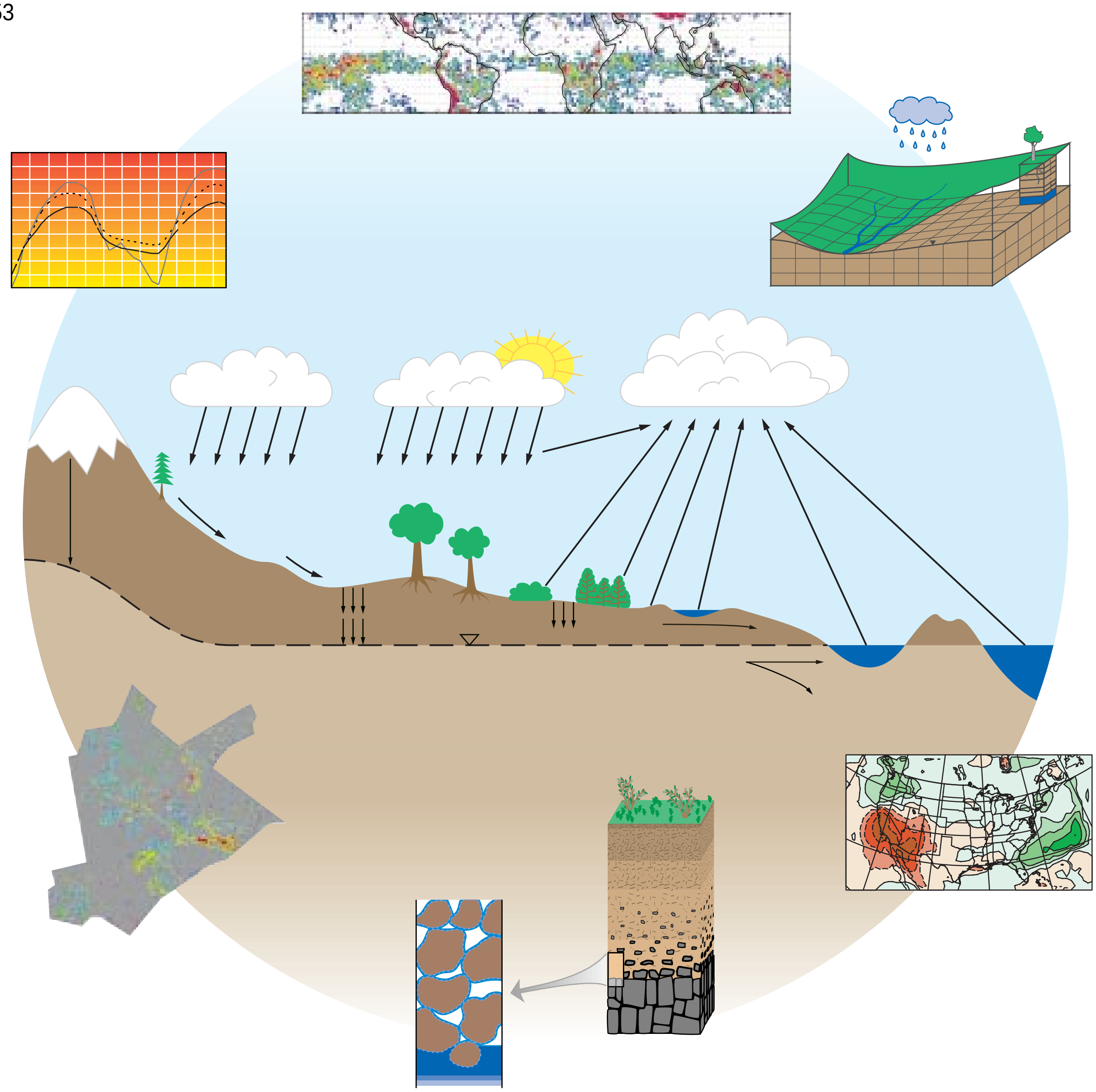
Global Water Cycle: Extension Across the Earth Sciences

Progress Report—March 1998

NASA Earth Observing System

NAGW-2686

NAG 5-4553



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Abstract

Despite the significance of water, our knowledge of it as part of the global, interacting system is meager. Consequently, we are far from understanding how the hydrologic cycle will respond to a changing Earth system, or the nature of water's influence across the components of the system. To address these issues, the primary research strategy of this investigation, centers on nesting or coupling coarse resolution GCMs, with high resolution mesoscale models, with models including soil moisture, vegetation, and surface and groundwater hydrology. In this manner, we are attempting to produce global change predictions, in response to a variety of factors ranging from increases in greenhouse gas concentrations to changes in land cover, at a spatial scale which is appropriate to assess their impact. This research strategy is accomplished through an emphasis on integrated regional studies and the development of coupled earth system models. A basic requirement to accomplish these goals is also to develop data sets for initialization and validation of the various models at a variety of spatial scales, and to focus on critical limitations in current models (e.g. cloud parameterizations). During this process, we also contribute to the production of data sets which describe changes in climate and the nature of climate variability.

Background

The critical facets of climate and hydrology research needs have been described in NRC reports (e.g. 1985), in planning documents of the USGCRP and the WCRP (e.g. CLIVAR and GEWEX), and in Earth System Science: A program for global change. The primary research objectives are clear: determine and understand the dynamics of the major reservoirs of water, the mechanisms for transfers of water between global reservoirs, predict changes in the distributions, volumes, fluxes of water resulting from change and from human activities, and understand better the coupling of water with other components of the Earth system. We are developing methodologies and modeling capabilities to describe quantitatively the presently uncertain rates associated with the sources, sinks, and fluxes of the global water cycle with the ultimate goal of increasing our ability to predict changes in the hydrologic cycle associated with natural variability and human activities. A key element is to address changes in the hydrologic cycle at a scale appropriate for considering its impact on human activities, including agriculture and water resources. The proposed research included 31 specific objectives, which are summarized here, for the sake of brevity, as 12 primary objectives:

1. Evaluate GCM capability to simulate hydrologic cycle components
2. Evaluate GCM sensitivity to lower boundary forcing
3. Generate global data sets for documentation of global change, specifically for hydrologic variables, and for global model validation and verification
4. Develop improved treatment of cloud and precipitation processes
5. Develop and test components of high resolution regional atmospheric models critical for water and energy fluxes
6. Test the adaptability of terrestrial hydrologic models for sensitivity to spatial and topographic scales
7. Develop and test indirect measures of soil water content, with the objective of integrating these results into mesoscale model simulations
8. Develop and test coupled (nested) GCM-Mesoscale-Hydrologic Forecast models
9. Develop comprehensive databases and GIS for regions, such as the Susquehanna River Basin, the Cape Region, and others, to facilitate the development and evaluation of the nested model approach to regional prediction.
10. Determine ice sheet mass balance, linking climate and hydrologic changes to the future evolution of the cryosphere
11. Develop and test a landscape evolution model in order to link climate and hydrologic changes to the evolution of the land surface
12. Develop improved climate-agriculture models in order to link climate and hydrologic changes to the human dimensions of global change

These objectives incorporate three major integrating elements: (1) Documentation of Earth system change (4-dimensional multiphase water, temperature and diabatic heating, ice sheet mass balance, and regional scale terrestrial and atmospheric water and energy budgets), (2) focused studies on controlling processes (cloud processes, the interface of the atmosphere with ocean, cryosphere, biosphere and land surface), and (3) integrated conceptual and predictive models (extension of predictive capability across a spectrum of spatial scales, verification and validation of hydrologic cycle predictive capability, and coupled Earth system models).

The objectives and the integrating elements include a large number of challenging scientific issues requiring focused research and the interactions of a significant number of disciplines. Such a comprehensive set of objectives presents challenges for even a large team of investigators. As a practical element, the significant advances of this project are occurring because of the development of regional-scale experiments; designed to improve understanding of important physical processes, develop coupled models, and assess and validate model predictions. Almost the entire research team contributes to these regional-scale experiments, each cooperatively seeking to advance the research objectives outlined above.

To date, much of the emphasis of the project has focused on the Susquehanna River Basin and the Southern Great Plains with additional research on the Cape region of Florida. Much of the future work is proposed for the Ohio and Tennessee River Basins. These regions have been the focal point for assessing GCM capability, coupling and evaluating GCMs with mesoscale models, incorporating improved surface processes within the mesoscale models, integrating soil moisture measurements and models, evaluating and linking terrestrial hydrologic models of surface flow and groundwater, developing comprehensive GIS with a full spectrum of data for specification of model boundary conditions and evaluating predictions, and linking these models with other elements of the Earth system (e.g. landscape evolution) and societally-important issues (e.g. impacts of changes in the hydrologic cycle on agriculture).

The primary research strategy of this investigation, therefore, centers on nesting or coupling coarse resolution GCMs, with high resolution mesoscale models, with models including soil moisture, vegetation, and surface and groundwater hydrology. In this manner, we are attempting to produce global change predictions, in response to a variety of factors ranging from increases in greenhouse gas concentrations to changes in land cover, at a spatial scale which is appropriate to assess their impact. Such a strategy introduces the potential that we will link the errors of one model with the errors of each of the nested models. However, we have not jumped to make regional global change predictions. Rather, our efforts are directed to a series of careful studies designed to improve understanding and assess model capability critically. The completed and planned studies of this investigation are not only describing the uncertainties, but are, perhaps more importantly, substantially increasing our knowledge of a variety of processes, and providing a strong foundation for high resolution, coupled Earth system models. We are establishing a greater capability to utilize EOS observations to describe key hydrologic and climatic processes, to further develop and validate models, increasing our understanding of the past and the future and their relationships to Earth system components and thus providing a more robust predictive capability.

Data Sets for Documentation of Global Change

An Integrated Moisture and Heat Budget Analysis

(F. R. Robertson, H.-I. Lu, and E.W. McCaul—MSFC)

Large-scale divergent circulations are part of the atmospheric dynamic response to diabatic heating from condensation, radiative processes, and surface heat fluxes. Vertical motion and the associated divergent wind is thus intimately tied to the hydrologic cycle and the global heat balance. Despite its importance, the divergent circulation is too small in comparison to the rotational flow to measure directly with any accuracy. Vertical motions are recovered diagnostically from reanalyses (e.g. the DAO, NCEP and ECMWF products) and, as such, are subject to shortcomings in model physics, numerics, and data availability.

Last year we began developing a variational methodology to use pre-EOS and EOS era data in computing global gridded moisture and heat budgets. The basic premise of this approach is that while the rotational flow (temperature and non-divergent wind) is reasonably treated in the global reanalyses, the divergent flow is still at the mercy of shortcomings in parameterized physics. Our variational algorithm seeks minimal modifications to the divergent winds so that the vertically integrated heat and moisture transports agree with satellite-observed precipitation (either MSU or GPCP), TOA radiation (ERBE), and surface radiation (SRB products). Surface evaporation and sensible heating estimates have yet to be modified.

Having developed the basic methodology in FY96, we spent this year implementing and analyzing preliminary results which were presented at the WCRP First International Conference on Reanalysis Results. Our preliminary assessment of the reanalyses showed considerable disagreement remaining in their estimates of the hydrologic cycle. For example, ECMWF precipitation during the period 1985–1989 was as much as 25% larger than the MSU and GPCP satellite estimates which agreed well with one another during the period. Furthermore the climatological January northward wind flow in the DAO equatorial upper troposphere was only half of the magnitude indicated by the NCEP reanalysis. These differences reflect large spin-up problems remaining in the reanalysis.

As an example of changes made by our variational approach we examine in Figure 1 interannual variability of the 300 to 500 hPa vertical velocities (September 1987 minus 1988). Both modified and original NCEP fields are presented. The variationally adjusted ‘87/’88 difference fields have a more continuous pattern spanning the Indian Ocean, Maritime Continent, and eastern Pacific ITCZ.

Ultimately we view this methodology as a way to build into diagnostic budgets the maximum possible observational consistency with EOS observations. It should be viewed not as a replacement for, but an improvement to global reanalyses. At present we are working to improve the vertical structure of divergence recovered by this scheme. Incorporating vorticity balance constraints is probably the preferred approach but is proving difficult. We are also investigating the incorporation of ISCCP cloud top data and cloud track winds and a means of specifying the maximum outflow layer of tropical deep convection.

A Tropical Deep Convective Ice Index

(F. R. Robertson, R. W. Spencer, C. Cohen, and D. E Fitzjarrald—MSFC)

Accurately measuring the amount of tropical deep convection, its interannual variability, and long term trend remains a challenge to climate researchers. Recent work has shown that large ice hydrometeors (dendrites, graupel or hail) produced by convective updrafts can be reliably extracted from MSU CH2 data. This measurement is important since it directly relates to sources of tropical upper-tropospheric moisture. Because frozen hydrometeors efficiently scatter upwelling

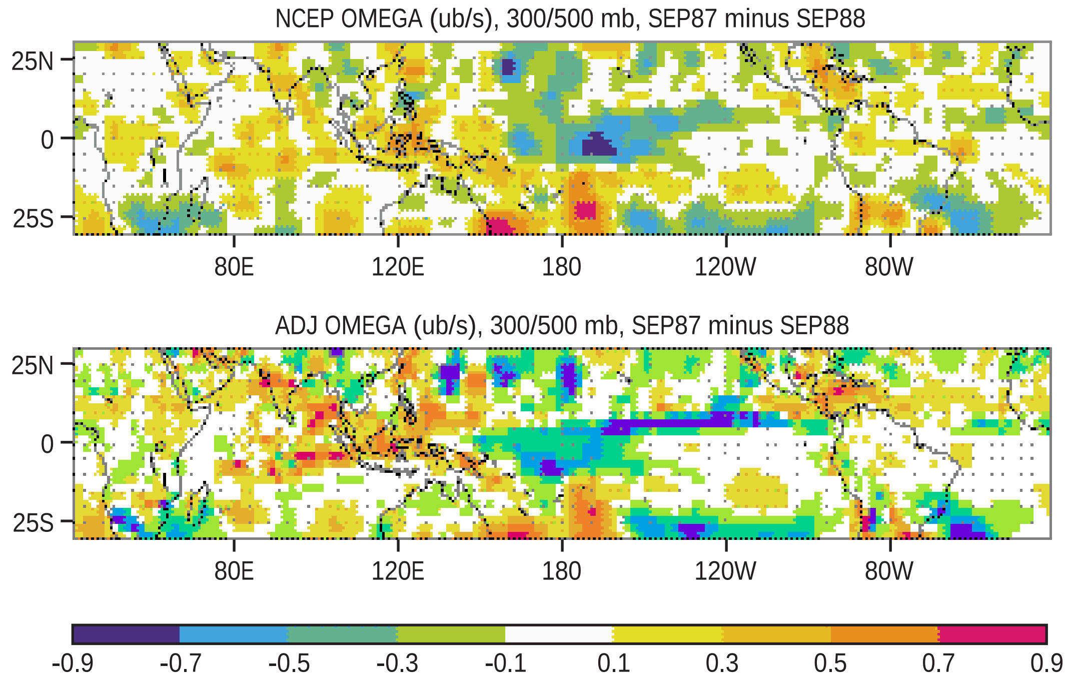

Figure 1. Interannual variations (SEP87 minus SEP88) in 500 to 300 mb verical motion (microbars/s) for NCEP reanalysis (top) and variationally adjusted flow (bottom).

radiation from the lower troposphere and surface, convective features show up as small-scale depressions in the otherwise "bland" background tropical temperature field. We extract these using a high-pass spatial filter. While the features are weak because of the large MSU footprint size (100 to 200 km square), monthly mean values correspond well to similar ice signatures seen in the SSM/I data.

Preliminary analysis of interannual variability of these signatures averaged over the tropical oceans (30^{o} N/S) has yielded very encouraging results. Positive anomalies of convective ice during El Nino years correlate well with elevated tropical-mean SSTs (near .85). Figure 2 shows how convective ice has been enhanced during the present El Nino episode (note the eastern tropical Pacific in January 1998 compared to January 1997). Preliminary comparisons to SSM/I rain rates produced by Frank Wentz have shown a remarkable agreement in interannual variability, especially since these two measurements come from different satellite series with differing algorithms.

Interestingly, many contemporary precipitation climatologies (e.g. GPCP, Xie-Arkin) correlate poorly with SST analyses or have strong biases (MSU CH1). Yet, theoretical and climate modeling simulations suggest the convective intensity and SST should be reasonably well-coupled. The reasons for this disagreement not yet clear although the issues of inter-calibrating multiple algorithms and multiple platforms for those climatologies are suspected. The current methodology with MSU CH2 is less sensitive to these issues because absolute calibration of radiances is not important for a high-pass filter. Aliasing of the diurnal cycle is a concern, however, and we are currently examining this over ocean and land.

More detailed comparisons to SSM/I tropical convective ice using coincident data are planned to better understand signal-to-noise issues. Future comparisons to OTD and TRMM LIS lightning frequencies should also be revealing. We anticipate that this data set will become valuable in climate change monitoring and as a validation source for climate modeling.

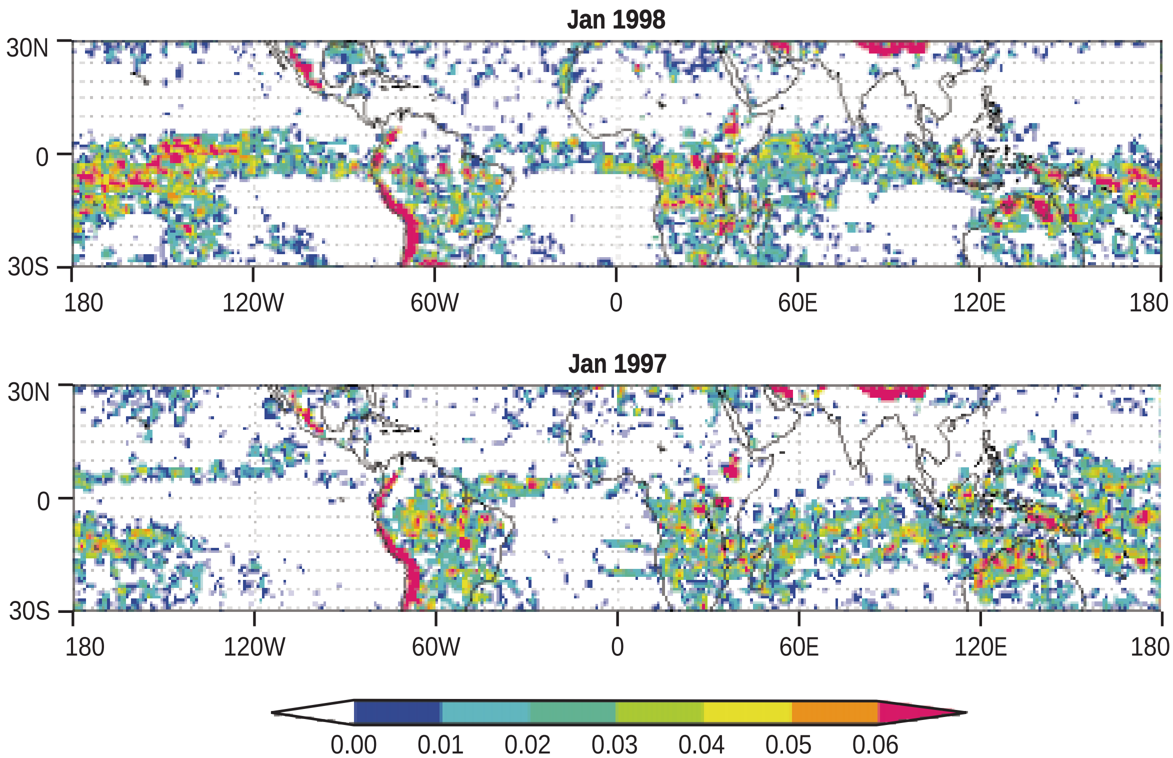

Figure 2. MSU Convective ice index (°K) for January 1998 and 1997. Note substantial increases in convection in 1998 for eastern Pacific and decreases over southern Indian Ocean and Maritime Continent.

Analysis of Microwave Sounding Unit (MSU) Data
(J. Christy—MSFC)

A description of the revised method for the MSU satellite inter-calibration and merging technique has been completed and accepted for publication (Christy et at. 1998). The revised method calculates the intersatellite biases using data selectively chosen based on higher signal-to-noise characteristics than was previously done. In addition, the inter-satellite variations tied to the annual cycle, due to differing shadowing effects on the individual instruments, is more precisely determined and removed. Various tests of reproducibility are included to assess the robustness of the final product. The results show that for the 19 years 1979–97 the lower troposphere, mid-troposphere and lower stratosphere have experienced trends (°C/ decade) of –0.04, +0.01 and –0.51 respectively. The 90% confidence interval for these trends is estimated to be +/– 0.03°C/decade.

Questions concerning the long-term stability of the merged MSU data were raised in a widely reported publication in March (Hurrell and Trenberth 1997). Though using no direct measurements of the atmospheric layer in question, Hurrell and Trenberth suggested the MSU data contained spurious jumps in the time series which appeared when compared with estimates of tropical tropospheric temperatures derived from two models forced by observed sea water temperatures (SSTs) (1) a simple linear regression model and (2) a GCM (CCM3). The comparison revealed relative shifts (MSU shifting to relatively cooler values) in late 1981 (by 0.25°C) and late 1991 (by 0.11°C).

Christy et al. (1997) responded to these suggestions with actual observations of the atmospheric layers, most specifically by showing direct comparisons of (1) completely independent radiosonde and MSU anomalies, and (2) simultaneously observed anomalies of individual (and independent) satellites. Radiosonde comparisons, both for the entire time series and for the alleged "breaks" indicated no shift in the MSU data at the few hundredths of a degree level. In addition, the independent comparisons of the two satellites operating across the alleged "breaks" were in excellent agreement, again with standard errors of the mean bias determined to a precision of less than 0.01°C (Figure 3). Thus the MSU merging technique was independently validated and verified as being accurate to within 0.01°C per overlap period.

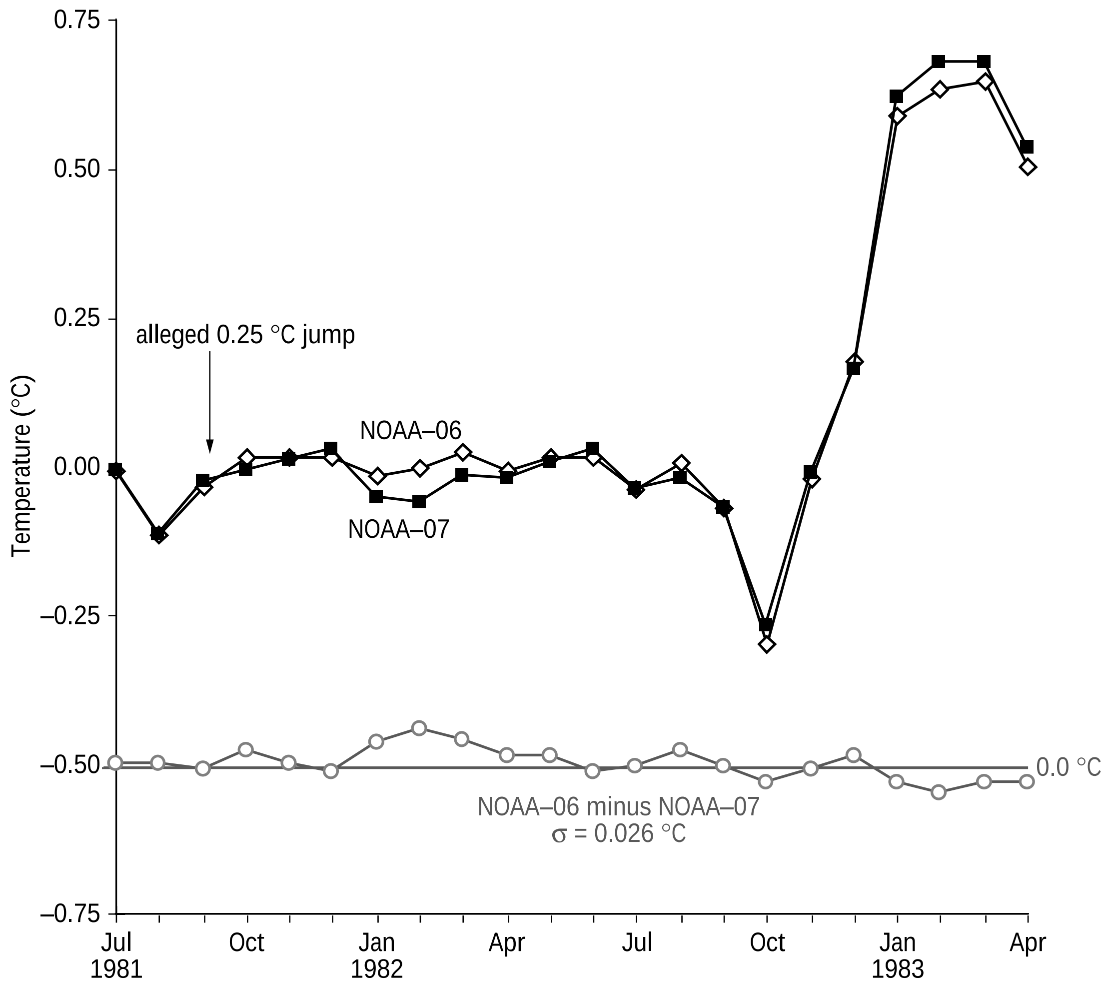

Figure 3. Monthly temperature anomalies (°C) for the tropics (20 S - 20 N) computed independently from two satellites, NOAA-06 and NOAA-7, for July 1981 to April 1983.

In answering the suggestions of Hurrell and Trenberth, a curious finding was discovered. A direct comparison between the SSTs and night marine air temperatures (NMATs) revealed two major "breaks" in late 1981 and late 1991. The NMATs are completely independent of the SSTs (and MSU). Thus, three independent measures of atmospheric temperature in the tropics (MSU, radiosonde and NMAT) all reveal the shift to cooler temperatures than seen by the SSTs. Since it is highly unlikely that all three atmospheric time series would have experienced errors at the same time and of the same sign, two possibilities are opened (1) there have been two major shifts in tropically-averaged atmospheric stability of the order of 0.1°C and/or (2) analyses of SST data have introduced warm biases in the past 15 years, perhaps due to the massive inclusion of buoy data which tend to measure the SST at about 1 m, a warmer depth than is typical of ships (about 5–10 m). Investigations are continuing on all aspects of these findings.

Characterizing the Gulf Coast Climatology During the 1997–98 El-Nino
(S. Goodman, R. Raghavan, and E.W. McCaul—MSFC)

We have begun to examine the relationships between the El Nino-Southern Oscillation Index (SOI) and the temporal and spatial patterns of storms in the Southeast U.S over a multi-year period. We seek to discover relationships that can be used to better understand the significance of the present warm ENSO event in comparison to the 1982–3 warm event as well to prior cold events and neutral years. It is this new understanding that offers the potential to provide more accurate seasonal predictions that address variations and changes in the frequency, tracks, intensity, duration, and the diurnal cycle of storms and their related socio-economic impacts (damaging tornadoes and extreme winds, river and flash floods, lightning injuries and deaths, power outages, disruptions of air traffic and shipping in the northern Gulf).

Our study is using data bases we have been developing over the past few years as part of on-going investigations of severe and hazardous weather in the SE U.S. These data bases include single site volume scan NEXRAD data, NEXRAD radar reflectivity composites from 1994–Present, national cloud-to-ground lightning data from 1994–Present, “Storm Data” reports of severe weather (1952–Present), cyclone and flood statistics (1952–Present), and NCEP reanalysis. Data from the Tropical Rainfall Measuring Mission (TRMM), launched in November, 1997 are being used to examine the details of storms in the SE U.S. and Gulf of Mexico.

Initially, our study will focus on the 1996/97–1997/98 period where we have consistent NEXRAD radar observations of convective systems and access to the NCEP standard products and NEXRAD-derived hourly rainfall products (produced by Ken Mitchell’s group at NCEP).

Our study area is located in the region between 37N–25N and 98W–78W. Our objectives include:

1. Characterize the amplitude of the diurnal cycle. Consider how the warm and cold phases influence this signal
2. Is there a geographic preference (latitudinal dependence) for the diurnal cycle peak (max/min) during either phases?
3. Is there a seasonal dependence of the diurnal cycle, i.e., signal modulation during a cold or warm phase in contrast to between phases.

We will conduct an uncertainty assessment to:

1. Determine the variability in the diurnal cycle using lightning measurements for the designated time period (duration of the lightning data)
2. Estimate bounds (thresholds) and identify warm/cold events based on deviation from these thresholds. Correlate these deviations with the SST signal (time series)
3. Determine that sufficient signal variability exists between neutral and warm/cold events
4. Verify signal in the radar data for 1996–97

A 1 Km Conterminous United States Soil Characteristics Data Set

(D.A. Miller, R.A. White, P.J. Kolb, and J.J. Voortman—PSU)

In 1997 we continued to support the first version of a multi-layer soil characteristics data set for the conterminous United States. CONUS-SOIL specifically addresses the need for soil physical and hydraulic property information over large areas. The State Soil Geographic Database (STATSGO) developed by the United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) served as starting point for CONUS-SOIL. The complete CONUS-SOIL database is available over the WWW by visiting the following URL: http://www.essc.psu.edu/soil_info. Table 1 lists locations on the WWW that have downloaded all, or a portion, of the CONUS-SOIL database. An article Miller and White (1998) is now in press at the WWW journal *Earth Interactions*.

Educational Institutions
- Auburn University
- Boston University
- Cornell University
- Duke University
- Florida State University
- Iowa State University
- Jacksonville State University
- Massachusetts Institute of Technology
- Mankato State University
- Middlebury College
- Ohio State University
- Oregon State University
- Princeton University
- Rutgers University
- South Dakota School of mines and Technology
- Southwest Texas University
- Texas A&M University
- Tulane University
- University of Akron
- University of Alabama
- University of Arizona
- University of California, Berkeley
- University of California, Riverside
- University of California, San Diego
- University of Connecticut
- University of Hawaii
- University of Idaho
- University of Illinois
- University of Maryland
- University of Michigan
- University of Minnesota
- University of Montana
- University of Nebraska
- University of Nevada
- University of New Mexico
- University of North Texas
- University of Oklahoma
- University of Oregon
- University of Pennsylvania
- University of Texas
- University of Utah
- University of Washington
- University of Wisconsin
- University of Wyoming
- Utah State University
- Washington State University
- Yale University

Federal Agencies and Laboratories
- Environmental Protection Agency
- Jet Propulsion Laboratory
- Lawrence Livermore National Laboratory
- National Oceanic and Atmospheric Administration
- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory
- Sandia National Laboratories
- United States Army
- United States Bureau of the Census
- United States Geological Survey

Foreign Countries
- Australia
- Belgium
- Brazil
- Canada
- Croatia
- Finland
- France
- Germany
- Greece
- Ireland
- Japan
- Mexico
- New Zealand
- Norway
- Poland
- Portugal
- Russia
- Slovenia
- Spain
- Sweden
- United Kingdom

Table 1. Locations which have downloaded all or a portion of CONUS-SOIL.

Cloud and Precipitation Processes

Modeling Studies of Marine Boundary-Layer Clouds

Evaluate the Validity of the Turbulence Parameterizations with Large-Eddy Simulation

(S. Wang—MSFC)

This work uses large-eddy simulation method to study the validity of top-hat parameterization of some turbulence statistics in cumulus and stratocumulus cloud-topped boundary layers (CTBLs), with an emphasis on scalar variance and covariance statistics. The results were explained in terms of joint frequency distribution function of relevant turbulent fluctuations. It is found that although top-hat parameterization based on commonly used conditional sampling methods provides useful approach to modeling vertical fluxes in the simulated CTBLs, it fails to realistically represent the scalar variances. It occurs because these sampling methods are heavily dependent on the sign of vertical velocity, not scalars in general, and thus cannot guarantee uniqueness of the sign of the scalar fluctuations in each individually defined plume. The cancellation between the positive and negative fluctuations induced by the physical processes such as cloud-top entrainment, radiative cooling, small-scale mixing between the different plumes considerably reduces the top-hat contribution to the variances. Therefore, one should not automatically assume applicability of a top-hat model in parameterizing scalar variances just because the same model has proved to be useful in modeling vertical fluxes. This work is summarized in Wang and Stevens (1998).

A Generalized Model of Stratocumulus and Trade-Wind Cumulus CTBLs

(B. Wang and P. Robertson—MSFC)

This work is a continuing efforts of developing a CTBL model to represent the cloud systems in a general circulation model. Based on the previous year's work, we have improved the cumulus transport scheme by including buoyancy-sorting concept. This model was tested in both shallow cumulus and stratus cloud environments. It is generally accepted that the interaction between stratocumulus and shallow cumulus is important for the transition from stratus to shallow cumulus. It is found that the stratocumulus clouds are sensitive to the detrainment thickness and the location near the top of the cloud layer. If the cumulus pump most of the moisture out of the cloud layer to very try inversion, then the environmental stratiform clouds dissipate rapidly due to the evaporation. If the detrainment occurs mostly within the boundary layer, then the detrained liquid water is not rapidly evaporated. Consequently, the stratiform clouds exist longer. This work is summarized in Wang and Robertson (1997).

Low-Frequency Oscillations in Precipitation, Temperature and Runoff

(T.-Y. Shun and C. Duffy—PSU)

We have examined space-time patterns of annual, interannual and decadal oscillatory components of precipitation, temperature and runoff (P-T-R) using long-record time series (>50 years of monthly data) across the steep topographic gradient of the Wasatch Front in northern Utah, the major contributing region to the Great Salt Lake. The analysis is based on the multi-channel singular spectrum method (MSSA). The method is a generalization of principal component analysis for space-time fields. In the case of precipitation and temperature, the decomposition shows that, in addition to the mean orographic effect and seasonal, interannual and decadal components (referred to as low-frequency oscillations or LFO's) also vary with altitude but account for a rather small fraction of the overall signal variance. For example, a weak low-frequency component with period ~10–15 years is found in precipitation as demonstrated by Lall

(1996). The overall or total variance of this oscillation is ~2% but varies with altitude. Interannual components in P and T are generally less than 1% of total variance and are of the same magnitude as higher frequency noise components. The runoff signal shows a more complex relation with altitude. The variance contribution for the low frequency component (period ~8–17 years) represents nearly 11% of the overall signal. This raises the question of the role of the drainage basin as a “filter” for low frequency oscillations and the importance of basin runoff in enhancing the relatively weak climate signal. The MSSA allows optimal reconstruction of the space-time structure of P-T-R. The phase-plane trajectories of the dominant components for P-T-R are reconstructed as a function of altitude showing the importance of LFO’s to mountain runoff, and the sources of input to the Great Salt Lake.

Scaling Issues and Long-Term Simulation of Water and Energy Budgets at the Land-Surface

(A. Barros and R. Bindlish—PSU)

The purpose of this research is to develop and evaluate physically-based approaches to downscaling climate model output for long-term simulations of water and energy budgets at the land surface. The ultimate objective is to use these data and tools to determine the impact of climate variability on regional water resources, and to investigate the linkages between the frequency and magnitude of extreme events such as floods and droughts and climate phenomena.

Modification and Validation of an Existing Land-Atmosphere Interactions Model to Include Cold-Region Processes

Previous work of development and testing a land-atmosphere interactions model with realistic physics has continued with the incorporation of cold-region processes. Preliminary test results indicate that the snow component of the model can reproduce the timing and shape of snow accumulation and melt for the Valdai dataset obtained from Dr. Alan Robock. Continuous model simulations using forcing data from PILPS (Project for the Intercomparison of Land Parameterization Schemes) have been used to test the model. In these simulations , the overall water budget error is inferior to 2 percent over a 5-year period without requiring tuning of model parameters. A conference presentation and a manuscript describing this work are currently being prepared to be submitted to the GCIP Mississippi River Climate Conference and a subsequent special issue of Journal of Geophysical Research.

Aggregation and Disaggregation of Terrain and Land-Surface Properties with Emphasis on Soil Moisture Processes

Soil parameterizations used in hydrological models are based on the assumption that for a spatial scale of interest, typically the model’s spatial resolution, the textural properties of soils and their ability to retain and transmit water can be established unequivocally. Measurement uncertainty, spatial heterogeneity, and the relationship between the constitutive properties of soils and their field counterparts are not taken into consideration. Therefore, many related problems arise in the study of the scaling properties of remotely sensed soil moisture observations, and in the applicability and transportability of soil moisture retrieval models. In this paper, we identify and assess potential sources of uncertainty in the interpretation, analysis and modeling of remotely sensed spatial soil moisture data from MacHydro-90 and Washita-92 experiments. The use of soil texture as the soil classification paradigm was evaluated, and we argue for the need to adopt a hydrologically oriented classification of soils such as the Great Soil Groups (GSG). One criterion used to classify soils by GSG is their moisture regime, as well as their role in the storage and distribution of water within a watershed. This reflects in an integrated manner how topography, climate, living organisms and land-use have determined over time the soil's ability to infiltrate, retain and transmit water. The contribution of topography and time-varying environmental factors (e.g., weather conditions and vegetation cover) to the observed space-time variability of remotely sensed soil moisture fields was also evaluated. A manuscript describing this work was submitted to *Water Resources Research*.

Contribution to SGP97

The Southern Great Plains 1997 (SGP97) Hydrology Experiment took place in a 40 x 250 km region extending from southwest to north central Oklahoma. The main objectives of the experiment were: 1) to establish that the retrieval algorithms for surface soil moisture developed at higher spatial resolution using truck and aircraft-based sensors can be extended to the coarser resolutions expected from satellite platforms; 2) to verify spatial-temporal estimators of soil moisture and to examine the utility of pedotransfer function in hydrologic modeling; 3) to examine the feasibility of inferring soil moisture and temperature profiles using surface observations in conjunction with in situ measurements; and 4) to examine the effect of soil moisture on the evolution of the atmospheric boundary layer and clouds over the Southern Great Plains during the warm season (SGP97 Experimental Plan). SGP97 combined field measurements with a host of aircraft and satellite observations covering a range of temporal and spatial scales.

The science objectives of our participation are as follows: 1) the formulation and accuracy of the algorithms used to transform the remotely-sensed signal (i.e. brightness temperature) into estimates of soil moisture; 2) scaling and the relationship between the scale of measurement and data resolution; 3) data assimilation into operational mesoscale models. Progress has been accomplished in the context of 1) and 2) above. A significant portion of our contribution consisted of providing support to the ground-based measurements conducted at Little Washita. Specifically, gravimetric soil moisture sampling (total of 23 sites) in the Little Washita Watershed was conducted every morning for 28 days as part of the core SGP97 experiment. In the afternoon, independent soil moisture sampling over long transects was conducted using TDR and GPS units. The TDR observations were obtained at the micronet, mesonet and flux stations in and around the Little Washita watershed, a total of 51 locations corresponding approximately to a coverage of 5x5 km^2 resolution. This allowed us to generate a watershed-scale view of the spatial distribution of soil moisture over the lower SGP domain, which complements the field-scale measurements conducted by other investigators.

Space-time Variability and Scaling Properties of Soil Moisture from Process and Interpretative Studies, Using Models and Remote Sensing

This study focused on the solution of the inverse problem in remote sensing of soil moisture when no ground data are available for calibration of retrieval algorithms. In particular, the sensitivity of Synthetic Aperture Radar (SAR) to the soil dielectric constant with variation in soil roughness and correlation length, which are used as constraining parameters in the inversion model, was assessed (Fung 1992). The dielectric constant values were used in the inversion algorithm, and the retrieved soil moisture values were cross-validated against gravimetric observations from the Washita-94 field experiments in the Little Washita Watershed in Oklahoma. This work demonstrated that it is possible to use multi-frequency and multi-polarization instruments such as SIR-C and X-SAR to invert the observed values of the dielectric constant without prior need to obtain the surface roughness parameters. Moreover, this case study provided the necessary proof-of-concept for further research using the inverse problem approach to evaluate soil water functional relationships at the scale of remote sensing instruments, and to facilitate the operational use of satellite data for hydrologic applications in data sparse regions (Bindlish et al. 1997)

Penn State/NCAR Mesoscale Model (MM5)

(W. Lapenta—MSFC; M. Laktakhia—PSU; W. Crosson and S. Dembek—ICGRE)

The land surface is a critical component of the Earth system through its portioning of radiation into sensible and latent heat fluxes and its redistribution of precipitation into evaporation, soil storage, groundwater recharge, or runoff. These water and energy exchanges between the atmosphere and the land surface are known to significantly impact weather and climate, which has motivated significant advancement in our understanding of the physical processes that govern these exchanges. A key scientific goal of this project is to develop a modeling system that can accurately represent the exchange of energy and moisture between the land surface and atmosphere and project basin runoff on time scales ranging from diurnal up to interannual. As a result, the Biosphere-Atmosphere Transfer Scheme (BATS) was coupled to the PSU/NCAR mesoscale model version 5 (MM5) several years ago (Laktakhia and Warner 1994). During the past year, significant improvements have been made to MM5/BATS so that it is now capable of replacing RegCM2 (which is based on MM4) as a regional mesoclimate model.

Model Improvements

1. The coupled land-atmosphere model has been modified such that the atmospheric component is now the latest version of MM5 (Version 2-7).

2. The code is now multi-tasked.

3. The MM5 preprocessor program INTERP has been modified and can now generate initial states and lateral boundary conditions for MM5/BATS from CCM3 history files.

4. In an attempt to improve the land surface hydrology simulated by MM5/BATS, we have added the capability of replacing the BATS soil hydrology subroutines with those of the Simulator for Hydrology and Energy Exchange at the Land Surface (SHEELS). The representation of soil water processes in SHEELS was patterned in many regards (infiltration, runoff, Darcy flow) after those in the SHM. These changes were made to produce better simulations of the strong near-surface moisture and temperature gradients that are often observed, especially in areas of sparse vegetation. Modifications include:

    a. The three nested layers of BATS were changed to three discrete layers in SHEELS.

    b. Sub-layers within each soil layer were added to give a better representation of the moisture profile.

    c. The evapotranspiration weighting functions, which control the extraction of water from each soil layer, were changed in form and to be sensitive to the moisture profile through the root zone.

    d. The skin temperature formulation in SHEELS is based on properties of the upper-most soil sub-layer, which has a typical thickness of 1 cm, compared to 10 cm of the upper layer in BATS.

Testing of the new scheme in MM5/BATS has been performed using point-scale data collected at bare soil and grass plots during the Huntsville '96 field experiment held at Alabama A&M University. Soil moisture profiles estimated by the model were in excellent agreement with measurements. We are currently testing MM5/BATS (with SHEELS) in simulations over the Southern Great Plains (SGP) and will validate results using observations collected from Cloud and Radiation Testbed (CART) sites for the U.S. Department of Energy's Atmospheric Radiation (ARM) Program.

Impact of SHM Soil Water Content Data on the Diurnal Cycle

We have begun to evaluate the impact of using SHM-derived soil water content (SWC) fields upon the simulated land surface energy and water budgets in MM5/BATS. As an initial test of the coupled model, we have performed a series of 36-hour simulations on eight consecutive days from 9 June through 16 June 1997. The assessment procedure consists of comparing model predicted near surface air temperature and specific humidity with all available observations. We will also validate components of the surface energy budget with available flux sites such as those from the Energy Balance Bowen Ratio (EBBR) systems deployed at the CART/ARM sites in the Southern Great Plains.

The experimental design employs two model configurations. In the MM5 runs, the standard force-restore surface energy budget is employed. In this formulation, determination of the Bowen ratio is dependent upon the moisture availability (MA) parameter, which represents the *fraction* of possible evaporation for a saturated surface. The MA is determined as function of the climatological land use. The MM5/BATS configuration uses BATS to account for vegetation and soil conditions. The land cover information is derived from the 1 km United States Geological Survey-EROS Data Center (USGS-EDC) Land Surface Characteristics Database (Loveland et al. 1991). Soil texture information is derived from the STATSGO database, and the vertical and horizontal distribution of SWC is initialized using output from the SHM. Both model configurations are used to generate a 36-h simulation beginning 1200 UTC on each of the eight days in the study period. The horizontal grid has a resolution of 36 km and covers the majority of the continental United States. A total of 32 layers are used in the vertical.

Figure 4 shows the initial MA and SWC fields for the 9 June 1997 case. An important feature to note is the soil in Arizona, New Mexico, and western Texas is quite moist and is representative of the antecedent precipitation pattern. In contrast, the climatological MA is extremely low with values less than 0.2. Given this difference, one would expect the simulated near-surface air temperatures to be too high in the MM5 runs as a significant portion of the energy exchange between the land surface and atmosphere will be in the form of sensible heat. Figure 5 shows the simulated time series of surface fluxes at a point within this region. The maximum sensible heat flux in MM5 is on order of 900 Wm^{-2} on both afternoons of 9 and 10 June while the latent heat flux is a maximum of 300 Wm^{-2}. The use of the SHM SWC greatly alters the energy budget as evidenced in Figure 5b, where the flux profiles are reversed. The integrated affect of these differences can be found in the simulated air temperatures where the MM5/BATS is nearly 2–4°C cooler in the region than MM5 which is in better agreement with available observations.

Our goal during the next year is to perform a series of 36-h simulations for each day over a 3 month period from May 1997 through July 1997. This will provide a robust set of numerical simulations that will allow us to evaluate the utility of using the coupled model and the SHM-derived SWC. We also plan on using SHEELS to represent the soil hydrology processes in these runs as it should provide a more realistic treatment of the affects of soil moisture on evaporation.

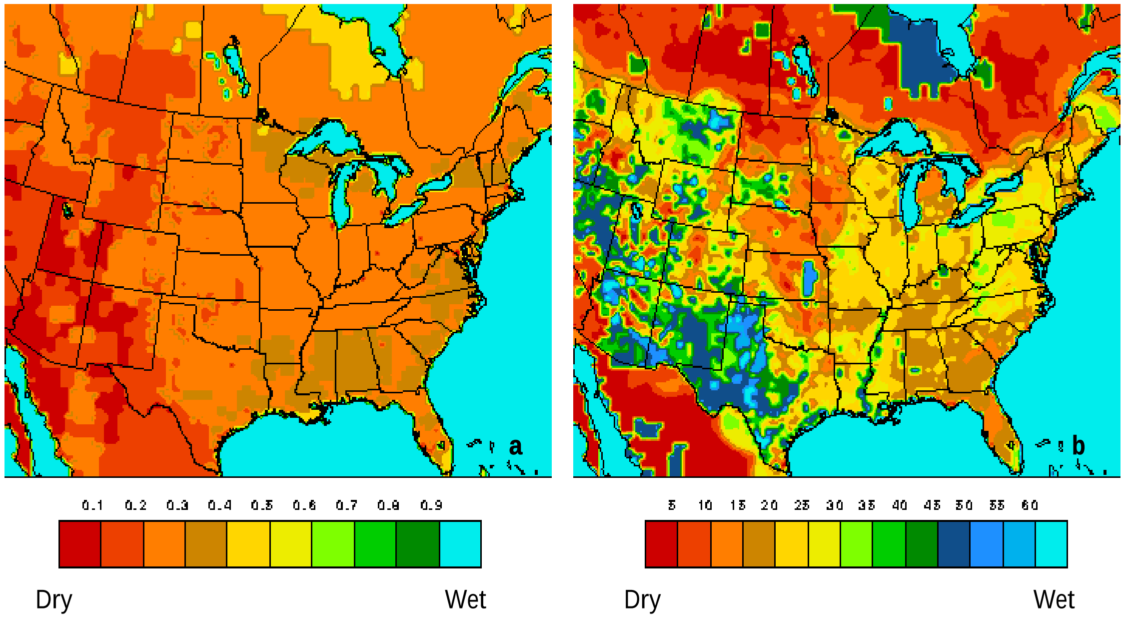

Figure 4. (a) Climatological moisture availability and (b) Upper 100 mm soil water content (mm) derived from the SHM. Valid 1200 UTC 9 June 1997.

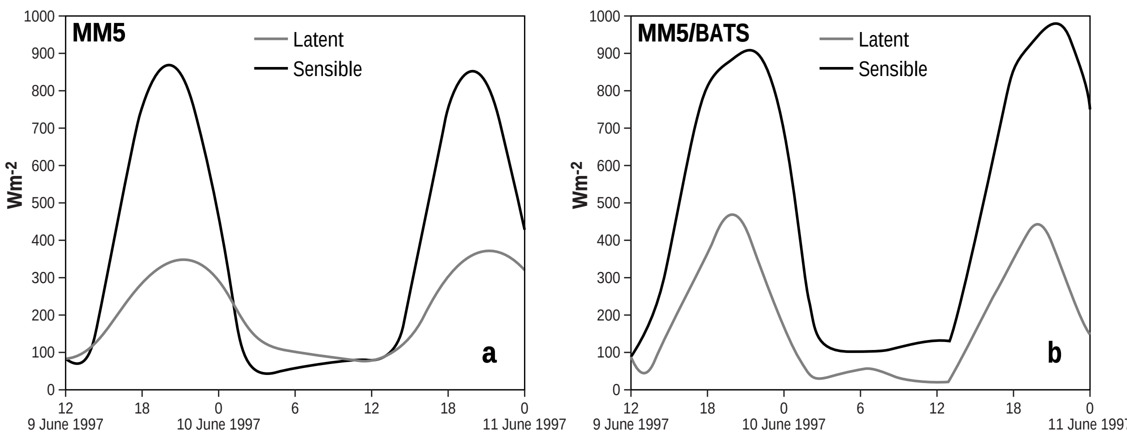

Figure 5. Simulated sensible and latent heat flux time series for the 36 hour period qbeginning 1200 UTC 9 June 1997 in southeastern Arizona for (a) MM5 only and (b) MM5/BATS initialized with SHM-derived soil water content.

In addition, comparisons of our model results with those from NCEP's Eta model will be conducted as it too represents a "state of the art" modeling/assimilation system that also accounts for vegetation and soil moisture in its representation of the land surface energy budget.

Satellite Assimilation

During the past year, we have developed a technique for assimilating GOES-IR skin temperature *tendencies* into the surface energy budget equation of MM5 so that the simulated rate of temperature change closely agrees with the satellite observations (McNider et al. 1994; Lapenta et al. 1997). A critical assumption of the technique is that the availability of moisture (either from the soil or vegetation) is the least known term in the model's surface energy budget (Wetzel et al. 1984; Carlson 1986). Therefore, the simulated latent heat flux, which is a function of surface MA, is adjusted based upon differences between the modeled and satellite-observed skin temperature tendencies. The fact that the rate of change of the satellite skin temperature is used rather than the absolute temperature means that sensor calibration is not as critical. An advantage of this technique for short-range forecasts is that it does not require a complex land-surface formulation within the atmospheric model. As a result, the need to specify soil and vegetative characteristics is eliminated.

We are in the process of applying both MM5/BATS and the GOES assimilation technique to a common case to better understand the performance and limitations of each method. A case from 7 July 1995 was simulated using a 1-way nested configuration with a coarse domain of 36 km as described above and a nest of 12 km centered over Oklahoma/Kansas. This region was chosen due to an west-east vegetation gradient (wheat stubble to the west, deciduous forest to the east). Given this variation in vegetation, one would expect the satellite-observed surface thermal response and inferred evapotranspiration to differ across the region.

A series of three 36-h simulations using different model configurations were performed for this case starting at 1200 UTC 7 July 1995. The control run (MM5) used the standard force-restore surface energy budget formulation during the entire simulation period as discussed in the previous section. As previously shown in Figure 4a, the MA used in MM5 is quite unrealistic and contains no virtually no horizontal variability. We also used the coupled model (MM5/BATS) and initialized the SWC using output from the SHM which exhibits considerably more variability than the MA (Figure 6). As discussed above, the GOES assimilation scheme adjusts the evaporative flux by altering the MA. In the assimilation run (MM5/GOES), the GOES-IR skin temperature tendencies were assimilated beginning at 1400 UTC and ending at 1800 UTC 7 July, after which the model is executed in free running mode. After assimilating GOES skin temperature tendencies, the adjusted MA exhibits a more realistic structure (Compare the OK-KS region in Figure 4a with Figure 7a) which matched well with the vegetation fraction index computed from NDVI (Figure 7b).

A more stringent check of the assimilation technique was done by comparing modeled surface evaporative flux data from observations obtained via Energy Balance Bowen Ratio (EBBR) systems deployed at the Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) sites for the U.S. Department of Energy's Atmospheric Radiation (ARM) Program (Splitt et al. 1995). Figure 8 shows a 36 h time series of EBBR observed evaporative flux at Cordell OK (denoted by E22 in Figure 6). Without the satellite assimilation, MM5 greatly overestimates the daytime evaporative flux by 300 Wm^{-2} (150%) on both 7 and 8 July. However, use of the assimilation run produces a much more realistic time series with an average difference for the 36 h period of less than 40 Wm^{-2}. Keeping in mind that the assimilation was terminated at 1800 UTC on 7 July, it is interesting to note that the moisture availability field generated through the assimilation continued to produce a very realistic time series of evaporative flux during the next diurnal cycle on 8 July. This indicates there is an "effective memory" or time-scale over which assimilation of the satellite data provides information within the model once the assimilation procedure is terminated. Further research on this memory is affected by subsequent drying or precipitation occurrence is warranted.

It is hypothesized that realistic partitioning of the surface energy fluxes will result in more realistic forecasts of near-surface air temperature and humidity. Figure 9 shows a comparison of simulated shelter air temperature and mixing ratio fields with available NWS observations. Assimilating GOES data in the mid-morning hours of 7 July resulted in improved afternoon forecasts. This was also found to be true through the remainder of the 36h forecast period

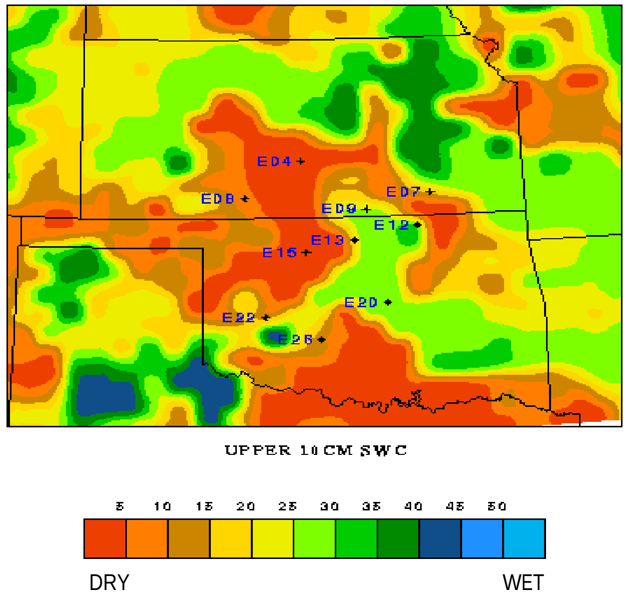

Figure 6. Initial soil water content (mm) for upper 100 mm of soil valid at 1200 UTC 7 July 1995 as derived from the SHM.

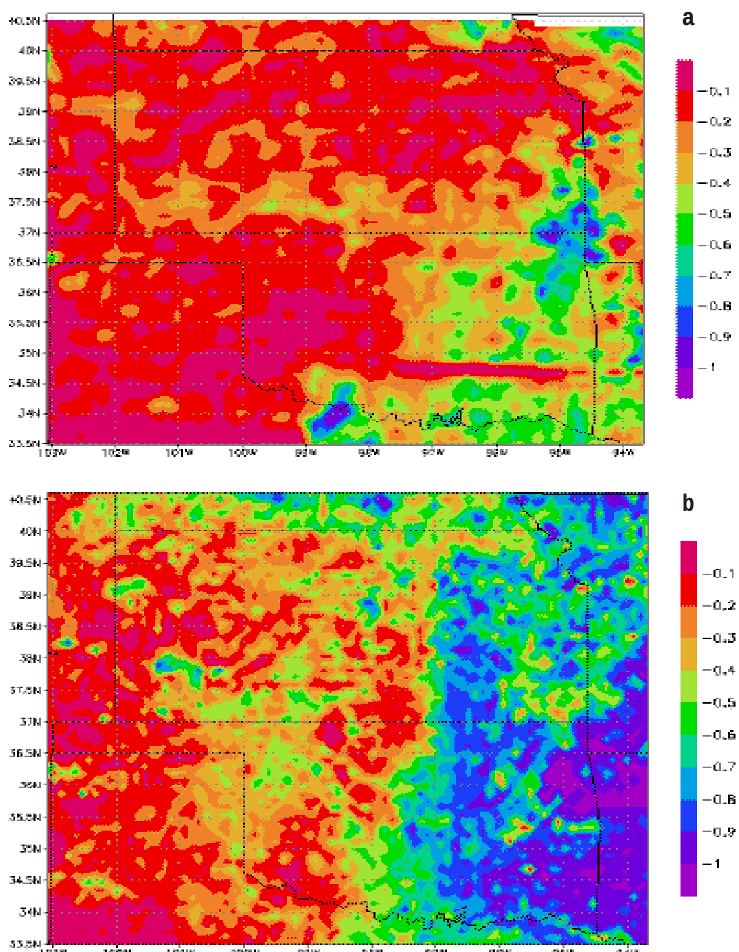

Figure 7. (a) Moisture availability derived from satellite assimilation and (b) 7 - 14 July 1995 composite NDVI derived from AVHRR.

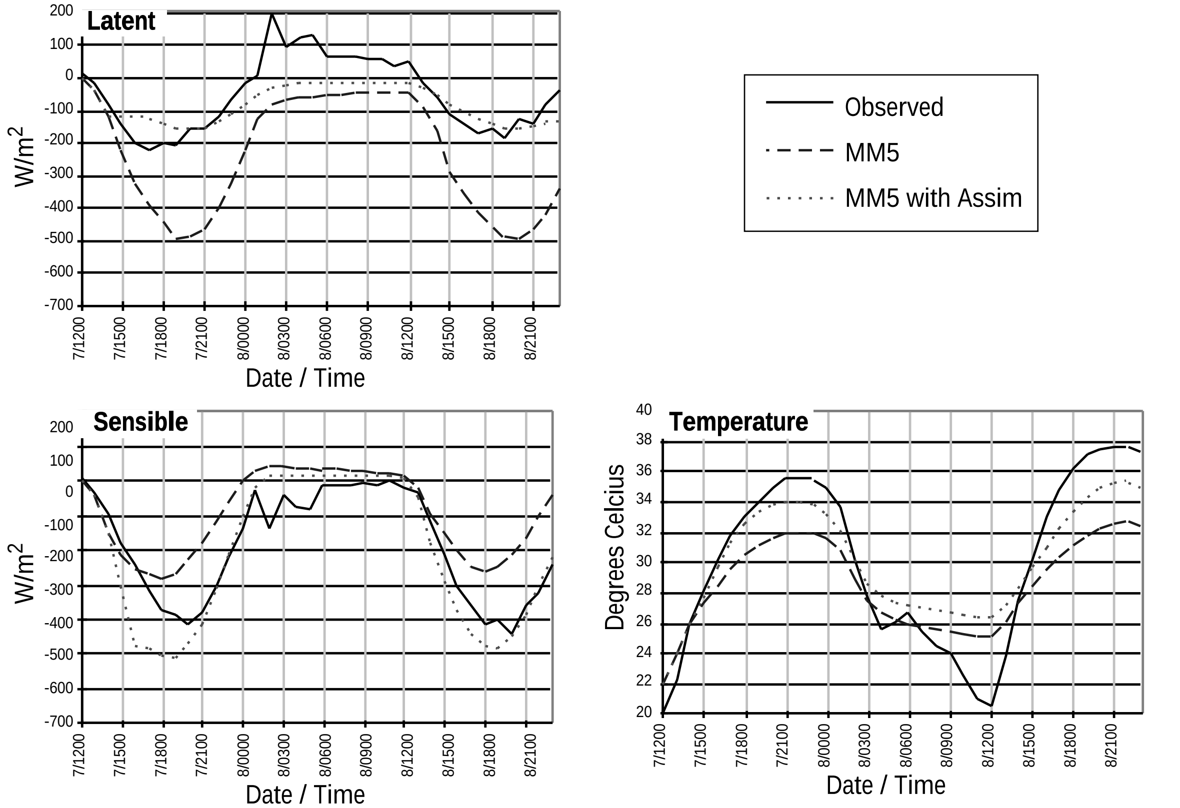

Figure 8. Time series of observed and simulated sensible heat flux, latent heat flux, and shelter air temperature for the 36 hour period beginning 1200 UTC 7 July 1995.

extending into the afternoon hours of 8 July (not shown). It is also noted that MM5/BATS resulted in an improved simulation over MM5. However, the assimilation run produced a slightly better simulation based on statistical analysis using all available observations.

Based on results presented herein and others (McNider et al. 94; Jones 1996) it is reasonable to expect that assimilation of GOES-derived land surface properties and the coupled modeling approach can have a positive impact on characterizing inhomogeneities in surface thermodynamics and subsequent boundary-layer evolution and initiation of convection during the warm season. During the past year, Dr. Lapenta has received funding to continue the development of the satellite assimilation technique that was initially developed under the EOS project. We plan on evaluating the utility of using the assimilation method to infer surface forcing conditions during periods when we are making regional climate runs with MM5/BATS prior to the availability of the SHM data.

Application of MM5/BATS on seasonal time scales

We have begun to run MM5/BATS in climate mode on a 52 km grid that encompasses the entire continental United States. The climate of this region has been simulated for a 60-day period beginning 15 May during the drought year of 1988 and a 60-day experiment for the Midwest flood period beginning 1 June 1993. These simulations will provide an opportunity to evaluate local and remote influences on the water cycle of the Central US. In addition, the 1988 drought simulation emphasizes thermal and dynamical processes and provides an initial understanding of how well MM5/BATS can represent regional climate during a period when surface thermal forcing within the domain is large and precipitation and latent-heat effects are minimal.

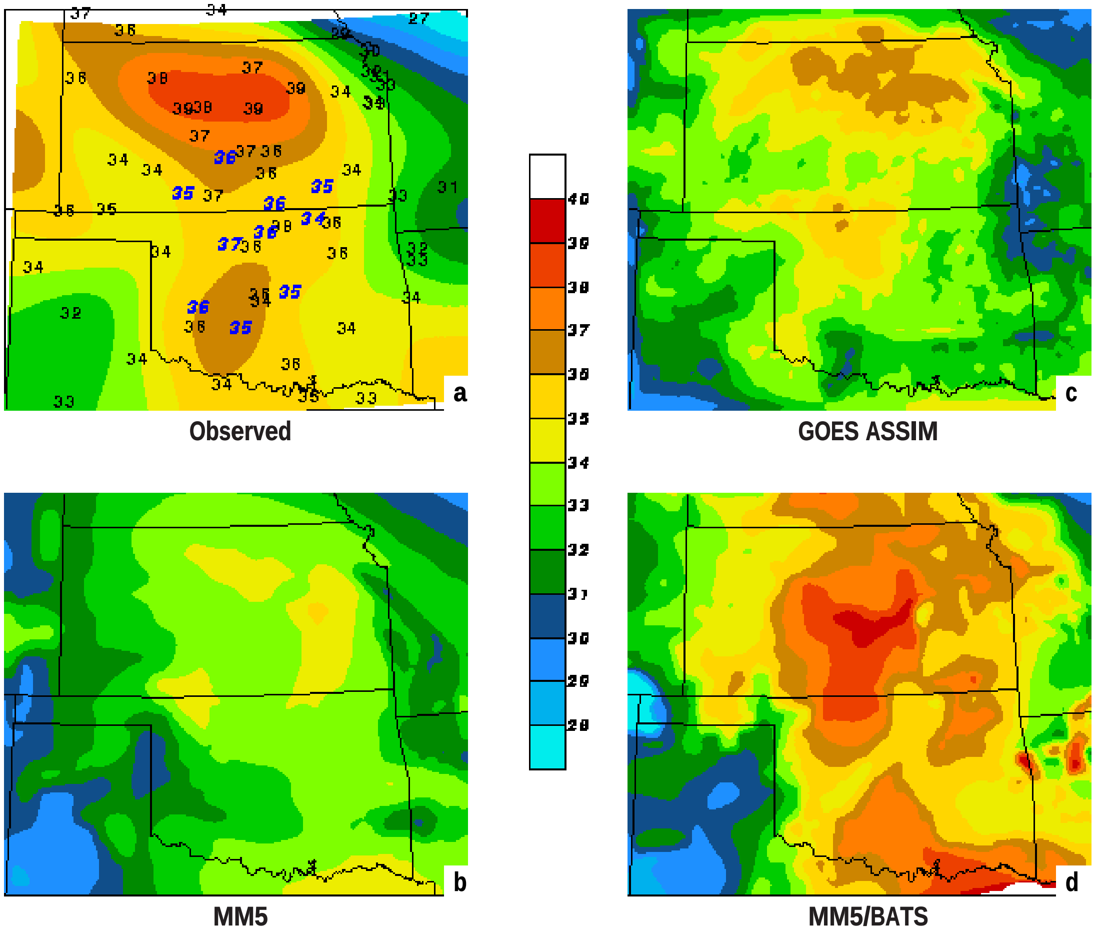

Figure 9. (a) Observed shelter air temperature (C) at 2100 UTC 7 July 1995 and 10 hour simulated for (b) MM5, (c) GOES Assimi, and (d) MM5/BATS.

The 1993 flood simulation emphasizes processes of the water cycle and will examine strengths and weaknesses of parameterizations of precipitation. This is demonstrated in Figure 10 which shows a time series of the simulated sensible and latent heat fluxes averaged over a 1500 km^2 region centered over southern Iowa. The flux trends in ‘88 are consistent with the drought conditions while those in ‘93 appear in line with the flooding in the Mid-West. The simulations have recently been completed and a complete analysis of the results is underway.

A useful approach for improving regional simulation by limited-area models is the comparison of simulations produced by different models with each other as well as with available observations. Strengths and weaknesses of model structures, numerics and parameterizations can be assessed side-by-side. The utility of model intercomparisons is greatly enhanced if the models operate under the same external constraints, such as dynamic and radiative input across model boundaries. To this end, Dr. Lapenta has become a participant in the Project to Intercompare Regional Climate Simulations (PIRCS). All participants in PIRCS will perform a common set of simulations with limited-area models and produce a common output set, both designed to highlight strengths and weaknesses of individual models and of this general approach to simulating regional climate.

During the next year, we will run MM5/BATS in regional climate mode during the same May–July 1997 time period coinciding with our SHM experiments. Comparison of the simulated soil

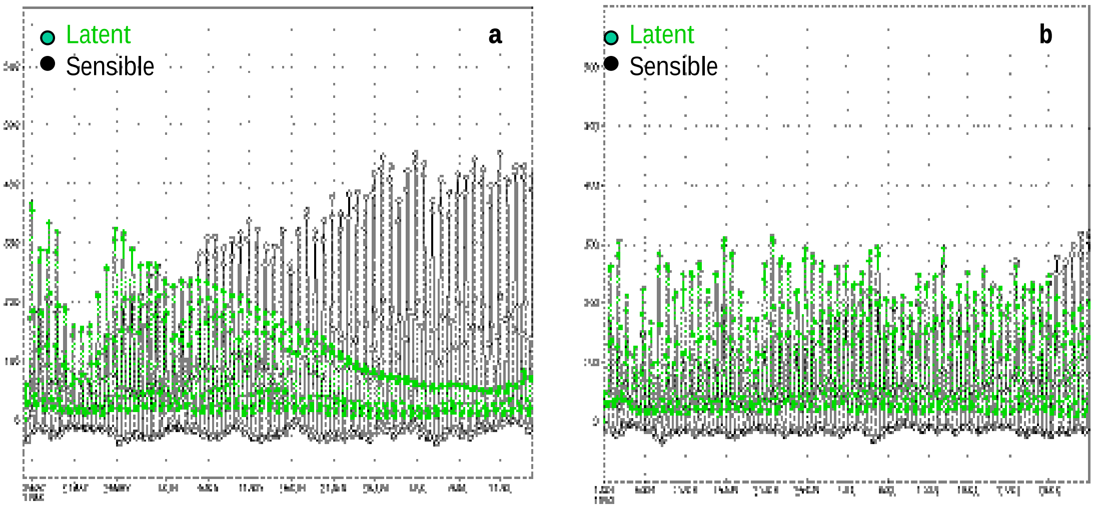

Figure 10. Areal averaged MM5/BATS sensible and latent heat flux times series for the 1500 km^2 region centered over southern Iowa for (a) 15 May–15 July 1988 and (b)1 June–31 July 1993.

hydrology over a 3-month period with that derived from the SHM will help us to evaluate the ability of MM5/BATS to be used in such a mode. We will also to re-run the 88 and 93 cases using SHEELS to better represent the soil hydrology processes.

Soil Hydrology Model (SHM)
The Real-Time SHM System
(M.N. Lakhtakia—PSU)

The real-time SHM (rtSHM) continues to be run operationally, and provides soil water content (SWC) profiles for a continental-scale domain (Figure 11) on a daily basis. This model is based on the one-dimensional model developed by Capehart and Carlson (1994). Following Smith et al. (1995), who applied SHM to each grid cell over a mesoscale domain, Lakhtakia et al. (1994) modified the SHM to update SWC profiles daily as shown in Figure 12.

The rtSHM is driven by conventional meteorological observations and land-surface information. Among the meteorological observations, precipitation is a critical SHM driving variable. As part of the PSU-MSFC collaboration of Lakhtakia and Goodman, MSFC have been providing a radar-derived precipitation product since March 1996. This product consists of 6 hourly cumulative precipitation analyses, at 2 km resolution over the 48 conterminous United States. This product is blended with station information, to produce the final analysis used in the rtSHM.

In most cases, the use of this radar-based precipitation information, has resulted in an improvement in the 12 hourly precipitation analysis used by the rtSHM, over that produced using the station precipitation only (Lakhtakia 1998).

As part of the same collaboration, and starting in the Spring 1997, MSFC have been providing an improved radar-derived precipitation product, based on applying the Convective-Stratiform Rainfall Classifier to composite radar reflectivity maps, as reported in our previous progress report. This product is now used as a first choice in the precipitation-analysis procedure, while the previous product is used as a backup. In the case that both products are missing (due to data or transmission problems), the precipitation analysis is performed using the station precipitation only.

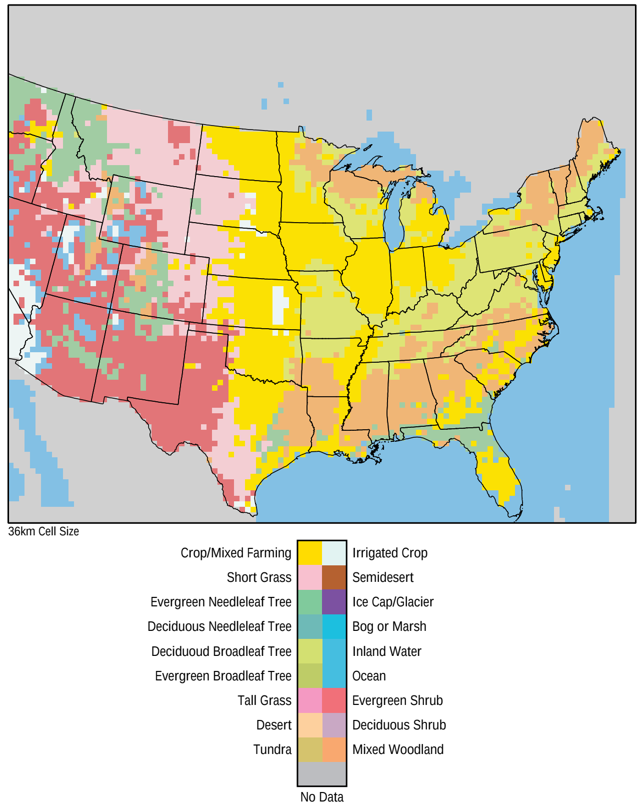

Figure 11. The Real-Time SHM system amd rtMM5 geographic domain with land cover distribution

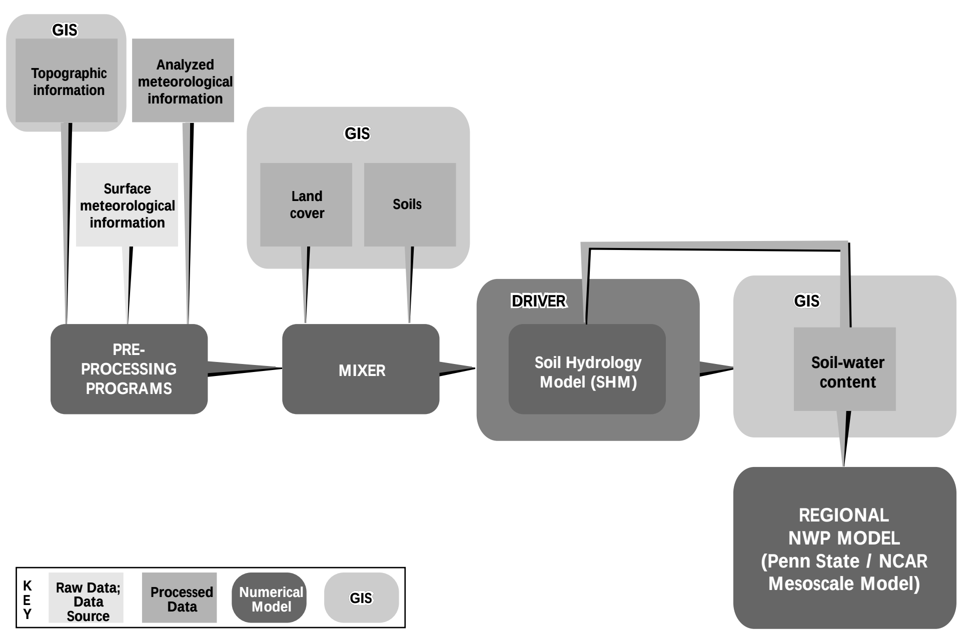

Figure 12. The real-time SHM system

The period of integration for the rtSHM started on 8 May 1995. Therefore, so far it has spanned an almost three year period, showing very encouraging (Lakhtakia 1997). The rtSHM, its results for the latest 7 day period, and other related information are located at the World Wide Web URL: http://www.essc.psu.edu/SWC. A manuscript discussing the model, its results and applications, is under preparation and should be ready for submission in the Spring of 1998 (Lakhtakia In preparation).

The De-Coupling Phenomenon and SHM

(M.N. Lakhtakia and T.N. Carlson—PSU)

Capehart and Carlson (1997) describe a “de-coupling” phenomenon, in which the SWC in the top layer of the soil (1 cm or less) may decrease to very small values very rapidly, without an accompanying reduction in SWC at depths of 5 cm or below. This phenomenon is likely to occur in some areas within a few days after a rainfall event, and is strongly modulated by vegetation amounts. Neglect of this de-coupling effect may produce important errors in the forecast of afternoon temperature and humidity, particularly during conditions of strong sunlight. Recent studies (e.g., Gillies et al. 1997) show that the surface SWC and the fractional vegetation cover (Fr) are the dominant land surface parameters governing the surface energy budget.

In order to study the de-coupling effect using the SHM, it is therefore important to put special emphasis on the existence of a shallow soil layer close to the surface and the specification of the land cover information, and, in particular, Fr. For this application, we have chosen the latest version of SHM (Capehart and Carlson 1994). This version allows for variable-depth soil layers, which is not available in the version used in the rtSHM. While the rtSHM uses constant soil depths of 10 cm down to a total depth of 2 m, the new SHM uses the following soil-layer depths: 2 cm, 3 cm, 5 cm, 15 cm, 25 cm, 25 cm, 25 cm, 50 cm, 50 cm, over the same 2 m soil depth. The new SHM was modified to run under the same system and over the same domain as the rtSHM, but not operationally.

The default Fr in SHM is calculated as a function of the land cover type and the time of the year. For this experiment, however, an NDVI-derived Fr data base was prepared. This data base spans the period July 1995–December 1996, has a horizontal resolution of 1 km and a bi-weekly temporal resolution. Two examples of the Fr distribution are given in Figure 13, for the two 2 week periods ending on 5 July 1996 and 19 July 1996. The process of “greening-up” of the vegetation is very apparent over the central United States from Figure 13a to Figure 13b. The Fr information was re-projected and aggregated to the 36 km grid cell domain for use in the new SHM.

Because de-coupling phenomenon is strongly modulated by the vegetation amount, we have also undertaken the modification of the SHM from a single vegetation type for each grid cell, to a “mosaic” vegetation. This means that, for each grid cell, SHM now allows the existence of up to 4 vegetation types. Using the BATS categories from the Global Land Cover Characteristics database from the EROS Data Center, we created a file containing the percentage of each BATS land cover type for each grid cell over the domain. Then, for each grid cell we looked for the categories with the highest percentages, keeping the ones that together accounted for more than 90% of the land cover for that grid cell or up to 4 land covers (whichever came first). The resulting information is ready for use in the new SHM, together with the NDVI-derived Fr information to study the de-coupling phenomenon.

The new SHM will be run for the period of 8 May 1995 through 31 December 1996. This period will be extended as soon as the NDVI information becomes available and is processed for 1997.

Figure 13. Fractional vegetation cover for (a) 5 July 1996 and (b) 19 July 1996

Susquehanna River Basin Experiment

Introduction

SRBEX is the first of several planned regional experiments which are to be undertaken in our EOS research program. The Susquehanna River Basin (SRB) is a 62,419 km^2 watershed covering portions of New York, Pennsylvania, and Maryland. (Figure 14). The overarching goals of SRBEX are to understand the hydrologic cycle of the basin through modeling and the analysis of observed data, and as a result of this understanding—to develop capabilities for monitoring and projecting changes in basin hydrology. The reason for SRBEX is clear: accurate projections mean that managers will be able 1) to lessen the impacts of variations in water quality and supply and 2) to optimize water resources. Thus, significant social and economic costs can be avoided and benefits can be realized by the research efforts of SRBEX.

More specifically, SRBEX includes the following policy-relevant objectives:

1. Identification of hydrologic parameters sensitive to climatic variation and change
2. Model experimentation to provide quantitative comparison of the hydrologic system sensitivities to various natural and human forcing functions
3. Observational studies to provide the context for comparisons of natural versus human-induced variations

Figure 15 summarizes the SRBEX suite of databases, data sets, and linked models.

Coupled Global-Regional Climate Model Simulations

(E.J. Barron, G. Jenkins, and J. Dutton—PSU)

Much of the research associated with coupled Regional-GCM simulations over the past year has been in the analysis of several simulations. There were four main themes associated with

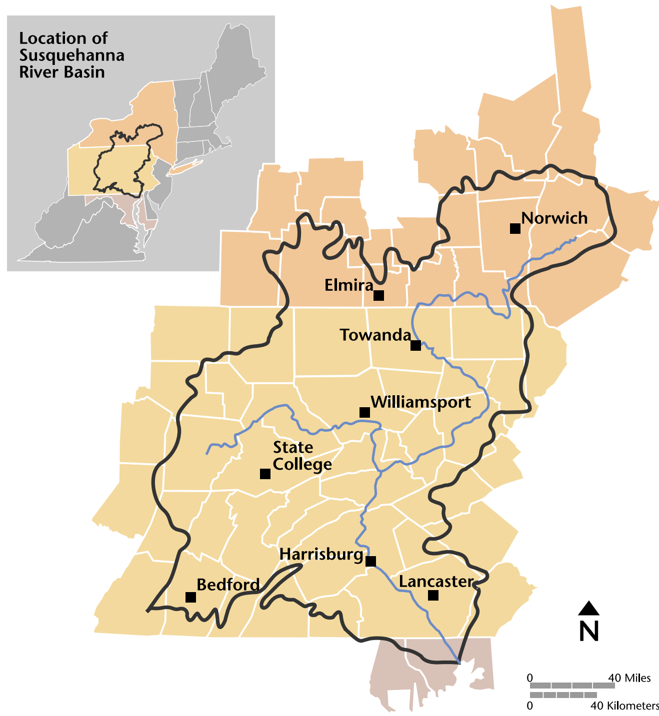

Figure 14. The Susquehanna River Basin

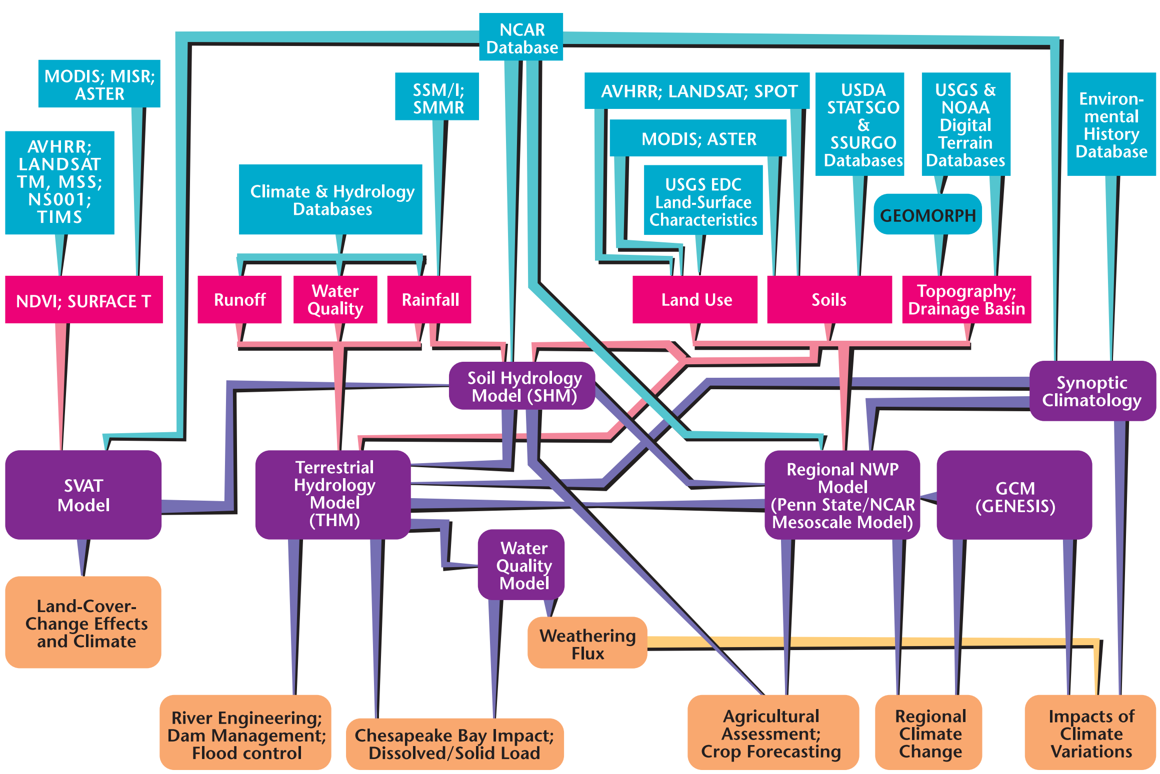

Figure 15. The structure of the Susquehanna River Basin Experiment

these simulations: 1) A comparison of mean decadal GCM and regional climate simulations to observations during the 1979–1988 period; 2) Investigation of seasonal variability in GCM and regional climate models during the ENSO winters of 1982–83 and 1986–87; 3) Investigation of seasonal variability and lateral boundary in GCM and regional climate models during the summer of 1988; 4) Examination of $1xCO_2$ and $2xCO_2$ simulations over the continental U.S. While the grid spacing in the regional climate model simulations are still relatively coarse, we have learned much from these simulations and they provide the groundwork for the near-future higher grid-spacing regional climate model simulations. The earlier reported work by Jenkins and Barron (1997) focused on the 1980 winter and spring period during a period of drought over the Northern Great Plains. In those simulations we found that the regional climate model produced a better representation of precipitation processes. We have also found this in the decadal simulation over the continental U.S. (Dutton and Jenkins 1998) which used time-varying observed sea surface temperatures (SSTs). The errors can be considerable for the dynamic components of the atmosphere (winds, 500 mb geopotential heights) when compared to observations in cases where the GCM driver is in error. Errors associated with the lateral boundary conditions provided to the regional climate model by the GENESIS GCM are not minimized in the limited area simulation.

When examining the simulations during the ENSO winter seasons of 1982–83 and 1986–87 we find that while both models capture the anomalous winter season geopotential height pattern, the warm temperature anomaly is displaced westward of the observed feature in the Northern great plains. Furthermore, conditions over the Gulf States are drier than observed during both seasons. The wetter conditions over California during the 1982–83 season are not fully captured in either model (Jenkins and Barron 1998a). The capture of the extratropic anomaly with a low resolution GCM is very positive and suggests that if errors of the lateral boundary conditions are minimized, then investigating the regional impacts of extreme events associated with natural variability is possible.

The errors associated with the lateral boundaries are of primary importance relative to those from model parameterizations of physical processes. The lateral boundary error is strongly manifested during the summer drought of 1988. As noted in our earlier report, when the regional climate model is driven at the boundaries by the ECMWF analyses the anomalous June atmospheric pattern is captured along with very warm and dry conditions over the Central and Eastern U.S. When the GENESIS is used to provide lateral boundary conditions the anomalous atmospheric circulation, temperature or precipitation patterns are not captured (Jenkins and Barron 1998b). The implications are realized at the surface where temperature differences over the Midwest are 7°C warmer in certain locations during June of 1988 for lateral boundary conditions from ECMWF. In addition, large difference in solar fluxes (75 Wm^{-2}), sensible heat fluxes (43 Wm^{-2}) and latent heat fluxes are found during June of 1988 in the two regional climate simulations (Jenkins 1998c).

We are continuing our analysis of the GENESIS-RegCM2 climate simulations when GENESIS uses a 50 meter mixed layer ocean. While the simulations show many similarities, we find the warmest temperatures associated with doubled CO_2 during the winter and summer seasons in the GENESIS simulation, but during summer and autumn seasons in RegCM2. Both models show the largest variability in temperatures during the winter and summer seasons. Both models show a decrease in snow depth during the winter seasons along with heavier rainfall amounts over much of the northern U.S. during the winter season. Thus both models show a conversion from snowfall to rainfall associated with doubled CO_2 conditions.

The precipitation differences (Figure 16) from present provide added insight (Dutton and Jenkins 1998) on potential CO_2 impacts. For example, the nested model indicates significant differences in summer dryness centered over the Ohio River valley and the Southwest. Much of the Northern US has slightly wetter winters with the southeast having substantially wetter winters. These simulations also provide a basis for comparison with other downscaling methods used in this study.

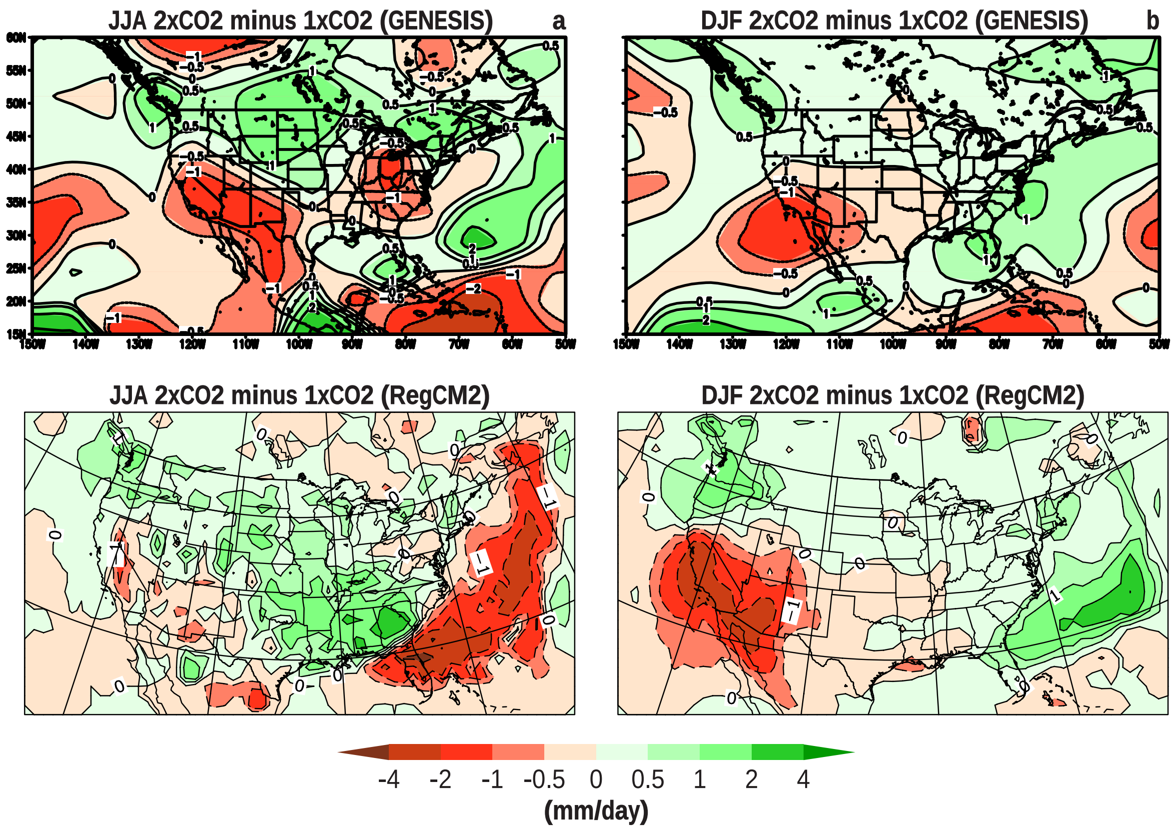

Figure 16. GENESIS and RegCM2 precipitation differences for $2xCO_2$ and $1xCO_2$ (mm/day) for (a) June-July-August and (b) December-January-February.

Synoptic Climatology and Downscaling

(R. Crane, B. Yarnal, B. Hewitson, and B. Frakes—PSU)

Because the nested numerical model downscaling is in its infancy in terms of providing scenarios adequate for human dimensions research, empirical downscaling and synoptic climatology fill an important gap in the SRBEX research chain. Present research includes methodological development using artificial neural networks (ANNs) and other methodological advances in synoptic climatology.

One ongoing study seeks to evaluate and optimize three short-term hydroclimatic relationships within the Upper West Branch of the Susquehanna River Basin using ANNs. A goal of this study is to evaluate the effectiveness of ANNs in predicting river flow based on observed precipitation. The ANN is being compared to HMS and HMS-GIS. Another goal is to evaluate the linkages between various atmospheric fields and observed rainfall. Different spatial and temporal resolutions are being investigated. The final goal relates the atmospheric circulation directly to daily river-flow. After isolating specific time scales, this work is examining which atmospheric fields are most intimately related to basin hydrology, as well as the effect of several spatial resolutions on this relationship. The linkages between the atmosphere and hydrosphere are complex and further compounded by processes operating at different spatio-temporal scales.

The neural net downscaling methodology has been refined to incorporate specific humidity. The transfer function uses 700 mb and 1000 mb heights for the nine grid cells centered on the target cell, as well as specific humidity at 1000 mb, 700 mb, and 500 mb for the central cell. Daily precipitation is “predicted” for the 0000z observation period using input data for 0000 z, the two preceding 12-hourly observations, and 1200 z the following day. The neural net is trained using the GSFC assimilated data set, and is applied to the GCM fields obtained from a present day and a 2xCO_2 experiment using GENESIS Version II at T31 resolution. The application of the neural net downscaling function to the doubled CO_2 climate model circulation and humidity fields suggests the possibility of a significant increase in spring and summer rainfall over the Susquehanna basin (Crane and Hewitson 1998).

We have experimented with several approaches to downscaling temperature. In each case, the downscaling in explained variances of over 90%. A neural net model using the same input data as the precipitation model produces a near prefect recreation of present-day daily temperatures. The problem with temperature downscaling occurs in the climate change experiment. The downscaling determines the temperature change due to the change in circulation patterns. However, it does not account for any temperature change that may result from the changing characteristics of the air mass. We are experimenting with different methodologies to attempt to capture this component of the temperature change, and a publication is in preparation.

We have added further refinements to the precipitation downscaling to incorporate a stochastic element to the local forcing that produces a more realistic daily precipitation history. This has been tested on South African data and will be applied to a high spatial resolution Susquehanna data set early in 1998. The temperature downscaling will be completed for the same high resolution data set in early summer, and the next major step will be to carry out the climate change analyses using time slices from several transient GCM experiments.

A third project has put special emphasis into developing the methodology by employing two types of ANNs (Cavazos 1998a; 1998b). When pre-processing the daily atmospheric controls with a cluster type of ANN (i.e., a self-organizing map, or SOM), the extreme events are much better simulated on daily and regional bases than if the data were treated otherwise. This finding is of great potential use for climate variation and regional climate change assessments. Notably, the results document the circulation anomalies conducive to extreme events.

Work continues on methods to improve standard synoptic climatological analyses (Frakes and Yarnal 1997; Yarnal and Frakes 1998). Especially important are the empirical relationships linking storm systems to basin response (Yarnal and Frakes 1997), thus providing representative scenarios for the linked model experiments described above.

Physically-Based Downscaling of Rainfall

(A. Barros and R. Bindlish—PSU)

There exists a disparity between the scales at which regional (mesoscale) climate models (e.g., MM5) and hydrologic models operate. In this study, the following associated scale issues are investigated: (a) scaling properties of the MM5-simulated precipitation fields at different resolutions, and (b) disaggregation and aggregation of precipitation and its effect on the hydrologic response. The latter is based on the hypothesis that spatial characteristics of precipitation fields are strongly influenced by the coupled variability of regional topography and storm wind fields.

The precipitation fields simulated by MM5 at 4x4 km^2 for two storm events over the West Branch of the Susquehanna River Basin in Pennsylvania were downscaled to 1x1 km^2 using three approaches: 1) *fractal interpolating* scheme, which takes into account the spatial characteristics of topography and wind fields over the domain, 2) *duplication of MM5 output* to the neighboring pixels, and 3) *binary interpolation*. Subsequently, the physically-based hydrologic model used in SRBEX was forced by the precipitation fields generated according to 1), 2) and 3) above, and the rainfall-runoff response of the West Branch of the Susquehanna River was evaluated. The experiments clearly illustrated the importance of small-scale orographic effects on the space-time variability of rainfall and on regional hydrology.

Disaggregation and aggregation of precipitation fields was conducted by making use of the spatial properties of regional topography and hourly wind direction for two typical springtime storms in Pennsylvania. The hydrological simulations demonstrated the importance of small-scale variability (1x1 km^2) of rainfall fields in the simulated (observed) streamflows. Because the West Branch of the Susquehanna is located in a region of complex terrain, where orographic mechanisms strongly affect the space-time properties of rainfall, this modeling experiment illustrates the benefits of using the topography-wind based fractal disaggregation approach to improve upon the spatial variability of rainfall fields generated by regional climate models or numerical weather prediction (NWP) operating at relatively coarse resolutions. This work was presented at the 1997 Fall meeting of the AGU, and a manuscript is currently in preparation.

Low-frequency Runoff, Precipitation and Temperature Response for a Large-scale Hydrogeological System: Susquehanna River Basin

(T.-Y. Shun and C. Duffy—PSU)

We have completed an analysis of a long record (>65 years) of monthly, runoff, precipitation and temperature time series (R-P-T) in the Susquehanna River Basin and isolated the dominant oscillatory components in the historical record. We have developed a methodology to define the hierarchical structure in a large-scale hydrogeological system by connecting the independent components with the physical parameters of the system. In this case we are concerned primarily with low-frequency space-time variability, and we focus our investigation on groundwater-stream interactions. We studied the spatial and temporal modes by using the multichannel single spectrum analysis (MSSA). Compared with Fourier analysis, where the basis functions are continuous (e.g. sins and cosines), the MSSA method allows the direct evaluation of the basis functions from space-time datasets. Four major oscillatory components are isolated at 1, 2–9, 10–21 year and 3–6 month frequencies. The lowest frequency (periods >10 years) in runoff is found in the low elevation regions with large groundwater reservoirs. This supports the idea of deep groundwater flow contribution to the stream. The annual and seasonal cycles are found among all three climatic fields. The variance fraction of the annual cycle in runoff is significantly larger than in precipitation. It appears that groundwater flow plays an important role in the low-frequency components of runoff. For the precipitation, the amplitude of the periodic component increases with the elevation, whereas the amplitude of the seasonal harmonics decrease with the elevation. A simple theory describes the characteristic aquifer length scale and the relaxation time of the groundwater system. The theory shows how low-frequency oscillatory components in runoff are produced by the groundwater system.

Hydrologic Model System (HMS)

(Z. Yu—PSU)

HMS, is comprised of four component models or modules: Soil Hydrologic Model (SHM), Terrestrial Hydrologic Model (THM), Ground Water Hydrologic Model (GHM), and Channel-Ground Water Interaction (CGI) (Yu et al. 1997c). HMS is designed to model hydrologic processes, such as vertical soil-moisture flow, evapotranspiration (ET), infiltration, overland flow, channel flow, and ground water flow, within a river basin (Figure 17).

Because of the evolution of four component models, HMS is written as a hybrid of various languages (mainly Fortran and C) with the current version implemented on an Ultra Sun Workstation. Each model is modularized and synchronized within the global time loop in HMS. SHM was developed by Capehart and Carlson (1994) to simulate the vertical profile of soil-moisture content and is driven by conventional meteorological and land use data. The original version of SHM was only applied to a point, but for implementation in HMS the model has been modified to be spatially distributed. This model is used to simulate the transient variation in soil moisture in the vadose zone, to evaluate each component of vertical moisture flow, and to calculate near surface fluxes (such as evaporation, ET, and infiltration) for each cell of the grid. These fluxes are inputs to THM, GHM, and CGI.

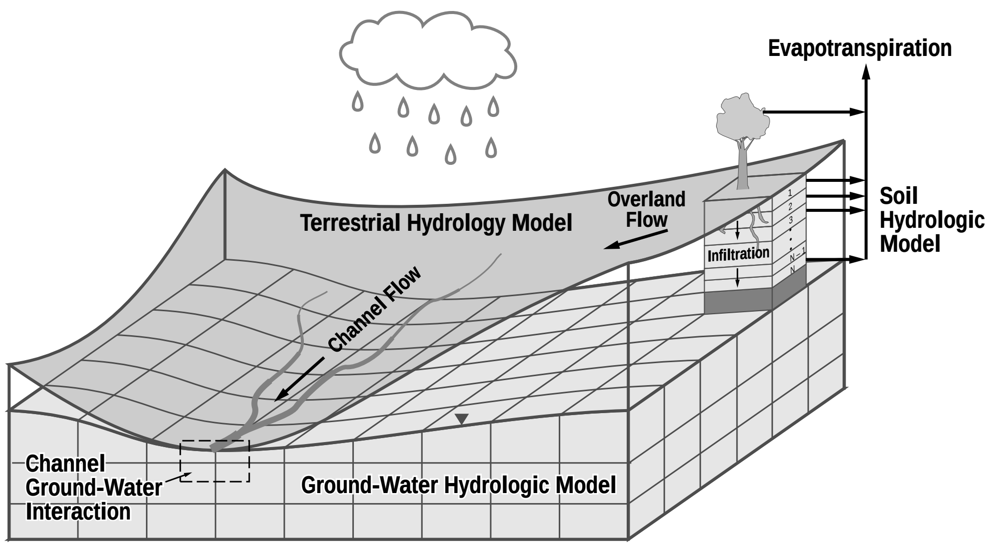

Figure 17. The Hydrologic Model System (HMS)

THM was developed by Johnson and Miller (1997) to simulate surface flows, given various types of rasterized data (e.g., digital elevation, precipitation, land use, and soil). The algorithm is based on the kinematic-wave theory and predicts runoff in the down-slope direction. The Muskingum-Cunge channel routing scheme is implemented in THM to route channel water through the stream network (derived from DEMs), to the outlet of the river basin. Any ground water recharge that results from precipitation is applied to GHM (Yu and Schwartz 1995a; Yu 1997) at appropriate cells of the grid and provides a basis for simulating the spatial and temporal changes in the water-table configuration. Leakage between the channel and ground water is calculated in CGI using Darcy's Law. Based on the output from THM and GHM, the composite hydrograph, representing the integrated flow response of the basin outlet, is simulated. A detailed description of each module is presented in the following sections.

A modified SHM offers the potential to link a multi-storm simulation simultaneously with MM5. In essence the spatially distributed soil-moisture content can be passed to MM5 at each time step in the simulation. The flow paths and hydrologic processes in SHM are illustrated in Figure 18. Unsaturated flow is described by the Richard's equation, which is solved using the Crank-Nicholson numerical scheme (Capehart and Carlson 1994) and a finite difference scheme of forward in time and backward in space. The treatment of the term with slope angle b is similar to the parameterization used in the Goddard Institute for Space Studies (GISS) GCM. The schemes relating hydraulic conductivity and potential to the volumetric water content in land-surface components of MMs and GCMs were also adopted in the SHM parameterization.

During the simulation, SHM receives information from HMS about the available-water depth on each grid node at each time step. The available-water depth is the summation of precipitation and water routed from neighboring cells in THM. Infiltration and evaporation are treated as a source or a sink, respectively, in Richard's equation, rather than the upper boundary condition of the soil profile. The infiltration and evaporation are distributed over the top layers. ET occurs across the entire root zone according to a weighting function, which depends on vegetation type and height. The calculation of evaporation on the bare soil and ET on the vegetation canopy follows the Penman-Monteith method. A Green-Ampt technique was implemented in SHM for the infiltration calculation. ET calculated by SHM is passed to HMS for water budget calculation in the next time step.

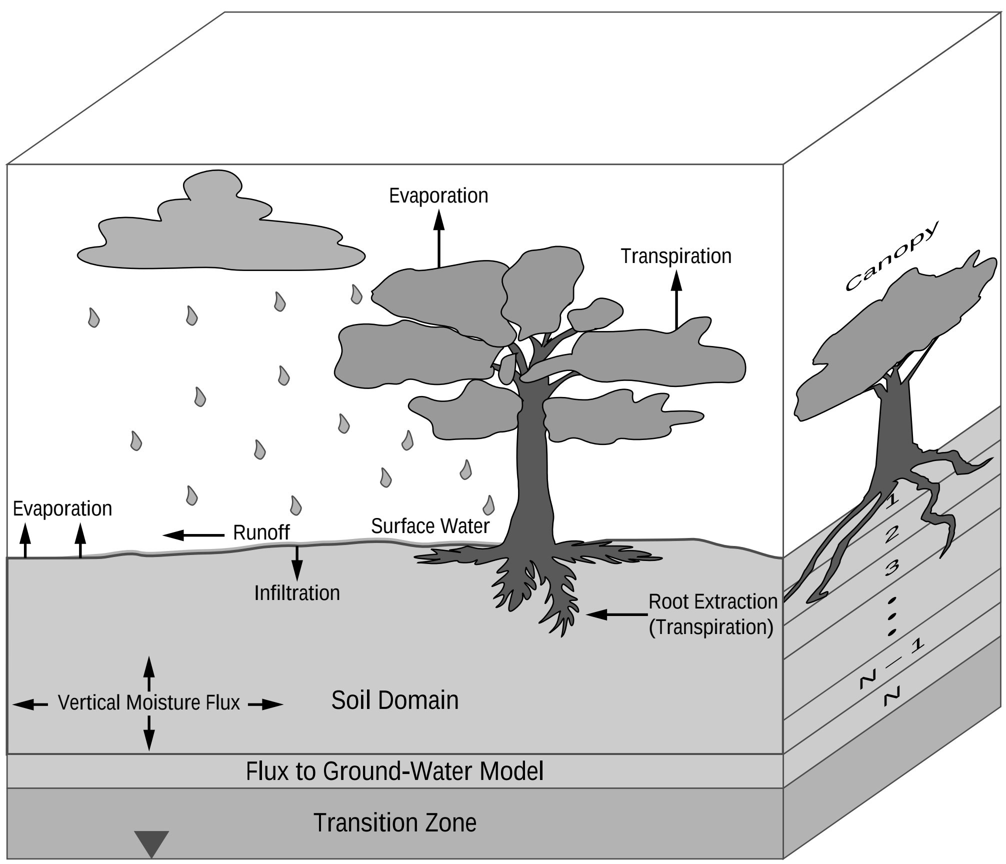

Figure 18. The Soil Hydrology Model (SHM)

Terrestrial Hydrology Model (THM)

THM includes routines for both overland and channel flows (Figure 17). Overland flow is formulated as a kinematic wave with a flow-direction algorithm to account for the overland-flow delay and storage in each grid cell. The kinematic-wave approach is straight forward computationally and has a predictive ability appropriate to the resolution and accuracy of the datasets.

Mathematically, overland flow is described as in Figure 19. Each grid cell and time step is further discretized into a large number of smaller segments. On each grid cell, the equation can be solved explicitly in a finite-difference form. This formulation provides hydrographs for overland flow on each grid cell. These hydrographs are added to produce collector hydrographs and, eventually, are transformed to channel or stream hydrographs.

The Muskingum-Cunge was implemented in THM for channel-flow routing through the stream networks. The Muskingum-Cunge procedure is applied on each stream grid cell to route the channel flow, through the stream networks, to the outlet of a river basin.

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = i^e$$

$$q = \alpha h^m$$

where:

$h = h_{(x,t)}$ = depth of overland flow

$q = q_{(x,t)}$ = rate of overland flow

i_e = net rainfall rate

α = conveyance factor

m = surface roughness

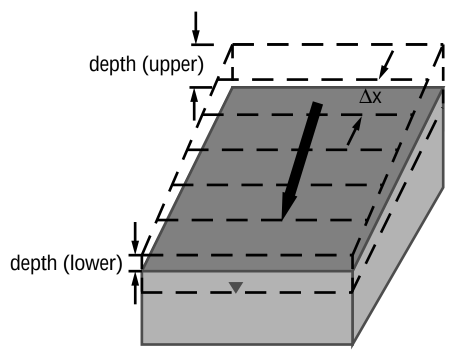

Figure 19. Kinematic wave methods for overland flow

Ground Water Hydrology Model (GHM)

A second-order partial differential equation is used to describe ground water flow in an aquifer. The simulation domain for a basin is shown schematically in Figure 20. It is discretized into a set of rectangular cells with dimensions Dz, Dx, and Dy. Dz is the vertical thickness of the aquifer, and Dx and Dy are the cell dimensions in the x- and y-coordinate directions. Although lateral flux can be specified across basin boundaries, the default condition is a no-flow boundary that corresponds with the basin boundary. A no-flow boundary is also assumed as the bottom boundary. This vertical boundary represents the boundary between the local ground water flow system of the simulated basin and the regional interbasin ground water flow system. A finite-difference scheme provides a solution to above equation. Details of the iterative alternating-direction implicit method are provided by Yu and Schwartz (1995a) and Yu (1997a).

Channel Ground Water Interaction (CGI)

The CGI module is designed to simulate the interaction between the stream system and ground water in HMS. The flux between these components, which is treated as either source or sink in GHM, is calculated using Darcy's Law. A layer of low permeable material in the stream bed is assumed to separate water in the channel from the ground water system at each stream cell. A conceptual model of channel ground water interaction is shown in Figure 21. Assuming that all parameters within a grid cell are constant, the inflow/outflow at a given stream cell is calculated using Darcy's Law.

$$\frac{\partial}{\partial x}(K_x\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z\frac{\partial h}{\partial z}) = S_s\frac{\partial h}{\partial t} + Q_w - Q_n$$

where:

K_x, K_y, K_z = components of the hydraulic conductivity tensor

h = hydraulic head

S_s = specific storage

t = time

Q_w = net groundwater withdrawl rate

Q_n = special source or sink rate

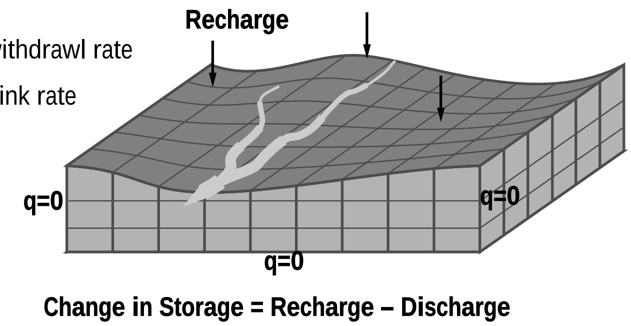

Figure 20. Ground Water Hydrology Model (GHM)

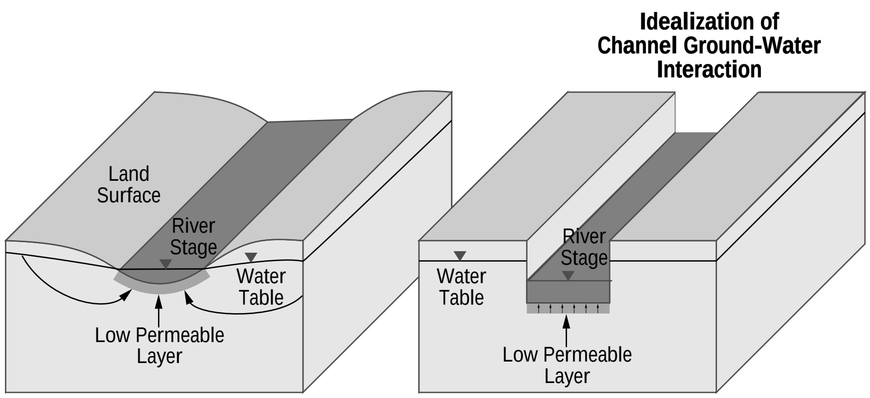

Figure 21. A conceptual model of Channel-Ground Water Interaction (CGI)

Optimization of Code Performance

(Z. Yu—PSU)

Modeling water movement within a watershed involves the numerical solution of a coupled system of two or three-dimensional partial differential equations. Normally, one can utilize fast workstations to solve these problems. However, the simulations are either limited to problems of small size or require long computing times. While some speedup in the execution of the computer code is possible by simply moving to supercomputers such as Cray Y-MP, J-series and T3D, most existing codes are not written to take advantage of the vector and parallel architecture of these compilers. This research developed new strategies for vectorizing finite-difference code and implemented new algorithms for a tridiagonal matrix solver in solving water flow problems. This method with no recursive natural-reduction and backsubstitution method, was implemented to improve code efficiency further. These approaches take advantage of both vector and parallel processing capabilities of the Cray Y-MP by eliminating data dependencies and implementing new algorithms. Code performance was also enhanced by other routine optimizing techniques. Indeed, optimization procedures were applied to every part of the entire code. Compared to the scalar code, the fully-vectorized and parallelized code runs 10 to 16 times faster, as measured in CPU time, and 24 to 36 times faster, as measured in wall-clock times (Yu and Schwartz 1995a; Yu 1997a).

Effect of Grid Size on Watershed Flow Simulation

(Z. Yu—PSU)

Interest in modeling large scale hydrologic systems in large drainage basins has created a significant need for the optimization of codes to take advantage of high-performance computers, as discussed in the previous section, and promoted interest in the scale problem of grid size—what is an appropriate grid size.

Based on the elevation data in the Big Darby Creek watershed, Ohio, a series of DEMs (grid spacing from 120 to 3600 feet) was produced and was used to examine the effect of DEM grid size on the representation of land surface and surface hydrologic simulation. The same series of grid sizes was applied to explore the effect of grid size on the simulations of channel network representation and ground water flow. The frequency distribution of slope tangents was calculated for each DEM grid size. A statistical approach, Monte Carlo sampling from known parameter distributions of a channel network, was used to generate a modified form of the channel network in the watershed. The algorithm, with one-direction flow, was used to calculate the spatial distribution of runoff travel time and to predict the simulated hydrographs for each grid size. The effect of grid size on the ground water flow simulation was also examined by simulating water-level configuration and stream-aquifer interaction.

The results show that the resolution gets better as the grid size gets finer for both surface water simulation and ground water flow modeling. Overall, a 1200-foot grid size provides basic estimations of both surface water and ground water simulations. A 600-foot grid size was suggested to be an appropriate one in the sense of the quality of simulated outputs and required CPU time (Yu, 1997b; 1997c). In summary, the quality of simulations depends on both the accuracy of the original elevation data and the resolution of grid size. The resolution of DEM grid size is constrained by the spacing of the original elevation data. The spacing of grid size that is less than the spacing of the original data doesn't enhance the accuracy of land surface representation.

Automated Calibration

(Z. Yu—PSU)

Interest in simulating hydrologic processes in larger watersheds over a long period of time has prompted a significant need for an automated calibration. An automated calibration procedure was implemented in a physically-based distributed model (Yu and Schwartz 1995a; 1997a). The hydraulic heads and ground water baseflows were selected as calibration targets. The hydraulic heads were collected from historical records. The ground water baseflows were extracted from streamflow hydrographs by using a method of numerical hydrograph separation. The calibration procedure was able to determine the best case and worst case predictions among the plausible parameter sets. In addition, chemical mixing methods were used to separate the streamflow hydrograph into two components: runoff and baseflow, based on the measured specific conductances of stream water samples at the watershed outlet, and surface runoff and ground water samples within the watershed. The variations of flow components identified by the chemical hydrograph separation method compare well with those simulated with the model (Yu and Schwartz 1997b).

Stormflow Simulation Using a Geographical Information System

(Z. Yu, Y. Guo, J. Voortman, R. White, and D.A. Miller—PSU)

With the increasing availability of digital and remotely sensed data such as land use, soil type, and digital elevation models (DEMs), Geographical Information Systems (GIS) have become an indispensable tool in preprocessing data sets for watershed hydrologic modeling and postprocessing simulation results. This study describes the terrain analysis conducted using GIS for extracting information relevant to overland flow and channel flow and the methodology for providing those analyzed data sets for hydrologic simulations of overland flow, channel flow, and ground water flow in river basins (Yu et al. 1997b). DEMs were utilized to derive stream networks, to determine flow direction, and to delineate watershed boundaries. The effects of DEMs with various scales on the hydrologic simulation of a river basin response were determined by analyzing those parameters derived from DEMs.

The rainfall–runoff scheme used in this study is a part of a Geographic Information System (GIS) based hydrologic model system (GIS–HMS) developed by Yu et al. (1997e). GIS–HMS is similar to the Curve Number approach of Soil Conservation Survey. The model system uses ARC Macro Language (AML) in the ARC/INFO GIS, which offers many raster functions that are useful for hydrologic applications. The spatial approach in GIS–HMS combines GIS data organization and distributed hydrologic modeling. The model architecture and design consistently consider data and processes at various scales (e.g., local, catchment, watershed, and regional). GIS–HMS includes thematic maps (topography, soil, and vegetation), and spatial and temporal hydrologic data (precipitation and runoff). Simulation of hydrologic response to one storm was conducted using GIS for a river basin. The predictive capability of this approach for simulating streamflow response was demonstrated in another storm.

Simulation of River Basin Response to Atmospheric Forcing

(Z. Yu, M.N. Lakhtakia, B. Yarnal, R. White, and D.A. Miller—PSU)

The goal of the Susquehanna River Basin Experiment (SRBEX) is to simulate the basin’s hydrologic response to atmospheric forcing at various time scales. An integral part of SRBEX is the linkage of meteorological and hydrological models (Yarnal 1997c). To link these disparate models, a nested version of the Penn State-NCAR mesoscale meteorological model (MM5) is used to simulate the precipitation from a storm system passing over the river basin. This high-resolution precipitation field, with grid increments as fine as 4 km, then drove the Terrestrial Hydrologic Model (THM) in the original version of the linked system, and the Hydrological Modeling System (HMS) more recently. As noted in a later section, HMS is composed of physically based, interactive surface-routing, groundwater, soil-water, and channel leakage components. Special attention is given to data resampling and reprojection. A key aspect of the system is the application of GIS to control the high-resolution soils, landuse, and digital terrain data at the model interface. The output from the modeling system is a simple hydrograph, which represents the integration of basin hydrology over time and space. Experiments have been performed to determine the sensitivity of the linked model system results to the surface-water abstraction method (i.e., Curve Number or Green-Ampt), and to the MM5 nesting scheme and are reported in the following paragraphs. These results highlight the strengths and weaknesses of the abstraction methods, and trade-offs between simulation accuracy and computation speed related to the various nesting schemes.

The first experiment linking MM5 to THM simulated the hydrographic response of the Upper West Branch of the Susquehanna River Basin to a single storm (Lakhtakia et al. 1998a). Synoptic climatology was employed to choose a representative hydroclimatic event. MM5 used three nested domains to simulate relatively high-resolution precipitation over the sub-basin. THM simulated surface runoff using both analyzed and simulated precipitation, while the hydrologic abstractions were handled using both Curve Number and Green-Ampt routines. The MM5 simulation captured the spatial and temporal structure of the storm event, while THM represents the timing of the hydrologic response well. Each HMS simulation consisted of two stages. The first stage brought the models to an equilibrium condition, to keep unrealistic initial conditions from affecting the outcome of the hydrologic simulation; the second stage simulated the hydrologic response. The hydrologic simulations were run for 200 hours. A manual trial–and–error calibration was utilized for ground water parameters (i.e., hydraulic conductivity and storativity) in the storm simulation using the analyzed precipitation.

The Susquehanna River Basin experienced moderate rainfall in a storm of April 1986, which followed the typical stages of wave–cyclone development. The overall structure of the storm was captured in the MM5 simulation (Lakhtakia et al. 1997; Yu et al. 1997d). HMS was driven by observed and MM5–simulated precipitation data. In each grid cell within the HMS domain of simulation, the precipitation is partitioned into components of evapotranspiration, infiltration, and surface runoff through either of two rainfall–runoff generation schemes: the Soil Conservation Survey curve–number (SCS) method or the Green–Ampt (GA) method.

The HMS response to the observed precipitation data shown in Figure 22a. Curves are displayed for the two rainfall–runoff generation schemes, along with the observed hydrograph and the temporal evolution of the areally integrated precipitation over the Upper West Branch. In general, the HMS–simulated hydrographs show a good match with the observed streamflow data. The simulated hydrograph in the SCS_moderate moisture case compares well with the observed one, while the simulated hydrograph in the SCS_wet moisture case overestimates streamflow. The simulated hydrograph using the GA approach underestimates streamflow. Because of the overland and channel flow routings, the response to the precipitation appear smoothed in all three simulated hydrographs. For the SCS_moderate case, the simulated hydrograph rises approximate by 4 hours earlier than the observed hydrograph, has about the same maximum streamflow, and recedes approximate 8 hours earlier. The simulation for the SCS_wet case overestimates the early part of the hydrograph because the wet soil condition induced more surface runoff from precipitation than observed conditions; however, this case does a better job on the latter part of the hydrograph, partially because observed soils were saturated after many hours of rain. The simulation using the GA scheme underestimated the streamflow for the entire simulation. This underestimation can be attributed to at least three reasons. First, the GA approach implements a threshold that limits the runoff calculation when the rainfall intensity is less than the saturated hydraulic conductivity (Yu et al. 1997c). Most grid cells have a saturated hydraulic conductivity greater than 2 mm/hr. As indicated by Figure 22a, the average precipitation intensity is less than 2 mm/hr for most 1–hour periods, so the model produces no runoff for most grid cells. Second, the coarse resolution of the soil data used in this study misses the actual heterogeneity in the hydraulic properties. Finally, the precipitation observations are at 1–hour intervals and the average separation between stations is approximate by 40 km in the study area. Therefore, the observed precipitation does not fully reflect the spatial and temporal heterogeneity in rainfall intensity. If

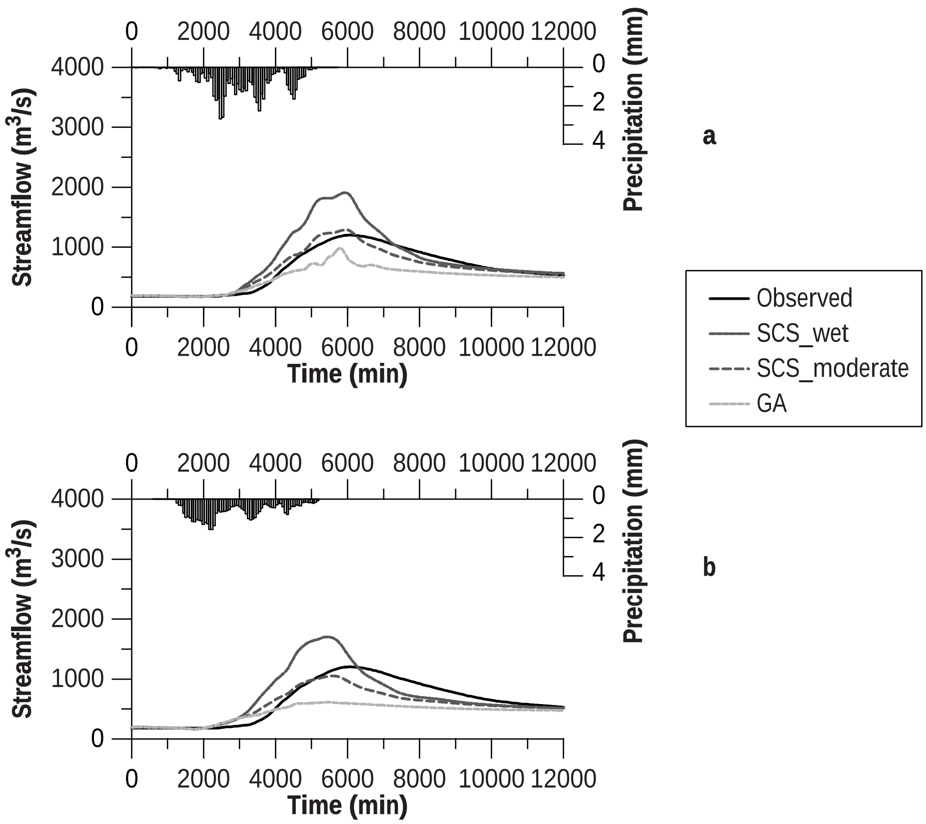

Figure 22. (a) Simulated and (b) Observed streamflow hydrographs for Storm 1 with observed precipitation data

those heterogeneities can be taken into account, the simulation of surface runoff will be improved. Figure 22b depicts the HMS–simulated hydrographs using the MM5–simulated precipitation. Trends are similar to those in Figure 22a. In the SCS_wet case, the simulation overestimates streamflow, while the simulations in the SCS_moderate and GA approaches underestimate streamflow. The simulated hydrograph shows a faster response than the observed one, partially because MM5 produced more precipitation than observed in this area early in the simulation (Figure 22a). Smoothing by the routing schemes causes the signal of the precipitation peaks to be nearly indiscernible in these diagrams. Again, the GA scheme significantly underestimates surface runoff; simulated precipitation in almost every period is less than 1.5 mm/hr, resulting in no runoff, except for direct precipitation to streams.

A second experiment used HMS to simulate the hydrologic response to three single-storm events passing over the Upper West Branch of the Susquehanna River Basin (Yu et al. 1997). Observed and simulated precipitation data from MM5 for those storms drove HMS and output from HMS was compared to the measured hydrographic trace at the sub-basin outlet. As in the first experiment, the high-resolution precipitation fields were provided by observations and by MM5 with three nested domains. The MM5 simulations successfully captured the storm patterns over the study area, although some temporal and spatial discrepancies exist between observed and simulated precipitation fields. The results from the Storm 1 hydrologic simulation (reported in the previous paragraph) were somewhat realistic when using the Curve Number partitioning, but showed considerable underestimation when using the Green-Ampt method because of the low intensity of the rainfall event. In contrast, Storm 2 had much higher rainfall intensities and produced good results with both partitioning methods. The results from the hydrologic simulations for Storm 3 were also realistic. The important point of this experiment is that the results were robust for more than one storm.

MM5 used a 36-12-4 km nested grid in the first two experiments. This nesting produced excellent simulations of the precipitation fields, but was computationally intensive and ran slowly with the current hardware and software configurations. Because future experimentation aims at simulating longer periods, this computational intensiveness might prove to make this methodology impracticable. Thus, it proved expedient to run various combinations of the nested grids to determine if a full three-grid nesting was necessary. Three simulations were run for each of the three storms described above (Storms 1, 2, and 3): a full 36-12-4 km nesting (called a 3-domain run); a 36-12 km nested pair (a 2-domain run); and a 36 km grid alone (a 1-domain run). In all, nine simulations were compared. Each resulting precipitation field was used to drive a GIS-based version of HMS (i.e., HMS-GIS; see the hydrologic modeling section for details). The results (Lakhtakia et al. 1998b) demonstrate that the finest scale of simulated precipitation (the 3-domain run) produced a realistic hydrologic response; the coarsest scale (the 1-domain run) generated poor results. Future research will retain the 36-12-4 km nesting, but efforts are being made to improve parameterizations and optimize code for MM5.

As noted in the last report, an important goal of the research is to develop a modeling system that can accurately project basin runoff on seasonal to interannual time scales. To reach this goal, MM5 is being modified considerably and several intermediate model experiments will need to be run.

The following modifications are being made to MM5: a radiation component was added to allow seasonal solar forcing; a new, optimized planetary boundary layer scheme was added and improved performance dramatically; and the model was optimized for multitasking. The model will be altered to receive GCM data. First steps are being taken to transform MM5 into a mesoclimate model .

As this transformation takes place, the following staged experiments will take place:

1. Two-storm and multi-storm simulations. These experiments will take place during summer 1998.

2. Annual cycle simulation. Next, the annual cycle will be modeled, accounting for changing base flows and snow melt, as well as individual storms. This experiment should be complete by late 1998.

3. ENSO event simulation. Finally, an ENSO cycle from the AMIP period will be simulated. This experiment will involve two separate runs. The first will simulate the event using global, regional, and local observations. The second will use GCM output for the large-scale (global and, perhaps, regional) inputs. These two model runs should happen in early 1999.

The ultimate aim of this evolutionary process is to use ENSO GCM forecasts to predict basin runoff up to 18 months in advance. The difference between this research and similar projects is that while others essentially use simple water-balance approaches for large basins, the SRBEX linked-model approach will explicitly model the evolving hydrology on a storm-by-storm basis. The output from this system will provide the fine spatio-temporal resolution required by many decision makers who manage or depend on water.

Soil-Vegetation-Atmosphere Transfer Modeling and Remote Sensing

(T.N. Carlson, D.A.J. Ripley, and S.T. Arthur—PSU)

Background

The soil-vegetation-atmosphere transfer modeling and remote sensing portion of our project focused on three areas of study in the past year. The first was intended to describe land use changes, specifically urbanization, in Centre County, Pennsylvania, using satellite measurements from NOAA (AVHRR) and Landsat imagery. Emphasis was on the application of the so-called 'triangle' method which allows us to describe these changes in land use and land cover in terms of physical parameters: vegetation fraction (Fr), surface moisture availability (Mo), evapotranspiration (ET) and evapotranspiration fraction (ET/Rn), Rn being the net radiation. It was shown (Owen et al., 1997) that neighborhood-scale changes could be detected and even quantified in terms of changes in the aforementioned parameters with the aid of AVHRR. More recently, our work has shifted to an increased use of Landsat imagery

The second phase of our work involves an investigation of land use changes in two widely diverse areas: Chester County, a moderate-sized and rapidly urbanizing county in Pennsylvania, and Costa Rica. While urbanization was the main focus, a correlative problem for Costa Rica is deforestation. To reduce the scope of the Costa Rican investigation to a manageable scale, we concentrated on the central portion of the country, around the principal city of San Jose and the La Selva region, which consists mostly cultivated plains and some forested areas north of mountains that border San Jose on the north

Analyses of AVHRR imagery for the San Jose region is now virtually complete, but this effort has been broadened to include Guanacaste, a region of dry, deciduous forest and vacation resorts in the northwestern part of the country. Landsat imagery has so far been confined to classification of the region around San Jose and La Selva. These results are being submitted for publication (Carlson and Sanchez 1998). The PI with his collaborator, Dr. Arturo Sanchez of the University of Costa Rica, Center for Sustainable Development (CIEDES), spent several days in January, 1997, touring this region, taking pictures and making GPS measurements for the purpose of validating the La Selva/San Jose image classification.

Chester County has provided a highly fruitful laboratory for an investigation of urbanization, leading us to develop an integrated methodology in which conventional image processing techniques (e.g., image classification, pattern recognition) are linked with diagnostic and predictive land use /land cover models to yield useful parameters for a variety of social issues. This approach has opened up a whole new vista in which satellite technology and imagery is to be applied to urban planning. Some of these results have been or will be reported in the literature (Arthur and Carlson 1997; Arthur et al. 1998), or they are to appear in conference proceedings and in an M.S. Thesis (Arthur 1997).

The third phase of the project involves new initiatives coming out of the first two phases. One involves creating an extension program to bring our technology to urban planners, developers, watershed managers and ecologists. The second pertains to prediction of urbanization and the application of diagnosed and predictive changes to societal issues. A third initiative is to broaden the Costa Rican study to include the region of Guanacaste.

Chester County, PA

Scaled Quantities

Landsat TM and AVHRR imagery has been geo-referenced for various years between 1986 and 1997. Image classification has been performed for all TM images tabulated in our previous report. Using the triangle method (Gillies et al. 1997), land surface parameters (ET/Rn; T* (scaled surface radiant temperature), Fr) for all AVHRR and TM scenes have been determined. Much of this material is contained in a thesis by Arthur (1997).

An underlying objective has been to streamline our procedures in order that they can be adopted by the non-specialist. To this end, we have been able to avoid the necessity of correcting the visible channel radiances for atmospheric attenuation, including haze, in order to determine Fr (Carlson and Ripley 1997), provided that NDVI is scaled by the method reported by Gillies et al., (1997). Similarly, rather than refer to the actual radiant surface temperature (Ts), with its high temporal variability, we adopt a scaled surface radiant temperature (T*), which is more intrinsic to the surface and a much more stable quantity than Ts (Gillies et al. 1997; Owen et al. 1997). As such T* constitutes the relevant surface temperature variable in all our discussions. Both T* and Fr vary from zero to one, as does ET/Rn.

Similarly, we scale the surface fluxes to obtain more stable quantities. Thus, we represent evapotranspiration (ET) as ET/Rn, which is closely related to the Bowen Ratio, and is therefore a fairly representative and stable surface parameter during the day.

In calculating these parameters we use both Landsat and AVHRR imagery. Despite its rather early overpass time (~09:30 AM local time), Landsat appears adequate for this purpose. When measured by Landsat, ET/Rn, being dependent on T*, has a surface resolution of 120 m, whereas; Fr and its derivative quantities pertain to a surface resolution of 28 m at nadir angle. (In contrast, AVHRR yields these parameters at 1.1 km resolution) We will, however, refer to averages for TM data over 1 km squares in order to equate results from both sensors and because these 1 km units are more easily interpreted.

Methodology

We start with a TM image, perform a conventional image classification and calculate radiant surface temperature (Ts) and normalized difference vegetation index (NDVI). These are used in conjunction with a soil-vegetation-atmosphere transfer (SVAT) model to yield T* and Fr from which ET/Rn is produced. From the classification we obtain two types of developed surfaces (urban commercial and residential) which are combined to one class-developed. This is used to obtain the impermeable surface area (ISA) which is defined only for developed surfaces as the fraction (1–Fr). Like Fr, ISA varies from zero to one. The justification here is that unvegetated surfaces in regions classified as developed consist mainly of surfaces such as concrete, macadam, or building material (e.g., roofs).

Runoff due to urbanization is estimated in two ways from the satellite imagery, from Delta (ET/Rn) and from the change in ISA. Until now, runoff estimates have never been made by satellite. Dow (1997) has shown that urbanizing watersheds exhibit a clearly increasing runoff and decreasing ET with increasing urbanization. This trend is due to two factors: (1) decreased surface area for evapotranspiration (increased ISA) and (2) increased runoff from impermeable surfaces during storm events. Therefore, we compute two estimates of runoff due to urbanization, from the change in ISA and from changes in ET/Rn with time; the latter is henceforth referred to as ‘Delta ET/Rn’ to mean the changes in this ratio from 1987 to 1996 or from 1986 to 1995, depending on whether the source of the calculations is TM or AVHRR imagery. For lack of better terminology we will refer to these two types of runoff estimates as ‘storm runoff’ and ‘urban runoff. These calculations are discussed in more detail below.

The quantities, Fr, T*, delta ET/Rn and the two runoff estimates, constitute the primary output variables produced by the diagnostic methodology. The methodology for predicting the evolution of these variables is accomplished by linking two models, the Clarke cellular automaton model (Clarke 1996) and an expert system model developed by Arthur (1997).

Runoff Estimates

A subset of Chester County centered on the town of Downington constitutes one focus of this study. Our intent was to become highly familiar with a relatively small but developing region within the county. Twenty points of interest were visited, photographed, GPS locations recorded and later analyzed. Most of these points of interest comprise a subset of 74 locations identified from the classification as having undergone an increase of development of at least 25% over a particular 1 km square area.

Consider a rapidly expanding urban area aside a State Park in Uwchlan Township. Here, all images encompass the same one-kilometer square. First, we present two estimates of ET/Rn. Each was computed differently. The decrease of ET/Rn of 0.77 to 0.64, about 20%, pertains to an average calculated from AVHRR for that one kilometer square, whereas the 5.3% reduction in ET/Rn refers to an area average for the 1 km square. ET/Rn calculated for the 1 km square experiencing at least a 25% increase in development from 1987 to 1996 and having an ISA of at least 20% in 1996 is shown in Figure 23. These changes are almost always negative and are closely related to ISA although fractional changes for the former are much smaller than for the latter. Dow’s (1997) results also suggest the same relationship between ET and the fraction of urbanization, specifically the percent of area attributed as urban. The solid line in Figure 23, although pertaining to somewhat different quantities, closely reflects our data and suggests that urbanization increases surface runoff. Figure 24 shows that the percent of surface cover classified as developed and ISA are closely related.

Figure 24 also shows that increasing urbanization results in a progressively dryer surface. Increasing ISA means less surface area free to evaporate. If so, the question arises as to why changes in ISA are so much larger in magnitude than Delta ET/Rn. Clearly, a one-to-one relationship between changes in ISA and changes in ET does not exist, although the two .are closely linked in the urban context. Two factors must be considered: (1) the decrease in the surface area available to evaporate or transpire and (2) a decrease in the surface area through which water can diffuse into the substrate. In both cases, impermeable surfaces restrict the processes involved in runoff. The reduction of areas available to evaporation or transpiration associated with an increase in ISA and the reduced area for rainwater can soak into the ground represent different processes.

Let us make the tentative hypothesis that the ISA change represents an upper limit for the change in storm runoff due to urbanization while changes in ET/Rn are more closely allied with changes in runoff resulting from changes in the ability of the surface to evaporate. For lack of better terminology we will refer to a decrease in ISA as an estimate of ‘storm runoff’ and to a decrease in ET/Rn as ‘urban runoff’. This hypothesis, which remains to be proven, suggests that the two runoff estimates may approximate, respectively, a transient maximum and a mean runoff estimates for a particular watershed or neighborhood. In order to convert ET/Rn into a representative value of ET, it is necessary to make a few assumptions. Consider a watershed with annual precipitation P. Assume further that the change in ET/Rn due to urbanization does not affect either Rn or P, whose yearly values are assumed to remain constant, but only the runoff and ET. Letting $X = ET/Rn$, $\delta X = \delta ET/Rn$ represents the change in this ratio over the interval, 1987–1996.

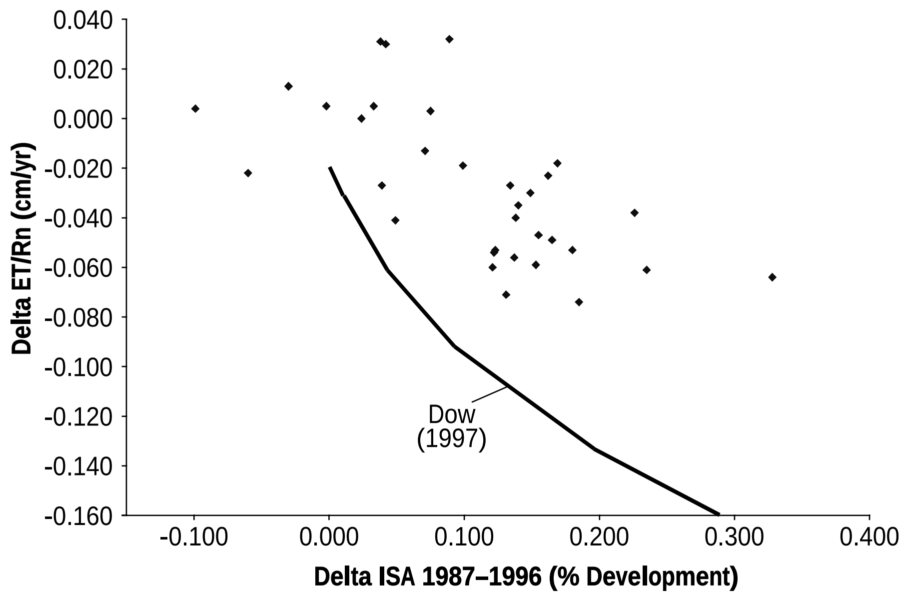

Figure 23. Change in evapotranspiration (Delta ET/Rn) versus change in impermeable surface area (ISA) for 1 km square areas in Chester County. These data pertain to surfaces which underwent an increase fractional area classified as developed of at least 25% from 1987 to 1996 with an ISA of at least 0.2 in 1996 (triangles). Solid line denotes the average change in ET (cm/year) versus fraction of urban/residential area as determined from watershed data from 1920 to 1990 for the eastern US (adapted from Dow 1997).

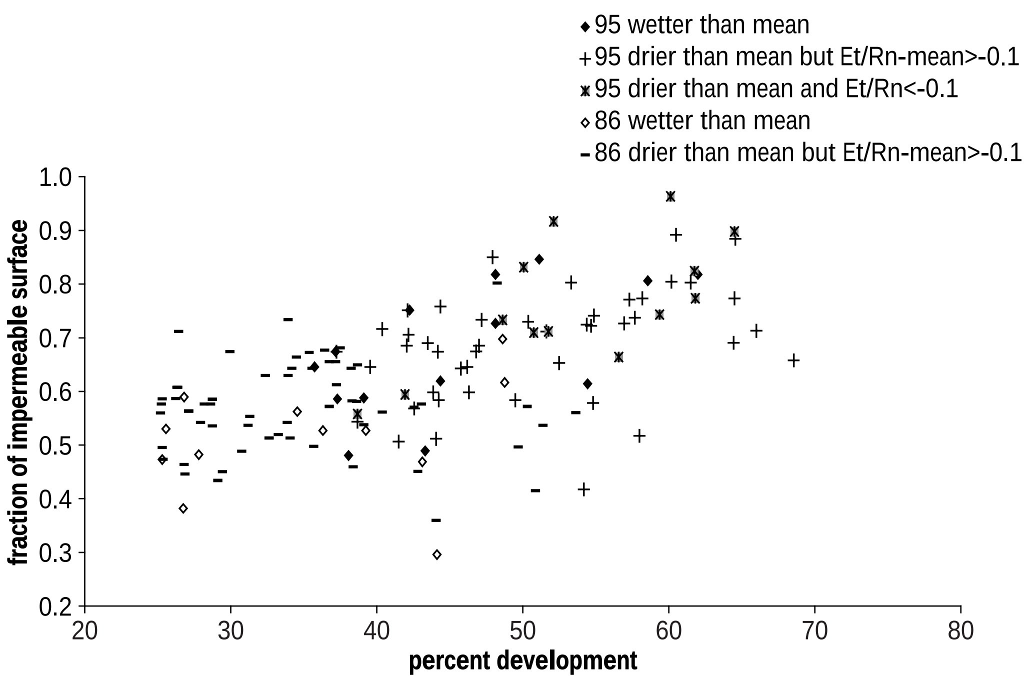

Figure 24. Percent development versus impermeable surface area as determined from AVHRR images for development exceeding 25%. Changes in the moisture characteristics are also indicated in the key, where the mean refers to an average over the eastern part of Chester County.

Employing a simple water balance and letting RO stand for runoff

$$P - ET = RO$$

Assume that the ratio ET/Rn characterizes the evaporation for this watershed and that the runoff RO is a fraction F of the precipitation and ET is therefore a fraction (1 – F) of the precipitation. Then, if $\delta ET = \delta RO$, we obtain the change in ET in terms of cm/yr as

$\delta ET = (dX / X)\, P\, (1 - F) / N$, where N is the number of years (9).

Typically F for the Susquehanna basis in about 0.2 (±0.07–0.1) (Z. Yu Private communication), P is about 100 cm and X is about 0.65 in our analyses of Chester County. Therefore

$$\delta ET \sim 1.3 \delta X$$

This formula translate ET/Rn into a change in runoff. Image analysis indicates a value of dET/Rn of 0.053, which corresponds to an estimated runoff of about 0.07 cm per year for the, one of the most heavily urbanized of the 20 points of interest. This value corresponds roughly to Dow's (1997) values in Figure 23, although the AVHRR estimates suggest a larger value for the urban runoff. As hypothesized, a change in ISA may represent a localized change in peak runoff from precipitation events, rather than to a fractional decrease in evaporation. Image analysis also indicates an increase of 18% in ISA from 1987 to 1996. If converted directly into reduced area of evaporating surface for a region experiencing 100 cm per year of rainfall, the reduction in evapotranspiration would be about 1.8 cm per year. This estimate is much larger than Dow's (1997) values, which range as high as 0.25 cm per year for the most heavily urbanizing watersheds and the 0.07 cm per year corresponding to an 0.053 decrease in ET/Rn.

Finally, it was also found that the relationship between ISA and Delta ET/Rn is much poorer for surfaces experiencing a very small change in ISA or where ISA remains less than 0.2.

ET/Rn and ISA on the Township and Watershed Scale

Inspection of the land use changes from 1987 to 1996 presents a striking picture of extensive urbanization, especially in the south and east of the county. In situ inspection of the county showed a considerable amount of new housing developments, including one that was as large in area as a small town. As pointed out in the previous report and in Arthur et al. (1998), most of this development in Chester County occurs at the expense of agricultural land. Uwchlan, though more rural than townships in the southeastern part of County, exhibits an impressive visual increase in the ISA (Figure 25), although the actual amount was only 4% in 9 years.

Similar runoff calculations were performed for a larger areas, such as Brandywine Watershed and Uwchlan Township. The increase in ISA for Uwchlan Township was about 0.44% per year; and the ISA over Brandywine Watershed, which increased from 4.6 to 7% , was about 0.27% per year. If converted directly to runoff changes, these estimates are realistic; approximately 0.44 and 0.27 cm per year for an annual rainfall of 100 cm per year, assuming that all of the water which falls on impermeable surfaces runs off. Runoff estimates based on changes in δET/Rn on the township or watershed scales were more uncertain. Isolating the urban effect, we considered only the pixels which changed from undeveloped to developed. For Uwchlan Township ET/Rn decreased by 0.046 from 1987 to 1996, the equivalent of about 0.06 cm decrease in ET. As this decrease pertained to only about 4% of the total township area, that which underwent a change

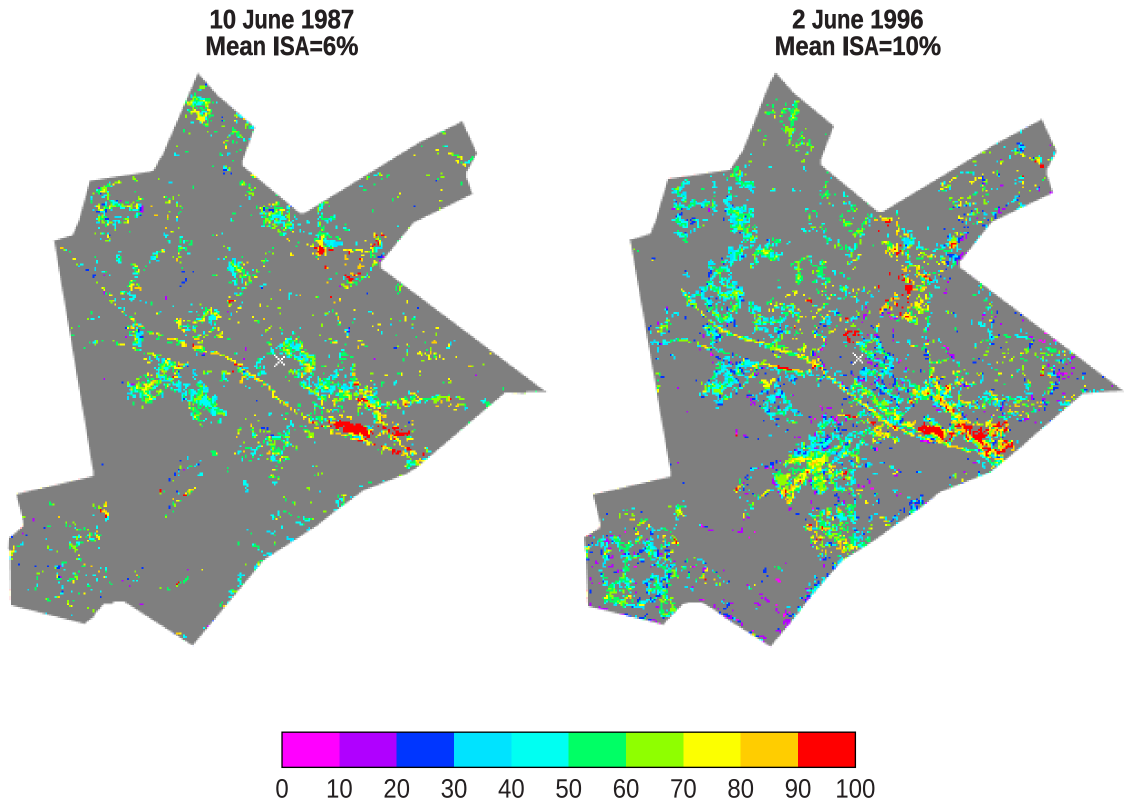

Figure 25. ISA for Uwchlan Township and vicinity, 1987 and 1996, as determined from TM imagery.

from undeveloped to developed, the change in ET averaged over the township area would have been less than 0.001 cm per year. This seems excessively small and suggests that ISA changes provide more realistic estimates of runoff changes due to urbanization on the township an watershed scale than does Delta ET/Rn. (It is not possible, however, to isolate the urban effect for these larger areas simply by summing over the entire area, as natural fluctuations tend to mask the small signal due to urbanization.) Viewed as a whole, township and watersheds exhibit a relatively small fraction undergoing urbanization, although the wide extent of the changes over the Township and its vicinity is visually striking. Clearly, further work is necessary to assess ISA and Delta ET/Rn for estimating runoff due to urbanization. No calculations were made of Delta ET/Rn for the Brandywine Watershed.

Urbanization as a Function of Parcel Size

Areas classified as developed, forested, agricultural, etc. can be clumped according to the size of the parcel. This has been done for developed parcels in Chester County, expressed in Figure 26 as a function of year in four size categories. Unlike the typical case of deforestation, urbanization in Pennsylvania proceeds not to ever increasing fragmentation but to ever increasing agglomeration of developed parcels in some size categories. Figure 26 shows a steady percentage increase in the biggest size category and a slight increase in the smallest one with time over nine years. Conversely, middle-sized parcels appear to be decreasing in number. We interpret this behavior as due to accretion and/or growth of middle sized parcels into large ones at the expense of smaller sizes. An increase in the smallest sizes may be due to a widespread proliferation of small single- and double-family housing units. Clumped statistics such as these also constitute a useful by product of the classification.

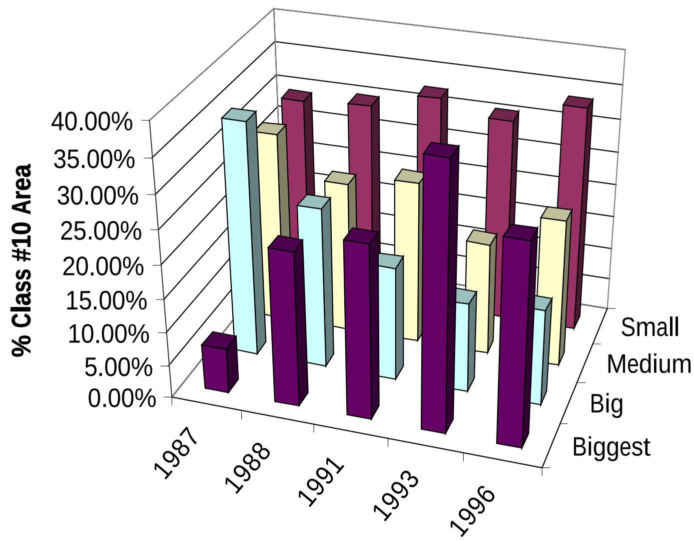

Figure 26. Histogram of parcel sizes for developed areas in Chester County by year. 'Small' parcels=0.01–0.1 km^2; 'medium'=0.1–1 km^2; 'big'=1–10km^2; 'biggest' ≥10km^2

Surface Microclimate Changes

Both scaled surface temperature (T*) and Fr exhibited a strong response to the rapid urbanization in this Marsh Creek area. In the context of the triangle, the pixel migrated from a region of high moisture availability, moderate vegetation cover and high ET/Rn to a warmer, dryer location (Figure 27); indeed urbanization attracts the pixels toward the lower right vertex of the triangle, toward dryer and warmer, though often along different paths. The paths of this migration depend on the type of surface (i.e., the initial locations within the triangle) and the extent of urbanization.

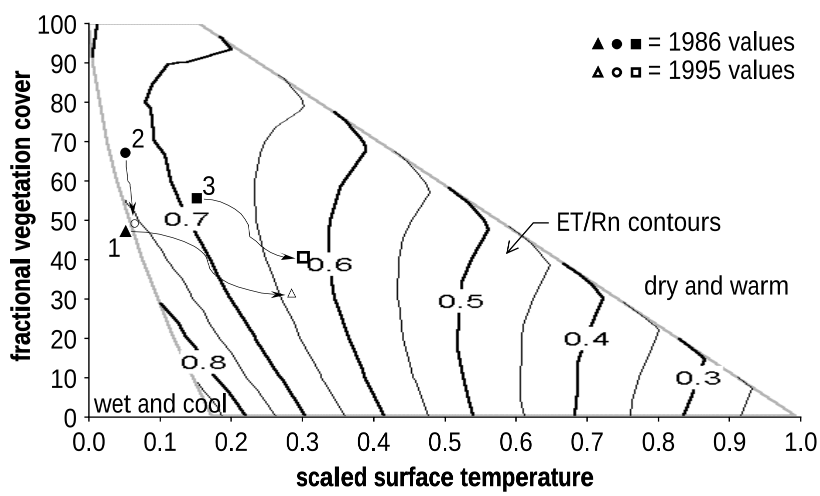

Figure 27. Triangle domain showing migration of AVHRR pixels over Marsh Creek area of Chester County (ref. Figure 3) for three housing developments (trajectories 1-3) between 1986 and 1995. Axes of triangle are fractional vegetation cover (Fr) and scaled surface radiant temperature (T*). Curved solid lines in the interior represent ET/Rn.

Development as a Function of Time

Most all areas that underwent a change from undeveloped to developed between 1987 and 1996 showed a decrease in ET; some locations, however, exhibited an *increase* in ET. A preliminary analyses of the images suggests a relationship between surface drying and landscaping, whereby development is not characterized by a steadily declining ET but by a decline and then increase in ET. These changes depend, in part, on construction and landscaping practices. Accordingly, five phases are identified in the evolution of a housing development:

(1) undeveloped, vegetated (agricultural), (2) excavation, bare soil exposed, (3) initial construction, bulldozed surfaces, (4) partial construction, a few streets and some rows of houses, (5) final construction, dense housing and streets with some new vegetation, (6) mature neighborhood.

Although we are investigating this sequence further, we suggest that ET/Rn may decrease sharply between phases (1) and (2) and perhaps decrease still further through phase (3) or phase (4). However, it may increase from phases (3) or (4) to phase (5) due to the addition of trees, lawns and shrubs. Consequently, changes occurring over a 9-year interval may be positive in ET/Rn if the initial image was made during phases 2 or 3 and the later image during phases 4 or 5. Thus, it appears that older residential areas may show a return to higher ET/Rn, although not as high as for the original undeveloped parcel. We think that this view of urban evolution a useful model for analysis of urban development and it will continue to be studied during the coming year.

Costa Rica

Costa Rica has been experiencing rapid deforestation, affording us the opportunity to apply the triangle method over rain forests. Parts of the country are relatively flat and nearly cloudless in the wintertime dry season. Most of Costa Rica, however, experiences some cloud cover even during the dry season. Clouds begin to form over the mountains during the morning and extend into the plains by mid afternoon. Consequently, the use of AVHRR, which has an afternoon overpass time, is very limited by cloud cover. Even in the absence of cloud application of the triangle method is limited. Much of the forest remains only on mountain slopes where use of surface radiant temperatures is severely compromised by the terrain. Landsat, whose images are made in the morning, is less severely subject to cloud cover, but the surface radiant temperature signal is also much weaker than during the afternoon. Thus, both AVHRR and Landsat are somewhat problematical in the use of their surface radiant temperature to describe land use changes except for a very small percentage of available images, and then only over a flat terrain.

Three areas were chosen to apply the triangle method because they are relatively cloudless and flat: San Jose, the principal city, the La Selva region north of the mountains which abut San Jose on the north, and Guanacaste to the west. We were able to find three applicable AVHRR images, for Dec 24,1990, Jan 21, 1995 and April 7, 1997. Two or three TM images are also considered usable. Working with a December, 1990, image, Professor Arturo Sanchez was able to classify the two central regions of San Jose and La Selva. These data were divided into four categories, crop, forest, urban and pasture, and clumped into 1 km squares for comparison with AVHRR. Figure 28 shows the distribution of these four land cover types based on the dominant category in each 1 km square. Most forested areas are found on mountain slopes or in areas covered by cloud on the AVHRR image.

Surfaces for which their radiant temperatures pertain to flat, cloudless areas are shown by the background (yellow) shading in Figure 29. Open squares with borders represent land surface elements in which the scaled surface radiant temperature (T^*) increased by 0.3. Closed squares

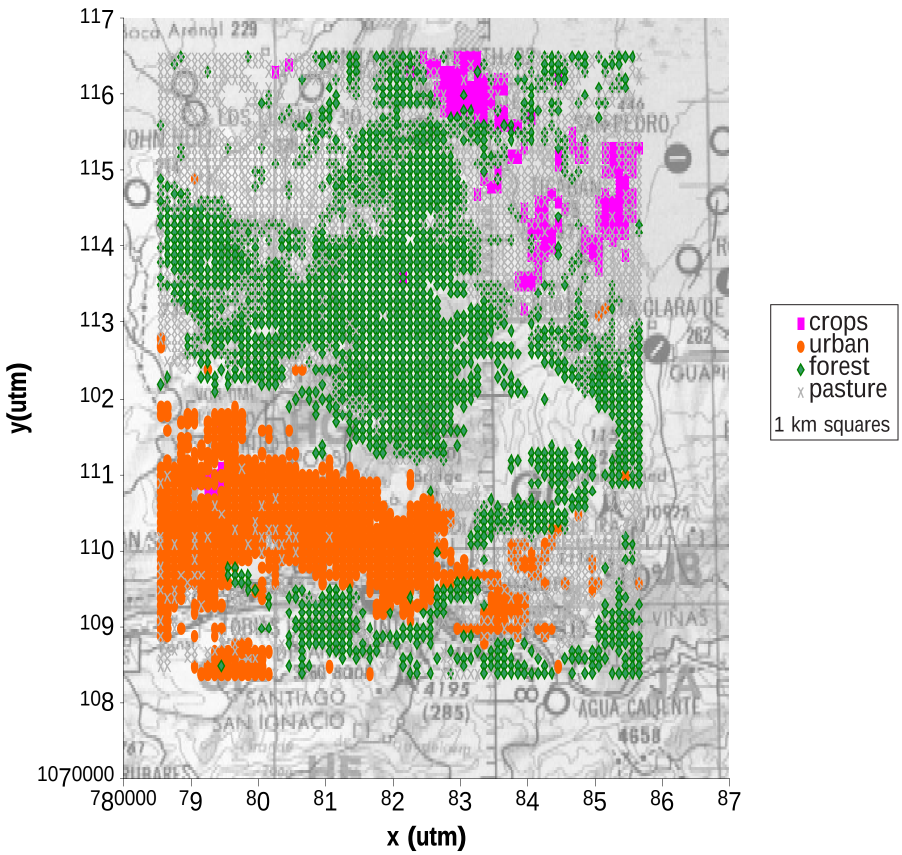

Figure 28. Land use classification of San Jose and La Selva areas of Costa Rica according to the dominant category in 1 km squares (crop, forest, urban, pasture). Blank area inside outer border represents bare soil or unclassified. Mixtures of equally dominant land types are represented by blending of symbols and colors.

with borders represent surfaces where Fr decreased by more than 0.3 while filled squares with no borders represent surfaces where both T* and Fr have changed by more than 0.3. These symbols mark the significant land surface changes during the period 1990 to 1997. Most of the change appears over the city of San Jose. Changes occurring over the La Selva region were largely the result of pasture or forest being replaced by crops, mostly bananas and coffee. For the most part these changes are reflected only by changes in Fr (Figures 29). One curious aspect of these analyses is that, although the altitude of the San Jose area (~1100 m) differs from that of the plains (~200 m), radiometric surface temperatures were similar in both locations. However, because of their altitude differences, San Jose and La Selva will be treated separately. San Jose experienced changes due to urbanization. As in the case of Marsh Creek (Figure 27), urbanization causes large changes in T* and Fr. For the most part, pixels migrated in the triangle toward the lower right hand vertex between 1990 and 1997 (Figure 30). Three separate clumps of pixels stand out in these vectors. Groups A, B, and C in Figure 31 represents the average path of the three groups, each one pertaining to a different location within San Jose (Figure 32). Group A (resembling two of the Marsh Creek trajectories in Figure 27) moved toward higher T* and lower ET and moisture availability (Mo) without much change in Fr; group B exhibits a similar path but with a somewhat higher vegetation fraction; group C shows a decrease in Fr, but less change in T* and ET and little change in Mo. By 1997, all three trajectories reach approximately the same

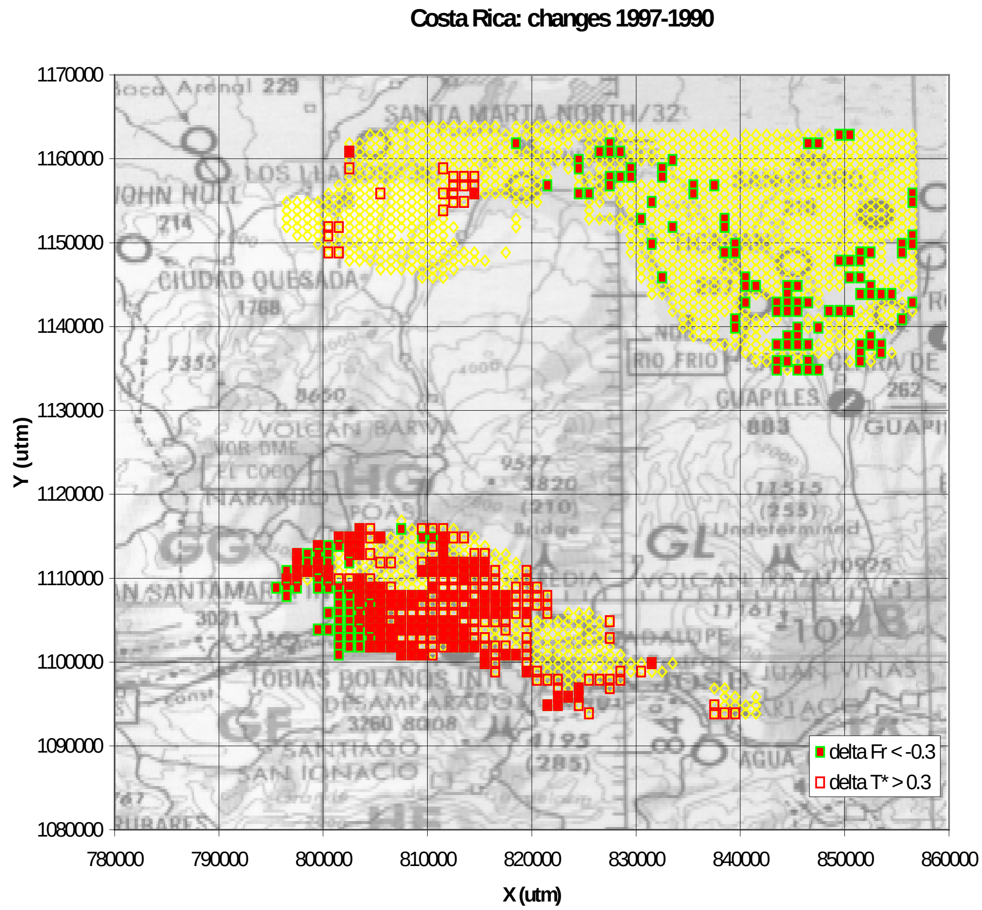

Figure 29. Areas showing a decrease in fractional vegetation cover (Fr; green squares with red dot in center) or increase in scaled surface radiant temperature (T*; open red squares) between 1990 and 1997 over San Jose and La Selva areas of Costa Rica. Yellow shading denotes flat, cloudless areas where analysis of change was performed. Areas undergoing significant changes in both T* and Fr denoted by closed red squares.

location in the triangle. A fourth area, group D, shown in Figures 32 and 33 exhibited mostly a decrease in Fr, although the path implies a higher ET/Rn (Figure 33).

Figure 34 shows the AVHRR scatter plot for the 1990 image, labeled according to land use types. For the most part, the dense clump of pixels located in the upper part of the triangle pertain to forest and (probably dense) pasture. Three narrow bands of pixels extend from the forest/ pasture clump toward the bottom of the triangle; these are loosely identifiable with groups A, B, and C in Figure 31. The figure suggests that pixels representing forest and pasture move toward the lower right as they evolve into urban or as forest is turned into pasture or pasture becomes more urbanized and possibly overgrazed. It seems a significant (though premature) result, that pixels undergoing a change from forest to crop do not move away from an area within the triangle characterized by high ET/Rn and Fr; indeed, although these pixels undergo a decrease in Fr, they also *may undergo a slight increase in evapotranspiration*. The significance of this last point will be made clear in the next section

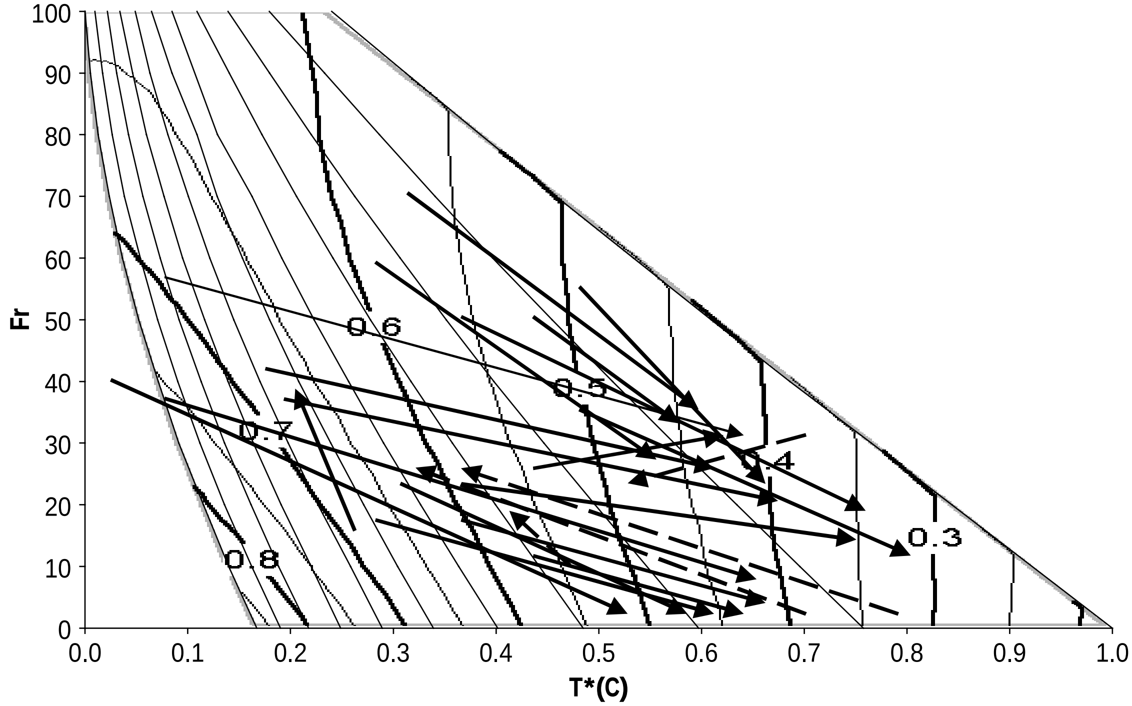

Figure 30. Same as Figure 27, but for selected pixels over San Jose, Costa Rica, 1990-1995.

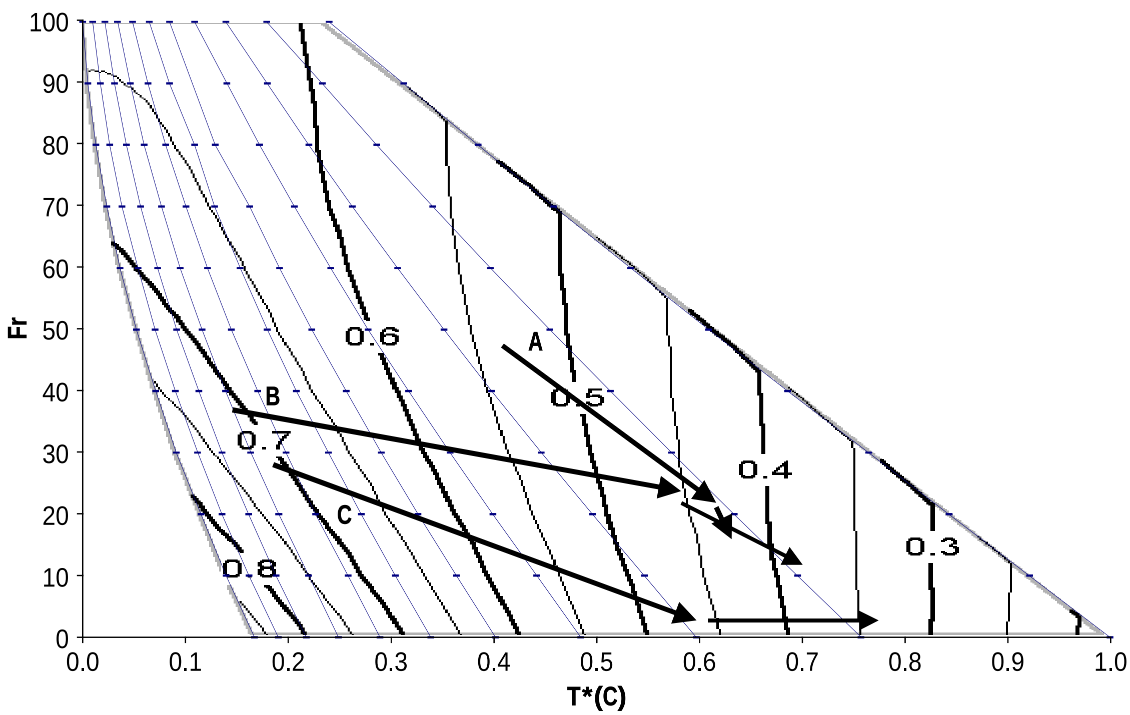

Figure 31. Same as Figure 30 but for average pixel displacement for trajectories stratified by location (For location of groups A, B and C, see Figure 32). Segments are broken into sections, representing displacement between 1990 and 1995 and between 1995 and 1997 (front ends).

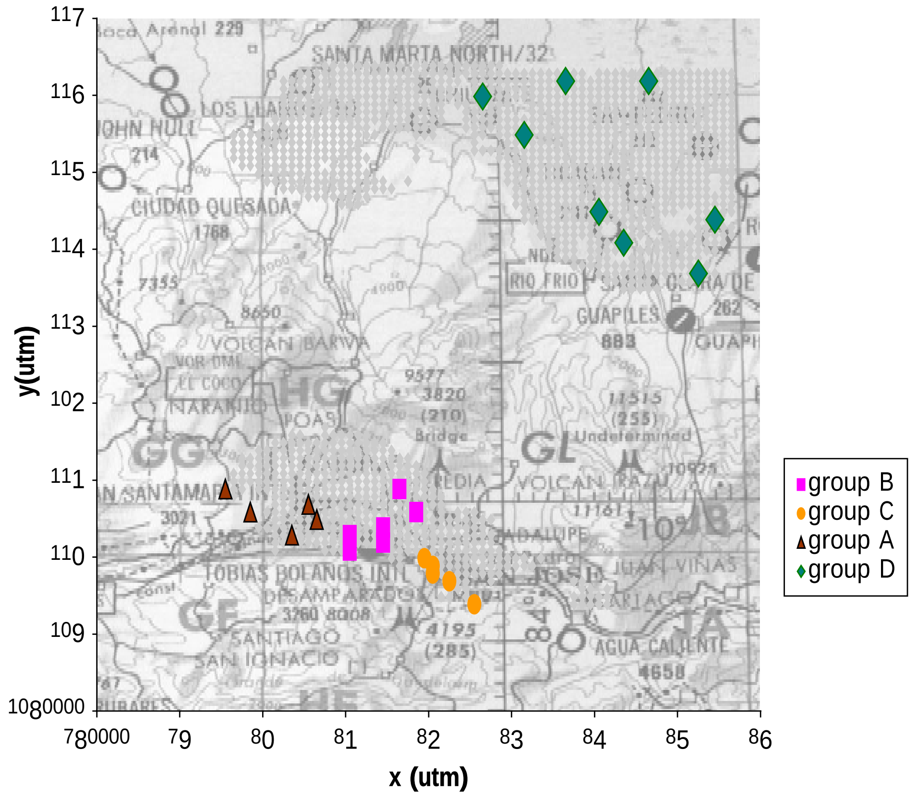

Figure 32. Locations of pixel groups A, B, C (ref. Figure 31) and D (ref. Figure 33), as denoted, respectively, by the triangles, squares, small diamonds and large diamonds. Yellow shading refers to the usable analysis area over the San Jose/La Selva region of Costa Rica referred to in Figure 29.

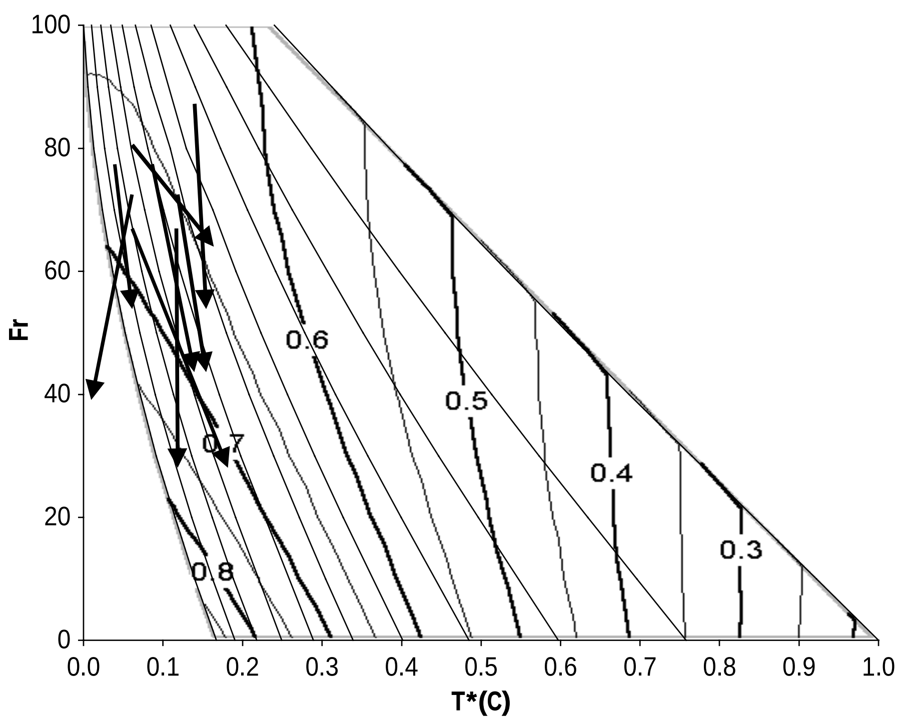

Figure 33. Same as Figure 30 but for area D on Figures 32 and 33.

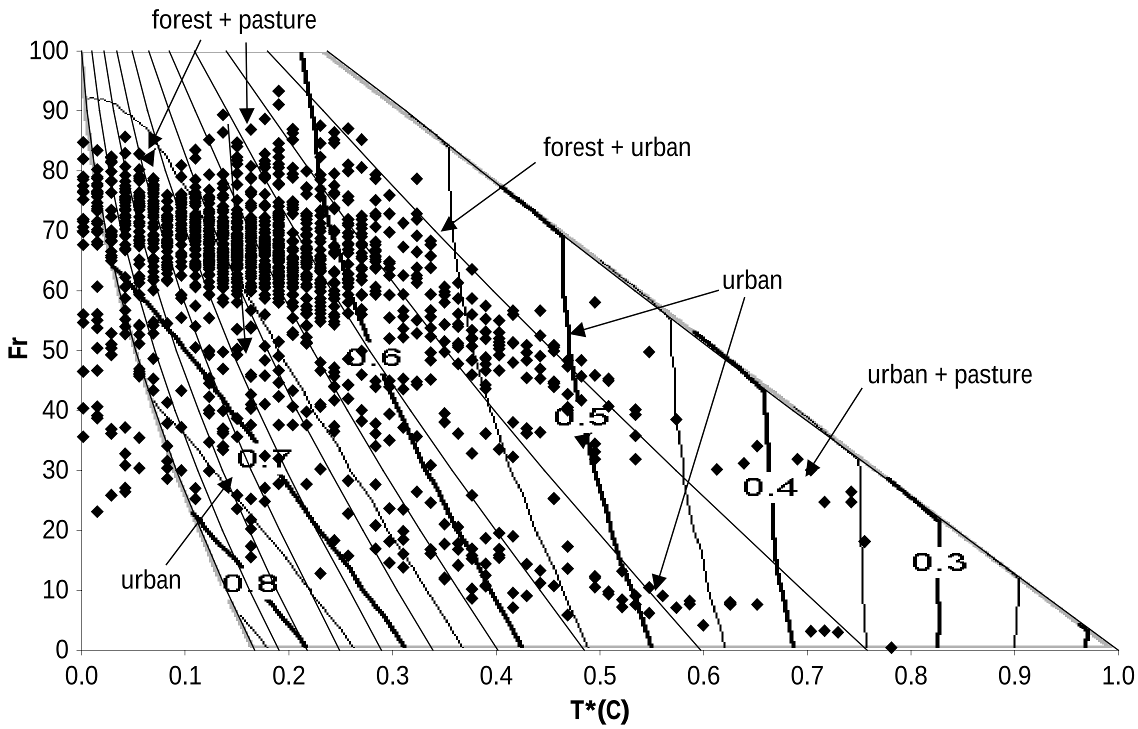

Figure 34. Scatterplot of pixels from AVHRR image for 24 December, 1990 over the San Jose/La Selva areas showing indication of land use types. Background contours are identical to those in Figure 30, 31, and 33.

Future Research on Applying Remote Sensing and SVAT Models to Urbanization

Future work falls into three categories: (1) service to the community; (2) analysis and prediction of urban development and (3) runoff relationships.

Service to the Community

If the Mission to Planet Earth is to achieve its original intent of using a new generation of satellites to address societal issues, the initiatives of individual scientists working with private and public agencies to make optimum use of the new generation of satellites will be required. Accordingly, we have begun a program whereby satellite imagery and its derived products will be used to assist urban planners, developers, watershed managers an ecologists in monitoring urban sprawl, and assess growth trends and their potential or current impact on environmentally sensitive areas. This will be done with public and private agencies using satellite data at the watershed, township and county scale. More specifically, we will instruct individuals in these agencies how to obtain information from satellite imagery appropriate for their own applications; in turn we will learn how best to use satellite data to solve particular problems in planning, development and ecology.

A general purpose and envisioned result of the project which is being proposed is to provide a Pennsylvania and university resource where planners, developers, watershed managers, and ecologists can work with project facilitators to make use of current and future satellite technology and imagery for solution of specific problems in their areas of interest. This project has already begun with seed money from the Earth System Science Center (ESSC), The Pennsylvania Space Grant Consortium, and NASA.

Training sessions will begin in the spring of 1998. Participants will come to Penn State as individual agency representatives for approximately a dozen or more half-day sessions. Most of the agencies interested in participating in the training sessions convened with the facilitators on October 6 at Penn State as part of the annual Pennsylvania Planners Conference, to which we presented two 90 minute sessions on the use of satellite technology and imagery in urban planning.

The first phase of the training project, is now being organized. Later in the program, training sessions may take the form of field trips and operations at the agency's home facility, with a continuing interaction between facilitators and participants. More agencies will be added after the first round of training sessions. To our knowledge, no such program now exists in Pennsylvania.

Analysis and Prediction of Urbanization

The interface of physical models, conventional classification methods and imagery allow us to calculate a number of physical parameters: surface evaporation, vegetation fraction, impermeable surface cover, runoff and a surface temperature index. Surface temperature index (related to comfort), vegetation amount, and evapotranspiration (related to runoff), while generated from satellite imagery, can be predicted with the aid of an 'expert system' model (developed by Ms. Arthur), given a particular urban development scenario posed in terms of changes in developed surface and vegetation cover. This will be expanded to include a calculation of ISA and runoff.

The expert system constitutes a vital interface between the output of an urban prediction model and the prediction of surface climate variables. Keith Clarke at the University of California, Santa Barbara, has helped us install his urban prediction model at Penn State. Called a cellular automaton model, it uses a seed layer based on the satellite classification of developed land, and several GIS overlays (elevation, roads, etc.) to predict the probability of urban development with an adjustable surface resolution, typically 250 m, for more than 50 years into the future (Clarke et al. 1996). Overlay information can be edited allowing various scenarios to be examined.

This approach exemplifies a totally different type of climate prediction than one is accustomed to hearing about, but one which can be used to explore future changes in urbanization and its effect on surface climate, ecology, demographics and hydrology. Such predictions can be used to assess societal impacts of an urbanization scenario, for example the inclusion of a highway through an environmentally sensitive region.

Future Research in Estimating Runoff

Among the newest and more unique applications of our methodology is in estimating runoff. We have discussed the puzzling contrast between increased runoff in watersheds over the eastern United States due to urbanization and the apparent decrease in runoff in Costa Rican watersheds associated with deforestation. We have seen also that the use of remote measurements over Costa Rica, especially radiant surface temperature, is compromised by cloud and mountainous terrain. One region of Costa Rica which does lend itself very well to remote sensing is Guanacaste. Guanacaste is almost always clear during the dry season. Moreover, Guanacaste presents one of the most interesting study sites in the tropics: with probably the only remaining patch of tropical dry forest in the tropics and great biodiversity. Guanacaste constitutes a principal source of tourism for the country, and, as such is undergoing considerable development in response to tourism and agriculture. Economic pressures between tourism—the primary source of income for Costa Rica (after bananas and coffee)—and agriculture remains a concern for Costa Rica

Accordingly, Landsat imagery over Guanacaste, supplemented by in-situ observations will be classified. Absence of cloud will permit us to extend our analyses back to 1985. Land use changes then can be charted by remote sensing using methodology developed in the Chester County study.

A further objective beyond the scope of this project will be to investigate hydrologic records in Costa Rica to determine if, indeed, runoff is decreasing with time and if this decrease is due to a decrease in rainfall or (more likely) an increase in ET. A suggestion that the latter is more likely can be found in the trajectory paths in Figure 33, which shows a possible increase in ET as pixels change from forest to crop or dense pasture. Additional support for this idea is provided by O'Brien (1995), who found that air temperatures *decreased* downwind from deforested patches in Chiapas, Mexico. We therefore wonder whether conventional wisdom has been in error in that *tropical deforestation may lead to a cooling and moistening of the surface, so long as a densely planted and viable crop canopy takes its place*.

Clearly, urbanization is not responsible for the peculiar behavior of the runoff-deforestation relationship in Costa Rica, except possibly in the vicinity of San Jose, where deforestation and urbanization may yield an increase in runoff, as in Chester County. Although most of the damage to primary forests has already been done, the country continues to undergo loss of primary forest to crops and pasture and it is experiencing continued urbanization. Determining subtle changes in ET with time over the area of a watershed using the triangle method, which involves the surface radiant temperatures (as we have done for Chester County) must yield rather uncertain results outside urban areas. A more conclusive assessment of the cause of the decreased runoff can be made through analysis of hydrographic records, coupled with simulations with a mesoscale model with a reliable land surface component.

Water Quality Modeling

(L.R. Kump and P. Richards—PSU)

In this year a change in emphasis of our water quality modeling efforts occurred, from the controls of the major element chemistry of rivers to the processes that control the nutrient element chemistry of individual and large, complex watersheds. Our new approach to watershed mass-balance studies, using GIS, remote sensing data (land use, land cover), soils and bedrock geology data, and field observations of river discharge and water chemistry, was published in the journal Hydrological Processes (Richards and Kump, 1997). Although Paul Richards has gone on to a postdoctoral appointment at the University of Michigan, we continue our collaboration on the WQ modeling component of SRBEX.

Our efforts during the second half of 1997 have been directed toward compiling a database (from STORET) on nutrient chemistry and discharge for small, intermediate, and large watersheds which we can use to develop an empirically based, unit chemical hydrograph approach to the analysis of the controls on river chemistry. We have identified a number of streams within the SRB that have high temporal resolution water chemistry data available (Table 2). From these we are constructing unit hydrographs and unit chemical hydrographs, classify these, and demonstrate that the chemical response of streams to rainfall events can be predicted empirically. We will then test this approach using data from streams for which water quality analyses were done infrequently (e.g., monthly). These, unfortunately, represent the bulk of watersheds in the SRB. We will reference each analysis to its position on the unit hydrograph and then combine the data from several years to generate a synthetic unit chemical hydrograph (SUCH) for the basin. Once we have developed our database of SUCH for the SRB, we will switch to predictive mode.

Stream	STORET ID	Period of Record	Number of Samples for WQ analysis	Agency
Little Conestoga Creek near Churchtown, PA	1576085	5/82–9/91	1000	USGS
Agricultural Field Runoff #1 near Churchtown, PA	1576083	3/83–5/89	714	USGS
Little Conestoga Creek, Site 3A near Morgantown, PA	157608335	3/84–9/91	500–600	USGS
Conestoga River at Conestoga, PA	1576754	10/84–6/94	500–600	USGS
Agricultural Field Runoff Site at Springville, PA	1576335	10/84–7/88	340	USGS
Potomac River at Great Falls, MD	230040	12/57–10/65	387	EPA
Poquessing Creek at Philadelphia, PA	DEL–15	10/62–7/83	630–700	Phil. Water Dept.
Neshaminy Creek at Philadephia, PA	DEL–17	10/62–7/83	600	Phil. Water Dept.
Hudson River at NYS Mile Point	130660	1/64–5/76	2618	NY Dept. Env. Conserv.

Table 2. High data density streams for water quality analysis.

Hydrological output from the Terrestrial Hydrology Model (described elsewhere) will be used to predict the chemical response (including nutrient elements and sulfate) to storm events, seasonal runoff patterns, and future climate scenarios.

Human Dimensions and Integrated Assessment Research on the Susquehanna River Basin

(B. Yarnal, D. Abler, E. Barron, R. Bord, J. Carmichael, R. Crane, W. Easterling, A. Fisher, G. Knight, S. Matthews, A. MacEachren, R. O'Connor, D. Peuquet, A. Rose, and J. Shortle—PSU)

If long-range projections of the Susquehanna River Basin's hydrology are to be accurate, the human dimensions of regional climate-hydrology interactions must be incorporated into the SRBEX research design. However, because it is necessary to focus present NASA EOS resources on understanding the physical dimensions of the research, the vital human dimensions must being supported by outside funds. Several human dimensions projects are underway that are the direct result of the initial SRBEX impetus, including significant projects funded by NSF, EPA, and NASA. Each project involves at least two NASA EOS investigators and is focused on the Susquehanna River Basin. Penn State researchers founded the Center for Integrated Regional Assessment (CIRA) in 1996 to link the physical and human dimensions of the global environmental change at the regional scale; that is, the scale of the Susquehanna River Basin.

Integrated regional assessment is an interdisciplinary, iterative process that involves scientific, policy, and societal stakeholders. Its goal is to promote a better understanding of how locales and regions contribute to and are affected by global change. To reach that goal, CIRA has developed a modular structure, with multiple, interactive components operating at one time. New projects are added as older ones are completed, allowing the flexibility needed to handle changing scientific requirements and personnel. Collaborative research, pooled resources, frequent research meetings and seminars, shared courses, and a focus on the Susquehanna River Basin ensure continual interaction of team members. Five overlapping projects reflect that approach: (1) methodologies in integrated regional assessment, with major thrusts in empirical downscaling, economic modeling, and complex representations of global change in time and space using a geographic information system (GIS) and geographic visualization system (GVIS); (2) decision-maker and public perceptions of vulnerability to climate variation and change; (3) vulnerabilities of water resources to climate variation and change, together with adaptation strategies and policy responses; (4) human health impacts of climatic variation and change; and (5) greenhouse-gas emissions, including socioeconomic drivers and mitigation strategies. Recent integrated assessment publications and conference publications directly relevant to SRBEX include Yarnal (1997; 1998) and Yarnal et al. (1997a; 1997b; 1998a; 1998b; 1998c).

GIS and Data Management System

(R.A. White, D.A. Miller, P.J. Kolb, and J.J. Voortman—PSU)

During 1997 we continued to maintain a GIS and data management system in support of our EOS-related research activities. Much of this aspect of our project involves providing easy access data and documentation for a wide range of spatial and tabular information used in support of our research objectives. We have made our growing database accessible to the public via the World Wide Web. Here, anyone may download model outputs from the MM5 atmospheric model meteorological observations, and land surface characteristics data

Approximately 6800 files were successfully downloaded from the database by non-ESSC users via WWW or anonymous FTP during 1997. Additionally, we provided information and assistance on using database products to more than a dozen users at U.S. and foreign universities, U.S. government agencies, and consulting companies.

We continued in the past to provide specialized regional data sets in support of research projects closely associated with the goals and objectives our research program and that of Mission to Planet Earth. In particular we contributed to the new Interdisciplinary Science Investigation led by Tom Jackson. This IDS Team conducted the Southern Great Plains 1997 Hydrology Experiment (SGP97) over central Oklahoma in June/July 1997. In support of this mission we developed a downloadable set of land surface characteristics covering the SGP97 region. Included in this data is a subset of EDC/University of Nebraska Global Land Cover Characterization database, subsets of the 1 km CONUS-SOIL dataset for the same region, digital elevation data, USGS stream network and river basin data, and point coverages of observation stations located within the SGP study area. Additionally, we developed a series of cartographic products that are also available as downloadable files in the PDF format. SGP investigators and collaborators found these data sets to be invaluable in various mission planning activities. We are continuing to work with other SGP97 investigators to develop a comprehensive data base of soil physical and hydraulic properties for this region.

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