1 INTRODUCTION

Savannahs are mainly located between the latitudes 5 to 15° north/south of the Equator. Savannah vegetation has also developed in the interiors of continents such as northern Australia, South America and most of Central Africa surrounding the Congo Basin. This wide distribution of savannah means that this biome is able to develop over a broad range of climatic conditions ranging from sparse grassland with scattered trees with an average annual precipitation of less than 100 mm to tall moist woodland savannah with an annual precipitation of more than 1500 mm (Scholes and Walker, 1993; Cole, 1982; Huntley, 1982).

Savannah vegetation accounts for more than 10% of the surface of the earth (Scholes and Hall, 1996) and about 50% of the area of Africa, South America and Australia (Scholes and Walker, 1993; Cowling et al., 1997). These landscapes are occupied by 20% of the human population and the majority of the world's livestock, including large mammals. This large number of inhabitants and herbivores results in a high pressure on the natural resources of those regions. Savannah ecosystems are therefore changing, and the dynamics of changes are currently poorly understood. Indeed, little attention has been paid to these areas in the past, particularly to the African savannah.

Characteristics of land cover have been widely recognized in the scientific community as a key element in the study of global change (e.g., IGBP, 1990; Henderson-Sellers and Pitman, 1992). Several climatic studies have indicated that atmospheric circulation and rainfall are significantly affected by the large-scale variation of soil moisture and evaporation (Savenije, 1996b; Enthekhabi et al., 1999). Furthermore, human or natural alterations of land cover also play a major role in the global-scale patterns of climate and biogeochemistry of the earth system (Nicholson et al., 1998; Mohr et al., 2002). While some of these changes in land cover are caused by natural processes, such as long-term changes of the climate due to astronomical causes, or shorter-term vegetation successions and geomorphological processes, human activity is increasingly modifying surface cover through direct actions, such as deforestation, farming activities, urbanization, or indirectly through human-induced climatic change (FAO, 1995, Turner, 1989).

The land surface has considerable control over the planet's energy balance, biogeochemical cycles, and hydrologic cycle, which in turn significantly influence the climate system (Turner et al., 1994; Bastiaanssen, 1995). Indeed, land cover is the biophysical state of the earth's surface and immediate subsurface (Turner et al., 1995). Changes in the land cover, including the savannahs, play a major role in global environmental change and could therefore lead to significant shifts in the earth-atmosphere interactions. The resultant global climate change may in turn force changes in land-use and land-cover, a cyclical process that may culminate in desertification and abandonment of land (Glowa-Volta Proposal, 1999).

Part of the energy reaching the ground is reflected directly, while another fraction, dependent on the vegetation cover, is utilized for photosynthesis and evaporation of free water or of water transpired by vegetation (Leroux, 2001). The remaining energy is absorbed by the soil, which reradiates at longer wavelengths and in its turn warms the overlying air. Therefore, variations in vegetation cover and physical characteristics of the land surface such as albedo, emissivity, roughness and plant transpiration could be the critical parameters to generate variations of weather and climate by altering the hydrologic cycle and land-atmosphere energy fluxes (Avissar et al., 1989).

In West Africa, hydrologic interactions between the atmospheric water content and vegetation layer enable specific hydrological processes to potentially have an impact on the evapotranspiration flux into the atmosphere (Marengo et al., 1997). The last droughts had severe impacts in the savannah environment of West Africa, and they occurred simultaneously with a rapid increase in the population of the area. The population of five Sahelian countries (Senegal, Niger, Mali, Sudan and Chad), for example, rose from 20 million in 1950 to 55 million in 1990, and is projected to rise to over 135 million by 2025 (WRI, 1994). This rise in population, as well as political constraints on nomadism (Middleton, 1999), could cause extensive land-cover conversion. In Sub-Saharian Africa, increased food production, food security, and poverty alleviation will require the intensification of agricultural production (Vlek, 1993). Overgrazing of the natural rangelands by livestock, natural vegetation conversion to agricultural land, agricultural intensification and an increased fuel-wood extraction, coupled with severe drought, are the most cited causes of land degradation in the Sahel

(Dregne and Chou, 1992; Middleton, 1999; Stephenne and Lambin, 2001). Previously uncultivated areas experience agricultural expansion as a result of migration into unsettled areas, aided by newly developed technologies (Goritz 1985; Goudie, 2000).

Some authors have challenged the view of large-scale land degradation (Nicholson et al., 1998; Nicholson, 2002) based primarily on satellite data from the late 1970s. Their investigations show that during the 1983 to 1988 period, the albedo change rate was remarkably small and in the range of 3% per year. This conclusion seems to be a major contradiction to previous studies by Charney (1975) or Entekhabi et al. (1992) supporting the hypothesis that a feedback between the atmosphere and surface hydrology has played a role in the droughts in the Sahel region.

Vegetation cover has been identified as one of the most important biophysical parameters of terrestrial surfaces due to its specific role in geosphere-biosphere-atmosphere interactions (Mennis, 2001). This parameter regulates the energy (including water) exchanges between the earth-atmosphere interfaces, and dominates the functioning of hydrological processes through modification of interception, infiltration, surface runoff, and its effects on surface albedo, roughness, evapotranspiration, and root system modification of soil properties (Middleton et al., 1997). Vegetation density is the parameter that controls the partitioning of incoming solar energy into sensible and latent heat fluxes, and changes in vegetation cover will result in long-term changes in local and global climates, which in turn will affect the vegetation growth (Dickinson and Henderson-Sellers, 1998; Lean and Warilow, 1989). Changes in the vegetation cover will have an impact on the water recycling function and therefore on the role of the vegetation in the hydrological cycle.

Evapotranspiration is a major component of the hydrological balance representing the water flux that returns to the atmosphere from land surfaces. On the global scale, it represents more than 60% of precipitation inputs (Vörösmarty et al., 1998) and, for example more than 70% of the annual precipitation of the United States (Brooks et al., 1997). In general, forest ecosystems have higher ET rates than non-irrigated agricultural or urban settings (Arnold and Gibbons, 1996). In the Volta Basin, West Africa, most evapotranspiration also consists of plant transpiration, and vegetation determines to a large extent the exchange of latent heat and momentum between the atmosphere and the earth surface (Glowa-Volta Proposal, 1999). A thorough knowledge of the vegetative cover in this basin is of great importance for studying the variability of evapotranspiration across different *LULC* types. Estimation of evapotranspiration has been investigated since the operation of earth resource satellites in the 1970s, and many remote-sensing-based evapotranspiration estimation techniques have been developed (e.g., Jackson et al., 1977; Moran and Jackson, 1991). Models such as Soil Vegetation Atmosphere Transfer Schemes (SVATS), Surface Energy Balance Index (SEBI) and Surface Energy Balance System (SEBS) have been widely applied in estimating spatially distributed energy balance equation components. Satellite remote sensing is a powerful tool providing a viable source of data from which updated land-cover information can be extracted efficiently and cheaply in order to inventory and monitor these changes effectively (Mas, 1999; Skole and Tucker, 1994). Remotely sensed data combined with ground data could be used to estimate surface energy fluxes, the partitioning of net available energy from incoming short and long wave radiation in general, and the spatial and temporal variation of the actual evapotranspiration using the Surface Energy Balance Algorithm for Land (*SEBAL*) model based on the energy balance approach (Bastiaanssen et al., 1998a, 2000)

The present work is part of **the Glowa Volta sub-project L4 Vegetation characterization and modeling** (Glowa-Volta Project Proposal, 1999). Within the Glowa Volta Project, management of surface water and the extension of irrigated agriculture are of extreme interest. One main concern is how to mitigate water scarcity in the basin. The main object in this study is to assess water loss to the atmosphere during times of limited water availability. For this, direct field measurements with the sap flow technique and the energy balance method with hydrological modeling and integrated with remote sensing data were combined to assess the status of evapotranspiration for different landscape parameters in the Navrongo area of the Volta Basin. The Surface Energy Balance Algorithm for Land (*SEBAL*) model and meteorological data will be employed to assess the spatial and temporal variation of ET_a. Landsat images acquired at two major time periods will be used to study the spatial distribution of the ET_a at the beginning and the end of the dry season in the Navrongo area. Field and satellite data will be integrated to characterize the landscape in terms of different parameters such as *LULC* types, hydrological units and tree density. Finally, the variability of evapotranspiration across these land units during the two dates will be evaluated.

1.1 Problem statement

Land use and land cover is increasingly recognized as being an important driver of global environmental change (Turner et al., 1994). To ensure a sustainable management of natural resources, it is necessary to understand and quantify the processes of landscape change. Patterns of landscape modification are the results of complex interactions between physical, biological and social forces (Turner, 1987). The changes in land cover, in particular tropical areas, have attracted attention because of the potential effects on erosion, increased run-off and flooding, increasing CO_2 concentration, climatological changes and biodiversity loss (Myers, 1998; Fontan, 1994). The amount, spatial distribution, and temporal pattern of vegetation are some of the most important physical properties of terrestrial surfaces, because they control the partitioning of the energy fluxes, hydrological fluxes through modification of the surface albedo, surface roughness, and soil moisture (Commeraat and Imeson, 1999). Large changes in vegetation distribution and composition will likely affect local climate, which in turn will modify the amount and distribution of vegetation. Monitoring the dynamics of vegetation and characterizing its spatial distribution will provide important indications about the changing environment and enable a better understanding of the physical processes across the geosphere-biosphere-atmosphere boundaries.

To understand and predict change processes, one needs to monitor and characterize spatial patterns of land-use and land-cover change. Field-based studies allow the observation and description of processes of land-cover change in a detailed and spatially disaggregated way. Such studies describe the interactions between human activities and their environment and thus highlight the driving forces of land-cover change (Lambin and Ehrlich, 1996). However, field studies are generally not sufficient to quantify and analyze all spatio-temporal patterns of land-use and land-cover changes at an aggregated level (Liverman et al., 1998).

Generally, land-use change in West Africa and especially in the the Volta Basin means intensification of the agricultural use of the land (Ademola, 2004; Duadze, 2004; Glowa-Volta project, 1999). Agriculture is intensified through reduction of the land under fallow and increased inputs in the form of labor, chemicals, and irrigation. Changes in the vegetation are, of course, the first and foremost result of land-use intensification. In turn, changes in vegetation may have desirable outcomes among others increased food security and rural income, but also negative ones such as diminishing soil nutrient status or intensified erosion (Ademola, 2004; Glowa-Volta, 1999). Land-use and land-cover change also plays a role in the capacity of the vegetation layer's water transpiration function in the hydrological cycle. As most evapotranspiration in the Volta Basin in fact consists of plant transpiration and as vegetation also determines to a large extent the exchange of latent heat and momentum between the atmosphere and the earth surface, it is of great importance to have a thorough knowledge of the vegetative cover if one is to know the relation between land use and climate. Therefore, it is necessary to analyze the role of $LULC$ types and their dynamics on the variability of ET_a. In the past, estimation of evapotranspiration on local to regional scales have for long time been based on thermodynamic and meteorological ground-based measurements (Penman-Monteith method, Blaney-Criddle method, Pan-evaporation method). Nowadays, new direct methods are based on Eddy covariance and scintillometric measurements. The computational methods (temperature based, radiation based) for calculating potential evapotranspiration (ET_p), however, vary in data demands from very simple (more empirically based), requiring only information on monthly average temperatures, to complex (more physically based), requiring daily to hourly meteorological data such as air temperature, solar radiation, relative humidity, soil moisture and wind speed, as well as characteristics of the vegetation indices.

The major advantage of using meteorological station data for evapotranspiration estimation is the availability of data, their simplicity and easy computation. However, the main disadvantage of this approach is that those meteorological methods are all based on point measurements and are therefore not representative of a large area. The reference output at the station is always an integration of the influence of a number of variables depending on land-cover type, wind speed and direction and soil moisture. The estimation of ET at a regional scale is usually obtained by scaling up measurements at the point, and that opt small watershed scales by statistical analysis (Lu et al., 2003). However, those methods are often based on different mathematical algorithms thus providing different results at local to regional scales. A solution such as by providing a sufficient number of measuring sites through a river basin could be costly and not affordable for developing countries of Africa such as Burkina Faso or Ghana that are located in the Volta Basin.

Solutions to these problems can be approached in three ways:

1) Application of remote sensing methods such as energy balance equation of the land surface,
2) Utilization of existing hydrological modeling (Savenije, 1997),
3) Utilization of appropriate up-scaling methods to spatially integrate point data.

Each of these methods has its limitations, and an optimal procedure probably would be a combination of the three approaches. To maximally profit from remote sensing and hydrological modeling, data assimilating is gaining popularity in hydrological studies (Walker et al., 2001; Jhorar et al., 2002; Schuurmans et al., 2003) as well as in climate studies (Dolman et al., 2001). Extensive reviews of remote sensing flux determination methods have been presented by Choudhury (1989), Moran and Jackson (1991) and Kustas and Norman (1996).

1.2 Research objectives

1.2.1 The Glowa-Volta Project

Because of the huge size of the Volta Basin, remote sensing data is useful to study the whole area. To cover the basin, one would need about 400.000 NOAA/AVHRR pixels or 400 million Landsat pixels. For all information to be manageable in the Glowa Project, it may be necessary to reduce the spatial resolution of the study. A standard pixel size of 3 km x 3 km has been proposed for modeling and for basin-wide information exchange between different vegetations and the atmosphere and underlying soil (Glowa-Volta Project Proposal, 1999). Therefore, there is a need to study representative biophysical and agro-climatic zones across the Volta Basin for detailed characterization in order to understand and to capture the soil-vegetation-atmosphere interaction and determine hydrological processes.

The present "Subproject L4 - Vegetation Characterization and Modeling" analyses the main vegetation covers under different land-use types in all different ecological zones. It will also develop a classification scheme to capture the significant fractions of land-cover within a 3 km x 3 km pixel that can be used in hydrological modeling. For this purpose representative agro-ecological experimental sites were selected and located at (1) Edjura in the humid tropical savannah; (2) Tamale in the transitional dry Guinea-Sudanese savannah; (3) Navrongo, Kompienga and Dano representative of Sudanese savannah; (4) the Boudtenga experimental site near Ouagadougou representative of the Sudanese-Sahelian zone. This study focuses on the Sudanese – Savannah in the Navrongo area.

1.2.2 Specific objectives

The main goal of the study is to estimate the spatial and temporal evolution of actual evapotranspiration (ET_a) in the Volta Basin in relation to the biophysical and hydrological characteristics of the savannah landscape. The specific objectives are to:

- classify the savannah environment into relatively homogeneous *LULC* types, tree density classes and hydrological units;
- assess the spatial distribution of the ET_a over the study area using the *SEBAL* model integrated with field and remote sensing data;
- measure the hydrological contribution of principal tree species to atmospheric water vapor applying the sap flow technique;
- evaluate the temporal variability of ET_a among the main landscape components, *LULC* types, hydrological units and tree density during the dry season.

1.2.3 Structure of the thesis

The thesis is organized in five main Chapters. Chapter 1 introduces the problem and defines the major objectives of the study. In Chapter 2, special attention will be paid to the general description of the study area. The general framework used in the study is also presented along with the main components of savannah landscape suitable for explaining the ET_a variation. Chapter 3 deals with the land classification process of the biophysical and hydrological characterization of savannah landscape using remotely sensed data. The first part is based on *LULC* classification to derive different vegetation types found in the study area. It also looks at the spatial distribution of fallow vegetation related to fire traces. The second part deals with delineating homogeneous hydrological units of similar moisture conditions applying the vegetation index temperature trapezoid (*VITT*) approach. The last part is related to an approach to deriving tree density from remotely sensed spectral vegetation indices and field data. Chapter 4 examines approaches of ET_a assessment in the study area. Firstly, the *SEBAL* model based on the energy balance method is used to compute the ET_a distribution on a pixel basis. To assess the evaporative input of water vapor from savannah biophysical and hydrological components, the ET_a, at the beginning and at the end of the dry season, this parameter is compared with *LULC* types, hydrological units and tree density classes. The final part of the chapter is concerned with the application of the sap flow technique to estimate water use/transpiration of individual trees and whole stand vegetation in savannahs. Chapter 5 synthesizes the findings of the thesis. The first data set summarizes the biophysical and hydrological characterization of the savannah landscape, while the second examines the spatial distribution of the ET_a and the parameters relationships with the biophysical and hydrological units. Third data set gives conclusions and recommendations of the study.