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Global Changes in Biogeochemical Cycles in Response to Human Activities

Final Report

NAGW-714

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This document relates to collaborative research between the Complex Systems Research Center at the University of New Hampshire and the Ecosystems Center of the Marine Biological Laboratory (Woods Hole, MA) under NASA Grant NAGW-714. The authors have organized the report as a brief synopsis, graphics, and a collection of published manuscripts which detail key methodologies and results.

The main objective of our research was to characterize biogeochemical cycles at continental and global scales in both terrestrial and aquatic ecosystems. This characterization applied to both natural ecosystems and those disturbed by human activity. The primary elements of interest were carbon and nitrogen and the analysis sought to quantify standing stocks and dynamic cycling processes. The translocation of major nutrients from the terrestrial landscape to the atmosphere (via trace gases) and to fluvial systems (via leaching, erosional losses, and point source pollution) were of particular importance to this study. Our aim was to develop the first generation of Earth System Models.

Our research was organized around the construction and testing of component biogeochemical models which treated terrestrial ecosystem processes, aquatic nutrient transport through drainage basins and trace gas exchanges at the continental and global scale. A suite of three complementary models were defined within this construct. The models were organized to operate at a 1/2 degree latitude by longitude level of spatial resolution and to execute at a monthly time step. This discretization afforded us the opportunity to understand the dynamics of the biosphere down to subregional scales, while simultaneously placing these dynamics into a global context.

The first model in the suite to be developed was the global drainage basin model, consisting of a coupled Water Balance/Water Transport Model (WBM/WTM). This model calculates the water

balance by transforming complex patterns of climate into soil moisture, evapotranspiration and runoff on single 1/2 degree cells. In addition, it simulates fluvial transport through a networking algorithm linking whole systems of grid cells. The next simulation is the Terrestrial Ecosystem Model (TEM), a geo-referenced nutrient cycling model for C and N standing stocks and nutrient fluxes. The TEM outputs standing stocks of C and N over the year, net primary production and respiration.

Numerous data sets were assembled and analyzed as part of this work. Data required for the WBM/WTM and the TEM include climatic drivers for irradiance, temperature, and precipitation, and spatial information regarding soil texture, vegetation coverage and elevation. The TEM requires a collection of ecosystem-specific datasets for initial calibration and a regional sensitivity analysis to remove extraneous input parameters or to restructure the simulation. A total of 42 such datasets were compiled and the relevant information catalogued within a computerized database. A subset is shown in Table 1. Each data set was processed to conform to our model requirements. Point data and spatial data at coarse scales for climate-driving variables were interpolated to the 1/2 by 1/2 degree latitude by longitude scale using a spherical interpolator developed by Willmott et al. (1985), at the University of Delaware. We developed a new map of potential vegetation classes at the 1/2 degree scale for the globe (Kicklighter et al., 1994) using Matthews (1983) and extant maps at various scales where available. These were compared to potential distributions derived from the bioclimatic driving variables from our climate data sets.

Both the WBM/WTM and the TEM have been successfully implemented in major dryland ecosystems at both the continental and global scales. Our work has demonstrated that a relatively simple hydrologic model, in conjunction with a suite of datasets at 1/2 degree spatial resolution, can generate reasonable hydrodynamic information over both space and time for use in global modeling studies. For example, WBM/WTM model results for South America mimic observed

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datasets for both the pattern of runoff generation and the resultant discharge hydrographs in the Amazon river (Vorosmarty et al 1989). The model was subsequently modified to account for submonthly soil water and evapotranspiration dynamics (Rastetter et al., 1991) and applied to the Zambezi drainage basin in southeastern Africa (Vorosmarty and Moore 1991, Vorosmarty et al 1991). This work is currently being expanded to cover the major river systems of the globe.

The TEM has been applied to South America and has produced the most spatially detailed estimates of monthly and annual fluxes of CO_2 and net primary production currently available (Raich et al., 1991). Application of the TEM to North America revealed that under elevated temperature net primary production increases primarily due to the enhanced availability of mineralized nitrogen (McGuire et al., 1992, 1993). Globally, the TEM has been used with climate data generated by four general circulation models (GCMs) to estimate changes in patterns of net primary production over the globe due to a doubling of atmospheric carbon dioxide (Melillo et al., 1993).

Early efforts at linking terrestrial and aquatic process models utilized simple accounting models both for landscape/mobilization and aquatic transport/retention of nutrients (Gildea et al., 1986, Vorosmarty et al., 1986) in large rivers (i.e., the Mississippi River). Although this approach provides an important tool for quantifying the translocation of materials across the continental land mass, it cannot predict the impacts of land use or greenhouse warming. A process modeling approach is needed. To this end, we have sought to link the WBM/WTM with the TEM. The result will be a mechanistic view of how carbon and nitrogen are first mobilized from the terrestrial landscape and transported through fluvial ecosystems with eventual delivery to the coastal ocean. We developed a hydrological database of discharge for the 25 worlds largest catchments in order to generate global estimates of water and nutrient transport. The simulated topology for these rivers is shown in Figure 11.

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With the emergence of Earth Systems Science has come the realization that there exist key linkages among the atmosphere, terrestrial biosphere and the worlds oceans. With this realization have also come calls for the development of geographically-specific models and associated data sets capable of describing the dynamics of ecosystems at continental and global scales. The collected works that have emerged from this NASA-funded initiative provide ample evidence that it is possible not only to quantify the existing state of key biogeochemical cycles over broad geographic domains, but to gain insight into the issue of anthropogenic change. The project has produced a first set of component Earth System Models, with a particular emphasis on terrestrial and aquatic dynamics. The process-based tools so developed have provided important guidance in our current spectrum of research activities, in particular those related to our NASA Earth Observing System Interdisciplinary Investigation.

FIGURES

Figure 1. The water balance model showing pools and water transfers. Through a retention function for soil water, the model transforms precipitation and potential evapotranspiration into soil moisture, evapotranspiration and runoff. Closed triangles represent inputs; open triangles are flux determinations made by the model. (From: Vorosmarty et al., 1989).

Figure 2. Seasonal pattern of runoff generation predicted by WBM/WTM for the Amazon/Tocantins basin. A northward movement of relatively high runoff is apparent from January through July, followed by low runoff in October throughout the majority of the basin. The extreme northwestern portion of the river system contributes high runoff throughout the year.

Figure 3. Observed and predicted mean annual runoff for South America. The observed dataset is from Korzoun et al (1977). The predictions were made using the global WBM developed under this research. (From: Vorosmarty et al. 1989)

Figure 4. The terrestrial ecosystem model (TEM). The state variables are: carbon in vegetation (C_V); nitrogen in vegetation (N_V); organic carbon in soils and detritus (C_S); organic nitrogen in soils and detritus (N_S); and available soil inorganic N (N_{AV}). Arrows show carbon and nitrogen fluxes: GPP, gross primary productivity; R_A, autotrophic respiration; R_H, heterotrophic respiration; L_C, litterfall C; L_N, litterfall N; NUPTAKE, N uptake by vegetation; NETNMIN, net N mineralization of soil organic N; NINPUT, N inputs from outside the ecosystem; and NLOST, N losses from the ecosystem. (From: McGuire et al. 1992)

Figure 5. Potential net primary productivity (NPP) in South America (as carbon) for the months of January, April, July and October. Values are $g\text{-}m^{-2}\text{-}mo^{-1}$ of carbon. Negative NPP values indicate autotrophic respiration exceeded gross primary production during that month. The blockiness in these figures is due to the poor spatial resolution of the cloudiness data set used to estimate the monthly irradiance of photosynthetically active radiation. (From: Raich et al. 1991)

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Figure 6. (top) Annual net primary productivity of potential vegetation in North America as determined by the terrestrial ecosystem model. (bottom). Annual net nitrogen mineralization of potential vegetation in North America as determined by the terrestrial ecosystem model. (From: McGuire et al. 1992)

Figure 7. Response of net primary productivity (NPP) and net nitrogen mineralization (NETNMIN) for temperate mixed forests of North America in an elevated-temperature experiment. Monthly temperature was increased 2° for the terrestrial ecosystem model (TEM) or the water balance model (WBM), which provides climatic inputs to TEM. Blank and diagonally-lined bars correspond to the NPP response when TEM was run with the carbon cycle uncoupled or coupled to the nitrogen cycle, respectively. The crosshatched bar is the NETNMIN response with the carbon cycle coupled to the nitrogen cycle. (From: McGuire et al. 1993)

Figure 8. Potential natural vegetation used by the TEM to estimate annual NPP for the global terrestrial biosphere. (From: Melillo et al. 1993)

Figure 9. Annual NPP estimated by the TEM for the global terrestrial biosphere. (From: Melillo et al. 1993)

Figure 10. Percent difference in annual NPP between contemporary climate at 312.5 p.p.m.v. CO_2 and the various GCM climates at 625.0 p.p.m.v. CO_2, as predicted by the TEM for eastern North America (left) and southeast Asia (right). Estimates were not made for open water or wetland ecosystems. (From: Melillo et al. 1993)

Figure 11. Network topology for the 25 largest rivers of the globe.

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LIST OF PRODUCTS

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Moore, B., III., M. P. Gildea, C. J. Vorosmarty, D. L. Skole, J. M. Melillo, B. J. Peterson, E. B. Rastetter, and P. A. Steudler, Biogeochemical cycles, in Global Ecology, E. Rambler, L. Margulis and D. Sagan (Eds.), Academic, Boston, Mass., 1989.

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Vorosmarty, C. J. and B. Moore. 1991. Modeling basin-scale hydrology in support of physical climate and global biogeochemical studies: An example using the Zambezi River. Surv. Geophys., 12: 271-311.

Vorosmarty, C. J., B. Moore III, A. Grace, B. J. Peterson, E. B. Rastetter and J. Melillo. 1991. Distributed parameter models to analyze the impact of human disturbance of the surface hydrology of a large tropical drainage basin in southern Africa. In: Proc. IAHS-Symposium on Hydrology for Water Management of Large River Basins, Vienna.

TABLE I Sample data holdings at UNH.

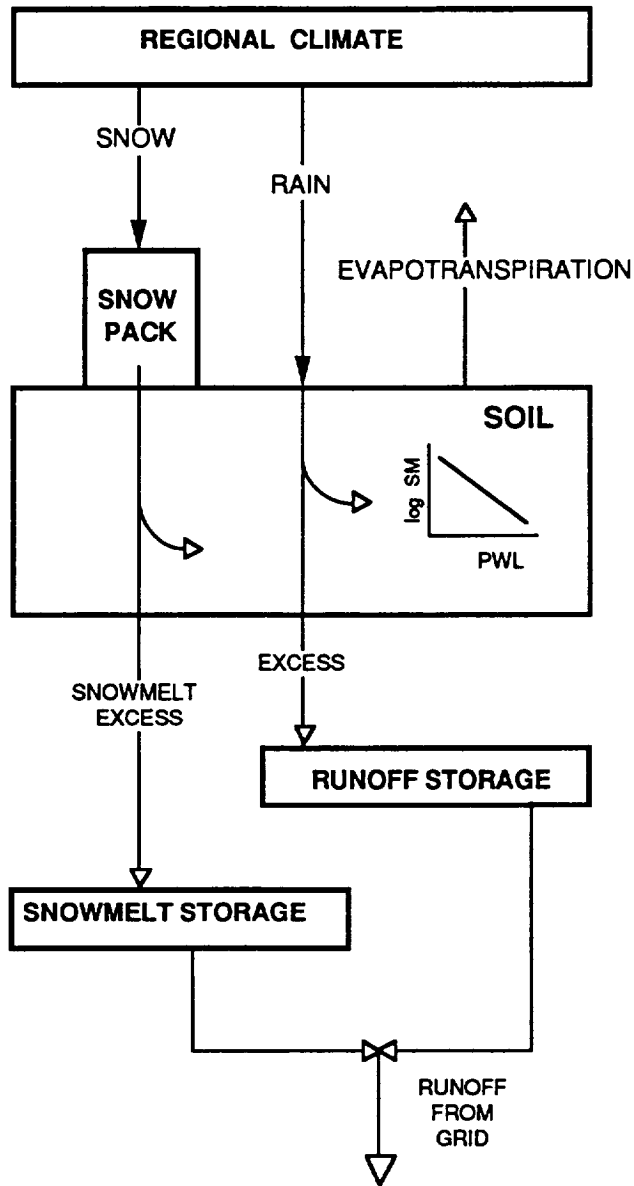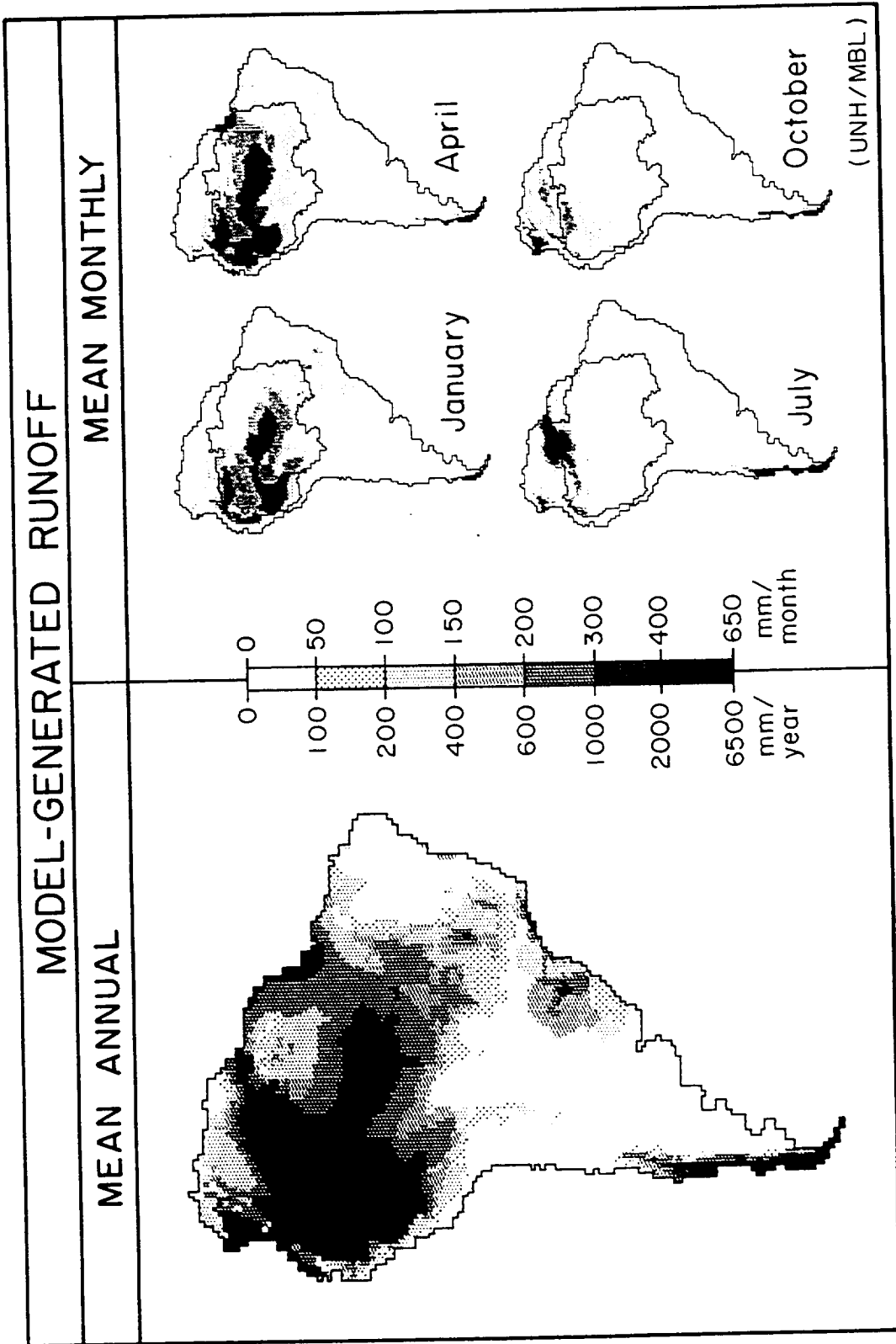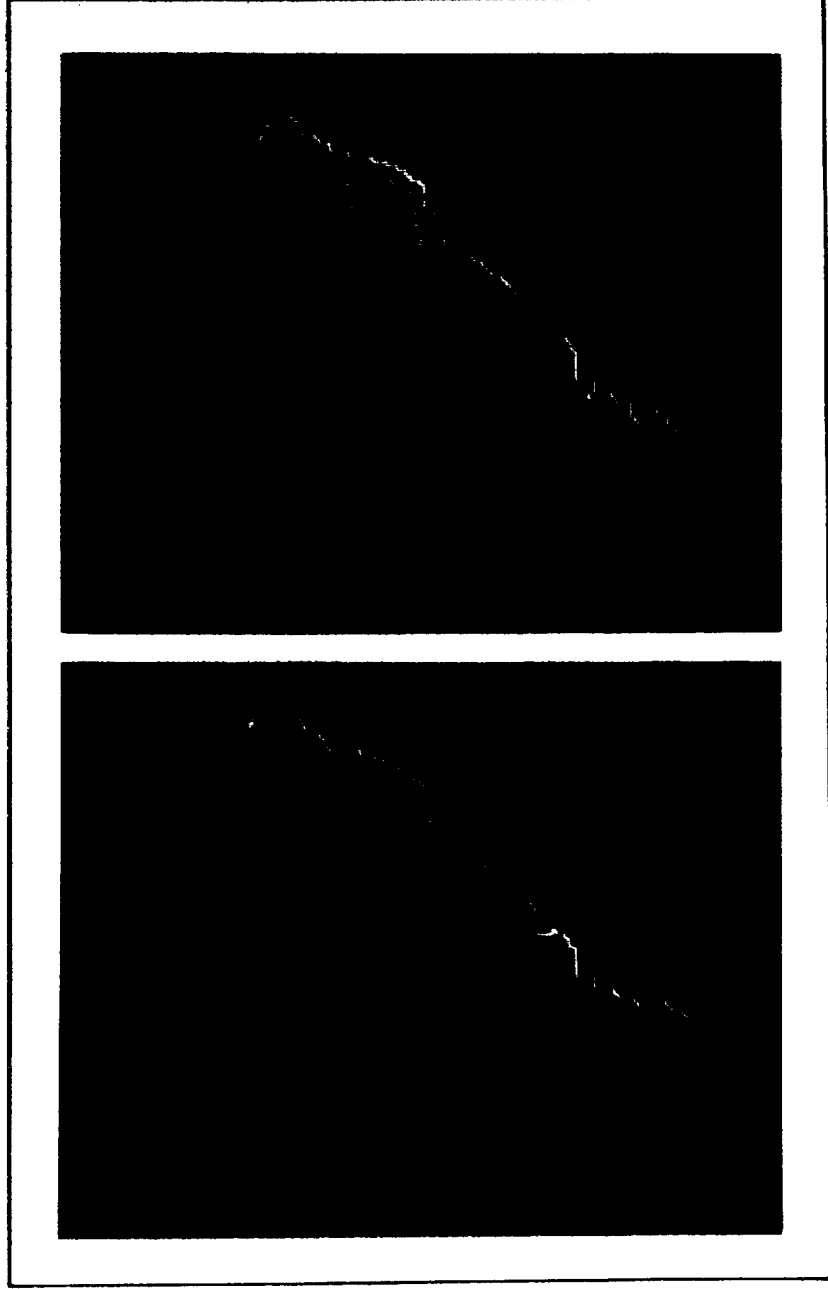| DATA TYPE	SOURCE	SPATIAL SCALE	TEMPORAL RESOLUTION
Physical Parameters			
Coastlines and Political Boundaries	World Data Bank II (CIA/NTIS)	Vector, rasterized to 0.5^o x 0.5^o	N/A
Elevation and Terrain Characteristics	NAVY (1984)	10 x 10	N/A
	ETOPO5 (1988)	5' x 5'	
Development Indicators			
Methane Emission from Animals	Matthews and Fung (1987)	1.0^o x 1.0^o	N/A
Population	World Data Bank	By country	
Urban Development	NAVY (1984)	10 x 10	N/A
Climate			
Air Temperature	Legates and Willmott (1988)	0.5^o x 0.5^o	monthly
	Spangler and Jenne (1988)	Available stations	monthly to 1988
Precipitation	Legates and Willmott (1988)	0.5^o x 0.5^o	monthly
	Spangler and Jenne, (1988)	Available stations	monthly
	Nicholson (1988)	Available stations (Africa only)	monthly
	NOAA	Available stations (Africa only)	monthly,10-day
Cloudiness, Net Irradiation,	Hahn et al. (1988)	varies, 2.5^o-30.0^o	quarterly
and PAR	3DNEPH/USAFETAC	25 nautical miles	daily, 1970-77
	RTNEPH/USAFETAC	25 nautical miles	daily, from 1973
Radiation, Solar and Thermal	NCAR (various GCM results)	Grid format, various resolutions	monthly
Wind, u- and v-components	GRID/FAO (1986)	Vector format	annual
	NCAR (GCM results, 1989)	Grid format, various resolutions	monthly
	HIRAS/USAFETAC	2.5^o x 2.5^o	daily
Soils	FAO/CSRC (1985)	0.5^o x 0.5^o	N/A
	USSR Inst. of Geogr./CSRC	Vector, rasterized to 0.5^o x 0.5^o	N/A
Vegetation			
Potential vegetation and Cultivation	Matthews (1983)	1.0^o x 1.0^o	N/A
Land Cover and Land Use	White (1983)	Vector, rasterized to 0.5^o x 0.5^o	N/A
Holdridge Life Zones	Emanuel et al. (1985)	0.5^o x 0.5^o	N/A
Contemporary Land Use	USSR Inst. of Geogr./CSRC	Vector, rasterized to 0.5^o x 0.5^o	N/A
Potential Ecozone Classification	MBL/CSRC (1990)	0.5^o x 0.5^o	N/A
Ecosystem Complexes	Olson et al. (1985)	0.5^o x 0.5^o	N/A
Hydrological Data			
Discharge hydrographs	UNESCO (various years)	Vector format	monthly
Direction of flow	Operational Nav. Charts	Vector format	N/A
Runoff	WMO/Global Runoff Center	Available stations	monthly
Watersheds	GRID/FAO (1986)	Vector format	N/A

WATER BALANCE
MODEL

REGIONAL CLIMATE

SNOW

RAIN

EVAPOTRANSPIRATION

SNOW
PACK

SOIL

log SM

PWL

SNOWMELT
EXCESS

EXCESS

RUNOFF STORAGE

SNOWMELT STORAGE

RUNOFF
FROM
GRID

FIGURE 1

MODEL-GENERATED RUNOFF

MEAN MONTHLY

April

October

January

July

(UNH/MBL)

MEAN ANNUAL

	mm/ month
0	0
100	50
200	100
400	150
600	200
1000	300
2000	400
6500	650
mm/ year	

FIGURE 2

MEAN ANNUAL RUNOFF
SOUTH AMERICA

ALL UNITS IN MM

0 -	100
101 -	200
201 -	400
401 -	600
601 -	800
801 -	1000
1001 -	1500
1501 -	2500
2501 -	3500
> 3500	

OBSERVED   PREDICTED

FIGURE 3
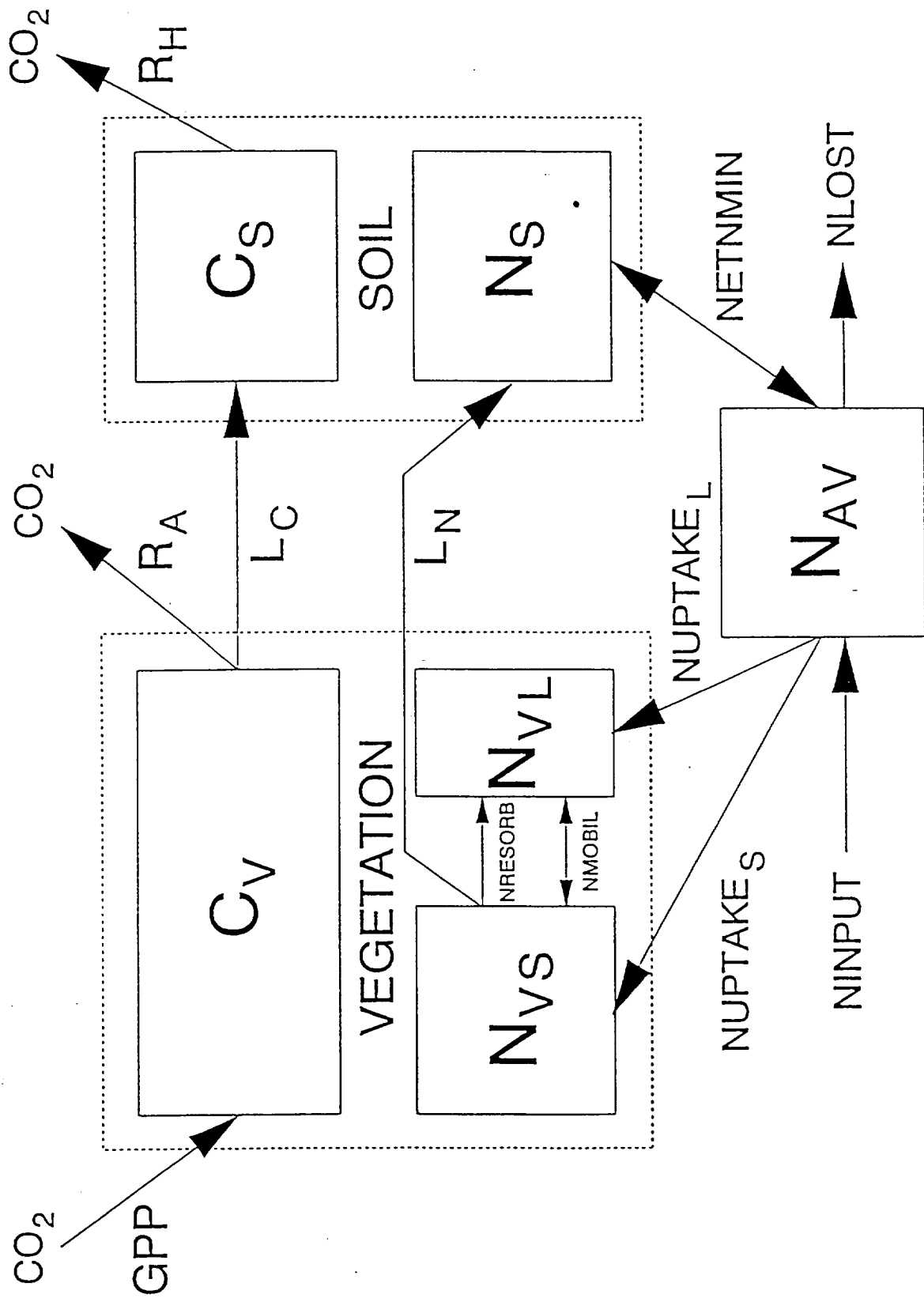
FIGURE 4
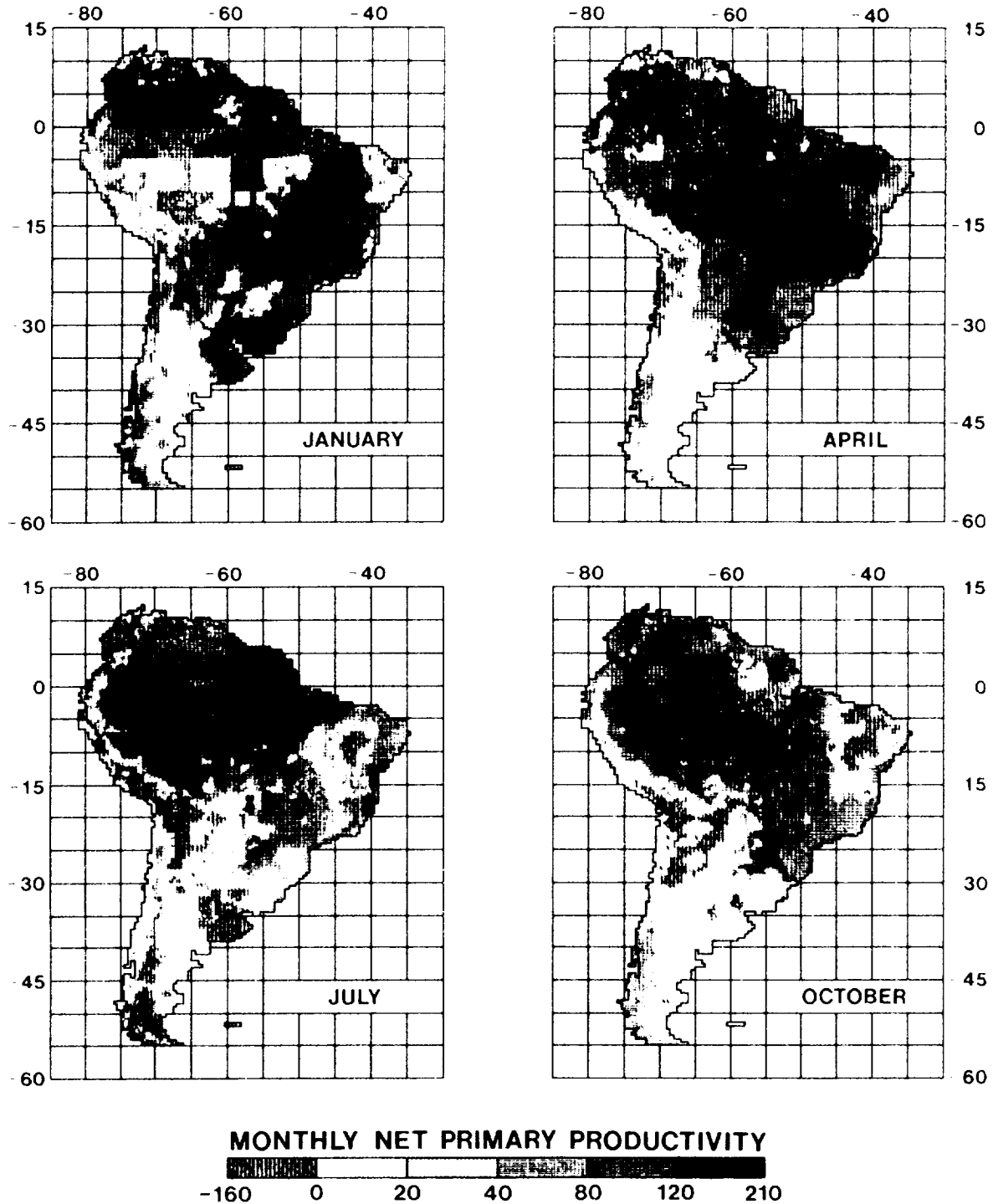
MONTHLY NET PRIMARY PRODUCTIVITY

-160   0   20   40   80   120   210

Potential net primary productivity (NPP) in South America (as carbon) for the months of January, April, July, and October. Values are g m mo of carbon. Negative NPP values (in red) indicate that autotrophic respiration exceeded gross primary production during that month. The blockiness in these figures is due to the poor spatial resolution of the cloudiness data set used to estimate the monthly irradiance of photosynthetically active radiation.

FIGURE 5

gC·m⁻²·yr⁻¹

Wetland Ice 50 150 300 500 750 1050 1400

Plate 2.

gN·m⁻²·yr⁻¹

Wetland Ice 1.5 3.0 4.5 9.0 15 21 27
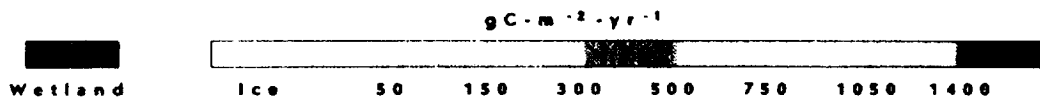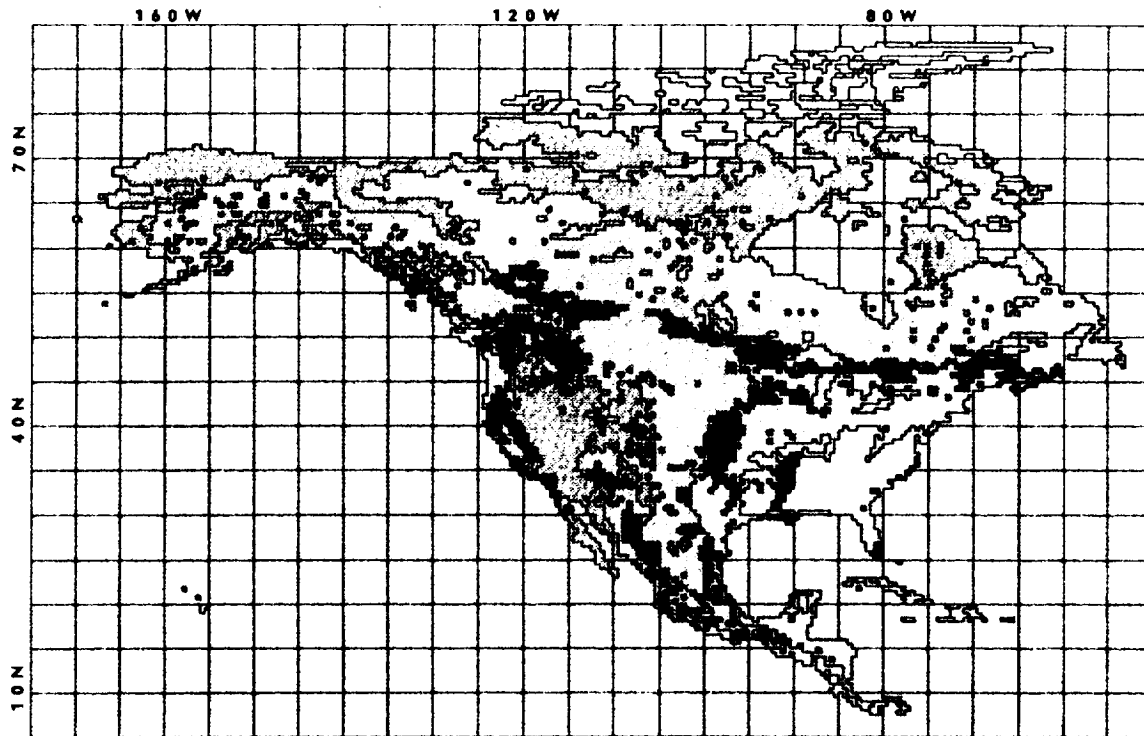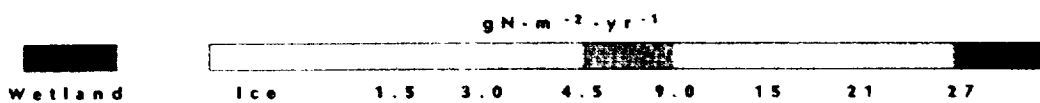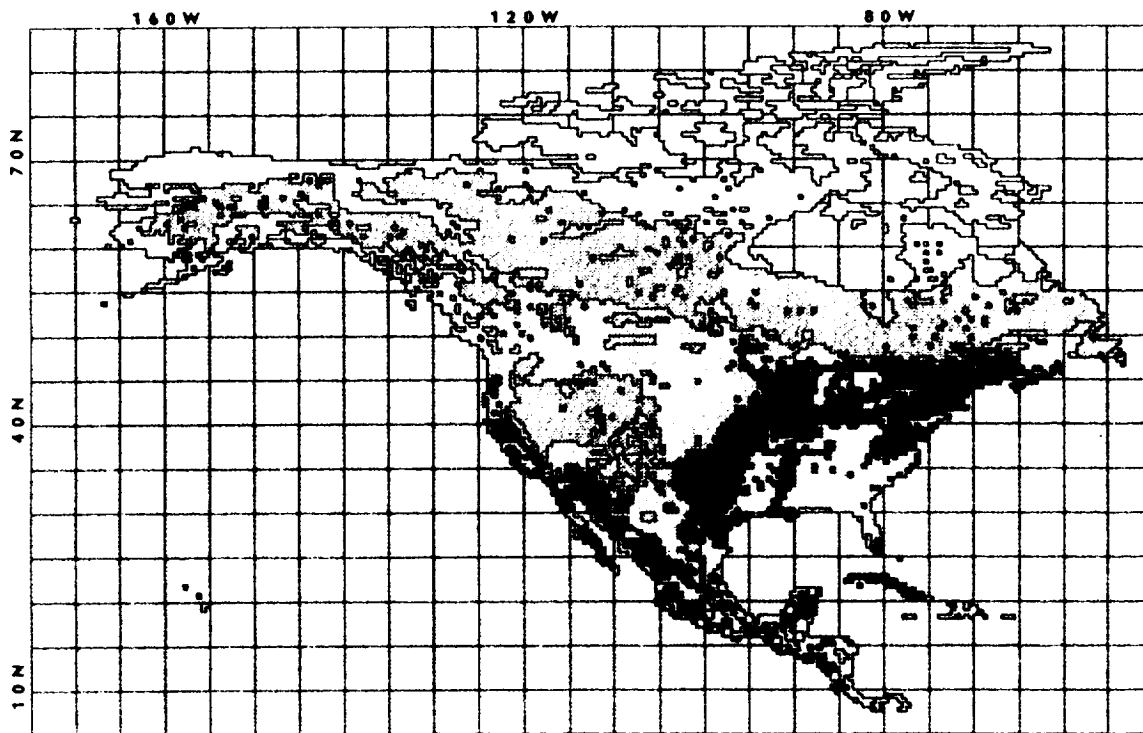
FIGURE 6

FIGURE 7

Vegetation

FIGURE 8

Legend (left column):
- Boreal Forest
- Boreal Woodlands
- Wet Moist Tundra
- Polar Desert
- Ice
- Wetlands

Legend (center column):
- Tropical Evergreen Forest
- Tropical Deciduous Forest
- Tropical Savanna
- Temp. Broad Leaf Evrg. Forest
- Temperate Mixed Forest
- Temperate Deciduous Forest
- Temperate Coniferous Forest

Legend (right column):
- Short Grassland
- Tall Grassland
- Mediterranean Shrubland
- Arid Shrubland
- Temperate Savanna
- Xeromorphic Woodland
- Desert

Annual Net Primary Production

gC -m-2-yr-1

Wetlands   Ice   50   150   300   500   750   1050   1400

FIGURE 9

GFDL 1

GFDL Q

GISS

OSU

Percent Difference in Annual NPP

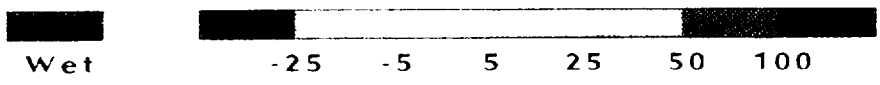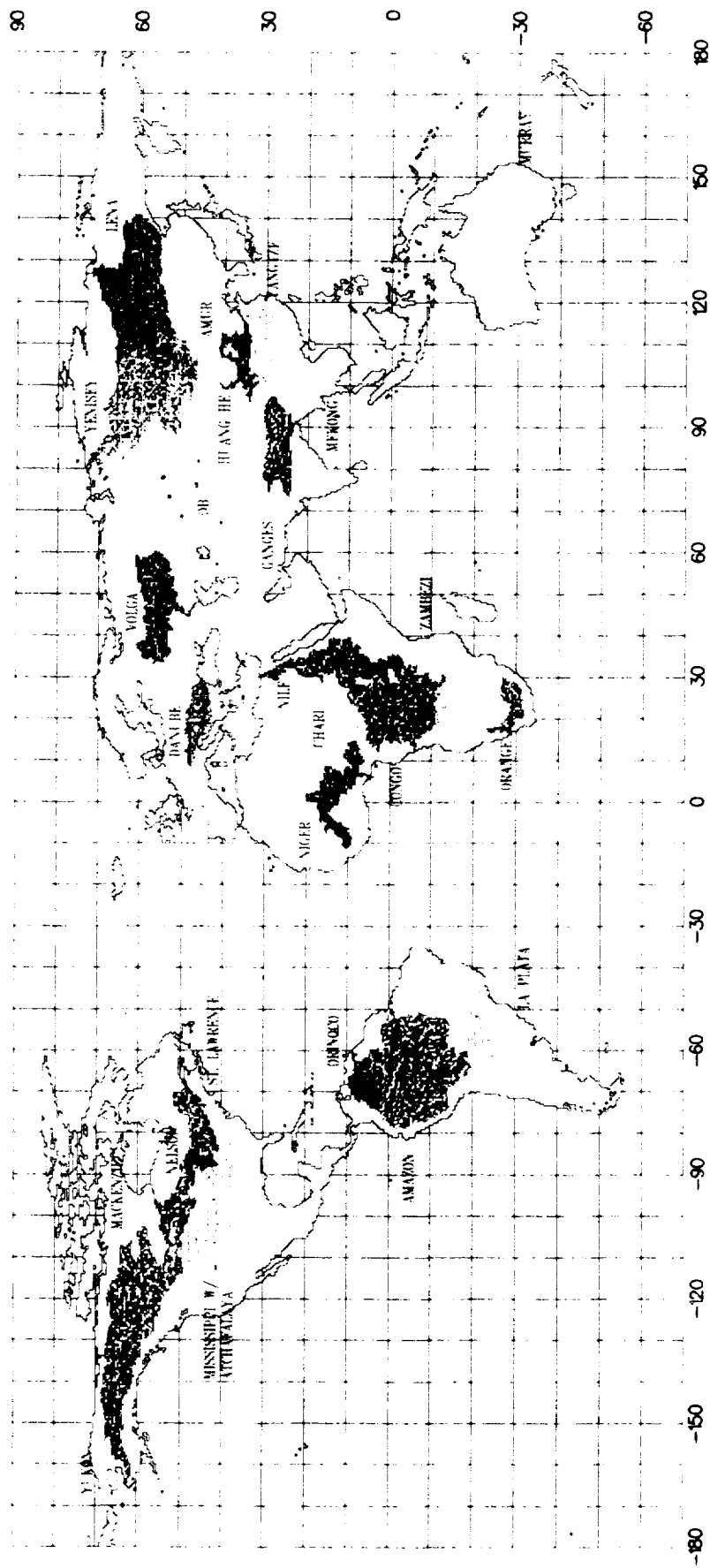Wet   -25   -5   5   25   50   100
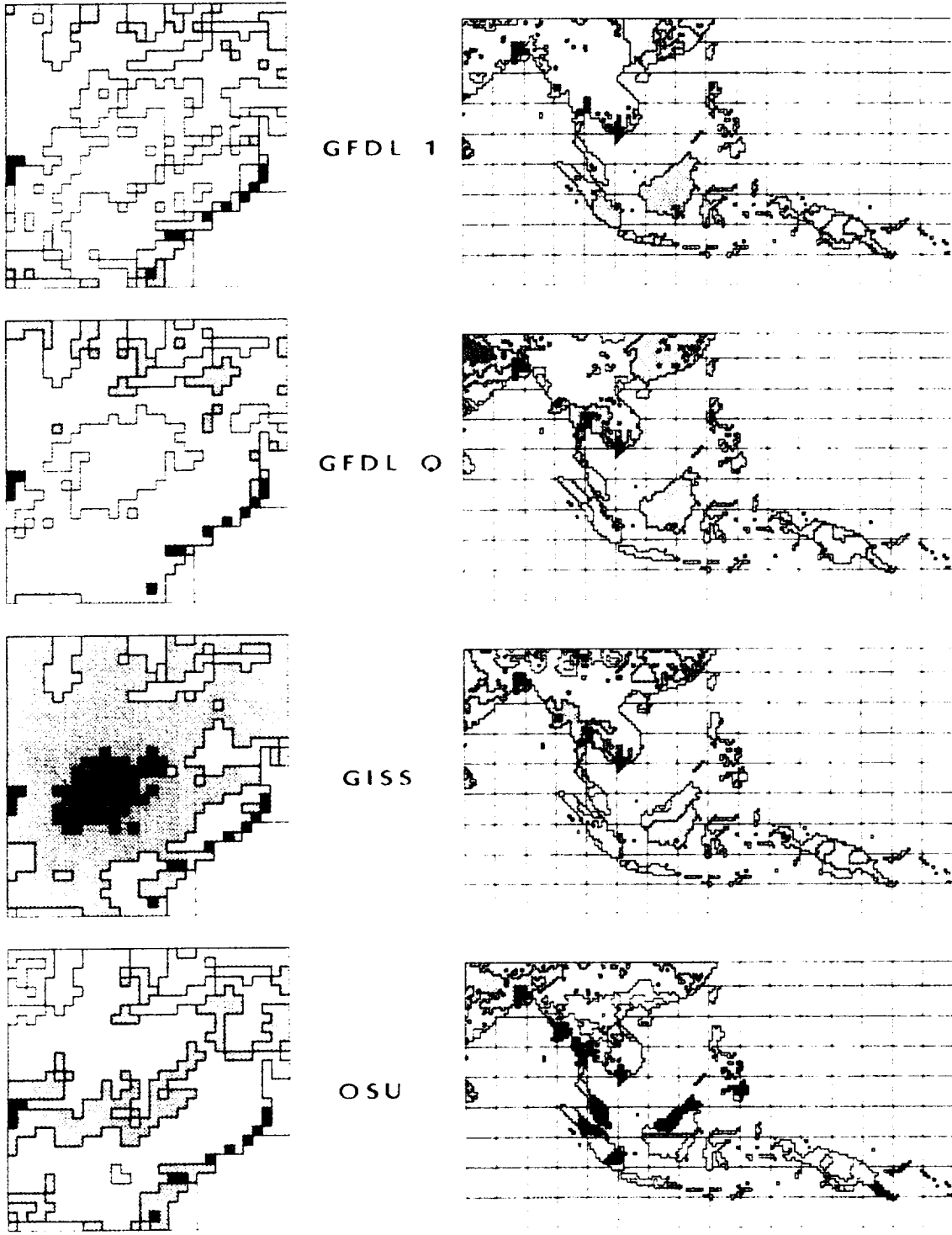
FIGURE 10

The Worlds Twenty-Five Largest River Systems

-- Simulated Topology --

Map Description

A Global Hydrologic Archive and Analysis System (GHAAS) is currently being developed at the Institute for the Study of Earth Oceans and Space at the University of New Hampshire as part of the larger effort to study the impacts of anthropogenic change on biogeochemical cycling at the global scale. The GHAAS maintained data on discharge, flow regulation, meteorology, typology and constituent loads. The GHAAS incorporates both grid-based and vectorized data on the terrestrial landscape and river systems.

This map displays above organizes clusters of 0.5 degree (latitude x longitude) grid cells into simulated catchments which topologically resemble actual drainage basins. The system gives ready access to a suite of global landscape parameters useful to drainage basin hydrology modeling, such as land cover, soils, elevation, population, urban centers, and nutrient stocks. The system maintains data sets from both ground-based studies as well as from remote sensing data and modeling experiments. Such an integrated information system, coupled to regional models, will be a critical determinant of our ability to identify and understand the dynamics of global change in the coming decades.

Map Development & Composition

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Ocean & Space
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Durham, NH USA

The Ecosystems Center
Marine Biological Laboratory
Woods Hole, MA USA

FIGURE 11