1 INTRODUCTION

1.1 Background

Over 70% of the population in West Africa depends primarily on rainfed agriculture for its livelihood. Moreover, the main source of power for socio-economic development is hydro-based and depends heavily on availability of rainfall and its distribution. Therefore, water resources are the life-blood of the economies of West African countries, and changes in amount and distribution of rainfall can significantly impact socio-economic activities in the region.

In an attempt to address the problem of efficient utilization of the scarce water resources in the Volta Basin of West Africa, the German government and its partner countries within the Volta Basin (Ghana & Burkina Faso) have set up a multidisciplinary research project on Global Change in the Hydrological Cycle, called the GLOWA-Volta project. The principal objective of the project is to develop a scientifically sound decision support system for the assessment, sustainable use and development of water resources in the Volta Basin.

A critical component of this multidisciplinary research involves regional climate modeling of the Volta Basin to identify and characterize the dynamics of the energy and hydrological cycles in the Basin. However, the location of the Volta Basin in the tropics, coupled with the complex nature of the landuse characteristics of the region demands a new approach for representing the relevant physics in climate models to accurately account for subgrid scale heterogeneity effects.

As the GLOWA-Volta project is multi-disciplinary in nature, the different subprojects made up of different disciplines must be optimally integrated across different scales to ensure the harmonious functioning of the project as a whole. The issue of scaling land surface characteristics is therefore a critical issue for scientific enquiry.

1.2 Motivation

Ongoing intensification of agriculture in West Africa has led to changes in land surface and subsurface characteristics, which directly affect evapotranspiration rates. If these changed evapotranspiration rates in turn affect regional precipitation patterns, rainfed and irrigated agriculture in West Africa may face changed boundary conditions because of the complex feedback mechanisms between the surface and atmosphere. The investigation of these feedback effects requires the application of regional climate models that accurately account for soil and vegetation states through SVAT schemes.

The land surface characteristics of the Volta Basin is characterized by mosaics of small patches made up of agricultural fields, fallows, villages and forest (savannah mosaic). The surface heterogeneity introduced by the composing surface elements of the savannah mosaic lead to complicated conditions affecting both local and regional climates. Depending on the horizontal scale of these surface heterogeneities, the planetary boundary layer (PBL) could be affected, and in effect, influence the regional climatic conditions. Three scales of surface heterogeneity have been identified and, depending on the horizontal scale, they can be classified as microscale or organized heterogeneity, mesoscale or disorganized heterogeneity, and macroscale or large scale heterogeneity respectively (Shuttleworth, 1988; Raupach, 1991; Mahrt, 2000).

For the microscale heterogeneity, the surface changes are disorganized at scales less than 10 km (Shuttleworth, 1988) such that the atmospheric boundary layer responds to only the composite structure. The influence of the local advection on the surface flux profiles becomes appreciable and a characteristic height called the blending height can be found where the fluxes are close to its surface values (Claussen and Klassen, 1992; Klassen and Claussen, 1995; Mahrt, 2000). For the mesoscale or organized heterogeneity, the atmospheric boundary layer responds independently over each patch of the surface and occurs on scales greater than 10 km (André et al., 1986; Chehbouni et al., 1995; Raupach, 1991). The blending height extends sufficiently high such that no level exists where the Monin-Obukhov similarity theory is applicable for estimating surface fluxes close to the surface value. In the case of the macroscale heterogeneity, the boundary layer establishes equilibrium with the local surface type, and the entire boundary layer is controlled by the local surface structure. At low wind speeds, macroscale heterogeneity can occur at the mesoscale scale length(Mahrt, 2000).

Regional climate models use landuse data in resolutions of 10-100 km because of the limitation of computing resources required for fine resolution runs over the domain of interest. However, information on land surface parameters is usually available at much finer resolution such that their implementation in the coarse resolution climate models do not properly account for the subgrid scale effects associated with the surface heterogeneity. More importantly, the scales at which most of these subgrid scale processes occur are far too fine to be captured by the coarse scale resolution at which climate runs are undertaken.

Although the relevance of parameterizing subgrid scale processes in climate modeling is well established, the question of how to represent and analyze the effects of spatial variability on the scaling of land surface parameterization has been an issue of great controversy. The main contention comes from the fact that assumptions related to different parameterization for the same physical process often lead to different inferences. As a result, several studies based on different approaches have recently focused on how to fully represent and parameterize this land surface heterogeneity so as to enhance model efficiency and accuracy. Therefore, a fundamental and not yet satisfactorily solved problem in hydrological research is how subgrid scale variability can be accounted for at coarse resolutions.

1.3 Objectives

The main objective of this work is to derive effective soil and vegetation parameters to account for subgrid scale variability in 1D SVAT and full 3D regional climate models.

The specific objectives of this research are:

- To undertake sensitivity analysis of SVAT model parameters with respect to surface energy fluxes (latent and sensible heat fluxes) and moisture indicators (Bowen ratio and evaporative fraction) to identify sensitive SVAT parameters.
- To develop a parameter estimation environment for SVAT models (stand-alone and full 3D).
- To identify suitable objective functions for the estimation of selected soil and vegetation parameters.

- To derive upscaling laws (an equivalent for lookup tables) for soil and vegetation parameters in SVAT models, with particular emphasis on the Volta Basin.
- To compare the developed method to existing aggregation/upscaling schemes.
- To investigate differences between derived effective parameters for SVAT models in stand-alone mode (1D) and fully 3D mode.
- To investigate the uniqueness of the estimated parameters.

1.4 Problem definition

The problem of representing subgrid scale effects can be formulated in several ways, based on the nature of the solution strategy adopted (Chehbouni et al., 1995; Hu et al., 1999; Shuttleworth et al., 1999). For this study, the subgrid scale problem is posed as an inverse problem and considered ill-posed.

The subgrid scale problem is posed as follows:

- Given a distributed heterogeneous land surface (characterized by land surface parameters of mean μ_p and standard deviation σ_p) at the subgrid scale, can we find an effective parameter p_{eff} at the grid scale such that the relative change in output response (e.g. surface energy fluxes and moisture indicators) is less than 10% (Hu et al., 1997)?
- If such an effective parameter p_{eff} exists, can we find a functional relation that maps the mean μ_p and standard deviation σ_p of the distributed land surface parameters at the subgrid scale to their corresponding effective parameter p_{eff} at the gridscale?

The first question addresses the problem of scale invariance in that it seeks an effective parameter for which the surface energy fluxes would be accurately partitioned. The second problem seeks an upscaling law that would enable the estimation of the effective parameter at the grid scale based on the mean and standard deviation of the distributed subgrid scale parameters. The problem is generally of highly nonlinear nature.

1.5 Overview

In this work, the estimation of optimal effective land surface parameters through inverse modeling is adopted. The subgrid scale effects are accounted for by the upscaling of land surface parameters through inverse-SVAT modeling. The solution strategy is based on the premise that solutions of existing methods are sub-optimal and hence parameter estimates obtained from these techniques can be used as initial parameters for driving the parameter estimation process. In effect, if good initial parameter estimates can be found such that they are within the neighborhood of the true solution, it is possible to iteratively adjust these parameters for the solution to converge to the optimal solution.

As the inverse problem is ill-posed, it is transformed into an almost well-posed problem via an approximate technique. Using prior information about the subgrid scale processes as a regularization constraint, the parameter estimation process is constrained to converge to the true solution. An exact algebraic solution does not exist, hence an approximate numerical solution using the Gauss-Levenberg-Marquardt algorithm is adopted.

To realize this, the SVAT model (OSU LSM) (Ek and Mahrt, 1991) was coupled to the nonlinear parameter estimation tool PEST (Doherty, 2002), which is able to iteratively adjust the SVAT parameters such that scale invariant outputs of heat fluxes are achieved. The SVAT model was driven by 1998 observation forcing data (4 days subset, January, 1- 4) obtained from the Meyer measurement site in Champaign (Meyers & Ek, 1999), which is characterized by the vegetation type “groundcover only” and soil type “silty loam”. A Monte Carlo random number generator was used to provide parameter inputs to the SVAT model. Initial parameter estimates derived from approximate methods of Hu et al. (1999) and related methods were used to initialize the nonlinear parameter estimation process. To verify, if the proposed method was independent of atmospheric forcing, extended runs ranging from 1 to 30 days were undertaken, and the results obtained do not differ significantly from the usual 4 day episode runs used in this exercise.

The experiment was extended to cover the full 3D mesoscale meteorological model MM5 to account for the lateral interactions between adjacent cells. The MM5 runs are initialized and run with National Center for Environmental Predictions (NCEP) reanalysis data. A one-way nested approach was applied for five domains, where the