Assimilation of Remotely Sensed Snow Observations into the NSIPP Land Surface Model

A proposal to:

The Global Modeling and Analysis Program (GMAP)
and
The EOS Interdisciplinary Science Program (EOS/IDS)

Submitted in response to NRA-99-OES-04

Jeffrey Walker
Universities Space Research Association

Paul Houser and James Foster
Laboratory for Hydrospheric Processes NASA/GSFC

Marc Stieglitz
Columbia University

Proposal Summary

Statement of Problem

Snow plays an important role in governing both the global energy and water budgets, as a result of its high albedo, thermal properties, and being a medium-term water store. However, the problem of accurately forecasting snow in regional and global atmospheric and hydrologic models is difficult, as a result of snow related features that display variability at scales below those resolved by the models and errors in model forcing data. Hence, any Land Surface Model (LSM) snow initialization based on model spin-up will be affected by these errors. By assimilating snow observation products into the LSM the effects of these errors may be offset, but special care must be taken to avoid erroneous systematic influences on the water budget as a result of the assimilation.

Objectives and Justifications

We propose to explore the assimilation of relevant remotely sensed snow observation products into the catchment-based LSM that is being used by the NASA Seasonal-to-Interannual Prediction Project (NSIPP). This work will be focussed on a retrospective study of North America, using the uncoupled NSIPP LSM, with a perspective of eventual coupled global implementation.

The proposed research is distinct, yet complimentary to the land surface data assimilation activities currently being undertaken by NSIPP. Under a current project, remotely sensed soil moisture observations are being assimilated into the NSIPP LSM, being the same model in which the snow observations will be assimilated under this proposal.

Prior Accomplishments

We have assembled a team of researchers targeted ideally for the snow assimilation problem. Both Jeffrey Walker and Paul Houser have been actively working on various aspects of the land surface assimilation problem, so the proposed study will be enhanced by their past research experiences, as well as ongoing research activities. James Foster has a long record of experience with remotely sensed snow products and will provide the much needed expertise in this area, in addition to the snow observation products required for assimilation. The catchment-based LSM was developed by Randal Koster, and uses the snow model component developed by Marc Stieglitz. While Koster will serve in an advisory capacity on development of the assimilation scheme within the LSM, Marc will contribute to development of the assimilation scheme within the snow component, as well as further development of the snow model.

Proposed Work and Methodology

We propose to develop a snow assimilation scheme that optimally merges snow product observations with the NSIPP LSM forecast. Specifically, the assimilation scheme will take account of snow melt as a result of bias in the LSM temperature. Such biases may exist as either a land surface bias or an air temperature forcing bias.

The assimilation scheme will be based on a one-dimensional Kalman filter for each catchment of the LSM, and will include an observation error checking algorithm. Snow observation products will include snow cover, snow water equivalent, snow depth and snow melt signature. A key component of this assimilation scheme will be the development of an appropriate model error covariance forecasting algorithm.

Budget: 1st Year: \$198.7K 2nd Year: \$198.6K 3rd Year: \$200.0K **Total:** \$597.3K

Table of Contents

Assimilation of Remotely Sensed Snow Observations into the NSIPP Land Surface Model

Submitted in response to NRA-99-OES-04
to the GMAP and EOS/IDS Programs

Jeffrey Walker[1] (PI), Paul Houser[2], James Foster[2] and Marc Stieglitz[3]
[1]*Universities Space Research Association/NASA-GSFC, Greenbelt, MD 20771*
[2]*NASA Goddard Space Flight Center, Greenbelt, MD 20771*
[3]*Columbia University, Palisades, NY 10964*

Technical Plan

1 Introduction and Statement of Problem

Snow cover, snow water equivalent and snow depth play an important role in governing the earth's global energy and water budgets, as a result of its high albedo, low thermal conductivity, and considerable spatial and temporal variability. While the energy balance is the primary driver of the earth's atmospheric circulation system and associated climate, the water budget is significantly modified through snow melt processes. With snow being a medium-term water store, it plays an important role in spring-time runoff generation and flood production. In the northern hemisphere, the mean monthly land area covered by snow ranges from 7% to 40% during the annual cycle, making snow cover the most rapidly varying large scale surface feature on earth [Hall, 1988]. Moreover, snow covered landscapes adjacent to bare soil regions have been found to produce mesoscale wind circulations [Johnson *et al.*, 1984]. Hence, any long term forecast in a fully-coupled climate system is dependent on an accurate initialization of the snow covered area, snow water equivalent, and snow depth.

The problem of realistically forecasting snow in regional and global atmospheric and hydrologic models is complex, as a result of snow related features that display considerable spatial variability at scales below those resolved by the models, and errors in model forcing data. Hence, any land surface model initialization based on spin-up will be affected by these errors. However, remote sensing observations can be used to provide an estimate of snow cover, snow water equivalent and snow depth, which can be used to update model predictions. As both the model predictions and remotely sensed observations contain differing amounts of error, the assimilation scheme needs to account for the relative amounts of uncertainty in each, in order to yield a statistically optimal prediction.

Previous work on assimilating snow observations into a land surface model has generally made a direct replacement of the modeled snow distribution with the observations [eg. Liston *et al.*, 1999]. The problem with this type of assimilation approach is that it assumes the observations are without error, and that the model forecast contains no information about the current snow cover status. This can result in unsatisfactory results, as sometimes the model prediction is more accurate than the observation (ie. densely vegetated areas). Moreover, little consideration is given to the impact that the snow assimilation scheme has on the water budget.

As an example, the National Center for Environmental Prediction (NCEP) currently updates the snow water in their operational North-American ETA model, using daily snow observations available from the National Environmental Satellite Data and Information Service (NESDIS) interactive multi-sensor snow and ice mapping system. We monitored the performance of the NCEP snow updating procedure, finding significant water imbalances in snow covered regions with warm surface temperature biases. In these areas, snow would quickly melt and be replaced by the updating scheme (Figure 1), leading to inflated surface water stores and fluxes. Our goal is to develop a methodology to constrain the snow cover with observations while also maintaining a realistic water balance, which will require additional observational constraints on the model temperature and possibly on its snow melt processes.

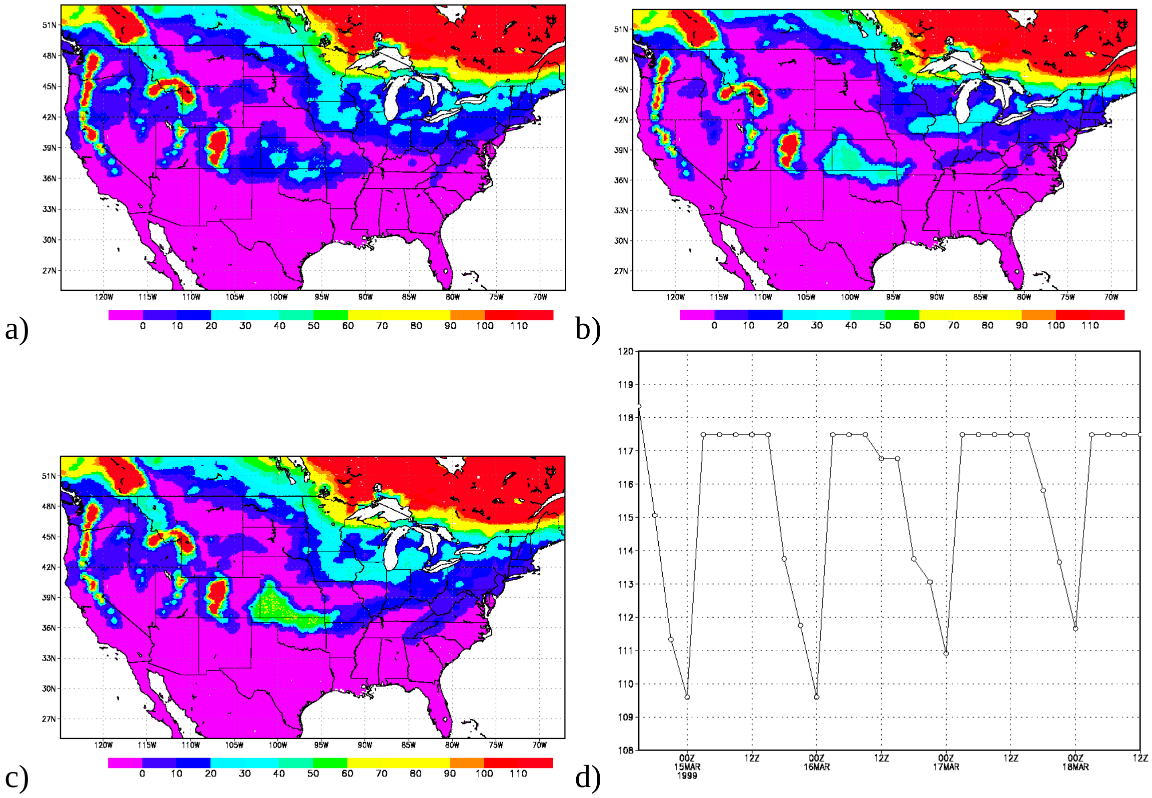


Figure 1: Temporal variation of snow depth in the NCEP ETA model. a) Snow depth at time 3Z on 3/15/99; b) snow depth at time 0Z on 3/16/99; c) snow depth at 3Z on 3/16/99; and d) snow depth at -107.5 longitude and 40.0 latitude from 15Z on 3/14/99 to 12Z on 3/18/99. Note, for example, the disappearance and reappearance of snow over Wyoming/South Dakota and fluctuation of snow line through Montana/North Dakota.

We propose to explore the assimilation of relevant remotely sensed snow observation products into the catchment-based Land Surface Model (LSM) that is being used by the NASA Seasonal-to-Interannual Prediction Project (NSIPP). This work will be focussed on a retrospective study of North America for the past 20 years using the uncoupled NSIPP LSM, with the perspective of the assimilation scheme being expanded globally and applied to the NSIPP fully-coupled General Circulation Model (GCM).

2 Goals and Objectives

The primary goal of the proposed research is to develop a framework for the assimilation of snow observation products into the NSIPP LSM. The specific objectives of this work are described below.

1. Development of a Kalman filtering based snow assimilation strategy, which overcomes the current limitations with assimilation of snow water equivalent, snow depth, and snow cover.
2. Investigate the utility of novel snow observation products in such an assimilation strategy. Such observations include snow melt signature and fractional snow cover.
3. Provide a basis for global implementation of an assimilation scheme for snow observation products, both for near-real-time forecasting and for the accurate initialization of seasonal-to-interannual predictions in the NSIPP fully-coupled GCM.

3 Relevance to ESE, NSIPP, DAO, GISS and the GMAP and EOS/IDS Programs

The proposed research is consistent with the Global Modeling and Analysis Program (GMAP) goal of developing and using models and model assimilated data sets to assess global climate system variability and trends on seasonal through interannual time scales. More generally, the proposed work contributes to the NASA Earth Science Enterprise (ESE) priority research themes, which include: (i) Global Water and Energy Cycle, and (ii) Climate Variability and Change; through its relevance to NSIPP.

The proposed research is also consistent with the EOS Interdisciplinary Science Program (EOS/IDS) goal of furthering the understanding of interdisciplinary earth system processes on regional to global scales, through the use of remote sensing data in determining an optimal model state for initialization of seasonal-to-interannual predictions. More generally, the proposed work contributes to the NASA interest in land-climate feedback through its relevance to NSIPP. Moreover, the proposal brings together expertise from a number of disciplines: namely land surface modeling (including a specialist in snow modeling), remotely sensed snow observations and data assimilation.

This work is directly relevant to the ongoing collaboration between NASA's Goddard Institute for Space Studies (GISS) and NASA's Goddard Space Flight Center (GSFC), through improvements in the current snow forecasting efforts from model development and data assimilation. Both institutions currently employ the snow model of Lynch-Stieglitz *et al.* (1994), and as such, any subsequent improvements will be incorporated within each of the NASA LSMs.

This proposed research is also consistent with land surface data assimilation activities being undertaken by NASA's Data Assimilation Office (DAO), with whom Paul Houser is affiliated. Since the DAO is most interested in obtaining high quality, instantaneous atmospheric profiles of moisture and temperature for use by EOS instrument teams, its land surface data assimilation research is focussed on surface soil skin temperature and atmospheric fluxes on short time scales.

Specifically, this research will contribute in a complementary manner to the NSIPP goals of: (i) demonstrating the value of remotely sensed observations in coupled model predictions of climate variability at seasonal-to-interannual time scales; and (ii) the development of assimilation strategies based upon remotely sensed observations in order to improve these predictions.

Furthermore, the proposed research is distinct, yet complimentary to the soil moisture land surface data assimilation activities currently being undertaken by NSIPP. Under the current project, remotely sensed soil moisture observations are being assimilated into the NSIPP LSM, being the same model in which snow observations will be assimilated under this proposal.

4 Background

4.1 Remote Sensing of Snow

Remote sensing using instruments operating in the gamma, visible and microwave portions of the electromagnetic spectrum are well suited for large-scale snow studies [Rango *et al.*, 1979; Carroll, 1993]. Microwave emission from a snow layer over a ground medium consists of contributions from the snow itself and from the underlying ground. Both contributions are governed by the transmission and reflection properties of the air-snow and snow-ground boundaries and by the absorption/emission and scattering properties of the snow layers [Chang *et al.*, 1976]. Snow crystals are effective scatterers of microwave energy for frequencies greater than 20 GHz. The snow crystals scatter part of the cold sky radiation, which reduces the upwelling radiation measured with a radiometer. The deeper the snow, the more snow crystals are available to scatter the upwelling microwave energy, and thus it is possible to estimate the snow water equivalent and depth of snow.

When the snow pack ripens, liquid water begins to appear between and around individual snow grains. Because the liquid water has a much higher dielectric constant than that of dry snow, wet snow behaves as an emissive media rather than a scattering media, and a noticeable increase or spike in the brightness temperature results. This information can be used to detect the onset of snowmelt [Foster *et al.*, 1984], and may prove valuable in providing information on the energy budget of the snow pack.

The algorithm developed by Chang *et al*. [1987] uses the difference between the 37 GHz and 18 GHz channels (in the case of the SMMR instrument) to derive a snow water equivalent/brightness temperature relationship for a uniform snow field. This algorithm is expressed as follows:

$$SWE = 4.77 * (TB_{18} - TB_{37}) \quad \text{mm} \qquad (1),$$

where SWE is snow water equivalent in mm, 4.77 is a constant related to the snow crystal size and TB is the brightness temperature. If the 18 GHz brightness temperature is less than the 37 GHz, then SWE is defined to be zero.

A revised version of this algorithm allows for more reliable estimates of snow water equivalent by including information on the fractional forest cover of a given microwave pixel and changes in snow crystals size from one region to another [Foster *et al*., 1997]. In addition, Armstrong *et al*. [1993], Josberger *et al*. [1995] and Tait [1998] have included information about the evolution of the snow structure, especially the growth of depth hoar crystals, in their algorithms.

To derive snow depth from the snow water equivalent, the snow water equivalent is simply multiplied by the snow density. It has been determined that in general, a snow density value of 300 kg m^{-3} is representative of mature mid winter snow packs in Eurasia and North America. However, this value is not valid for all areas and all times during the snow season.

Walker and Goodison [1993] set limits on brightness temperature differences in an algorithm they developed to assess whether the snow pack is wet or not (ie. snow melt signature). For example, if the vertically-polarized (TB_v) 37 GHz data is > or = to 241K and if $TB_{v18} - TB_{v37}$ is > or = to 9K, then the presence of wet snow is presumed.

4.2 Modeling of the Land Surface

While sophisticated multi-layer snow models have been developed and successfully applied at the local scale [Davis *et al.*, 1995; Hardy *et al.*, 1998; Jordan, 1995], the treatment of snow processes, especially those used within GCMs, have been relatively simple. Some models consider the winter snow pack only as a store of soil moisture [Abramopoulos *et al.*, 1988; Bonan, 1996; Koster and Suarez, 1996], while others blur the distinction between the snow and the ground surface altogether by envisioning a composite soil and snow layer [Dickinson *et al.*, 1993; Pitman *et al.*, 1991]. Still others do distinguish between separate snow and ground layers, yet represent the entire pack with a single snow layer regardless of the actual pack depth [Slater *et al.*, 1998; Verseghy, 1991]. However, most of these simple schemes have considerable flaws. Lynch-Stieglitz [1994] demonstrated that an insufficient representation of snow processes can lead to a corruption of surface energy fluxes and a degradation of the snow insulation between the cold atmosphere and the warm ground; ultimately impacting the seasonal development of ground freeze-thaw processes, and compromising the normal hydrologic processes of runoff, ground water movement, infiltration, etc., for a good part of the year. Further, Betts *et al*. [1998] have recently shown that an insufficient representation of snow processes at high latitudes leads directly to a poor evolution of the atmospheric boundary layer in weather forecasting models.

Recently, sophisticated snow physics have been included in LSMs and demonstrate a clear improvement in the overall simulation of the hydrologic cycle, including ground freeze-thaw processes [Koster *et al.*, 1999; Loth and Graf, 1998a; Loth and Graf, 1998b; Loth *et al.*, 1993; Lynch-Stieglitz, 1994; Yang *et al.*, 1997]. Typically, these multi-layer snow schemes explicitly model the heat and mass (water) transport within the pack. Radiation conditions determine the surface energy fluxes, and the heat flow within the pack is accomplished via linear diffusion along the thermal gradient. Meltwater generated within a given layer can drain to a lower layer, where it will refreeze, remain in the layer in the liquid state, or pass through.

Under this proposal we will employ the global catchment-based LSM of Koster *et al*. [1999] coupled to the snow model of Lynch Stieglitz *et al*. [1994]. This three-layer snow model accounts for snow melting and refreezing, dynamic changes in snow density, snow insulating properties, and other physics relevant to the growth and ablation of the snowpack. As the boundaries of the snowpack move up and down under the influence of snowfall, mechanical and wet compaction, condensation, etc., three variables are needed to completely describe the system; layer thickness (Z_i), water equivalent (W_i), and heat content (H_i). The coupling to the catchment framework, however, necessitated some modifications to the original scheme. In particular, we now ensure a smooth transition between snow-free and snow-covered conditions in order to capture the gradual growth of a snowpack's spatial extent and to avoid abrupt (discontinuous) changes in the surface energy balance calculations. The approach used is straightforward. We assume a minimum local snow water equivalent, *SWE*, of 13 mm, a value that allows the resolution of the diurnal surface temperature signal yet still produces a stable solution with a 20-minute timestep. If a given volume of snow falls on a snow-free catchment, that volume is spread uniformly over a fraction of the catchment so that the local water equivalent at any snow-covered point is 13 mm. Thus, if the snow falling on a snow-free catchment during a timestep has a total water equivalent volume, V_s, and if the area of the catchment is A, then the snow-covered areal fraction, A_s/A, is taken to be $V/(A*SWE)$. The snow-covered areal fraction increases as more snow falls until A_s/A reaches 1, at which time the local snow water equivalents across the catchment start increasing uniformly. When the fractional coverage is less than one, the snow model is represented with a single snow layer, whereas three model layers are used when the snow coverage is complete [Lynch-Stieglitz, 1994]. The transition between the single layer and three layer representations involves a simple conservative redistribution of layer heat and water contents. Surface energy calculations are performed separately over the snow free and snow covered areas.

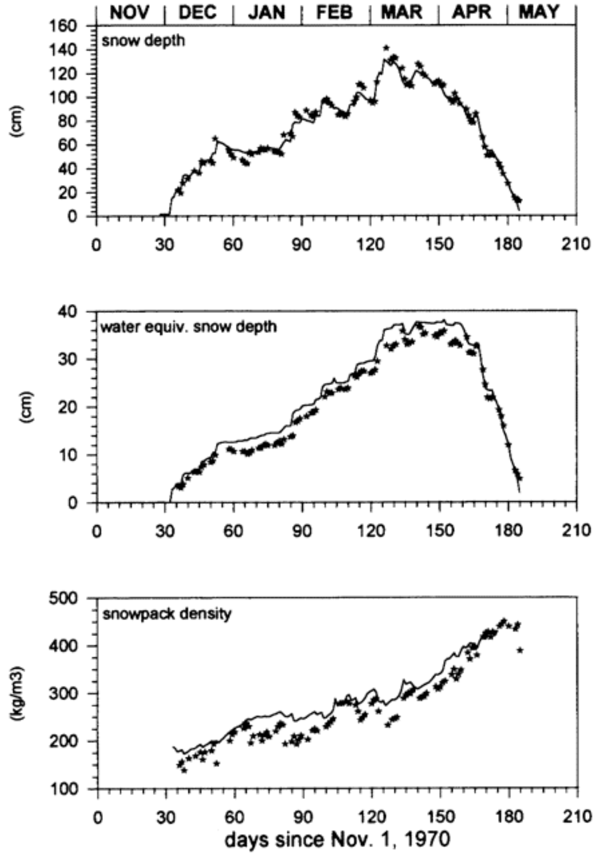


Figure 2: Model-predicted snow depth, water equivalent snow depth, and snow pack density for the 1970/71 snow season (solid line) and observed snow characteristics at the NOAA-ARS snow research station (stars).

Results at the Sleepers River watershed in Vermont (8.4 km^2) demonstrate that not only are the radiation temperatures of the ground and snow surface adequately modeled, but that all the features of snowpack ripening that characterize pack growth/ablation are also well simulated (Figure 2) [Lynch-Stieglitz, 1994]. At the Basin scale we can evaluate the ability of the model to simulate spatial coverage of snow, as well as snow amounts, over large areas. To this end, ISLSCP data was used to drive the model over North America for the period 1987/88. Special Sensor Microwave Imager (SSM/I) and the Northern Hemisphere EASE-Grid Weekly Snow Cover data set are currently being used to evaluate simulated spatial snow coverage and snow water equivalent amount, respectively.

4.3 Snow Data Assimilation

Charney *et al.* [1969] first suggested combining current and past data in an explicit dynamical model, using the model's prognostic equations to provide time continuity and dynamic coupling amongst the system states. This concept has evolved into a family of techniques known as *four-dimensional data assimilation*. “Assimilation is the process of finding the model representation which is most consistent with the observations” [Lorenc, 1995]. In essence, data assimilation merges a range of diverse observations with a model prediction to provide that model with the best estimate of the current state of the natural environment, so that it can then make more accurate predictions. Thus, the numerical model must have the capacity to predict dynamic changes occurring in the system, and accept the on line insertion (assimilation) of new observation data distributed heterogeneously in time and space. Theoretically, the use of data assimilation should lead to an estimate of the system states which is better than that which can be achieved from either the numerical model or observations alone. The application of data assimilation in hydrology has been limited. While several studies have investigated the assimilation of near-surface soil moisture observations into LSMs, very few studies have investigated the assimilation of snow observations.

5 Detailed Work Plan

The assimilation of remotely sensed snow observations into a LSM has several requirements. These requirements are:

1. A high quality model of the land surface processes for forecasting of the LSM system states (ie. soil moisture, soil temperature, snow cover, etc.).
2. Observations of the land surface forcing (meteorological data) for driving the forecast of land surface system states when the LSM is running off-line to the atmospheric and ocean models.
3. An appropriate spin-up strategy for initializing the LSM system states, particularly those that are not being updated by the remotely sensed observations.
4. Remotely sensed snow observation products for updating the LSM forecast of snow cover, snow depth and snow water equivalent, and constraining the snow melt processes.
5. An appropriate data assimilation scheme to update the LSM forecast of snow with the snow observation products.
6. Evaluation of the data assimilation scheme and its ability to provide correct predictions of the snow dynamics, as well as its influence on the water and energy budgets.

We will firstly outline our proposed approach for assimilating snow observations into the LSM, and then detail the specifics of the approach in turn.

5.1 Proposed Approach

It is proposed that the snow assimilation scheme for updating of snow forecasts in the NSIPP LSM be developed using a 20 year retrospective data set for North America, using a version of the LSM that is uncoupled from the atmospheric and ocean models. Using an uncoupled LSM for an individual continent allows for development of a global snow assimilation scheme without the computational burden of a fully coupled global simulation. Moreover, this approach is consistent with the current soil moisture assimilation work being undertaken by NSIPP.

In this snow assimilation strategy, the catchment-based LSM of Koster *et al.* [1999] is used to forecast the snow pack during the inter-observation period, and for areas that are either not observed or have erroneous observations. Moreover, the LSM is important for establishing the relationship between snow, soil moisture, soil temperature, the energy budget, and the water budget. In order to run the model (off-line from a GCM), high quality meteorological data are required for forcing of the model system state forecasts. This is particularly important for the forecasting of model states other than snow (and soil moisture), which are not being assimilated and yet have a feedback to the forecasting of snow (particularly soil temperature). In addition to high quality forcing data, the model forecast is dependent on the initial state values given to the LSM. As the LSM states (other than snow, near-surface soil moisture and surface temperature) cannot be observed directly from remote sensing observations, the

LSM must be spun-up to realistic initial state values prior to commencing the forecasting. Hence, errors in the land surface initialization, forcing data and LSM physics all contribute to errors in the forecast land surface states.

To correct for these errors in forecast system states, remotely sensed observations of the land surface states may be assimilated into the LSM. In this proposal, the assimilation of snow observation products will be added to the assimilation of soil moisture, which is already funded under a current project. Since current snow assimilation procedures suffer from continual melting of the snow as a result of the LSM running too hot (or accumulation in the case of the LSM running too cold), this assimilation scheme will correct for biases in the land surface temperature of snow covered areas, through the correlation of snow melt and land surface temperature.

5.2 Land Surface Model Characteristics and Development

As stated earlier, to avoid abrupt discontinuities in the surface energy balance calculations, we account for sub grid-scale variability in snow cover when the pack is thin. However, even when snow cover is substantial, snow heterogeneity can be significant [Liston and Sturm, 1998]. Unfortunately we currently ignore the role topography plays in the development of snow cover heterogeneity and the impact that this heterogeneity has on the surface energy fluxes. Gradients in elevation, differences in aspect, and the interactions between wind, topography and vegetation will all result in snow cover heterogeneity. As an ongoing part of this effort we will improve the models representation of sub-grid scale snow heterogeneity. To account for elevation effects in regions of high relief, a temperature lapse rate will be used along with binned elevation bands to distribute snow cover and snow melt throughout the landscape [Bowling and Lettenmaier, 1998]. To account for the effects that wind, vegetation, and topography have on the distribution of snow cover, we will adapt the work of Liston and Sturm [1998] to our modeling framework. While their spatially explicit model is not directly compatible with the statistical treatment of topography presented here, the empirical equations governing wind blown snow can be used to treat snow distribution in much the same way we currently treat soil moisture heterogeneity; through a statistical representation in which valleys are regions of snow accumulation and uplands are regions of snow ablation. Finally, this new model development will be incorporated within the overall data assimilation effort.

5.3 Land Surface Model Forcing Data

Successful data assimilation requires a reasonably high quality, generally unbiased, land surface model prediction. The use of high quality global atmospheric forcing of the land surface is essential to produce reasonable land surface predictions. The off-line LSM requires wind speed, air temperature, humidity, precipitation, and radiation on a sub-hourly basis. Many of these land surface forcing variables can be reliably provided by operational Numerical Weather Prediction (NWP) models at NCEP, ECMWF, or NASA-DAO, run in either a real-time or reanalysis mode. However, precipitation and radiation are generally poorly predicted by NWP models because we have not mastered the complex prediction of cloud physics and dynamics, which can lead to gross errors in land surface simulations. Therefore, the NSIPP land-surface initialization team are replacing these fields by some recently emerging observational products, when available. Unfortunately most high-quality long-term global land surface observations have been processed on monthly time scales for use in climate variability studies, and therefore lack the high temporal resolution required by land surface modeling efforts. These low temporal resolution observations can still be used to improve NSIPP land surface predictions by reducing the longer-term land surface forcing biases through a ratio correction. Essentially, NSIPP uses the NWP model forcing as high-resolution temporal weights on the longer-term observation averages when high-resolution observed forcing are unavailable. It is recognized that the timing of forcing is also of particular importance in land surface prediction, and therefore emerging temporal and spatial downscaling techniques are being explored to mitigate these effects.

Generally land-surface precipitation and radiation forcing is most critical to land surface prediction, with surface winds, humidity, and air temperature being of second-order importance. Therefore, using precipitation observations based on gauges, GOES Precipitation Index (GPI) estimates [Arkin and Meisner, 1987], shortwave passive microwave (as available with the SSM/I instrument, TRMM, and AMSR) estimates, and ground-based Doppler radar estimates are a priority. The Global Precipitation Climatology Project (GPCP) [McCollum *et al*., 1999] has developed a long-term, globally continuous combination of microwave, infrared, and gauge measurements that is an attractive product for use in land surface modeling applications. Global downward shortwave radiation fluxes are available [Pinker and Laszlo, 1992] using surface solar irradiance models. This is a theoretical-spectral model and has shown success in producing the global surface solar radiation flux using ISCCP C1 data as input [Whitlock *et al*., 1993], and has been extended to use ISCCP D1 data. Gupta [1989] developed a parameterization for longwave surface radiation using satellite measurements. Recently, he improved and modified the algorithm [Gupta et al., 1992] for direct use of ISCCP D1 data. The use of air temperature, winds, and humidity surface observations are also being explored to improve land-surface predictions.

5.4 Land Surface Model Spin-up

Initialization values for the system states of the LSM will be obtained by undertaking a land surface spin-up. This will involve running the catchment-based LSM repeatedly for a given year of forcing data, until the system states for the start of the year converge to consistent set of values. The spin-up will be undertaken for the first year of forcing data (ie. 1978). This will allow for forecasting of the system states from 1978 through to present.

5.5 Snow Observation Products

Since November 1978, the Scanning Multichannel Microwave Radiometer (SMMR) instrument on the Nimbus-7 satellite, and the Special Sensor Microwave Imager (SSM/I) on the Defense Meteorological Satellite Program (DMSP) series of satellites have been acquiring passive microwave data that can be used to estimate snow extent and snow water equivalent. The SMMR instrument failed in 1987, the year the first SSM/I sensor was placed in orbit. On SMMR, the channels most useful for snow observations are the 18 and 37 GHz channels. For the SSM/I, the frequencies are slightly different (19 and 37 GHz). Additionally, an 85 GHz channel is available on the SSM/I. This frequency has been demonstrated to be beneficial in detecting shallow snow packs (< 5 cm thick). Passive microwave data for most places on the globe are available for alternate days. The data are placed into ½ degree latitude by ½ degree longitude grid cells, uniformly subdividing a polar stereographic map according to the geographic coordinates of the center of the field of view of the radiometers. Overlapping data in a cell from separate orbits are averaged to give a single brightness temperature, assumed to be located at the center of the cell. Because when the snow pack is wet, snow water equivalent information is difficult to extract using passive microwave radiometry, only dry snow conditions will be examined. This necessitates using only the nighttime satellite overpasses so that there will be a higher probability that the snow pack is not actively melting.

Remotely sensed snow cover extent and snow water equivalent observations for all of North America will be produced from the twenty plus years of microwave brightness temperature data. In addition to the passive microwave snow products, high resolution (1 km or less) visible and near-infrared satellite data from Landsat, the NOAA series of satellites and the DMSP optical sensors will be employed to look at snow cover extent in more detail where warranted. Moreover, airborne gamma data are available over much of the northern U.S. and southern Canada for the period from the late 1970s through the present time. This data set can be used to “spot check” the passive microwave snow water equivalent products.

Meteorological stations, at airport locations and from the U.S. network of volunteer observers, provide a measure for snow depth on the ground once each day. Snow courses and SNOTEL sites collect more detailed snow data (snow depth, snow water equivalent, snow temperature), but these data, in the U.S., are only collected in remote areas of the mountainous western states. However, snow courses in Canada are widely distributed throughout all of the provinces and territories. These data are available for the past twenty-year period and can be used to corroborate the remotely sensed snow cover and snow water equivalent estimates.

5.6 Snow Observation Error Checking

An error checking procedure will be established to correct or eliminate erroneous snow observation data [Bengtsson, 1985]. This is necessary because incorrect data can have a detrimental effect on the model update, and can significantly reduce the quality of the updated system states. Observations can contain different types of error, including errors due to faulty instruments, improper processing or unsatisfactory communication of the data. This error checking procedure will include verifying areas with snow water equivalent observations greater than zero against snow cover observations. Experience in previous land surface data assimilation efforts [Houser *et al.*, 1998] suggests that we will require two levels of data checking. The first will involve checking for gross errors before the data enters the data assimilation process. The second check is more subtle, and involves comparison against modeled predictions and nearby observations, with rejection of values deviating more than a prescribed tolerance.

5.7 Snow Assimilation Strategy

Previous studies have found that an assimilation scheme having the characteristics of the Kalman filter is most effective for updating of forecast land surface states with observations [Walker, 1999]. The reason for this is that statistical assimilation schemes can update more than just the observed state value, through its correlation with other states, and state values in other locations. This characteristic is most important for updating of the land surface temperature through the snow observations, so as to prevent the continual snow melt problem observed in previous snow assimilation schemes (Figure 1). We plan to develop a largely one-dimensional Kalman filtering based snow assimilation strategy that builds upon previous work. The justification for using a one-dimensional Kalman filter is that the system states of adjacent catchments (of order 50 km on a side) generally have a low correlation. Moreover, by applying a one-dimensional Kalman filter the computational burden is reduced considerably. The significance of this is that only the system states of observed catchments can be updated by the assimilation scheme.

5.7.1 The (Extended) Kalman Filter

The Kalman filter assimilation scheme is a linearized statistical approach that provides a statistically optimal update of the system states, based on the relative magnitudes of the covariances of both the model system state estimate and the observations. The principal advantage of this approach is that the Kalman filter provides a framework within which the entire system is modified, with covariances representing the reliability of the observations and model prediction.

The Kalman filter algorithm [Kalman, 1960] tracks the conditional mean of a statistically optimal estimate of a state vector **X**, through a series of forecasting and update steps. To apply the Kalman filter, the equations for evolving the system states must be written in the linear state space formulation of (2). When these equations are non-linear, the Kalman filter is called the extended Kalman filter, and is an approximation of the non-linear system that is based on first-order linearization. The forecasting equations are [Bras and Rodriguez-Iturbe, 1985]

$$\hat{\mathbf{X}}^{n+1/n} = \mathbf{A}^{n} \cdot \hat{\mathbf{X}}^{n/n} + \mathbf{U}^{n} + \left(\mathbf{w}^{n}\right) \qquad (2)$$

$$\acute{\mathbf{O}}_{\mathrm{x}}^{n+1/n} = \mathbf{A}^{n} \cdot \acute{\mathbf{O}}_{\mathrm{x}}^{n/n} \cdot \mathbf{A}^{n^{\mathrm{T}}} + \mathbf{Q}^{n} \qquad (3),$$

where **A** is the state propagation matrix relating the system states at times $n+1$ and n, **U** is a vector of forcing, **w** is the model error, $\acute{\mathbf{O}}_{\mathrm{x}}$ is the covariance matrix of the system states and **Q** is the covariance matrix of the system noise (model error), defined as E[$\mathbf{w}\cdot\mathbf{w}^{\mathrm{T}}$]. The notation $n+1/n$ refers to the system state estimate at time $n+1$ from a forecasting step, and n/n refers to the system state estimate from either a forecasting or updating step at time n.

The covariance evolution equation consists of two parts: (i) propagation by model dynamics, and (ii) forcing by model error. The first, which is computationally the most demanding step in the Kalman filter algorithm, expresses how the error covariance matrix is affected by the dynamical processes that are present in the forecast model. The second part of the covariance evolution equation represents, loosely speaking, the cumulative statistical effect of all processes that are external (ie. not accounted for) to the forecast model [Dee, 1991; Dee, 1995].

For the update step, the observation vector **Z** must be linearly related to the system state vector **X** through the matrix **H**.

$$\mathbf{Z} = \mathbf{H} \cdot \hat{\mathbf{X}} + (\mathbf{v}) \qquad (4),$$

where **v** accounts for observation and linearization errors.

Updating of the best estimate of the system state vector $\hat{\mathbf{X}}$ by the observation vector **Z** is performed by means of Bayesian statistics. The system state vector and associated covariances are updated by the expressions [Bras and Rodriguez-Iturbe, 1985]

$$\hat{\mathbf{X}}^{n+1/n+1} = \hat{\mathbf{X}}^{n+1/n} + \mathbf{K}^{n+1}\left(\mathbf{Z}^{n+1} - \mathbf{H}^{n+1} \cdot \hat{\mathbf{X}}^{n+1/n}\right) \qquad (5)$$

$$\acute{\mathbf{O}}_{\mathrm{x}}^{n+1/n+1} = \left(\mathbf{I} - \mathbf{K}^{n+1} \cdot \mathbf{H}^{n+1}\right) \cdot \acute{\mathbf{O}}_{\mathrm{x}}^{n+1/n} \cdot \left(\mathbf{I} - \mathbf{K}^{n+1} \cdot \mathbf{H}^{n+1}\right)^{\mathrm{T}} + \mathbf{K}^{n+1} \cdot \mathbf{R}^{n+1} \cdot \mathbf{K}^{n+1^{\mathrm{T}}} \qquad (6),$$

where **I** is the identity matrix. The Kalman gain matrix $\mathbf{K}^{n+1}$ weights the observations against the model forecast. Its' weighting is determined by the relative magnitudes of model uncertainty embodied in $\acute{\mathbf{O}}_{\mathrm{x}}^{n+1/n}$ with respect to the observation covariances $\mathbf{R}^{n+1}$, defined as E[$\mathbf{v}\cdot\mathbf{v}^{\mathrm{T}}$]. The Kalman gain is given by

$$\mathbf{K}^{n+1} = \acute{\mathbf{O}}_{\mathrm{x}}^{n+1/n} \cdot \mathbf{H}^{n+1^{\mathrm{T}}} \cdot \left(\mathbf{R}^{n+1} + \mathbf{H}^{n+1} \cdot \acute{\mathbf{O}}_{\mathrm{x}}^{n+1/n} \cdot \mathbf{H}^{n+1^{\mathrm{T}}}\right)^{-1} \qquad (7).$$

The key assumptions in the Kalman filter are that the continuous time error process **w** is a Gaussian white noise stochastic process with mean vector equal to the zero vector and covariance parameter matrix equal to **Q**, and that the discrete-time error sequence **v** is a Gaussian independent sequence with mean equal to zero and variance equal to **R**. The initial state vector $\hat{\mathbf{X}}^{0/0}$ is also assumed Gaussian with mean vector $\hat{\mathbf{X}}^{0/0}$ and covariance matrix $\acute{\mathbf{O}}_{\mathrm{x}}^{0/0}$.

Given the initial state vector $\hat{\mathbf{X}}^{0/0}$ with covariance matrix $\acute{\mathbf{O}}_{\mathrm{x}}^{0/0}$, the system states and covariances are forecast (denoted by the time superscript $n+1/n$) using (2) and (3) respectively. When a set of observations become available, an update of the system states and covariances is made (denoted by the time superscript $n+1/n+1$) using (5) and (6) respectively.

Prior to implementation of the Kalman filter assimilation algorithm for a particular model, the initial system state covariance matrix $\textbf{Ó}_{\mathrm{x}}^{0/0}$, the model error covariance matrix **Q**, and the observation error covariance matrix **R** must be identified. Very few methodologies have been proposed and tested for estimation of the covariance matrices [Georgakakos and Smith, 1990]. Hence, these covariances are generally chosen ad-hoc [Ljung, 1979].

5.7.2 Model Error Covariance Forecasting

The key to implementation of a successful snow assimilation scheme with the Kalman filter is adequate specification of the model system state error covariance matrix. The important factor is that the model system state error covariance matrix correctly identifies the cross correlation between snow water equivalent, snow depth and the land surface temperature. In this way, the land surface temperature can be updated from a snow water equivalent/snow depth observation, through its correlation with snow water equivalent and snow depth.

The Kalman filter model error forecasting equation in (3) is dependent upon: (i) an initial system state error covariance matrix; (ii) a model error forcing term; and (iii) the system state forecasting equation being described by the linear state space formulation given in (2).

The system state error covariance matrix is often initialized using degree-of-belief estimates of the errors in initial states to specify the diagonal elements (variances) of the initial covariance matrix, with the off-diagonal elements (covariances) set to zero [Georgakakos and Smith, 1990]. Rather than use such an ad-hoc approach, it is proposed that the system state error covariance matrix be initialized by a statistical analysis of the spin-up system state values for time of initialization.

The model error forcing term **Q** results from inaccurate specification of the model structure as a result of: (i) linearization of the model physics (including sub-grid variability); (ii) estimation errors in the values of model parameters; and (iii) measurement errors in the model input (eg. snow fall). This is the most difficult component of the Kalman filter to identify correctly [Georgakakos and Smith, 1990]. Hence, this term is generally chosen ad-hoc. A collaborative proposal by Praveen Kumar (*Parameterizing sub-grid variability of snow in data assimilation systems for seasonal-to-interannual prediction*) submitted to NRA-99-OES-04-GMAP will, if funded, investigate this model error term.

Forecasting of the snow prognostic variables in the snow component of the land surface model does not comply with the requirements of a linear state space formulation as given by (2). Hence, forecasting of the system state error covariance matrix cannot be achieved as per the standard Kalman filtering covariance forecasting equations given by (2) and (3). However, a number of alternative approaches for estimating the forecast system state error covariance matrix have been presented in the literature and are reviewed by Todling and Cohn [1994]. These simplified covariance estimation schemes have been divided into six main categories. Of these categories, the *dynamics simplification* approach is the most appropriate. This approach utilizes approximate but non-trivial system state dynamics to evolve the forecast system state error covariances. This will require the development of a linear set of snow pack forecasting equations, which are used solely for the purpose of forecasting the system state error covariance matrix through (3).

5.7.3 Observation Error Covariance Estimation

The variance of the observations **R** can be identified reliably in most cases, since it depends on the characteristics of the measuring device [Georgakakos and Smith, 1990]. In the case of this proposal, the uncertainty of the passive microwave snow depth and snow water equivalent estimates will be assessed by evaluating each microwave pixel (at a ½ degree latitude by ½ degree longitude resolution) for all of North America. For snow water equivalent, this will involve a two-part error analysis process that accounts for the influence of vegetation and changes in crystal structure. In the case of snow depth, this will include the effect of uncertainty in snow density.

The primary source of uncertainty in observing snow water equivalent is the masking effect of vegetation. The brightness of the snow, measured in radiance, is related to the percentage and density of vegetation that covers the given pixel. In dense boreal forest areas, the uncertainty is expected to be very high, upwards of 50%, since the emissivity of the overlying forest canopy confounds the scattering signal form the snow pack. In tundra and prairie areas, the confidence is much greater, perhaps as high as 90% in many pixels, because vegetation is sparse and thus there is little extraneous emission. Hence, the uncertainty in snow water equivalent observations as a result of vegetative cover will be estimated from a relationship with a brightness/vegetation index.

The secondary source of uncertainty in observing snow water equivalent results from changes in crystal size (which is very important in scattering microwave energy) due to diurnal fluctuations in temperature. For instance, in continental interiors, the diurnal temperature range can be quite large compared to coastal areas, and snow crystals (depth hoar crystals at the bottom of the snow pack) are typically larger in places like North Dakota than in New England. Since temperature and vapor gradients are known to control the growth rate of snow crystals, the diurnal temperature range, as measured by the difference in the maximum and minimum daily temperature, can be used as an index for temperature gradient and potential crystal size. Hence, the uncertainty due to changes in crystal size may be assessed from the diurnal temperature range.

The final estimate of uncertainty in snow water equivalent will involve the addition of these two main error sources. As snow depth is derived from snow water equivalent by making an assumption about the snow density, which changes during the snow season, the uncertainty in snow depth may be easily estimated from the uncertainty in snow water equivalent and the uncertainty in snow density.

5.7.4 Snow Cover Observations

Snow water equivalent and snow depth are prognostic variables within the LSM. Hence, observations of these land surface states may be directly assimilated into the LSM. However, snow cover is diagnostic, and requires special consideration for assimilation. In regions where the LSM indicates that there is snow cover and the snow cover observations indicate there is no snow, it is obvious that the assimilation strategy should nudge the LSM towards no snow cover. In regions where the LSM indicates that there is no snow cover and the snow cover observations indicate that there is snow cover, then the assimilation strategy is less obvious, as the snow cover observation gives no information on the amount of snow. Hence, these observations will be most useful when used in conjunction with snow water equivalent and snow depth observations for input data verification. However, the snow cover observations may be used to apply a snow cover of minimal depth in circumstances where snow water equivalent and snow depth observations are missing. While, this will have minimal impact on the water budget calculations, it will have a much greater impact on the energy calculation through the higher albedo of snow covered areas in comparison to bare areas.

5.7.5 Air Temperature Bias

It is possible that the snow melt problem observed in previous snow assimilation schemes is a result of a warm bias in the air temperature, in addition to and resulting in warmer than normal land surface temperatures. Such a bias, if it exists, may be added as a parameter for each catchment of the LSM. By augmenting the temperature bias parameter with the forecast system states [Goodwin and Sin, 1984], the Kalman filter may be used to identify the temperature bias, in addition to updating the forecast system states. In uncoupled simulations, this bias correction would be in addition to the bias corrections in the forcing data from direct meteorological observations, while in coupled simulations this would be the only source of bias correction.

5.7.6 Novel Snow Observation Products

While snow water equivalent and snow depth observations provide specific information on the water storage of the snow pack, they do not give any direct observation of the heat storage of the snow pack. There is however a snow observation product that yields this type of information and, to the best of our knowledge, has never been used for assimilation into a LSM. This observation is the snow melt signature, which gives information on the energy budget of the snow pack.

The snow melt signature is an indicator of whether the snow is undergoing melting or freezing. This type of observation yields important information with respect to the temperature of the snow pack. Hence, assimilation of the snow melt signature into the LSM will further alleviate any water budget imbalances as a result of temperature biases in the land surface. In addition, the snow melt signature may be used as a constraint in the LSM, which prevents the snow from melting based on the observed snow melt signature.

During fall and spring, the coverage of snow is often sparse, resulting in only fractional coverage of the LSM catchments. The importance of this fractional snow cover is its control on the land surface albedo and its impact on the energy balance. This fractional coverage cannot be observed with the low resolution passive microwave sensors (½ degree or approximately 50 km). However, the high resolution (1 km or less) visible satellite data can provide information on the fractional cover. The extraction of this information from historic data is labor intensive, but a new sensor soon to come on line (MODIS) has a cloud discriminating band, which shall allow automation of this process. Hence, the utility of fractional snow cover observations will be investigated for a localized area over a short duration of time from the historic data.

5.8 Evaluation of Snow Assimilation Scheme

An effective evaluation of any large scale modeling endeavor is always the most difficult and yet most important aspect of the project. In this project, we propose to evaluate the assimilation of remotely sensed snow observation products into the catchment-based LSM using historic ground observations of the snow depth, snow water equivalent and land surface temperature at isolated points throughout North America (snow courses and SNOTEL sites), in addition to water budget and energy budget calculations. Comparisons will also be made of snow forecasts with and without the snow assimilation, and the effect on the respective water and energy budgets.

While a single point measurement of the snow depth, snow water equivalent and land surface temperature within a catchment does not relate directly to the spatially averaged values indicated by the catchment-based LSM, it may be used in a qualitative sense. Moreover, if there are a number of these measurements within a catchment, the average of these measurements should be representative of the spatially averaged value given by the LSM. In addition to comparing the forecast and observed snow values at isolated points throughout North America, the trends in forecast and observed snow will be compared at these locations. This will identify if the previously observed continual topping up of the snow pack (Figure 1) without any consideration to the annual water budget has been rectified.

The updating of land surface temperature resulting from the assimilation of snow observations will be evaluated by comparing the forecast near-surface temperature with remotely sensed land surface temperature. Moreover, the temporal variation in land surface temperature will be investigated to ensure that the assimilation scheme is not producing unrealistic diurnal variations.

James Famiglietti's group at University of Texas is currently adding a river routing component to the catchment-based LSM. The addition of this river routing component allows for the effect of snow assimilation into the LSM on the water budget be assessed. This issue will be addressed by making comparisons of forecast runoff both with and without the snow assimilation, with observed river flow in key locations. These key locations will consist of rivers that obtain a large proportion of their water from spring-time snow melt processes.

6 Role of PI and Other Personnel

The proposed work will be conducted through the Laboratory for Hydrospheric Processes at NASA's Goddard Space Flight Center and the Lamont-Doherty Earth Observatory at the University of Columbia, New York. We have assembled a team of scientists ideally target for the snow assimilation problem, each bringing complementary expertise. Jeffrey Walker (0.2 MY) will be responsible for overall project direction and co-ordination, and will provide scientific input for data assimilation strategies. Jeffrey will be supported by a post-doctoral research assistant (1.0 MY), who will implement and test the assimilation strategies. In addition to providing a connection with the ongoing assimilation activities of the DAO and LDAS, Paul Houser (0.1 MY) will also provide scientific input for data assimilation strategies. James Foster (0.1 MY) will oversee the acquisition and processing of snow products for assimilation into the LSM and evaluation of the assimilation strategies. Foster will be supported by a post-doctoral researcher (0.2 MY). The catchment-based LSM to be used in this proposal was developed by Randal Koster and uses the snow model component developed by Marc Stieglitz. Stieglitz (0.1 MY) will oversee the snow model development and assist with the model error covariance forecasting within the snow component of the LSM. Stieglitz will be supported by a post-graduate student (1.0 MY). If this project is funded, Randal Koster of the NSIPP core project will serve in an advisory capacity with respect to the LSM and its operation in NSIPP, and will provide important insights with respect to the LSM sensitivities and modifications required to include the modified snow model and assimilation.

7 Supporting Facilities and Equipment

NASA's Goddard Space Flight Center and its Laboratory for Hydrospheric Processes maintains a formidable variety of technical expertise and computational resources (Silicon Graphics, Sun, and Hewlett Packard workstations) in support of scientific analysis. More specifically, Paul Houser's Land Surface Assimilation Group has a 2 processor Silicon Graphics Origin 200 and a 2 processor Alpha workstation that will be available for use in the assimilation component of this proposal.

At Lamont-Doherty, computing facilities consisting of an extensive network of SUN and Macintosh workstations, limited mass storage, printers, color plotters, graphic workstations, and the IBM SP-s computer are available. On-line access to marine and land geophysical databases are maintained, as are tools for geophysical data interpretation, graphics and mapmaking.

8 Management Approach and Schedule

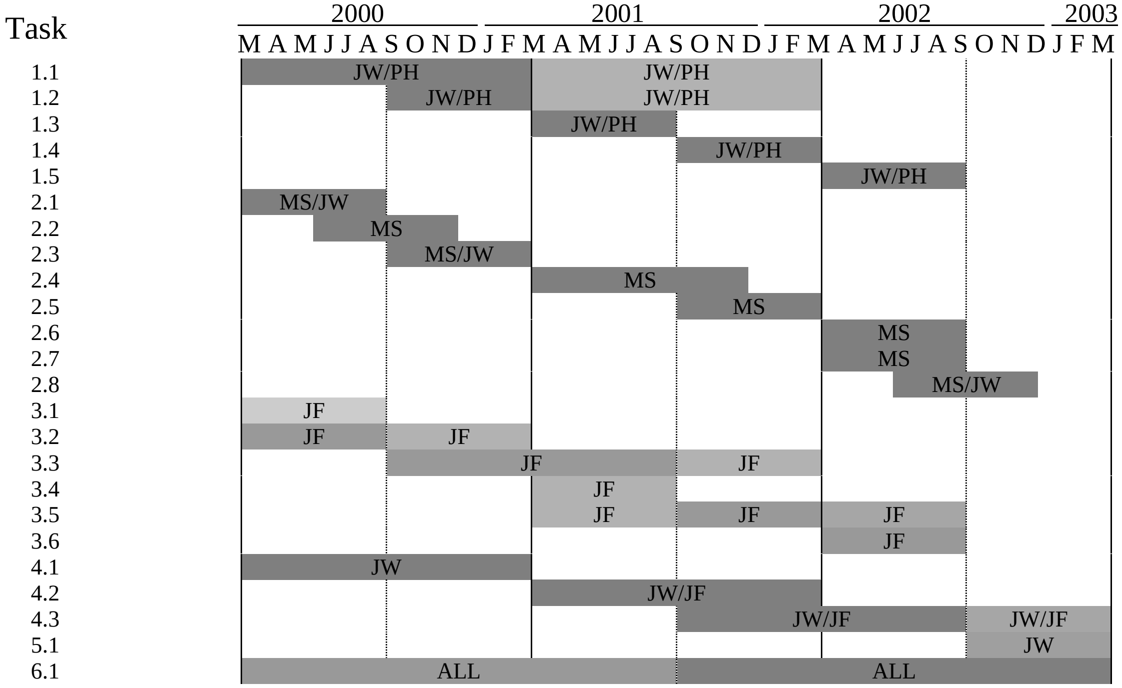
This project will be three years in duration. Activity during the first year will focus on the development of an appropriate snow assimilation strategy using synthetic snow observation data and the current snow model. In parallel with this effort, a 20 year snow observation product data set will be assembled for a regional scale catchment within North America, to allow for further development of the assimilation scheme while the entire 20 year snow observation data set is assembled. Such development of the assimilation strategy will continue into the second and third years as the snow observation data sets become available and the snow model evolves to account for sub grid-scale variability.

Staging the project in this manner will allow for the project to progress unhindered by its dependence on the snow observation products and snow model. Moreover, the use of synthetic data during the early stages of the project will allow for development of the assimilation scheme without the influence of observation and model error. A detailed schedule of the project tasks is given below.

Project Tasks

1. Algorithm Development	1.1 Develop model error covariance forecasting algorithm and Kalman filter observation equation for assimilation of snow cover, snow water equivalent and snow depth.
	1.2 Develop an observation error checking algorithm.
	1.3 Include augmentation of air temperature bias correction in the assimilation scheme.
	1.4 Develop a scheme for assimilating snow melt signature observations.
	1.5 Develop a scheme for assimilating fractional snow cover data.
2. Snow Model Development	2.1 Linearize current snow model
	2.2 Evaluate linearized snow model processes at small watershed scale and snow coverage at basin scales.
	2.3 Integrate linearized snow model into the LSM for covariance forecasting.
	2.4 Develop sub-grid scale snow forecasting scheme.
	2.5 Evaluate sub-grid scale snow forecasting scheme.
	2.6 Linearize new snow model, which includes sub-grid scale variability.
	2.7 Evaluate the new linearized snow model.
	2.8 Integrate the new snow model into the LSM.
3. Snow Obs. Products	3.1 Acquisition of SSM/I, SMMR satellite data, gamma airborne data and meteorological data for North America.
	3.2 Algorithm testing, error analysis and assembling of snow water equivalent, snow depth and snow cover products for a regional catchment of North America.
	3.3 Algorithm refinement, error analysis and assembling of snow water equivalent, snow depth and snow cover products for remainder of North America.
	3.4 Assembling snow melt signature observation product for a regional catchment of North America.
	3.5 Assembling snow melt signature observation product for North America.
	3.6 Assembling fractional snow cover product of a regional catchment of North America for a limited time period.
4. Evaluation	4.1 Evaluate the assimilation scheme with synthetic snow data.
	4.2 Evaluate the assimilation scheme with actual snow data for a regional scale catchment in which snow plays a dominant role in the hydrological cycle.
	4.3 Evaluate the assimilation scheme with actual snow data for the entire North America.
5. Augmentation	5.1 Augment the snow assimilation scheme with the soil moisture assimilation scheme and make available to NSIPP.
6. Communication	6.1 Communicate results and recommendations to the scientific community.

Task Schedule



Degree of shading denotes activity on each sub-task.

9 References

Abramopoulos, F., Rosenzweig, C., and Choudhury, B., 1988. Improved ground hydrology calculations for global climate models (GCMs):Soil water movement and evapotranspiration. *J. Climate*, **1**:921-941.

Armstrong, R., Chang, A., Rango, A., and Josberger, E., 1993. Snow depths and grain size relationships wit relevance for passive microwave studies. *Annals of Glaciology*, **17**:171-176.

Betts, A.K., Viterbo, P., Beljaars, A., Pan, H.L., Hong, S.Y., Goulden, M., and Wofsy, S., 1998. Evaluation of land-surface interaction in ECMWF and NCEP/NCAR reanalysis models over grassland (FIFE) and boreal forest (BOREAS). *Journal of Geophysical Research-Atmospheres*, **103**(D18):23079-23085.

Bengtsson, L., 1985. *Four-Dimensional Data Assimilation.* International conference on the results of the global weather experiment and their implications for the world weather watch, Geneva, Switzerland, 27-31 May 1985, GARP Publications Series No. 26, pp187-216.

Bonan, G.B., 1996. *A Land Surface Model (LSM Version 1.0) for ecological, hydrological and atmospheric studies: Technical description and user's guide*. NCAR, Boulder, CO, 150pp.

Bowling, L.C., and Lettenmaier, D.P., 1998. A macroscale hydrological model for the arctic basin, in FALL AGU, San Fransisco.

Bras, R.L., and Rodriguez-Iturbe, I., 1985. *Random Functions and Hydrology.* Addison Wesley, Reading, Massachusetts, USA, 559pp.

Carroll, S.S., and Carroll, T.R., 1993. Increasing the precision of snow water equivalence obtained from spatial modeling of airborne and ground-based snow data. *Proceedings of the 50th Eastern Snow Conference*, Quebec, Canada, pp83-88.

Chang, A., Gloersen, P. , Schmugge, T., Wilheit, T., and Zwally, J., 1976. Microwave emission from snow and glacier ice. *Journal of Glaciology*, **16**:23-39.

Chang, A.T.C., Foster, J.L., and Hall, D.K., 1987. Nimbus-7 derived global snow cover parameters. *Annals of Glaciology*, **9**:39-44.

Charney, J.G., Halem, M., and Jastrow, R., 1969. Use of incomplete historical data to infer the present state of the atmosphere. *Journal of Atmospheric Science*, **26**:1160-1163.

Davis, R.E., McKenzie, J.C., and Jordan, R., 1995. Distributed snow process modelling: An image processing approach. *Hydrological Processes*, **9**(8):865-875.

Dee, D.P., 1991. Simplification of the Kalman filter for meteorological data assimilation. *Quarterly J. Royal Meteorol. Soc.*, **117**:365-384.

Dee, D.P., 1995. On-line estimation of error covariance parameters for atmospheric data assimilation. *Mon. Wea. Rev.*, **123**:1128-1145.

Dickinson, R.E., Henderson-Sellers, A., Kenndy, P.J., and Wilson, M.F., 1993. *Biosphere Atmosphere Transfer Scheme (BATS) version 1e as coupled to the NCAR community climate model*. NCAR, 72pp.

Foster, J., Hall, D., and Chang, A., 1984. An overview of passive microwave snow research and results. *Reviews of Geophysics and Space Physics*, **22**:195-208.

Foster, J.L., Chang, A.T.C., and Hall, D.K., 1997. Comparison of snow mass estimates from a prototype passive microwave algorithm, a revised algorithm and a snow depth climatology. *Remote Sensing of Environment*, **62**:132-142.

Georgakakos, K.P., and Smith, G.F., 1990. On improved hydrologic forecasting – Result from a WMO real time forecasting experiment. *J. Hydrol.*, **114**:17-45.

Goodwin, G.C., and Sin, K.S., 1984. *Adaptive Filtering Prediction and Control.* Prentice-Hall Inc., New Jersey, 540pp.

Hall, D.K., 1988. Assessment of polar climate change using satellite technology. *Reviews of Geophysics*, **26**(1):26-39.

Hardy, J.P., Davis, R.E., Jordan, R., Ni, W., and Woodcock, C.E., 1998. Snow ablation modelling in a mature aspen stand of the boreal forest. *Hydrological Processes*, **12**(10-11):1763-1778.

Houser, P.R., Shuttleworth, W.J., Famiglietti, J.S., Gupta, H.V., Syed, K.H., and Goodrich, D.C., 1998. Integration of soil moisture remote sensing and hydrologic modeling using data assimilation. *Water Resour. Res.*, 34(12):3405-3420.

Johnson, R.H., Young, G.S., and Toth, J.J., 1984. Mesoscale weather effects of variable snow cover over northeast Colorado. *Mon. Wea. Rev.*, **112**:1141-1152.

Jordan, R., 1995. Effects of capillary discontinuities on water-flow and water- retention in layered snow covers. *Defence Science Journal*, **45**(2):79-91.

Josberger, E., Gloersen, P., Chang, A., and Rango, A., 1995. The effect of snow grain size on passive microwave signatures for the upper Colorado River basin snow pack. *Journal of Geophysics Research*, **101**:6679-6688.

Kalman, R.E., 1960. A new approach to linear filtering and prediction problems. *Trans. ASME, Ser. D, J. Basic Eng.*, **82**:35-45.

Koster, R.D., and Suarez, M., 1996. *Energy and Water Balance Calculations in the Mosaic LSM*. NASA Tech. Memo, 59pp.

Koster, R.D., Suarez, M.J., Ducharne, A., Stieglitz, M., and Kumar, P., 1999. A catchment-based approach to modeling land surface processes in a GCM - Part I: Model structure. *Journal of Geophysical Research*, submitted.

Liston, G.E., and Sturm, M., 1998. A snow-transport model for complex terrain. *Journal of Glaciology*, **44**(148):498-516.

Ljung, L., 1979. Asymptotic behavior of the extended Kalman filter as a parameter estimator for linear systems. *IEEE Trans. Automat. Cont.*, **AC-24**(1):36-50.

Lorenc, A.C., 1995. *Atmospheric Data Assimilation*. Meteorological Office Forecasting Research Division Scientific Paper No. 34.

Loth, B., Graf, H.F., and Oberhuber, J.M., 1993. Snow cover model for global climate simulations. *Journal of Geophysical Research-Atmospheres*, **98**(D6):10451-10464.

Loth, B., and Graf, H.F., 1998a. Modeling the snow cover in climate studies - 1. Long-term integrations under different climatic conditions using a multilayered snow-cover model. *Journal of Geophysical Research-Atmospheres*, **103**(D10):11313-11327.

Loth, B., and Graf, H.F., 1998b. Modeling the snow cover in climate studies - 2. The sensitivity to internal snow parameters and interface processes. *Journal of Geophysical Research-Atmospheres*, **103**(D10):11329-11340.

Lynch-Stieglitz, M., 1994. The development and validation of a simple snow model for the Giss GCM. *Journal of Climate*, **7**(12):1842-1855.

McCollum, J.R., Gruber, A., and Ba, M. B., 1999. Discrepancy between gauges and satellite estimates of rainfall in equatorial Africa. *J. App. Meteor.*, submitted.

Pitman, A.J., Yang, Z.-L., Cogley, J.G., and Henderson-Sellers, A., 1991. *Description of Bare Essentials of Surface Transfer for the Bureau of Meterological Research Centre*. AGCM, BMRC, Australia.

Rango, A., Chang, A., and Foster, J., 1979. The utilization of spaceborne microwave radiometers for monitoring snow pack properties. *Nordic Hydrology*, **10**:25-40.

Slater, A.G., Pitman, A.J., and Desborough, C.E., 1998. The validation of a snow parameterization designed for use in general circulation models. *International Journal of Climatology*, **18**(6): 595-617.

Pinker, R.T. and Laszlo, I., 1992. Modeling surface solar irradiance for satellite applications on a global scale. *J. Appl. Meteor*., **31**:194-211.

Tait, A., 1998. Estimation of snow water equivalent using passive microwave radiation data. *Remote Sensing of Environment*, **64**:286-291.

Todling, R., and Cohn, S. E., 1994. Suboptimal schemes for atmospheric data assimilation based on the Kalman filter. *Mon. Wea. Rev.*, **122**:2530-2557.

Verseghy, D.L., 1991. Class-a Canadian land surface scheme for GCMs. 1. Soil model. *International Journal of Climatology*, **11**(2):111-133.

Walker, A.E., and Goodison, B.E., 1993. Discrimination of a wet snow cover using passive microwave satellite data. *Annals of Glaciology*, **17**:307-311.

Walker, J.P., 1999. *Estimating Soil Moisture Profile Dynamics From Near-Surface Soil Moisture Measurements and Standard Meteorological Data*. Dissertation Thesis, Department of Civil, Surveying and Environmental Engineering, The University of Newcastle.

Whitlock, C.H., Charlock, T.P., Staylor, W.F., Pinker, R.T., Laszlo, I., Dipasquale, R.C., and Ritchey, N.A., 1993. *WCRP surface radiation budget shortwave data product description-Version 1.1*. NASA Tech. Memo. 107747.

Yang, Z.L., Dickinson, R.E., Robock, A., and Vinnikov, K.Y., 1997. Validation of the snow submodel of the biosphere-atmosphere transfer scheme with Russian snow cover and meteorological observational data. *Journal of Climate*, **10**(2):353-373.

BUDGET SUMMARY

Year 1

For period from March 1, 2000 to Feb 28, 2001

- Provide a complete Budget Summary for year one and separate estimates for each subsequent year.
- Enter the proposed estimated costs in Column A (Columns B & C for NASA use only).
- Provide as attachments detailed computations of all estimates in each cost category with narratives as required to fully explain each proposed cost. See *Instructions For Budget Summary* on following page for details.

		NASA USE ONLY	
	A	**B**	**C**
1. Direct Labor (salaries, wages, and fringe benefits)	$113,285		
2. Other Direct Costs:			
a. Subcontracts	$0		
b. Consultants	$0		
c. Equipment	$2,000		
d. Supplies	$1,009		
e. Travel	$3,786		
f. Other	$23,535		
3. Facilities and Administrative Costs	$55,043		
4. Other Applicable Costs:	$0		
5. SUBTOTAL--Estimated Costs	$198,658		
6. Less Proposed Cost Sharing (if any)	$0		
7. Carryover Funds (if any)			
a. Anticipated amount : _______			
b. Amount used to reduce budget	$0		
8. Total Estimated Costs	$198,658		XXXXXXX
9. APPROVED BUDGET	XXXXXX	XXXXXXX	

BUDGET SUMMARY

Year 2

For period from March 1, 2001 to Feb 28, 2002

- Provide a complete Budget Summary for year one and separate estimates for each subsequent year.
- Enter the proposed estimated costs in Column A (Columns B & C for NASA use only).
- Provide as attachments detailed computations of all estimates in each cost category with narratives as required to fully explain each proposed cost. See *Instructions For Budget Summary* on following page for details.

		NASA USE ONLY	
	A	**B**	**C**
1. Direct Labor (salaries, wages, and fringe benefits)	$112,846		
2. Other Direct Costs:			
a. Subcontracts	$0		
b. Consultants	$0		
c. Equipment	$1,000		
d. Supplies	$1,100		
e. Travel	$7,411		
f. Other	$19,418		
3. Facilities and Administrative Costs	$56,864		
4. Other Applicable Costs:	$0		
5. SUBTOTAL--Estimated Costs	$198,639		
6. Less Proposed Cost Sharing (if any)	$0		
7. Carryover Funds (if any)			
a. Anticipated amount : ________			
b. Amount used to reduce budget	$0		
8. Total Estimated Costs	$198,639		XXXXXXX
9. APPROVED BUDGET	XXXXXX	XXXXXXX	

BUDGET SUMMARY

Year 3

For period from March 1, 2002 to Feb 28, 2003

- Provide a complete Budget Summary for year one and separate estimates for each subsequent year.
- Enter the proposed estimated costs in Column A (Columns B & C for NASA use only).
- Provide as attachments detailed computations of all estimates in each cost category with narratives as required to fully explain each proposed cost. See *Instructions For Budget Summary* on following page for details.

		NASA USE ONLY	
	A	**B**	**C**
1. Direct Labor (salaries, wages, and fringe benefits)	$114,386		
2. Other Direct Costs:			
a. Subcontracts	$0		
b. Consultants	$0		
c. Equipment	$0		
d. Supplies	$1,100		
e. Travel	$6,485		
f. Other	$17,449		
3. Facilities and Administrative Costs	$60,599		
4. Other Applicable Costs:	$0		
5. SUBTOTAL--Estimated Costs	$200,019		
6. Less Proposed Cost Sharing (if any)	$0		
7. Carryover Funds (if any)			
a. Anticipated amount : _______			
b. Amount used to reduce budget	$0		
8. Total Estimated Costs	$200,019		XXXXXXX
9. APPROVED BUDGET	XXXXXX	XXXXXXX	

Jeffrey P. Walker

Education:

Ph.D	**1999**	Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Australia
B.E. (Civil)	**1995**	Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Australia
B.Surv.	**1995**	Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Australia

Research Experience:

1999-present	Postdoctoral Research Fellow, USRA Visiting Scientists Program, NASA/GSFC, Greenbelt, Maryland, USA
1996-1999	Doctoral Scholar, Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Australia
1995	Honours Scholar, Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Australia

Awards and Honours:

1995	University Medal in Civil Engineering
	University Medal in Surveying
	The Deans' Medal
	The Tony Herzog Award
	The Peter Kleeman Medallion
	The Spruson & Ferguson Prize in Civil Engineering
	The Hunter Water Corporation Achievement Award
	The Institution of Engineers Australia Civil and Structural Branch Prize in Civil Engineering
	The Board of Surveyors' Medal
	The ACSE Prize in Structural Engineering
	The Consulting Surveyors New South Wales Prize in Land Studies
	The Institution of Surveyors Australia Hunter-Manning Group Prize in Surveying
	The James Hardie Pipelines Water Resources Engineering Prize
	Mine Subsidence Technological Society Prize in Geotechnical Design
	The Metal Building Manufacturers' Association Prize
1994	The SRIA University Award for Concrete Design
1993	The Astley Pulver Prize for Second Year Surveyors
1992	The BHP Rod & Bar Products Division Prize in Civil Engineering

Professional Affiliations:

Member, American Geophysical Union

Journal Papers:

Walker, J. P., Willgoose, G. R., and Kalma, J. D., 1999. Profile Soil Moisture Retrieval by Assimilation of Remote Sensing Observations. In preparation.

Walker, J. P. and Willgoose, G. R., 1999. Investigation of Cartometric and Photogrammetric Digital Elevation Model Accuracy. In preparation.

Walker, J. P. and Willgoose, G. R., 1999. On the Effect of Digital Elevation Model Accuracy on Hydrology and Geomorphology. *Water Resources Research*, **35**(7): 2259-2268.

Conference Papers:

Walker, J. P., Willgoose, G. R. and Kalma, J. D., 1999. Recent Advances in Profile Soil Moisture Retrieval, *Water 99, 25th Hydrology and Water Resources Symposium,* Brisbane, 6 - 8 July 1999.

Walker, J. P., Willgoose, G. R. and Kalma, J. D., 1998. Towards Profile Soil Moisture Retrieval From Remote Sensing, *EOS, Transactions American Geophysical Union,***79**(17): S41.

Walker, J. P., Troch, P. A., Mansini, M., Willgoose, G. R., and Kalma, J. D., 1997. Profile Soil Moisture Estimation Using the Modified IEM. In: *Proceedings International Geoscience and Remote Sensing Symposium (IGARSS)*, Singapore, 3 - 8 August, 1997, 1263-1265.

Reports:

Walker, J. P., 1999. *Estimating Soil Moisture Profile Dynamics From Near-Surface Soil Moisture Measurements and Standard Meteorological Data.* Dissertation Thesis, Department of Civil, Surveying and Environmental Engineering, The University of Newcastle.

Walker, J. P., 1995. *Accuracy of DEMs*. Honours Thesis, Department of Civil, Surveying and Environmental Engineering, The University of Newcastle.

JAMES LOUIS FOSTER

AST, Earth Sciences Remote Sensing
Hydrological Sciences Branch
Laboratory for Hydrospheric Processes

RESEARCH AREA EXPERIENCE

Remote sensing of snow and ice from relevant parts of the electromagnetic spectrum to better estimate albedo, snow cover extent, snow depth and snow water equivalent and to determine how these parameters effect water resources and weather and climate

EDUCATION

1969 - B.S. in Geography, University of Maryland
1977 - M.A. in Geography, University of Maryland
1995 - Ph.D. in Geography, University of Reading

PREVIOUS POSITIONS

1973-1977	Faculty Research Assistant, University of Maryland
1977-1978	Research Analyst, Systems and Applied Sciences Corporation
1978-Present	Remote Sensing Scientist in the Hydrological Sciences Branch at Goddard Space Flight Center

SPECIAL EXPERIENCE/RESEARCH PROJECTS

Eastern Snow Conference-Executive Committee, (President 1988-89).
American Meteorology Society, (Hydrology Committee 1995-97)
Int. Committee of Snow and Ice, Snow and Climate Working Group

PROFESSIONAL SOCIETY MEMBERSHIPS

American Meteorological Society
Eastern Snow Conference
International Geophysical and Remote Sensing Society

RECENT REFEREED PUBLICATIONS

Hall, D.K., J.L. Foster, J. Chien, and G. A. Riggs, Determination of absolute snow cover using Landsat TM and digital elevation model data in Glacier National Park, Polar Record, 31, 191-198, 1995.

Foster, J.L., Improving and evaluating remotely-sensed snow/microwave algorithms and snow output from general circulation models, Ph.D. Dissertation, Department of Geography, University of Reading, Reading, England, 1995.

Chang, A.T.C., J.L. Foster, and D.K. Hall, Effects of forest on the snow parameters derived from microwave measurements during the BOREAS winter field experiment, Hydrological Processes, 10, 1565-1574, 1996.

Foster, J.L. and nine others, Snow cover and snow mass intercomparisons of general circulation models and remotely sensed data sets, J. Clim., 9(2), 409-426, 1996.

Foster, J.L. and nine others, Snow mass intercomparisons in the boreal forests from general circulation models and remotely sensed data sets, Polar Record, 32, 199-208, 1996.

Chang, A.T.C., J.L. Foster, D.K. Hall, B.E. Goodison, A. E. Walker, J. R. Metcalfe, and A. Harby, Parameters derived from microwave measurements during the BOREAS campaign, J. Geophys. Res., 102, 29663-29671, 1997.

Foster, J.L., A.T.C. Chang, and D.K. Hall, Comparison of snow mass estimates from a prototype passive microwave snow algorithm, a revised algorithm and a snow depth climatology, Remote Sens. Environ., 62, 132-142, 1997.

Foster, J.L., Snowmelt and floods, Practical uses of math and Science (PUMAS), Document ID 01__ 29__ 98__ 1, 1998.

Foster, J.L., A.T.C. Chang, D.K. Hall, W.P. Wergin E.F. Erbe, and J. Barton, Carbon dioxide crystals: an examintion of their size, shape and scattering properties at 35 GHz and comparisons with water ice (snow) measurements, J Geophys. Res. (Planets), Vol. 103, # E11, 25, 893-25, 850, 1998.

Foster, J.L., A.T.C. Chang, D.K. Hall, W. P. Wergin, E.F. Erbe, and J. Barton, Effect of snow crystal shape on the scattering of passive microwave radiation, IEEE (GeoScience and Remote Sensing), Vol-37, #2, 1165-1168, 1999.

Hall, D.K., J.L Foster, D.L. Verbyla, A.G. Klera, and C. S. Benson, Assessment of snow mapping accuracy in a variety of vegetation-cover densities in central Alaska, Remote Sensing of the Environment, in press 1998.

Hall, D., J. Foster, A Chang, C. Benson and J. Chein, Determination of snow covered area in different land covers in central Alaska, U.S.A., from aircraft data April 1995, Annals of Glaciology, Vol. 26, 149-155, 1999.

Tait, A., D. Hall, J. Foster, A. Chang, and A. Klein, Detection of snow cover using millimeter-wave imaging radiometer (MIR) data, Remote Sensing of the Environment, Vol. 68, 53-60, 1999.

March 7, 2000

Paul R. Houser

Hydrological Sciences Branch & Data Assimilation Office
NASA's Goddard Space Flight Center

NASA-GSFC Code 974; Greenbelt, MD 20771
Tel: 301/614-5772 *Fax:* 301/614-5808
Email: Paul.Houser@gsfc.nasa.gov
Web: http://land.gsfc.nasa.gov

CAREER OBJECTIVE:

To perform environmentally significant scientific research and instruction in hydrology, near-surface meteorology, and remote sensing. Specific interests include local to global land surface-atmospheric observation (both in-situ and remotely-sensed) and numerical simulation, development of hydrologic data assimilation methods, and multi-scale soil moisture investigations.

EDUCATION:

Doctorate in Hydrology and Water Resources: *Remote-sensing Soil Moisture using Four-dimensional Data Assimilation,* College of Engineering and Mines, The University of Arizona; Tucson, AZ: November 1996.

Bachelor of Science in Hydrology and Water Resources: College of Engineering and Mines, The University of Arizona; Tucson, AZ: May 1992. Magna Cum Laude.

EXPERIENCE:

NASA Research Scientist: Goddard Space Flight Center, Greenbelt, MD: 4/97-present. Data assimilation research that integrates hydrologic observations into land surface process models.

NASA Program Manager: NASA Headquarters, Washington DC: 9/99-3/00. Management and planning of NASA's Land Surface Hydrology Program.

Post-Doctoral Research Scientist: Universities Space Research Association, Greenbelt, MD: 1/97-4/97. Soil moisture remote sensing and data assimilation research.

Research Associate: University of Arizona, Tucson, AZ: 8/95-12/96. Developed data assimilation techniques for integrating remotely sensed soil moisture into hydrologic models.

Micrometeorological Site Development: University of Arizona; Tucson, AZ: 1/93-8/96. Developed and operated an Eddy Correlation, Bowen Ratio, Sigma-T and Automatic Weather Station.

Teaching Assistant: University of Arizona, Hydrology Department; Tucson, AZ: 6/93,6/94,6/95. Instructed undergraduate and graduate students in summer hydrology field camp.

Teaching Assistant: University of Arizona, Hydrology Department; Tucson, AZ: 1/93-5/95. Instructed ~40 undergraduate students in Hydrology 250:"Principles of Hydrology".

Research Assistant: University of Arizona, Hydrology Department; Tucson, AZ: 5/92-9/92. Characterized flow through fractures in volcanic tuff using air permeability techniques.

Laboratory Assistant: University of Arizona, Tree Ring Laboratory; Tucson, AZ: 1/92-4/92. Measured and analyzed tree rings for paleoclimate reconstruction.

Research Assistant: Los Alamos National Laboratory, New Mexico, Environmental Sciences: Summer 1991. Emplaced field experiments to measure water balance relationships in various landfill scenarios.

Hydrologic Technician: U.S. Geological Survey, Water Resources Division; Portland, OR: 1988-90. Used various field and laboratory techniques to assess the surface and ground water quality in the Yakima river basin, in south-central Washington State.

HONORS:

Goddard Space Flight Center Special Act Award, December 1997.
American Geophysical Union Hydrology Section Outstanding Student Paper, Spring 1996.
National Aeronautics and Space Administration Fellow in Global Change Research.
The National Science Foundation Graduate Fellowship.
Department of Energy Environmental Restoration and Waste Management Scholarship.

ACTIVITIES:

American Geophysical Union; Remote Sensing Committee.
American Meteorological Society.
The Institute of Electrical and Electronics Engineers, Inc.
International Association of Hydrological Sciences.

RECENT PUBLICATIONS:

Houser, P. R., D. C. Goodrich, and K. H. Syed, 1999: Runoff, Precipitation, and Soil Moisture at Walnut Gulch. In Spatial Patterns in Catchment Hydrology: Observations and Modeling, edited by R. Grayson and G. Bloschl.

Houser, P. R., 1999: Infiltration and Soil Moisture Processes. In Handbook of Weather, Climate, and Water, edited by T. Potter and B. Bradely.

Houser, P. R., H. V. Gupta, W. J. Shuttleworth, and J. S. Famiglietti, 1999: Multi-Objective Calibration and Sensitivity of a Distributed Land-Surface Water and Energy Balance Model. Under review.

Houser, P. R., and B. P. Mohanty, 1999. The spatial-temporal structure of U.S. Southern Great Plains soil moisture - an analysis of in-situ SGP97 profile observations. In the American Meteorological Society Proceedings of the 14th Conference on Hydrology, January 10-14, 1999.

Mohanty, B. P., P. R. Houser, P. J. Shouse, and M. Th. Van Genuchten, 1999. Soil moisture content at deeper depths - SGP97, Oklahoma. In the American Meteorological Society Proceedings of the 14th Conference on Hydrology, January 10-14, 1999.

Bosilovich, M. G. P. R. Houser, A. Molod, and S. Nebuda, 1999. A comparison of FIFE observations with GEOS assimilated data including a heterogeneous land-surface model. In the American Meteorological Society Proceedings of the 14th Conference on Hydrology, January 10-14, 1999.

Famiglietti, J. S., J. A. Devereaux, C. A. Laymon, T. Tsegaye, P. R. Houser, T. J. Jackson, S. T. Grham, M. Rodell, and P. J. van Oevelen. Ground-based investigation of soil moisture variability within remote sensing footprints during the Southern Great Plains 1997 (SGP97) Hydrology Experiment. Water Resources Research, 35)6_:1839-1851.

Elliott, R. L., P. R. Houser, and B. K. Mohanty, 1999. Inter-comparison of three methods for measuring soil moisture during SGP97. In the American Meteorological Society Proceedings of the 14th Conference on Hydrology, January 10-14, 1999.

Houser, P. R., R. Yang, M. Bosilovich, A. Molod, and S. Nebuda, 1999. Spin-up time scales of the off-line land surface GEOS assimilation (OLGA) system. In the American Meteorological Society Proceedings of the 14th Conference on Hydrology, January 10-14, 1999.

Molod, A., S. Nebuda, M. Bosilovich, P. Houser, and R. Yang, 1999. The impact of the Mosaic land surface model on the climate of the GEOS data assimilation system. In the American Meteorological Society Proceedings of the 14th Conference on Hydrology, January 10-14, 1999.

Nebuda, S., A. Molod, M. Bosilovich, P. Houser, and R. Yang, 1999. Interaction of predicted and prescribed soil moisture with the moist physics parameterizations in the GEOS data assimilation system. In the American Meteorological Society Proceedings of the 14th Conference on Hydrology, January 10-14, 1999.

Yang, R., P. Houser, and J. Joiner, 1999. Comparizon of surface ground temperature from satellite observations and the off-line surface GEOS assimilation system. In the American Meteorological Society Proceedings of the 14th Conference on Hydrology, January 10-14, 1999.

Houser, P. R., C. Harlow, W. J. Shuttleworth, T. O. Keefer, W. E. Emmerich, and D. C. Goodrich, 1998: Evaluation of Multiple Flux Measurement Techniques Using Water Balance Information and a Semi-Arid Site. In: The American Meteorological Society Proceedings, February 12-16, 1998, Phoenix, AZ.

Houser, P. R., 1998: Microwave Soil Moisture Remote Sensing. Proceedings of the ECMWF/GEWEX MMP Workshop on Modeling and Data Assimilation for Land-Surface Processes, June 29 - July 2, 1998; ECMWF, Reading, UK

Houser, P. R., W. J. Shuttleworth, H. V. Gupta, J. S. Famiglietti, K. H. Syed, and D. C. Goodrich, 1998: Integration of Soil Moisture Remote Sensing and Hydrologic Modeling using Data Assimilation. *Water Resources Research,* **34**(12):3405-3420.

Houser, P. R.,J. S. Famiglietti, W. J. Shuttleworth, J. A. Berglund, 1997. Integration of Remote Sensing and Hydrologic Modeling Using Data Assimilation. In the American Meteorological Society Proceedings of the 13th Conference on Hydrology, February 2-7, 1997.

Houser, P. R., 1997: The Spatial-Temporal Structure of U.S. Southern Great Plains Soil Moisture: A Preliminary Analysis of SGP97 Observations. In the proceedings of the *Characterization and Measurement of the Hydraulic Properties of Unsaturated Porous Media International Workshop*.

Unland H., A. Arain, C. Harlow, P. Houser, H. Garatuza, R. Scott, O. Sen, and W. Shuttleworth, 1997: Evaporation from a Riparian System in a Semi-arid Environment. *Hydrol. Process.* **12**(1998):527-542..

White, C. B., P. R. Houser, A. M. Arain, Z. L. Yang, K. Syed, and W. J. Shuttleworth, 1997. The aggregate description of semi-arid vegetation with precipitation-generated soil moisture heterogeneity. *Hydrology and Earth Systems Sciences*, 1, 205-212.

Houser, P. R., 1996: Remote Sensing Soil Moisture using 4-Dimensional Data Assimilation. Ph.D. dissertation, Department of Hydrology and Water Resources, The University of Arizona.

Unland, H. E., P. R. Houser, W. J. Shuttleworth, and Zong L. Yang, 1996. Surface Flux Measurement and Modeling at a Semi-Arid Sonoran Desert Site, submitted to*: Journal of Agricultural and Forest Meteorology*, September 1, 1995; approved for publication.

Twine, T. E., W. P. Kustas, J. M. Norman, D. R. Cook, P. R. Houser, T. P. Meyers, J. H. Prueger, P. J. Starks, 1999: Underestimation of Eddy Covariance Fluxes over a grassland. Under review.

Yang R., S. Cohn, A. da Silva, J. Joiner, and P. Houser, 1999: Internal Physical Features of a Land Surface Model Employing a Tangent Linear Model. Submitted to *Monthly Weather Review*.

INVITED CONFERENCE PAPERS:

Houser, P. R., 1998: Soil Moisture Remote Sensing: Microwave Estimates. ECMWF/GEWEX MPP Workshop on Modeling and Data Assimilation for Land Surface Processes, Reading, UK.

Houser, P. R., 1998: Land Surface Data Assimilation. NOAA/NESDIS Office of Research and Applications Seminar Series, Camp Springs, MD.

Houser, P. R.,J. S. Famiglietti, W. J. Shuttleworth, J. A. Berglund, 1997. Integration of Remote Sensing and Hydrologic Modeling Using Data Assimilation, invited oral presentation at the American Meteorological Society Meeting, Long Beach, CA.

Houser, P. R.,J. S. Famiglietti, W. J. Shuttleworth, J. A. Berglund, 1996. Remote Sensing Soil Moisture using Four Dimensional Data Assimilation, invited oral presentation at the American Geophysical Union spring meeting, Baltimore, MD.

RESEARCH GRANTS:

Houser, P. R., and J. S. Famiglietti, 1999-2001: Optimal Land Initialization for Seasonal Climate Predictions, NASA NRA 98-OES-07, $600k.

Houser, P. R., J. R. Wang, and B. Choudhury, 1999-2001: Remote Sensing Soil Moisture using Four Dimensional Data Assimilation of TRMM Microwave Observations, NASA NRA 98-OES-02, $330k.

Houser, P. R., and B. Choudhury, 1998-2000: Continental-Scale Soil Moisture Data Assimilation, NASA NRA 97-MTPE-12, FY 1998-2000, $240k (see http://ldas.gsfc.nasa.gov).

Houser, P. R., H. Gupta, W. J. Shuttleworth, D. Goodrich, J. Famiglietti, and J. Berglund, 1994-1998: Remote Sensing Soil Moisture Using Four-Dimensional Data Assimilation, NASA Project NAGW-4165, NASA-MTPE Water Cycle Processes Program.

McLaughlin, D. (MIT), D. Entekhabi (MIT), and P. R. Houser, 1999-2001: Soil Moisture Data Assimilation for Continental-Scale Land Surface Hydrology Applications, NASA NRA-98-OES-11, $360k,

Christa Peters-Lidard (Georgia Tech), Paul R. Houser and Peggy E. O'Neill (NASA-GSFC), 1999-2001: Quantifying the Relationship Between Remotely-Sensed and Modeled Soil Moisture, NASA NRA-98-OES-11, $360k.

Curriculum Vitae
Marc Stieglitz

Present Address:	Lamont Doherty Earth Observatory Route 9W, Palisades, NY 10964 Phone: (914) 365-8342 email: marc@ldeo.columbia.edu
Degrees:	1983 - B.A. Physics, Columbia College, Columbia University 1985 - M.S. in Applied Geophysics, Graduate School of Engineering, Columbia University 1995 - Ph.D., Graduate School of Arts and Sciences, Columbia University, Department of Geological Sciences Dissertation title: The development and validation of a new land surface model for regional and global climate modeling

Current Rank: July 1997 - present, Associate Research Scientist, Lamont Doherty Earth Observatory of Columbia University

Previous Positions:
1995 - 1997: Visiting UCAR Postdoctoral Scientist at The Ecosystems Center, Marine Biological Laboratory: Woods Hole, MA
1990 - 1995,Graduate Research Fellow, Department of Geological Sciences, , Columbia University
1986 - 1990: Staff Scientist, Science Application International Corporation
1985 -1986: Technical Staff Member

Areas of Interest: Regional and global climate modeling, with emphasis on hydroclimatology and land atmospheric interactions, impacts of climate change, and interactions between climate, hydrology, and terrestrial biology, including terrestrial carbon and nitrogen cycling

Academic Awards:

NOAA Global Climate Change Fellowship, July 1995 – June 1997
Columbia University Fellowship, January1990 - June 1995
AMOCO Foundation Fellowship, 1984 - 1985

Selected Publications:

Stieglitz, M., J. Hobbie, A. Giblin, G. Kling, Hydrologic modeling of an arctic watershed: Towards Pan-Arctic predictions, *in press at JGR*

Stieglitz, M., A. Giblin, J. Hobbie, G. Kling, M. Williams, Effects of climate change and climate variability on the carbon dynamics in Arctic tundra, *submitted to Global Biogeochemical Cycles*

Koster, R. D., M. J. Suarez, A. Ducharne, M Stieglitz, P Kumar, A catchment-based approach to modeling land surface processes in a GCM - Part I: Model structure, *in preparation for JGR*

Ducharne, A. and R. D. Koster, M. J. Suarez, M. Stieglitz, P. Kumar, A catchment-based approach to modeling land surface processes in a GCM - Part II: Parameter estimation and model demonstration, *in preparation for JGR*

Stieglitz, M., D. Rind, J. Famiglietti, C. Rosenzweig, 1997, An efficient approach to modeling the topographic control of surface hydrology for regional and global climate modeling, *J. of Climate*, *V*ol. 10, No. 1, 118-137

Lynch-Stieglitz, M., 1994, The development and validation of a simple snow model for the GISS GCM, *J. of Climate*,7, 1842-1855.

Rind, D., C. Rosenzweig, M. Stieglitz, 1997, The role of moisture transport between ground and atmosphere in global change, *Annual Reviews of Energy and the Environment*, vol. 22.

Selected Presentations and Workshops:

Stieglitz, M., A. Giblin, J. Hobbie, G. Kling, Climate change in Arctic tundra: Alterations in the hydrologic cycle and feedbacks to carbon sequestration, Presented at American Geophysical Fall Meeting, San Francisco, Dec. 5-9, 1998

Ducharne, A., K.D. Koster, M.J. Suarez, M. Stieglitz, P. Kumar, Behavior of a New-Catchment based Land Surface Model for GCMs, Presented at American Geophysical Fall Meeting, San Francisco, Dec. 6-10, 1998

Stieglitz, M., and A. Giblin, Bio-Physical feedbacks in an Arctic environment Presented at American Geophysical Fall Meeting, San Francisco, Dec. 8-12, 1997

Stieglitz, M., Modeling of hydrological and biogeochemical fluxes in Arctic watersheds. Presented at NOAA Global Climate Change Institute, Steamboat Springs, Colorado, June 17-21, 1996.

Stieglitz, M., A simple application of TOPMODEL equations for regional and global climate modeling Presented at the TOPMODEL Symposium, Lancaster University, Lancaster, England, September 20-23, 1995

Lynch-Stieglitz, M., The development and validation of a simple snow model for the GISS GCM, Presented at American Geophysical Fall Meeting, San Francisco, Dec. 1-6, 1993

Thesis Advisor: D. Rind, GISS/NASA
Postdoctoral Advisor: J. Hobbie, The Ecosystems Center, MBL

Collaborators over last 48 months:

A.Ducharne
J. Famiglietti
A. Giblin
J. Hobbie
G. Kling
R. Koster
P. Kumar
M. Williams
D. Rind
C. Rosenzweig
M. Suarez