NCAR Integrated Biosphere-Atmosphere Studies Program
Report to NSF Biocomplexity Program

Executive Summary:

The Integrated Biosphere-Atmosphere Studies Program (IBASP) at NCAR integrates observation and modeling of physical and biological processes to study biogoechemical and water cycles. The increasingly global nature of human influence on the environment requires a global-scale perspective in parallel with regional and process measurement and modeling activities. The activities listed in this report are an important contribution towards understanding how human and biotic activities interact to change the Earth system.

FY'04 NSF Biocomplexity funds supported a wide range of IBASP activities, leveraging NCAR's skills, assets, and previous work to address key components of the NSF's Biocomplexity Program, including coupled biogeochemical cycles, dynamics of coupled natural and human systems, and instrument development. Our efforts focused on three new themes which set the trajectory for future work in biosphere-atmosphere studies at NCAR:

1) Building common land model components for use in climate (CLM) and weather (WRF) models. The development of common land surface representations to work at both regional and global scales is a new effort for NCAR. Ongoing work includes development of the CLM and Noah models to include hydrological routing and urban processes. Future work includes the use of CLM as a module within the WRF model to increase commonality between WRF and CCSM modeling efforts.

2) Building a unified model of biosphere-atmosphere exchange on the framework of global and regional land, atmosphere, and chemical models. The development of high resolution surface emission and deposition models and datasets which are then made publicly available, such as MEGAN and the N deposition dataset, are new efforts that build strongly on NCAR's expertise. This phase focused on development of off line modules and datasets. Future plans include evaluation of the off-line results and building the model elements that will enable fully coupled simulation of chemistry, climate, and land surface components.

3) Conducting ground-based field and modeling experiments to augment existing collaborative field studies. NCAR played leadership roles in the Carbon in the Mountains Experiment (CME), and in the Chemistry and Production of Smoke in Brazil (CAPOS-Brazil) study. These efforts were made possible by participation in the Integrated Biosphere Atmosphere Studies Program with significant leverage from a variety of other funding sources. The field portion of both studies is now complete. Future work will include analysis, model evaluation, and instrument development to lay the groundwork for future studies.

Education and outreach forms a critical element of the Program. Funds supported (a) planning and development of biosphere content for Windows to the Universe, an online, bilingual, science education resource that is widely used by the K-12 educational community, (b) testing and implementation of the Greenhouse Gas Wizard, a web-based tool for undergraduate education, and (c) the research of three students in the SOARS minority participation program. Future plans include continuation of the work listed above and development of the NCAR Mesa Lab visitor exhibit "Climate Future."

The Integrated Biosphere-Atmosphere Studies Program has catalyzed a synergy of inter- and multi-disciplinary perspective both within NCAR and between NCAR and the university community. The Program is a partnership among seven NCAR Divisions or Programs, four NCAR Strategic Initiatives, and the UCAR Office of Education and Outreach, and is a central part of NCAR's new Institute for Multi-disciplinary Earth Studies (TIMES). The NCAR Program has established close partnerships with several Biocomplexity projects at universities, and has fostered collaborations with scientists at many other universities and research institutes.

The work of the NCAR Integrated Biosphere-Atmosphere Studies Program complements and contributes to several important national and international programs, including the North American Carbon Cycle Plan, the IGBP Fast Track Nitrogen and Iron Initiatives and the IGBP iLEAPS (Integrated Land Ecosystem Atmosphere Process Study) program. The completed global modeling work contributes to the IGBP Analysis, Integration and Modeling of the Earth System (AIMES) Project, and to the IPCC 4th Assessment WG1 Report.

***Introduction**:* NCAR's Biocomplexity Program is called the Integrated Biosphere-Atmosphere Studies Program. It focuses on the atmospheric intersection of the carbon, nitrogen, mineral, and water cycles. The overarching goal is to study biogoechemical and water cycles at local to global scales through integrated observation and modeling of physical and biological processes.

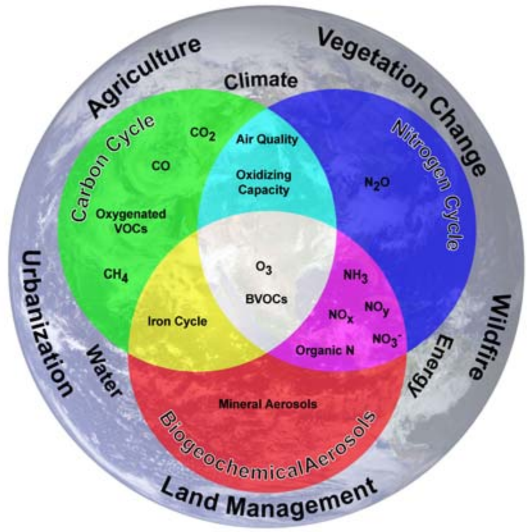

Figure 1: Key biogeochemical cycles: the carbon, nitrogen, and mineral cycles, interactions among them and their interactions with the water and energy cycles and human forcing. The water cycle is a central driver of all biogeochemical cycles.

The new themes that catalyzed biocomplexity science across NCAR programs and divisions for FY04 are: 1) building common land model components (e.g. hydrological routing and urban processes) for use in climate (CLM) and weather (Noah) land surface models; 2) building a unified model of bio-atmospheric exchange on the framework of global and regional land, atmosphere, and chemical models (Figure 2); 3) conducting ground-based field and modeling experiments (Figure 3) to augment existing collaborative field studies. NCAR played leadership roles in the Carbon in the Mountains Experiment (CME) which was coordinated with the NSF-Biocomplexity-funded Airborne Carbon in the Mountains Experiment (ACME), and in the Chemistry and Production of Smoke in Brazil (CAPOS-Brazil) study. CME is a collaboration between three NCAR divisions and three universities (University of Colorado, Colorado State University, and the University of Miami, Florida), and funded by the NSF Biocomplexity Program. CAPOS-Brazil is a collaboration between NCAR and five universities (University of Montana, University of California- Riverside, Desert Research Institute, University of Washington and the University of Sao Paulo) and is funded by the NSF-ATM Atmospheric Chemistry Program and the NCAR Biogeosciences and Wildland Fire strategic initiatives.

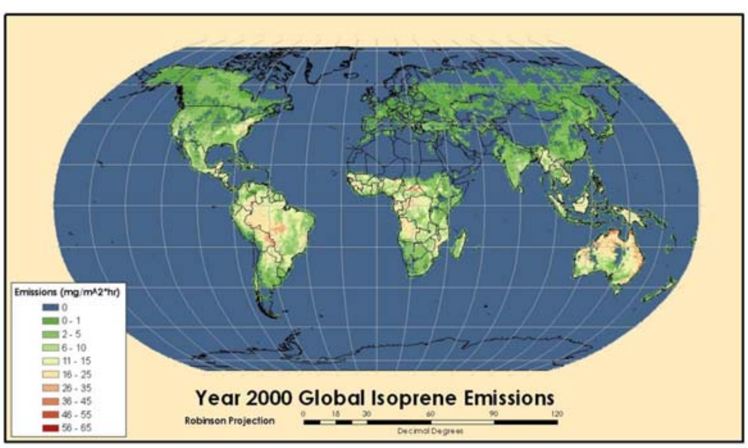

Figure 2: Isoprene emission output from the Model of Emissions of Gases and Aerosols from Nature (MEGAN). MEGAN is a global model with 1 km^2 resolution that is being used for regional (WRF-CHEM) and global (MOZART) models. MEGAN is being developed as a community effort and the initial version is available on the NCAR community data portal.

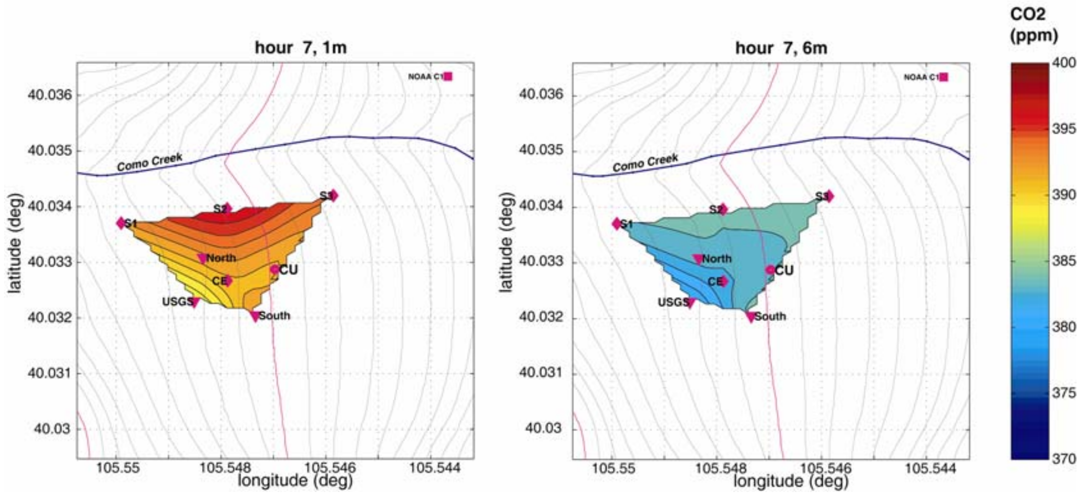

Figure 3: Tower CO_2 measurements from the pilot study for the Carbon in the Mountains Experiment (CME). CO_2 spatial distribution is sensitive to small-scale topography at 1m height, but to large-scale topography at 6m height, indicating that the local drainage flow is shallower than 6m. This impacts carbon budget calculations, especially the treatment of the nocturnal boundary layer.

Intellectual Merit: The objective is to study the interacting cycles of energy, water, and matter among the hydrosphere, atmosphere, and biosphere and to transfer the results to Earth system and human dimension models, in support of NCAR's mission with regard to biocomplexity research and education related to atmospheric sciences. There are three areas of effort: 1) modeling, 2) instrumentation, and 3) field programs.

1) The modeling work's primary foci are development of NCAR's global Community Climate System Model (CCSM) including the Community Land Model (CLM), and construction of components that unify modeling capabilities at global (CCSM) and regional (Weather Research and Forecasting [WRF]) scales.

   Biocomplexity funds supported several projects to implement biogeochemistry, vegetation dynamics, and land cover change in the CLM and the CCSM. This research broadly addresses how coupling of energy, water, carbon, nitrogen, iron, and sulfur cycles affect climate, air quality, radiative forcing, and ecosystem function on regional to global scales and the human perturbations of these cycles through land cover change:

   a) Influence of carbon cycle-climate feedbacks: The role of the global carbon cycle as a feedback in the climate system is a primary focus of further development of the CCSM. A suite of multi-century, fully coupled carbon-climate integrations was performed for the flying leap experiment (K. Lindsay in cooperation with I. Fung [UC, Berkeley] and S. Doney [WHOI]). Significant progress was made in further development of the terrestrial ecosystem model needed to implement the global carbon cycle in the CCSM (P. Thornton). Development of the carbon and nitrogen biogeochemistry for the CLM used eddy covariance measurements of water and carbon fluxes and other site-level observations in collaboration with the AmeriFlux and FLUXNET communities to evaluate, constrain, and improve the CLM. Preliminary climate model simulations demonstrated that the land biogeochemistry behaves reasonably and that the improvements have a significant impact on the simulated climate.

   b) Influence of mineral aerosols: Significant mobilization of mineral aerosols in marginal arid lands impacts the atmospheric radiative budget, atmospheric chemistry, and terrestrial and ocean biogeochemistry. CCSM experiments were conducted to quantify the climatic effects of mineral aerosols, primarily in terms of the atmospheric radiative budget (N. Mahowald).

c) Influence of land-use changes: Changes in land cover resulting from human use of land are increasingly being recognized as an important forcing of climate. Parameterizations of urban land cover and agroecosystems for the CLM are being developed and implemented (G. Bonan, K. Oleson, S. Levis, collaborators at U. Kansas and U. Wisconsin). The global climate forcing associated with land use is being studied (G. Bonan, K. Oleson, S. Levis, L. Mearns, collaborators at U. Kansas). Climate model simulations using land cover for the year 2100 showed that climate forcing by land use changes in key regions such as tropical South America and the U.S. can be large, equaling those due to changes in greenhouse gases (Figure 4).

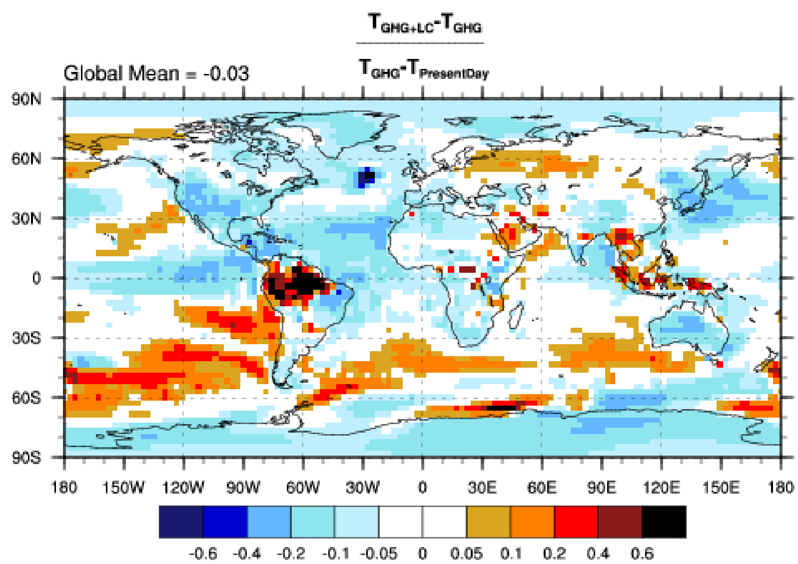

Figure 4: Changes in mean annual air temperature resulting from changing land cover, expressed relative to greenhouse gas-induced temperature changes, between present day (1961-1990) and future (2070-2099) periods.

d) Influence of climate-vegetation feedbacks: Large-scale changes in the geographic distribution of vegetation as a result of past and future climate changes themselves alter climate. The CLM includes a model of global vegetation dynamics and is being applied to study the vegetation forcing of climate and the contribution of vegetation to climate sensitivity (G. Bonan, S. Levis).

e) Carbon data assimilation system: The extreme heterogeneity of the land surface and the multiple time scales of biogeochemical processes have long posed challenges for model parameterization NCAR is developing an assimilation approach to parameterization and to support integration of field and modeling programs generally. Carbon data assimilation involves two "levels" of analysis. The first is inversion of concentrations to infer fluxes. This is done by inverting an atmospheric transport model to find the estimated fluxes that best explain observed concentration data. The NCAR system uses a 4-dimensional variational scheme to accomplish this step. The second is inversion of fluxes to infer states and parameters governing the underlying biophysical system. This is a much newer approach, applicable with global concentration and local eddy covariance scale data. At NCAR, we have pioneered a Markov Chain Monte Carlo approach to solving this problem using carbon fluxes estimated from either local eddy covariance data or larger-scale airborne fluxes. We have developed and tested this capability and are using it to significantly augment the analyses associated with the ACME field program (D. Schimel, D. Baker, T. Vukicevic, B. Stephens, W. Sacks, P. Hess, S. Aulenbach, D. Ojima [CSU], R. Monson [CU]).

NCAR's Biocomplexity Program also supports several complementary modeling studies:

f) Development of a unified Noah Land Surface Model: A spatially distributed version of the 1-D Noah LSM has been developed and implemented into the NCAR High Resolution Land Data Assimilation System for use in the WRF regional model. Results show that higher spatial resolutions allow local terrain details to play an increasing role in altering local water budgets and potentially exert significant influence on land-atmosphere exchanges. (D. Gochis, D. Yates, F. Chen).

g) Development of a unified Biosphere-Atmosphere Exchange Model for both regional and global scale models:

(i) Investigation of carbon-nitrogen cycling: Maps of N deposition fluxes and continental- scale N budgets have been constructed from site-network observations for the U.S . and Western Europe, and published through the Oak Ridge National Laboratory's Data And Archiving Center (ORNL-DAAC) (Figure 5). Oxidized N species dominate in the US, reduced N dominates in Europe. Estimated U.S. N emissions far exceed measured deposition, suggesting significant export, or under-sampling of urban influence. The data compiled have been used to evaluate the wet deposition schemes used in both the CCSM-CHEM and WRF models. Both models are working toward the development of a common wet deposition scheme (E. Holland, J.-F. Lamarque, J. Sulzman, R. Braswell [UNH]).

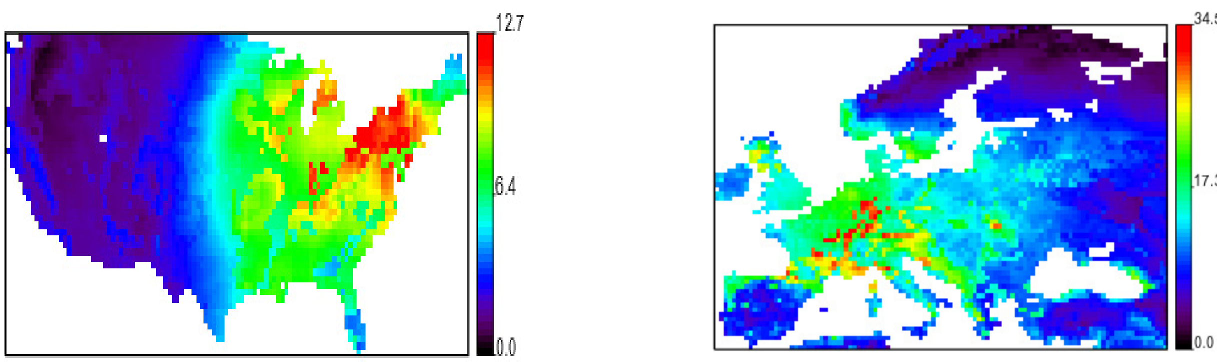

Figure 5. Estimated N deposition fluxes (kgN ha^{-} yr^{-1}) over the conterminous United States and western Europe. Fluxes include wet deposition of NH_4^+-N and NO_3^--N, and dry deposition of HNO_3-N (g) (from the V_d for HNO_3), particulate NH_4^+, and, in Europe, NO_2 (g). Annual totals are 3.7-4.5 Tg N yr^{-1} for the US, and 8.4-11.2 Tg N yr^{-1} for western Europe. The regions considered are of comparable area.

(ii) Investigation of biogenic aerosols: Comparisons of model analyses with NCAR observations showed that observed isoprene concentrations can produce observed concentrations of hydroxy-acetone, methyl glyoxal and glycolaldehyde, and that isoprene can significantly contribute to global organic aerosol, possibly as much as do monoterpenes and other larger compounds, and far exceeding previous estimates. The models are to be applied in the upcoming MIRAGE experiments and will support the understanding of urban plume interactions with the biosphere (local forest biomes). With the development of the MEGAN emissions inventory at 1 km^2 resolution, the WRF and CCSM models will use the same emission inventory for key biogenic VOCs (Figure 2) (S. Matsunaga, A. Guenther, C.Wiedinmyer, T. Karl, J. Orlando).

(iii) Integration of marine ecosystems: A marine biogeochemistry-ecosystem model is being developed by collaborators at Woods Hole Oceanographic Institution and the University of California, Irvine. This model is a component of the CCSM, and is adaptable to regional scales.

h) Assessment of the consequences of increasing atmospheric CO_2 on coral reef ecosystems: Biocomplexity funding to J. Kleypas supported planning and field efforts to improve observations of seawater chemistry changes at a NOAA Coral Reef Early Warning System (CREWS) station in the Bahamas, and stimulated collaborations with colleagues at NOAA and the University of Miami to improve biogeochemical observations at other sites (J. Kleypas).

2) Instrument development has increased field program capabilities, guiding new areas for modeling and testing hypotheses generated by models. Instrumentation developments included:

   a) Reconfiguration of PTRMS for airborne eddy covariance measurement (S. Shertz, T. Karl).

   b) Completion of development of airborne and tower disjunct eddy accumulation systems for measuring biogenic emissions of reactive carbon and nitrogen (A. Guenther, A. Turnipseed, S. Shertz, P. Shepson [Purdue], B. Lamb [WSU]).

   c) Reconfiguration and optimization of the 18-inlet “hydra” CO_2 analyzer used in the CME field program, and development of a new gas calibration system for this and other CO_2 analyzers (S. Burns, T. Delaney, S. Shertz, B. Stephens).

   d) Improvement of a tunable diode laser system for measurement of carbon isotopes. Sensitivities of $<10^{-6}$ are now routinely demonstrated in the laboratory, and the new noise -reduction strategies will soon be applied to the field instrument (A. Fried, D. Richter, P. Weibring).

   e) A prototype flexible data system for the adaptive sensor array. This will enable a three-fold increase in the vertical resolution of micrometeorological flux measurements.

3) The field programs integrate the capabilities and perspectives of our efforts in both instrument development and in regional and global modeling. Supported field programs include:

   a) The ground -based CME (R. Monson [CU], D. Schimel, B. Stephens, J. Sun, E. Patton, D. Anderson [United States Geological Survey], R. Braswell [UNH]), in which tower measurements and model analyses characterized CO_2 concentrations, fluxes and advection in complex forested terrain in the Colorado Rockies. Findings include:
   (i) CO_2 respiration from the ground does not effectively ventilate through the canopy, due to within-canopy stratification. This increases the importance of advection, even in daytime.
   (ii) CO_2 advection over mountain areas is associated with local, small-scale circulations and is sensitive to major steep slopes and small gullies embedded in these steep slopes.

   b) The Chemistry And Production Of Smoke (CAPOS) study in the Brazilian Amazon (T. Karl, A. Guenther, P Harley, J. Greenberg; D. Blake [UC, Irvine], B. Yokelson and T. Christian [U. Montana], M. Potosnak [Desert Research Institute], E. Alvardo [U. Washington], P. Artaxo [Universidad Sao Paulo, Brazil], J. Caravalho [CPTEC, INPE, Brazil]), in which airborne and ground measurements characterized the primary emission composition of VOCs and other gases from tropical fires and within aging plumes. Findings include:
   (i) Pyrogenic oxygenated VOCs significantly exceed the IPCC2001 estimate. Terpenoid emissions vary significantly. Isoprene and monoterpene emissions dominate pristine PBL chemistry. The canopy reduction factor for isoprene proposed in the IPCC 2001 report is significantly overestimated.
   (ii) Some land use changes (urbanization, soybean plantations, and hydroelectric reservoirs) decrease isoprene, but some agricultural land use may increase isoprene.
   (iii) Turbulent transport is modified by clouds and is overestimated by scaled gradient functions.

   c) Planning for the MIRAGE-Mex (2006) experiment (S. Madronich, X. X. Tie).

   d) Long-term planning for a biogeochemistry, water, and Wildland Fire focused study of the upper Rio Grande Basin (2007) (D. Gochis, R. Rasmussen).

Educational Outreach Achievements:

a) New content and interactives are in development for the Windows to the Universe educational website (leveraging its existing content base and large audience) which express the biosphere’s importance in the Earth system and the relevance of biosphere research. New classroom activities on the nitrogen cycle and accompanying educator resources are being developed and tested with teachers and students. Content, interactives, and activities will be available in English and Spanish (R. Johnson, L. Gardiner, R. Russell).

b) The Web-based Greenhouse Gas Wizard: A Biogeochemical Tool for University Education was tested and implemented. This is an Internet-based greenhouse gas simulation and gaming environment for exploring alternative strategies to reduce net emissions of CO_2, CH_4, and/or N_2O from agricultural systems to the global atmosphere. It integrates the UNH Denitrification-Decomposition (DNDC) model and our DAYMET meteorological database into an exciting interactive toolkit for use in university education and research (R. Harriss, P. Thornton).

c) NSF Biocomplexity funds supported the research of three students in the SOARS (Significant Opportunities in Atmospheric Research) minority education program : A. Drevon - Using wavelet analysis to understand carbon interactions in the Carbon in the Mountains Experiment; M. Zauscher - Improving the quality of $\delta^{18}O\text{-}CO_2$ data from the NOAA/CMDL Network; B. Edwards - Evaluating the convective atmospheric boundary layer by using surface station data. NCAR biocomplexity scientists contribute to SOARS program design, serve on and lead the SOARS Steering Committee, and recruit and mentor students. SOARS won a Presidential Award for Excellence in 2001.

d) Development of the Climate Future exhibit in the Mesa Lab is leveraging expertise available through scientists in the Biocomplexity Program. The new exhibit should open in spring 2005.

Project Management: The NCAR Biocomplexity Program is a partnership among seven NCAR Divisions and Programs and four NCAR Strategic Initiatives: Atmospheric Technology Division (ATD, now Earth Observing Laboratory, EOL), Atmospheric Chemistry Division (ACD), Climate & Global Dynamics Division (CGD), Mesoscale & Microscale Meteorological (MMM) Division, Research Application Program (RAP), the Education and Outreach Program, the Environmental and Societal Impacts Group (ESIG, now the Institute for the Study of Society and the Environment, ISSE), and the Biogeosciences, Water Cycle, Wildland Fire Collaboratory, and Assessment Strategic Initiatives. The Integrated Biosphere-Atmosphere Studies Program is a central part of NCAR's newly established Institute for Multi-disciplinary Earth Studies (TIMES).

The NCAR Biocomplexity Program project management team includes representatives of each program, with responsibilities for program plan development, priorities and execution. Elisabeth A. Holland (ACD, BGS) is project lead, with Roy Rasmussen (RAP, Water Cycle) as co-chair. A Steering Committee representing the program participants includes Gordon Bonan (CGD, BGS, Assessment, Water Cycle), Janice Coen (MMM, RAP, Wildland Fire), Aiguo Dai (CGD, Water Cycle), Roberta Johnson (Education and Outreach), Alex Guenther (ACD, BGS, Wildland Fire), Joanie Kleypas (ESIG, Assessment), Dirk Richter (ATD), Britton Stephens (ATD, BGS), and Rich Wagoner (RAP, Wildland Fire). Management oversight has been provided by a committee of division directors led by Daniel McKenna (ACD) and including Rit Carbone (ATD), Jim Hurrell (CGD), and Bob Harriss (ESIG).

This integrated program provides a remarkable synergy of inter- and multidisciplinary perspective between NCAR and the university community and across NCAR programs. It leverages NCAR skills and assets, including scientific expertise, facilities, and computing infrastructure unique to NCAR to address key components of the NSF's Biocomplexity Program, including coupled biogeochemical cycles, dynamics of coupled natural and human systems, and instrument development. The program builds on NCAR's considerable modeling and observational strengths and provides an important resource for the university community.

Broader Impacts: The ongoing activities listed here are an important step towards understanding how human and biotic activities interact to change the Earth system. The increasingly global nature of human influence on the environment requires a global-scale perspective in parallel with regional and process measurement and modeling activities. The unification of global and regional modeling of land surface and chemistry represents an important step forward in our modeling capabilities. Once unification and evaluation of the model components is complete, the models will be distributed to the science community through the established CCSM and WRF processes, including annual meetings and scheduled releases.

National and International Partnerships: The NCAR Biocomplexity Program has established close partnerships with several university Biocomplexity projects including those at Washington State University, led by Brian Lamb; Purdue, led by Paul Shepson; Rice University, led by Frank Tittel; and University of Colorado,

led by Russ Monson. Participants in the NCAR Biocomplexity program also collaborate with and participate in NSF funded IGERT programs, including the BART program at the University of Michigan, and the CCSI program at the University of Colorado. The carbon dioxide -focused ground, airborne, data assimilation, and modeling components of the program contribute directly to the North American Carbon Cycle Plan.
The completed global modeling work represents important steps towards an Earth System Model, complements Earth system modeling efforts in Europe, and contributes to the IGBP Analysis, Integration and Modeling of the Earth System (AIMES) program, part of the Earth System Science Modeling Partnership. The modeling and experimental work represents an integral component of the emerging land and land-atmosphere projects of the IGBP. The mineral aerosol modeling studies contribute to the IGBP Fast Track Iron Initiative. A US Nitrogen Science Plan for atmospheric-terrestrial exchange of reactive nitrogen was developed following a community workshop and has provided a template and a point of cooperation for the IGBP Fast Track Nitrogen Initiative and the IGBP iLEAPS (Integrated Land Ecosystem Atmosphere Process Study) program. The NCAR Biocomplexity Program contributes directly to the IPCC WG1 Report, particularly Chapter 9, *Coupled Biogeochemical Cycles*.

Future Plans: Ongoing Integrated Biosphere Atmosphere Studies will build on the three themes described here: 1) Building common land model components for use in climate (CLM) and weather (WRF) models: Ongoing work includes development of the CLM and Noah models to include hydrological routing and urban processes. Future work includes the use of CLM as a module within the WRF model to increase commonality between WRF and CCSM modeling efforts. 2) Building a unified model of biosphere-atmosphere exchange on the framework of global and regional land, atmosphere, and chemical models: This phase focused on development of off line modules and datasets. Future plans include evaluation of the off-line results and building the model elements that will enable fully coupled simulation of chemistry, climate, and land surface components. 3) Conducting ground-based field and modeling experiments to augment existing field studies: The field portions of the Carbon in the Mountains (CME) and Chemistry and Production of Smoke in Brazil (CAPOS-Brazil) studies are now complete. Future work will include analysis, model evaluation, and instrument development to lay the groundwork for future studies. Education and Outreach achievements included (a) planning and development of biosphere content for the K-12 online resource "Windows to the Universe", (b) testing and implementation of the undergraduate-level web-based tool "Greenhouse Gas Wizard", and (c) support of three students in the SOARS minority participation program. Future plans include continuation of the work listed above and development of the NCAR Mesa Lab visitor exhibit "Climate Future."

Data Products and Publications: The accomplishments, publications, data sets, and presentations listed below were partially supported by FY'04 NSF Biocomplexity funds. Some prior work is also listed that provided the scientific infrastructure and leveraging that were prerequisites for the success of the Integrated Biosphere Atmosphere Studies Program.

Community data sets:

Airborne Carbon in the Mountains Experiment (ACME), May and July, 2004, Colorado. Airborne CO_2, O_3, water vapor mixing ratios and fluxes, and CO mixing ratios; http://swiki.ucar.edu/acme

Biogenic VOC emissions data; http://bvoc.acd.ucar.edu

Carbon in the Mountains Experiment (CME) CO_2 and meterological data, Aug 1-Oct 5, 2004, Colorado; http://www.atd.ucar.edu/rtf/projects/cme04/

Gulf of Tehuantepec Experiment (GOTEX), February-March, 2004, Huatulco, Mexico. Airborne CO_2, O_3, water vapor mixing ratios and fluxes, and CO mixing ratios; http://raf.atd.ucar.edu/Catalog/taplog.hrt.150.html

MEGAN emissions model; on the NCAR community data portal at https://cdp.ucar.edu

Nitrogen deposition in the US and Europe; http://daac.ornl.gov/CLIMATE/guides/nitrogen_deposition.html

Rain in Cumulus over the Oceans, December (RICO), 2004 and January, 2005, Antigua, W.I., Airborne O_3, water vapor mixing ratios and fluxes, and CO mixing ratios; http://www.joss.ucar.edu/catalog/rico/

Publications:

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