The Distribution of Cloud Cover Over Lake Malawi/Niassa/Nyasa and Its Watershed

by

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A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF ARTS

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Abstract

This study addresses four aspects of cloud cover over Lake Malawi and its watershed, and it is a contribution to the Management Strategy for the long-term conservation of the biodiversity of Lake Malawi as it involves production of maps showing variations of the appropriate parameter under study. The first aspect of this study refers to the temporal variation of cloud cover, the second to the spatial distribution, and the third to the frequency of low, middle and high clouds. The last aspect refers to the variation of solar radiation with cloud cover. Diurnal variation of cloud cover was evaluated with ground observations. Seasonal variation was derived from NOAA-14 AVHRR daytime imagery.

Diurnally, cloud cover decreases over the lake while it increases over the watershed. The differential heating between the lake and the watershed influences the diurnal variation. Seasonally, the lake and the watershed have shown two peaks of cloud cover, one in the rainy season and one in the dry season. The movements of Inter Tropical Convergence Zone and Sub-Tropical Pressure System influence the seasonal variation.

Both the lake and the watershed presented a longitudinal gradient of cloud cover. The western lakeshore and watershed are the regions with more cloud cover. In addition, there is a latitudinal gradient in the watershed. There is more cloud cover in the north of the watershed. Topography and airflow influence the spatial distribution of clouds.

Low clouds and middle clouds are frequent all year. Over the lake, low clouds were constant, while on the watershed low clouds increased in the first months of the dry season. In both areas, the middle clouds have shown two peaks, one in the rainy season and one in the dry season. High clouds were mainly present during part of the year that coincides with the rainy season.

Correlation between cloud cover and solar radiation was made for two months, July and January. Solar radiation at the lake surface is negatively correlated with cloud cover in both months. However, the correlation coefficient for July is higher than for January. It appears that the low correlation coefficient in January is due to the type of clouds rather than amount of cloud cover.

Acknowledgements

I am deeply indebted to all: my mother Dorothea, my father José, my sisters Rita, Lulu and Tininha, and my lovely daughter Letícia, for encouragement and support to go ahead and accomplish my masters degree.

I wish to express my sincere thanks to my advisor Dr. David Barber for helpful comments on an earlier version of the thesis and the SADC/GEF, Lake Malawi Biodiversity Conservation Project for providing the satellite and the radiation datasets used in this study.

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List of Abbreviations

AVHRR	Advanced Very High Resolution Radiometer
GIS	Geographical Information System
IR	Infrared
ITCZ	Inter Tropical Convergence Zone
IOC	Interoceanic Confluence Zone
LAC	Local Area Coverage
LMBCP	Lake Malawi Biodiversity Conservation Project
NOAA-14	Satellite number 14 from the National Oceanic and Atmosphere Administration
STPS	Sub-Tropical Pressure System
VIS	Visible
ZAB	Zaire Air Boundary

Chapter I Introduction

Lake Malawi/Niassa/Nyasa (hereafter referred to as Lake Malawi), is the ninth largest lake in area in the world, but it is the third largest lake in Africa, after Lake Victoria and Lake Tanganyika. It is an important fresh-water resource for people living on the shoreline and its watershed. The people depend largely on the lake for fish, which is a very important source of protein. Not only is the lake important for food, but it also has a tremendous diversity of fish species. With an estimate of more than 600 species, Lake Malawi exceeds any other lake in the world for species diversification (Ribbink, *et al.*, 1983). As more than 90% of these species of fish are endemic to Lake Malawi (Kline, *et al.*, 1993), conservation of them is an urgent need.

Conservation of the biodiversity and sustainable management of the resources of the Lake require a good understanding of the Lake's environment and dynamics. For this reason, the three countries that share the lake: Malawi, Mozambique, and Tanzania, designed the Lake Malawi Biodiversity Conservation Project (LMBCP). This project consists of an integrated research program that focuses on three main objectives. Firstly, the project intends to develop a Biodiversity Atlas for Lake Malawi. Secondly, it aims at producing an identification guide for the fish species of the lake. Thirdly, the project will produce a Management Strategy for the long-term conservation of the biodiversity of Lake Malawi (LMBCP, 1996).

It is well known that the degree of scientific uncertainty regarding the lake and its watershed needs to be addressed if the Management Strategy for Lake Malawi is to be developed. Consequently, an improved understanding in research areas such as taxonomy, ecology, limnology, and cloud climatology will contribute significantly to the Management Strategy. In particular, clouds form an important part of the physical system associated with Lake Malawi, as they can impact both lake dynamics and erosion from the lake's watershed.

1.1 Thesis Rationale

Lake Malawi is well known for its endemic fauna. Conservation of this unique biodiversity requires knowledge of physical, chemical and biological aspects of the lake and its watershed. To date, there has not been a study which focuses on the distribution of clouds over Lake Malawi and its watershed. The absence of such studies makes the variability caused by clouds on the lake's dynamics and biological processes poorly understood. This deficiency was noted by (Symoens, *et al.*, 1981). Information on cloud climatology is critical to the overall success of the LMBCP and is vital for studies covering a wide range of concerns such as climate change, limnology, and ecology.

This study is designed to investigate the nature of spatial and temporal variability of clouds over and around Lake Malawi. It will provide estimates of cloud amount, cloud altitude, and effects of cloudiness on solar radiation. This information will be useful to the LMBCP as it involves production of maps showing variations of the appropriate parameter under study. Therefore, this study acts as a baseline that will provide preliminary results on cloud climatology on Lake Malawi and its watershed.

1.2 Thesis Objectives

The objectives of the thesis are as follows:

1) to determine the temporal variation of cloud cover over Lake Malawi and its watershed;
2) to determine the spatial distribution of cloud cover over Lake Malawi and its watershed;
3) to assess the frequency of low, middle and high clouds over Lake Malawi and its watershed;
4) to examine the variation of solar radiation with cloud cover over Lake Malawi.

1.3 Thesis Structure

This thesis is structured in a series of six chapters. Chapter 1 provides an introduction and a scientific rationale for this work. Chapter 2 is a background of the pertinent literature required to understand the ramifications associated with each of the stated objectives. Chapter 3 describes the main characteristics of physical geography and climate of the study area. Chapter 4 presents the data and methods used to compute the temporal and spatial distribution of cloud cover, the frequency of low, middle and high clouds and the relationship between cloud cover and solar radiation. Chapter 5 is devoted to the presentation of the results and detailed discussion. Finally, in Chapter 6, a summary of the significant conclusions of the study and recommendations for further research is given.

Chapter II Background

In this background, clouds are examined from a variety of perspectives, each which are important to the study of clouds in the Lake Malawi region. Section 2.1 of this chapter describes pertinent literature relating clouds to water exchanges (evaporation and precipitation). This background is critical to understanding the role which clouds play in water balance. Section 2.2 focuses on the role that clouds play in fluxes of energy between the atmosphere and the Earth's surface. This section examines the role which clouds play in evaporation and the thermal stratification of Lake Malawi. This background concludes with section 2.3, which addresses the relevant remote sensing approaches for the detection of clouds.

2.1 Cloud and water exchanges

Clouds play an important role in the hydrological cycle, which is an essential process in the earth's climate (Neuberger and Cahir, 1969; Rossow and Garder, 1993). Through precipitation, clouds play a critical role in the hydrologic cycle of Lake Malawi. For example, precipitation over the lake is its main source of water supply. About, 41 $km^3\ y^{-1}$ of the water of the lake comes from precipitation, compared to only 29 $km^3\ y^{-1}$ from the main inflow rivers (Crul, 1995). The inflowing rivers and the unique outflowing River Shire make minor contributions to variations in water level of the lake.

The water level of Lake Malawi is strongly related to rainfall and evaporation and is highly coupled to short, and long-term climate variation. Variability in climate, mainly precipitation, can result in changes in the status of Lake Malawi, i.e., closed/open basin (Spiegel and Coulter, 1996). In the past years, Lake Malawi has had a closed-basin status because of its narrow-basin shape. Probably, this status occurred because of a deficit in the water balance, mainly lower precipitation and/or higher evaporation causing lowering of level below the outlet. Increasing precipitation, as well as water input from the rivers relative to evaporation, caused the lake level to rise, extend its shores and attain an open-basin status until the present time (Spiegel and Coulter, 1996).

Significant changes in water level in Lake Malawi affect the ecosystem directly. For example, the vast majority of rock-dwelling cichlids species occur in a depth range of 3-10m, which enables vertical immigration (Ribbink, *et al.*, 1983). Less than 5% of the potentially habitable substrata of Lake Malawi is suitable for rock-dwelling species. Some of the species are endemic to only one particular island, or are geographically restricted to parts of the rocky shore (Hert, 1990). Decreasing water levels reduce the size of the habitat available for fish, thereby limiting their vertical distribution. In addition, it increases competition for space and food source among the fish, thus contributing to losses of fish diversity in Lake Malawi.

Direct rainfall over the lake may provide a large part of the nutrient supply (e.g., phosphorus) which is important for primary production. It is estimated that rainfall provides an estimated 7.8 mmol m^{-2} yr^{-1} of phosphorus input to Lake Malawi (Mwita *et al.*, 1999). A geographic comparison of wet phosphorus deposition with other lakes, (e.g., Lake Valencia, Uganda, Colorado Mountains) shows that Lake Malawi has higher atmospheric phosphorus deposition (Mwita *et al.*, 1999). Domestic cooking and vegetation clearance are potentially contributory to the atmospheric loading of phosphorus in Lake Malawi (Mwita *et al.*, 1999).

The watershed of Lake Malawi is susceptible to erosion processes. In areas of steep topography, characterized by high rates of precipitation, large quantities of sediment can be washed down the slopes after heavy rainfall. Much of this sediment ends up directly in the lake or in streams and rivers that flow into the lake. Once in the lake, the deposition of sediments can have a negative impact on the lake's ecosystem. Nearly all cichlids in the lake feed on aufwuchs, a conglomeration of algae that form a mat over hard substrate (Konings, 1995). Sediment deposition over the aufwuchs dramatically reduces its productivity. Hence, losses in biodiversity as well as a decrease in fishery potential can occur as a result of erosion and sedimentation.

2.2 Cloud and energy exchanges

Solar radiation is an important variable in the surface energy budget (Rossow and Garder, 1993; Sohn and Robertson, 1993). However, most of the clouds reflect the incoming solar radiation back to space, thereby reducing the energy within the earth-atmosphere system (Sohn and Robertson, 1993). On average, clouds cover about half of the globe giving them a major influence on the planetary radiation balance (Petterssen, 1969; Critchfield, 1983).

The amount of solar radiation reaching the bottom of the atmosphere is affected by the distribution of cloud cover. For a particular region, the lower amount of radiation that reaches the land-water surface is due to the greater cloudiness of that particular region (Barry and Chorley, 1968; Mason, 1975). For example, the maximum total annual solar radiation reaching the earth's surface is found not at the equator, but rather at about latitudes 20° N and 20° S (Trewartha and Horn, 1980). Even with the perpendicular rays reaching the surface, the lesser amount near the equator is due to the greater cloudiness of the equatorial region (Barry and Chorley, 1968). In general, clouds enhance the reflection of solar radiation thus cooling the earth-atmosphere system (Wielicki *et al.*, 1995).

Solar radiation received at the surface is also affected by the type of cloud. The reflection of clouds varies considerably with thickness (Figure 1).

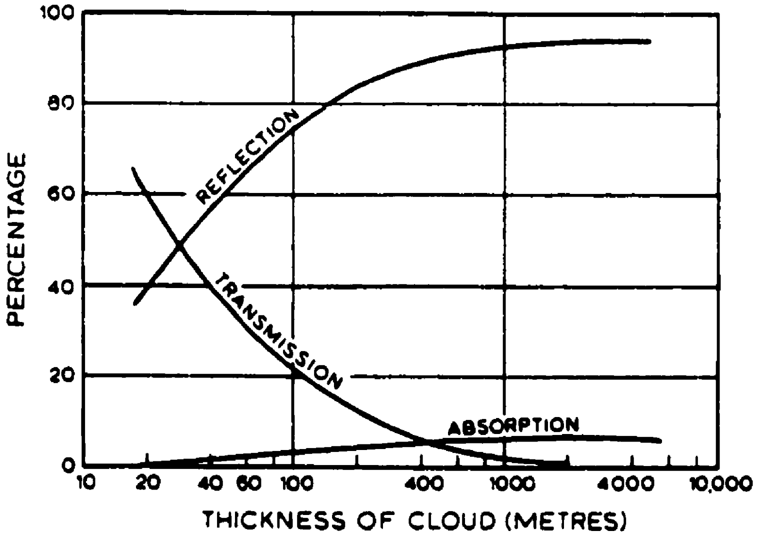


Figure 1. Percentage of reflection, absorption and transmission of solar radiation by cloud of different thickness (Adapted from Hewson and Longley, 1944).

For example, thick clouds, on average reflect about 70-80% while thin clouds reflect between 25-50% (Critchfield, 1983). Measurements have shown that the reflection of a complete overcast sky ranges from 44 to 50% for cirrostratus to 90% for cumulonimbus (Barry and Chorley, 1968). Particularly, high convective clouds have a twofold affect on solar radiation. Firstly, they reduce the surface solar radiation by reflecting it back into space. Secondly, they increase local surface solar radiation by reflecting radiation off their sides due to their vertical and limited horizontal size (Gautier, 1988). The absorption of solar radiation by cloud is a minimal part of the total atmospheric transmission (Figure 1), but can increase significantly when water in liquid form is available within the cloud.

Reflecting part of the incident solar radiation, clouds have a direct influence on evaporation from Lake Malawi. Although, the water balance of the lake is mainly controlled by rainfall, it is also greatly affected by evaporation, while river inflow and outflow contribute the least. Evaporation accounts for 54 km^3 y^{-1} of the water loss from the lake (Crul, 1995). Only 20% of the total annual water loss from the lake is due to the Shire River outflow (Wuest *et al.*, 1996), which at present is estimated to be about 12 km^3 y^{-1} (Crul, 1995).

Seasonal variations in radiation are responsible for variations in water surface temperature of Lake Malawi. The absorption of radiation in water is the principal cause of thermal stratification on the lake (Spiegel and Coulter, 1996). Ramanathan and Collins (1991) have suggested bright clouds act as a 'thermostat' that resists warming of the tropical oceans. On Lake Malawi, cloud cover has a cooling effect in the rainy season (Crul, 1995). Unfortunately, the work by Crul (1995) does not provide information about the amount and type of clouds that produce this cooling effect.

Solar radiation is also an important component to the lake's primary productivity. Light measurements carried out in 1980 appeared to be relatively constant through the year (Degnbol and Mapila, 1982 in Crul, 1995). The seasonal difference in photosynthesis is related with amount of nutrients in the epilimnion (Crul, 1995).

In addition to the effect on the shortwave radiation, clouds also affect the outgoing longwave radiation. They can reduce the longwave energy loss to space that is emitted from the earth's surface and the lower atmosphere (Dhuria and Kyle, 1990; Sohn and Robertson, 1993). The high cloud tops in the tropics tend to be bright and cold, thus they diminish considerably outgoing longwave radiation (Harshvardhan *et al.*, 1990; Schmetz *et al.*, 1990). This process of reducing the outgoing radiation, referred to as the cloud greenhouse effect, can result in an increased surface temperature.

On the other hand, in the tropics the lowest layers of the atmosphere generally have a very high water-vapor content that essentially saturates most of the longwave spectrum of the downwelling radiation (Harshvardhan *et al.*, 1990). This water vapor can balance the greenhouse effect. The presence of an emitting cloud base does not result in much enhanced downward longwave radiation in the tropics. The downward radiation from the cloud base is a major component of the downward longwave flux, unless the cloud base is very high (Harshvardhan *et al.*, 1990). Dhuria and Kyle (1990), indicate that decreasing the cloud altitude and/or the cloud amount in the tropics tends to increase the outgoing longwave radiation.

2.3 Cloud cover and remote sensing

Since the 1960s, knowledge and understanding of the atmosphere has been improved through the use of satellites. Today, more advanced technology on board satellites enables the scanning of the earth and its atmosphere both during the day and at night. The many capabilities of satellites allow mapping of a wide range of parameters valuable to cloud research. These parameters include cloud cover, movement of cloud, cloud types, cloud heights, storm systems and precipitation (Barret and Martin, 1981; Bunting and Hardy, 1984; Lo, 1986; Cracknell and Hayes, 1991). Furthermore, satellites enable the collection of such information over spatial scales unavailable to surface-based instruments, and over temporally complete season and inter-annual scales.

Satellite-based remote sensing of cloud climatology has recently witnessed the advent and rapid development methodological approaches. The retrieval of cloud information from satellite data may be accomplished using either manual or automated means. The former is implicit in the typical satellite nephanalysis methods, where cloud fields are classified according to certain broad-scale characteristics (Harris and Barret, 1978; Mcguffie and Robinson, 1988). For clouds occurring on the scale of a pixel or a small collection of pixels, manual methods may still be employed although they are time-consuming when compared with the use of automated means.

During the last decades, a large number of automated cloud-monitoring techniques using visible (VIS) and infrared (IR) portions of the electromagnetic spectrum have been developed, with varying degrees of complexity (Harris and Barrette, 1978; Stowe *et al.*, 1988; Welch, *et al.*, 1992). Visible images are caused by reflected sunlight from the top of clouds that strikes a satellite sensor and causes the sensor to measure the intensity of radiation in the visible portion of the electromagnetic spectrum (Figure 2). A satellite obviously cannot collect visible images at night since sunlight is needed to produce images. To overcome this problem, IR images are used. Infrared sensors measure the intensity of IR radiation (Figure 2). This range of the electromagnetic spectrum is used to measure the amount of heat that is radiated from the tops of clouds.

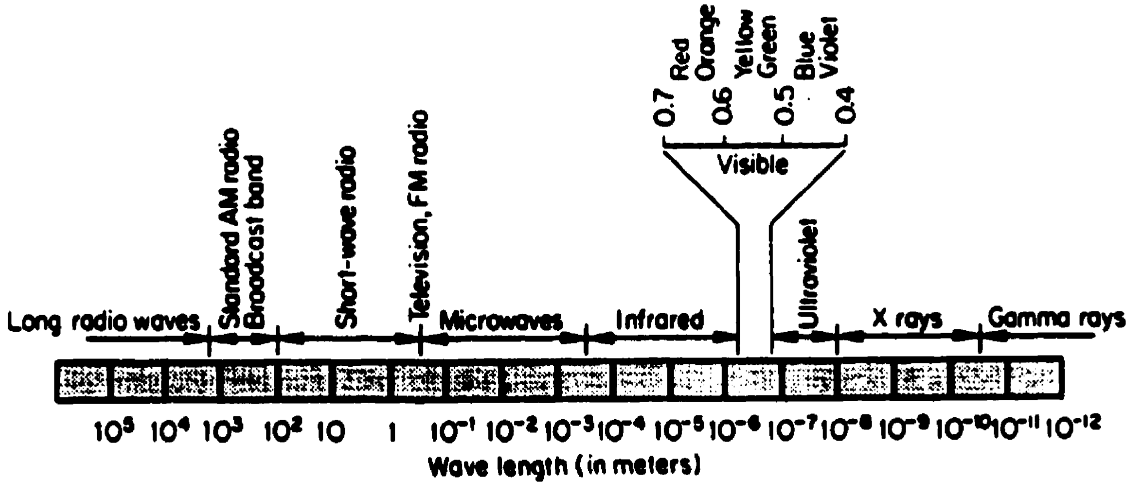


Figure 2. The electromagnetic spectrum (Adapted from Critchfield, 1983).

Cloud classification is best achieved using combinations of visible and infrared data. These data can provide a great range of characteristics, notably the cloud reflectance, which is a function of cloud optical thickness, cloud morphological characteristics (texture, form), and cloud level which is a function of cloud top temperature. However, no technique is able to deal effectively with all types of cloud conditions. Therefore, different kinds of techniques have been proposed to detect clouds from satellite imagery. These techniques can generally be divided into two classes: those physically based (thresholds); and those using statistical assumptions.

The threshold technique treats each pixel independently and uses the simplifying assumption that the pixel is either completely clear or cloud-covered, depending upon whether the satellite-measured radiances are greater or smaller than the threshold value. In other words, if f is the fraction of the pixel covered by clouds, f is allowed only the values 0 and 1 (Rossow, *et al.*, 1985). Thresholds can be entered into cloud detection algorithms in at least four ways. Firstly, they can be empirical constants so that the same constants are applied to all samples of imagery data. Secondly, they can be derived from weather or geographical databases. For example, infrared thresholds can be derived from surface reports of temperature that are sampled over many landmasses (Bunting and Hardy, 1984). Thirdly, thresholds can be derived from the image itself if the area includes clear and cloudy areas (Rossow and Gardner, 1993). Finally, to ensure that these thresholds represent clear/cloud boundaries, and not cloud-layer boundaries, they can be determined from a series of images at different times, and the extreme radiance (dark visible or warm infrared) can be used as the threshold (Donald *et al.*, 1992).

Statistical techniques for cloud detection are more complicated than simple thresholds. Statistical methods compare adjacent pixels in the field rather than on a pixel-by-pixel basis. The linear regression analysis method is often used to derive associations between the satellite sensor response and a conventionally measured parameter under a wide range of conditions. These techniques are called clustering algorithms, which attempt to find natural groupings of pixels in an image (Arking and Childs, 1985).

Statistical methods have the advantage of forming natural data groupings without a prior classification, and they are sometimes described as unsupervised procedures that produce unlabeled categories. These methods are especially proposed to deal with clouds that fill only part of a pixel (Chou, *et al.*, 1986). If the cloud layers are generally larger than the pixels, and the cloud and surface radiance are fairly uniform, then those pixels (clear and cloudy) will tend to cluster in the multi-dimensional scatter plot, while pixels with values between 0 and 1 will spread out (Arking and Childs, 1985; Desbois, *et al.*, 1982). The number of clusters to be found may be limited, but the algorithms are otherwise free to find as many clusters as the image suggests.

All cloud algorithms consist of two basic steps, i.e., cloud detection, and cloud analysis. The first step separates the radiance values into those representing clear and cloudy scenes. The second step involves the quantitative determination of cloud proprieties from the measured radiance. This step may be as simple as counting cloudy pixels to obtain a single cloud parameter (e.g., cloud cover) or as complex as utilizing radiative transfer models to obtain a set of cloud proprieties. For the latter, each algorithm is built on assumptions regarding which atmospheric, surface and cloud proprieties affect the satellite measurements and by how much (Carleton, 1991). In principle, although the respective radiative model may distinguish different algorithms, any radiative model can be employed to obtain cloud properties with any cloud detection logic (Arking and Childs, 1985).

Although several methods already exist for the assessment of the amount and properties of cloud through satellite imagery, there is no widely accepted scheme for automatic cloud detection. The determination of reliable information of cloud cover and their properties from a satellite needs to account for varying important aspects. Examples include natural aspects such as effects of atmospheric absorption, scattering and reflection by atmospheric gases, attenuation by aerosols, and changes in solar elevation according to time of day and season. In addition, technical aspects like changes in the sun-earth-satellite geometry and the sensor spectral resolution need to be considered (Barker and Davies, 1989 in Carleton, 1991).

Cloud information from satellites is dependent, to a large degree, on the nature of the underlying surface cover type, and its change in time. The task is relatively easy over the water surfaces of oceans and lakes, but much more difficult over land. Land is characterized by large spatial variations in reflectance and infrared temperature (Rossow, *et al.*, 1985). In some cases, the infrared radiation from the ground combines with the radiation from the cloud and gives the cloud a digital value indistinguishable from the surface. Some of these difficulties occur even over water surfaces. As an example, a thin cirrus cloud may be undetected over a water surface for the same reason as previously indicated (Matthews and Rossow, 1987).

The spatial resolution of satellite measurements affects the results of all algorithms. When pixel size is larger than individual cloud elements, then the varying fraction coverage of the pixels produces a wide scatter of radiance values. Consequently, difficulties in estimating cloud cover are likely to occur for certain kinds of cloud, such as small clouds (e.g., cumulus). There is a high likelihood that for a threshold method, f is neither zero nor one, but somewhere in between (Arking and Childs, 1985). In other words the larger the pixel, the less accurate the results are because the greater the likelihood that f is neither 0 nor 1. Higher spatial resolution sensors such as Advanced Very High Resolution Radiometer (AVHRR) clearly decrease the error in this assumption. For example, the AVHRR sensor is capable of identifying small-size clouds such as fair-weather cumulus clouds (Phulpin *et al.*, 1983).

The threshold technique tends to exaggerate the tendency noted from surface observations of cloud clover, so that when the sky is mostly cloud-covered but has gaps present, the satellite may compute a complete overcast for a particular pixel. In other words, clear or overcast skies tend to occur more often than partly cloudy skies (Carleton, 1991). Fixed thresholds can be useful for restricted areas such as oceans and lakes. Water surfaces are usually quite dark in the visible bands with the exception of the reflection known as sunglint (usually brighter than clouds), when sun and satellite angles are equal in the same plane. Therefore, these areas should not be processed in visible images (Schott and Henderson-Sellers, 1984; Saunders, 1985). Lake and ocean surface temperatures vary slowly during the day and from day-to-day, so that a fixed temperature threshold may be useful within restricted latitude ranges and times of year (Rossow *et al.*, 1985).

A great limitation of the algorithms is that they may not be transferable without modification to other climatic regimes or latitudes. For example, cloud detection utilizing visible and/or thermal infrared data and developed for tropical regions will not be directly applicable to semi-arid or arid land areas where the sub-cloud layer is much drier (Griffith *et al.*, 1981). Nowadays, many modifications and combinations of the statistical and threshold cloud retrieval methods are still being developed as ways to increase information taken from satellite as reliably as possible.

Chapter III Study Area

In this chapter, information is provided on the main characteristics of physical geography and climate of Lake Malawi and its watershed. Section 3.1 describes the geographical location and characteristics of Lake Malawi and its watershed, while section 3.2 describes the climate of this region. This section also includes a description of wind, cloud, and solar insolation patterns in the region of Lake Malawi.

3.1 Geographical Location

Lake Malawi lies in Southern-central Africa, located in the southern end of the East African Rift Valley system. It shares boundaries with three countries, Malawi, Mozambique and Tanzania. The lake is located at an altitude of 475m above sea level with geographical boundaries at 9°30′ - 14°30′ S, and 33°50′ - 35°20′ E (Crul, 1995). It is long and narrow with an approximate length of 570km, and a maximum width of 75km (Figure 3). The lake covers a surface area of about 28,800km^2 and attains a maximum depth of 700m.

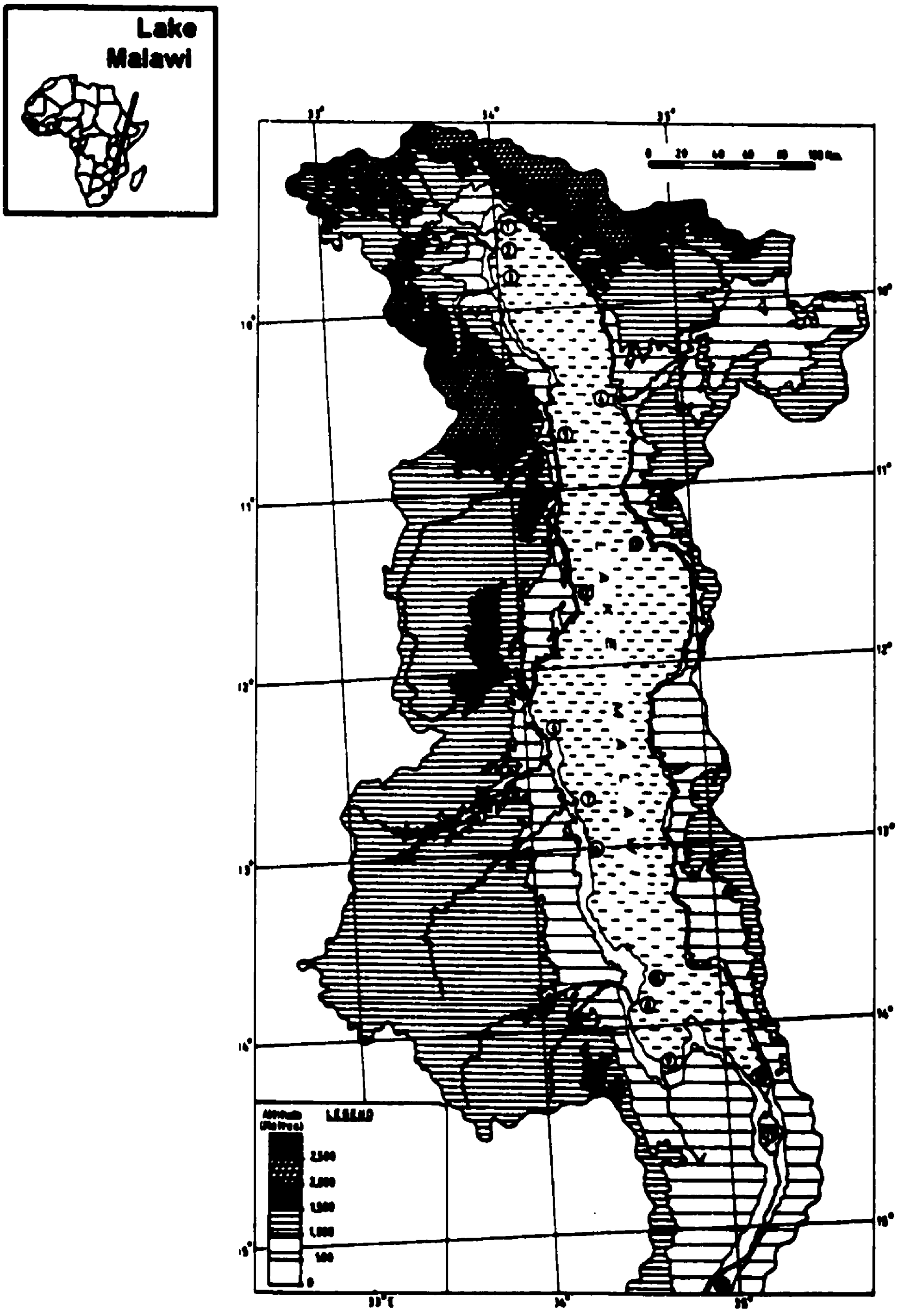


Figure 3. Lake Malawi and its watershed (Adapted from Crossley, 1984). The Lake Malawi Biodiversity Conservation Project research station was located at (13°42′ S, and 34°37′ E), the western lakeshore (left side of number 15 in the figure).

The total watershed area of Lake Malawi covers parts of Mozambique, Tanzania and Malawi. Its approximate area of 97,700km^2 (126,500km^2 including the lake) lies mostly within the country of Malawi. South of latitude 11° on the eastern side of the lake, the watershed is narrow (Figure 3). North of this line, the watershed widens to include the Ruhuhu River located in Tanzania. From the northwest point to the south, it follows first the Malawi-Zambia border, and next the Malawi-Mozambique borders.

The watershed of Lake Malawi is a land of considerable variety of sharp contrasts in landscape. The major geographical feature marking the watershed from north to the south is a series of faults, known as the Rift Valley system. The topography of the watershed area has two main features, i.e., the plateau region and the highland areas. The western plateaus vary between 760 and 1500m above sea level, with gentle slopes interspersed by broad valleys, while the highland areas are rugged steep areas of granite and other crystalline rocks (Moyo, *et al.*, 1993). Generally, in the western lakeshore the land rises smoothly towards the western crest of Rift Valley (Figure 3). About two-thirds of western shoreline are characterized by gently sloping sandy beaches or swampy river estuaries (Crul, 1995).

On the eastern side, the watershed varies considerably throughout the area. It consists of a series of plateaus, while in many regions is broken by highlands (Hatch, 1972). The plateau begins at about 300m above sea level rising steadily to about 2000m in many areas (Berry, 1971). There is a general rise in altitude from the eastern lands towards the lakeshore that delineates the eastern crest of Rift Valley. The highlands can reach altitudes above 2500m. The eastern shoreline of Lake Malawi is characterized by steep slopes at many places.

3.2 Regional climate

The climate in eastern Africa is one of the most complex in the African continent, and remains a subject of scientific debate (e.g., Kenworthy, 1971; Torrance, 1972; Nicholson, 1996; Rozanski, *et al.*, 1996). This climate is associated with regional factors and changes rapidly over short distances, hence, only a few generalities can be made concerning the region as a whole or its link to global climate (Nicholson, 1996). The latitudinal extent of Lake Malawi and the great variations in altitude (topography of the watershed) are responsible for these complex climatic conditions. In general, the climate varies from tropical to sub-tropical, ameliorated by influxes of maritime air mostly from the Indian Ocean (Moyo, *et al.*, 1993). At the southern end of Lake Malawi, the climate is affected by the Southern Hemisphere Sub-Tropical High Pressure System, (STPS), (Torrance, 1972).

Variations of topography creates various microclimates that are experienced in different areas, even those located at the same latitude, e.g., Likoma Island, Chintheche, and Mzimba (all located at 12° S). These regions display very different patterns of rainfall (Malawi Government, 1983). Another example are the Shire Highlands in the south that experience annual rainfall of up to 2500 mm, while areas in the Shire Valley have as little as 375 mm of rainfall per annum (Moyo, *et al.*, 1993).

There are two main seasons in Malawi: 1) the rainy season that lasts from November to April; and 2) the dry season which lasts from May to October (Chi-Bonnardel, 1973). During the rainy season, a broad belt of maximum convective activity known as the Inter-Tropical Convergence Zone (ITCZ) invades the country from the north on its southward movement to its southern limit, and on its way back to the north. The ITCZ is the main rain system, and it marks the meeting point of North-east Monsoon air masses and the South-east Trade Winds (Figure 4).

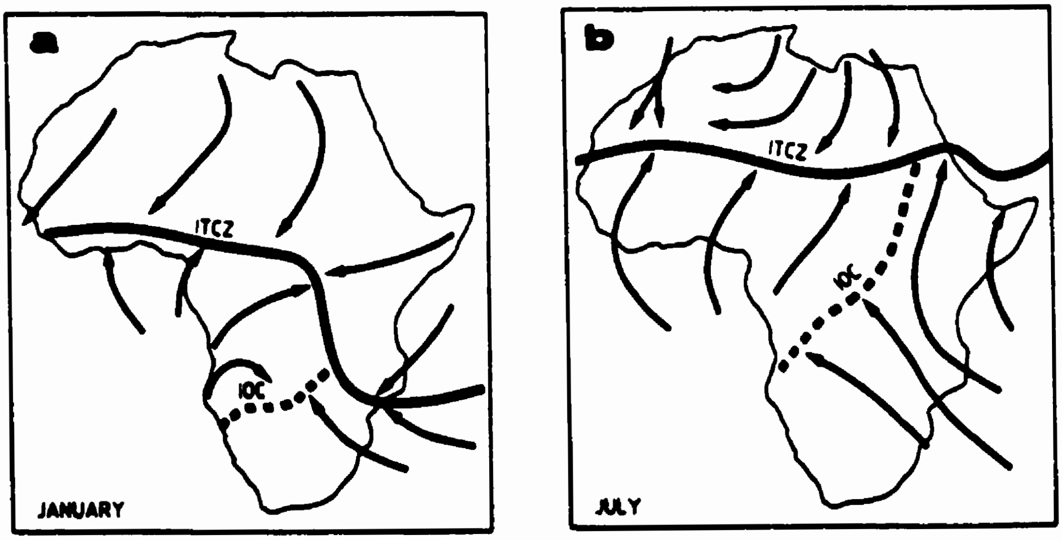


Figure 4. The seasonal displacement of the Intertropical Convergence Zone (ITCZ) and the Interoceanic Confluence (IOC) in (a) January and (b) July. (Adapted from Lacaux *et al.*, 1992).

The other system is the moist Zaire Air Boundary (ZAB), which marks the boundary between the Indian Ocean southeast trades and the South Atlantic air that reaches Malawi via Zaire. This system is also known as the Interoceanic Confluence Zone (IOC) (Figure 4). The ZAB system also brings widespread rains, which becomes heavy when associated with the ITCZ (Pike and Rimmington, 1965). The variable date of establishment of the ITCZ over the Malawi region determines the length of the rainy season. Occasionally, the Lake Malawi region is affected by tropical cyclones that originate from the Mozambique Channel in the Indian Ocean. Depending on its position over the Mozambique Channel, a cyclone can result in either a wet or dry spell in Malawi (Torrance, 1972).

The northward movement of the ITCZ in April allows a regular retreat northwards of the main rains and the initiation of the dry season. During the dry season, the weather is influenced by the STPS. In June and July, a strong high-pressure cell over the South African coast brings cool and moist southerly air into Malawi (Figure 4). Kamdonyo (1988) claims that the cool and moist air leads to condensation when it is forced over highlands and east-facing escarpments along the lakeshore.

(a) Wind

Overall, the Malawi region is seasonally under the influence of two major airstreams. From November to April, the prevailing winds are northeast. This trade wind crosses the Indian Ocean and brings a humid air current to the region (Hatch, 1972). From April on, the prevailing wind is the southeast and, because it has again crossed the Indian Ocean, it brings humid air. July is therefore the period when the southeast airflow from the southern Indian Ocean high dominates conditions over the eastern side of the watershed (Berry, 1971). In addition, it brings rains in some regions (Hatch, 1972). The mean flow patterns of surface winds are shown in (Figure 5). Generally, Lake Malawi generates a land breeze in the night and a lake breeze in the daytime with a substantial moderating effect on the winds in its vicinity (Crul, 1995).

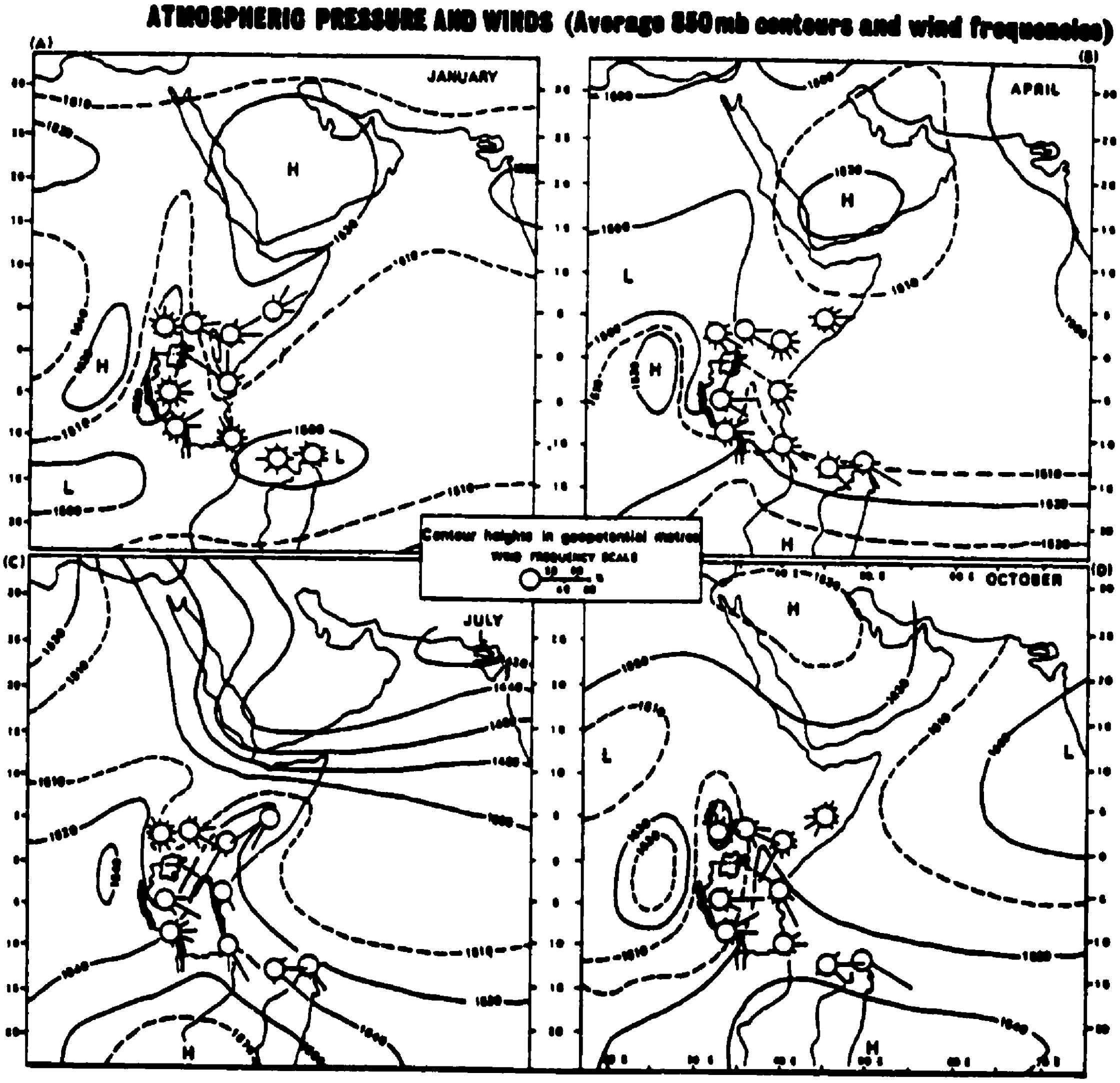


Figure 5. Mean surface airflow patterns for the months January, April, July and October in the east of Africa (Adapted from Berry, 1972).

There are seasonal variations in wind speed with an increase in the dry season (Crul, 1995). The wind pattern on individual days varies greatly. The most important factor affecting local wind patterns is the topographic features of the Lake Malawi basin and the rift escarpments (Malawi Government, 1983). During June, July and August the wind can reaches speeds in excess of 15m/s, which can persist for periods of several days (Spiegel and Coulter, 1996). Diurnal patterns of winds over the lake are generally low with a nighttime minimum; speeds up to 8m/s are common at night and 11m/s during the day (Berry, 1971).

(b) Cloud cover

There is a serious shortage of research pertaining to clouds in the Lake Malawi area (thus the reason for this thesis topic). There are however, a few summary conditions that set the stage for the more detailed research that is presented in subsequent chapters.

Cloud cover in Malawi is influenced by convective motion and orographic processes (topography of the region). Deep convection is the cause of most rainfall in the tropics, as it is a major aspect of the tropical atmosphere (Riehl, 1954, cited by Kilonsky and Ramage, 1976). The early rains in November are due to moist southeast air masses producing convective thunderstorms as they pass over the highlands and rift escarpments (Shela, 1990). Generally, in Malawi the thunderstorm effects and convective showers occur late in the afternoon when local heating is greatest. In other words, on land higher cloud coverage will probably occur late in the afternoon (Malawi Government, 1983).

The southeast trade winds are succeeded by the ITCZ and ZAB winds, which cause widespread medium to heavy storms across the region during the rainy season. After the rainy season in May, the cloud cover is again influenced by the moist southeast trades that get re-established after the ITCZ has moved northward. Shela (1990) indicated that in May rain occurs mainly over the highlands and southeast-facing escarpments. Therefore, highlands of steep topography facing the prevailing southeast winds of the region lead to high-cloud cover.

In Lake Malawi, cloud cover is influenced by lake-land temperature differences (Malawi Government, 1983). As an example, cloud cover on the lakeshore occurs with a greater percentage in the early hours of morning. As the land cools down during the night, convectional storm activity is likely to occur over the relatively warmer waters of the lake (Malawi Government, 1983). During the day, the situation is reversed. Usually, there is a descending air cell over the lake that leads to scattered or absent cloud cover over the lake, while clouds are formed over nearby land (Symoens *et al.*, 1981).

(c) Sunshine

The number of hours of sunshine varies seasonally with the maximum occurring in September or October, while the minimum is in December or January when cloud cover is greatest (Malawi Government, 1983). Areas of low rainfall have the highest sunshine hours. Particular to the western region, the maximum sunshine occurs in the rain shadow areas of the Shire Valley and southern lakeshore (Malawi Government, 1983). Mountainous and high plateau areas, which tend to be wet and cloudy, have comparatively few sunshine hours (Berry, 1971; Malawi Government, 1983).

Chapter IV Data and Methods

The following sections describe the data and methods of analysis utilized to accomplish the four objectives of this study. Section 4.1 describes generally the surface and the satellite data utilized in this study. Section 4.2 describes the analysis applied in this study. This section is divided in four subsections, with each one referring to one of the stated objectives.

4.1 Data

(a) Surface data

Clouds have conventionally been reported from local land-based observations. The surface data for this study are cloud amounts, surface radiation and digital pictures taken with the use of a digital camera. Cloud data were provided from four meteorological stations around Lake Malawi (Figure 6).

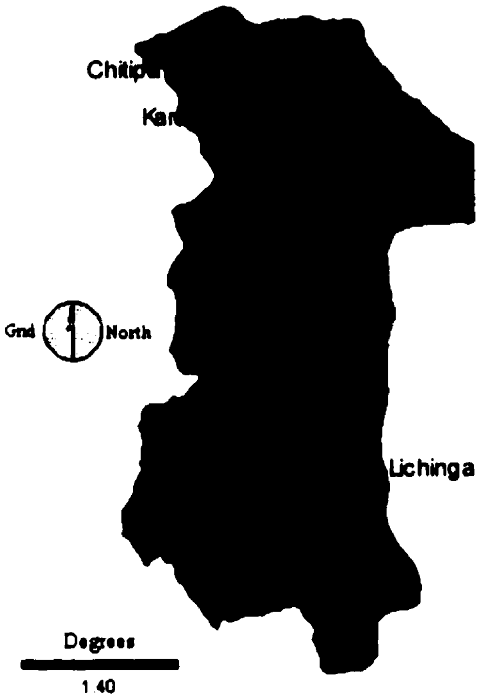


Figure 6. The watershed area of lake Malawi and the locations of the four meteorological stations.

Salima and Karonga meteorological stations are located close to the lakeshore, at an estimated distance of about 1 km from the lakeshore. Because of their locations, these two meteorological stations are suitable to evaluate the cloud variability over the lake. Lichinga and Chitipa, meteorological stations located far from the lakeshore, are more suited to evaluating cloud variability over the watershed (Figure 6).

The Malawi Meteorological Department provided monthly means of cloud cover for Salima, Karonga and Chitipa. In addition, for Salima annual hourly means were provided.

Mozambique Meteorological Service provided data of cloud cover for Lichinga and pertain to monthly means and annual hourly means.

Pictures were taken with a Nikon 600 digital camera. They were taken vertically with the camera facing the sky directly at the LMBCP research station (13°42′ S, and 34°37′ E). Seventy-three pictures (from February to June 1999) were used in this study.

The solar radiation measurements at the surface were taken using a Campbell LI200X model pyranometer calibrated for the daylight spectrum (400 to 1100nm). This instrument was located at the LMBCP research station. The output of the pyranometer was sampled every 5 seconds and averaged over half-hourly and daily intervals. The solar radiation dataset in the analysis included two sets of radiation measurements: daily average; and the measurement coincident with the time of the derived cloud cover (e.g., satellite overpass). Appendix A lists the dates from which the collected data were used.

(b) Satellite data

Cloud cover can be computed from in situ measurements made at meteorological stations. However, the large size of Lake Malawi (28,800km^2) and its watershed area (97,700km^2) hampers this method of measurement. Satellite remote sensing offers an effective tool to measure cloud cover of the whole watershed area and Lake Malawi.

This study makes use of satellite imagery captured from NOAA-14, which allows a better chance of cloud cover detection. Small-size clouds such as cumulus clouds are well identified by the AVHRR (Phulpin *et al.*, 1983). The NOAA satellite orbits the earth once every 102 minutes at an altitude of about 850km. The flight direction can be either south to north, that is the daytime overpass for the region of Lake Malawi (around 14:00 hrs local time) or north to south, a nighttime overpass for the same region (around 2:00 hrs local time).

The AVHRR sensor on board of NOAA-14 scans the earth in five spectral wavebands. These wavebands include two solar reflective, channels 1 (0.55-0.68μm) and 2 (0.73-1.1μm), one near-infrared, channel 3 (3.55-3.93μm), and two thermal channels, channel 4 (10.5-11.5μm) and 5 (11.5-12.5μm). Each channel collects data to 10-bit precision at a spatial resolution of 1.1km x 1.1km directly below the satellite (at nadir). The spatial resolution degrades from centre outwards along the satellite's swath so that the images are more distorted at their edges.

The AVHRR dataset was captured at the project station of LMBCP, and are local area coverage (LAC). The sizes of images were 512 X 512 and 512 X 1024 at pixel resolution of AVHRR. The infrared channel (channel 4) was available for all dataset of daytime images used in this study (see Appendix B). All the images were map-corrected and the channel 4 pixel brightness counts were calibrated to temperature, in accordance with procedures of the BURL receiver system (BURL, 1993). The channel 4 was scaled from

10-bit to 8-bit that gives a range from 0 to 255 of gray levels. This range represents temperatures from 200 - 302K.

4.2 Methods

(a) Temporal variation of cloud cover

The diurnal variability of cloud cover over the lake and watershed were evaluated through in situ measurements made at meteorological stations, Salima and Lichinga respectively. Because of their locations, these two meteorological stations are suitable to evaluate the cloud variability over the lake and watershed (Figure 6).

The seasonal variability of cloud cover was derived from satellite data and analyzed within IDRISI, a Geographical Information System (GIS) software, (Clark University, 1995). Cloud cover percentage over the two geographical areas, the lake and the watershed, were determined in the following manner: 1) from each daily satellite image two images were derived, one representing the lake and other the watershed; 2) the number of cloudy pixels within the area (e.g., lake or watershed) were counted and then divided by the total number of pixels representing the area; and 3) for each area the daily percentages were average to calculate the monthly mean percentage of cloud cover.

A threshold technique was used to differentiate cloudy and clear scenes within each of the pixels within the study area. The threshold is a simple method used for cloud detection in many areas of the globe including regions of low latitudes (Rossow *et al.*, 1985; Stowe *et al.*, 1988; Reinke *et al.*, 1992; Rossow and Gardner, 1993). Pixels were classified as either clear or cloudy according to whether its measured temperature differed for less than some predetermined threshold amount. If the pixel was classified as cloudy, it was assumed to be 100% cloud covered.

The lowest surface temperature for Lake Malawi ever recorded is 296K (Eccles, 1974). For this study, the pixel that had a temperature equal or lower than 288K was computed as cloudy. The use of 288k as a threshold, instead of the value 296K or one close to it, was intended to reduce overestimation of cloud cover caused by pixels that were partially cloud covered. The same threshold of 288K was also applied for the watershed. This takes into account that on the watershed of Lake Malawi, local heating is usually greatest in the afternoon (Malawi Government, 1983). As the satellite daytime overpass in Lake Malawi occurred around 14:00 hrs local time, it was very likely that at that time the temperature on land was greater than the threshold. It then follows that there is a low probability for clear pixels on land being computed as cloud covered.

Validation of satellite cloud detection requires comparison with coincident ground observations. In order to evaluate the reliability of the satellite-derived cloud measurements, a comparison with cloud pictures taken with a digital camera on the ground was conducted. Only pictures taken during the satellite overpass time were used as ground validation for satellite cloud detection.

However, this approach has its limitations for direct comparison. Depending on the horizontal/vertical distribution of clouds, the overhead cloud fraction deduced from the ground observations (in this study a digital camera) might not be consistent with the cloud fraction obtained from satellite measurements (Schreiner, *et al.*, 1993). Then some considerations were taken into account. First, it was assumed that digital pictures 50%, or more than 50% cloud covered were considered as totally cloud covered, whereas pictures less than 50% cloud covered were considered as clear. Second, only the pixel of the satellite image at the geographic location where the digital camera was positioned (13°42′ S, and 34°37′ E) was evaluated for comparison. The statistical chi-square test was calculated to evaluate the proportions (cloudy and clear) of the two independent observations (camera and satellite). The chi-square test was computed using the STATISTICA program (StaSoft, 1997).

(b) Spatial distribution of cloud cover

The spatial distribution of cloud cover over the lake and the watershed was derived from satellite data and analyzed within IDRISI, GIS software, (Clark University, 1995). Three periods were chosen in this study, the rainy season (from November to April), the dry season (from May to October) and the entire year. For each period, cloud cover frequency maps were determined by computing the ratio of cloudy scenes at the pixel location to the total number of images representing the period. The cloud detection technique to differentiate cloudy and clear scenes is provided in the previous subsection (a). The maps were smoothed using a *mode* filter. The *mode* filter creates a new image in that each pixel's value is based on its value and those of its immediate neighbors (Clark University, 1995). The nature of this operation was determined by the values stored in a 5 x 5 template.

For each period, correlation between cloud cover and topography was evaluated with the use of a Digital Elevation Model (DEM) of the entire watershed. The correlations were computed with IDRISI software (Clark University, 1995).

(c) Frequency of low, middle, and high clouds

The height attributed to clouds was based on the top temperature of clouds and was defined by the channel-4 of AVHRR, which was assumed to represent temperature at the top of the thick clouds. The different layers of clouds are indicated in accordance with limits given by (Schmetz *et al.*, 1990), see (Table 1).

Table 1. Cloud layers.

Cloud layers	**Temperature**	***K***
Low (cloud top height > 700 mb)	Temperature from climatological profile at 700 mb	$T > 281$
Middle (cloud top height between 700-400 mb)	Temperature from climatological profile at 400 mb and 700 mb	$258k \leq T \leq 281k$
High (cloud top height < 400 mb)	Temperature from climatological profile at 400 mb	$T < 258k$

Low clouds were defined as clouds with top pressure (>700mb), middle clouds defined as those between (700 - 400mb), and high clouds defined as clouds with top pressure (≤400 mb). A climatological profile of pressure versus mean temperature available from the Malawi Meteorological Department was used, and the temperature at a particular pressure was extracted (Table 1).

In Table 2, there is a list of cloud types that are labeled as low, middle and high clouds. In the same table, cumulonimbus cloud is indicated as high cloud because it can develop a thickness over 12km (Oliver and Hidore, 1984). As the satellite views the earth from above and hence only the tops of clouds, a cumulonimbus cloud with large vertical extent is classified as a high cloud.

Table 2. Cloud types evaluated as low, middle and high clouds.

Cloud layer	**Cloud type**
Low	Nimbostratus, Stratocumulus Stratus, Cumulus
Middle	Altostratus, Altocumulus
High	Cirrus, Cirrocumulus, Cirrostratus Cumulonimbus (Deep convective cloud)

The cloud layers derived from satellite data were analyzed within IDRISI, GIS software, (Clark University, 1995). The percentage of each cloud layer over the two geographical areas, lake and watershed, was determined by the following steps: 1) two images were derived from each daily satellite image, one representing the lake and other the watershed; 2) from the two images the ratio of cloudy pixels of each particular cloud layer to the total number of pixels representing the area (e.g., lake) was calculated; 3) for each area (e.g., lake) the daily cloud amounts for each of the three cloud layers were averaged to produce monthly means.

(d) Variation of solar radiation with cloud cover

In this section, the daily cloud cover for July 97 and January 98 was derived from available AVHRR images. July and January were chosen to represent the dry and the rainy seasons respectively. Following Gautyer (1988) the cloud cover percentage was computed from within an area of 50 x 50 pixels centered on the location of the surface radiation measurements (LMBCP research station) (Figure 7).

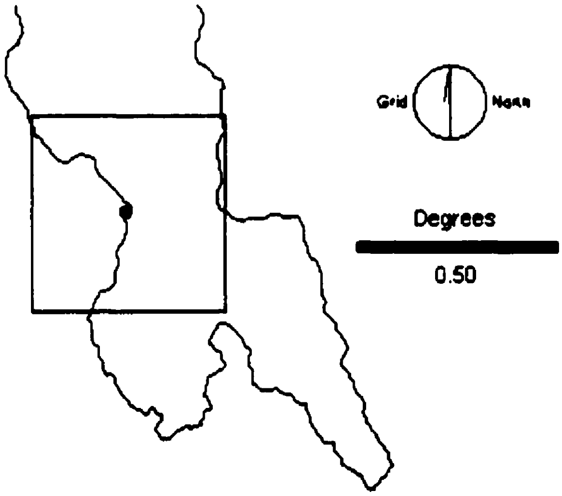


Figure 7. Area of Lake Malawi from which cloud cover percentage was derived through the satellite. The dot indicates the location of LMBCP weather station (13°42′ S, and 34°37′ E).

The derived cloud cover is obtained from only one daily measurement (the satellite overpass around 14:00h local time). Because of that, it was assumed that the satellite-derived cloudiness represents the cloud cover for most of the daytime, (Figure 8 and discussions of cloud diurnal variation, in the next Section 5.1 (b)). Cloud cover measurements were analyzed within IDRISI, GIS software (Clark University, 1995). The cloud detection technique to differentiate cloudy and clear scenes is provided in the previous subsection (a).

In general, research has shown that a linear relationship exists between the amount of radiation that is received at the earth's surface and percent cloud cover (Henderson-Sellers and Robinson, 1996). This study examines the nature of the correlation between cloud percent cover and radiation receipt at the surface of Lake Malawi for conditions typical of a dry season (July 97) and a wet season (January 98). The correlations between cloud cover and the two sets of radiation (coincident measurement with derived cloud cover and daily average) were computed using the STATISTICA program (StaSoft, 1997). Since taking a daily average in effect removes the influence of the diurnal cycle, the coincident time served as verification for a direct comparison with derived cloud cover. Hence, the correlations included two sets of radiation measurements for each month: daily average, and the measurement coincident with the time of the derived cloud cover (see Appendix A).

Chapter V Results and Discussion

This chapter presents the results and discussions in a series of four sections. In Section 5.1, the focus is on the temporal distribution of cloud cover over the watershed and Lake Malawi. Section 5.2 examines the spatial distribution of cloud cover over Lake Malawi and its watershed. Section 5.3 describes the frequency of low, middle and high clouds over the lake and watershed. Finally, the variation of solar radiation with cloud cover at the surface of Lake Malawi is presented in section 5.4.

5.1 Temporal variation of cloud cover over Lake Malawi and its watershed

This section firstly analyses the performance of the cloud detection algorithm applied in this study. In subsection (b), the diurnal variation of cloud cover is investigated. Next subsection (c) extends the discussion to the seasonal variation of cloud cover. The last subsection (d) analyzes the correlations between seasonal cloud cover derived from satellite and ground observations (meteorological stations).

(a) Algorithm validation

Seventy-three digital pictures were taken during the period February-June 1999. Table 3 shows the cloudy and clear proportions of both the digital camera and corresponding satellite images.

Table 3. The observed cloudy/clear frequencies of the satellite pixel and digital camera pictures.

	Clear	*Cloudy*
Digital camera	36	37
Satellite pixel	41	32

The applied chi-square test (with Yates' correction applied) shows no significant difference at P=0.05 in cloudy/clear proportions between the satellite images and digital camera pictures. This result indicates that as a threshold, the 288K temperature is suitable for cloudy/clear cloud detection to the region of Lake Malawi. There is some disagreement however, between the satellite and surface-derived estimates (Table 3). Some of these discrepancies are subsequently presented to provide a context of the satellite-based cloud climatology.

The earth location of each image pixel varies with time, due to relative motion of the satellite and the earth (Rossow and Gardner, 1993). If there is a shift of the image through the map geocorrection, then it is possible that the pixel of the satellite image will not match exactly with the location of the digital camera. Consequently, the digital camera can report a clear scene, while the satellite computes a cloudy scene or vice-versa. This will affect the clear/cloudy proportions between satellite and camera.

A problem with the spatial resolution of AVHRR is that it deteriorates from the centre outwards along the satellite's swath. Hence, different resolutions occur since some images used in this study were captured farther away from nadir point. This alters the pixel-by-pixel representation of a particular cloudy case. In other words, the low angle of the satellite view increases the size of the pixels and increases the probability of the occurrence of clear pixels. This type of problem is particularly acute with cumulus cloud types. A cumulus cloud at very low altitude can cover more than 50% of the digital picture and then the picture is considered cloud covered. On the other hand, the satellite sees the same cloud as a small element within the pixel. If the cloud does not change the irradiance of the pixel to a value lower than that of the threshold, then the pixel is computed as clear.

A type of cloud such as cirrostratus, which in Malawi in some cases is very thin especially during the month of June, can easily go undetected by the satellite. The thermal irradiance from the lake/land can pass through the cloud giving the cloud a temperature greater than that of the threshold. Consequently, the camera shows the presence of cloud, but there will be no cloudy case for the satellite pixel.

The chi-square analysis indicates that the surface and satellite based estimates of cloudy and clear scenes are indistinguishable statistically. Given the caveats reviewed in the preceding paragraphs, then it is reasonable to assume that over larger space and time scales the satellite provides a good estimate of cloud cover. In the next subsections, information on the diurnal and seasonal evolution of clouds is presented as a prerequisite to producing a cloud climatology for Lake Malawi and its watersheds.

(b) Diurnal variation of cloud cover

In this subsection, cloud diurnal variability is only evaluated with cloud data (ground observations) from Salima and Lichinga meteorological stations (Figure 6). In addition, to help the discussion in this section some notes of cloud conditions obtained at the LMBCP station during January to July 1999 are used. Furthermore, it is assumed that Salima represents cloud variation over the lake, while Lichinga does likewise over the watershed.

Figure 8 shows annual means of percentage of cloud cover of Salima at different times of the day. Variation in cloudiness decreases from 06:00 hrs, until 10:00 hrs then increases slightly from 11:00 hrs to 17:00 hrs.

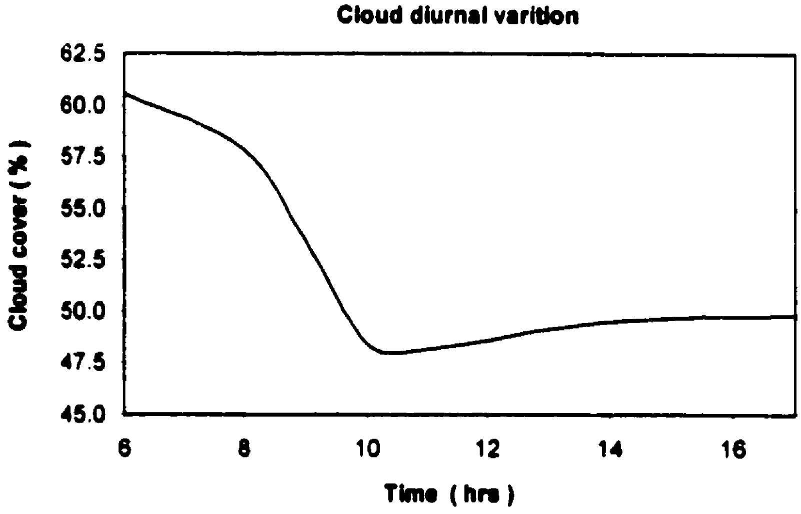


Figure 8. Diurnal variation of cloud cover of Salima. Salima is assumed to represent typical 'lake' conditions. The means are from one year (1977).

Daytime variability of cloudiness over the lake is influenced by the differential heating between lake waters and land surface. The resulting difference in temperature generates an airflow from the lake to the land. This pattern is well observed and it is linked to when the sun rises over the region. As the sun rises, it is frequently possible to observe clouds over the lake moving onto the land. In addition, the airflow creates a descending air cell over the lake (Symoens, *et al.*, 1981) and thereby reduces cloud cover over the lake so that it is either scattered or absent. Because of these factors, cloud cover over the lake is reduced to a minimum during most of the daytime. In addition, depending on the weather conditions of the day the cloud amount at 17:00 hrs can vary suddenly from one day to another. The lakeshore and nearby land can be clear or completely cloud covered.

On the other hand, Salima has high cloud amount at 06:00 hrs (Figure 8). It is very likely that the high cloud cover is linked with reversal airflow that occurs during nighttime to early in the morning. At night, the land cools rapidly while the lake remains warm (Crul, 1995). The cooler air flows down the gradient from land to lake as a land breeze. Consequently, nocturnal convection takes place over the lake and facilitates cloud formation over the lake.

Figure 9 shows annual means of cloud cover of Lichinga at different times of the day. Cloud cover rises in the morning 09:00 hrs reaching a maximum around 15:00 hrs. From 15:00 hrs cloud cover decreases towards the evening 21:00 hrs.

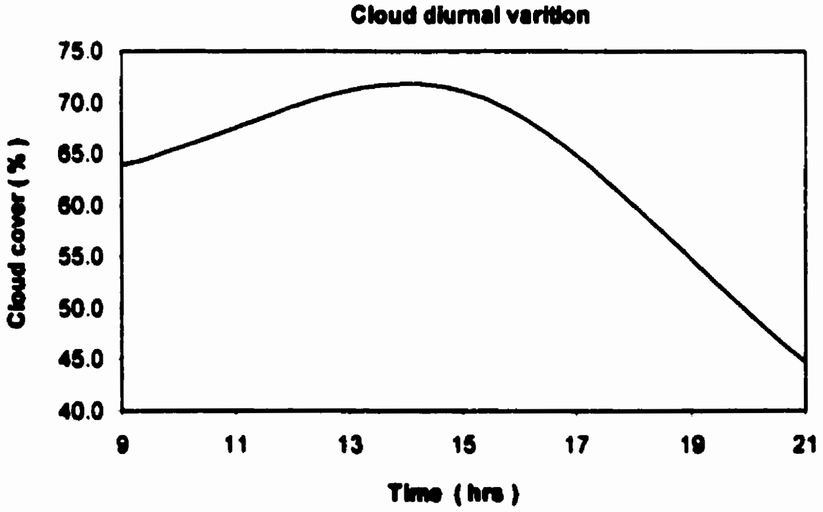


Figure 9. Diurnal variation of cloud cover of Lichinga. Lichinga is assumed to represent typical 'watershed' conditions. The means are from one year (1997).

Watershed cloud cover increases as the convection reaches its maximum around 15:00 hrs. This pattern is mainly due to higher surface temperatures around 14:00 hrs (Malawi Government, 1983). The clouds form on land by convection and by orographic processes. For example, cumulus clouds that form on hills near the lakeshore are influenced by the air that flows from the lake onto the land. It appears that orographic processes and convection are the main factors influencing the great cloud cover on the watershed during daytime. However, as is shown on Figure 9, after 15:00 hrs the cloud cover over the watershed decreases. Important factors affecting this pattern include the movement of clouds, surface heating and reversal of the airflow.

Late in the afternoon, clouds formed over land move closer to the lake or over the lake. The majority of these clouds break down over the lake, but some remain. For example, at LMBCP station clouds like altostratus, altocumulus and dense cirrus were frequently observed moving from eastward over the lake around 16:00 hrs local time. It is likely that because of this movement of clouds, cloudiness over the watershed decreases after 15:00 hrs to increase a little over Lake Malawi and areas on the lakeshore late in the afternoon (Figure 8).

Reduced heating is another factor that could be related with variation of cloud cover on watershed from late afternoon towards the evening 21:00 hrs (Figure 9). As the sun sets, the heating of land surface ceases so that convection over land is continuously reduced to a minimum, thus affecting the formation of clouds. In addition, at night the relatively warm lake establishes a reversal of airflow. Consequently, cloud formation over the land by orographic process is also well reduced. This is accompanied with a decreasing wind speed during the nighttime (Berry, 1971). Actually, the variability of cloudiness on land is in agreement with findings from a study for the African continent undertaken by Saunders (1985), who found that during daytime, the African continent shows maximum cloudiness in the afternoon.

(c) Seasonal variation of cloud cover

Satellite observation of cloudiness can be used to estimate seasonal patterns of cloud over the lake and its watershed (Figure 10).

(a)

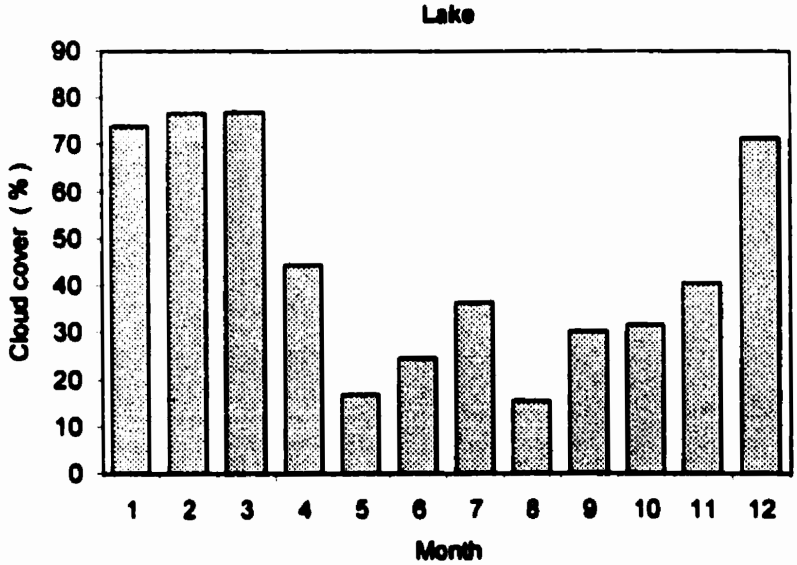


Figure 10. Monthly means of cloud cover computed from satellite for the lake (a) and the watershed (b) (*continued*).

(b)

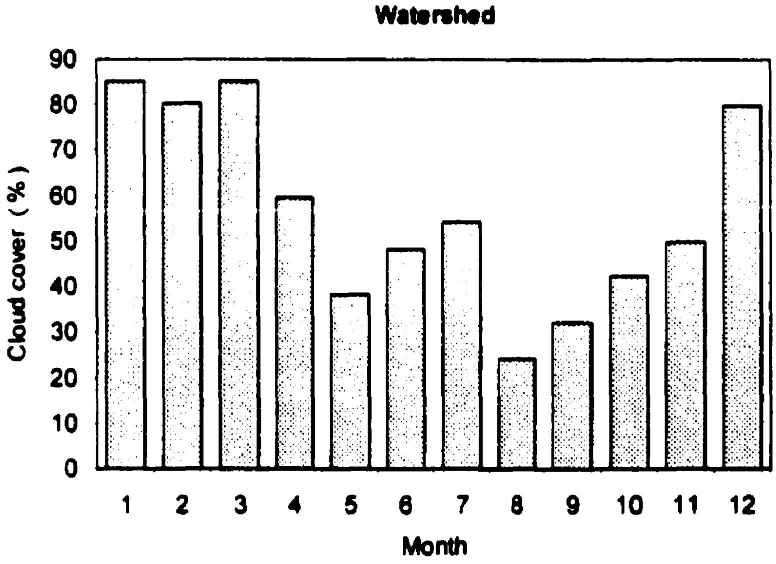


Figure 10. (*Continued*) Monthly means of cloud cover computed from satellite for the lake (a) and the watershed (b).

Low cloud coverage of between 15~30% for the lake and of 20~40% over land was computed for most of the months of the dry season, the period from May to October. Medium coverage (30~60%) over the lake occurred during the months of April, July and November (Figure 10a). On land, medium cloud cover (40~60%) occurred during April, June, July and November. Months of persistently high cloud cover (coverage greater than 60%) were computed for December, January, February and March (Figure 10b). Both the lake and the watershed show the same pattern of high cloud cover for the same period, December to March.

In general, the variation of cloud cover is consistent with a normal annual variation for tropical regions where high cloud cover occurs during the rainy season with low cloud cover during the dry season. Probably the most important factors affecting the pattern of cloud cover over the entire region of Lake Malawi are the movement of the ITCZ and the prevailing winds with southeast direction (STPS).

During December/January, the ITCZ is situated well south of the Equator. As a result, extensive cloudy areas appear at 10°S to 15°S latitude zone (Critchfield, 1983; Stowe, *et al.*, 1988). The ITCZ brings a belt of low pressure that increases cloudiness over the Lake Malawi region. Because of its effects over the region, which begin in November and last until March/April, both the lake and watershed show high cloud coverage, (Figure 10).

Not only the cloud cover over the lake and watershed is affected by ITCZ over the period from November to April, but also it could be influenced by the Zaire Air Boundary (ZAB) system and tropical cyclones that originate in the Indian Ocean. For example, the ZAB could bring widespread cloud cover with it over Malawi (Pike and Rimmington, 1965). If a cyclone moves over land and reaches Malawi, then the southern half of the lake and its watershed usually experience exceptional cloud cover (Torrance, 1972). The variable date of establishment of the ITCZ over Malawi, generally determines the length of time of high cloud cover.

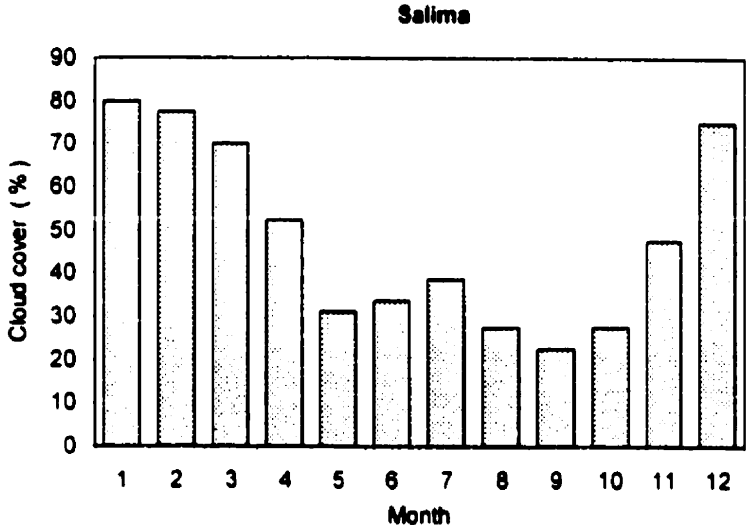
With its movement back to the north in April, the ITCZ continuously reduces the cloudiness over the Malawi region. After May, cloud cover increases even with the retreat of the ITCZ northwards (Figure 10). This variation occurs during the dry season and, it is probably influenced by the prevailing southeasterly winds (STPS) from May to September. The STPS over southern Mozambique bring cool moist air to Malawi. Consequently, the cloud cover is highest when winds are directed towards escarpments that directly face the prevailing southeast winds. Usually during the dry season, highlands and shoreline have a high presence of a particular cloud type such as altocumulus, stratocumulus and cumulus cloud.

The difference in cloud cover between lake and watershed is accentuated from April to July (Figure 10), as described above. In this period, winds play an important role in cloud cover. The watershed area is characterized by high hills and mountains with great slope. Because of such topography, there is more cloud cover over the watershed than over the lake, which is a flat surface. Little difference in cloud cover is seen during rainy season as the presence of ITCZ has great influence over the lake and watershed areas.

(d) Satellite versus local cloud observations

As the ITCZ moves northward, it reduces the cloudiness over the lake and watershed. This pattern is clearly seen on the Karonga and Chitipa meteorological stations (Figure 11).

(a)



(b)

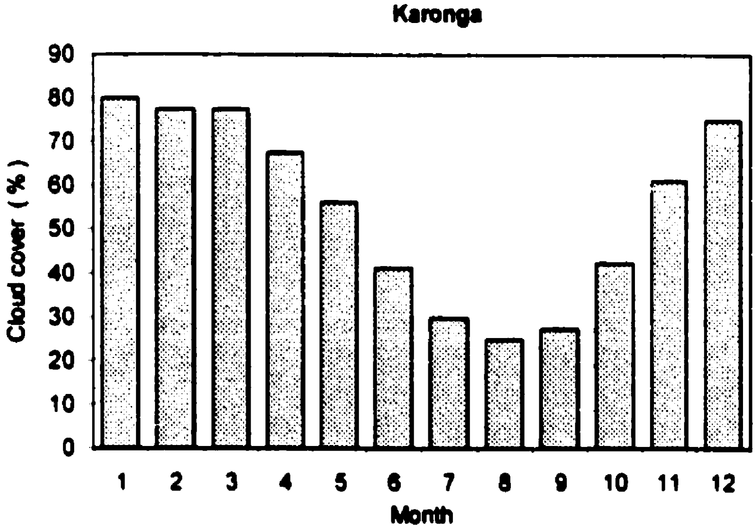
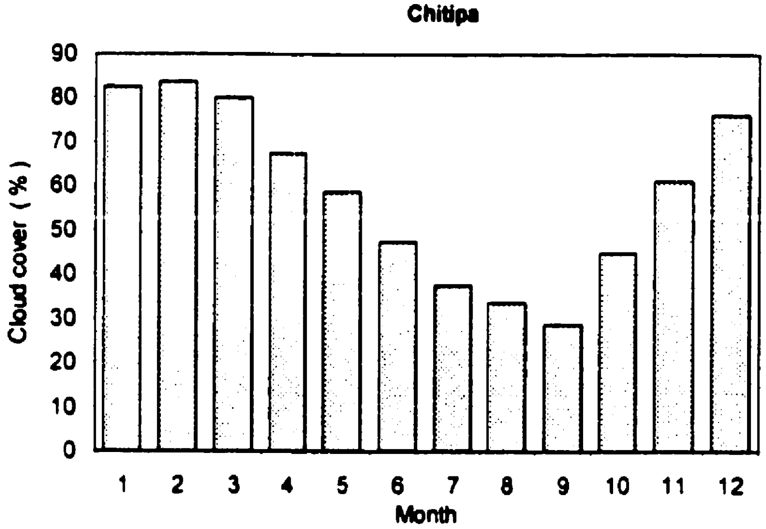


Figure 11. Monthly means of cloud cover of four meteorological stations Salima (a), Karonga (b), Lichinga (c), and Chitipa (d). For Chitipa and Karonga the data are from (1981-90); for Salima are from (1967-77); for Lichinga are from (1997) (*continued*).

(c)



(d)

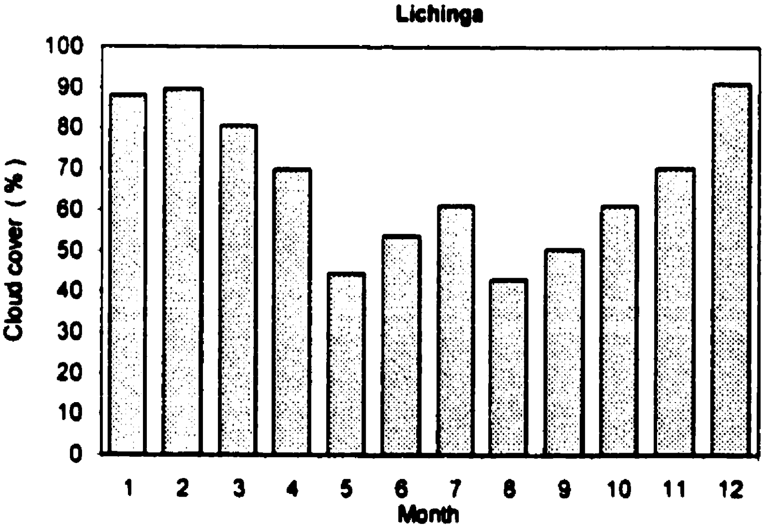


Figure 11. (*Continued*) Monthly means of cloud cover of four meteorological stations Salima (a), Karonga (b), Lichinga (c), and Chitipa (d). For Chitipa and Karonga the data are from (1981-90); for Salima are from (1967-77); for Lichinga are from (1997).

Unlike Karonga and Chitipa which are located in the north, (see locations in Figure 6), the cloud cover derived from satellite (Figure 10) and those observed at Lichinga and Salima (Figure 11) does not show the same pattern. There is a peak of cloudiness around July. As indicated, cloud cover is highest where the highlands face the prevailing southeast winds. This is the case for areas located just northwest of Salima and highlands around Lichinga meteorological stations. Where the lakeshore parallels the wind direction, the effect of southeast winds is minimal or even absent. An example is the topography around Karonga (Malawi Government, 1983).

In addition, it is the southern half of Malawi that usually experiences greater influence of the STPS. Frequently, winds reach their maximum speed around the month of July and remain high throughout the month. Figure 12 shows the wind speed (7 day running average) measured at LMBCP station. This increase in speed probably explains the high cloud cover around July at the two south located stations, Salima and Lichinga (Figure 11). This trend is also seen with cloud cover computed from satellite for the lake and its watershed (Figure 10).

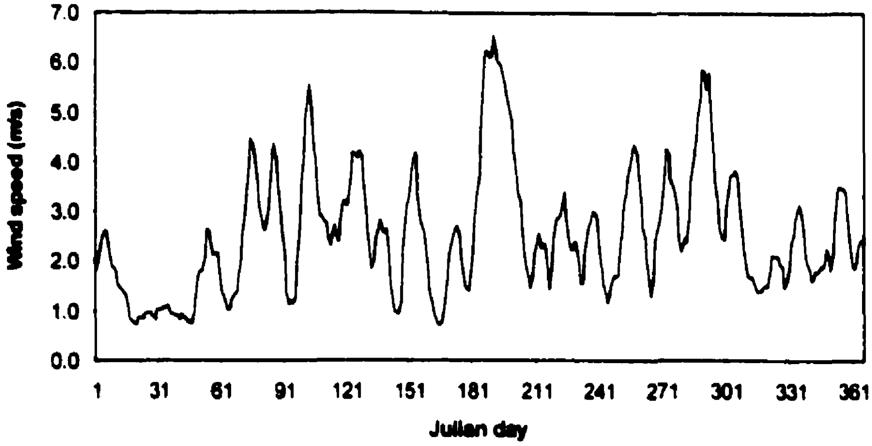


Figure 12. Daily mean average of wind speed at LMBCP station in 1997.

Assuming that Lichinga and Chitipa meteorological stations represent typical 'watershed' conditions, and Salima and Karonga typical 'lake' conditions, correlations with satellite data were then calculated (Table 4).

Table 4. Statistics for correlations between cloud cover derived from satellite and four meteorological stations. Correlation coefficients in bold type are significant. (r = regression correlation coefficient; r^2 = coefficient of determination; p = probability; n = number of cases)

Satellite	**Meteorological stations**	**Mean Cloud (%)**	**Std. Dv. Cloud (%)**	**r**	**r^2**	**p**	**n**
Lake		44.98	23.61				
	Salima	48.65	21.70	**0.95**	**0.91**	0.000	12
	Karonga	55.10	21.02	**0.84**	**0.70**	0.001	12
Land		56.58	21.46				
	Lichinga	63.94	20.03	**0.96**	**0.93**	0.000	12
	Chitipa	58.54	19.82	**0.89**	**0.80**	0.000	12

Statistical analyses of the correlation between the satellite and surface-based cloudiness reveal a significant correlation between Salima (0.95), Karonga (0.84) and the lake cloud cover computed from satellite (Table 4). There are also significant correlations between satellite cloud cover computed for the watershed and the two stations Lichinga (0.96) and Chitipa (0.89) (Table 4). These high correlations confirm that the satellite-derived seasonal cloud climatology agrees with ground-based meteorological station estimates of the seasonal variation of cloudiness both within the watershed and over the lake.

5.2 Spatial distribution of cloud cover over Lake Malawi and its watershed

This section extends the results and discussion of spatial distribution of cloud cover over Lake Malawi and its watershed. Processes that create spatial distribution patterns are presented.

The spatial distribution of cloud cover is studied over three time scales: annual (twelve months); rainy season (six months); and dry season (six months). Figure 13 shows the three periods (a) annual, (b) rainy season, and (c) dry season, of the geographical distribution of cloud cover over Lake Malawi and its watershed. The cloud cover represents the cloud occurrence frequency (percentage) at each AVHRR pixel location. It should be noted that these maps were created using the daytime satellite overpass.

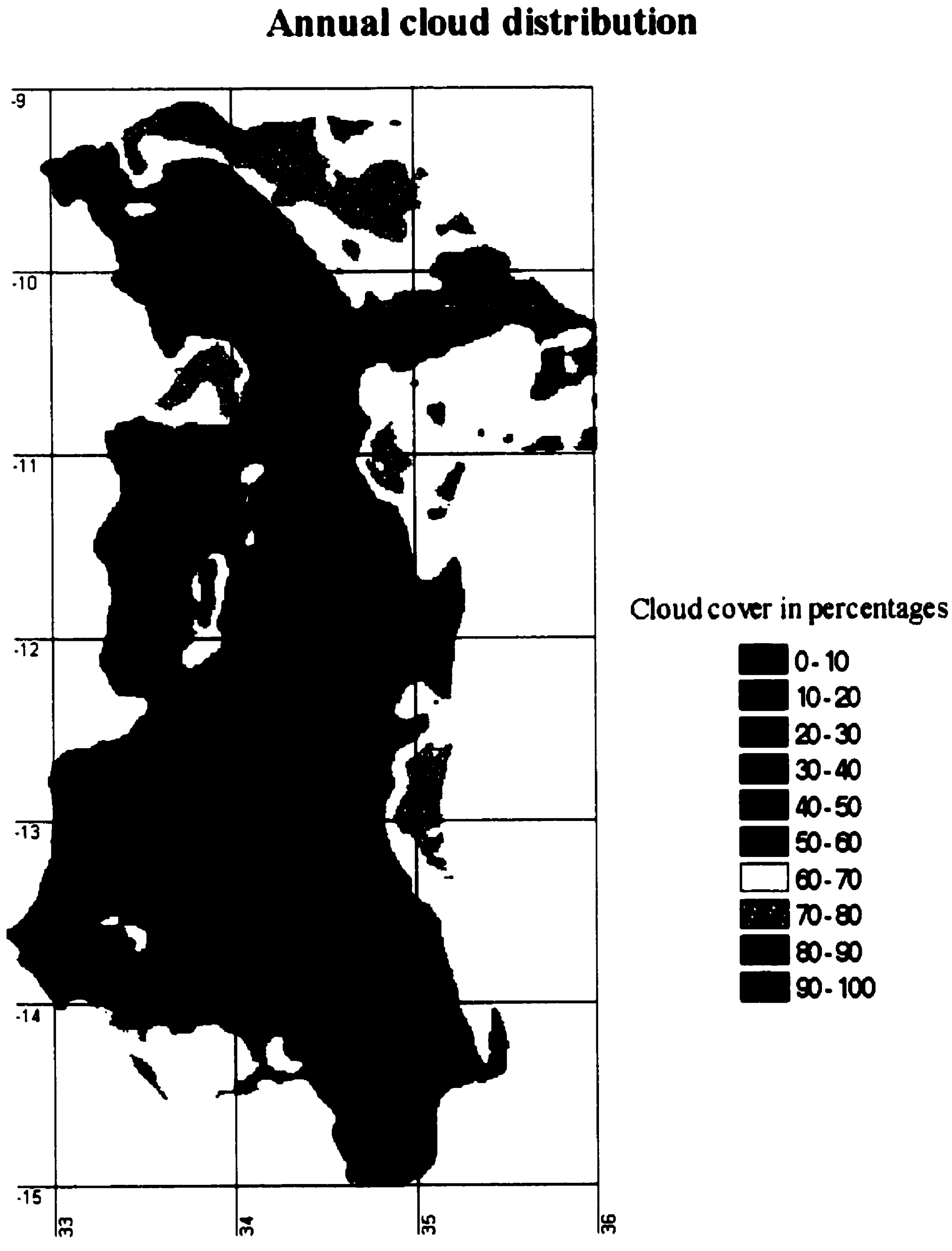


Figure 13. Spatial distribution of cloud cover percentage over Lake Malawi and its watershed: (a) annual, (b) rainy season and (c) dry season. The maps were smoothed using a 5x5 mode filter (*continued*).

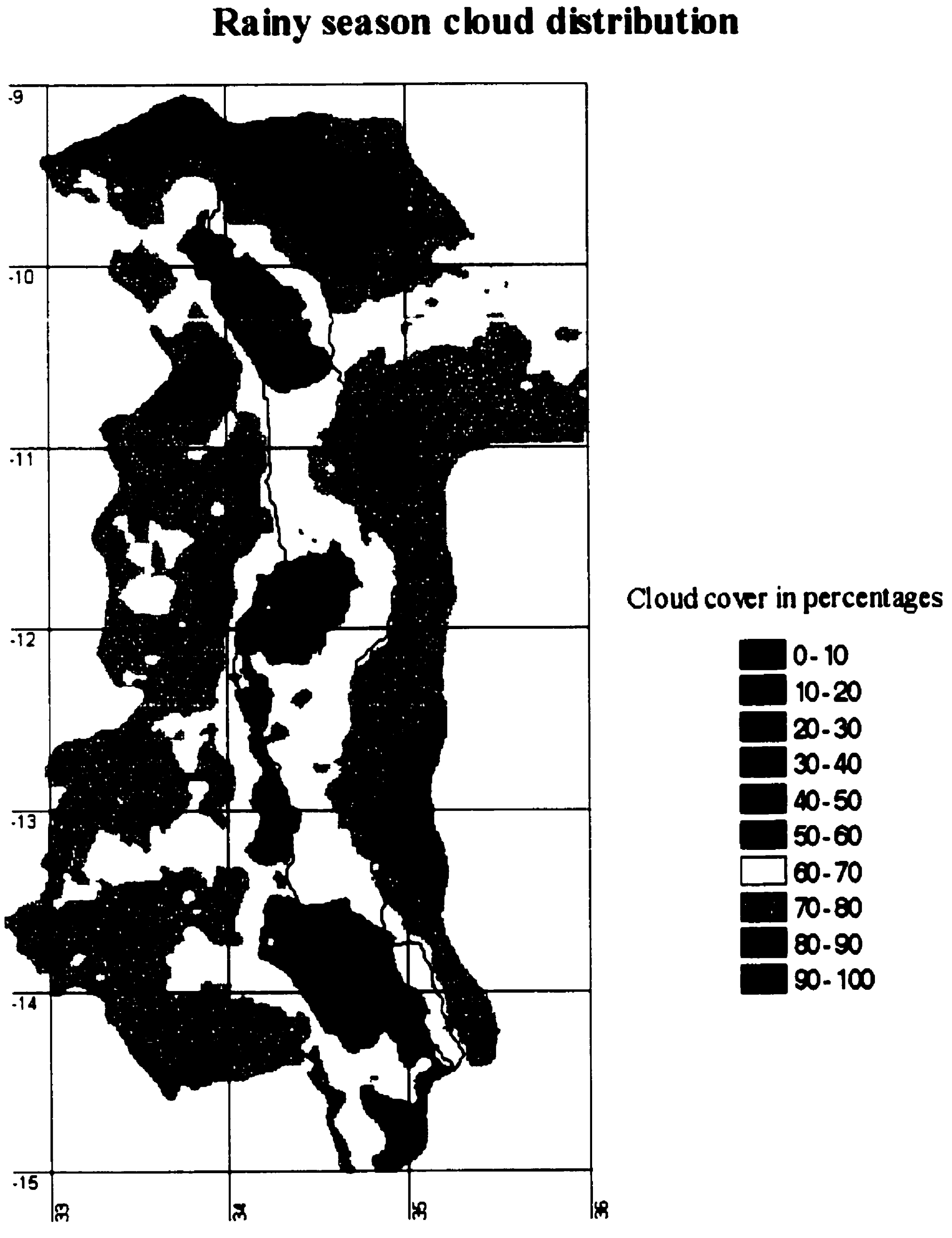
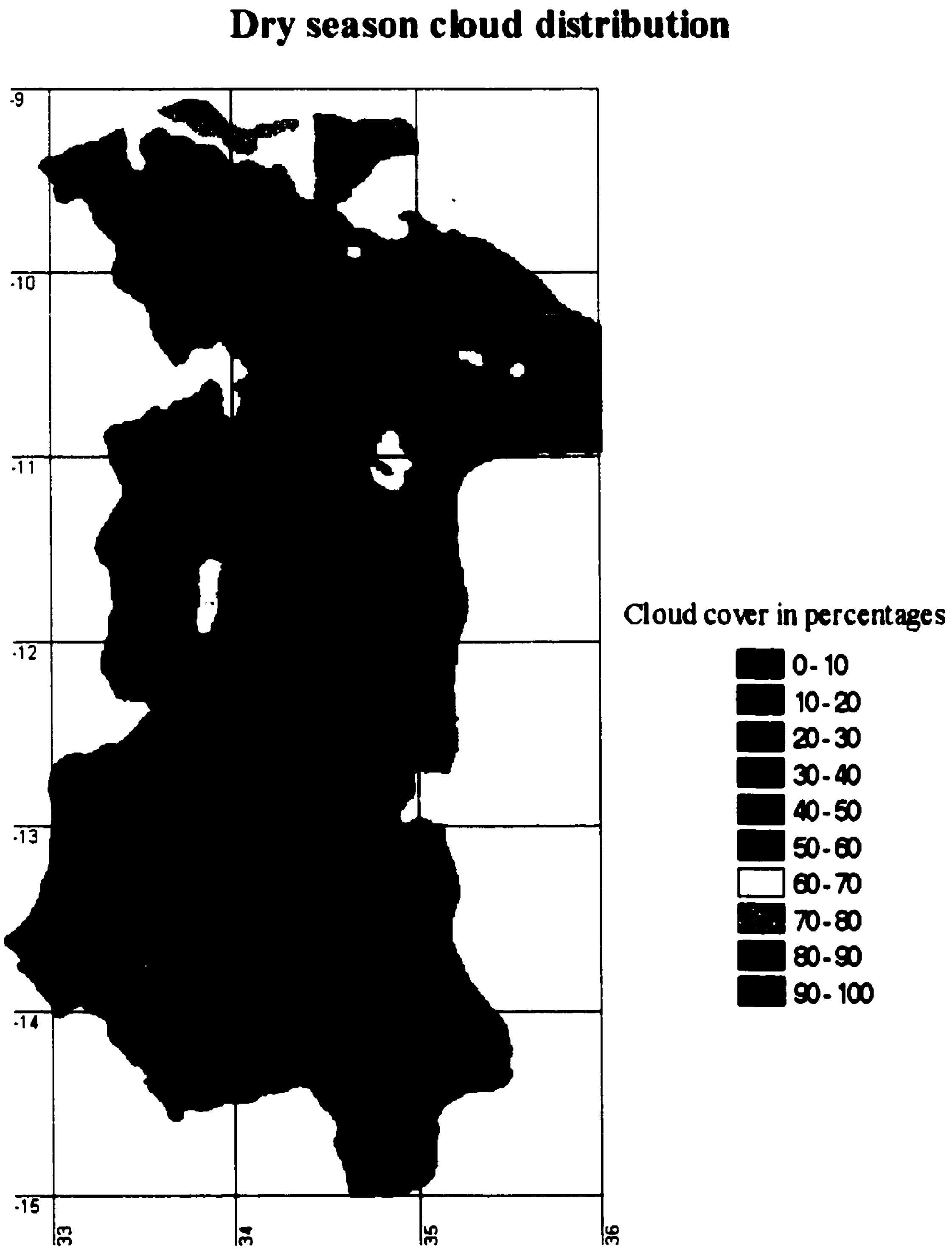


Figure 13. (*Continued*) Spatial distribution of cloud cover percentage over Lake Malawi and its watershed: (a) annual, (b) rainy season and (c) dry season. The maps were smoothed using a 5x5 mode filter.



Dry season cloud distribution

Figure 13. (*Continued*) Spatial distribution of cloud cover percentage over Lake Malawi and its watershed: (a) annual, (b) rainy season and (c) dry season. The maps were smoothed using a 5x5 mode filter.

Over the lake and watershed, high cloud cover is mainly situated on the eastern regions around latitudes 9° 45′ S, 11° S and 13° S, while low cloud cover generally occurs at the western regions (Figure 13a). During the rainy season, the lake appears to be divided in three distinct areas with less cloud cover (Figure 13b). During the dry season, this pattern declines over the lake while the difference between east and west increases over the watershed (Figure 13c). The longitudinal west-east gradient is easy explained by taking into account the topography of the watershed, lake-land temperature differences, the shape of the lakeshore, and seasonal variations in cloud cover.

Over the lake, the pattern of cloud cover is affected by the shape of shoreline. Figure 3 shows the topography of the lake watershed. Most of the eastern shoreline is characterized by steep slopes in many places and has heights over 500m. It is this characteristic of the shoreline that makes the eastern region of the lake particularly cloudy during the rainy season (Figure 13b). As indicated in Section 5.1 (b), over the lake the cloud cover tends to be scattered or absent, because of the temperature difference between the watershed and the lake. The rapid heating of land causes onshore winds and a compensating offshore movement aloft. Onshore winds may form a distinct line marked by cumulus cloud development over the windward side of mountains (orographic lift). However, because of the return air aloft, those cumulus clouds which develop over land also migrate towards the lake, thereby increasing the cloud cover over Lake Malawi. A particular case is the region where high cloud cover crosses the lake at 11° S latitude (Figure 13b). At that latitude, both west and east shorelines have steep topography and associated high cloud cover.

The spatial distribution of cloud cover over the lake is also affected by the predominance of cumulonimbus cloud that characterizes the eastern watershed of Lake Malawi. Individual cumulonimbus, which principally develop in the ITCZ, sometimes reach more than 20km in height (Barry and Chorley, 1968), and spread leeward to form an anvil of cirrus clouds. From ground observations, the anvil portion was often observed covering the eastern side of the lake. This explains the high cloudiness values presented in Figure 13b. In addition, turbulence along the front of an advancing cumulonimbus often creates a roll of dark cumulus or stratus. These clouds were often observed over the eastern side of the lake.

Another factor contributing to high cloud amounts on the eastern side is that long ranges of mountains on the eastern watershed may affect the Indian Ocean airflow that crosses them. The airflow on this side of the watershed is frequently northeast in the rainy season and southeast in the dry season. In both directions, these trade winds cross the Indian Ocean (see Figure 4 and Figure 5), and bring a humid air current to the land (Hatch, 1972). A displacement of air upwards over the mountains forms standing airwaves in the leeward side of the mountains. Generally, the development of leeward airwaves is commonly associated by the presence of clouds. It is very likely that airwaves form in the eastern watershed and lakeshore of the lake, thus contributing to highest cloud cover.

Figure 13c shows differences in cloud cover between west and east sides of the watershed. It is in this season when the airflow is the main feature contributing to cloud cover over the region (see also Section 5.1 (c)). It is very probable that the prevailing southeast winds are stronger on the eastern side than the western side of the lake, thus creating high cloud amounts (orographic lift). Another aspect is that the airflow, after crossing the eastern watershed, can present low humidity due to condensation (formation of clouds) in the eastern region. When the wind reaches the western side the low humidity reduces the formation of clouds.

There is a gradient of cloud cover between the northern and southern sides of the watershed (Figure 13a). The northern side, particularly around 9° 15′ S 34° E has more cloud cover than the south side. It is likely that the northern region is strongly affected by the movement of the ITCZ and local topography. When the ITCZ moves southward, it first reaches the northern end of the watershed, then promoting high cloud cover in that region. On moving back north, the ITCZ allows a regular retreat northwards of the main rains in Malawi, contributing again for high cloud cover in the north during the first months of the dry season (Figure 13c).

In addition, the STPS also affects cloud cover in the north. During the dry season, the strong southeast winds tend to blow along the south-north axis of the lake, being funneled along the length by mountains on either side (Crul, 1995). Furthermore, it is at the northern end of the lake where the adjacent watershed has high altitudes, over 2500m. The southeast airflow rises over the rift floor and south facing escarpments, thus increasing cloud cover. Crossley (1984) claims that the northern part of the watershed has highest rainfall due to air-laden moisture from Lake Malawi. In other words, the orientation of the lake with respect to wind direction also influences the spatial distribution of cloud cover over the watershed.

An attempt was made to compare the results (maps) of this study to a Digital Elevation Model (DEM) of the Lake Malawi watershed. The results of this correlation are presented in (Table 5).

Table 5. Correlation results between topography and cloud cover.

Cloud cover	**Annual**	**Rainy season**	**Dry season**
Correlation	0.70	0.74	0.58

The highest positive correlation is associated with the rainy season, when most of the watershed is frequently cloud covered. The lowest value, that of the dry season, is related to the low frequency of cloud cover. As shown on (Figure 13c), there is a marked contrast between western and eastern sides of the watershed. As the correlation is done with the DEM for the whole watershed, that contrast could be affecting the result of the correlation. In other words, it is most likely that the dry-season correlation value is affected by any meteorological variable rather than the topography versus cloud cover frequency values. In general, the spatial distribution of cloud cover over the watershed is positively associated with topography as is evident from the annual correlation (Table 5).

In addition, these results are in accordance with findings by the Malawi Government (1983), who have indicated that cloud cover is related to topography. Highlands in Malawi lead to high cloud coverage.

Overall, Figures 13a, 13b and 13c show a significant difference of cloud cover between the lake and the adjacent watershed. This supports the argument that in the daytime, cloudiness decreases over the lake while over the watershed it increases. The results from this section and those in section 5.1 (b) agree with the findings of other researchers (Symoens *et al.*, 1981; Malawi Government, 1983).

5.3 The Frequency of Low, Middle, and High clouds over Lake Malawi and its watershed

This section presents results from analysis of cloud level within the watershed and over Lake Malawi. It begins with the subsection of the high cloud layer followed by middle and low cloud layers. Processes that create these patterns are discussed. It should be noted that the cloud amounts computed in this study were observed from above, as the satellite views the top of the clouds. Obviously, in this manner the underlying cloud layers are obscured by the higher layers of clouds and hence not computed or computed with less certainty. In this section, information based on ground observations (January to July 1999) is taken into account. The notes were taken during the satellite overpass at the LMBCP research station as part of field verification.

(a) High clouds

Figure 14 shows monthly means for low, middle and high level clouds.

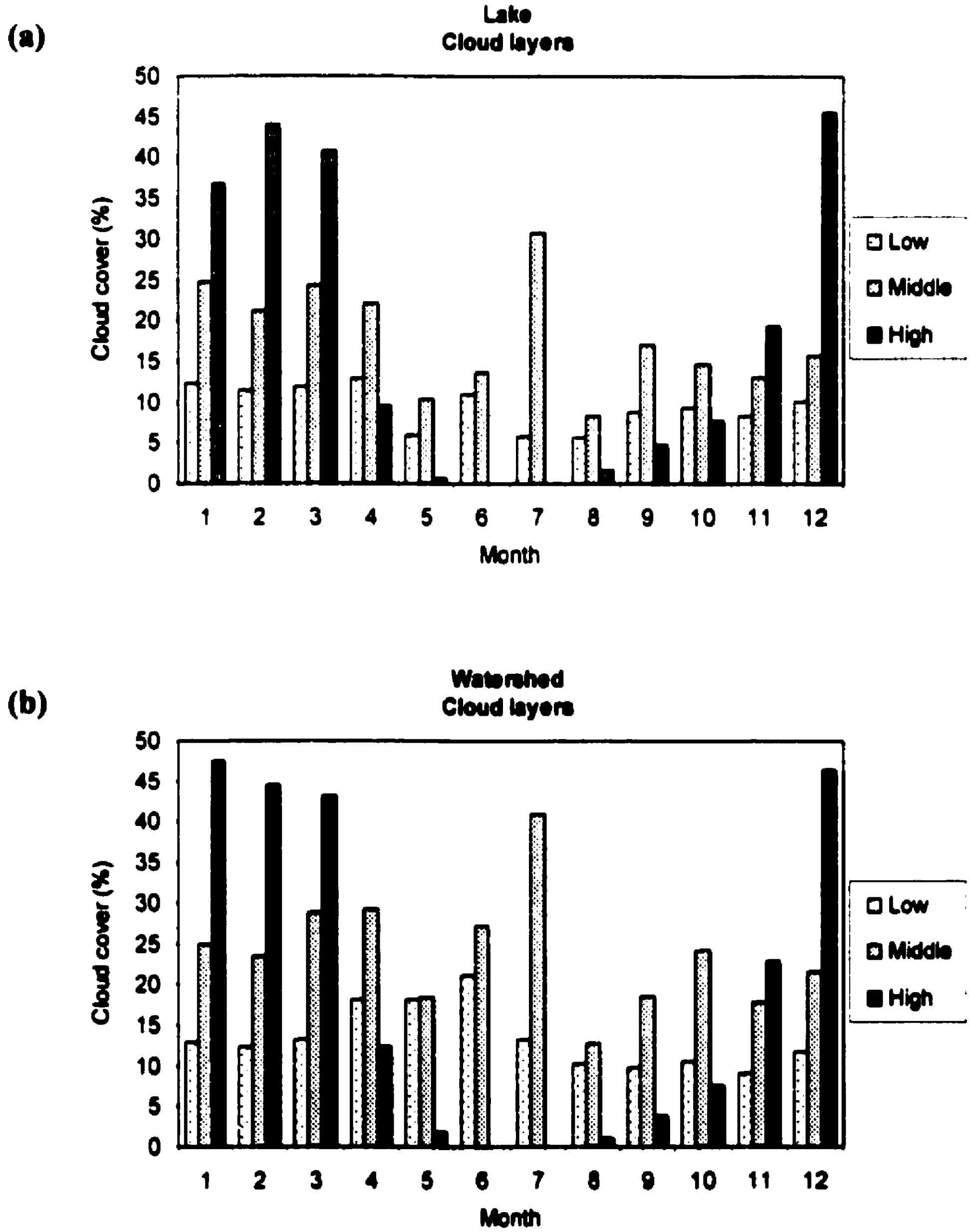


Figure 14. Monthly means of low, middle and high cloud layers for Lake Malawi (a) and its watershed (b).

The variability of high clouds over the lake and the watershed was much higher than for low and middle clouds, as shown in (Figure 14). In the lake and watershed the high cloud layer was more persistent in the rainy season. During this season, high coverage of high level clouds occurred from December up to March. The dry season presented very low amounts of high clouds. In June and July, both the lake and watershed had zero percentage of high level clouds (Figure 14). Throughout the year, the watershed had more high clouds coverage than the lake. However, differences between the lake and watershed are small, except in January where the difference is approximately 10%.

Overall, the frequency variability of high clouds is strongly associated with the southward and northward motion of the ITCZ that coincides with the rainy season of Lake Malawi. As the ITCZ invades and develops over the Malawi region, it creates a strong convection that forms deep convective cells. It is noticed that cumulonimbus cloud, a deep convective cloud, is identified as high cloud (Table 2). Field observations during January and March indicated the presence of cumulonimbus on every day. Furthermore, it was common to observe more than one cumulonimbus at the time of satellite overpass. It is considered likely that the presence of this type of cloud is the main factor contributing to the coverage of high clouds being greatest during the rainy season.

On the other hand, through the ground observations at the LMBCP station, cumulonimbus clouds were reported as clouds that form over the watershed. None of this cloud type was observed to form over the lake. However, as a cumulonimbus cloud has high vertical extent, the upper part of the cloud can change its appearance to an anvil shape, generally extending horizontally. In most cases, this portion of the cloud was observed over the lake and generating dense cirrus cloud or even a dense cirrostratus cloud. It is most likely that over the lake the high cloud coverage is represented by cirrus, cirrostratus or cirrocumulus cloud rather than cumulonimbus cloud itself.

During June and July, no significant amounts of high clouds were computed through the satellite (Figure 14). It should be noticed that high clouds like cumulonimbus were not observed from the LMBCP research station during this period. Lahuec (1988) in his study (1987) also found an absence of convective clouds during the month of July in the region where is located Lake Malawi. This change in high clouds is associated with the seasonal variation in the location of the ITCZ. During this month, the ITCZ is situated in the northern hemisphere. In addition, the STPS lies to the south of Malawi from May to September and as a high-pressure system it suppresses vertical cloud development.

However, for some days of June the coverage of high clouds was observed over the lake and watershed. Clouds such as cirrostratus were very thin and transparent while most cirrus cloud had very delicate filaments. Some cirrocumulus clouds were also observed with very small elements. It is likely that the characteristics of these clouds being thin, delicate filaments and small elements, made them undetectable by cloud detection algorithm used in this study, or classified in a different category, (e.g., middle clouds)

The cloud detection method applied in this study involves the assumptions that no pixels are partially filled and that the clouds are opaque. For example, a thin cirrus cloud has a warm radiometric count relative to thick cirrus (Saunders, 1985). This happens when irradiance from the surface combines with cloud irradiance. As a result, the cloud appears to be located at a lower altitude and it is evaluated as middle or low cloud. In fact, it is possible that some high clouds during the dry season were computed to a different class, thus affecting their estimation through the satellite observations. It is difficult to quantify this confusion in the class separation since access to radiosonde data to estimate cloud heights was not available at the LMBCP site.

(b) Middle clouds

Over the lake and watershed, the middle cloud layer is present all year (Figure 14). As noted for high clouds, the watershed shows higher middle cloud coverage than the lake. This tendency occurs during both the rainy and dry seasons.

Middle clouds are persistent during the rainy season and show small variability throughout the season. The variability ranges from 13% to 25% over the lake and on the watershed from 18% to 30% (Figure 14). The variability of middle clouds during the rainy season is likely affected by the presence of the ITCZ when it develops over the region. This system brings to the region large-scale convection currents. The air throughout the troposphere rises slowly and uniformly, extending across the watershed and the lake. This large-scale ascent can produce clouds such as altostratus and altocumulus. Field observations indicated that two types of middle clouds, altostratus and altocumulus, are frequently present at the same time and it is not unusual for altostratus to change into altocumulus and vice versa.

During the dry season, the variability of middle clouds is very high. The lake has a range from 8% to 30% and the watershed from 12% to 41% (Figure 14). During this season, the ITCZ is normally furthest north, thereby allowing the STPS to shift north and over Malawi. The resulting large-scale subsidence is critical to the formation of persistent low and middle stratiform clouds (Randel and Haar, 1990). In many cases during the dry season, particularly (May-July 1999), altostratus and to a lesser extent altocumulus were observed over the land moving from the east and southeast over the lake, in the afternoon. This movement is likely to be influenced by the airflow that originates over the Indian Ocean (Figure 4).

Particular to the watershed, the highest middle cloud coverage occurs during July, the month in the middle of the dry season. One reason for this highest coverage could be the influence of the southern trend winds, which increase during the dry season. When this horizontal moving air encounters higher land, a range of mountains for example, the air is forced to rise. Under these circumstances clouds are formed. Particularly in Malawi, the winds are strong in July (Figure 12). This strength is enough to create turbulence on the leeward side of mountains and then to form clouds such as altocumulus. When the ITCZ is displaced southward, the STPS cannot move north so the middle clouds decrease (Figure 14).

In some cases high cloud cover of middle clouds include the possibility that they are all composed of high thin and low clouds. It should also be noted that stratocumulus (a low cloud) is frequently present during the dry season. Although stratocumulus is usually considered to be as low cloud, via satellite observation they can easily be classified as middle clouds (Stowe, *et al.*, 1988). Hence, it is likely that the highest peak of middle clouds during dry season is affected in part by the presence of low clouds.

(c) Low clouds

The lake and watershed have a persistent coverage of low level clouds throughout the year (Figure 14). The watershed not only has higher coverage than the lake, but also has different variability. In the watershed, low cloud coverage is high during the dry season, with a maximum in June, (21.1%) (Figure 14). Over the lake low clouds have a high coverage during the rainy season, with the maximum occurring in April, (13.6%) (Figure 14). In fact, these differences agree with ground observations taken during satellite overpasses.

With the presence of ITCZ, low clouds during the rainy season were often cumulus, stratocumulus and stratus in nature. In general, most of these clouds originated near noon and over the watershed. This explains why the watershed has higher coverage of low clouds than the lake for all months (Figure 14). On the other hand, few low clouds originated over the lake. As indicated in Section 5.1 (b), cloud coverage over the lake reduces to a minimum around noon. Just after local noon, which coincides with the satellite pass (around 14:00 hrs local time), some clouds which formed over the land moved towards the lake, increasing the amount of low clouds over the lake. This phenomenon was only observed on the eastern lakeshore. It is probable that the amount of low clouds over the lake is mainly due to the motion of clouds formed on the watershed (see previous section 5.2 for more details).

The lake and watershed have a difference in low cloud variability during the dry season. Over the lake, low clouds tend to reduce in their frequency while over the watershed they tend to increase, (Figure 14). Accordingly, ground observations during the first months of the dry season, i.e., May-July, the main types of low clouds were cumulus and stratocumulus. These clouds formed readily over the land and near shoreline when the southern winds (STPS) start blowing over the region. As a result, low clouds increase over the watershed, while over the lake the reverse occurs. Most of the time, particularly in May, low level clouds were almost absent.

As noted before, satellite does not detect underlying low clouds when middle and high layers of clouds are present. Hence, the low values for the lake and in particular those for the watershed can be explained partly due to the low clouds being obscured when the middle and high clouds are present. This would account entirely for the low values of low clouds, principally during the rainy season when the frequency of low clouds is high. This limitation is most severe where high clouds coverage is high, e.g., over the watershed. Rossow and Lacis (1990), have shown that estimates of low cloud cover are most uncertain in the tropics where the coverage of high level clouds is high.

5.4 Variation of solar radiation with cloud cover at the surface of Lake Malawi

In this section, the correlations between cloud percentage cover and radiation receipt at the surface of Lake Malawi for the conditions typical of a dry season and a wet season are presented.

The results of these correlations between solar radiation and cloud cover indicate that surface radiation and cloudiness are negatively correlated, but show complex relationships over the coincident (*H*) and the daily (*D*) timescales examined here (Table 6).

Table 6. Statistics for correlations between cloud cover and solar radiation. *H* indicates measured radiation coincident with satellite overpass and *D* the daily mean. Correlation coefficients in bold type are significant. (r = regression correlation coefficient; r^2 = coefficient of determination; t = T statistic; p = probability; n = number of cases)

		Mean	**Std. Dv.**	**r**	**r^2**	**t**	**p**	**n**
July 97	Cloud (%)	41.769	47.652					
	H (kw)	0.458	0.171	**-0.938**	**0.879**	**-7.143**	0.000	9
	D (kw)	0.175	0.056	**-0.908**	**0.824**	**-5.725**	0.001	9
January 98	Cloud (%)	75.364	30.597					
	H (kw)	0.773	0.175	-0.458	0.209	-1.544	0.157	11
	D (kw)	0.249	0.044	**-0.759**	**0.576**	**-3.497**	0.007	11

In general, July has the highest percent of explained variance and these correlations are both significant (Table 6). Results from the January analysis show that the coincident surface radiation and the satellite cloud cover do not illustrate the expected negative relationship, while the daily averaged radiation data do show a statistically significant negative relationship (Table 6). In general, this difference in the correlation values indicates an expected tendency for Lake Malawi. Some of these discrepancies are subsequently discussed.

For the month of July, the r^2 values of the cloud cover and radiation relationship are very high for both sets of radiation (Table 6). It follows that less than 20% of the variation in solar radiation is not accounted for by variation in cloud cover. As indicated in the previous sections (section 5.3 (b) and 5.3 (c)), the STPS is located over Malawi during July and is critical to the formation of persistent low and middle stratiform clouds. This pattern of clouds is also displayed in (Figure 14.a). As in this particular month the rainfall in Lake Malawi is insignificant (Malawi Government, 1983), low and middle clouds are present the same structure all the month round. In addition, when these clouds are present they can remain for a significant period over Lake Malawi. Then, it is likely that radiation in July is most affected by cloud amount, thus explaining the highest values of correlation between cloud cover and the two sets of radiation data.

In January Malawi is influenced by the ITCZ, which brings high convection and extensive cloudy areas. Although the ITCZ influences high cloudiness, in Lake Malawi the cloudiness during daytime reduces to a minimum (section 5.1 (b)). In other words, the sky is partly cloudy during most of the daytime, and as a result the relationship between cloud cover and radiation is most likely complex.

For example, discrepancies in solar-radiation measurements can occur when the highest radiation values are measured on partly cloudy days (Appendix A). This happens when the sun is unobscured on scattered skies, despite the relative amount of cloud cover. On the other hand, the reverse can occur when the lowest radiation values are measured on clear days (e.g. cloudiness less than 20%). This is the case when a cloud temporarily cuts off the direct solar radiation, then giving low reliance upon the relationship between radiation and cloud cover. This discrepancy frequently occurs when cumuliform cloud, a typical convective cloud, is present. In Lake Malawi, cumulus clouds are very frequent in January. It is likely that the weak correlation between cloud cover and the coincident radiation (H) for January is affected by those factors above indicated. In addition, it should be noted that the weather station from which the radiation data were gathered measures at half-hour intervals. Any significant variation of cloudiness occurred before the time or after when the cloud cover was derived strongly affects any correlation.

Another important factor, which affects the solar radiation versus cloud amount in January, is cloud structure. In highly convective regions of the tropics, changes in radiation flux are more dominated by optical thickness than by cloud amount (Hartman and Doelling, 1991; Sohn and Robertson, 1993). Consequently, different radiation values can occur even with the same cloud cover percentage (Appendix A). During January, variation in cloud thickness and density occur in Lake Malawi, as the month lies within the rainy season. An overcast day where clouds are likely to produce precipitation has a different radiation at the surface from an overcast day with clouds that will not produce precipitation. Iribarne and Cho, (1980), claim that a cloud with about 100m in thickness and a concentration around of 2000 droplets/cm^3 could reflect almost all solar radiation. During the rainy season observed clouds such stratus, stratocumulus, cumulus and nimbostratus over Lake Malawi frequently varied from bright to very dark when seen from the surface. Rossow and Lacis (1990) indicated that in the tropics, cloud proprieties do neither all act in concert with the radiation nor do their effects vary with the same amplitudes and phases, so that sometimes cannot be described by simple linear correlations.

Particular for January, it seems that the correlation between daily radiation values (*D*) and cloud cover (Table 6) is not strongly affected by cloud structure variation and clear/partly cloudy sky conditions during the day. In general, the daily radiation average in effect balances the influence of those factors. Since for both months, January and July, the correlations between derived cloud cover and daily average of radiation are significant, a preliminary lake-wide scenario of radiation patterns for Lake Malawi is, therefore, provided (Figure 15).

Solar radiation

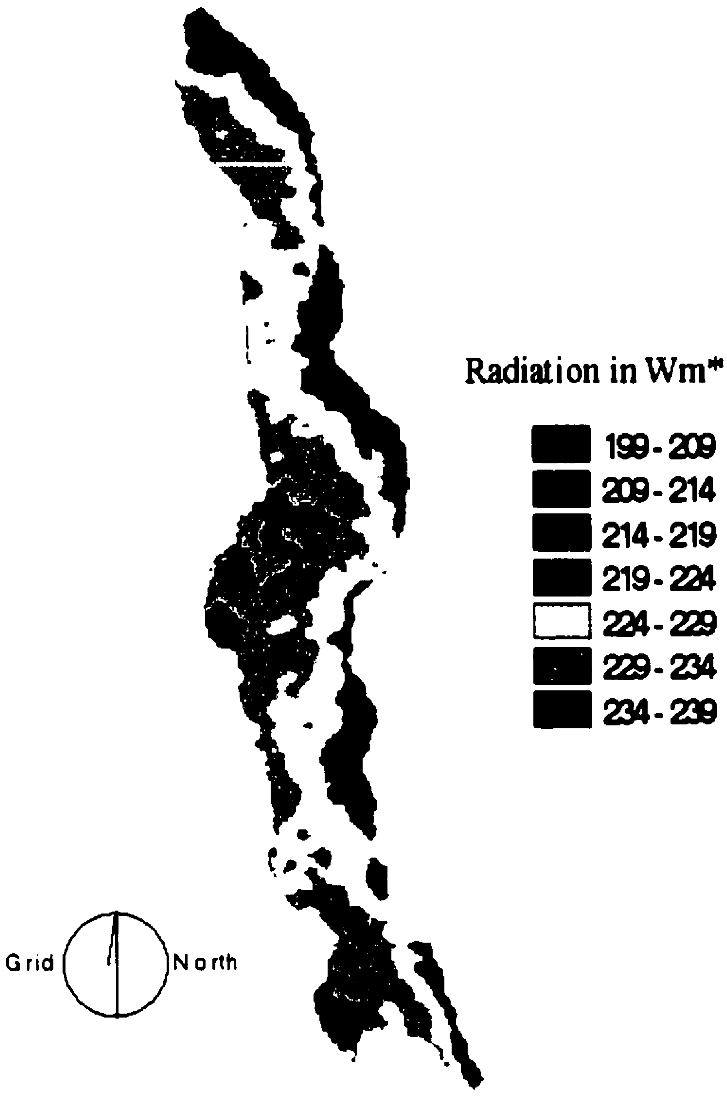


Figure 15. Map of daily annual mean of solar radiation at the surface of Lake Malawi. The map was constructed with the use of the regression equations of July and January. The regression equations are indicated in the Appendix C. July was assumed to represent the dry season and January the rainy season.

Figure 15 shows surface radiation patterns (east to west) similar to those of cloud cover over the lake (section 5.2). Low means of radiation occur at the eastern lakeshore where cloud cover is high, and high radiation at western lakeshore where cloud cover is low. This pattern of radiation is mostly dominated by the spatial distribution of clouds in the rainy season (Figure 13b), rather than the dry season where the cloud distribution over the lake is almost similar (Figure 13c).

Chapter VI Conclusions and Recommendations

This chapter presents conclusions and recommendations about cloud climatology over Lake Malawi and its watershed. Section 6.1 describes the most significant conclusions of this study. Section 6.1 is presented in a series of four subsections. Each subsection is linked to one of the four objectives of this study. In section 6.2, some recommendations for further research are presented.

6.1 Conclusions

(a) Temporal variation of cloud cover over Lake Malawi and its watershed

The first objective of this thesis was to determine the temporal distribution of cloud cover over Lake Malawi and its watershed. This study examined diurnal and seasonal patterns of cloudiness by presenting data both in ground observations of cloudiness and computed cloudiness from a satellite dataset. Lake Malawi and its watershed experience very distinct diurnal and seasonal patterns of cloud cover throughout the year.

During the day, Lake Malawi has low cloudiness around noon (11:00 hrs) and high cloudiness early morning (06:00 hrs). The watershed, in contrast, has more cloud cover around (15:00 hrs) and less at night. The reasons for these patterns are related to differential heating of the water and land, and the influence of orographic effects associated with both land and lake breezes, which are established diurnally.

Seasonally, the lake and watershed have high cloudiness during the rainy season, November to April. Low cloudiness occurs during the dry season, May to October. In general, high cloud coverage during the rainy season is influenced by the ITCZ in its movement to and from Malawi region. In particular, the dry season is characterized by having a peak of cloudiness and it is influenced by the STPS. Cloud cover over the watershed is higher than that over the lake throughout the year.

Results from this study also indicated that cloud cover from satellite imagery could be extracted for Lake Malawi and its watershed. The monthly variability of cloudiness computed from satellite agrees with convectional cloud measurements from local meteorological stations.

(b) Spatial distribution of cloud cover over Lake Malawi and its watershed

The second objective of this thesis was to determine the spatial distribution of cloud cover over Lake Malawi and its watershed. Data of the spatial distribution of cloud cover were presented using time sequential AVHRR satellite data. Spatial patterns of cloudiness were examined for the dry season, the rainy season and a year period. Finally, correlations between cloud cover and topography of the watershed were examined.

Over the watershed, there is a clear latitudinal gradient of cloud cover amount. The northern side of the watershed has more cloud cover than the southern side. This pattern is influenced by the ITCZ and the southerly airflow. On the other hand, there is also a gradient between the eastern and the western sides of the watershed. The eastern side has more cloud cover than the western side. In particular, high cloud cover occurs on the east around 11° S and 13° S latitude. During the dry season, the contrast of cloud cover between the west and east is high, more cloud cover being on the eastern side. This contrast is influenced by the airflow that crosses the Indian Ocean. There is evidence that over the watershed, the cloud cover is associated with topography due to orographic processes. High altitude and high slope environments both result in a higher probability of cloud cover.

Over the lake, the pattern of cloud cover is dominated by a contrast between the western and eastern shorelines. Low cloud cover occurs along the western shoreline and high cloud cover over the eastern shore. The center of the lake, around 12° S, and the south-side at 14° S latitude are the areas with low cloud cover. During the rainy season, the cloud is lessened not only at those two latitudes but also in the north between 10° S and 10° 45′ S latitude. During the dry season, most of the lake is under the same amount of cloud cover. It is evident that the spatial distribution of cloud cover over the lake is affected by the geomorphological differences around the perimeter of the Rift Valley. Overall, the spatial distribution of cloud cover over the lake is influenced by the orientation of the lake with respect to the airflow, the shape of the lakeshore, temperature differences between the lake and watershed, and finally the topography of the adjacent watershed.

(c) The Frequency of low, middle, and high clouds over Lake Malawi and its watershed

The third objective of this thesis was to assess the frequency of low, middle and high clouds over Lake Malawi and its watershed. The frequency of these three cloud layers was evaluated with the use of AVHRR satellite data for a one-year period.

Results from this study show that from November to April, the high layer of clouds is the most frequent, followed by the middle and low cloud layers. Although April is in the rainy season, it is the only month where the high clouds are less than the middle and low. In the middle of the year, June and July, high clouds are absent. The variability of the high clouds is influenced with the movement of ITCZ. Both the lake and watershed follow the same variation of high clouds.

The middle layer of clouds is frequent all year. Both areas, the lake and the watershed, shown two peaks with respect to the occurrence of middle clouds, one in the rainy season and one in the dry season. During the dry season, the middle cloud frequency is very high in only one month (July), while in the rainy season it is constantly high in all months. The highest frequency occurs in July, and is probably influenced by the winds and the STPS. The watershed has more middle cloud coverage than the lake.

Like middle clouds, the low layer of clouds is also frequent throughout the year. Over the lake, low clouds were constant with a small reduction during the dry season, while on the watershed low clouds increased in the first months of the dry season. During the dry season, the variability of low clouds is influenced by the airflow. The watershed has higher low cloud coverage than the lake.

(d) Variation of solar radiation with cloud cover at the surface of Lake Malawi

The fourth objective of this thesis was to examine the variation of solar radiation with cloudiness at the surface of Lake Malawi. This study presented cloudiness derived from AVHRR and solar radiation at the surface measured with the use of a pyranometer. The nature of correlations between cloudiness and radiation (daily average and coincident measurement with derived cloud cover) were examined for July 97 (typical conditions of a dry season) and January 98 (typical conditions of a rainy season).

There is an indication that on Lake Malawi variation in solar radiation is linked with cloud cover. What the results of this study indicated are that the variability of radiation with cloud cover is negative and dependent upon season. Solar radiation and cloud cover are strongly correlated in July, a month of the dry season, while moderate correlation is in

January, a month of the rainy season. Probably this difference is associated with the type of clouds that occurs during the presence of ITCZ (in January) and the STPS (in July).

There is high correlation between measured daily radiation and satellite-derived cloud cover. However, there is a high probability that an underestimation occurs with coincident radiation. This is the case for January a month of the rainy season, when convective clouds (vertical development) are frequent. Overall, although the results indicate a negative correlation between cloud cover and radiation, there is some subjectivity about the relationship between radiation and cloud cover on Lake Malawi. The understanding of cloud effect on solar radiation, however, is far from complete.

6.2 Recommendations

The NOAA-14 AVHRR imagery dataset was utilized as the basis for this study. The spatial resolution on the satellite data (1.1km x 1.1km) appears sufficient to resolve the temporal and spatial cloud cover and cloud heights over the lake and its watershed. However, it appears that some gaps exist in knowledge of cloud cover over Lake Malawi and its watershed. The accuracy of cloud cover will improve as the quality of the data improves. It is therefore recommended that:

a) there is a need for more data from other meteorological stations around the lake, particular in Tanzania (northeastern watershed), in order that a better understand of cloud cover variations and a better comparison among different areas can be gained.

b) satellite data should be more systematically collected and analyzed. Attention should be addressed to collect data with great time resolution. This could be most effectively achieved by the use of geostationary satellite data.

c) through satellite observation an evaluation of cloud cover at night is carried out, showing its diurnal and seasonal variation over the lake and its watershed.

d) hourly sampled events of cloud cover and radiation, e.g. daytime averages from 06:00 hrs to 18:00 hrs, will be useful to better understanding how clouds affect solar radiation at surface. Particular attention should be addressed to the radiation measurements. It is recommended to increase the time resolution of the pyranometer (e.g., 1 minute average), particularly if the derived cloud cover is from satellite.

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APPENDIX A

Cloud cover and Radiation measurements

Table 1. Cloud cover and solar radiation data. As the pyranometer sampled every 5 seconds and averaged over half-hourly, the next half-hourly measurement after the derived cloud cover (satellite overpass) is used.

	Satellite overpass Time	Cloud cover (%)	Coincident radiation Time	Coincident radiation kW/m*2	Daily mean of radiation kW/m*2
July-97					
7	14:13	100.0	14:30	0.217	0.092
8	14:02	99.5	14:30	0.253	0.099
9	13:51	75.8	14:00	0.281	0.119
10	13:40	7.8	14:00	0.647	0.210
15	14:26	0.0	14:30	0.597	0.222
16	14:15	90.4	14:30	0.404	0.178
17	14:01	2.6	14:30	0.522	0.200
24	14:28	0.0	14:30	0.605	0.229
26	14:06	0.0	14:30	0.597	0.225
January-98					
2	14:59	100.0	15:00	0.410	0.234
3	14:48	73.4	15:00	0.734	0.285
6	14:15	55.2	14:00	0.879	0.272
8	13:23	100.0	13:30	0.867	0.250
12	14:29	69.2	14:30	0.835	0.188
14	14:27	74.7	14:00	0.962	0.270
15	14:16	99.4	14:30	0.476	0.192
16	14:12	0.8	14:00	0.908	0.337
17	13:24	56.4	13:30	0.796	0.269
18	13:43	99.8	14:00	0.857	0.213
21	14:51	100.0	15:00	0.784	0.229

APPENDIX B

AVHRR data from NOAA-14 satellite

Table 1.1. NOAA-14 AVHRR images used in this study. Due to various equipment and measurements problems, some data were missing from the records.

Month	Daytime Satellite overpass Date	Cloud cover Mean (%) Lake	Cloud cover Mean (%) Watershed
July-97	7,8,9,10,15,16,17,24,26	36.4	54.2
August-97	2,3,4,12,13,14,15,16,19,20,22,23,25,26,28,30	15.5	24.1
Sptember-97	2,3,6,7,8,11,12,13,14,15,16,17,22,24,25,26,29,30	30.4	32.2
October-97	6,7,9,10,13,14,15,16,17,18,19,22,24,27,29,31	31.8	42.3
November-97	1,2,6,10,11,13,18,21,22,24,27,28,29	40.5	49.7
December-97	1,2,3,11,12,16,20,24,30,31	71.4	79.7
January-98	2,3,6,8,12,14,15,16,17,18,21	73.9	85.3
February-99	10,11,15,16,17,18,20,21,22,23,24,25,26,27	76.8	80.3
March-99	1,2,3,4,5,6,7,8,9,10,11,12,13,15,16,17,20,21,22,23,24,25,26,27,28,29	77.1	85.2
April-99	2,3,4,5,7,8,9,10,11,12,14,15,17,18,19,21,24,25,27,28,29,30	44.5	59.7
May-99	1,3,4,6,7,8,9,11,12,13,15,18,20,22,23,24,25,27,29,30	16.9	38.2
June-99	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,20,21,23,24,26,27,28,29,30	24.6	48.2

APPENDIX C

Plots of cloud cover versus solar radiation

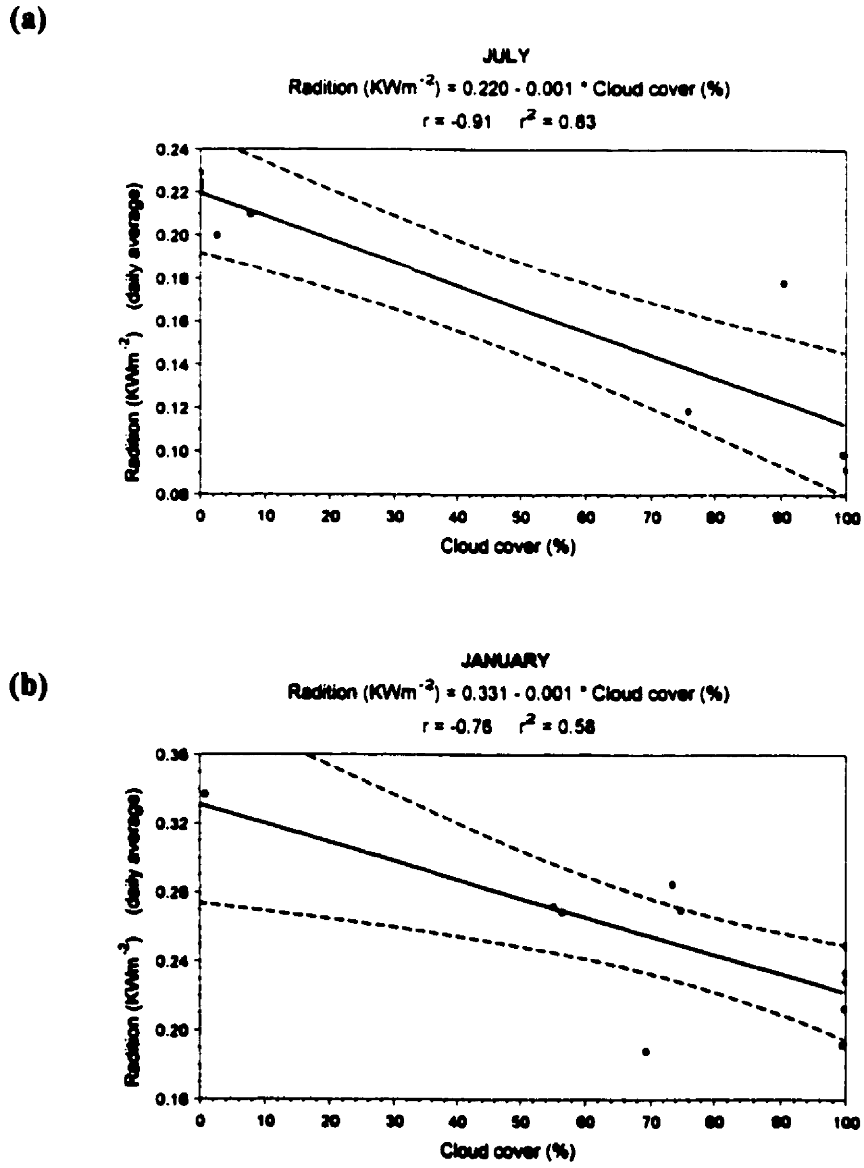

Figure 1. Plots of the cloud cover versus daily average of solar radiation. (a) July 1997 data and (b) January 1998 data.

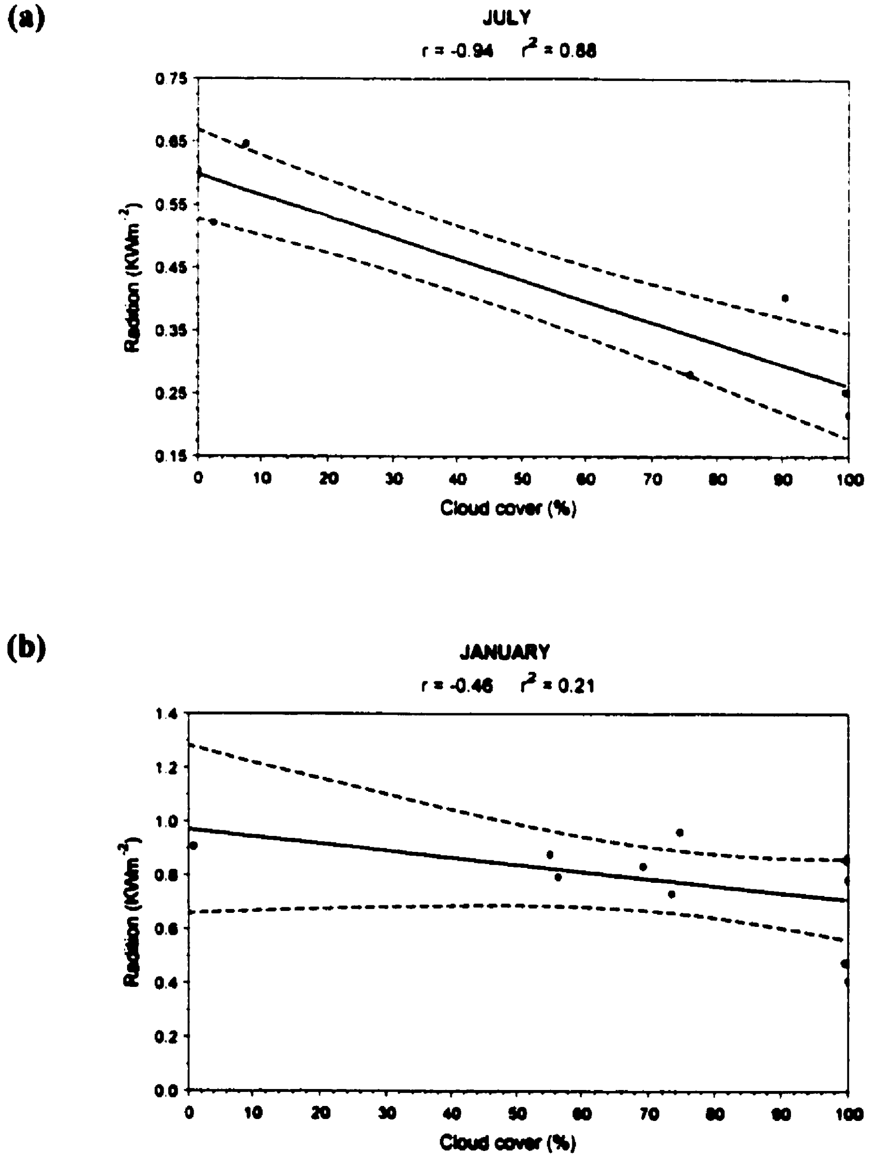

Figure 2. Plots of the cloud cover versus coincident measurement of solar radiation. (a) July 1997 data and (b) January 1998 data.