then the rates of CO_2 evasion for the respective areas. Newly available remote sensing datasets made it possible to quantify seasonal water coverage for representative low and high water periods, showing that up to 20% of the quadrant is flooded at high water. When we combined the areal extent of flooding and measurements of the distributions of $p\mathrm{CO}_2$ with a gas evasion model, we observed a pronounced seasonality in evasion fluxes, corresponding to the annual hydrograph and the elevated CO_2 concentrations (Fig. 4). Integrating over the year and over environments, we computed that the surface waters of the central Amazon basin export 1.2 ± 0.3 Mg C ha^{-1} y^{-1} of CO_2 to the atmosphere over the entire quadrant. A critical ecological question is, where does the carbon come from that ultimately is evaded? From estimates of potential source strengths, we hypothesized that evasion is driven primarily by in-stream respiration of organic carbon fixed originally on land and to a lesser extent along river margins and mobilized into flowing waters, and not just by dissolved CO_2 in groundwater.

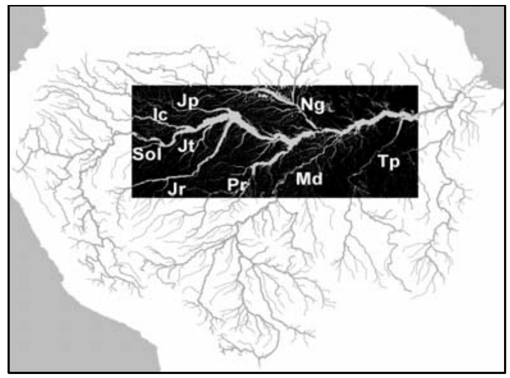

Fig. 3. Flooded area of central Amazon basin at high water, mapped from JERS-1 radar data, on digital river network.

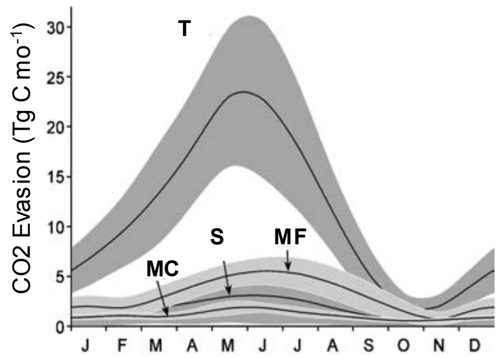

Fig. 4. Spatially integrated sequences of monthly CO_2: **T**ributaries (> 100 m), **S**treams (<100 m), **M**ainstem **C**hannel, **M**ainstem **F**loodplain.

Developing a Model of River Organic Carbon Transport and Dynamics. Large rivers receive and transform inputs from heterogeneous landscapes, making it difficult to ascertain geographic origins and the role of small-scale riparian transformations on the resulting organic matter. If labile carbon is exported from land to aquatic systems, then it is critical to identify the processes controlling organic matter composition and dynamics over the full range of aquatic environments in the watershed. The issue we face is trying to decompose this aggregate signal into its sources of origin. The previous two decades of research by the CAMREX group has built a solid foundation of understanding carbon cycling in basins.

The framework for quantifying the role of evasion from rivers in the basin was developed by Richey and Victoria (1996). They implemented a Lagrangian transport-reaction model that tracked parcels of water and its constituents as they moved downstream. With this past grant, we worked at extending the model from the mainstem to include tributaries and floodplains interacting with the mainstem. In part with NASA support, we initiated application of the grid-based hydrological model VIC (Variable Infiltration Capacity, see below). The objective is to quantify the main characteristics of soil moisture and runoff production that move water and chemical species across the basin.

To then couple organic carbon evolution and CO_2 mobilization into this framework, we are synthesizing our understanding (most recently Hedges *et al*. 2000; Aufdenkampe *et al*. 2001; Devol and Hedges, 2001; Mayorga and Aufdenkampe, in press; Bernandes *et al*. in review) into a "River Basin Organic Matter and Biogeochemistry Synthesis" model (ROMBUS, Aufdenkampe and Mayorga, in prep). The overall goal of this model development is to predict the concentration and flux of dissolved and particulate carbon in rivers throughout a tropical river basin over an annual cycle, when coupled to the hydrologic model. The model partitions the carbon reservoirs within a river into measurable dissolved and particulate organic carbon pools (DOC and POC, respectively; each exhibit distinct dynamics and compositional traits that hold over very broad range of geological, hydrological and climatic conditions, Hedges *et al*. 1994). The POC pool is divided in fine and coarse fractions because of their significantly different compositions, sources and degradation histories. Both the POC and DOC pools are further divided by molecular weight to account for the observed increase in degradation state as the molecular size of the organic matter decreases (Amon and Benner 1996a, 1996b) and to facilitate the parameterization of organo-mineral associations. In contrast, most land-surface carbon models divide OM into unmeasurable (conceptual) pools with characteristic turnover times that are difficult to verify (e.g., the CENTURY model, Parton *et al*. 1994). Our ROMBUS design is more consistent with newer initiatives in the soil carbon modeling community (Christensen 1996a; Elliott *et al*. 1996). Unique to ROMBUS is the explicit parameterization of organo - mineral interactions, which are increasingly acknowledged as fundamental to OM stabilization (Hedges *et al*. 1995; Christensen 1996b; Baldock *et al*. 2000; Arnarson and Keil 2001).

NSF OCE9711792, $300,000, May 1997 – April 2000, (R.G. Keil, P.I.) "The importance of sorption to mineral on microbial activity and organic matter preservation, and its continuation grant NSF OCE0095287, $439,837, May 2001 – April 2004. Interactions between organic matter and minerals in marine sediments.

This work continues the theme of determining the factors that promote remineralization of organic matter and resolve the biotic and abiotic factors that prevent certain components of organic matter from being degraded within aquatic systems. The main focus is on organic-mineral interactions, with a focus on many fluvial systems, including riverine systems (Keil *et al*., 1997; Mayer *et al*., 1998), intertidal regions (Van Mooy and Keil, in press), particles settling along continental margins (Van Mooy *et al*., 2002), and continental margin sediments (Keil and Fogel, 2001; Keil *et al*., 1998). In all these systems, one common theme is that a large proportion of the organic matter is tightly associated with the mineral grains in the form of organo-mineral aggregates (Arnarson and Keil, 2001). The formation and stability of these aggregates provide several unifying features for fluvial and static sedimentary systems that we exploit in order to better understand the cycling of organic carbon in the environment. This is particularly relevant in a high-sediment area, such as Southeast Asia, where "organic-free" particles

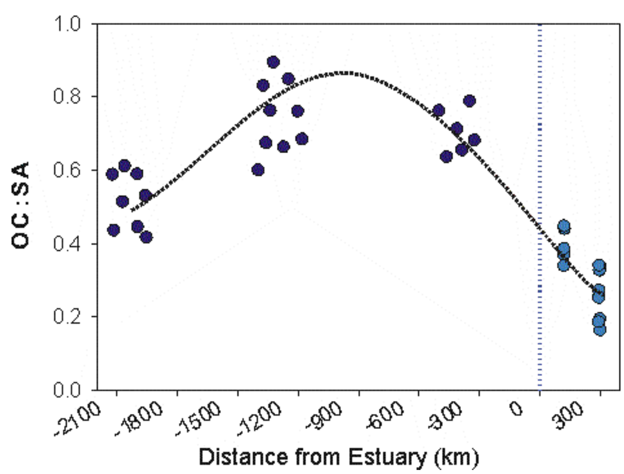

Fig. 5. Trends in OC:SA (mg OC m^{-2}) as a function of distance along the Amazon river mainstem. The dashed line is a hand-fit curve illustrating the 'loading' of organic matter into organo-mineral aggregates within the river system and then the subsequent unloading within the estuary.

will be generated in the high Himalayas, and then pick up carbon in their transport to the sea.

The foremost example of coupling organic matter with sediment transport (key to the work proposed here) is the normalization of organic carbon content of a system to its mineral surface area (OC:SA ratios, units of mg OC m^{-2}). By normalizing to an essentially conservative property, it is possible to discern small changes in organic matter dynamics not observable by measuring only dissolved and particulate pools of organic matter. This provides 'resolving power' for evaluating changes in carbon transport or burial efficiency within a given system. For example, in a number of tropical and temperate rivers (Amazon, Mississippi, Huange He, Johnstone, Fly, Changjiang, Eel) we have used OC:SA ratios and normalizations to mineral properties to show that these riverine and deltaic systems are extremely efficient at remineralizing organic matter to CO_2 and nutrients within both the river and the delta prior to burial (Keil *et al*., 1997; Mayer *et al*., 1998). Riverine organo-mineral aggregates are therefore an essential factor governing organic matter transport within riverine systems and the subsequent delivery of nutrients to coastal waters. Because the formation of, and fluvial transport of, mineral particles is so tightly linked to the processing of terrestrial organic matter in both rivers and coastal waters, knowing the sources of, general types of, and quantities of mineral components within riverine systems is required for understanding organic carbon cycling within these systems.

NSF, INT-9726959, $49,000, 1998-1999 (J. Richey, P.I.), Enhancement of Integrated Regional Models in the Asia-Pacific with Virtual Workshops,

With initial funding from the NSF/EPA Waters and Watershed, we began to investigate the porting of the basic Amazon model construct to Southeast Asia. The original funding, subsequently augmented by this and related funding, led to the Southeast Asia Integrated Regional Model: River Basin Inputs to the Coastal Zone (*SEA/BASINS*) project (http://boto.ocean.washington.edu/seasia). *SEA/BASINS* is a joint endeavor between the UW (J. Richey) and the Southeast Asia START Regional Centre (A. Snidvongs, Chulalongkorn University, Bangkok). The process of *SEA/BASINS* has been to develop a multi-scale integrated computer model *NAGA (*a mythological sea serpent for water resources) of how materials are mobilized and transported from the land surface to the coastal zone as a function of climatology and surface features (Richey *et al*. 2000). A key aspect of this project relative to the proposed work has been the development of a network of Partners, including the Mekong River Commission. SEA-START is an institution responsible for networking multiple institutions for training and information throughout Southeast Asia.

The hydrology model we are using is the Variable Infiltration Capacity (VIC) model (Liang *et al*. 1994, 1996, 1998). It has been applied to such large continental river basins as the Columbia (Nijssen *et al*., 1997), the Arkansas-Red (Abdulla *et al*., 1996), and the Upper Mississippi (Cherkauer and Lettenmaier, 1999). VIC is then coupled to a linear streamflow routing scheme that transports the runoff generated within each grid cell through a specified channel network (Lohmann *et al*. 1996; 1998). For our application, the *NAGA* geospatial model was re-aggregated to ¼ degree spatial resolution, with VIC implemented in daily water balance mode (Goteti *et al* in prep). We drove the model with climatology data from the NOAA Climate Prediction Center Summary of the Day data archived at the National Center for Atmospheric Research for the period January 1979 through December 2000, augmented with local validation with data from the Tropical Rainfall Measurement Mission (TRMM) for 1998-present. Overall model performance, simulating 16 stations throughout the Mekong basin over a 20-year period, was robust (Fig. 6). To account for physical infrastructure, we are developing a Mekong water management model (MWMM), which operates on a monthly time scale and is

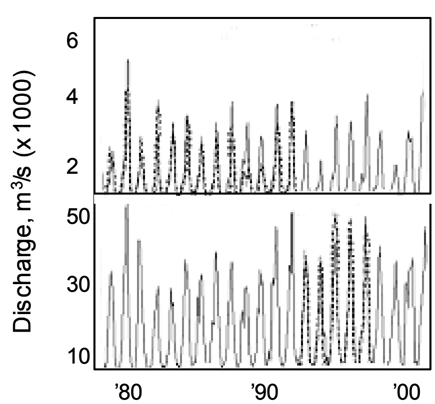

Fig. 6. VIC application to a mainstem (Stung Treng, M below) and tributary station (Ubon); out of 16 stations modeled. Solid - modeled, dashed -obs

driven by streamflow data simulated by the VIC model. VIC and the MWMM are then being used to investigate the impacts that long-term changes in vegetation (simulated by imposing different land covers) and flow regulation might have on basin water flow.

The development of biogeochemical models, including sediment transport (a mandatory precursor for POC), and is much more problematic than spatial and hydrological models. An important consideration is the differentiation of the sediment yield into pristine versus anthropogenic flux. It is probable that modern human induced erosion and reservoirs is responsible for a significant mobilization of terrestrial materials into river systems, with burial behind dams (Stallard 1998). Sediment flux and accompanying POC flux from Southeast Asia is very under-determined, with estimates based on extrapolations of existing data, which are themselves weighted to the large rivers of passive margins and temperate regions. We have evaluated several simple models of sediment yield and carbon ratios, applied by geographic zone. The consequence is 1) the observation that river sediment input to the coastal zone may be several-fold higher than previously though, but 2) uncertainty is so high as to render conclusions suspect (cf. Milliman and Syvitski, 1992).

Large-scale models of chemical flux typically use a multiple regression approach of aggregate basin attributes and measured fluxes (e.g., Ludwig *et al* 1996). Such models are intrinsically not based on actual processes, and may be less sensitive to capturing regional differences or changes. We are working towards cell-based deterministic models. As a test-of-concept for grid-based DOC model of Southeast Asia, we developed a simple two-step model (Fig. 7a). First, as water entering the river channel has passed through the soil column, an initial DOC concentration corresponding to the upper soil layer (O-Horizon) is assigned based on the land cover of a gridcell. The concentration reflects the potential for DOC production by that land cover e.g. wetland areas will have higher DOC concentration than areas covered by bare rock. Second, the DOC concentration is decreased based on the soil texture within the gridcell. The removal of DOC in the soil column is simulated by removing a percentage based on the fineness /coarseness of the soil texture, and mobilizing it with a hydrology model. The result is a DOC concentration for each gridcell in the basin, and overall regional concentrations and fluxes can be calculated.

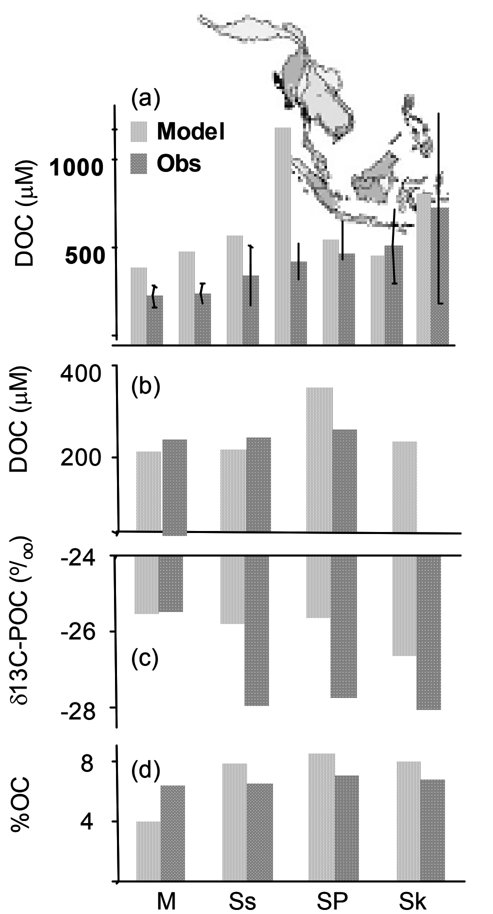

Fig. 7. (a) Pixel-based, coupled DOC/hydrology model, for Fly, Solo, Mae Klong, Bang Pakong, Bang Nara, Mekong/Chao Phrya, and Sabah rivers, (l to r). Insert is annual flux computed across region. Preliminary Mekong data (b,c,d) from mainstem, at confluence of Tributaries Sesan (Ss), Sre Pork (SP), and Sekong (Sk); Oct '00 ■ Mar'01 ■

To lay the groundwork for improving this model and working towards a field program we initiated preliminary sampling of the Mekong system, through cooperation with the Mekong River Commission. We are now processing two collections at different stages of the hydrograph (Fig. 7 b,c,d). Significant differences can be observed between the Mekong and the three tributaries (which drain central Laos), with more enriched $\delta^{13}C$ and reduced % OC of particulates.

C.3. Proposed Research

Regional analyses based strictly on site-specific detailed data are generally difficult to realize; data are simply too sparse. Our strategy is to develop geospatially-explicit computer models coupled to field observation systems can provide regional interpolations, use what data do exist as validation points, and in the process estimate overall dynamics and specific fluxes of water and chemical constituents in areas where data are unavailable.

Objective 1. Enhance *NAGA* Model Environment and Construct Time Series

Task 1.1. Physical template. At this time we have the basic "physical template" (topography, river networks, land cover, soils) of Southeast Asia represented at a nominal 1 km resolution (from multiple data sources (e.g. Fig. 2). The current landcover data in *NAGA* is based on AVHRR products, representing approximately 1994 conditions. We propose to expand these data into time series, both on a multi-decadal basis and on a seasonal basis. This will allow us to investigate the impact multiple landcovers and climatologies have on water, sediment, and chemical mobilization. For example, as a start, Gotei *et al* (in prep), "replaced" cropland with forest in the Mekong Basin for a historical scenario, then "replaced" forest with cropland in a futures scenario. We propose to expand on that approach here. We have since acquired a LANDSAT based forest cover change product (1-km), for 1973 and 1985, from the Michigan State University Forest Cover Change project (D. Skole, pers. comm.). We have acquired a 300-year historic land cover change product (at a coarser resolution of 0.5^{o}), 1700-present in 50 year increments (Klein Goldewijk, K. 2001; Klein Goldewijk, C.G.M. and J.J. Battjes, 1997). We will take these data sets and process them into a format suitable for coupled model analysis. For contemporary conditions we will utilize two sources. MODIS (Moderate Resolution Imaging Spectroradiometer) data are becoming available, which would allow us to update landcover on a seasonal to annual basis (e.g. Fig. 8). This work will be done in cooperation with and augmented by groups, with whom we have affiliations, working explicitly with landuse- land cover change information. For example LANDSAT ETM+ based products are becoming available; including through the Southeast Asian Resource Research and Information Network (SEARRIN). For future scenarios we will work with agencies and groups in the region, such as the Basin Development Program of the Mekong River Commission, to develop products based on realistic assumptions (relatively speaking) of future growth scenarios.

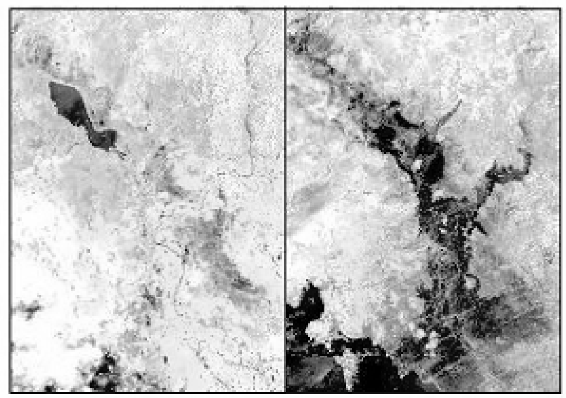

Fig. 8. Composite images from MODIS data of The lower Mekong, for the floods of 2000. Left June 8-16, right Aug 28-Sep 4. The feature in the Upper left is the "Great Lake," the Tonle Sap.

Task 1.2. Flow Regimes. We propose to determine the seasonality of terrestrial runoff and inundation by using the VIC hydrology model on land and routing runoff to predict water flow across the river networks by expanding our coverage of VIC from the Mekong to the overall region at 1/4^{o} resolution (VIC is currently applied to the region only at 2^{o}). We will then use those estimates to drive a surface area model and subsequently the material flux models (below). Remote sensing data will be used to validate the predictions at larger scales, and field surveys at smaller scales (below). River discharge observations from national hydrological agencies (where available) will be used for validation of hydrological fluxes across the basins. For the climatology to drive the model, we will rely on NOAA products, regional products, and especially TRMM.

A prerequisite to predicting the dynamics of riverine exchange of carbon with the atmosphere is the ability to predict the movement of water from the surface and subsurface to streams, and subsequently its movement in the channel system. Clearly, a focus on the large scale is essential here, as the river basins of interest are large continental rivers, that is, drainage areas in excess of 500,000 km^2. The Variable Infiltration Capacity (VIC) model was designed from such applications. VIC (see Liang *et al*, 1994) is a physically based model, which nonetheless parameterizes small scale processes to allow application to large river basins, which typically are resolved at spatial resolutions from 1/8 degree latitude by longitude (e.g., where the resolution of the precipitation, temperature, radiative, and other surface forcings are available or can be derived, such as in the continental U.S., Maurer *et al*, in review), to coarser resolutions such as the 2 degree global application described by Nijssen *et al* (2002). The model has parameterizations to represent the vertical exchange of moisture and energy between the vegetation canopy and the atmosphere, similar in many respects to other Soil-Vegetation-Atmosphere Transfer Schemes (SVATS). Its main distinction from other SVATS is its representation of the effects of spatial variability in soil, topography, and vegetation, and their effects on runoff generation, which is assumed to occur dominantly via the saturation excess mechanism (which is usually a defensible assumption in humid environments). The model also represents a "slow", or baseflow, runoff response via a nonlinear deep soil drainage parameterization.

Although the model has been applied to many large global rivers (e.g., continental U.S., as mentioned above, the Mekong, by Goteti and Lettenmaier (2001), the pan-Arctic drainage by Bowling *et al* (2000), the focus of our evaluations has always been on vertical fluxes (e.g., evapotranspiration, as verified via either tower flux observations for large areas, or atmospheric budgets for large areas), and streamflow at the mouth of large rivers and tributaries thereof. For the present application, it is important not only that river discharge be reproduced accurately, but also that the processes that can effect carbon exchange (e.g., pathways by which moisture moves through the subsurface, and channel travel times including tributaries of all stream orders) be represented properly. In the spirit of the VIC macroscale structure, these processes will be parameterized, but some attention will need to be given to verification and/or development of new parameterizations that describe the pathways by which moisture reaches river outlets, as well as the bulk fluxes.

To do so, we will utilize our high-resolution hydrologic model, the Distributed Hydrology Soil Vegetation Model (DHSVM, see Wigmosta *et al*, 1994 for details). Unlike VIC, DHSVM is intended for application to small to moderate (typically less than about 1000 km2) drainage areas, over which digital topographic data allows explicit representation of the mechanisms by which water travels over the surface and through the subsurface. Like VIC, it represents runoff generation via the saturation excess mechanism. Unlike VIC, it explicitly represents topographic effects, including the formation of perched water tables, on runoff generation, incident solar radiation (hence net radiation), and explicitly represents the vegetation and its properties (like root depth), as well as soil properties, on a pixel-by-pixel basis. The model grid resolution typically is 30-150 m, several orders of magnitude higher than VIC. However, because of the large computational burden, DHSVM is restricted to relatively small catchments. We have conducted some limited experiments comparing DHSVM sensitivity, for instance, to vegetation and vegetation change (Van Shaar *et al*, 2002). Although the macroscale performance of the two models is similar in gross features (e.g., ability to reproduce seasonal fluctuations in runoff), there are important differences in predicted runoff and other surface fluxes, especially at shorter time scales. In this respect, DHSVM provides a useful "laboratory" for evaluation of VIC parameterizations that will affect, for example, contact times of subsurface moisture with various elements of the soil horizon, and movement through the stream channel system (which, unlike VIC, DHSVM represents directly from digital topographic information, down to first order streams as identified using a support area concept, which is field-verifiable). For the DHSVM-based development and evaluation of VIC subsurface and channel algorithms, we will make use of an ongoing application of DHSVM to the Pang Khum experimental watershed in northern Thailand by Tom Giambelluca and colleagues at the University of Hawaii. We will also pick a set of (probably about three) similar index catchments representing a range of hydroclimatic regimes within the region, at which we will conduct similar development and evaluation work on improved VIC subsurface and channel algorithms.

Task 1.3. Establish multiple scale inundation regimes. A key element of our proposed work is evaluating the outgassing of CO_2. This is dependent on knowing systematically the surface area of "wet" environments. Based on our experience examining Amazon wetlands (Hess *et al*. 1995, Melack and Wang 1998), we propose to apply to Southeast Asia lowland, wetland systems a multi-stage methodology using Japanese Earth Resources Satellite (JERS-1) data for mapping the wetland vegetation and inundation required for the outgassing calculations. While optical remote sensing methods are hampered by clouds in the humid tropics, Synthetic Aperture Radar (SAR), can detect flooding beneath a vegetation canopy because smooth water surfaces produce strong specular reflections, which are reflected back toward the sensor by branches and trunks. The returns received from flooded forest stands are brighter than those from unflooded stands, particularly using horizontally polarized L-band radar (Hess *et al*. 1995, Wang *et al*. 1995). A similar mechanism enables flooded marsh to be distinguished from unflooded marsh or other herbaceous vegetation such as pasture. The Japanese Earth Resources Satellite (JERS-1) carried a horizontally polarized L-band radar and was used as part of the Global Rain Forest Mapping Project of the National Space Development Agency of Japan to generate a mosaic covering tropical Southeast Asia and neighboring islands. A similar product was produced for tropical Africa and South America, and we have been part of the team preparing the radiometrically and geographically corrected mosaic for South America (Siqueira *et al*. 2000). We propose:

1. *Delineation of wetland boundaries* by automated segmentation of the JERS-1 mosaic using SPRING software, clustering and labeling of the resulting polygons as either wetland or non-wetland, and extensive editing of polygons by a human interpreter (Barbosa *et al*., in press). Human interpretation is both necessary and effective because, while the L-HH backscattering statistics of several key non-wetland land cover types such as forest clearings match those of wetland cover types, the spatial patterns and contextual characteristics of such features enable them to be readily labeled as wetland or non-wetland by a trained interpreter. The result is a highly accurate (user's accuracy > 90% for the central Amazon) wetlands/non-wetlands mask.

2. *Mapping of wetland vegetation and inundation status* using the JERS-1 mosaic. For areas within the wetlands mask, a set of decision rules will be applied to individual pixels, classifying them into cover states consisting of vegetative classes (i.e., non-vegetated, herbaceous, shrub, woodland, and forest) and inundation status (flooded or non-flooded) based on the two-date L-HH backscattering coefficients. The change in method from polygon-based to pixel-based follows from the different spatial scales of the land cover units targeted during the two phases of the mapping.

We will use a knowledge-based classifier employing a hierarchical set of decision rules. The rules will be derived from a database of SAR scattering statistics derived mostly from training areas on the JERS-1 mosaic but also from ancillary data. The rules will be consistent with theoretical explanations of SAR scattering as a function of structure and dielectric constant of vegetation canopies and ground surfaces. A similar approach was used successfully by Dobson *et al*. (1996) in mapping land cover types using JERS-1/ERS-1 composite images.

3. *Field validation* - Field surveys will be required at selected wetlands to validate our classifications. These surveys will entail low altitude videography and surface inspections. Geolocation of flight lines and surface sites will be done with portable GPS units.

Task 1.3. Material Transport Models. With the landscape and flow regimes represented by the above work, we propose to couple models of sediment and finally carbon generation and transport. In the transport of geochemical compositions across the landscape we will conceptualize overland flow and in-channel sediment transport as processes characterized by precipitation, drainage area, slope, and vegetation. We need to be able to assess the mobilization of POC across the landscape, from source to the ocean. This breaks down into a set of complicated problems. The first is how sediments move, and then how those particulates acquire their characteristic organic signatures (below).

For the sediments we propose to build on the erosion potential approach of Montgomery (Table 1). We will link the pathways for geochemical transport with the distinction of two zones of processes, hillslopes and channels (parameterized as Eqs 1 and 2). A number of landscape evolution models also incorporate some form of a landslide transport law, such as that adopted by Roering *et al*. (1999, Eq. 3). A key issue is how to parameterize such large-scale erosion and landscape evolution models given their relatively coarse grid scales. Koons' (1989) early model of the topographic evolution of the Southern Alps of New Zealand highlighted the problem of how to parameterize hillslope processes, as the hillslope diffusivity needed to generate appropriately scaled relief was orders of magnitude greater than any measured from field studies on actual hillslopes. Dietrich and Montgomery (1998) derived an expression for the effective diffusivity that would be apparent from subsuming channel processes in headwater portions of the drainage network into the representation of hillslope processes in models with coarse-scale grid resolution (Eq. 4). The effective diffusivity incorporates the influence of sub-grid scale channels, and hence, the hillslope diffusivity (*K*) in landscape evolution models is inherently scale dependent. In addition, as channel slopes derived from DEMs are grid scale dependent, the fluvial erosivity constant is also scale-dependent. Rates of fluvial and hillslope erosion are governed by processes characterized by different erosion laws, but the net large-scale erosional potential of a landscape increases with precipitation, drainage area and slope.

Table 1. Terms of a landscape evolution and sediment transport regional model. Q_S is the sediment transport rate, k and K are coefficients, A is drainage area, S is slope, m and n are exponents, and the subscript c denotes a threshold value associated with the onset of sediment transport or erosion, S_C is a critical gradient that defines the maximum stable slope angle, K* is the effective diffusivity that incorporates the influence of sub-grid scale channels, I_E is erosional intensity," based on the product of local slope (S) and discharge determined by summing the annual precipitation (P) over the matrix of upslope grid cells each of drainage area A.

Eq. 1. Fluvial transport $Q_S = kA^m S^n - (A^m S^n)_c$

Eq. 2. Hillslope transport: $Q_S = KS$

Eq. 3. Landslide transport: $Q_S = KS / [1-(S/S_C)^2]$

Eq. 4. Effective diffusivity $K^* = KS + kA^m S^{n-1}$

Eq. 5. Erosional Intensity $I_E = \sum [P_i A_i]\ S$.

Finally, Montgomery *et al*. (2001) and Finlayson *et al*. (2002) evaluated large-scale patterns in erosion potential by using a simple parametric measure of "erosional intensity" based on the product of local slope and discharge determined by summing the annual precipitation over the matrix of upslope grid cells each of drainage area *(Eq. 5,* Fig. 9*)*. They used this simple approach because (1) it is not clear which process formulation is most appropriate for modeling landscape-scale erosion rates across 1 km grid cells in which net erosion reflects an aggregation of finer-scale effects from multiple, interacting processes; (2) vegetation and land use, which cannot be predicted from DEMs, complicate simple relationships between precipitation and erosion rate; (3) erosion models at this scale inherently require calibration because slopes calculated from coarse-resolution grids are gentler than actual gradients (Zhang and Montgomery, 1994); and (4) data on differences in erosivity due to soil type and parent lithology generally are not available at the scale of interest. The erosion intensity index can be calculated over all of Southeast Asia and can be calibrated against locations of know sediment yield or average annual discharge (e.g., Finlayson *et al*. 2002). The

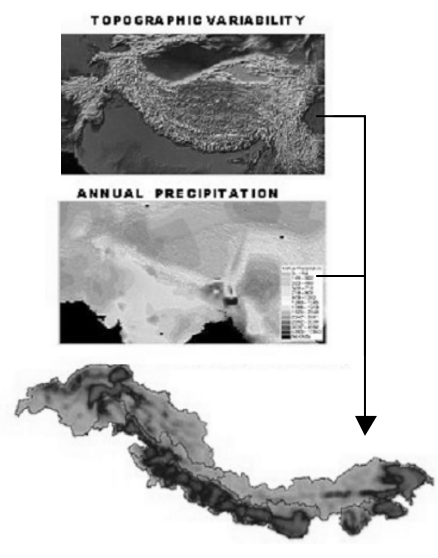

Fig. 9. Erosional intensity map for S. Himalayan arc, as product of topographic variability and annual precipitation. We will Extend this model over SE Asia.

mechanics of flow after the onset of erosion for "in-channel" processes also follows relationships linked to slope of the bed, the shear stress exerted by the flow and the weight of the particles. In certain circumstances the presence of particles in a fluid may actually drive the motion. As in silt-laden currents in estuaries and nearshore coastal systems buoyancy difference between the suspension and ambient fluid may drive the dispersion within a drift cell along a section of river of certain size, velocity, and configuration.

Once again, our investigation seeks to identify the interaction of the physical characteristic of the landscape (topography, precipitation, and vegetation) to identify these physical constrains. The terms of the model will be derived from our geospatial model. The approach requires calibration from field measurements. These will be described below.

Task 1.4. Carbon Processing: Adsorption to Mineralization and Evasion. Our general objective in creating this system of linked process-based transport models is to quantitatively describe the evolution of organic matter and DIC sub-components from the land through the river corridor to the sea, and from carbon fixation by autotrophs to its conversion into CO_2 by heterotrophs and long-term protection via sorption to minerals. This approach explicitly includes the contributions and transformations in each landscape element. We now turn to the implementation of ROMBUS to examine the overall dynamics and controls on carbon cycling and exports. ROMBUS is designed to be applicable in both terrestrial and aquatic settings, assigning a central role to sorptive processes and dissolved phases. Its coupling to the hydrological modeling framework was described above.

Within ROMBUS each of the organic and inorganic carbon pools are represented by state variables that characterize the nitrogen-to-carbon ratio (for the OM pools), $\delta^{13}C$ signature and age (via $\Delta^{14}C$). Within each pixel, the transformations between these pools are calculated by ROMBUS for three sub-pixel elements (surface water; riparian soils; and upland soils) each at three sediment/soil horizons. Horizontal and vertical transport between sub-pixel elements and from one pixel to the next are determined via the modified VIC hydrology model and our stream and river channel network. Therefore, for a given sub-pixel element, the concentration of each individual chemical species (or state variable) is tracked by a mass balance. First order kinetics are used to parameterize transformation rates, with rate constants from the literature and previous work that are subsequently modified by environmental variables such a temperature and moisture. These key characteristics provide information about carbon sources and cycling times within the basin and, importantly, can be compared to direct measurements made in the field (below). ROMBUS will track a substantial number of biogeochemical species in each spatial compartment, including organic matter dissolved and particulate size fractions, organic matter age (evaluated against $\Delta^{14}C$), $\delta^{13}C$, DIC species (including CO_2), organic and inorganic nitrogen, and oxygen. The coupled models will therefore predict concentrations and fluxes of these species in terrestrial and riverine environments. Redox conditions will be estimated directly via O_2 concentrations. This comparison of predicted and observed state variables will serve as a major test of whether our model predictions of OM cycling and respiratory input of dissolved CO_2.

Objective 2. Field-Sampling Campaign

We propose to conduct a field sampling campaign, to (1) determine the patterns and process dictated by the above modeling framework, and (2) to provide independent data sets to subsequently be used for model validation.

Task 2.1. Establish sampling network (permanent stations, circuits) We propose a sampling strategy that focuses on the Mekong and to a lesser extent the Chao Phrya, and is augmented by collections on other river systems of the region (Pearl, Red, perhaps the Irrawaddy). Again, the intention is to provide sufficiently robust sampling across the region to provide validation for the broader Southeast Asia. Sites will be selected both on the basis of information and access. For the Mekong we will focus on a mainstem station at Kratie (near Phnom Penh). We will target the Mŭn River, which drains the heavily impacted northeast sector of Thailand, and several tributaries in Laos (Kong, Se San, and Srepok, Fig.

7) which drain different regions but converge together in a small reach of the mainstem, making them efficient to sample, and the region of the Tonle Sap (the "Great Lake"). This selection covers a wide range of environments and scales (and is logistically feasible). For the Mekong, up river sites near Chiang Rai would provide access to a range of environments, potentially including the high-sediment upper Mekong. Our existing GIS models will be refined as necessary to describe new regions. The Chao Phrya can easily be sampled near Bangkok, and we will establish a laboratory in the upper sections of the river, at Chiang Mai (with colleagues at Chiang Mai University).

Task 2.2. Measurements of Instantaneous Flow Velocity and Sediments Concentrations. The classic protocol for obtaining horizontally- and vertically-integrated measurements of overall material transport (critical for quantitative assessments, given the cross-channel variability in constituent concentrations), is an equal-width-increment procedure with vertical integration (detailed in Richey *et al*. 1986; Richey *et al.* 1990). In the Amazon we used a (massive) variable-speed hydraulic winch deploying an instrument array consisting of a 130-kg sounding weight, a Price AA current meter, and a collapsible-bag sampler by lowering it from the surface to the bottom and back at a constant velocity. Multiple equidistant vertical sampling profiles were taken across the channel, with positioning determined by shipboard monitoring of a 3-marker baseline on shore. While accurate, this methodology is very time consuming, and requires significant investment in a sampling platform (boat), which is very limited in range. Hence this methodology is not well-suited to the broad spatially and temporal extent desired here.

Rather we propose to deploy acoustic Doppler current profiling (ADCP) techniques. This technology has been used on the Amazon River by the Brazilian Hydrologic Service, and yields results comparable to ours. Derivation of suspended solids concentrations from ADCP backscatter data is proving to be increasing feasible (particularly if each sampling is accompanied by point data for calibration). Hence we will use the ADCP calibrated with suspended sediments pumped from specific depths in survey mode across the region to get a synoptic view of current velocities (also necessary for evasion calculations) and ultimately the flux of suspended sediments. These data will then be used to calibrate and evaluate and sediment erosion model (above).

Task 2.3. Determine Distributions of pCO_2 and Gas Exchange Rates. We propose to conduct an intensive field-sampling program of pCO_2 measurements that resolves both spatial and temporal variability in the river system. Such a pCO_2 survey will provide the first order estimate, when combined with gas CO_2 gas transfer rate measurements discussed below, of the CO_2 evasion rate for the basins and be used to validate model predictions. Downstream DIC trends provide insight into the effect of respiration and gas exchange of the carbon budget and alkalinity is a tracer of weathering reactions.

Accurate analysis is critical for $p\mathrm{CO}_2$. Given that the entire CO_2 system can be characterized by measurement of any two of its components (Stumm and Morgan, 1996), these variables are frequently calculated from other system variables such as pH and alkalinity as we have done previously (Devol *et al*., 1995). However, although alkalinity samples are easily stored for precise lab measurement, field measurements of pH are often not precise enough for accurate calculation of pCO_2 and DIC. Differences of 0.05 pH units can cause 10-20% errors in the calculation of pCO_2. In contrast both $p\mathrm{CO}_2$ and DIC can be determined directly with an infrared gas analyzer (IRGA) (Cole and Caraco 1998). We will evaluate which combinations of measurements are most appropriate for which sampling situations. For example, in instances where survey samples are to be collected, poisoned and stored for analysis back at the laboratory the best combination of measurements might be alkalinity and DIC. On the other hand, for experiments where instrumentation is available in the field the best combination might be pCO_2 and DIC. The measurement of pH will be done by electrode with a meter capable of 0.005 pH unit resolution and alkalinity will be done by micro-Gran titration, as described in Devol *et al*. (1995). We will employ an Infrared Gas Analyzer (IRGA) for both the $p\mathrm{CO}_2$ and DIC measurements. $p\mathrm{CO}_2$ will be measured by a head space equilibration as described by Cole and Caraco (1998), with the extracted CO_2 determined in the field with a battery-operated IRGA. Measurement of dissolved oxygen concentrations (for stoichiometry with CO_2 and for respiration rates) will use polarographic oxygen electrode techniques (or a scaled down version of the standard Winkler titration, if necessary). Samples will be taken more selectively for DOC, basic nutrients, and isotopes.

Gas fluxes between surface waters and the overlying atmosphere can be calculated from saturation gradients such as Flux = $K(C_{sat}-C)$, where K is an exchange coefficient, C_{sat} is the atmospheric equilibrium concentration, and C is the measured aqueous concentration, measurement of gas concentration change over time in “domes” floating on water surface (Devol, *et al*., 1990; Bartlett *et al*.1990), purposeful tracer additions (SF_6 and ^3He, Clark *et al*., 1996) or from eddy correlation studies. Pending funding approval, we will be starting experimental work in the Amazon on the relation of flow conditions to gas evasion. We will incorporate the results of that work here (rather than repeat it), and focus on measured gas gradients and floating domes.

Task 2.4. Organic Carbon and Carbon Attributes. We have established a set of organic matter measurements that is both synoptic in scope and rapid in process. Samples from soils, rivers and tributaries will be routinely divided into dissolved, coarse particulate (>63 μm) and fine particulate (<63 μm) organic matter and evaluated for $\Delta^{14}C$ ‘age’, $PO^{13}C$ and $PO^{15}N$ (and C:N ratio), OC:SA ratio (mgOC m^{-2}), and XPS (organic matter ‘quality’). Combining particulate and dissolved analyses for major elemental features has proven to be a productive tool for evaluating the sources and fates of organic matter in rivers (Hedges *et al*., 1986; Keil *et al*., 1997; Onstad *et al*., 2000; Richey *et al*., 1990). Particularly fruitful has been the combined evaluation of stable isotopic compositions (and ^{14}C ‘ages’) of particulate organic matter in rivers. By creating a grid of sample data distributed through time and space, we will be able to both provide input for the models as well as provide direct evidence and quantification for carbon processing in the river without the need for extensive experimentation or routine time-intensive analysis of individual organic components.

The main hypothesis we will evaluate is whether the mineral delivery of the river essentially ‘sets’ the quantity of particulate organic matter that can be protected from remineralization within the river. Within the Amazon system, we have shown that the quantity of organic matter exported by the river to the ocean is strongly dependent on the flux of mineral material (e.g Fig. 5). Given that within the Amazon system ~10X more organic matter is processed to CO_2 than is transported to the ocean, it is very important to determine whether the rivers of Southeast Asia have an efflux/export ratio that is also ~10:1. This ratio, and thus the balance of the entire riverine ecosystem in terms of its net effect on atmospheric CO_2, may well depend on the relative weathering and aggregate potential of minerals within the drainage basin as well as the aggregate delivery of total organic matter to the river. Within the Mekong River, which has a larger average sediment load and a greater array of potential mineral sources, the importance of mineral transport remains unevaluated.

One example of our ‘synoptic’ approach to field sampling is our use of X-ray photoelectron spectroscopy (XPS) as a tool to evaluate organic and inorganic components of particulate material. XPS is a surface-specific tool that nondestructively provides information on the abundance and oxidation state of all elements higher than He. In XPS, shifts in binding energy are directly related to chemical conformation of the parent atoms, providing detailed and reproducible information about the chemical structure of the atoms and their neighbors. XPS has the advantage of collecting information for both C and N (as well as O and Si and other important elements) all within a rapid, non-destructive analysis (Arnarson and Keil, 2001). We have successfully used XPS analyses to distinguish between terrigenous organic matter and planktonic materials in a coastal fjord (Grocock and Keil, 2002). This gives us confidence that we can evaluate the organic components found in Southeast Asia with reasonable detail and be able to determine shifts in the types of organic matter composing the mixtures as a function of hydrograph or location. This will provide powerful clues as to the reactivity and fate of organic carbon that enters the system in particulate form.

The power of XPS is uniquely fit for our purposes because in addition to providing a rapid overview of the ‘quality’ of organic matter in samples, it provides the same level of information on the inorganic components of the sample. It is well established that mineralogy influences the strength of organic-mineral aggregates, their degradation rates and potentials for providing 'safe harbor' for organic matter from mineralization (Alexander and Scow, 1989; Baldock, 2000; Hedges and Oades, 1997; Kaiser and Guggenberger, 2000). In this regard, XPS analysis has been used to study organic matter and mineral functionalities in the Seine river (Boughriet *et al*., 1992). Within the Mekong system, as different terrains deliver different mineral types and quantities to the river, XPS analysis will allow a first-cut evaluation of the types of minerals in collected samples (Arnarson and Keil, 2001). Additionally, we will use our sampling regime to evaluate the potential role of anthropogenic influences on carbon cycling in the river system. The Mekong drains through various types of soils including saline and sulfidic soils that mobilize salts and metals into the river (Minh *et al*., 1997). Our analysis sweep including routine analysis of nutrients, pH and XPS analysis will likely allow measurement of the influence (if there is one) of different soil types and anthropogenic influences on river carbon cycling. Published data for a small component of the river (Ahlgren 1996) suggests that our approach will yield quantitative information on the types and sources of minerals and metals found in the river.

<u>Objective 3. Towards Understanding the Dynamics of River Carbon: Modeling and Synthesis</u>

With the modeling environment and field analyses in place, we will be able to address a series of region-wide questions whose solution will directly bear on our working hypothesis. We will use the fully- coupled model, now incorporating the dynamics learned from the field and experimental work, to compute seasonal and interannual fluxes culminating in CO_2 evasion under different climate and landuse scenarios. We will focus on the contemporary dynamics representing the field campaigns (2003-2005). We will perform retrospective analyses, using reconstructed landcovers and the discharge and climate variability of our 20 year + records (Fig. 6). We will analyze future scenarios, focusing on climate change and landuse change (including reservoirs) drivers. In this environment, we will ask:

- *Across Southeast Asia,*
  - What is the size and character of the riverine carbon pool and the timing of its mobilization compared to net atmosphere-land carbon uptake?
  - What are the factors controlling the partitioning of carbon between evasion and fluvial export across Southeast Asia?
  - What is the effect of climate variability and human forcing on fluvial carbon mobilization?

- *How do the dynamics of fluvial carbon in Southeast Asia compare to the Amazon, and ultimately define the role of riverine systems in the carbon budget of the humid tropics, and in the global carbon cycle?*

C.4. Execution of the Proposed Work

Extensive work is proposed here, in geographically disparate locations. What makes the project feasible is that it is a truly cooperative effort among institutions that are based in these regions and have extensive experience and logistic and personnel support.

Logistics. We have proposed a four-year project. Year 1 of the project will be devoted to two tasks. The first is to focus on getting the modeling environment set up and operational, with coupling between the spatial, hydrology, sediment transport, and chemical elements of the models. We will set up to assimilate field data, and run sensitivity analyses on different parameter sets, to determine what additional field work is needed (or not needed). We will focus on identifying exact sampling sites, and the logistics of working at those sites. While we have extensive experience in mobilizing fieldwork in large scale river systems, we recognize that delays can occur if adequate advance work is not done. In so far as possible, we will begin preliminary sampling. Years 2 and 3 will be for extensive fieldwork. By having (at least) two years, some climate variability can be incorporated. We will maintain model development and refinement. In Year 4 we will not conduct fieldwork, and focus on data synthesis and modeling.

With the staff, students, networks, and logistics available through the SEA-START RC, Chulalongkorn University, and the Mekong River Commission, the overall work force will be substantially greater than the investment requested from NSF. The Principal Investigators of the project will be Jeffrey Richey and Anond Snidvongs. This collaboration will benefit each institution and the regions they represent. A letter from Dr. Snidvongs is attached under Facilities (Section H). They will also be responsible for organizing field sampling and the CO_2 work. Dr. Dennis Lettenmaier will be responsible for the hydrology modeling, Dr. Richard Keil the organic chemistry, and Dr. David Montgomery (on sabbatical, support letter attached) the sediment transport. The SAR inundation work will be conducted in collaboration with Dr. John Melack (UCSB). The basic working personnel model will be to have graduate students (and local undergraduate students) working on the respective tasks, with the supervision and participation of (at least) one of the senior personnel. Specific sites will depend on students recruited from the respective region. Routine field samples will be analyzed in the field, or at near-by base labs. The more complex isotope and biomarker samples will be analyzed at both CU and the UW, by professional staff (and by the students as they become sufficiently trained).

Education and Human Resources. Our group has an extensive record of supporting not only U.S. students but international students. The basic premise of the SEA/BASINS project has been the development of human resources. The process will continue here. As noted above, we will involve students not only at the UW and CU, but also from regional institutions. In this web-enabled world, results and word of such a project circulates rapidly. We maintain a *SEA/BASINS* website, which leads not only to frequent "hits" but frequent requests for information. We will devote effort to upgrading the site, and making it as informative as possible. Part of the upgrade will be to use our PRISM technology to make sub-set versions of "virtual" river basins available to the classroom (including our own) and to the public. We will continue with the training workshops that we have been doing (with funding from such international organizations as the Asia Pacific Network and START).

Extension of Proposed Work to Society. If proven true, the flux of CO_2 via riverine systems will impact considerations of the global carbon cycle. We believe that this program addresses not only key multi-scaled aspects of river basins, but it has the potentially unique capability to address changes in river response due to anthropogenic impacts in globally important river ecosystems. Of most direct utility will be to use the power of the emerging modeling and information synthesis represented here for regional planning and water resource management. We are already working in that direction, through the Millennium Assessment Project (as a "candidate sub-global assessment"), the Assessments of Impacts of and Adaptations to Climate Change in Multiple Regions and Sectors (AIACC) project, and cooperation with the MRC.

Intellectual Merit and Broader Impacts. As the final outcome, we believe that the most significant intellectual merit of our proposed work is two-fold. First, a significant anomaly in the global carbon cycle may be addressed. Second, the work represents a convergence of historically separate lines of earth science – carbon cycle biogeochemistry from local and regional to global scales, riverine ecology, hydrology and geomorphology- into a significant "new" view of the global importance of the processes and magnitudes of land-water-atmosphere coupling. As such, the work could contribute to a "unifying theory," melding traditional earth science disciplines into the next-generation interdisciplinary science. Outside of the immediate science and education consequences of the proposed work, we see that the most important broader impacts of the work will most likely come via significantly improved tools and information networks for "sustainability" - resource assessment and management in a region of multiple transboundary environmental pressures.

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H. FACILITIES

The proposed analyses will be conducted at field sites and at laboratories at the University of Washington, and Chulalongkorn University.

The UW Stable Isotope Laboratory has two Finnigan isotope ratio mass spectrometers, a MAT 251 and DeltaXL, the latter of which is about one year old. The MAT 251 has an automated multisample inlet device that allows 24 gas samples to be admitted sequentially to the mass spec. The MAT 251 has three collectors for masses 32, 33, and 34 for simultaneous measurement of the $^{17}O/^{16}O$ and $^{18}O/^{16}O$. The DeltaXL has an automated on-line Elemental Analyzer sample preparation system that measures the $^{13}C/^{12}C$ and $^{15}N/^{14}N$ (and C/N) of particulate organic material. The DeltaXL also has an HP 6590 GC and Finnigan in-line combustion device (GC/C III) for compound-specific $^{13}C/^{12}C$ and $^{15}N/^{14}N$ analysis by the GC/C/IRMS method allowing isotopic measurements on picomolar size samples. The DeltaXL has a Finnigan in-line pyrolysis device coupled with the HP 6590 GC for measuring the D/H on individual compounds. The Stable Isotope Lab has high vacuum sample preparation lines for the following measurements: the $^{18}O/^{16}O$ and $^{17}O/^{16}O$ of dissolved O_2, the $^{13}C/^{12}C$ of atmospheric CO_2, CO and CH_4, dissolved inorganic carbon (DIC) in seawater and particulate organic material, the D/H of atmospheric H_2 and CH_4 and particulate organic material, and the $^{15}N/^{14}N$ of NO_3 and particulate organic material. We have two GCs: one for the measurement of ambient atmospheric concentrations of CH_4, and CO_2 and the other for ambient atmospheric H_2 and CO measurements. There is a combustion furnace, drying oven, and glass blowing facilities for repair of the sample preparation lines. We moved into brand new laboratory space (~2200 sq. ft.) during Spring 2000. Importantly for the work proposed here, the new UW facility is housed in a "^{14}C-free building. No enriched ^{14}C studies are allowed in the building and the Stable isotope Lab is routinely checked by AMS swipes to verify that no contamination has occurred. The UW facility operates a Windows 2000/UNIX (NTFS) network with ~300 Gb of storage, including three Sun workstations and multiple PCs.

Facilities at Chulalongkorn University include water and sediment samplers, a water analysis laboratory (pH, alkalinity, routine, chemistry, AAS), and data base/information management systems (including GIS) are available. Transportation is available. MRC maintains access to local universities and river boats.

Southeast Asia

START

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Regional Center

RC No. 02/03/103

2 March 2002

Professor Jeffrey E. Richey
Department of Oceanography
University of Washington
Seattle, WA

Dear Professor Richey,

I am writing to you to fully endorse your proposal to be submitted to NSF on "Carbon Export to the Atmosphere and Oceans from the Humid Tropical Drainage Basins of Southeast Asia". The research will provide very crucial information on carbon source and sink of the region, which were listed by countries in Southeast Asia as one of the top priority research. The information will also be crucial for all countries in the region when they prepare the next National Communication to UNFCCC in the next few years.

Southeast Asia START Regional Center (SEA START RC) will fully continue to collaborate with University of Washington and will mobilize all possible resources and regional network to support the activities under the project, especially activities to be carried out in the region. We also looking forward for additional capacity our personnel and institution will gain from this project. In addition it will strengthening the relationship between University of Washington and Chulalongkorn University and could be a topic of discussion during the visit of President McCormick to Chulalongkorn University this June.

I am looking forward for the success to get funding to start the project and if there may be any other matters that SEA START RC can render any assistances please let me know.

Yours sincerely,

Anond Snidvongs
Director

Southeast Asia START Regional Centre (SEA START RC)
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***START -** the Global Change SysTem for Analysis, Research and Training*
of the International Human Dimensions of Global Environmental Change Programme (IHDP),
The International Geosphere-Biosphere Programme (IGBP), and the World Climate Research Programme (WCRP)

Professor Jeffrey Richey

School of Oceanography

University of Washington

RE: CARBON EXPORT TO THE OCEANS AND ATMOSPHERE FROM DRAINAGE BASINS OF SOUTHEAST ASIA

Dear Jeff,

As per our conversations regarding your proposed project on carbon export from ocean basins of Southeast Asia, I would be delighted to interact and collaborate with your group on this exciting study. As we have conducted preliminary analyses of the erosion potential for much of SE Asia as part of a study of the erosion potential in the Himalayas (Finlayson et al., March 2002 issue of GEOLOGY), we should be able to contribute to the project with little cost. Our GIS lab is well suited to conduct the analysis of erosion potential for this region and we are looking forward to working on the project.

David Montgomery
Professor (on sabbatical)

5 March 2002

Dr. Jeff Richey
School of Oceanography
University of Washington
Seattle, WA 98195

Dear Jeff,

Based on our long-running collaborations, I look forward to extending our recent analysis of evasion of carbon dioxide from central Amazonian wetlands to Southeast Asia. I am committed to active participation in the use of remote sensing to assess inundated areas and wetland extent.

Sincerely,

John Melack
Professor