RESEARCH FOR THE MANAGEMENT
OF THE FISHERIES ON LAKE
TANGANYIKA

GCP/RAF/271/FIN-TD/86 (En)

GCP/RAF/271/FIN-TD/86 (En)

May 1998

HYDRODYNAMICS OF LAKE TANGANYIKA: Results for 1996

by

Piet VERBURG, Bomba KAKOGOZO, Lawrence MAKASA,
Stanslaus MUHOZA and Jean-Marie Tomba

FINNISH INTERNATIONAL DEVELOPMENT AGENCY

FOOD AND AGRICULTURE ORGANIZATION
OF THE UNITED NATIONS

Bujumbura, May 1998

PREFACE

The Research for the Management of the Fisheries on Lake Tanganyika project (LTR) became fully operational in January 1992. It is executed by the Food and Agriculture Organization of the United Nations (FAO) and funded by the Finnish International Development Agency (FINNIDA) and the Arab Gulf Program for the United Nations Development Organization (AGFUND).

LTR's objective is the determination of the biological basis for fish production on Lake Tanganyika, in order to permit the formulation of a coherent lake-wide fisheries management policy for the four riparian States (Burundi, Democratic Republic of Congo, Tanzania, and Zambia).

Particular attention is given to the reinforcement of the skills and physical facilities of the fisheries research units in all four beneficiary countries as well as to the build-up of effective coordination mechanisms to ensure full collaboration between the Governments concerned.

Prof. O.V. LINDQVIST
LTR Scientific Coordinator

Dr. George HANEK
LTR Coordinator

LAKE TANGANYIKA RESEARCH (LTR)
FAO
B.P. 1250
BUJUMBURA
BURUNDI

Telex: FOODAGRI BDI 5092

Tel: (257) 22.97.60

Fax: (257) 22.97.61

E-mail: ltrbdi@cbinf.com

GCP/RAF/271/FIN PUBLICATIONS

Publications of the project are issued in two series:

* a series of **technical documents (GCP/RAF/271/FIN-TD)** related to meetings, missions and research organized by the project;

* a series of **manuals and field guides (GCP/RAF/271/FIN-FM)** related to training and field work activities conducted in the framework of the project.

For both series, reference is further made to the document number **(01)**, and the language in which the document is issued: English **(En)** and/or French **(Fr)**.

For bibliographic purposes this document should be cited as follows:

Verburg, P., B. Kakogozo, L. Makassa, S. Muhoza, and J.-M.
1998 **Tumba**. Hydrodynamics of Lake Tanganyika: Results of 1996. FAO/FINNIDA Research for the Management of the Fisheries of Lake Tanganyika. **GCP/RAF/271/FIN-TD/86 (En): 37p.**

TABLE OF CONTENTS

1. INTRODUCTION

Lake Tanganyika is the second deepest lake in the world (1470 m), and the second largest in Africa. It is located between 3 and 9° S, 670 km long and has a maximum width of 48 km (Fig. 1). The warm wet season is in general from October to April but there are differences from north to south in rainfall (Fig. 2).

Below about 200 m depth the lake water is permanently anoxic, and relatively rich in nutrients (Coulter, 1991). Upwelling of nutrients is considered to be of paramount importance in sustaining the food webs in the lake (Coulter, 1991). Upwelling and mixing of epilimnetic and hypolimnetic waters occur primarily in the dry season (May - September), driven by strong trade winds from the south-east. A fishery which is primarily active off-shore, targeting mainly pelagic fish species, supplies an important source of protein in the area around the lake.

Meteorological observations at Lake Tanganyika were first given by Burton (1860). Although several hydrological and limnological studies have been conducted on Lake Tanganyika (Stappers, 1914; Cunnington, 1920; Beauchamp, 1939; Capart, 1949, 1952; Servais, 1957; Dubois, 1958; Coulter, 1967; Ferro, 1975), the hydrodynamics of the lake are still poorly understood. Previous studies have been localized rather than lake-wide (Coulter, 1991). Accurate automatic recording devices were not previously used on the lake.
The Lake Tanganyika Research (LTR) hydrodynamic component has established several meteorological and hydrological sampling stations around and on the lake. Data have been collected with automatic recorders since March 1993, and were previously presented by Kotilainen *et al*. (1995) and Verburg *et al*. (1997). The diel cycle of meteorological and hydrological parameters was presented by Verburg (1997).

This is an interim report, describing the dynamics of the upper 300 m of the lake water and relations with meteorological parameters for 1996. Internal wave action is demonstrated, the wind speed vector field over the lake was analyzed, and a heat budget was calculated.

2. MATERIAL AND METHODS

Rainfall data were obtained from the Meteorological Departments of Tanzania and Zambia.

2.1 Automatic recorders

Data were collected by two stations around the lake and two offshore stations (Huttula *et al.*, 1993; Kotilainen *et al.*, 1995; Verburg *et al*., 1997a), equipped with automatic meteorological and hydrodynamical data recording instruments of

Aanderaa Instruments (Fig. 1). Weather stations were located at the north end (Bujumbura, Burundi) and at the south end of the lake (Mpulungu, Zambia). Two buoys were located off Kigoma and off Mpulungu. The depth of water at the Kigoma and Mpulungu buoys was *c.* 400 and 350 m respectively.

Data of wind speed, wind gust, wind direction, air pressure, air temperature, relative humidity, solar radiation and water temperature at different depths were collected. The parameters were recorded as momentary values, except wind speed and wind gust. The arithmetic mean of wind speed was recorded over the recording time interval and the maximum wind speed over a 2 s period at any time during the interval gave wind gust.

2.2 The Wedderburn number

The intensity of stratification, mixing, and the influence of wind stress can be examined by the calculation of the dimension less Wedderburn number (Monismith, 1986):

$$W = g'h^2/(u_*^2 L_m)$$

The formula combines mixing depth h (in m), the reduced acceleration of gravity g' ($m.s^{-2}$), proportional to the density jump across the thermocline, shear velocity u_* ($m.s^{-1}$), and lake length L_m (m), with

L_m = 673000 m
$g' = 2g(r_2-r_1)/(r_2+r_1)$
r_1, r_2 = densities of epilimnion and hypolimnion respectively
g = acceleration of gravity, 9.8 $m.s^{-2}$
$u_*^2 = (r_{air}/r_{water})CV^2 = 0.0011 * 0.0014 * V^2$
C = coefficient of drag
V = wind speed

Daily Wedderburn numbers were calculated, for positions off Mpulungu, Kigoma and Bujumbura, using Chen and Millero's (1977) formula for calculating water density from water temperature and salinity, and salinity from conductivity (dissolved salt content, $g.kg^{-1}$ = 0.5 x conductivity, $mS.cm^{-1}$).

Daily mean wind speed data were collected at the buoy off Mpulungu, the buoy off Kigoma and the weather station at Bujumbura. Daily mean water temperature data were collected at 1 m and 300 m at the buoys off Mpulungu and Kigoma. For periods without data for temperature at 300 m, the mean value was used (23.43 °C) since there was little variance in temperature at this depth. For Bujumbura, weekly temperature measurements taken offshore at 1 m were used. Water temperature at 1 m at Bujumbura was interpolated assuming a linear daily change between the weekly measurements. Epilimnion density (r_1) was calculated using conductivity data collected weekly at 10 m off Mpulungu, Kigoma and Bujumbura. Conductivity data were collected once every 6 weeks at 300 m. For the calculation of density at 300 m

(r_2), the mean conductivity at 300 m was used (0.694 $mS.cm^{-1}$). To calculate daily Wedderburn numbers, weekly conductivity data were interpolated.

In August - December 1996 conductivity data were not collected and, for Mpulungu and Kigoma, the mean of conductivity at 10 m (0.651 $mS.cm^{-1}$) was used, since temporal conductivity differences were small, and the influence of salinity at 10 m on the Wedderburn number was found negligible.

For the mixed layer or epilimnion depth h (Imberger, 1985), a fixed depth of 50 m was assumed. The seasonal thermocline surfaces in the dry season at the south end of the lake, and the depth scale of the temperature measurements with the buoy thermistors was not precise enough to discern exact temporary thermocline depths. Taking an isotherm depth as indicator of h was no option, since the 24 °C isotherm surfaces in some years at the south end of the lake, and is far below the seasonal thermocline in the wet seasons. The 25 °C isotherm, at the lower interface of the metalimnion during the wet seasons, surfaces every year for 2 - 3 months during the wet seasons. An epilimnion depth of 0 m would give W = 0, which only makes sense when complete overturn occurs. It would limit the capacity for comparisons between dry seasons, and the Wedderburn number would thereby lose much of its value.

2.3 Wind direction and wind speed vectors

Monthly mean wind direction distributions (%) were calculated for 16 different wind directions.

North/south (N/S) and east/west (E/W) wind speed vectors were calculated by multiplying, for each measurement, the north and east components of the wind direction with the wind speed (Equations 1 and 2, with numerical examples, in Appendix III). Using this method, a negative N/S wind speed vector would indicate that wind stress was from the south. In order to find the relative contribution of each of four wind directions to the wind stress over averaged periods, the north, south, east and west components of the wind speed vectors were then calculated for every measurement of wind speed and wind direction. This was done by equaling for instance a negative N/S vector to zero wind from the north, and the absolute value to wind from the south. The north minus the south wind speed vector thus represents the N/S wind speed vector.

2.4 Evaporation

Evaporation at Bujumbura and the Mpulungu buoy was calculated from wind speed, air temperature, air pressure and relative humidity data, using a simplified form of the Thornthwaite-Holzman equation for vapour transport (Chow *et al.*, 1992; Verburg *et al.*, 1997; Verburg, 1997). For Bujumbura, values for all 4 variables were recorded at 13 m height on a jetty in the harbour. For Mpulungu, wind speed and air temperature data were collected from the buoy and humidity and air pressure from the weather station at Mpulungu. For Mpulungu the humidity data were adjusted to account for the distance of the sensor from the lake shore (Verburg *et al.*, 1997). A linear relation was used between humidity at the weather station and humidity at a jetty at the lake shore at Mpulungu (Verburg *et al.*, 1997). Calculations of evaporation were made for every 10 min for Bujumbura, and for every hour for Mpulungu.

2.5 Water level recorders

Telog water pressure sensors at the harbours of Bujumbura, Kigoma and Mpulungu, were used to record the lake levels. The sensors were positioned in open ended tubes fixed to jetties, to avoid influence from wave action on the position of the sensor. Water pressure was measured every 2 s. Hourly means of the water levels were recorded, as percentages of the depth range of the sensor, where 0 % = 0 cm and 100 % = 175.77 cm depth. Further information concerning the structure and operation of the water level recorder is provided by Huttula *et al*. (1993) and Kotilainen *et al* (1995). When it was necessary to lift or lower the sensor, to prevent either submergence deeper than its depth range or its emergence above the surface, the level data were adjusted by the distance between the mean level of the previous day and the day following the day of the sensor's change in depth, since the water level showed greater variability within a day, than between consecutive mean daily levels.

The Telog data were scaled to meters above sea level by comparing with data collected daily with benchmarked gauge plates, by the Department of Hydrology at Kigoma harbour.

3. RESULTS

Monthly means are shown in Tables 1 - 4 (Appendix I).

3.1 Lake hydrodynamics

At the south end of the lake isotherms in the upper 100 m decreased in depth from June, due to strong winds from the south east, cooling at the surface by increased evaporation and lower air temperature (Figs. 3-6). The thermocline tilted towards the north in the dry season. The tilt was highest in July (*c.* 80 m for the 24.5-25 °C isotherms, Fig. 14). At this time the isotherms along the boundary of epilimnion and metalimnion in the north were close together and the thermocline was sharp. At the south end, where cooling was strongest, the thermocline surfaced and the upper 100-150 m became almost isothermal. Mixing was most intense at the south end in this season and upwelling occurred of cold hypolimnetic water. The tilt of the thermocline was reversed when wind stress relaxed after the dry season, and was greatest towards the south in November (*c*. 30 m for the 24.5 - 25.5 °C isotherms, Fig. 14).

The thermocline never disappeared in the north, and mixing off Kigoma was less than off Mpulungu (see also Wedderburn numbers). During the wet season the surface waters warmed up, by increased air temperature and solar radiation and diminished wind speed and evaporation. Off Mpulungu the thermocline reestablished in September and stratification set in.

The seasonal thermocline tended to be deeper off Kigoma than off Mpulungu (Fig. 7-9). The seasonal thermocline off Kigoma rose in the early part of the wet season (October) to *c*. 40 m depth, and was most of the year at 60 - 80 m depth. Off Mpulungu, the thermocline surfaced in July - August, and was located most of the year at *c*. 40 m depth.

The depth of the steepest density gradients (as mean depths between the nearest thermistors) occurred shallow (in the upper 5 m), in the dry season off Mpulungu, and in the wet season off Kigoma (Fig. 9), i.e. when stratification was weak and the respective seasonal thermoclines surfaced or ascended. The next steepest density gradient occurred as deep as 100 - 200 m depth off Mpulungu in the dry season, and at 5 - 50 m off Kigoma in the wet season.

Cooling and mixing was less off Kigoma than off Mpulungu and started about 1 month later than off Mpulungu. Off Kigoma only the uper 50 m became isothermal in July - August and stratification did not break down as in the south. Variation in water temperature was less than at the Mpulungu buoy (Figs 4 and 6).

Internal waves were observed (Figs 10 - 14), both in the wet and in the dry season. Internal wave action was evidenced by fluctuations with periods of *c*. 1 month in isotherm depths, for the shallower isotherms (>24 °C) superimposed on the major seasonal vertical movements. Periodic changes in temperatures were highest at 30 and 50 m (Fig. 5).

There was no perceptible damping of the oscillation towards the dry season. Negative correlations between the depths of isotherms at the Mpulungu and Kigoma buoys indicated internal waves with a lake wide phase relationship and the fundamental mode appearing as a uninodal seiche (*cf*. Coulter and Spigel, 1991). The maximum tilt of the 23.5 and 23.75 °C isotherms between the Mpulungu and Kigoma buoys was *c.* 60 m (*c.* 0.12 $m.km^{-1}$)

The tilt along the length of the lake of deep and shallow isotherms depended for the former on internal wave action and for the latter primarily on the seasonal wind-driven vertical water displacement, mixing and surface cooling (Figs. 13 and 14 respectively). The 24.5 - 25.5 °C isotherms surfaced in the dry season off Mpulungu (Fig. 14). When the 24.5 °C was close to the surface off Mpulungu, the northward tilt was 70 - 90 m. The deeper isotherms off Mpulungu tilted almost permanently towards the south (Fig. 13).

3.2 The Wedderburn numbers

High values of W indicate stability and a well developed stratification, while from low numbers (particularly for $W < 0.5$) a strong shear stress at the thermocline, tilting of the thermocline with related mixing and possible upwelling at the windward end of the lake can be inferred.

At all three stations, lowest Wedderburn numbers occurred in the dry season, generally in months with the highest wind speed, with the lowest values occurring *c.* one month later in the north (August - September) than in the south (July). The lake was most stable in January - February off Mpulungu and Kigoma and from February to April off Bujumbura (Fig. 15). Off Bujumbura stable, stratified lake conditions developed later in the wet season than in the south, since off Bujumbura surface water temperature was generally lowest during the first half of the wet season (October - January) and highest late in the wet season, from April to May.
Upwelling occurred primarily at the south end of the lake and mixing was most intense off Mpulungu and least off Bujumbura (Fig. 15 and Table 1). In the wet season, the lake reached most stable conditions off Mpulungu and stratification was weakest off Kigoma of the three stations. The seasonal differences in the Wedderburn number were thus much larger off Mpulungu, than off Kigoma. Off Mpulungu, wind speed and surface water temperature correlated more than off Kigoma and Bujumbura, with coinciding periods of highest wind speed and lowest surface temperature (July), thereby reinforcing the effects on mixing. During the dry season, density differences between epilimnion and hypolimnion (g', Table 1) were much smaller, and wind speeds higher, off Mpulungu, compared with off Kigoma, giving relatively low Wedderburn numbers for the Mpulungu area. During the wet season, the density differences over the thermocline were higher off Mpulungu than off Kigoma. The curves for g' versus time were, as expected, very similar to the curves for the temperature at 1 m depth.

Table 1. Mean seasonal Wedderburn numbers and values of g', an indication of the density jump across the thermocline (n.a. = not available).

W	Mpulungu	Kigoma	Bujumbura	g'	Mpulungu	Kigoma	Bujumbura
June-Aug				mean	0.0076	0.0081	0.0079
1996	1.31	1.51	n.a.	min	0.0015	0.0053	0.0045
				max	0.0133	0.0124	0.0126
Nov-March							
1995-96	3.69	2.35	3.04				

3.3 Maximum heat content

The 'maximum heat content' was calculated as the total heat per unit surface area that entered the lake between the month of lowest and the month of highest monthly mean heat content of the lake water (defined by Horne and Goldman, 1994). The heat content was calculated up to 300 m depth, and lake area differences at different depths were ignored.

In the south the lake gained its heat in the early part of the wet season (July - November), and more heat was absorbed at the surface than in deeper layers (Figs 16 and 17). At 150 m depth and deeper, the annual temperature increases were about zero. At the Mpulungu buoy the heat uptake by the lake was 19079 $cal.cm^{-2}$.

The heat gain was highest in October (*c.* 350 $cal.cm^{-2}.day^{-1}$). The heat loss was highest in June (*c.* 320 $cal.cm^{-2}.day^{-1}$). Off Mpulungu, the heat gain at different depths to 150 m was simultaneous. The monthly heat change, or storage rate, of the upper 150 m of the water column was therefore proportional to the monthly change in surface temperature, as is clearly shown by the close correlation in Figure 18.

Off Kigoma, the heat gain and loss at different depths did not occur simultaneously, and the monthly heat storage rate in the upper 150 m and the change in surface water temperature were often not proportional (Fig. 18). The upper 30 m gained its heat mainly already in August - October 1995, i.e. before the minimum heat content of the lake was reached, when the deeper water layers were still cooling. In November 1995 - May 1996, water at 50 - 150 m depth gained its heat. Therefore, annual temperature increases, between months of minimum and maximum heat content, were maximum at 50 m depth (Fig. 16).
At the Kigoma buoy, the heat was gained during the whole wet season (Fig. 17). In October 1995 to May 1996 the heat uptake was 9301 $cal.cm^{-2}$, *c.* 50 % of the total annual heat uptake in the south (Figs 16 and 17). The loss of heat was highest in July (*c.* 180 $cal.cm^{-2}.day^{-1}$).

3.4 Evaporation

The annual evaporation at the Bujumbura weather station was 1160 mm (Fig. 19). Evaporation rates at the Mpulungu buoy were on average x 2 those at Bujumbura. Adjusting the humidity values at Mpulungu for humidity at the lake shore, lowered the calculated evaporation with 12 % annually.

Monthly mean evaporation at Bujumbura was highest in August. At the Mpulungu buoy it was highest in April. Maximum daily evaporation rates occurred in July, coinciding with high wind speeds.

3.5 Rainfall

Rainfall at Kigoma was highest in February (Fig. 20) and was in 1996 higher than the annual mean (Fig. 2). At Mpulungu it was highest in January. For Mpulungu no data were available for December. At Mpulungu 72 % of the rain fell at night (1900 - 0800 h).

3.6 Solar radiation

The mean solar radiation was higher at Mpulungu (251 $W.m^{-2}$) than at Bujumbura (221 $W.m^{-2}$). At Bujumbura it was only 4 $W.m^{-2}$ lower and at Mpulungu 2 $W.m^{-2}$ higher during the wet season, compared with the dry season. There was more variance in the solar radiation at Bujumbura than at Mpulungu (Fig. 21).

3.7 Relative humidity

Humidity was lowest in August at both stations, and maxima were reached in the wet seasons (Fig. 22). Humidity at Mpulungu (mean 46 and 63 % in the dry and wet seasons respectively) was lower than at Bujumbura at 13 m height (65 and 73 % in the dry and wet seasons respectively). The humidity at 4 m height at Bujumbura was on average 4 % higher than at 13 m height. When humidity was highest at Mpulungu, in January - February, it was similar to the humidity at Bujumbura at 13 m height.

3.8 Air pressure

Mean monthly air pressure was, both at Bujumbura and at Mpulungu, highest in June - July (924.6 mbar at Bujumbura) and lowest in March and November (921.8 mbar at Bujumbura). The annual mean at Bujumbura was 922.8 mbar (Fig. 23). Air pressure at Mpulungu was on average 1.8 mbar lower than at Bujumbura, due to the position of the Mpulungu weatherstation on a hill, 40 m above the lake surface.

3.9 Air temperature

Mean monthly air temperature was highest in March - May and September - November at all stations. The lowest mean monthly air temperature was reached in July at all stations (Fig. 24).

Air temperature was on average highest at the Mpulungu buoy and lowest at Bujumbura. Only in June - August were air temperatures at the Kigoma buoy above those at the Mpulungu buoy. Only in August - October were air temperatures at Mpulungu slightly higher than at the Mpulungu buoy. There was more seasonal difference at Mpulungu and the Mpulungu buoy than at Bujumbura and the Kigoma buoy.

Air temperature at the Mpulungu buoy was on average 0.2 °C higher than at Mpulungu. This was due to the influence of the surface temperature of the lake, which was usually higher than the air temperature at 2.6 m above the lake surface.

3.10 Wind speed and gust

The mean monthly wind speed was highest in June, except at Bujumbura (August). It was lowest in February (Fig. 25). Wind speed was on average lowest at the Bujumbura and Mpulungu weather stations and highest at the Mpulungu buoy. At the Mpulungu buoy and weather station the wind speeds showed the greatest seasonality. Variance in daily mean wind speed was highest at the Mpulungu buoy with maximum daily means *c.* 8 $m.s^{-1}$. Maximum daily means at Bujumbura, the Kigoma buoy and Mpulungu were *c.* 5, 6 and 7 $m.s^{-1}$ respectively.

The highest wind gusts were measured between 5 January and 8 February at the Kigoma buoy (23 $m.s^{-1}$), the Bujumbura weather station (21 $m.s^{-1}$), the Mpulungu buoy (20 $m.s^{-1}$), and the Mpulungu weather station (19 $m.s^{-1}$). These maximum wind gusts occurred simultaneously with relatively large decreases in air temperature during the same hour (between -2.0 °C at the Mpulungu buoy and -6.0 °C at the Bujumbura weather station).

3.11 Wind direction

The different directions from which the wind blew are shown in Figures 26 - 29. At the Bujumbura and Mpulungu weather stations the wind distribution was similar the whole year. The proportion of the south-east winds increased at all stations during the dry season. Winds from the land were more frequent at all stations during the dry season, except at the Kigoma buoy.

At Bujumbura, the wind direction was primarily from the north and there was a slightly smaller south-south-east component. At the Kigoma buoy the main wind direction was from the south-south-east. In October - November it was mostly from the east. At the Mpulungu buoy, wind came primarily from the south-east during the dry season. At the Mpulungu weather station, the south-east wind was the most common in each month.

3.12 Wind vector components

The south and east wind components were in general higher than the north and west components at all stations (Figs 30 - 33). The south and east wind components were generally highest in the dry season, around the lake. The north and west wind components generally increased slightly in the wet season. At the Mpulungu buoy seasonality was greatest.

3.13 Lake Level

The lake level was highest in April-May (maximum of daily measurements was 774.35 m) and lowest in November (Fig. 34). The fall in lake level during the dry season was 0.89 m (between daily means) and the mean lake level was 773.82 m. In Figure 34B monthly means of lake levels recorded with conventional gauge plates at the Kigoma and Mpulungu harbours are shown. Those at Mpulungu have not been bench marked and the zero reference of the level data was found by comparison with the gauge plates of the Kigoma Department of Hydrology. The data of the conventional gauge plates fitted well with the Telog recorder data.

4. DISCUSSION AND CONCLUSIONS

Wind, its speed and its direction, has an important influence on the introduction of nutrients to the epilimnetic ecosystem and on the mixing intensity. Below about 200 m depth the lake water is permanently anoxic, and relatively rich in nutrients (Coulter, 1991). Upwelling of nutrients is considered to be of paramount importance to sustain the food webs in the lake (Coulter, 1991). The productivity in the lake depends largely on the intensity and direction of water movements, upwelling and horizontal currents, driven by wind speed and influenced by density based buoyancy differences.

Mixing of epilimnetic and hypolimnetic waters and upwelling occurs primarily in the dry season (May - September), driven by strong winds from the south-east. The annual yields of the offshore fishery may vary significantly with the extend of annual upwelling and mixing intensity.

During the dry season the position of the Inter Tropical Convergence Zone (ITCZ) is found far north of Lake Tanganyika (Asnani, 1993). The local winds are then mainly caused by the temperature differences between the rift lake and the sloping coastline (Podsetchine *et al.*, 1996). Lake winds blow during the day and land winds during the night (Beauchamp, 1939; Verburg, 1997; Savijärvi, 1997). Wind speeds from the lake were higher than from the land at Bujumbura and Kigoma. The land-lake breeze air circulations are intensified by the weak but steady large-scale south-east tradewinds during the dry season (Podsetchine *et al.*, 1996). During the wet season the ITCZ moves south, bringing rain and weak winds from the north-west to Lake Tanganyika.

The wind forcing from the south in the dry season resulted in a downward tilting of the thermocline at the northern part of the lake. In the dry season wind speeds were higher and air temperature lower at the Mpulungu buoy than at the Kigoma buoy. This accellerated the weakening of the stratification and mixing rates at the south end of the lake. Upwelling occurred at the south end of the lake and surface water, mixed with upwelled nutrient rich water, flowed northwards (Coulter and Spigel, 1991).
When the strong south wind ceased at the end of the dry season, forces on the tilted thermocline were relaxed. Adjustment of the density equilibrium by redistribution of the water masses followed, the thermocline developed and stratification set in at the south end of the lake. Upwelling may have occurred at the north end of the lake where the thermocline ascended in September - December (this report and Coulter and Spigel, 1991). During the wet season the surface water temperature at the south end of the lake increased more than in the north, due to the redistribution of the water masses and a higher air temperature in the south.

When at the end of the dry season the strong south wind ceases, and forces on the tilted thermocline are relaxed, gravitational adjustment of the density equilibrium causes vertical periodic oscillations of water masses (Coulter and Spigel, 1991). The period of 25 - 30 days of the fundamental mode of the internal waves corresponded with previous studies and theoretical values for internal waves in Lake Tanganyika (Coulter and Spigel, 1991; Podsetchine and Huttula, 1996). Waves of this duration (and amplitude and periodicity) have not been observed in any other lake (Coulter and Spigel, 1991).

The Wedderburn number (W), derived from wind speed and the density gradient across the thermocline, is an indicator of stress on the lake surface and therefore lake mixing. High values of W indicate stability, while from low numbers (particularly for $W < 0.5$) a strong shear stress at the thermocline, tilting of the thermocline with related mixing and possible upwelling at the windward end of the lake can be inferred (Monismith, 1986). At $W < 0.5$ strong mixing between the epilimnion and the hypolimnion and upwelling is expected as the thermocline surfaces at the upwind end of the lake (Coulter and Spigel, 1991; Patterson and Kachinjika, 1995). The upwelled hypolimnetic water is then advected downwind in the surface layer.

The Wedderburn values found here for off Mpulungu are lower than expected. Values for $W < 1$ occurred for a large part of the year off Mpulungu. An increase or decrease in epilimnion depth (h) by 5 m, changed the Wedderburn number by *c.* 30 %. An epilimnion depth of 50 m gives a Wedderburn number *c.* 2x that found with h = 35 m. The seasonal thermocline tended to be deeper off Kigoma than off Mpulungu. The seasonal thermocline off Kigoma was between 40 - 80 m depth. Off Mpulungu, the thermocline surfaced in July - August, and was located the rest of the year at *c.* 40 m depth. This would, if taken into account for the determination of h, increase the calculated differences in W from north to south, with lower W at the south end of the lake.

Wedderburn numbers given for Nkhotakota, at Lake Malawi by Patterson and Kachinjika (1995) were less often < 1 compared with off Mpulungu. One cannot readily compare W between lakes, since it largely depends on wind speed, which in turn depends on the location where the wind speed was measured, for instance inshore (as in Patterson and Kachinjika, 1995) where usually relatively low wind speeds are found, or near an escarpment or on the open lake (this study). It can be used for comparisons of sites within lakes, and for comparison on temporal scales.

Coulter and Spigel (1991) estimated the annual heat budget at 11650 $cal.cm^{-2}$ for Lake Tanganyika (up to 150 m depth), based on a hypothetical temperature distribution in August, and one temperature profile in March 1973 at the south basin, about 150 km north of Mpulungu. The values found in this report at the Mpulungu buoy were much higher, probably since at the south end of the lake (40 km north of Mpulungu), annual temperature changes are much larger.

At the north end of the lake mixing was strongest in the daytime, and at the south end nighttime mixing prevailed, as indicated by the diel cycles of wind speed and evaporation (Verburg, 1997). Wind speed and evaporation were highest in the daytime in the north and highest at night in the south.

In Lakes Victoria and Malawi, evaporation rates and wind speeds were found to be higher at their southern ends, especially in the dry season, and humidity increased towards the north (Coulter and Spigel, 1991), as was found in this study for Lake Tanganyika. The lower evaporation in the north is caused by increasing vapour pressure of the air downwind across an open water surface (Linsley *et al.*, 1988), and winds coming generally from the south, along the length of the lake, especially in the windy dry season.

The fall in lake level in the dry season (0.89 m) was higher than the mean 0.82 m for 1941 to 1959, given by Bultot (1965). In 1996 the lake level reached the lowest level since 1959.

The lake outflow by the river Lukuga, calculated by an equation given by Devroey (1949), relating outflow to lake level, was between 160 and 50 m^3.s, and a mean 93 m^3.s in 1996. This accounted for about 5 % of the water budget (the sum of rainfall on the lake and river inflow, or of evaporation and outflow; Verburg, in prep.). Devroey (1949) found the sill of the river Lukuga at 772.7 m. This means that in 1996 the lake level was less than 1 m above its lowest possible level.

5. ACKNOWLEDGEMENTS

We wish to express our sincere thanks and gratitude to all who have assisted in the data collection and maintenance of recorders. We acknowledge the encouragement and support of LTR's FAO field Co-ordinator Dr. G. Hanek. We thank the crew of RV Tanganyika Explorer for their assistance. Rainfall data were received from the Meteorological Departments of Tanzania and Zambia.

6. REFERENCES

Asnani, G.C., 1993. Tropical meteorology. Ind. Inst. Trop. Met, 1202 p.

Beauchamp, R.S.A., 1939. Hydrology of Lake Tanganyika. Int. Rev. Ges. Hydrobiol. Hydrogr., 39: 316-353.

Bultot, F., 1965. A propos de l'evaporation du lac Tanganika. Acad. R. Sci. Outre-Mer (Brussels) Bull. Séances, 4: 1226-1241.

Burton, R.F., 1860. The lake regions of Central Africa, a picture of exploration. Dover Publications, New York. 572 pp.

Coulter, G.W., 1967. Hydrological processes in Lake Tanganyika. Fish. Res. Bull. Zambia 4: 53-56.

Coulter, G.W., 1991. Lake Tanganyika and its life. British Museum and Oxford University Press, Oxford, 354 pp.

Coulter, G.W., and R.H. Spigel, 1991. Hydrodynamics. *In*: G.W. Coulter (ed), Lake Tanganyika and its life. Natural History Museum publications, Oxford, 49-75.

Capart, A., 1949. Sondages et carte bathymétrique du Lac Tanganika. Résultats scientifique de l'exploration hydr obiologique du lac Tanganika (1946-1947). Inst. Roy. Sc. Nat. Belg. 2(2): 1-16.

Capart, A., 1952. Le milieu géographique et géophysique. Résultats scientifique de l'exploration hydrobiologique du lac Tanganika (1946-1947). Inst. Roy. Sc. Nat. Belg.1: 1-28.

Chen, C.T., and F.J. Millero, 1977. The use and misuse of pure water PVT properties for lake waters. Nature 266: 707-708.

Chow, V.T., D.R. Maidment, and L.W. Mays, 1992. Applied hydrology. McGraw-Hill Book Co., 572 pp.

Cunnington, W.A., 1920. The fauna of the African lakes: a study in comparative limnology with special reference to Lake Tanganyika. Proc. London Soc. Zool. 3: 507-622.

Dubois, J. Th., 1958. Evolution de la témperature, de l'oxygène dissous et de la transparence dans la baie nord du Lac Tanganika. Hydrobiologia 10: 215-240.

Ferro, W., 1975. Limnological observations from the north of Lake Tanganyika (1972-1975).FAO FI:DP/BDI/73/020: 1-29. Horne and Goldman, 1994. Limnology. Mc Graw-Hill Inc., 2nd ed., 576 pp.

Huttula, T., A. Peltonen and J. Nieminen, 1993. Hydrodynamic measurements on Lake Tanganyika. FAO/FINNIDA Research for the Management of the Fisheries on Lake Tanganyika. GCP/RAF/271/FIN-FM/02 (En): 48p.

Imberger, J., 1985. The diurnal mixed layer. Limnol. Oceanogr., 30(4): 737-770.

Kotilainen, P., T. Huttula, and A. Peltonen, 1995. Lake Tanganyika hydrodynamics (results of March 1993 - December 1994). FAO/FINNIDA Research for the Management of the Fisheries on Lake Tanganyika. GCP/RAF/271/FIN-TD/43 (En): 97p.

Linsley, Kohler, Paulhey, 1988. Hydrology for engineers. McGraw-Hill.

Monismith, S., 1986. An experimental study of the upwelling response of stratified reservoirs to surface shear stress. J. Fluid Mech., 171: 407-439.
Patterson, G., and O. Kachinjika, 1995. Limnology and phytoplankton ecology. *In*: Menz, A. (ed.), The fishery potential and productivity of the pelagic zone of Lake malawi/Niassa. UK/SADC report, 1-68.
Podsetchine, V., and T. Huttula, 1996. Hydrological modelling: activity report for the periods of 01.04-31.05.1995 and 01.09.-30.09.1995. FAO/FINNIDA Research for the Management of the Fisheries on Lake Tanganyika. GCP/RAF/271/FIN-TD/45: 109p.
Podsetchine, V., T. Huttula and H. Savijärvi. Development of a 3D numerical upwelling model for Lake Tanganyika. In prep.
Savijärvi, H., 1997. Diurnal winds around Lake Tanganyika. Accepted to Quart. J. R. Met. Sc.
Servais, F., 1957. Étude théorique des oscillations libres (seiches) du lac Tanganika. Résultats scientifique de l'exploration hydrobiologique du lac Tanganika (1946-1947). Inst. Roy. Sc. Nat. Belg. 3(3): 1-311.
Stappers, L., 1914. Recherches bathymétriques sur les lacs Moero et Tanganika. Ann. Biol. Lacustre.
Verburg, P., T. Huttula, B. Kakogozo, A. Kihakwi, P. Kotilainen, L. Makasa and A. Peltonen, 1997. Hydrodynamics of Lake Tanganyika and meteorological results. FAO/FINNIDA Research for the Management of the Fisheries on Lake Tanganyika. GCP/RAF/271/FIN-TD/59 (En): 67p.
Verburg, P., 1997. Lake Tanganyika hydrodynamics and meteorology: the diel cycle. FAO/FINNIDA Research for the Management of the Fisheries on Lake Tanganyika. GCP/RAF/271/FIN-TD/73 (En): 51p.

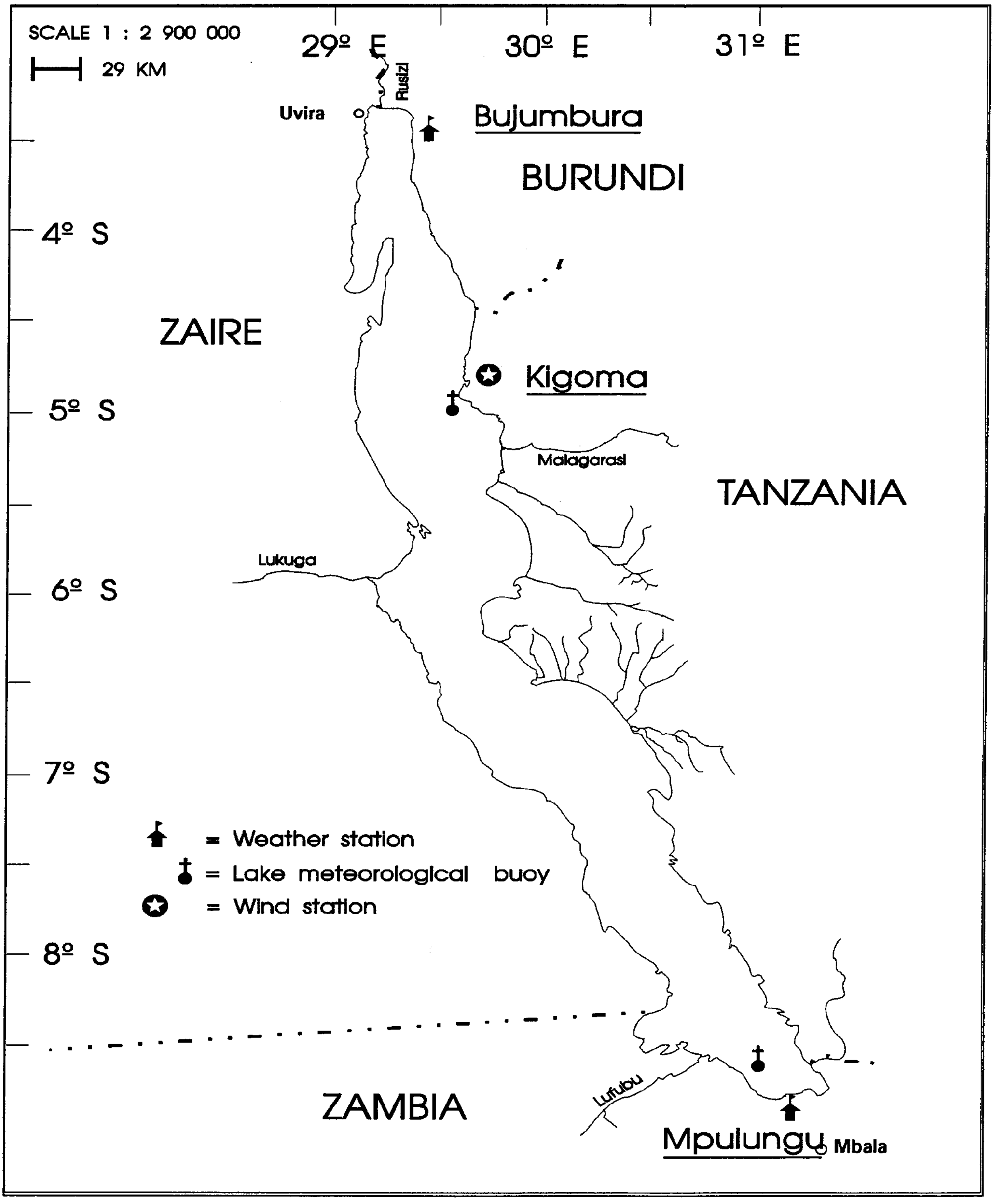


Figure 1. The positions of the meteorological instruments at Lake Tanganyika.

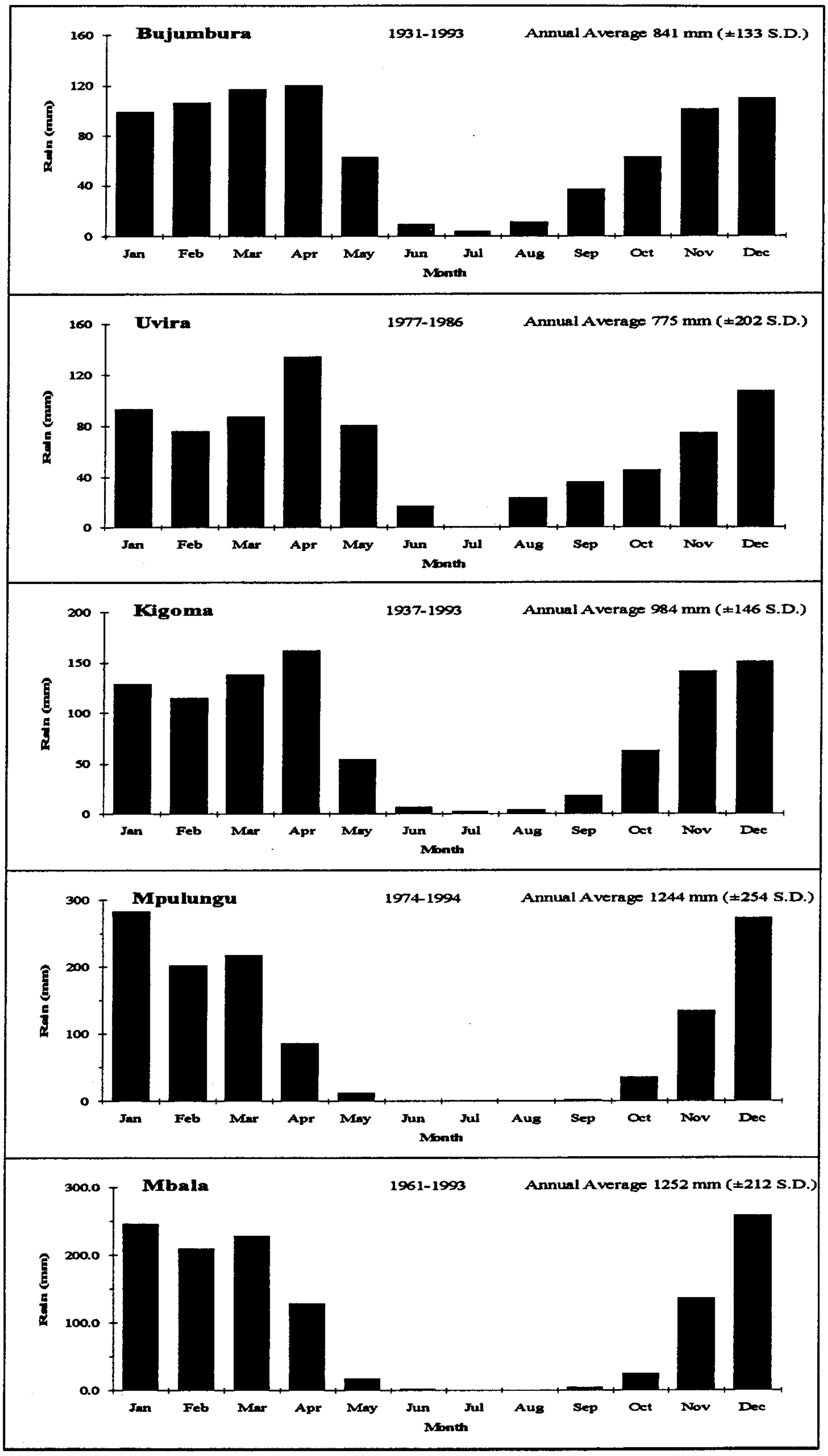


Fig. 2. Mean monthly rainfall on or near the shores of Lake Tanganyika, at Bujumbura (Burundi), Kigoma (Tanzania), Mpulungu and Mbala (Zambia) and Uvira (Zaire). Data supplied by respective national meteorological services. The data collection period and the annual average are mentioned. Note that the y-axes are not drawn to the same scale. For locations see Figure 1.

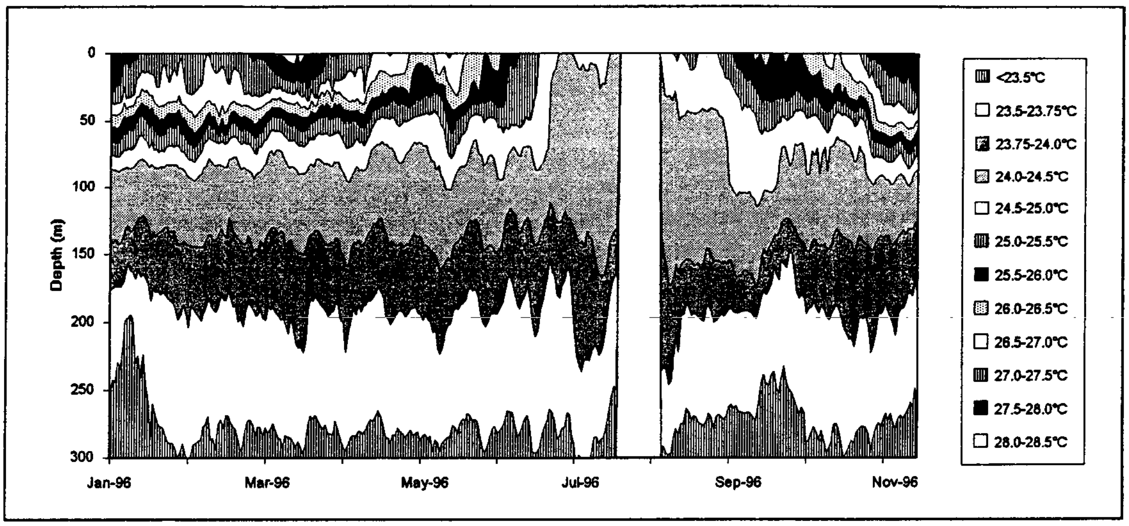


Figure 3. Mean daily temperature (°C) of the water column (0 - 300 m depth) at the Mpulungu buoy.

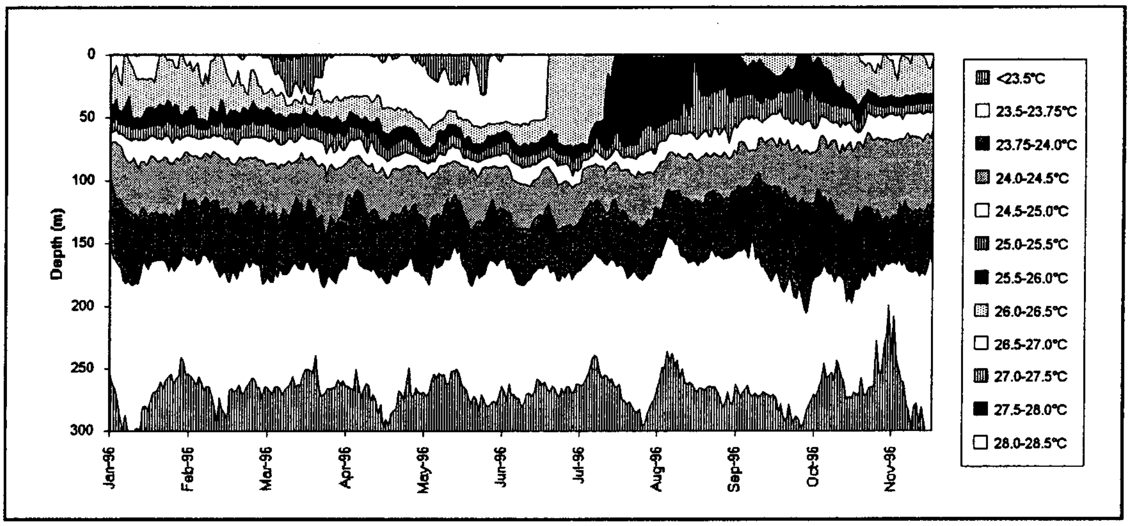


Figure 4. Mean daily temperature (°C) of the water column (0 - 300 m depth) at the Kigoma buoy.

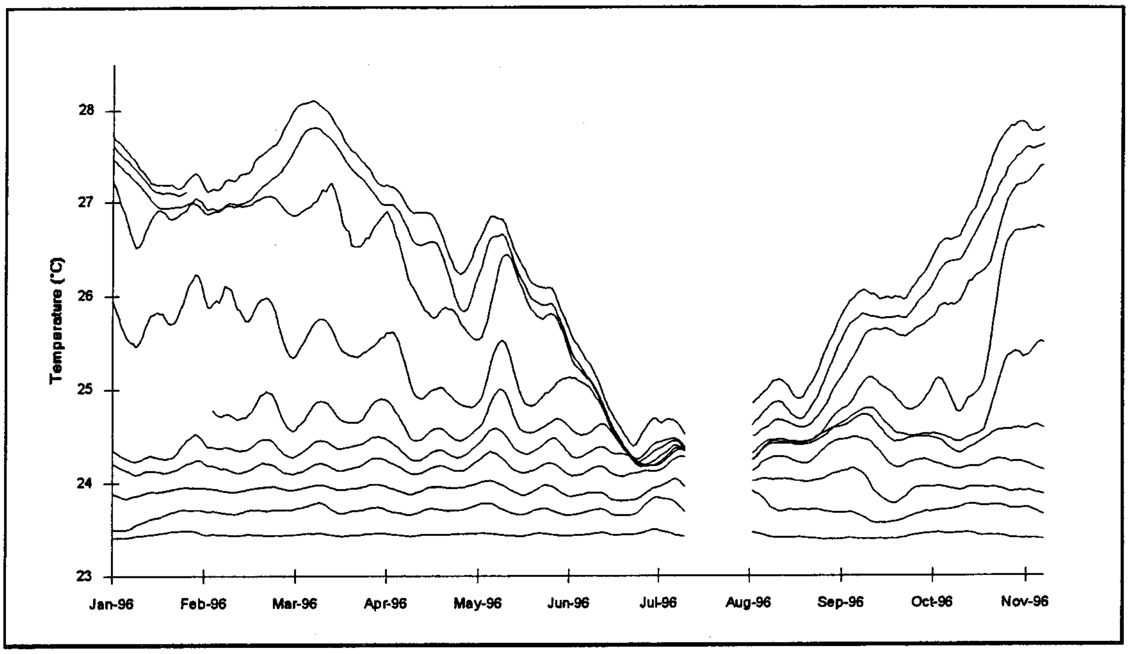


Figure 5. Seven day running averages of water temperatures at the Mpulungu buoy. Water depths were 1, 5, 15, 30, 50, 90, 110, 150, 200 and 300 m up to February 1996 and 1, 15, 30, 50, 70, 90, 110, 150, 200 and 300 m from February 1996.

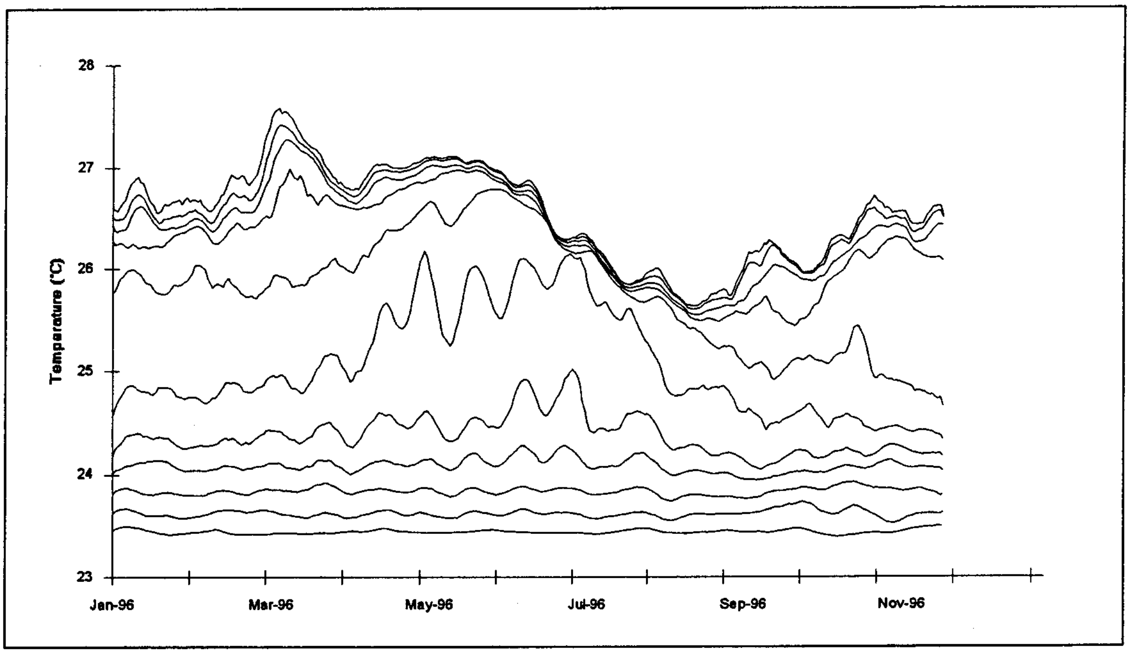


Figure 6. Seven-day running averages of water temperatures at the Kigoma buoy. Water depths were 1,5, 15, 30, 50, 70, 90, 110, 150, 200 and 300 m.

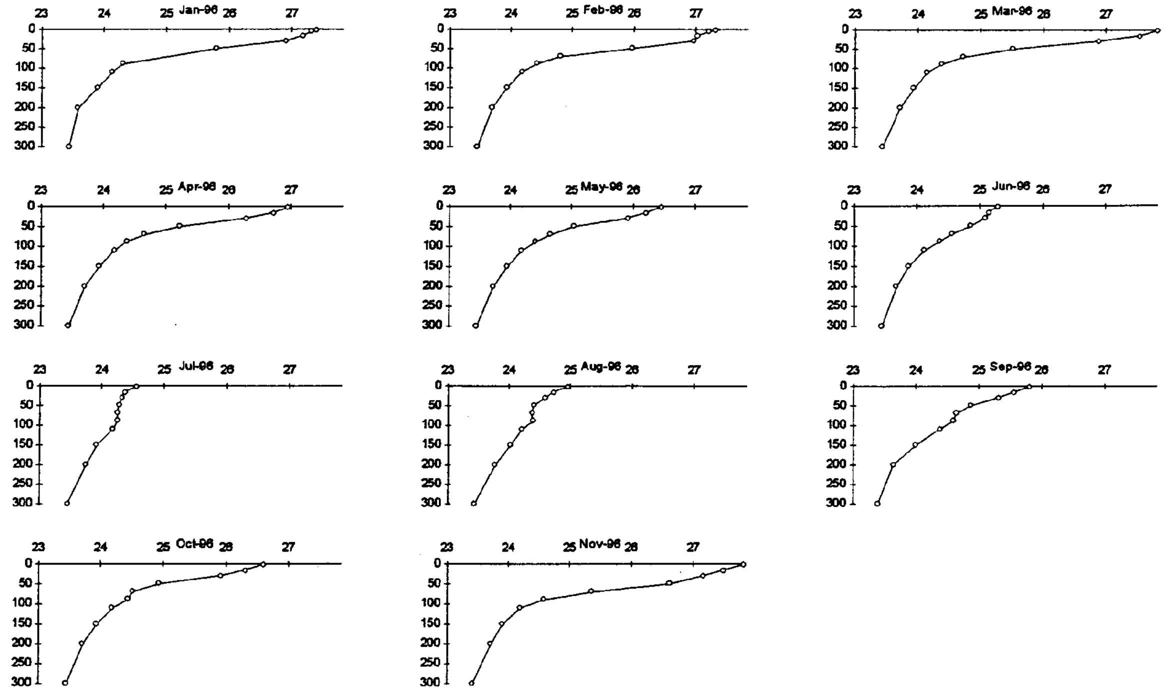


Figure 7. Monthly mean depth distribution of water temperature at the Mpulungu buoy

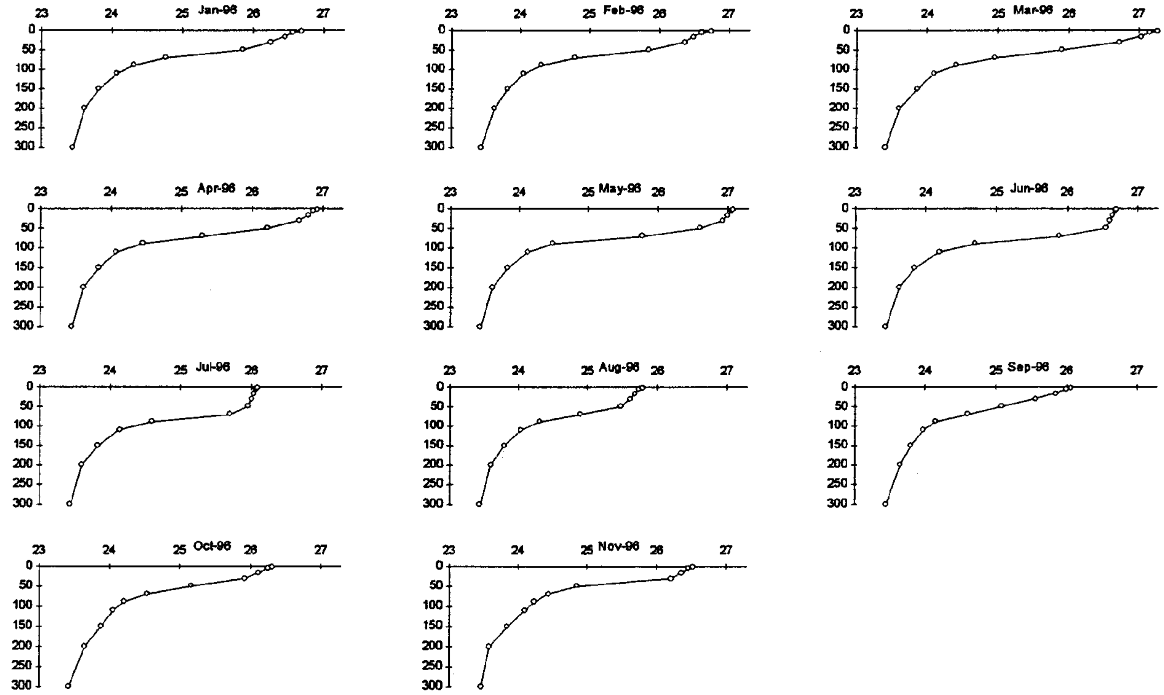
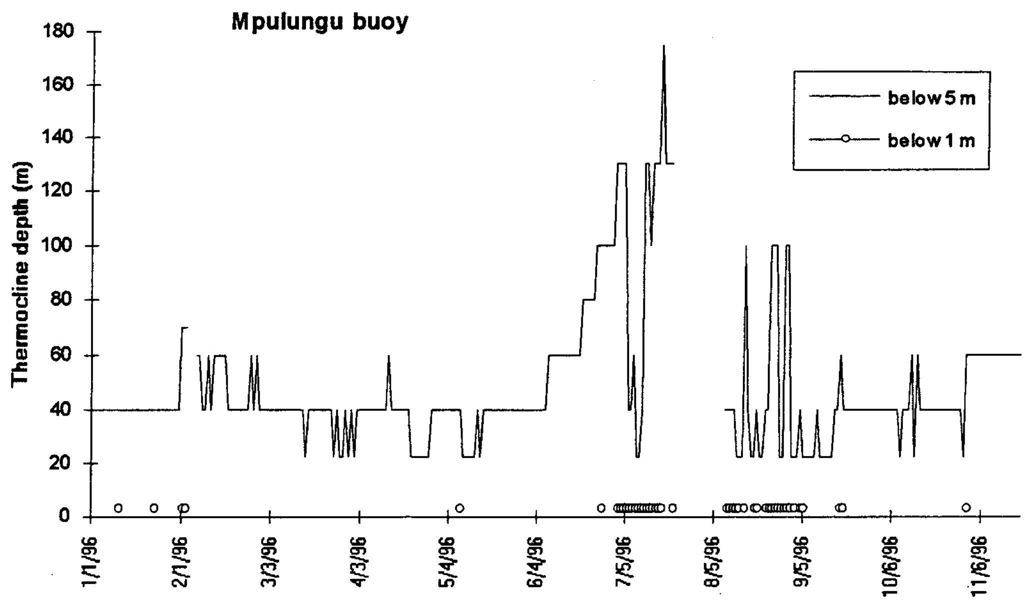


Figure 8. Monthly mean depth distribution of water temperature at the Kigoma buoy.



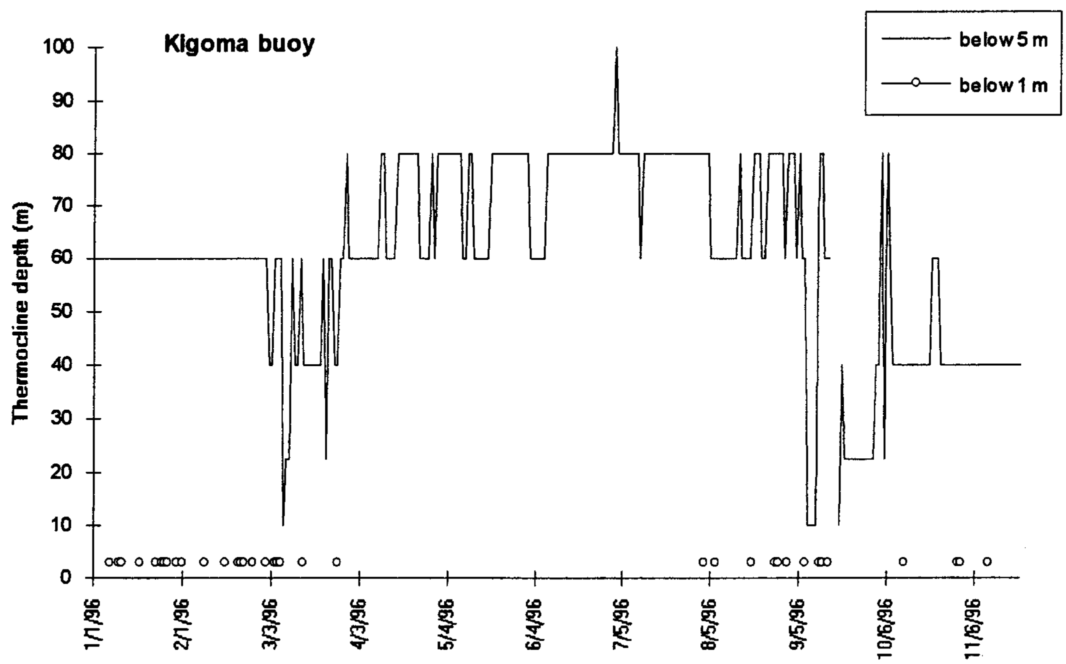


Figure 9. Daily thermocline depth (depth of steepest density gradients between thermistor sensors, below 5 m depth). Days on which the gradient was steepest between 1 and 5 m depth are shown with open circles (generally the wet season at Kigoma and the dry season at the Mpulungu buoy).

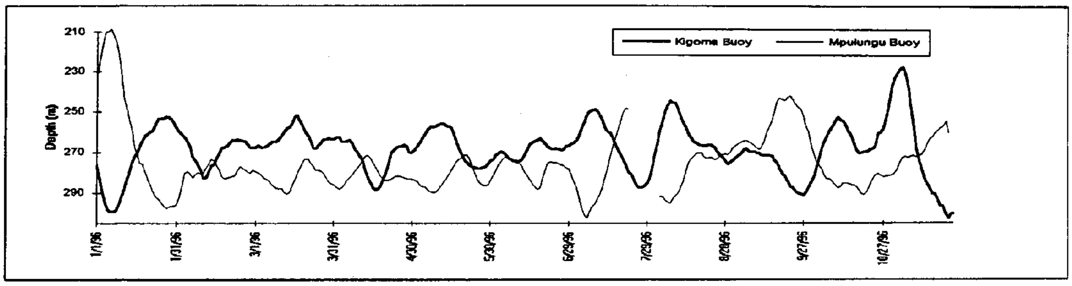


Figure 10. Seven-day running averages of depths of the 23.5° C isotherm at the Kigoma and Mpulungu buoys.

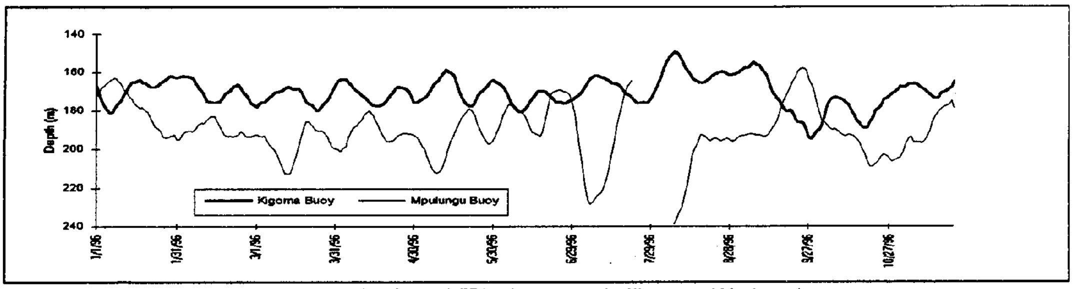


Figure 11. Seven-day running averages of depths of the 23.75° C isotherm at the Kigoma and Mpulungu buoys.

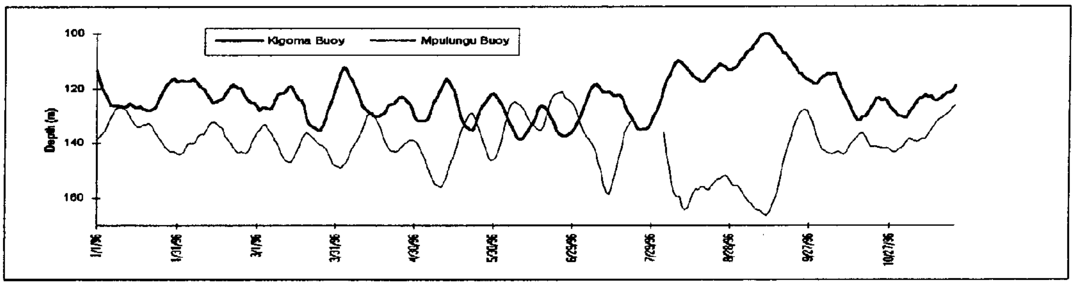


Figure 12. Seven-day running averages of depths of the 24.0° C isotherm at the Kigoma and Mpulungu buoys.

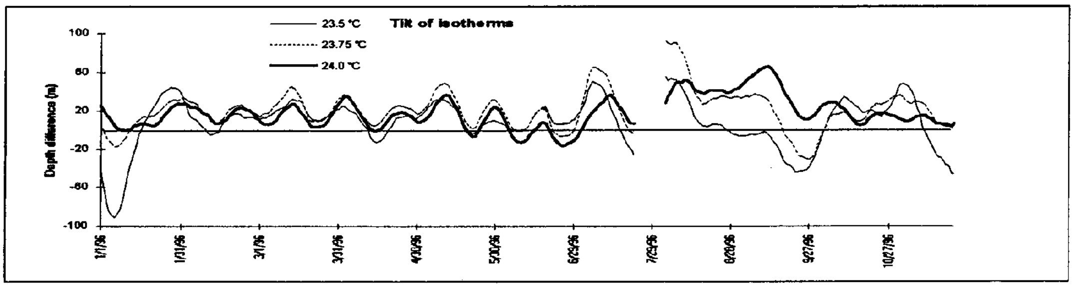


Figure 13. Seven-day running averages of the tilt of isotherms between the Mpulungu and Kigoma buoys, for 1 January - 20 November 1996. The depth of the isotherms at the Kigoma buoy is subtracted from the respective depths at the Mpulungu buoy.

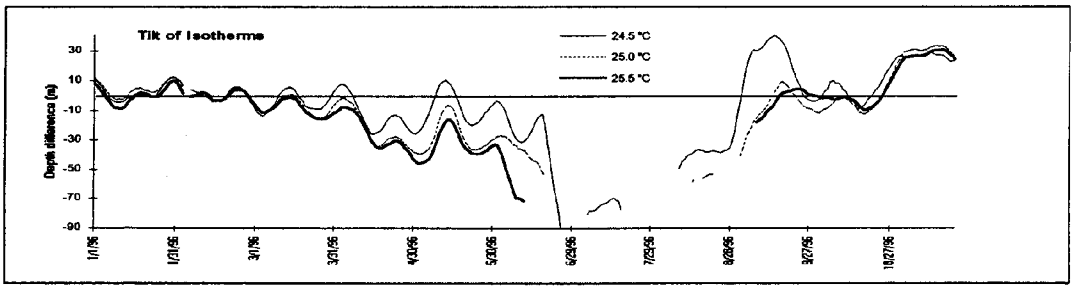


Figure 14. Seven-day running averages of the tilt of isotherms between the Mpulungu and Kigoma buoys, for 1 January - 20 November 1996. The depth of the isotherms at the Kigoma buoy is subtracted from the respective depths at the Mpulungu buoy.

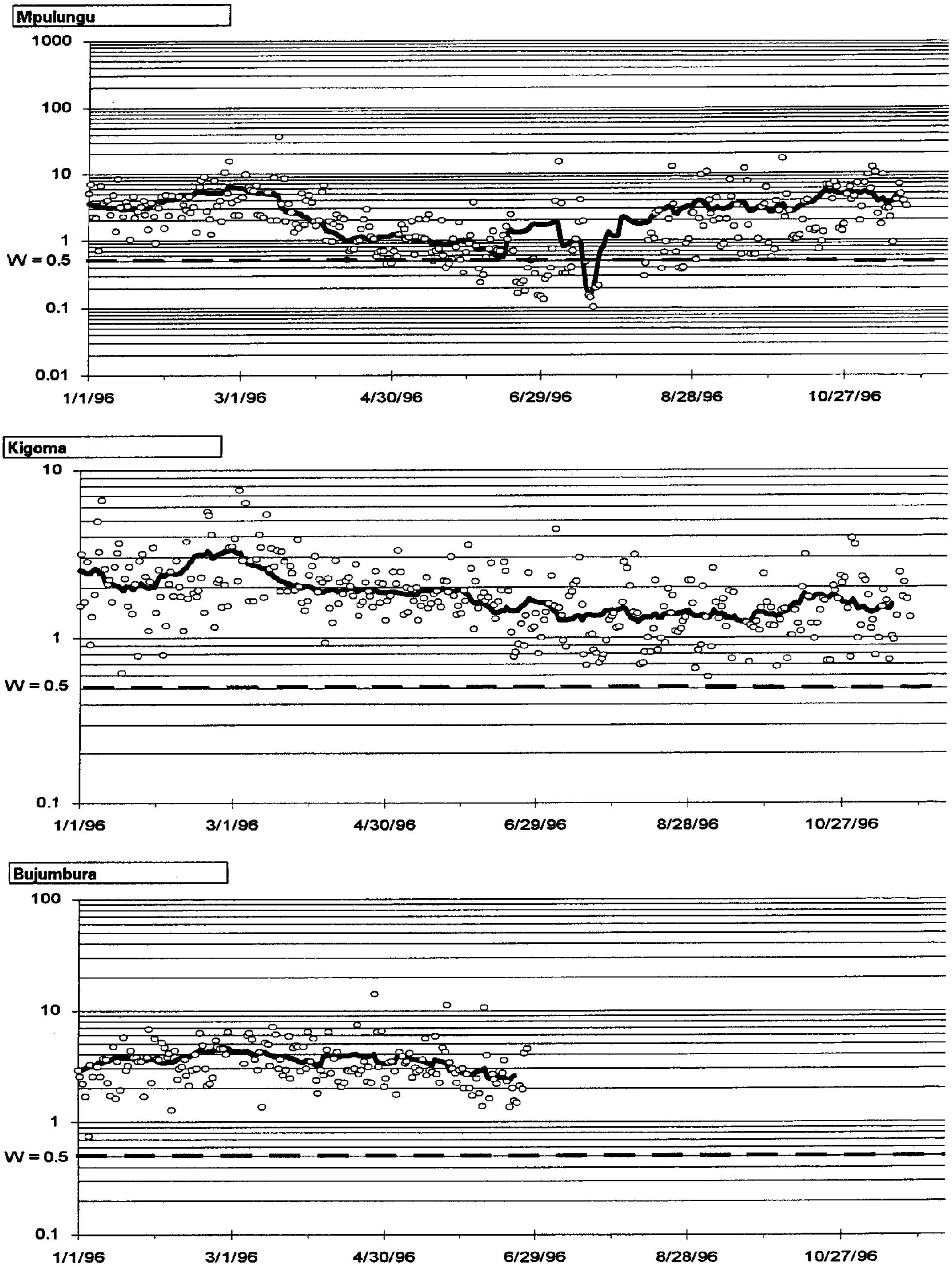


Fig. 15. Daily values of Wedderburn numbers (open circles) off Mpulungu, Kigoma and Bujumbura, with a 21-day running average to indicate the main seasonal trends. Notice the different scales. W = 0.5 is indicated by a broken line.

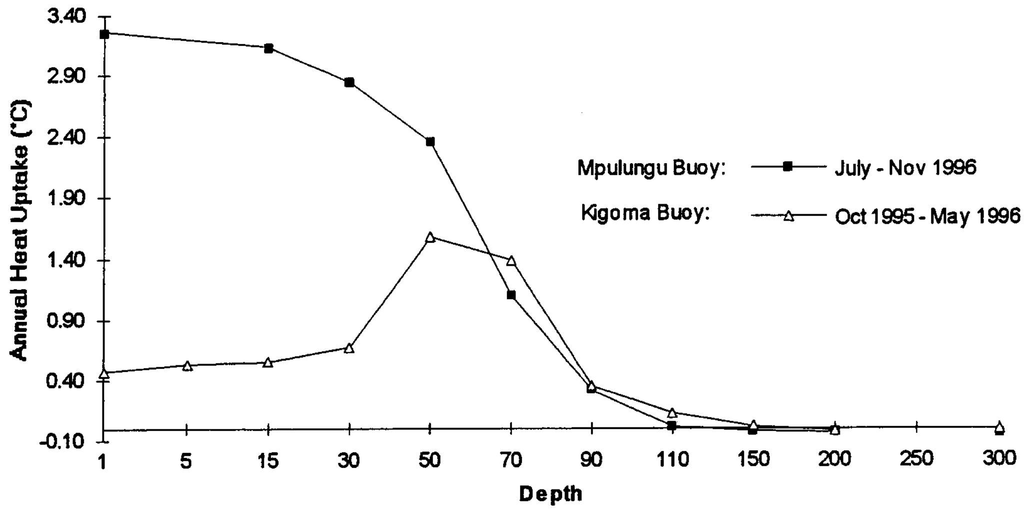


Figure 16. Annual heat uptake (°C), between minimum and maximum heat content at the Mpulungu and Kigoma buoys, versus depth.

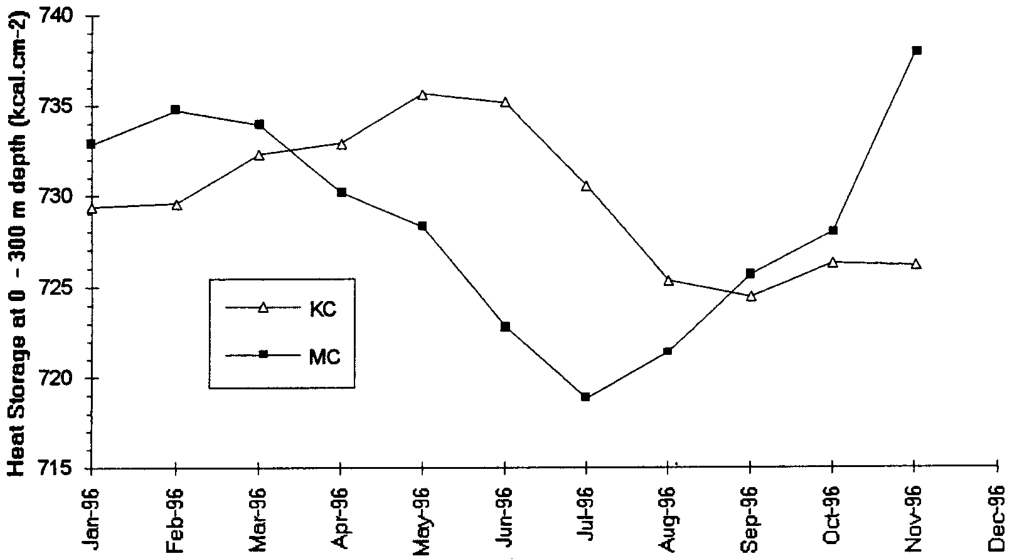
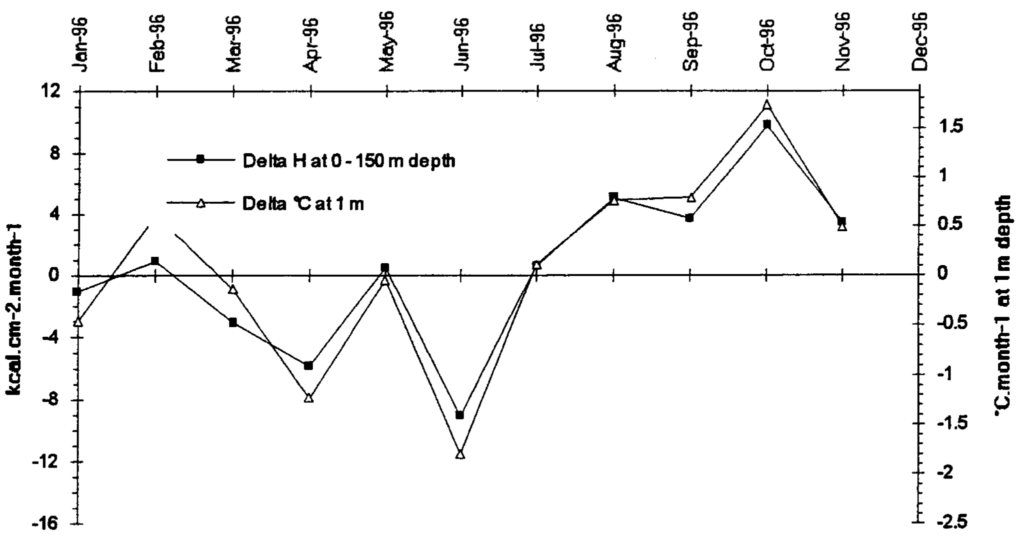


Figure 17. Monthly mean heat content down to 300 m, at the Mpulungu (MC) and Kigoma (KC) buoys.

A. Mpulungu buoy



B. Kigoma buoy

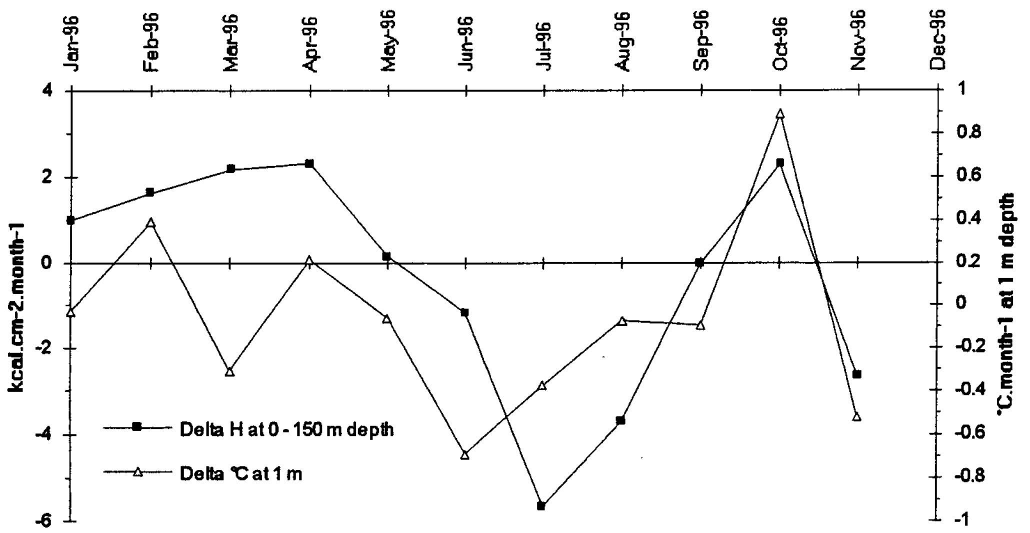


Figure 18. Monthly heat storage rate in upper 150 m, and monthly change in temperature at 1 m depth, at the Mpulungu buoy (A) and Kigoma buoy (B).

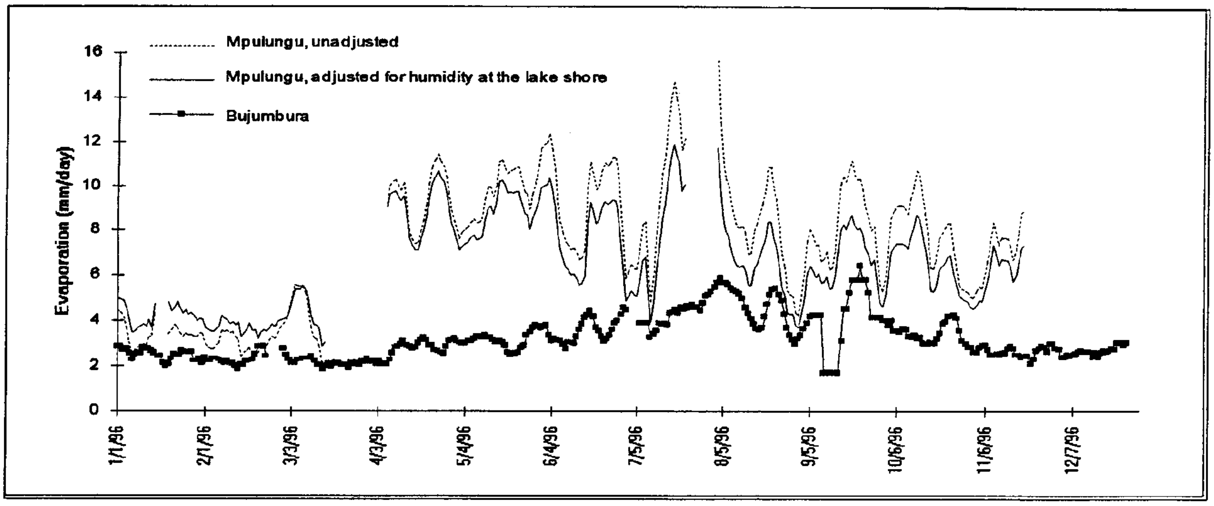


Figure 19. Seven day running averages of evaporation, calculated for Bujumbura harbour and the Mpulungu buoy.

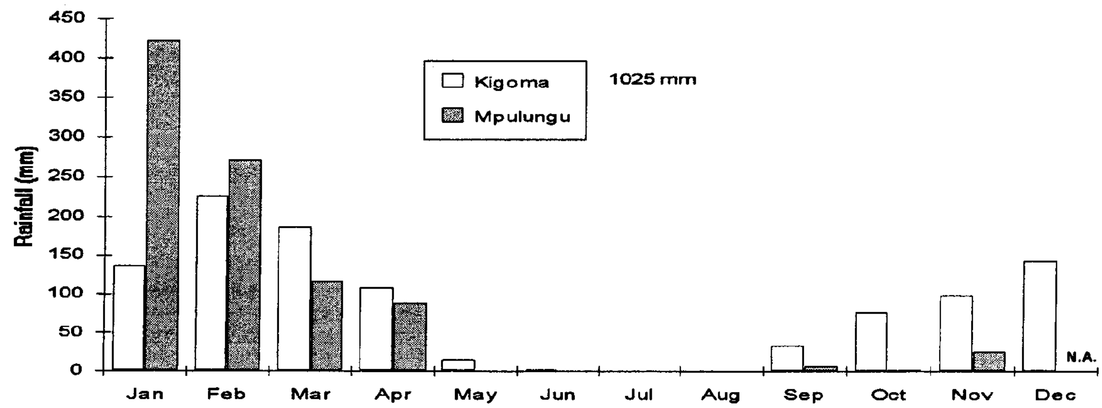


Fig. 20. Rainfall at Kigoma and Mpulungu.

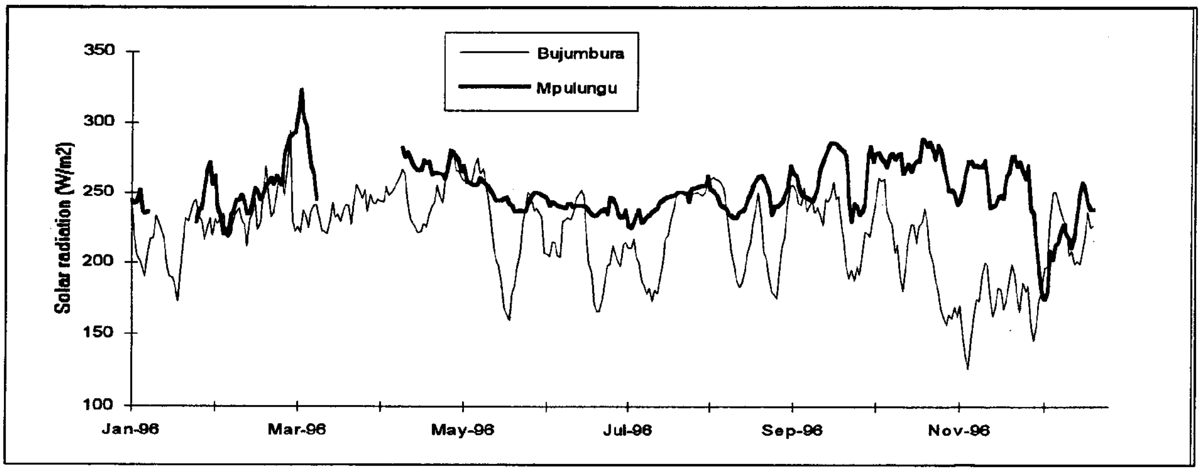


Figure 21. Seven day running averages of solar radiation at the Bujumbura and Mpulungu weather stations.

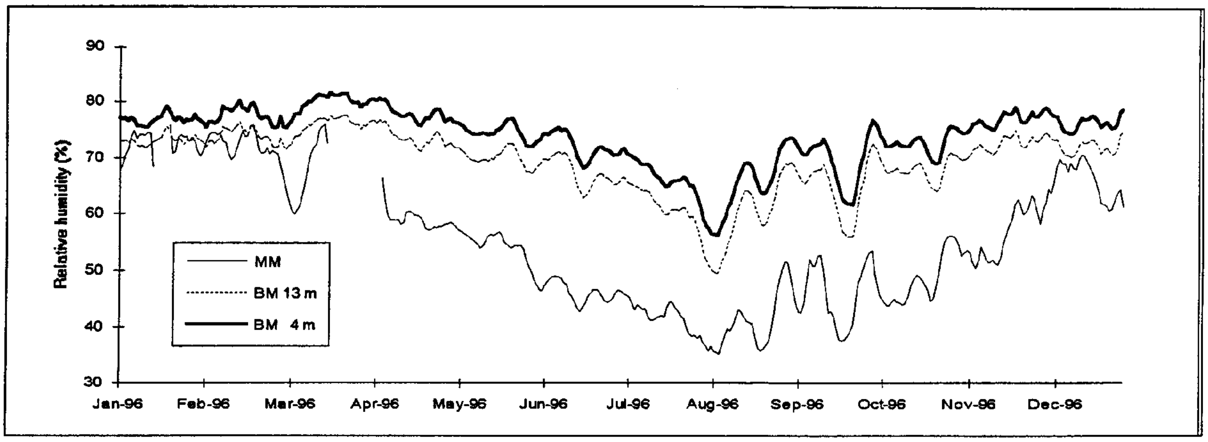


Figure 22. Seven day running averages of humidity for the Mpulungu (MM, 9.5 m height) and Bujumbura (B 4 and 13 m height) weather stations.

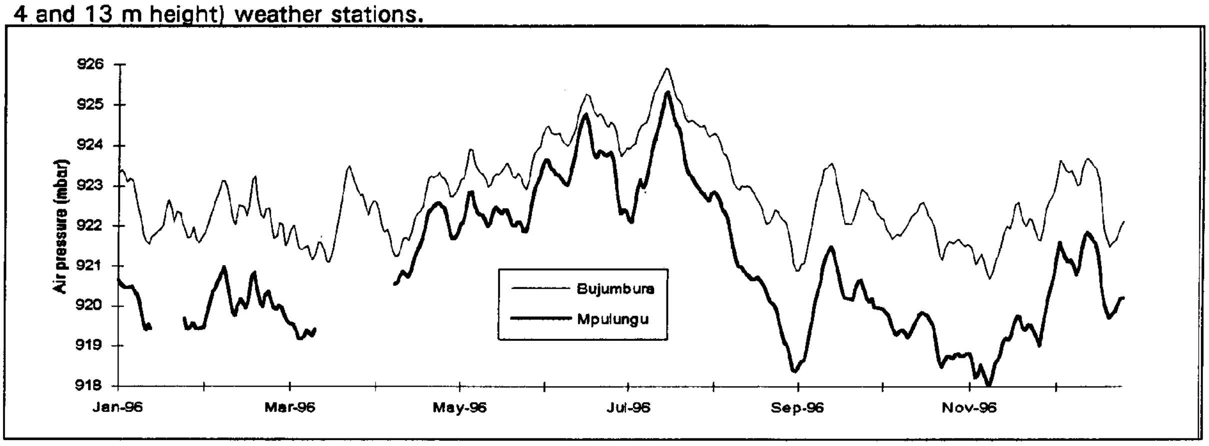


Figure 23. Seven day running averages of air pressure for the Bujumbura and Mpulungu weather stations.

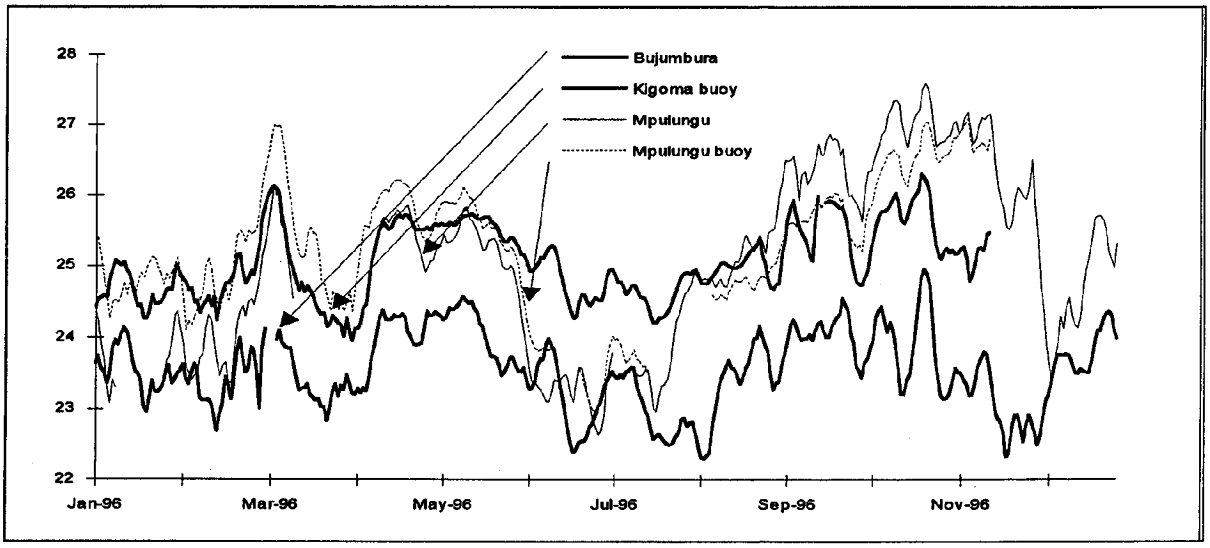


Figure 24. Seven day running averages of air temperature at Bujumbura and Mpulungu, and off shore near Kigoma and Mpulungu.

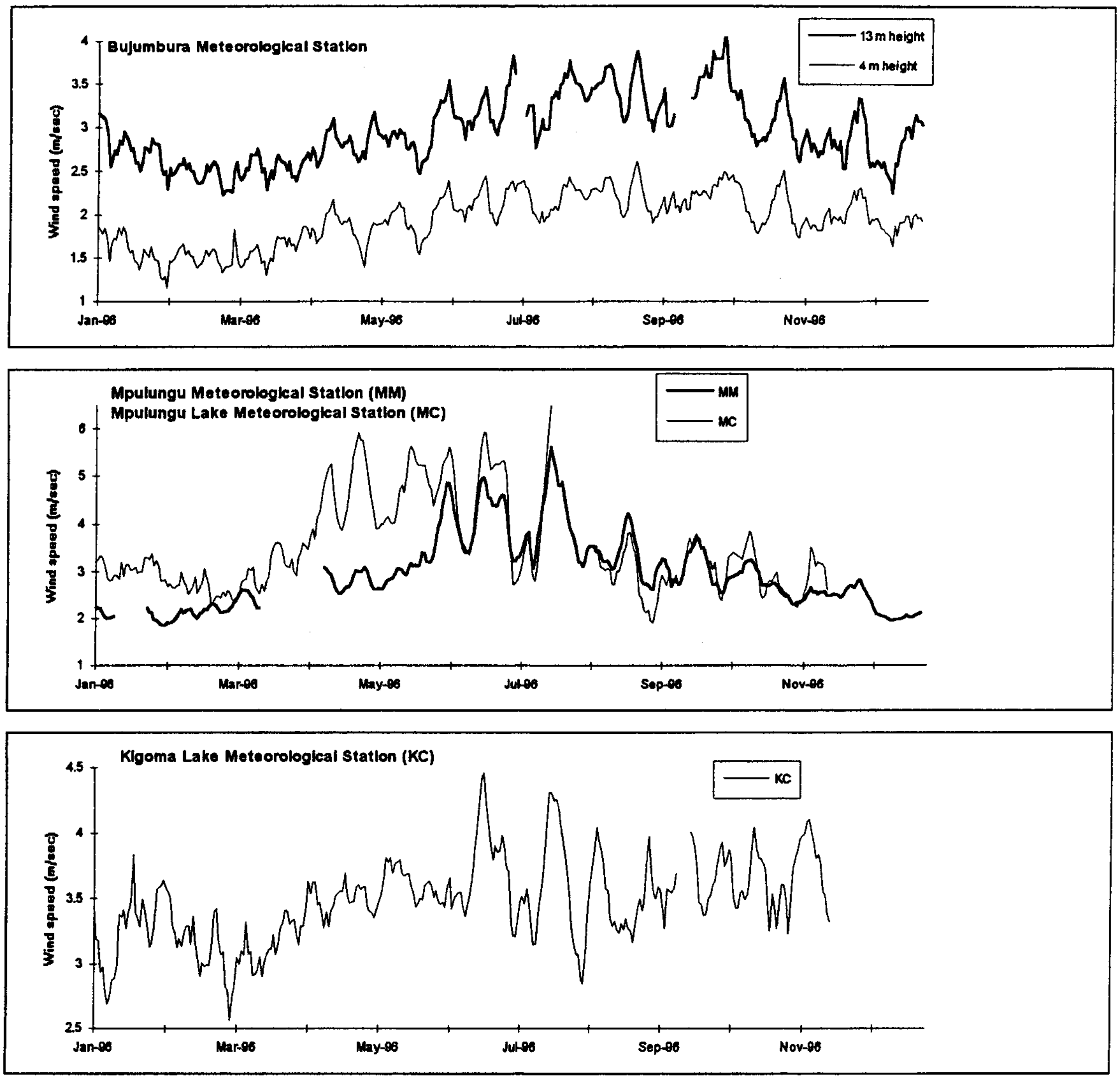


Figure 25. Seven day running averages of wind speed for Bujumbura, Kigoma buoy and Mpulungu weather station and buoy.

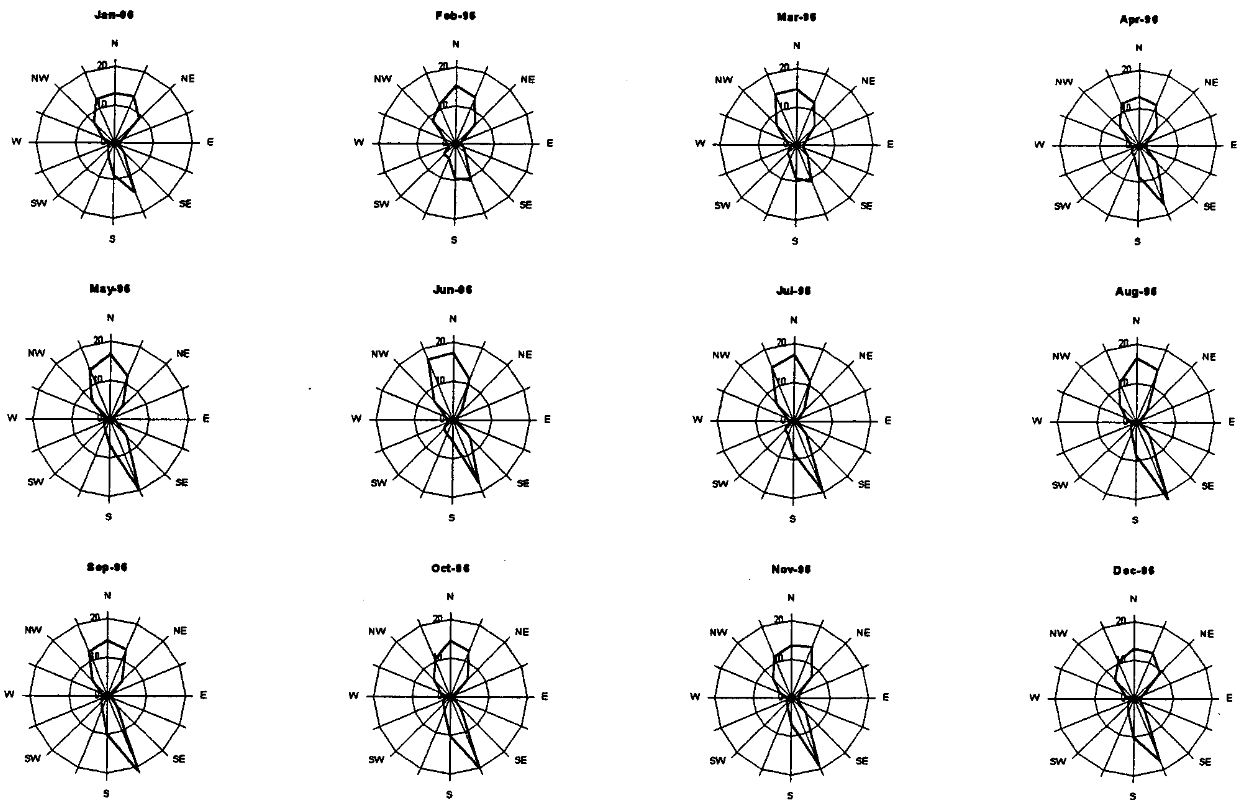


Figure 26. Wind direction distributions (%) on a monthly basis, at Bujumbura weather station.

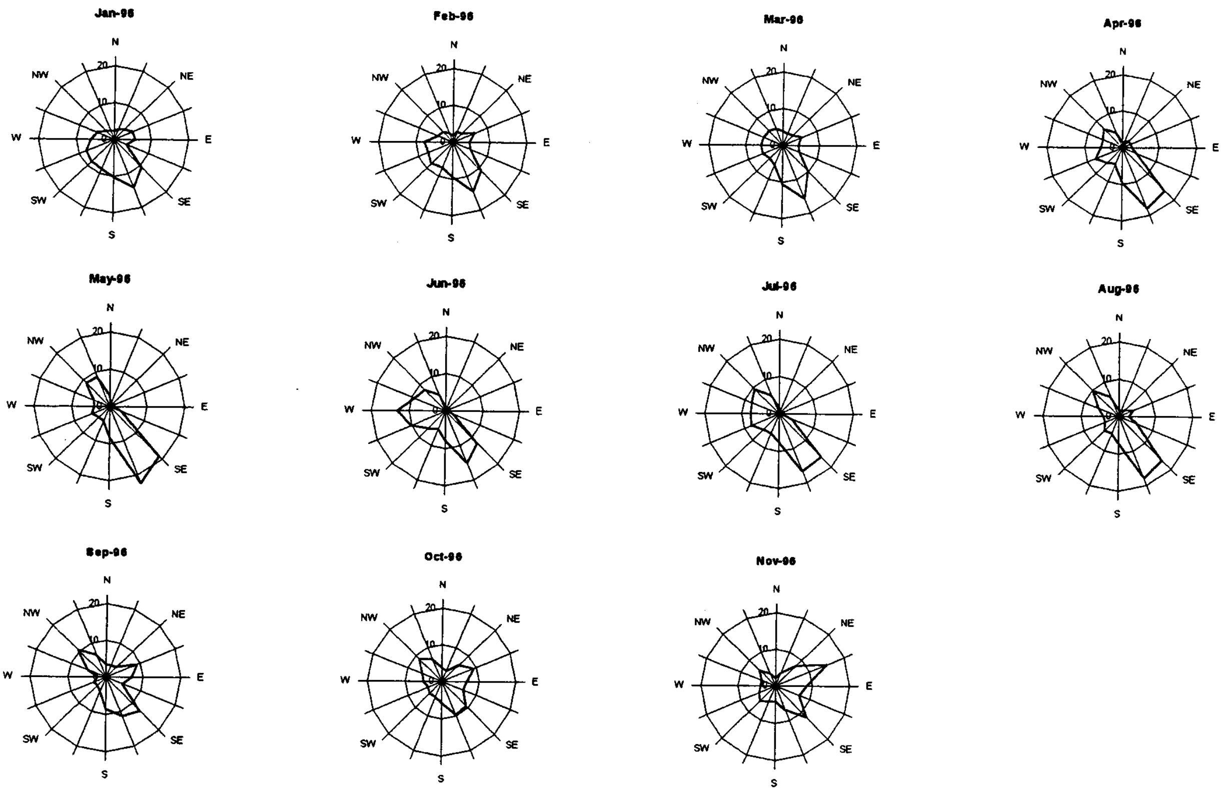


Figure 27. Wind direction distributions (%) on a monthly basis at the buoy off Kigoma.

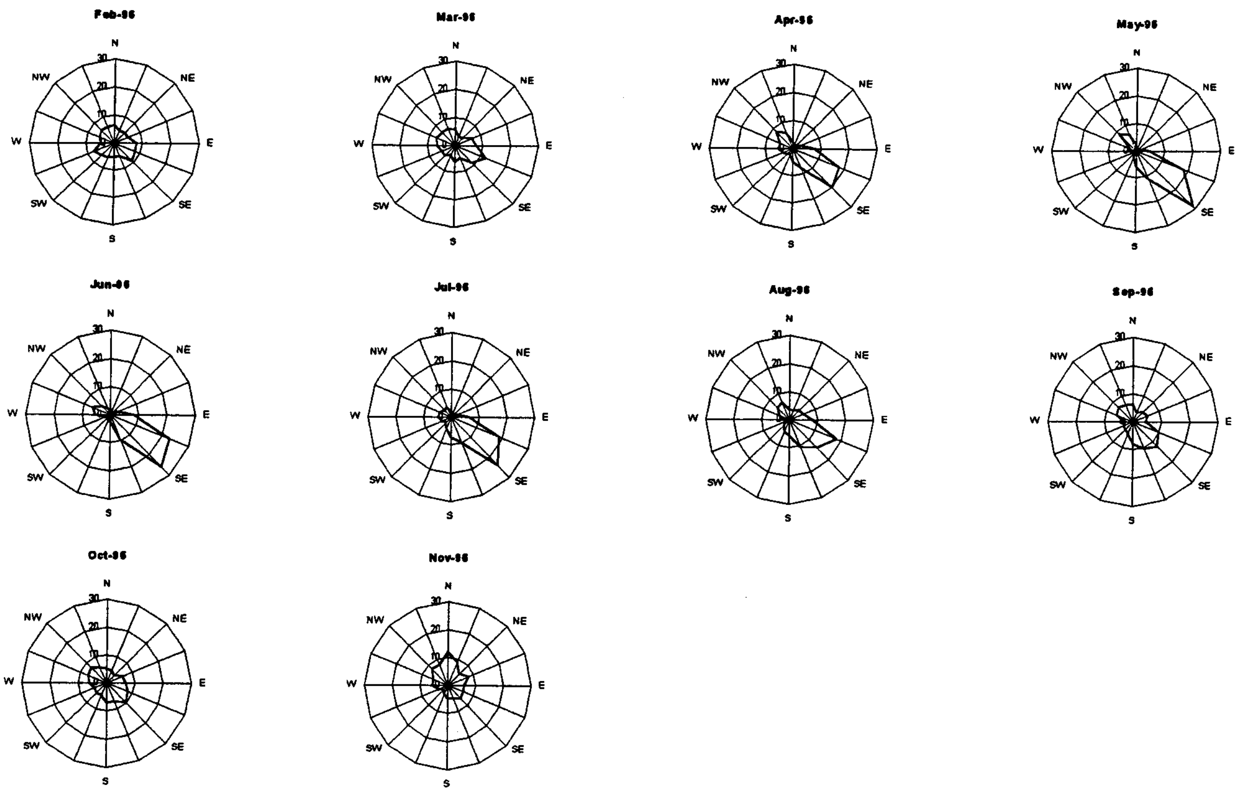


Figure 28. Wind direction distributions (%) on a monthly basis at the Mpulungu buoy.

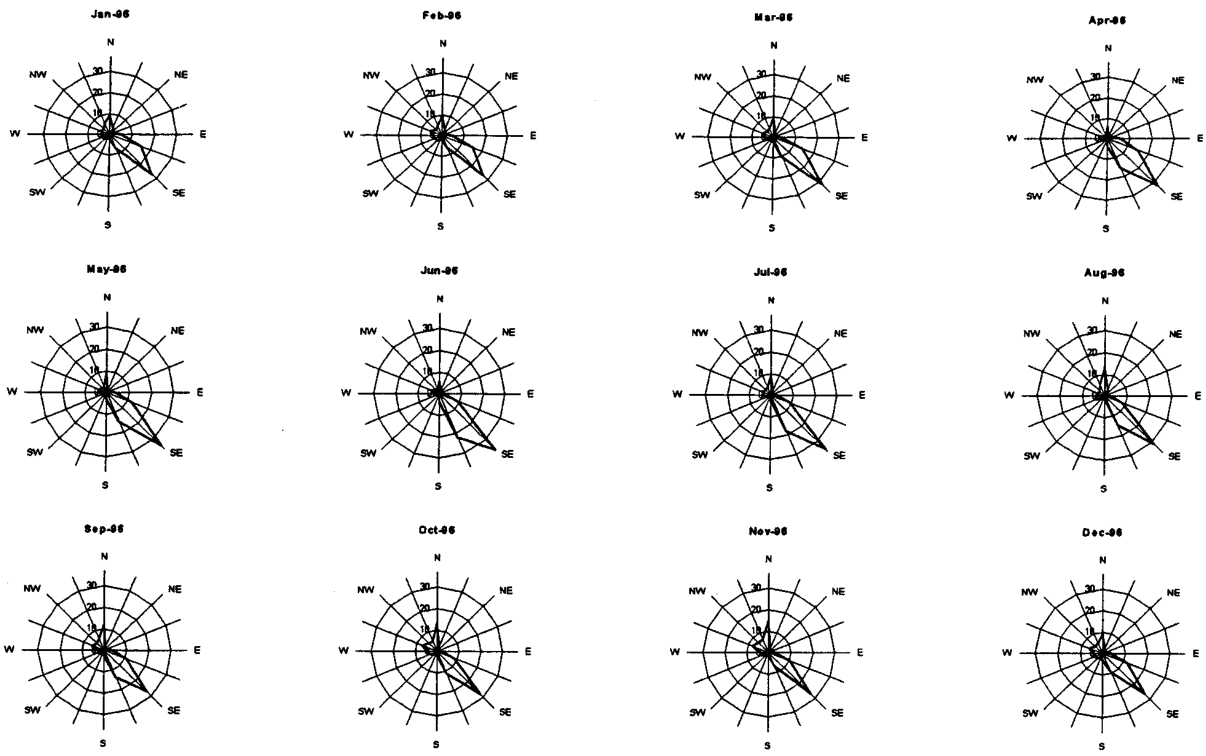


Figure 29. Wind direction distribution (%) on a monthly basis at Mpulungu weather station.

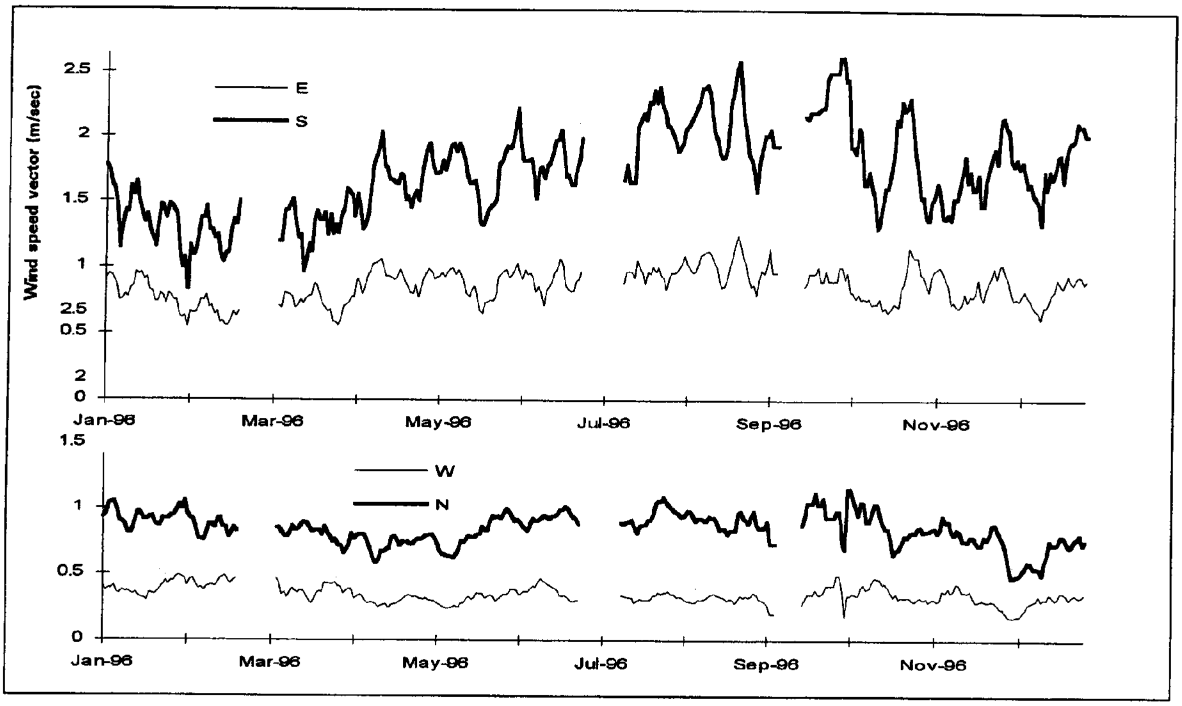


Figure 30. Seven-day running averages of wind speed vector components at Bujumbura.

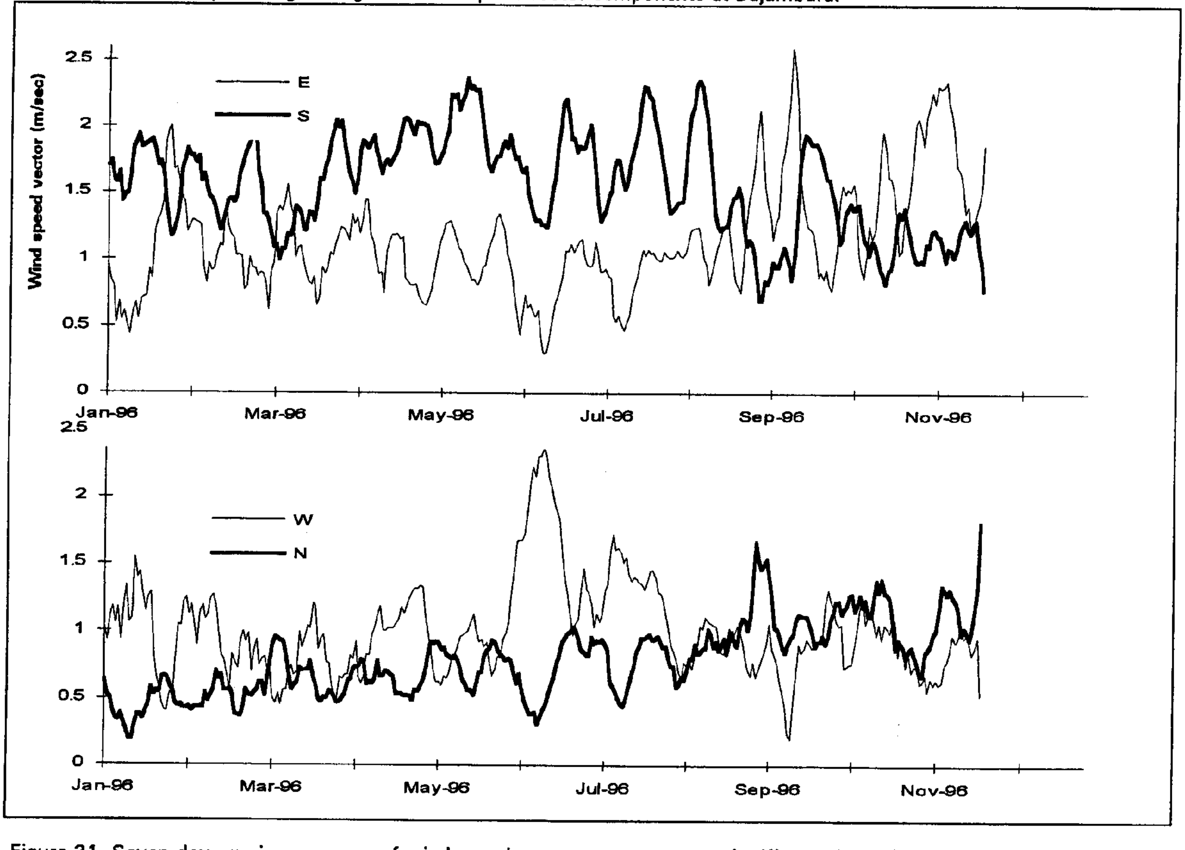


Figure 31. Seven-day running averages of wind speed vector components at the Kigoma buoy for January - November.

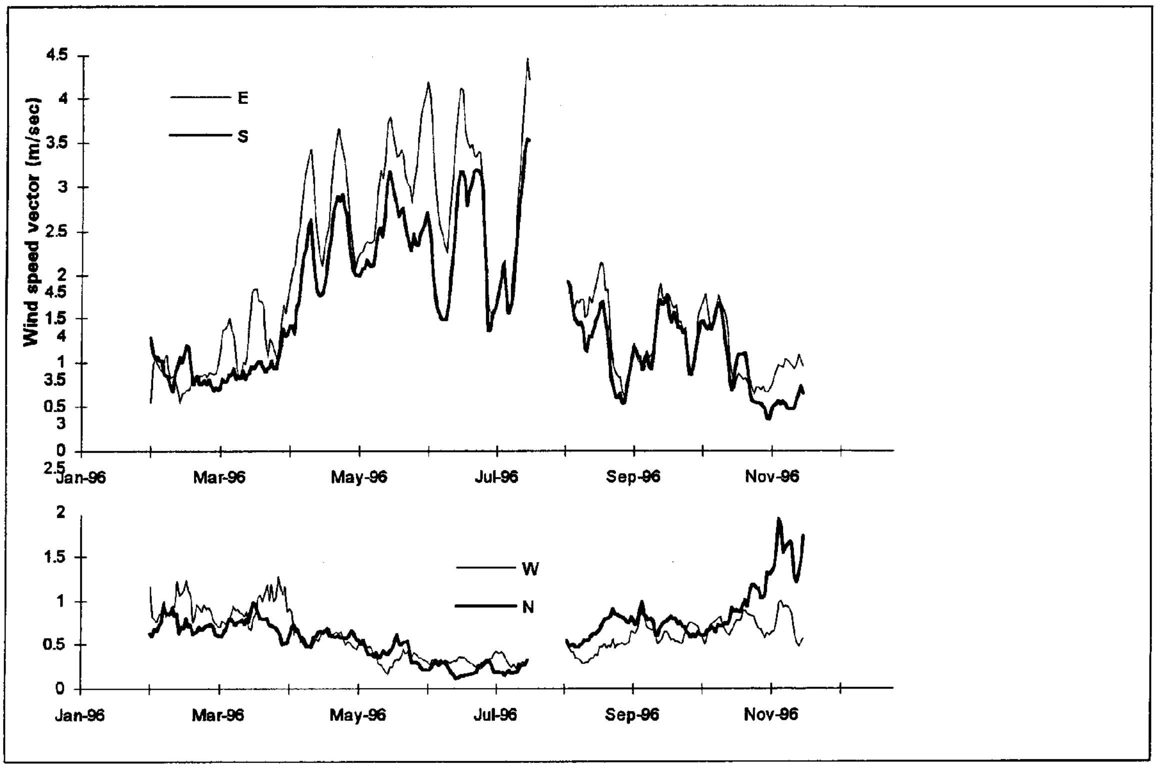


Figure 32. Seven-day running averages of wind speed vector components at the Mpulungu buoy for 1 February - 20 November.

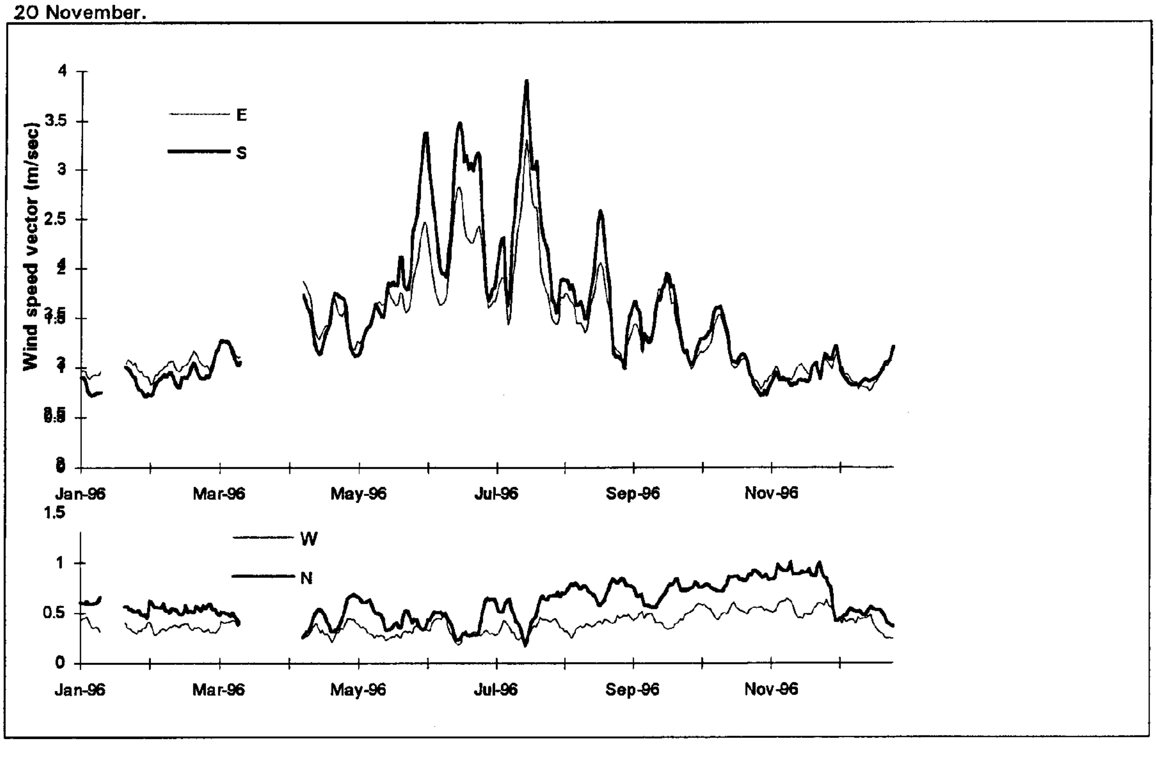


Figure 33. Seven-day running averages of wind speed vector components at the Mpulungu weather station.

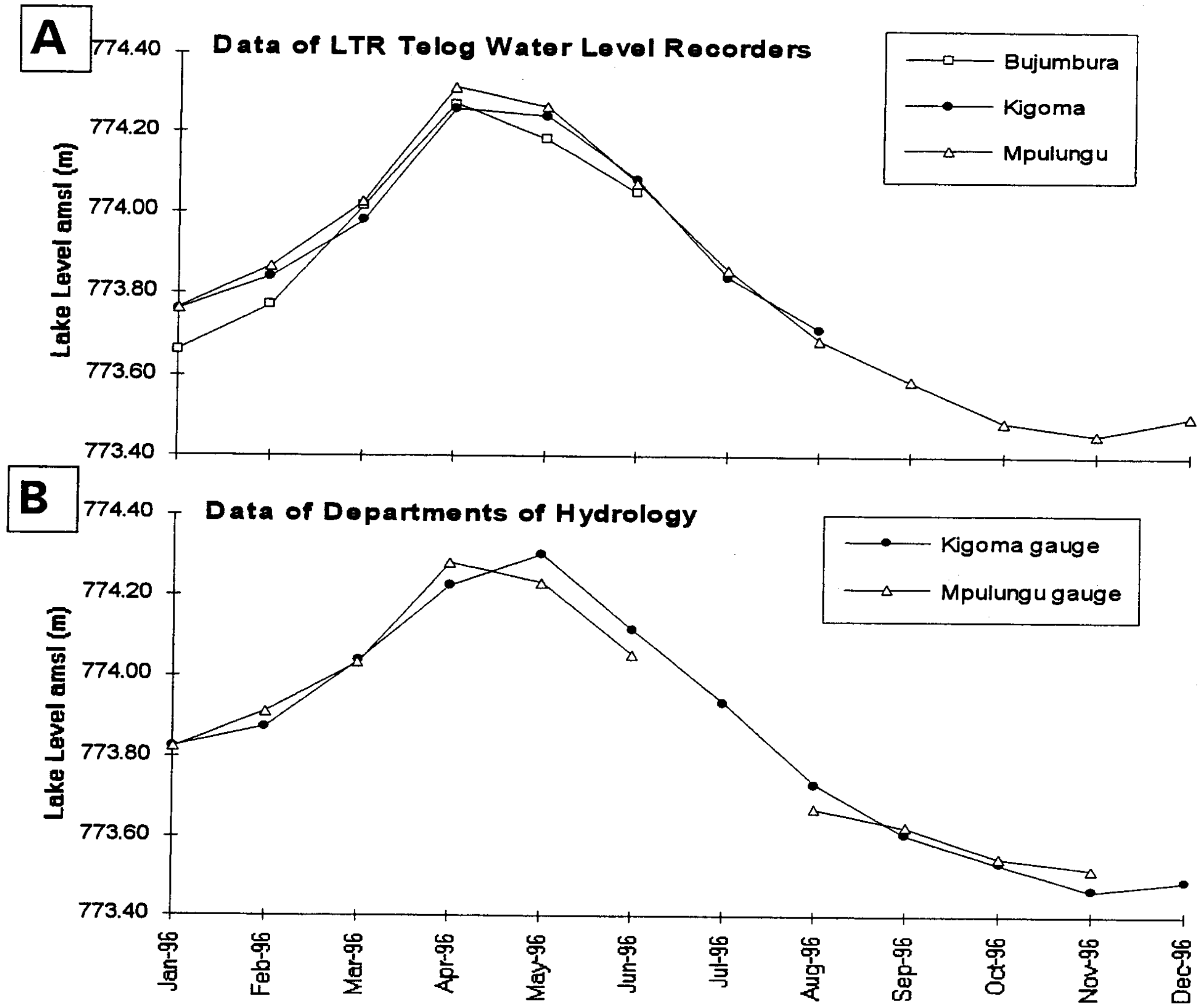


Fig. 34. Monthly mean water levels, A: measured with LTR's Telog automatic recorders, B: measured with conventional gauge plates by the Hydrology Departments of the riparian countries.

APPENDIX II

Table 1. Monthly means of parameters at the Bujumbura weather station.

	Wind speed m/s, at 13 m	Wind gust m/s, at 13 m	Humidity %, at 13 m	Solar Radiation W/m², at 13 m	Air pressure mbar, at 13 m	Rainfall mm	Wind speed m/s, at 4 m	Humidity %, at 4 m	Air temp °C, at 4 m
Jan-96	2.8	4.2	73	219	922.4	6	1.6	77	23.6
Feb-96	2.5	3.7	74	236	922.4	2	1.5	78	23.4
Mar-96	2.5	3.8	76	240	921.9	0	1.6	80	23.5
Apr-96	2.8	4.0	74	242	922.3	0	1.8	78	23.8
May-96	2.9	4.0	71	233	923.2	0	1.9	75	24.1
Jun-96	3.2	4.3	68	216	924.5	0	2.2	72	23.2
Jul-96	3.4	4.5	63	211	924.7	0	2.2	68	23.1
Aug-96	3.5	4.6	57	227	923.3	0	2.3	63	23.2
Sep-96	3.1	4.6	64	230	922.3	23	2.1	69	24.0
Oct-96	3.2	4.5	68	224	922.2	148	2.2	72	24.0
Nov-96	2.8	4.1	72	165	921.6	9	1.9	76	23.1
Dec-96	2.8	4.0	72	208	922.7	137	1.9	77	23.5

Table 2. Monthly means of parameters at the Kigoma buoy.

	Wind speed	Wind gust	Air temp	Water temp (°C), at depth (m):										
	m/s	m/s	°C	1	5	15	30	50	70	90	110	150	200	300
Jan-96	3.2	4.9	24.6	26.7	26.6	26.5	26.3	25.8	24.8	24.3	24.1	23.8	23.6	23.5
Feb-96	3.3	5.0	24.7	26.8	26.6	26.5	26.4	25.9	24.8	24.3	24.1	23.8	23.6	23.4
Mar-96	3.1	4.7	25.0	27.3	27.2	27.0	26.7	25.9	25.0	24.4	24.1	23.9	23.6	23.4
Apr-96	3.5	5.1	25.1	26.9	26.9	26.8	26.7	26.2	25.3	24.4	24.1	23.8	23.6	23.5
May-96	3.6	5.2	25.6	27.1	27.1	27.0	26.9	26.6	25.8	24.5	24.1	23.8	23.6	23.4
Jun-96	3.7	5.5	24.9	26.7	26.7	26.6	26.6	26.5	25.9	24.7	24.2	23.9	23.6	23.4
Jul-96	3.7	5.3	24.6	26.1	26.1	26.0	26.0	25.9	25.7	24.6	24.1	23.8	23.6	23.4
Aug-96	3.4	4.8	25.0	25.8	25.7	25.7	25.6	25.5	24.9	24.3	24.0	23.8	23.6	23.4
Sep-96	3.6	5.2	25.5	26.1	26.0	25.8	25.6	25.1	24.6	24.1	24.0	23.8	23.7	23.5
Oct-96	3.7	5.3	25.6	26.3	26.2	26.1	25.9	25.2	24.5	24.2	24.1	23.9	23.7	23.4
Nov-96	3.7	5.4	25.1	26.5	26.5	26.4	26.2	24.8	24.4	24.2	24.1	23.9	23.6	23.5
Dec-96														

Table 3. Monthly means of parameters at the Mpulungu buoy.

	Wind speed	Wind gust	Air temp	Water temp (°C), at depth (m):										
	m/s	m/s	°C	1	5	15	30	50	70	90	110	150	200	300
Jan-96	3.1	5.5	24.9	27.4	27.3	27.2	26.9	25.8		24.3	24.1	23.9	23.6	23.4
Feb-96	2.7	4.8	24.9	27.3	27.2	27.0	27.0	26.0	24.8	24.4	24.2	23.9	23.7	23.5
Mar-96	3.0	5.2	25.7	27.8		27.6	26.9	25.5	24.7	24.4	24.2	23.9	23.7	23.5
Apr-96	4.5	6.9	25.5	27.0		26.7	26.3	25.2	24.7	24.4	24.2	23.9	23.7	23.5
May-96	4.7	6.9	25.7	26.4		26.2	25.9	25.0	24.7	24.4	24.2	24.0	23.7	23.5
Jun-96	4.9	7.4	24.0	25.3		25.1	25.1	24.9	24.6	24.4	24.1	23.9	23.7	23.5
Jul-96	3.9	6.0	23.6	24.6		24.4	24.3	24.3	24.3	24.3	24.2	23.9	23.8	23.5
Aug-96	3.2	5.1	24.7	25.0		24.7	24.6	24.4	24.4	24.4	24.2	24.0	23.8	23.4
Sep-96	3.0	4.9	25.6	25.8		25.6	25.3	24.9	24.6	24.6	24.4	24.0	23.6	23.4
Oct-96	2.9	4.9	26.2	26.6		26.3	25.9	24.9	24.5	24.4	24.2	23.9	23.7	23.5
Nov-96	2.8	4.6	26.8	27.8		27.5	27.2	26.6	25.4	24.6	24.2	23.9	23.7	23.4
Dec-96														

Table 4. Monthly means of parameters at the Mpulungu weather station.

	Wind speed m/s	Wind gust m/s	Air temp °C	Humidity %	Solar radiation W/m²	Air pressure mbar
Jan-96	2.1	3.9	23.7	72	229	920.2
Feb-96	2.1	3.8	23.9	73	249	920.2
Mar-96	2.4	4.2	25.2	67	268	919.6
Apr-96	2.9	5.3	25.5	59	266	921.4
May-96	3.0	5.4	25.3	56	253	922.2
Jun-96	4.3	7.4	23.6	47	242	923.6
Jul-96	4.1	7.1	23.4	43	244	923.6
Aug-96	3.4	5.8	25.0	38	248	921.5
Sep-96	3.1	5.5	26.3	46	261	919.9
Oct-96	2.8	5.0	26.7	48	266	919.6
Nov-96	2.5	4.5	26.6	55	257	918.9
Dec-96	2.2	4.0	24.9	65	226	920.6

APPENDIX III

FORMULAE

1) C = SIN(A)*B
2) D = COS(A)*B

with

A = Wind Direction, in degrees clockwise from north
B = Wind Speed ($m.s^{-1}$)
C = East/west Wind Speed Vector (E/W)
D = North/south Wind Speed Vector (N/S)

In Table 11, below, numerical examples are shown of the different calculated components of the wind vectors.

Table 11. Numerical examples of calculated components of wind speed vectors. For explanantions of terms A-D, see formula

				Components of the wind vectors				Actual mean wind speed of each wind component			
Wind	Wind speed (m/s)	E/W	N/S	East	West	North	South	East	West	North	South
	3.0	0.0	3.0	0.0	0.0	3.0	0.0			3.0	
30	3.0	1.5	2.6	1.5	0.0	2.6	0.0	1.5		2.6	
60	3.0	2.6	1.5	2.6	0.0	1.5	0.0	2.6		1.5	
90	3.0	3.0	0.0	3.0	0.0	0.0	0.0	3.0			
120	3.0	2.6	-1.5	2.6	0.0	0.0	1.5	2.6			1.5
150	3.0	1.5	-2.6	1.5	0.0	0.0	2.6	1.5			2.6
180	3.0	0.0	-3.0	0.0	0.0	0.0	3.0				3.0
210	3.0	-1.5	-2.6	0.0	1.5	0.0	2.6		1.5		2.6
240	3.0	-2.6	-1.5	0.0	2.6	0.0	1.5		2.6		1.5
270	3.0	-3.0	0.0	0.0	3.0	0.0	0.0		3.0		
300	3.0	-2.6	1.5	0.0	2.6	1.5	0.0		2.6	1.5	
330	3.0	-1.5	2.6	0.0	1.5	2.6	0.0		1.5	2.6	
Means:		0.0	0.0	0.9	0.9	0.9	0.9	2.2	2.2	2.2	2.2