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HYDRODYNAMICS OF LAKE TANGANYIKA AND METEOROLOGICAL RESULTS

by
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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, Tanzania, Zaïre 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.

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TABLE OF CONTENTS

SUMMARY

From March 1993 to December 1995 meteorological data were collected on Lake Tanganyika with 5 automatic recorders, at least once per hour. Of these 5 recorders, 3 were placed at the stations around the lake and 2 were attached to buoys in the north and south of the lake. Those attached to buoys also collected data on water temperature at 11 different depths, from 1 to 300 m.

From wind vector analysis it was found that the wind system of Lake Tanganyika was very stable from month to month, with the main feature being lake winds during the day and land winds during the night. The wind force did vary from season to season, with the highest wind speeds in the dry season (May to September). Winds blowing from the lake were the strongest, except in the south during the dry season. They usually occurred only in the afternoon, when air temperature over the land was higher than over the lake.

Wind force is the main factor inducing nutrient regeneration by upwelling in Lake Tanganyika. Strong south winds during the dry season concentrated upwelling at the south end of the lake. Stratification decreased in the dry season in the south, and was virtually absent there in July. The surface water cooled down in the dry season by lower air temperature and high evaporation, due to the strong south wind.

From 1993 to 1995, on annual basis, wind speed was found to decrease lake-wide, coinciding with decreasing air pressure and increasing solar radiation and air temperature. The changes were strongest in the south. This occurred both in the wet and dry seasons. In 1995, annual wind speed was *c.* 9 % less than in 1993. In the dry season of 1995 upwelling was far less intense than in 1993. The 24° C isotherm reached the surface in the dry season of 1993, but was > 100 m depth in 1995. Water temperature at 1 m depth was *c.* 0.3 ℃ higher in the dry season of 1995, than in the previous 2 years. In the wet season the difference was even greater, and stratification was stronger in the wet season at the end of 1995 than in the previous two wet seasons. Increase in water temperature from 1993 to 1995 was significant at all depths down to 300 m.

Throughout the whole period, internal waves were calculated, with periods of 25 - 30 days. The fundamental mode appeared to be uninodal with an inverse relation between depths of the deeper isotherms in the north and south ends of the lake.

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1. INTRODUCTION

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 is still poorly understood. Previous studies have been localised 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 hydrological sampling stations around and on the lake. Data have been collected since March 1993. Data up to end of 1994 were presented by Kotilainen *et al.* (1995). Work on hydrological modelling on Lake Tanganyika was presented by Huttula and Podsetchine (1994), and by Podsetchine and Huttula (1995,1996). In this report additional analysis is presented (a.o. wind vector analysis, evaporation and heat budget) from March 1993.

The main aim of this report is to describe the hydrodynamics of the lake and physical changes in the lake over the period 1993 - 1995. This reports deals with three components appertaining to and influencing the dynamics of the water masses, water temperature distributions, evaporation and it describes the wind system over the lake. A number of meteorological parameters are described in Appendices.

2. RECORDING EQUIPMENT AND DATA PROCESSING

2.1 Automatic recorders

Three stations around the lake and two offshore stations were equipped with automatic meteorological and hydrodynamical data recording instruments of Aanderaa Instruments (Fig.1). Recording intervals, sensor types and the installation dates of the sensors of each station are presented in Table 1. The first stations were installed in March 1993 and the last in May 1994. In May 1995 the weather station at Mpulungu was extended from 3 to 7 sensors (Table 1).

The parameters were recorded as momentary values, except rainfall, wind speed and wind gust. The total rainfall (at Bujumbura) was measured during the recording intervals. 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. The processing of wind direction data is described below.

The Bujumbura weather station was installed at Bujumbura port, on a pier, in March 1993. The station had 10 sensors at two different heights, at 4 and 13 m above the lake surface. The structure of the weather station and technical specifications have been described in more detail by Huttula *et al.* (1993). The Kigoma wind station was installed on a cliff south of Kigoma port in July 1993. The sensors are placed about 6 m above the ground, 50 m above the lake surface, and less than 50 m away from the lake shore. The sensors of the weather station in Mpulungu are placed on a hill, *c.* 9.5 m above the ground, 40 m above the lake surface, and 300 m away from the lake. The lake meteorological station 40 km north-west from Mpulungu was installed in the lake in March 1993 (Fig.1). The thermistor chain originally had eleven temperature sensors set at 1, 5, 30, 50, 70, 90, 110, 150, 200, 250 and 300 m. From 2 May 1995 a new chain was installed with an extra sensor at 15 m and no sensor at 250 m.

A similar station was installed 14 km south-west of Kigoma in March 1994 (Fig.1). The depths of the water temperature sensors were the same as the second Mpulungu chain. The sensors above the surface were also similar to those at Mpulungu. The depth of water at the Kigoma and Mpulungu buoys was *c.* 400 and 350 m respectively.

The sensors did not record continuously, usually because of instrument failure. For example no data were collected with the sensors below 5 m at the Mpulungu temperature chain between May 1994 to May 1995. In May 1994 the weather station at Bujumbura was hit by a cargo boat, and the station was out of operation for about 3 months. The air pressure sensor was recalibrated before reinstallation at the end of August 1994, and other sensors had to be repaired and some were replaced.

The weather, lake and wind stations were programmed and unloaded using Aanderaa Instruments P3059 software (Huttula *et al.*, 1993; Kotilainen, 1994).

Table 1. Automatic recording stations, recording intervals, sensor types and installation dates of the sensors.

STATION	Recording interval	Sensor type	Recording from:
Weather station at Bujumbura	10 min	Wind speed, 13m Wind gust, 13m Wind direction, 13m Air Temperature, 13m Air pressure, 13m Humidity, 13m Solar radiation, 13m Rainfall, 13m Wind speed, 4m Humidity, 4m Air temperature 4m	March '93
Wind station at Kigoma	10 min	Wind speed Wind gust Wind direction	July '93
Weather station at Mpulungu	30 min	Wind speed Wind gust Wind direction	May '94 - April '95
	10 min	Wind speed Wind gust Wind direction Air temperature Air pressure Humidity Solar radiation	May '95
Lake meteorological station off Kigoma	30 min	Wind speed Wind gust Wind direction Air temperature Water temperature at 1, 5, 15, 30, 50, 70, 90, 110, 150, 200 and 300 m depth	March '94
Lake meteorological station off Mpulungu	60 min	Wind speed Wind gust Wind direction Air temperature Water temperature at 1, 5, 15, 30, 50, 70, 90, 110, 150, 200, 250 and 300 m depth	March '93

2.2 Wind direction

Wind direction measurements were processed as follows (Equations 1 - 4 and numerical examples are given in Appendix II):

Wind direction distributions

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

North/south (N/S) and east/west (E/W) wind speed vectors

N/S and 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). Using this method, a negative N/S wind speed vector indicated wind stress was from the south.

North, south, east and west wind speed vectors

In order to find the relative contribution of each wind direction 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 equalling 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 is equal to the N/S wind speed vector.

The actual mean force of north, south, east and west wind components

To determine how strong the wind was on average, if it did come from one of the 4 wind directions, the values equal to zero, i.e. when the wind was coming from the opposite direction, were ignored in the daily, weekly and monthly averages. In this method, the daily, weekly or monthly mean components of the wind speed vector, relate to those periods only in which the wind was coming from a particular direction.

2.3 Evaporation

Evaporation at the Bujumbura and Mpulungu stations was calculated, from wind speed, air temperature, air pressure and relative humidity data recorded at the automatic stations. For Bujumbura, values for all 4 variables were recorded at 13 m height. For Mpulungu, wind speed and air temperature data were collected from the buoy. Evaporation was calculated using a simplified form of the Thornthwaite-Holzman equation for vapour transport (Chow *et al.*, 1992). Calculations of evaporation were made every 10 min for Bujumbura, and every hour for Mpulungu. Before 1995, evaporation for Bujumbura was calculated from monthly means of wind speed, air temperature, air pressure and relative humidity. An underestimation of 10 - 15 % was calculated for evaporation derived from monthly means compared to those calculated from 10 min values in 1995. This probably applies as well to pre 1995 data. Air density, the gas constant for moist air, specific humidity, the saturation vapour pressure and the actual vapour pressure were calculated as given by Chow *et al.* (1992). Density of water was assumed constant (997 kg.m^{-3}) and 0.0006 m was used for roughness height (Chow *et al.*, 1992). Measurement heights, as used in the Thornthwaite-Holzman equation, were 13.0 m for Bujumbura and 2.6 m for Mpulungu.

3. RESULTS

3.1 Hydrodynamics

3.1.1 Mpulungu buoy

Seven day running averages of the water temperatures at different depths at the Mpulungu buoy are shown in Fig. A.III.1. In the dry season upwelling took place and in the water column, 0 to 300 m depth, temperature was almost uniform. At the onset of the wet season the thermocline was reestablished. In the dry season of 1995 the mean temperature of this water column was > 1993. The mean temperature near the surface (1 and 5 m) was also higher in 1995 than in 1993. Surface temperatures in 1994 and 1993 were similar. Upwelling and surface cooling was less intense in 1995. At the beginning of the wet season in 1995, water temperatures increased more than in the wet seasons of 1993 and 1994 especially at 50 m depth. Stratification was stronger than in 1993, and the thermocline was deeper. In Figs A.III.2 and A.III.3, monthly mean temperature depth distributions are shown for 1993 - 1995. From March 1993 to April 1994 the thermocline was found at *c.* 40 m depth. In the dry season the thermocline disappeared, and in July - August 1993 there was < 1°C difference between 1 and 300 m depth (daily minimum 0.55° C on 2 August 1993). In 1995, however, the temperature difference between 1 and 300 m depth was > 1 °C in every month. From October to December 1995, the thermocline was at *c.* 70 m depth.

Isotherm depths based on daily mean temperatures are shown in figs 2 and 3. In 1993/94 the 24 °C isotherm was usually at *c.* 100 m depth in the wet season, and came to the surface in July - August 1993. In 1995 (Fig. 3) the 24 °C isotherm did not reach the surface in the dry season, but remained below 100 m depth. In 1995 there were 18 days in which the surface water temperature was < 24.5 °C compared to 70 days in 1993. In 1993/94 the 23.5 °C isotherm descended only on few occasions below 250 m depth. From May 1995 this isotherm was found much deeper (generally between 250 and 300m depth). The 23.5, 23.75 and 24 °C isotherms were generally deeper during the second period. On two occasions the 23.5 °C isotherm was below 300 m (6 June 1995 and 1 February 1996).

Dry season water temperatures at 1 and 5 m depth were significantly higher (*c.* + 0.3 °C, $P < 0.01$) in 1995 than in 1993 and 1994 (Table 8). Temperature differences between 1993 and 1994 were not significant ($P > 0.05$). Temperatures at 30, 50, 70, 90, 110, 200 and 300 m depth were significantly ($P < 0.001$) higher and those at 150 m depth were significantly ($P < 0.05$) lower in 1995 than in 1993.

When wet seasons were compared (Table 9), temperatures at 1, 5, 200, 250 and 300 m were significantly ($P < 0.01$) higher and those at 50 m depth were significantly ($P < 0.01$) lower in March - April 1994 than in March - April 1993. In October to December 1995, temperatures at 1 and 5 m were significantly ($P < 0.0001$) higher (*c.* + 0.6 °C), than in the same period in 1994. At all depths, temperatures were significantly ($P < 0.0001$) higher than in the same period in 1993, except at 150 m where tempereatures were significantly ($P < 0.05$) lower.

The results presented in Tables 8 and 9 were based on daily means. When hourly values were compared (t test) for 1 and 5 m depth between 1994 and 1995, the results were:

	Annual mean water temperatures 1994	1995	N	significance P two-tail
1 m	26.27 °C	26.54 °C	8534	0.00001
5 m	26.14 °C	26.44 °C	8534	0.00001

The lowest daily mean temperatures at 1 m depth in 1993, 1994 and 1995 were 23.98, 24.09 and 24.26 °C respectively. Lowest annual temperatures at 5 m depth also increased with time: 23.93, 23.94 and 24.21 °C respectively. In 1995 there were 96 days in which the temperature at 1 m depth was > 27.5°C compared to 38 days for the period 7 March 1993 to 6 March 1994.

Hourly values (daily means in brackets) of temperatures at 1 m depth at the Mpulungu buoy ranged between 23.85 °C (23.98 °C) and 29.01 °C (28.47 °C). Temperatures at 300 m depth ranged only between 23.33°C (23.35) °C and 23.51 °C (23.51°C).

Table 7 shows a correlation matrix for temperatures at each sensor depth of the Mpulungu buoy, for each hourly measurement between 8 March 1993 and 12 May 1994 ($n = 10332$). The correlations generally decreased with increasing distance between depths. With few exceptions, all correlations were very significant ($P < 0.001$), even between 1 and 300 m ($r = 0.16$).

3.1.2 Kigoma buoy

At the Kigoma buoy variation in daily mean water temperature was less than at the Mpulungu buoy (Fig. A.III.4). The surface temperature decreased much less than in the south in the dry season. In the dry season of 1995 the surface temperature at the Kigoma buoy was on average 1.16 °C > the temperature at the Mpulungu buoy. In the wet seasons of 1994/1995 and 1995/1996 it was 0.48 and 0.76 °C below the surface temperature at the Mpulungu buoy respectively. It was lowest during August and September and highest in January to May. The minimum difference in daily mean water temperature between 1 and 300 m occurred about one month after it occured in the south. This difference remained much larger than in the south (2.17 °C in 1994, 2.37 °C in 1995 and

2.06 ℃ in 1996). The thermocline was deepest in the dry season (*c.* 70 m). In the early part of the wet season the thermocline at the Kigoma buoy rose to *c.* 40 m depth, and subsequently descended to remain during the rest of the wet season at *c.* 60 m depth. In May 1994 and May 1995 there were large fluctuations in temperature at 50 and 70 m depth.

In May to December 1995, the 23.5, 23.75 and 24 ℃ isotherms were generally at the same depths as at the Mpulungu buoy (Fig. 4). The 23.5 ℃ isotherm reached the 300 m depth twice in March 1994 to December 1995, on 15 May 1995 and on 24 October 1995.
In general the surface water temperature was low from about July to December (Figs 4 and A.III.4). The surface was < 26 ℃ in August - September and November - December in 1994 (no data available for 1 June - 28 August 1994), and in 1995 only in August and September. The minimum surface water temperature was 25.54 ℃. The surface water was > 28 ℃ on only 2 days in January 1995, and was > 27.5 ℃ on 17-21 January, 20 March and 5-6 May 1995. The warming phase of the surface started in 1995 sooner than in 1994.

At the Kigoma buoy, as at the Mpulungu buoy, water temperatures were at nearly all depths significantly (P < 0.05) higher in 1995 than in 1994, both in the wet season and in the dry season (Tables 8 and 9).

3.1.3 Stratification

The standard deviation of daily mean water temperatures at different depths was used as a stratification index. This is similar to an index based on water density since the range of the water temperatures at Lake Tanganyika is small. For the Mpulungu buoy the standard deviation of daily mean water temperatures at 1, 5, 30, 50, 90, 110, 150, 200 and 300 m depth varied from 0.19 (2 August 1993) to 2.06 (3 December 1995). The stratification was strong throughout the wet season, and very low in the dry season. Stratification was higher in the dry season of 1995 than in 1993, (a mean index of 0.59 in 1993 and 0.73 in 1995). Also in October to December 1995 stratification was stronger, 1.76 (1.48 in the same period in 1993). For the complete wet seasons of 1993/1994 and 1995/1996 the values were 1.53 and 1.63 respectively.

The stratification at the Kigoma buoy (using water temperatures at the same depths as at the Mpulungu buoy) was strongest at the end of the wet season and weakest at the end of the dry season. The latter coincided with a rise of the thermocline. At the Kigoma buoy the variance in stratification was smaller than at the Mpulungu buoy (Fig. A.III.6). The stratification index varied only from 0.83 to 1.79, and there was less mixing of the upper 300 m in the dry season than at the Mpulungu buoy.

The stratification index correlated extremely well with the temperature (daily means) at 1 m depth, both at the Mpulungu buoy (r = 0.99, n = 880, F test P < 0.00001) and at the Kigoma buoy (r = 0.95, n = 818, F test P < 0.00001). Linear regression coefficients for temperature at 1 m depth and the stratification index were not significantly (t test, $P > 0.05$) different for data collected at the Mpulungu and Kigoma buoys (Fig. A.III.7).

3.1.4 Thermo density gradients over the thermocline

To estimate the steepness of the thermocline the water density was calculated, using daily mean temperatures at all depths, from the equation given by Plisnier (1996). In this equation variation in salinity was not considered. The daily thermo density gradient ($kg.l^{-1}.m^{-1}$) over the thermocline was then calculated as the steepest of the gradients, i.e. the density differences per m distance, between each two adjacent measured depths (excluding the range between 1 and 5 m because of the effects of air temperature. In July to September the highest gradients were almost always between 1 and 5 m). At the Mpulungu buoy (Fig. A.III.8) density gradients over the thermocline were steepest in the wet season (1.99 [1.90] * 10^{-5} $kg.l^{-1}.m^{-1}$ in 1993/1994, with values in November to December in brackets) and least in the dry season (0.58 $kg.l^{-1}.m^{-1}$ in 1993). Within the wet seasons, January to April was the period of maximum stability, with maximum and stable gradients (Fig. A.III.8).

Also at the Kigoma buoy the gradient over the thermocline showed a similar pattern as the stratification index, with low values at the end of the dry season and high values at the end of the wet season. At the Kigoma buoy the thermo density gradients at the thermocline were within a smaller range than at the Mpulungu buoy, as was the stratification index. They did not reach the steep levels found at the Mpulungu buoy, and did not decrease at the end of the dry season to the same extent as this occurred in the south. In October, both in 1994 and 1995, a sudden increase in the thermo density gradient was followed by a decrease and low values in December. This coincided with a thermocline ascent and decreasing stratification in November and December.

3.1.5 Internal waves

Internal waves were observed during the whole measuring period at the Mpulungu buoy (Figs 2 and 3). Both in the wet and in the dry seasons, isotherms oscillated at all depths down to 300 m, in a similar fashion. In general temperatures at all depths decreased every 25 - 30 days, when cold water from the hypolimnion was forced upwards by internal waves. Internal waves were most noticeable below the thermocline. Temperatures at 30 and 50 m were most affected by the internal waves (Fig. A.III.1). The amplitude of the internal waves appeared to be widest at greater depths, where temperature differed little over a larger depth range.

In the south, the 23.5 °C, 23.75 °C and the 24 °C isotherms (the latter around 100 m depth in the wet season, and up to the surface in July - August 1993), each showed amplitudes of about 50 m, during the period of March 1993 to May 1994, even during upwelling. There was no perceptible damping of the oscillation towards the dry season. The amplitude of the waves at the 23.5 °C isotherm appeared wider in May - December 1995 (*c.* 70 m) than in March 1993 - May 1994, but were narrower after December 1995. Internal wave oscillations with a period similar to in the south were inferred from temperature data collected at the Kigoma buoy.

Correlation between the depth of the 23.5 °C isotherm at the Mpulungu and Kigoma buoys was negative (r = -0.25, n = 303) and significant (P < 0.00001). The correlations between the depths at the Mpulungu and Kigoma buoys of the 23.75°C isotherms (r = -0.54) and the 24 °C isotherms (r = -0.48) were negative and higher than for the 23.5 °C isotherm (n = 303, P < 0.00001 for both). These neagtive correlations indicated a lake wide phase relationship of internal waves with the fundamental mode appearing as a uninodal seiche (*cf*. Coulter and Spigel, 1991). The 23.5, 23.75 and 24 °C isotherms at the Kigoma buoy were generally measured deeper than their mean depths when they were relatively shallow at the Mpulungu buoy and vice versa (Fig. A.III.9). The maximum tilt of the 23.5 and 23.75 °C isotherms between the Mpulungu and Kigoma buoys was *c.* 70 and 60 m respectively (*c.* 0.14 - 0.12 $m.km^{-1}$). The amplitudes of the internal waves at the 23.75 and 24 °C isotherms were smaller at the Kigoma buoy than at the Mpulungu buoy. This supports the concept of an uninodal seiche since the Kigoma buoy is nearer the middle of the lake than the Mpulungu buoy.

There was evidence for a second mode with a smaller period superimposed on the fundamental mode (Fig. A.III.10). In June 1995, hourly depths of the 23.5 °C isotherm at the Mpulungu buoy show 2 oscillations of *c.* 5 days, with an amplitude of *c.* 40 m, before the onset of the upward surge of the fundamental mode.

The maximum and mean daily changes in depth, of the 23.5 - 27 °C isotherms at each buoy are shown in Table 10. In general the deeper isotherms changed depth faster. Highest speeds were reached in Mpulungu, with 48 m/day for the 23.5 °C and 63 m/day for the 24°C isotherm. At the Kigoma buoy and at the Mpulungu buoy in May 1995 to May 1996, changes in depth were generally faster in the wet season. This was not the case at the Mpulungu buoy in March 1993 to May 1994.

3.1.6 Heat budget

The annual heat budget was estimated proportionally by taking the difference between the annual minimum and maximum monthly mean heat content, following Hutchinson (1957). The heat content was calculated up to 300 m depth, and area differences at different depths were ignored. In the south the lake gained its heat in the early part of the wet season, and more heat was absorbed at the surface than in deeper layers (Figs A.III.11 and A.III.12). At 150 m depth and deeper, the annual temperature increases were about zero. At the Mpulungu buoy, in 1993, from August to December, the sum of the heat changes at each depth (each multiplied by the depth range over which they occurred) was 17560 $cal.cm^{-2}$. In July to November of 1995, the heat uptake was much higher, 20039 $cal.cm^{-2}$. The water column down to 300 m absorbed 14 % more heat (between the minimum and maximum heat content) in 1995 than in 1993. This difference was primarily due to a larger heat uptake at *c.* 50 m depth in 1995. The heat stored in the lake (0 - 300 m) was 0.56 % more in July 1995 than in August 1993, and 0.89 % more in November 1995 than in December 1993. The heat gain was highest in September 1993 and October 1995 (*c.* 350 $cal.cm^{-2}.day^{-1}$) and the heat loss was highest in June (1993, 1996) and May 1995 (*c.* 370 $cal.cm^{-2}.day^{-1}$). The monthly change in heat content of the upper 150 m was similar to the change in temperature at 1 m depth (Fig. A.III.13). Water at 150 to 300 m absorbed only 1 (1993) to 2 % (1995) of the entire annual heat budget between 1 and 300 m depth.

At the Kigoma buoy, the heat was gained during the whole wet season (Fig. A.III.12). Annual temperature increases were maximum at 50 m depth (Fig. A.III.11), both in 1994/95 and 1995/96, probably due to warm water currents from the north and/or the south. Monthly temperature increases were maximum at 50 m in November and in March - April, both in 1994/95 and 1995/96. At 150 to 300 m the temperature change was negative during the wet seasons. Both in 1994/95 and 1995/96 the change in heat content between 150 and 300 m depth, was -1% of the entire heat budget between 1 and 300 m depth. The total heat budget was about 50 % of that in the south (Figs A.III.11 and A.III.12). In November 1994 to May 1995, the heat uptake was 9470 $cal.cm^{-2}$. In October 1995 to May 1996 the heat uptake was 1.8 % lower, 9301 $cal.cm^{-2}$. The lake (0 - 300 m depth) contained at the Kigoma buoy 0.33 % more heat in October 1995 than in November 1994, and 0.30 % more heat in May 1996 than in May 1995.

The contribution of the water layers below 150 m depth to the heat budget did not depend on evaporative cooling and heating by radiation. It depended to a large extent on the phase of internal waves and changes in heat content from month to month at 150 - 300 m were sometimes comparatively large. The monthly heat content change at 150 - 300 m was regularly positive while the heat content change at 0 - 150 m was negative and vice versa.

3.1.7 Air temperature over the lake surface

At the Mpulungu buoy air temperature was higher than the water temperature at 1 m depth only from mid August to mid October, the heating phase at the start of the wet season (Fig. A.III.14). For the rest of the year the air temperature was lower than the water temperature at 1 m. In 1994 the air temperature was an average 1.0 ℃ less than the water temperature at 1 m and in 1995 it was 0.8 ℃ lower. After October the air temperature decreased, but the water temperature increased reaching a maximum in December, 1993, and January, 1995. At the Kigoma buoy the air temperature was similar to the water temperature at 1 m in August - September. For the rest of the year the air temperature was *c.* 2 ℃ less than the water temperature at 1 m depth (annual mean 1.5 ℃ less than the water temperature at 1 m depth both in 1994 and 1995).

3.2 The wind system

3.2.1 Wind speed and gust

The wind speed was highest in the dry season and lowest in the wet season at all stations (Fig. A.IV.1.1). At the Mpulungu weather station and lake buoy the wind speeds followed a similar pattern although at the former they were lower. At the Mpulungu weather station they were lowest compared to the other stations in almost every month except in the middle of the dry season. At the Mpulungu buoy the wind speeds were generally highest and showed the greatest seasonality. At the Kigoma wind station wind speeds were generally higher than at Bujumbura. Variance in daily mean wind speed was highest at the Mpulungu buoy with maximum daily means *c.* 10 $m.s^{-1}$. Maximum daily means at Bujumbura and the Kigoma wind station were *c.* 5 and 6 $m.s^{-1}$ respectively.

At the Mpulungu buoy, annual mean wind speed in 1995 was significantly ($P < 0.01$) lower than in 1993, but not significantly different ($P > 0.05$) from 1994 (Table 2). Also when dry seasons were compared, wind speed at the Mpulungu buoy was significantly ($P < 0.01$) lower (9 %) in 1995 compared with 1993 (Table 4). At the Mpulungu buoy and Bujumbura, wind speed was significantly ($P < 0.01$) lower in October - December 1995 than in the same period in 1993 (Table 5). At the Mpulungu weather station, the wind speed was higher ($P < 0.01$) in October - December 1995, than in the same period in 1994. This was found in no other station. Wind speed at Bujumbura and the Kigoma wind station was significantly ($P < 0.01$ and 0.05 respectively) higher in the 1994/95 wet season, compared with the 1993/94 wet season (Table 5). This was not the case at the Mpulungu buoy. The annual mean wind speed in 1995 at Bujumbura was significantly ($P < 0.05$) higher than in 1994 (Table 2).

On average the hourly wind gust was x 1.4 to x 1.6 the wind speed at all stations, except for the Mpulungu land-based meteorological station (x 1.9). At the Mpulungu buoy in 1995 the relationship between the hourly mean wind speed (v) and the wind gust (g) during the same hour was :

$$g = 1.41 + 1.21 * v \qquad r = 0.95, P < 0.00001, N = 8620$$

There was no seasonality in the monthly maximum wind gust. The highest monthly wind gust was in general between 15 and 20 $m.s^{-1}$ each month. Highest wind gust was measured at the Mpulungu buoy (31 $m.s^{-1}$), the Kigoma buoy (30 $m.s^{-1}$) and the Bujumbura weather station (29 $m.s^{-1}$). These 3 values were recorded in October to December of 1995.

3.2.2 Wind direction

The different directions from which the wind blew are shown in Figures A.IV.2.1-5. These were given by Kotilainen *et al.* (1995) for pre 1995 data. Wind directions at the Mpulungu buoy, March 1993 to April 1994, are given since they were not shown for the whole of this period by Kotilainen *et al.* (1995). The wind direction sensor malfunctioned from May 1994.

The wind direction patterns in 1995 at all stations were very similar to the patterns in 1993 and 1994, with the exception of the Kigoma buoy (Kotilainen *et al.*, 1995). At the Kigoma wind station most of the wind came from the east-north-east and a small part came from the west. The east-north-east component increased in the dry season. At Bujumbura, the wind direction was primarily from the north and there was a slightly smaller south-south-east component. The latter increased in importance in July - September. At the Mpulungu buoy, wind came primarily from the south-east and the north-west to north-north-west. Most wind came from the south-east in March 1993 to November 1993, with maximum percentages in June and July 1993, and in April 1994. In December 1993 to February 1994, wind from the north-west and north-north-west became slightly more important, and the wind came from more different directions than in the dry season. At the Mpulungu weather station, the south-east wind was the most common in each month. The south-east wind component only slightly increased in the dry season. In the early wet season (September to December) the portion of the wind coming from the north slightly increased. This was more the case in 1995 than in 1994.

3.2.3 Wind vector components

Mean east/west and north/south components of the wind vectors contain less information than wind vectors split in 4 components and are not discussed in this report. Seasonal patterns of the 4 wind vector components were similar at Bujumbura and at the Mpulungu buoy and weather station (Fig. A.IV.3.1-5). The monthly mean south and east wind components were in general higher than the north and west components, and were highest in the dry season. The north and west wind components were similar throughout the year. At the Mpulungu stations the north and west components increased slightly in the wet season. This did not occur at Bujumbura. At Bujumbura, the east wind component was in 1995 less than in 1993. It increased in the dry season of 1993 and not in the dry season of 1995. At the Mpulungu buoy seasonality was greatest and the south and east components were less than the north and west components in the middle of the wet season.

For the Kigoma buoy there were only data for wet seasons available. The components of the wind vector at the Kigoma buoy did not show clear seasonal patterns.
At the Kigoma wind station the east wind component was generally highest of all components and the south wind was the lowest. They were highest in the dry season. The west wind component was highest in October. In October and November it was higher than the east wind component. The north wind component was generally lower than the west wind component and was highest in the wet season.

When the calculated monthly mean components of the wind speed vectors were related only to those hours during which the wind was actually blowing from a particular direction, the seasonal patterns and differences between the components were generally similar. Only at the Kigoma wind station this was not the case (Fig. A.IV.3.3). The west wind was strongest of all, during the whole year, with highest values in the dry season.

In Table 6, annual maximum monthly means for wind vector components for each station are given. Also the diel maxima of wind vector components over the day and the annual means are shown. The highest monthly means for the west and north wind components occurred at the Kigoma wind station, and the lowest at the Mpulungu weather station. The highest monthly means for the south and east components were found at the Mpulungu buoy, and the lowest at Kigoma and Bujumbura respectively.

Diel maxima of wind vector components were highest at stations where they were lake winds, compared to stations where they were land winds. Although the diel maximum of the north wind component was highest at Mpulungu of all stations, the diel maximum of the south wind component was highest of all wind vector components at Mpulungu.

The annual means were for the west and north wind vector components highest at Kigoma, and for the south and east components highest at the Mpulungu buoy.

3.2.4 Annual differences in wind vector components

At Bujumbura, in general the north and west wind components increased and the east wind component decreased in the period 1993 to 1995, both in the dry and wet seasons (Tables 3 - 5). For instance, between 1993 and 1995 the annual mean north wind component increased (19 %, $P < 0.00001$), the west wind component increased (7 %, $P < 0.05$) and the east wind decreased significantly (24 %, $P < 0.00001$, see Fig. A.IV.3.1). Between dry seasons and between wet seasons over this period changes were similar. The values for 1994 were intermediate. The south wind component at Bujumbura did not differ significantly between years ($P > 0.05$).

At the Kigoma wind station, the main findings were a general increase of the north and west wind components and a decrease of the south wind component in the period 1993 to 1995, both in the dry and wet seasons. The south wind component was significantly ($P < 0.01$) lower in 1995 than in 1993 and 1994 (23 and 15 % respectively). Between dry seasons and between wet seasons over this period changes were similar. The north wind component was significantly higher in 1995 than in 1993 (16 %, $P < 0.05$). The west wind component was significantly higher in the dry season in 1995 than in 1993 (11 %, $P < 0.05$).

At the Mpulungu weather station in general the north and west wind components were higher in 1995 than in 1994. The east and south wind components generally occurred at the same time at Mpulungu (Fig. A.IV.2.1) and the sum of the south and east vector components did not change appreciably between 1994 and 1995.

3.3 Evaporation

Monthly evaporation at Mpulungu between May and December 1995 was x 2 to x 4.5 the evaporation at Bujumbura (Fig. A.V.1). The total annual evaporation in 1995 for Bujumbura was 1190 $mm.yr^{-1}$. At Bujumbura in August 1994, the highest measured monthly wind speed, combined with the lowest monthly humidity, resulted in the highest monthly evaporation (6 $mm.day^{-1}$). At Mpulungu the highest monthly evaporation occurred in August 1995 (14 $mm.day^{-1}$). Evaporation was lowest in the wet season. At Mpulungu evaporation was lowest in December 1995. If the evaporation in the missing months January to April 1995 at Mpulungu, was assumed to be the same as in December 1995, the annual evaporation would be *c.* 3200 $mm.yr^{-1}$. Correction of the humidity for the underestimation caused by the position inland of the weather station, by adding 9 % (see Appendix A.VI.5), gave an annual evaporation of 2630 $mm.yr^{-1}$ at Mpulungu.

The evaporation calculated for Bujumbura between August 1994 and December 1995 was much higher than between March 1993 and April 1994. The expected underestimation of 10 - 15 % for 1993-1994 (see section 2.3) does not account for the large difference in evaporation. It was mainly due to differences in humidity.

4. DISCUSSION AND CONCLUSIONS

4.1 Hydrodynamics: upwelling, mixing, internal waves and heat budget

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). Complete overturn, which would cause massive fish kills due to anoxia and high concentrations of H^2S and NH^3 in the hypolimnion (70 % of the water volume, Coulter and Spigel, 1991), did not occur.

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, and stratification and thermocline descent 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 increased at the south end of the lake, 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). The internal waves persist during the whole wet season. Waves of this duration (and amplitude and periodicity) have not been observed in any other lake (Coulter and Spigel, 1991). Phase relationships of internal waves in different parts of the lake were demonstrated for the first time in this report (Coulter and Spigel, 1991). The fundamental mode appeared uninodal with an inverse relation between the deeper isotherm depths in the north and the south. Near the wave node, halfway along the basin amplitudes of internal uninodal waves can diminish to near zero (Coulter and Spigel, 1991). Minor waves, superimposed on the fundamental wave, as found in this study (5 days period), have been reported by Coulter and Spigel (1991). They mention waves of about 3 days period in the south. Ferro (1975) found a 15-day oscillation in the north.

Upwelling was less in 1995 than in 1993 and 1994. Temperature distributions and the stratification index indicated less mixing of the epilimnion in the south, in the dry season of 1995. Wind speed from the south-east and air pressure decreased and solar radiation, air temperature and wind speed from the north-west increased from 1993 to 1995. The differences between 1993 and 1995 were highest in the south and occurred both in the wet and dry seasons. The increase in air temperature was highest in the south (*c*. 0.2 °C at Bujumbura and the Kigoma buoy between 1995 and 1993/1994, and *c*. 0.4 °C increase at the Mpulungu buoy). It was highest in the dry season (0.4 °C at Bujumbura and 0.5 °C at the Mpulungu buoy).

Nutrient regeneration from the hypolimnion by upwelling was probably less in 1995 than in 1993 and 1994. Deep water masses with high nutrient levels (Plisnier, 1996), which came to the surface in 1993, remained far below the photic zone (*c*. 40 m depth) in 1995. It is likely that this has repercussions for the pelagic ecosystem. A lower primary production may lead to declining secondary production, and fish catches may decrease.

Three factors may explain the deeper position of the thermocline at the onset of the wet season of 1995/1996 compared with 1993/1994 at the Mpulungu buoy. The epilimnion temperatures were higher to start with at the beginning of the wet season, due to the reduced upwelling in the preceding dry season of 1995. Heat uptake by the epilimnion was higher in 1995 than in 1993 and 1994, due to above mentioned meteorological changes and more warm surface water may have been driven from the north to the south by the higher wind speeds from the north-west in 1995 than in 1993 and 1994.

The decrease in upwelling from 1993 to 1995 may very well be due to interannual variation, and not indicate a trend. Patterson and Kachinjika (1995) and Patterson *et al.* (1995) found in Lake

Malawi that in the dry season Wedderburn numbers were lower in 1993 compared with 1992, indicating more mixing in 1993. They estimated that primary production and fish larval production was lower in 1992.

However, in the present century there may have been an overall increase in water temperatures of Lake Tanganyika with interannual variance superimposed on a long term change. Upwelling intensity in the present century may have been affected, either by a decreasing wind force, or by increasing differences in the water density of the water masses. Both factors restrict mixing. Coulter and Spigel (1991) mentioned lower surface water temperatures in the dry season in the south than found in 1993 (< 23.75 °C in 1965). Minimum temperatures in the hypolimnion were found by Capart (23.25 °C, 1952) and Craig *et al*. (23.28 °C, 1974), at 500 to 800 m depth. Lowest hypolimnion temperatures were recorded by Jacobs (in Coulter and Spigel, 1991) in 1912-1913. He found the water below 400 m to be almost homothermal between 23.13 and 23.15 °C.

More heat from solar radiation was absorbed by the lake than by the air above it. Lakes at high altitudes (Lake Tanganyika: ± 773 m) and low latitudes (Lake Tanganyika: 3 - 9° S) receive more heat from the sun (Wetzel and Likens, 1991). The travel distance of the light through the atmosphere influences the amount of radiation reaching the lake. This travel distance is lower at high altitudes and at low latitudes, the latter due to a generally smaller angle of the sun from the perpendicular. Also, when the angle of the sun is minimal, as at midday in the tropics, only a small part of the radiation which reaches the lake is reflected from the lake surface and absorbtion of solar energy is high. Evaporative cooling, backradiation by the water surface and sensible heat transfer (heat lost by conduction from the water to air) decrease the heat content of the lake. Heat loss increases with wind speed (Goldman and Horne, 1983). 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, since at the south end of the lake, annual temperature changes are much larger.

4.2 The Wind system

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; Kotilainen *et al.,* 1995; Savijärvi, 1997). Wind speeds from the lake were higher than from the land at Bujumbura and Kigoma. During the day differences in temperature between land and lake are usually larger than during the night causing stronger winds (Beauchamp, 1939). Differences in temperature between land and lake are also larger during the dry season than during the wet season

(Kotilainen *et al.*, 1995). 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. Differences between years (and seasons) in the relative amount of wind from the north-west and south-east as ocurred between 1993 and 1995 are due to differences in the position of the ITCZ (Asnani, 1993).

4.3 Evaporation

Besides the supply of heat energy, evaporation decreases with increasing humidity and increases with increasing wind speed near the water surface and air temperature. Monthly evaporation was highest in August - September, although heat uptake at the surface was high in those months.

The calculated evaporation at Mpulungu (2630 $mm.yr^{-1}$) was high compared with other studies. Bultot (1965, 1993) found an annual evaporation rate from Lake Tanganyika of 1700 $mm.yr^{-1}$, both derived from the water and energy balance methods. Beauchamp (1939, quoting Theeuws, 1920) gives 1350 $mm.yr^{-1}$ for the average annual evaporation. This value was later often quoted by others (Coulter and Spigel, 1991; Edmond *et al.*, 1993; Hecky and Degens, 1973; Haberyan and Hecky, 1987). Capart (1952) estimated the annual evaporation at Lake Tanganyika at 1580 to 2000 $mm.yr^{-1}$ from measurements elsewhere. For comparison, Piper *et al.* (1986) give an evaporation rate of 1600 $mm.yr^{-1}$ for Lake Victoria. The annual mean evaporation rate recorded during more than 20 years at 4 stations along the western shore of Lake Malawi was 2240 $mm.yr^{-1}$ (SD 350 mm, Patterson and Kachinjika, 1995). Drayton (1984) reported a mean annual evaporative loss of 1600 $mm.yr^{-1}$ at Lake Malawi.

At Mpulungu and at Bujumbura, the humidity was measured near the shore. Probably the humidity over the lake is higher than the humidity measured on land, which would decrease the evaporation.
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 vapour pressure of the air increasing 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 wind speeds in the dry season at the south end of the lake are highest during the night, causing a relatively large proportion of evaporation to take place during the night.

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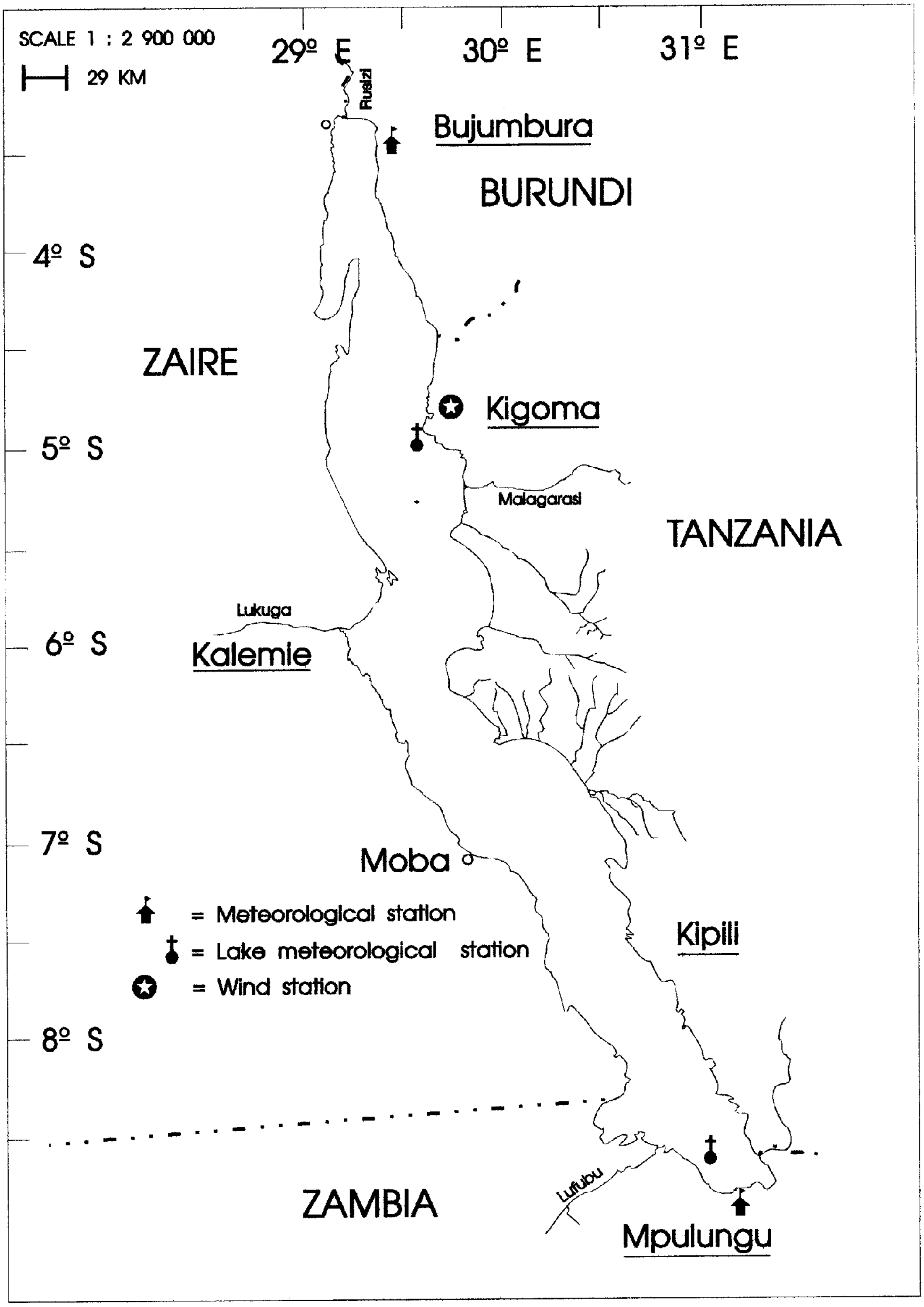


Figure 1: Locations of LTR stations in hydrodynamics.

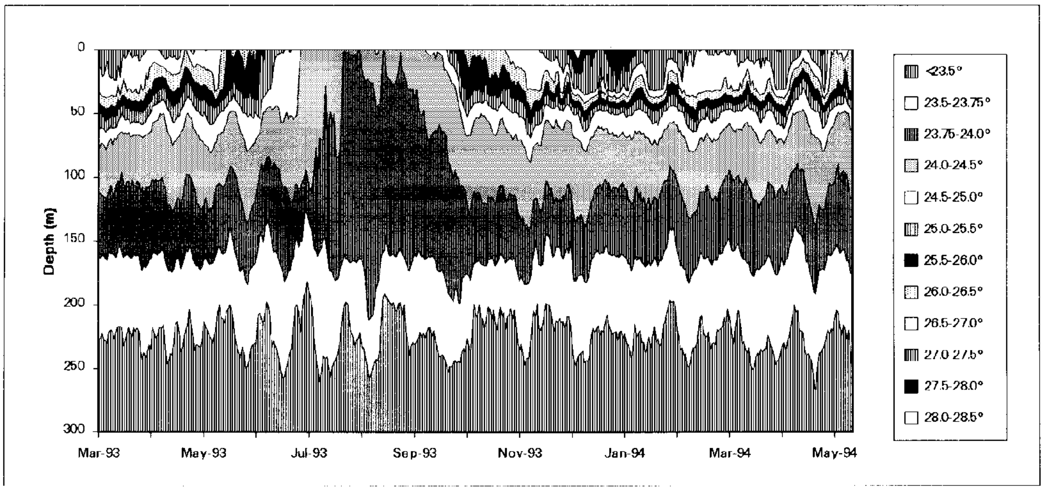


Figure 2. Mean daily temperature (°C) of the water column (0 - 300 m depth) from March 1993 to May 1994 at the Mpulungu buoy .

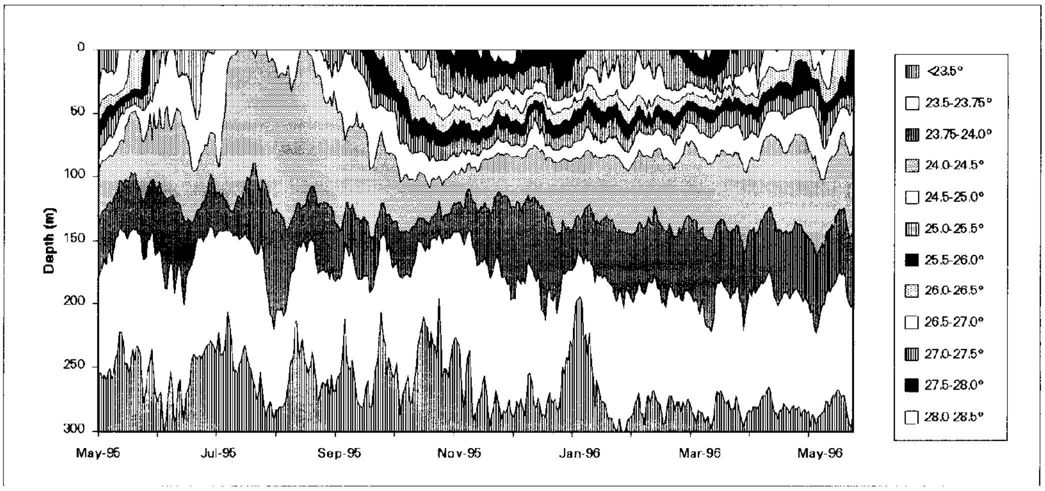


Figure 3. Mean daily temperature (°C) of the water column (0 - 300 m depth) from May 1995 to May 1996 at the Mpulungu buoy .

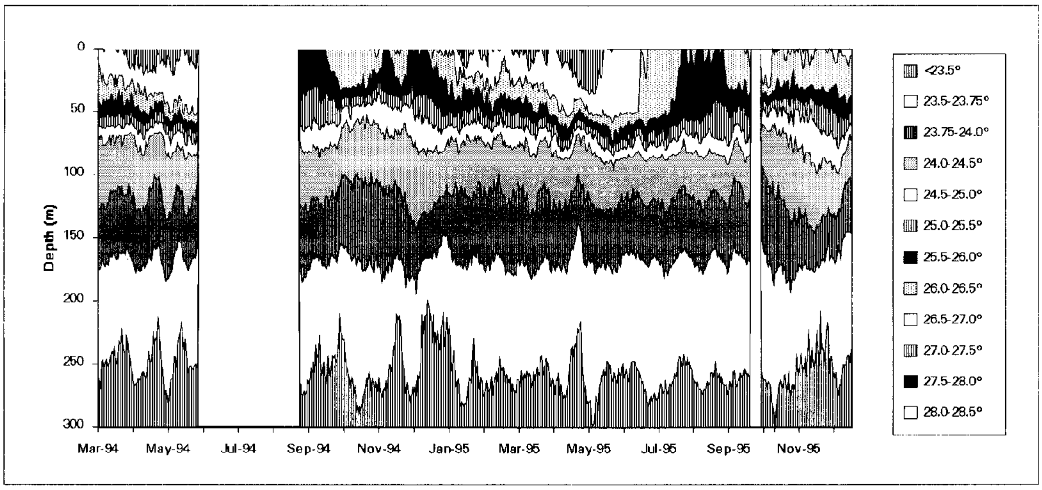


Figure 4. Mean daily temperature (°C) of the water column (0 - 300 m depth) from May 1994 to December 1995 at the Kigoma buoy .

APPENDIX I

Table 2. Mean daily values of wind speed (m/s), air temperature (°C), relative humidity (%), air pressure (mbar) and solar radiation (W/m2) for Bujumbura, Kigoma and Mpulungu for 1993, 1994 and 1995. Comparisons were made between years by student t tests. Ns = non-significant, * = $p<0.05$, ** = $p<0.01$ and *** = $p<0.001$.

Station	Parameter	means		N	sign.	means		N	sign.	means		N	sign.
		93	94			94	95			93	95		
Bujumbura (weather)	Wind speed	2.99	3.03	172	Ns	2.88	3.01	245	*	3.19	3.17	270	Ns
	Air temperature	23.65	23.77	172	Ns	23.63	23.85	244	*	23.66	23.85	269	*
	Humidity	84	75	172	***	79	71	244	***	83	68	269	***
	Air Pressure	924.4	924.5	172	Ns	924.5	923.4	245	***	925.0	923.4	270	***
	Solar radiation	220	230	171	Ns	218	226	242	Ns	220	231	268	*
Kigoma (lake chain)	Wind speed					2.88	2.75	118	Ns				
	Air temperature					25.01	25.25	205	**				
Kigoma (wind)	Wind speed	3.91	4.03	91	Ns	3.85	3.78	149	Ns	3.69	3.86	150	Ns
Mpulungu (lake chain)	Air temperature	25.39	25.35	295	Ns	25.17	25.48	293	***	25.15	25.52	233	***
	Wind speed	4.41	4.24	295	Ns	3.99	3.90	355	Ns	4.45	4.13	295	**
Mpulungu (weather)	Wind speed					2.99	3.03	216	Ns				

Table 3. Mean daily values of wind components (m/s) for Bujumbura, Kigoma and Mpulungu for 1993, 1994 and 1995. Comparisons between years were made when data were available for the same time periods within each year, by student t tests. Ns = non-significant, * = $p<0.05$, ** = $p<0.01$ and *** = $p<0.001$. For methods of processing wind data see text.

Station	Parameter	**means**		change		N	sign.	**means**		change		N	sign.	**means**		change		N	sign.
		93	94		%			94	95		%			93	95		%		
Bujumbura	E/W	0.75	0.53	-	-29	166	***	0.50	0.43		-13	235	Ns	0.87	0.57	-	-35	262	***
(weather)	N/S	-0.84	-0.76		-10	166	Ns	-0.63	-0.58		-7	235	Ns	-1.06	-0.87	-	-18	262	**
	E	1.08	0.87	-	-20	166	***	0.85	0.81		-4	235	Ns	1.18	0.90	-	-24	262	***
	W	0.33	0.33		2	166	Ns	0.35	0.38	+	8	235	*	0.31	0.33	+	7	262	*
	N	0.82	0.92	+	12	166	***	0.90	0.99	+	9	235	***	0.81	0.96	+	19	262	***
	S	1.66	1.68		1	166	Ns	1.53	1.57		2	235	Ns	1.87	1.83		-2	262	Ns
Kigoma	E/W							0.29	0.29		0	117	Ns						
(lake chain)	N/S							-0.03	-0.60	+	1637	117	***						
	E							1.09	1.00		-8	117	Ns						
	W							0.80	0.71		-11	117	Ns						
	N							0.88	0.58	-	-34	117	***						
	S							0.92	1.18	+	29	117	***						
Kigoma	E/W	0.53	0.15	-	-72	90	*	0.43	0.60		39	149	Ns	0.14	0.10		-32	149	Ns
(wind)	N/S	0.03	0.19		489	90	Ns	0.15	0.27		81	149	Ns	0.35	0.67	+	89	149	**
	E	1.94	1.78		-8	90	Ns	1.87	1.94		4	149	Ns	1.60	1.65		3	149	Ns
	W	1.41	1.63	+	16	90	**	1.44	1.34		-7	149	Ns	1.46	1.55		7	149	Ns
	N	0.80	0.93		16	90	Ns	0.85	0.87		2	149	Ns	1.01	1.17	+	16	149	*
	S	0.77	0.74		-3	90	Ns	0.70	0.59	-	-15	149	**	0.65	0.50	-	-23	149	***
Mpulungu	E/W	1.35	1.32		-3	65	Ns												
(lake chain)	N/S	-1.11	-1.13		1	65	Ns												
	E	1.85	1.82		-2	65	Ns												
	W	0.50	0.50		1	65	Ns												
	N	0.86	0.81		-5	65	Ns												
	S	1.97	1.94		-2	65	Ns												
Mpulungu	E/W							0.83	0.97	+	17	209	*						
(weather)	N/S							-1.12	-0.91		-19	209	Ns						
	E							1.19	1.38	+	16	209	***						
	W							0.36	0.40	+	12	209	*						
	N							0.61	0.64		6	209	Ns						
	S							1.73	1.55		-10	209	Ns						

Table 4. Mean daily values of wind speed (m/s), air temperature (°C), solar radiation (W/m2) and wind components (m/s) for Bujumbura, Kigoma and Mpulungu for the dry seasons of 1993, 1994 and 1995 (May - September, Max N = 153 days). Comparisons between years were made when data were available for the same time periods within each year, by student t tests. Ns = non-significant, * = $p < 0.05$, ** = $p<0.01$ and *** = $p<0.001$. For methods of processing wind data see text.

Station	Parameter	**means**		change		N	sign.	**means**		change		N	sign.	**means**		change		N	sign.
		93	94		%			94	95		%			93	95		%		
Bujumbura	air temperature	24.15	24.85	+	3	48	***	24.74	24.51		-1	52	Ns	23.64	24.08	+	2	129	***
(weather)	solar radiation	241	238		-1	48	Ns	236	235		0	51	Ns	224	241	+	8	128	**
	wind speed	3.46	3.32		-4	48	Ns	3.23	3.29		2	52	Ns	3.47	3.41		-2	129	Ns
	E/W	1.07	0.60	-	-44	46	***	0.58	0.57		-2	48	Ns	1.02	0.62	-	-40	125	***
	N/S	-1.40	-1.32		-6	46	Ns	-1.27	-0.93		-27	48	Ns	-1.37	-1.18	-	-14	125	*
	E	1.35	0.90	-	-33	46	***	0.89	0.91		3	48	Ns	1.31	0.94	-	-28	125	***
	W	0.28	0.31		8	46	Ns	0.31	0.34		11	48	Ns	0.29	0.32	+	12	125	**
	N	0.77	0.79		2	46	Ns	0.78	0.98	+	26	48	***	0.78	0.94	+	20	125	***
	S	2.17	2.11		-3	46	Ns	2.05	1.91		-7	48	Ns	2.16	2.12		-2	125	Ns
Kigoma	wind speed	3.95	3.98		1	80	Ns	3.82	3.75		-2	141	Ns	3.95	4.07		3	80	Ns
(wind)	E/W	0.57	0.39		-32	79	Ns	0.54	0.71		31	141	Ns	0.57	0.46		-19	79	Ns
	N/S	0.05	0.01		-75	79	Ns	0.08	0.21		142	141	Ns	0.05	0.26	+	466	79	*
	E	1.98	1.91		-4	79	Ns	1.92	1.99		4	141	Ns	1.98	2.03		2	79	Ns
	W	1.41	1.52		8	79	Ns	1.38	1.28		-7	141	Ns	1.41	1.56	+	11	79	*
	N	0.81	0.79		-2	79	Ns	0.79	0.81		2	141	Ns	0.81	0.87		7	79	Ns
	S	0.76	0.78		2	79	Ns	0.71	0.60	-	-15	141	**	0.76	0.61	-	-21	79	**
(lake chain)	air temperature							25.66	25.69		0	64	Ns						
Mpulungu	air temperature	24.62	24.81		1	148	Ns	24.80	25.13	+	1	147	**	24.65	25.15	+	2	152	***
(lake chain)	wind speed	5.04	4.86		-4	148	Ns	4.84	4.59		-5	147	Ns	5.07	4.61		-9	152	**
	E/W	1.83	2.10		15	11	Ns												
	N/S	-1.57	-1.08		-31	11	Ns												
	E	2.34	2.46		5	11	Ns												
	W	0.51	0.36		-30	11	Ns												
	N	0.76	0.85		12	11	Ns												
	S	2.33	1.93		-17	11	Ns												
Mpulungu	wind speed							3.38	3.39		0	138	Ns						
(weather)	E/W							1.07	1.28	+	20	134	**						
	N/S							-1.62	-1.39		-14	134	Ns						
	E							1.40	1.64	+	18	134	***						
	W							0.33	0.36		10	134	Ns						
	N							0.54	0.54		0	134	Ns						
	S							2.15	1.93	-	-10	134	*						

Table 5. Mean daily values of wind speed (m/s), air temperature (°C), solar radiation (W/m2) and wind components (m/s) for Bujumbura, Kigoma and Mpulungu for the wet seasons of 1993, 1994 and 1995 (October - April, Max N = 212 days). Comparisons between years were made when data were available for the same time periods within each year, by student t tests. Ns = non-significant, * = $p<0.05$, ** = $p<0.01$ and *** = $p<0.001$. For methods of processing wind data see text.

Station	Parameter	means		change		N	sign.	means		change		N	sign.	means		change		N	sign.
		92-93	93-94		%			93-94	94-95		%			94-95	95-96		%		
Bujumbura	air temperature	23.32	23.43		0	50	Ns	23.43	23.56		1	192	Ns	23.30	23.61	+	1	74	*
(weather)	solar radiation	219	234		7	50	Ns	208	222	+	7	191	*	221	225		2	73	Ns
	wind speed	2.58	2.67		4	50	Ns	2.74	2.94	+	7	193	**	3.08	3.08		0	74	Ns
	E/W	0.43	0.49		15	48	Ns	0.57	0.33	-	-41	187	***	0.52	0.70	+	33	72	**
	N/S	-0.38	-0.36		-6	48	Ns	-0.51	-0.43		-15	187	Ns	-0.66	-0.82		24	72	Ns
	E	0.80	0.85		5	48	Ns	0.93	0.73	-	-21	187	***	0.85	0.99	+	16	72	**
	W	0.38	0.36		-6	48	Ns	0.36	0.40	+	12	187	**	0.33	0.30		-10	72	Ns
	N	0.87	0.93		7	48	Ns	0.87	1.02	+	17	187	***	1.00	0.92	-	-8	72	*
	S	1.25	1.29		3	48	Ns	1.38	1.45		5	187	Ns	1.66	1.74		5	72	Ns
Kigoma	wind speed							3.63	4.36	+	20	11	*	4.38	4.29		-2	8	Ns
(wind)	E/W							0.20	-1.58	-	-900	11	***	-1.52	-1.34		-12	8	Ns
	N/S							-0.08	1.44	-	-2020	11	**	1.33	1.50		13	8	Ns
	E							1.63	0.88	-	-46	11	***	0.94	0.95		1	8	Ns
	W							1.43	2.46	+	71	11	***	2.47	2.29		-7	8	Ns
	N							0.73	1.91	+	161	11	**	1.82	1.89		4	8	Ns
	S							0.81	0.46	-	-42	11	*	0.49	0.39		-20	8	Ns
(lake chain)	air temperature							25.11	25.17		0	58	Ns	24.44	24.96	+	2	83	***
	E/W							0.90	-0.03	-	-103	57	***	-0.29	0.59	-	-308	60	***
	N/S							0.31	-0.36	-	-214	57	**	-0.36	-0.82	+	126	60	***
	E							1.64	0.60	-	-63	57	***	0.56	1.37	+	145	60	***
	W							0.74	0.63		-15	57	Ns	0.85	0.78		-8	60	Ns
	N							1.24	0.56	-	-55	57	***	0.54	0.60		11	60	Ns
	S							0.93	0.92		-1	57	Ns	0.90	1.42	+	57	60	***
Mpulungu	air temperature	25.81	25.74		0	55	Ns	25.79	25.81		0	211	Ns	26.48	26.52		0	27	Ns
(lake chain)	wind speed	3.85	3.80		-1	55	Ns	3.50	3.47		-1	211	Ns	3.50	3.37		-4	89	Ns
	E/W	1.26	1.16		-8	54	Ns												
	N/S	-1.02	-1.14		12	54	Ns												
	E	1.76	1.69		-4	54	Ns												
	W	0.50	0.53		7	54	Ns												
	N	0.88	0.80		-8	54	Ns												
	S	1.90	1.94		2	54	Ns												
Mpulungu	wind speed													2.24	2.41	+	8	74	**
(weather)	E/W													0.38	0.42		9	74	Ns
	N/S													-0.18	-0.03	-	-81	74	*
	E													0.80	0.90	+	11	74	**
	W													0.42	0.48	+	14	74	*
	N													0.74	0.84	+	12	74	*
	S													0.93	0.87		-6	74	Ns

Station	Parameter	means		change		N	sign.	means		change		N	sign.
		93-94	95-96		%			92-93	94-95		%		
Bujumbura	air temperature	23.87	23.59	-	-1	92	*	23.29	23.72	+	2	48	*
(weather)	solar radiation	216	221		2	92	Ns	219	227		4	48	Ns
	wind speed	3.12	3.03		-3	92	Ns	2.57	2.79		9	49	Ns
	E/W	0.87	0.62	-	-29	92	***	0.43	0.31		-28	45	Ns
	N/S	-0.96	-0.71	-	-26	92	*	-0.39	-0.34		-15	45	Ns
	E	1.19	0.94	-	-21	92	***	0.81	0.71		-13	45	Ns
	W	0.32	0.33		2	92	Ns	0.38	0.39		3	45	Ns
	N	0.81	0.94	+	17	92	***	0.87	1.04	+	19	45	**
	S	1.77	1.65		-7	92	Ns	1.26	1.37		9	45	Ns
Kigoma	wind speed	3.40	3.61		6	70	Ns						
(wind)	E/W	-0.35	-0.32		-9	70	Ns						
	N/S	0.70	1.13	+	61	70	*						
	E	1.16	1.22		6	70	Ns						
	W	1.51	1.55		2	70	Ns						
	N	1.23	1.51	+	23	70	*						
	S	0.52	0.38	-	-28	70	**						
Mpulungu	air temperature	26.68	26.52		-1	27	Ns	25.80	26.07		1	54	Ns
(lake chain)	wind speed	3.74	3.37	-	-10	89	**	3.87	4.03		4	54	Ns

Table 6. Maxima for wind vector components. Maximum monthly means, and the maximum wind vector components over the day are given (m/sec). Also annual means are shown.

	Maximum monthly means				**Maxima over the day**			
	Bujumbura	Kigoma wind station	Mpulungu lake buoy	Mpulungu weather station	Bujumbura	Kigoma wind station	Mpulungu lake buoy	Mpulungu weather station
East	1.4	2.5	3.0	1.8	3.0	5.4	5.7	2.9
West	0.5	2.4	1.1	0.5	1.2	8.4	2.4	2.5
North	1.1	2.0	1.3	0.9	2.0	2.9	4.4	3.6
South	2.5	0.8	3.4	2.9	7.4	3.0	6.2	4.2

annual means:

	Bujumbura	Kigoma wind station	Mpulungu lake buoy	Mpulungu weather station
East	0.8	1.6	1.8	1.2
West	0.4	1.4	0.7	0.4
North	1.0	1.1	0.9	0.6
South	1.7	0.5	2.0	1.4
sum	3.9	4.5	5.4	3.5

Table 7. Matrix of Spearman's correlation coefficients comparing temperatures measured once per hour at various depths between 8 March 1993 - 12 May 1994 (n = 10332). All correlation coefficients are significantly different from zero at $P < 0.001$, excluding those marked by an asterisk (also not significant for $P < 0.01$).

	5 m	30 m	50 m	70 m	90 m	110 m	150 m	200 m	250 m	300 m
1 m	0.9924	0.9076	0.7780	0.7776	0.7111	0.5684	0.1122	-0.0708	0.0195*	0.1638
5 m		0.9193	0.7866	0.7898	0.7258	0.5816	0.1163	-0.0697	0.0217*	0.1711
30 m			0.8696	0.8395	0.7573	0.6035	0.1479	-0.0655	0.0181*	0.1560
50 m				0.9264	0.8361	0.7096	0.2589	0.0184*	0.0760	0.1319
70 m					0.9367	0.8134	0.3085	0.0404	0.1022	0.1833
90 m						0.8857	0.3495	0.0845	0.1574	0.2449
110 m							0.5295	0.2034	0.2359	0.3183
150 m								0.5684	0.4216	0.3988
200 m									0.7625	0.6236
250 m										0.7530

Table 8. Mean daily values of water temperatures (°C) at different depths for Kigoma and Mpulungu for the dry seasons mof 1993, 1994 and 1995 (May - September, Max N = 153 days). Comparisons between years were made when data were available for the same time periods within each year, by student t tests. Ns = non-significant, * = p<0.05, ** = p<0.01 and *** = p<0.001.

Buoy	Depth	**means**		change		N	sign.	**means**		change		N	sign.	**means**		change		N	sign.
		93	94		°C			94	95		°C			93	95		°C		
Mpulungu	1 m	24.91	24.97		0.05	146	Ns	24.96	25.25	+	0.29	145	**	24.98	25.32	+	0.34	152	***
	5 m	24.82	24.81		-0.02	146	Ns	24.80	25.16	+	0.36	145	***	24.89	25.23	+	0.35	152	***
	30 m													24.63	24.99	+	0.36	152	***
	50 m													24.30	24.59	+	0.29	152	***
	90 m													24.01	24.23	+	0.22	152	***
	110 m													23.94	24.07	+	0.14	152	***
	150 m													23.81	23.79	-	-0.02	152	*
	200 m													23.58	23.62	+	0.04	152	***
	300 m													23.40	23.41	+	0.02	152	***
Kigoma	1 m							26.46	26.67	+	0.21	64	*						
	5 m							26.43	26.63	+	0.20	64	*						
	15 m							26.36	26.57	+	0.21	64	*						
	30 m							26.24	26.46	+	0.22	64	*						
	50 m							25.84	25.95		0.10	64	Ns						
	70 m							24.86	24.99	+	0.12	64	*						
	90 m							24.26	24.30	+	0.04	64	*						
	110 m							24.07	24.05		-0.02	64	Ns						
	150 m							23.85	23.82	-	-0.04	64	***						
	200 m							23.59	23.60		0.01	64	Ns						
	300 m							23.43	23.44	+	0.01	64	*						

Table 9. Mean daily values of water temperatures (°C) at different depths for Kigoma and Mpulungu for the wet seasons of 1993, 1994 and 1995 (October - April, Max N = 212 days). Comparisons between years were made when data was available for the same time periods within each year, by student t tests. Ns = non-significant, * = p<0.05, ** = p<0.01 and *** = p<0.001.

Buoy	Depth	**means**		change		N	sign.	**means**		change		N	sign.	**means**		change		N	sign.
°C		92-93	93-94		°C			93-94	94-95		°C			94-95	95-96		°C		
Mpulungu	1 m	27.06	27.24	+	0.18	55	***	27.16	27.18		0.02	211	Ns	27.09	27.66	+	0.57	91	***
	5 m	26.95	27.11	+	0.17	55	***	27.05	27.06		0.02	211	Ns	26.98	27.57	+	0.59	91	***
	30 m	26.23	26.31		0.08	55	Ns												
	50 m	25.11	24.90	-	-0.21	55	**												
	70 m	24.40	24.38		-0.02	55	Ns												
	90 m	24.13	24.14		0.01	55	Ns												
	110 m	23.99	24.00		0.01	55	Ns												
	150 m	23.82	23.82		0.01	55	Ns												
	200 m	23.56	23.59	+	0.03	55	***												
	250 m	23.44	23.46	+	0.01	55	**												
	300 m	23.39	23.41	+	0.02	55	***												
Kigoma	1 m							27.05	27.11		0.06	58	Ns	26.26	26.58	+	0.31	83	***
	5 m							26.96	27.00		0.04	58	Ns	26.17	26.47	+	0.29	83	***
	15 m							26.87	26.86		-0.01	58	Ns	26.05	26.37	+	0.31	83	***
	30 m							26.54	26.61		0.07	58	Ns	25.78	26.14	+	0.35	83	***
	50 m							25.78	26.04	+	0.25	58	***	24.91	25.24	+	0.33	83	***
	70 m							24.55	24.91	+	0.36	58	***	24.49	24.68	+	0.18	83	***
	90 m							24.22	24.26	+	0.05	58	***	24.19	24.33	+	0.14	83	***
	110 m							24.04	24.04		0.00	58	Ns	24.04	24.11	+	0.07	83	***
	150 m							23.83	23.86	+	0.02	58	***	23.86	23.85		0.00	83	Ns
	200 m							23.58	23.61	+	0.02	58	***	23.60	23.59		-0.01	83	Ns
	300 m							23.41	23.43	+	0.02	58	***	23.43	23.44	+	0.01	83	**

Buoy	Depth	**means**		change		N	sign.	**means**		change		N	sign.
		93-94	95-96		°C			92-93	94-95		°C		
Mpulungu	1 m	27.04	27.66	+	0.62	91	***	27.05	27.04		-0.02	54	Ns
	5 m	26.94	27.57	+	0.63	91	***	26.95	26.92		-0.03	54	Ns
	30 m	26.35	26.95	+	0.60	91	***						
	50 m	24.93	26.13	+	1.20	91	***						
	70 m												
	90 m	24.17	24.44	+	0.27	91	***						
	110 m	24.03	24.16	+	0.13	91	***						
	150 m	23.85	23.82	-	-0.03	91	*						
	200 m	23.55	23.63	+	0.07	91	***						
	250 m												
	300 m	23.40	23.44	+	0.04	91	***						

Table 10. Maximum and mean daily change in depth (m) of isotherms for the Kigoma and Mpulungu buoys. Kig = Kigoma, 3 may 1994 - 31 December 1995, Mp1 = Mpulungu, 7 March 1993 - 11 May 1994, Mp2 =Mpulungu, 2 May 1995 - 31 May 1996.

	max			mean			stdv			n		
Isotherms °C	Kig	Mp1	Mp2	Kig	Mp1	Mp2	Kig	Mp1	Mp2	Kig	Mp1	Mp2
27	14	16	18	3	3	3	3	4	4	134	179	183
26.5	21	25	18	3	3	2	3	3	2	305	258	227
26	14	15	16	3	2	2	3	3	3	496	302	267
25.5	17	12	11	2	2	2	2	2	2	567	319	278
25	13	15	28	2	2	3	2	2	3	567	336	327
24.5	12	31	28	2	3	4	2	3	4	567	358	369
24	16	63	15	4	5	3	3	6	3	567	426	390
23.75	21	29	23	4	4	5	3	4	5	567	430	390
23.5	46	27	48	7	6	8	6	5	7	567	430	390

APPENDIX II

FORMULAE

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

with

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

In table 11, 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 explanations of terms A - D, see formulae.

A	B	C	D	Components of the wind vectors				Actual mean wind speed of each wind component			
Wind direction	Wind speed (m/s)	E/W	N/S	East	West	North	South	East	West	North	South
0	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

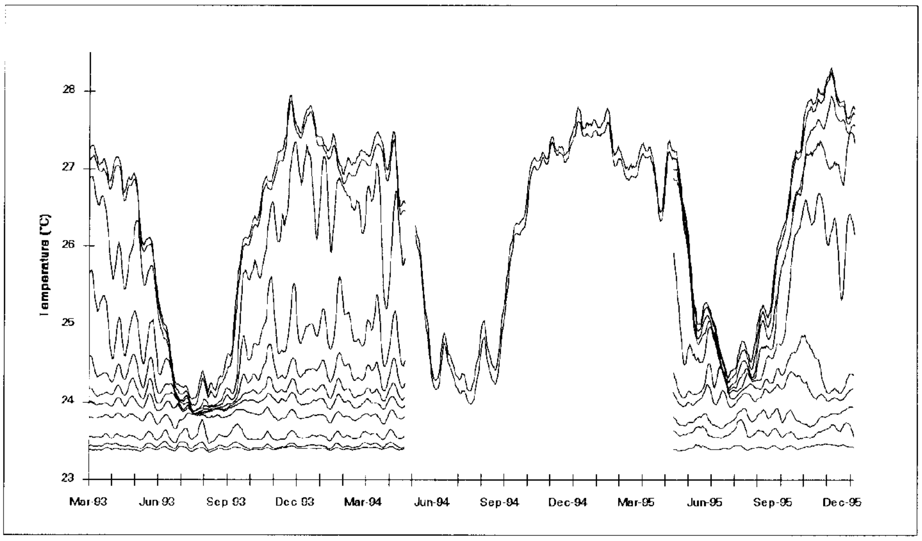


Figure A.III.1. Seven day running averages of water temperatures at the Mpulungu buoy. Water depths were 1,5, 30, 50, 70, 90, 110, 150, 200, 250 and 300 m up to May 1994, 1, 5, 15, 30, 50, 90, 110, 150, 200 and 300 m from May 1995, and 1 and 5 m during the period in between.

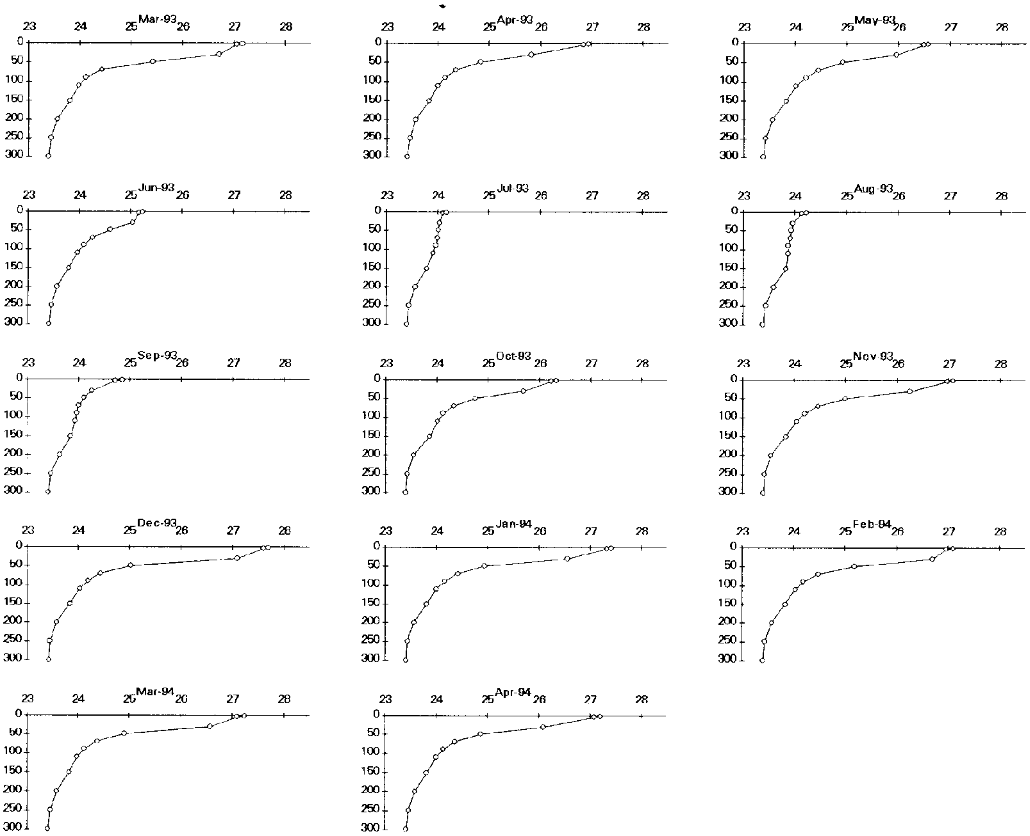


Figure A.III.2. Depth distribution of temperature at the Mpulungu buoy, for March 1993 to April 1994.

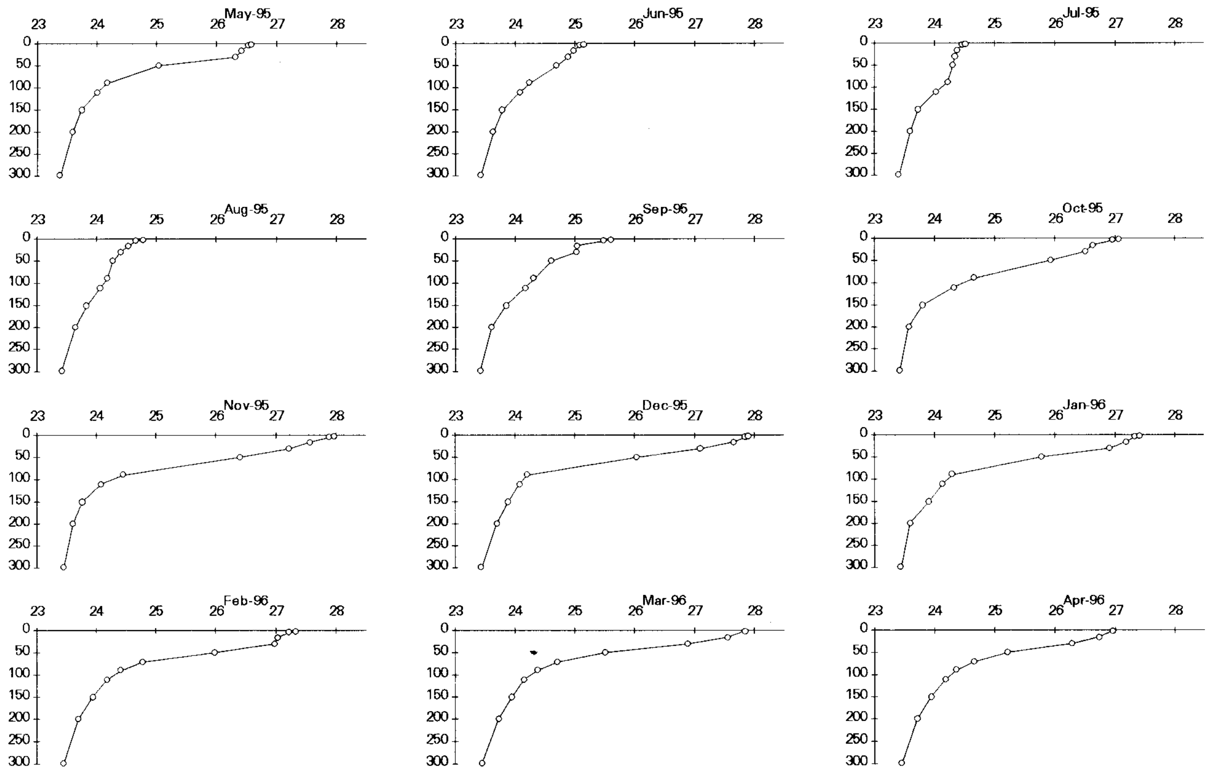


Figure A.III.3. Depth distribution of temperature at the Mpulungu buoy, for May 1995 to April 1996.

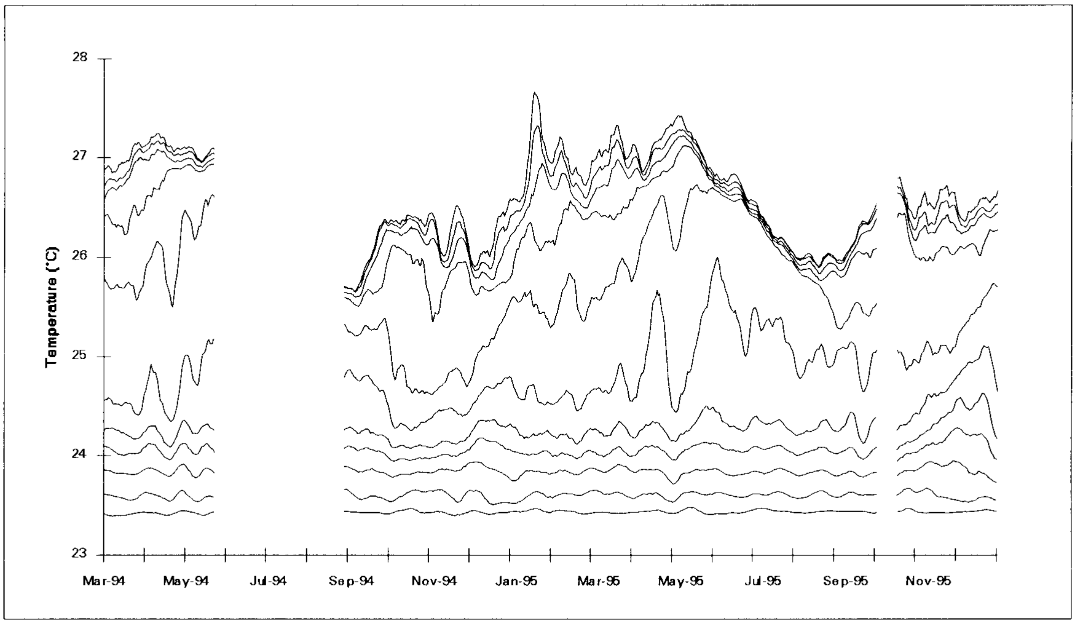


Figure A.III.4. Seven day running averages of water temperatures at the Kigoma buoy. Water depths were 1,5, 15, 30, 50, 70, 90, 110,150, 200 and 300 m.

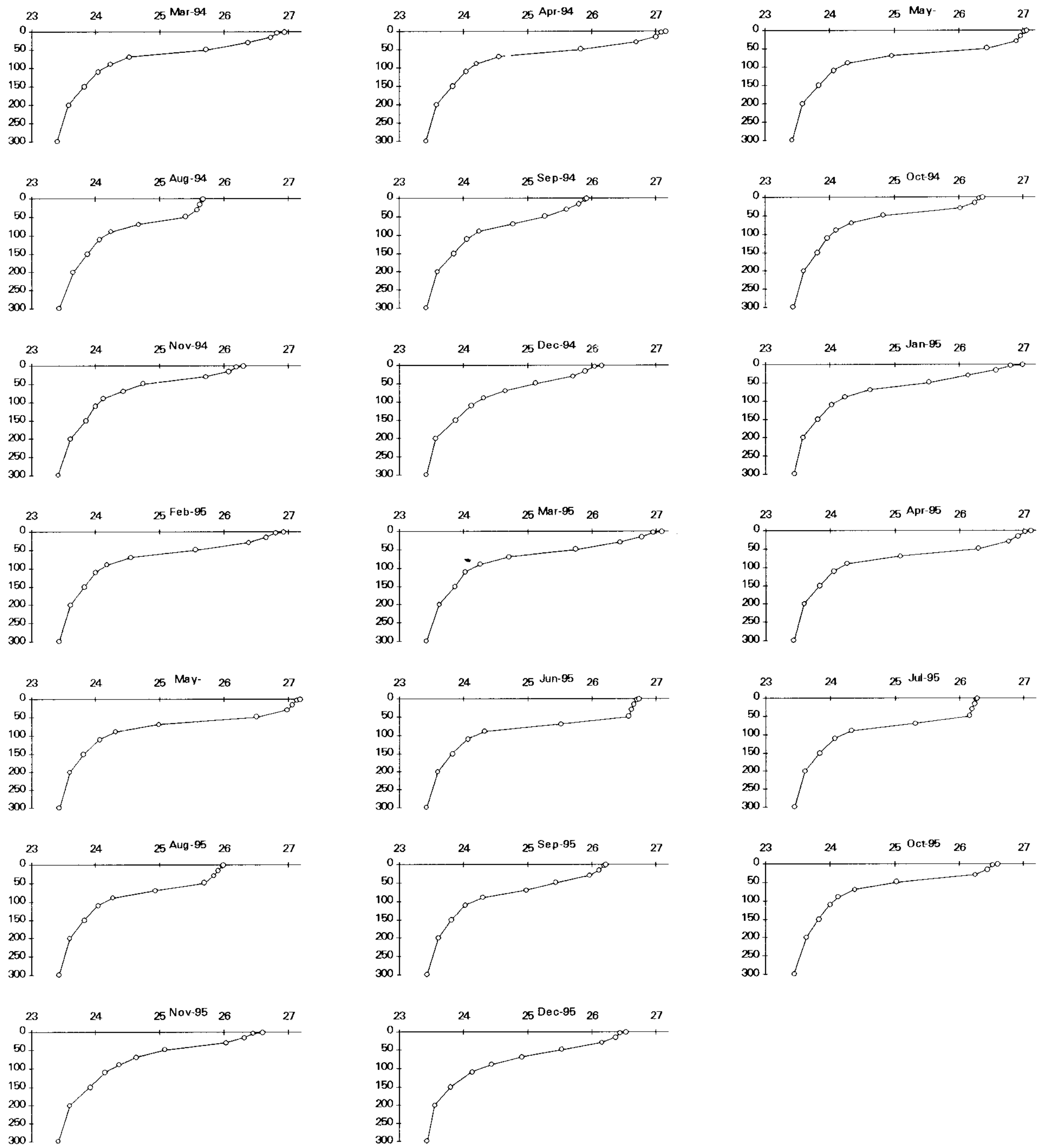


Figure A.III.5. Monthly mean depth distribution of temperature at the Kigoma buoy.

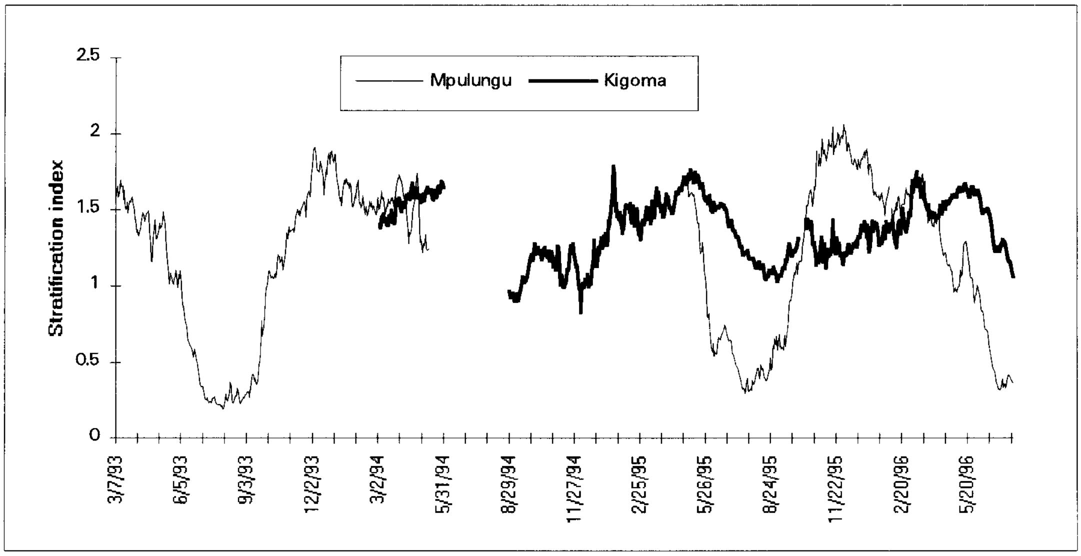


Figure A.III.6. The daily stratification index (standard deviation of temperatures at different depths) for the Mpulungu and Kigoma Buoys.

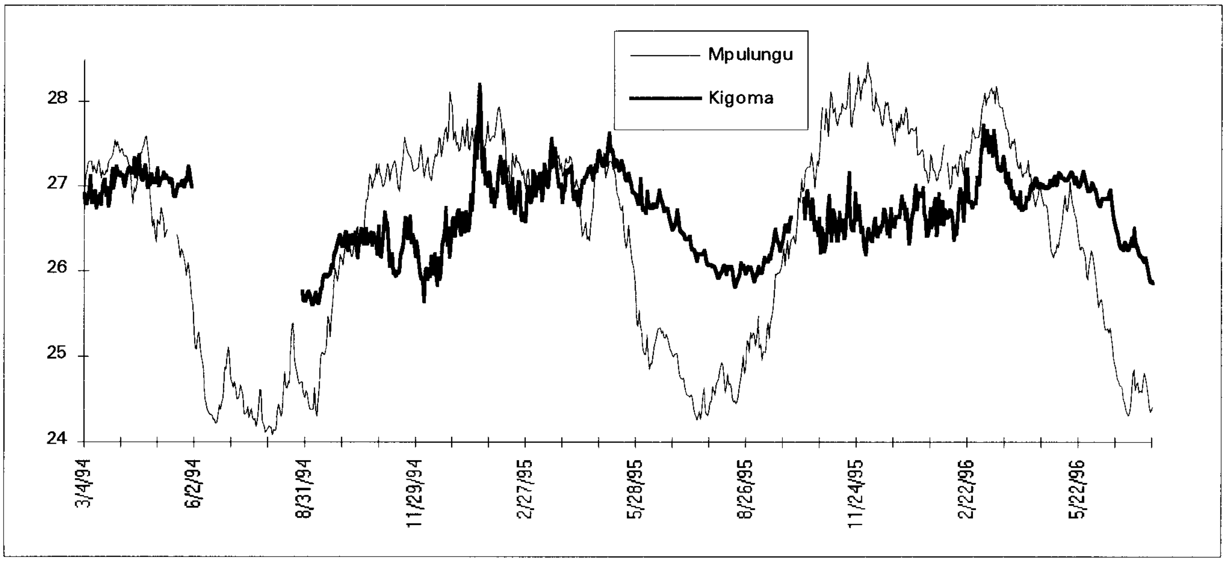


Figure A.III.7. Daily means of water temperature at the Mpulungu and Kigoma Buoys at 1 m depth.

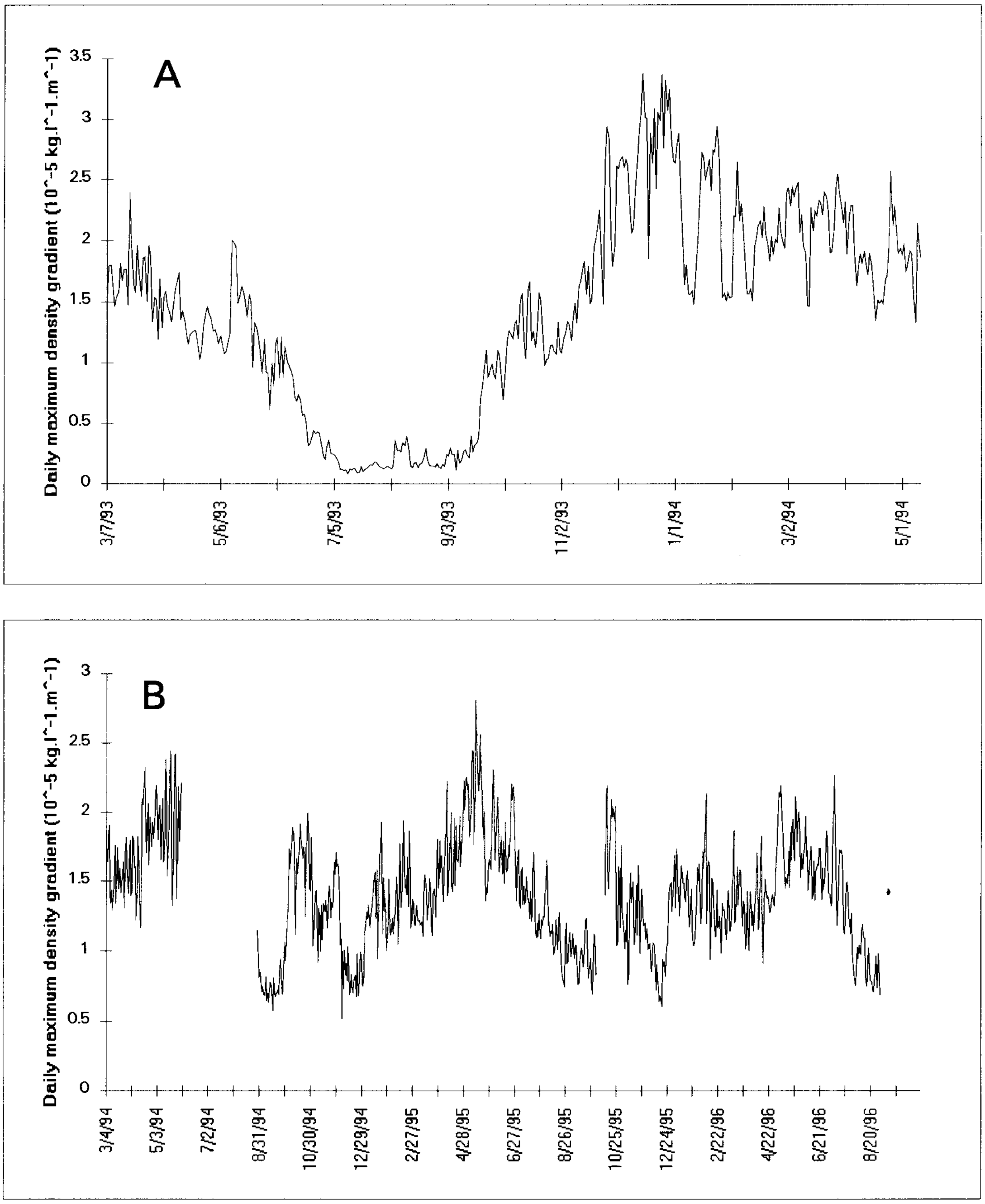


Figure A.III.8. Density gradient over the thermocline, for daily mean temperatures. A: the Mpulungu buoy (March 1993 - May 1994), B: the Kigoma buoy (March 1994 - August 1996).

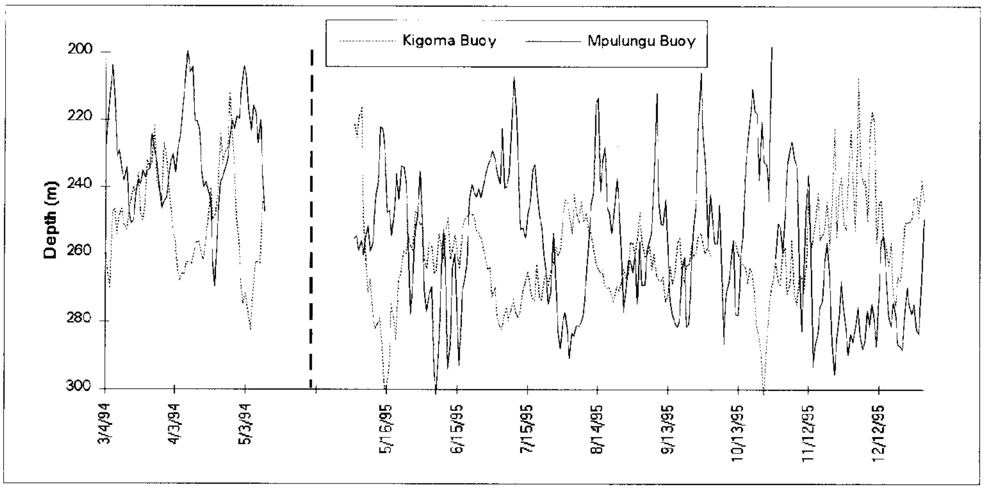


Figure A.III.9A. Depths of the 23.5° C isotherm at the Kigoma and Mpulungu Buoys.

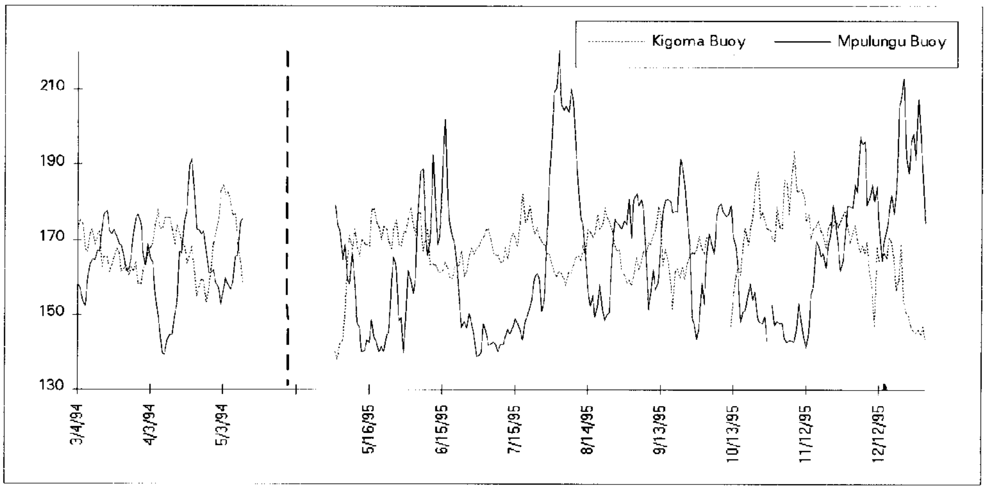


Figure A.III.9B. Depths of the 23.75° C isotherm at the Kigoma and Mpulungu Buoys.

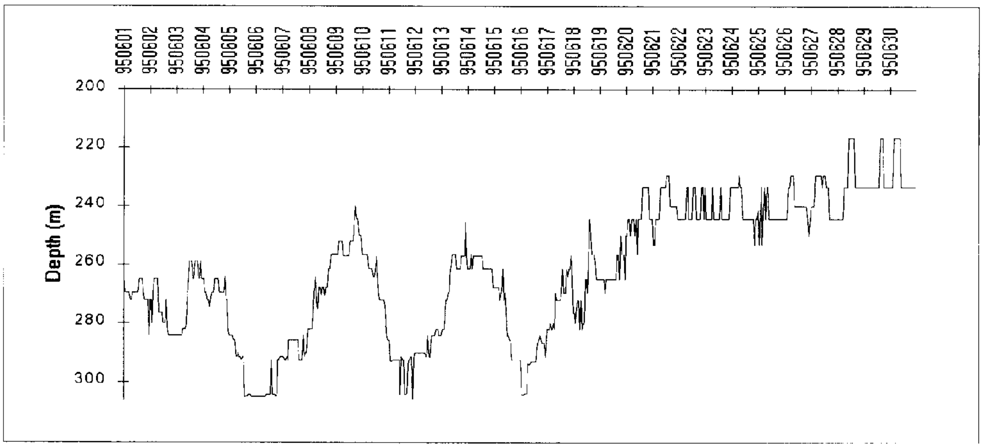


Figure A.III.10. Depth of the 23.5° C isotherm in June 1995 at the Mpulungu Buoy, every hour.

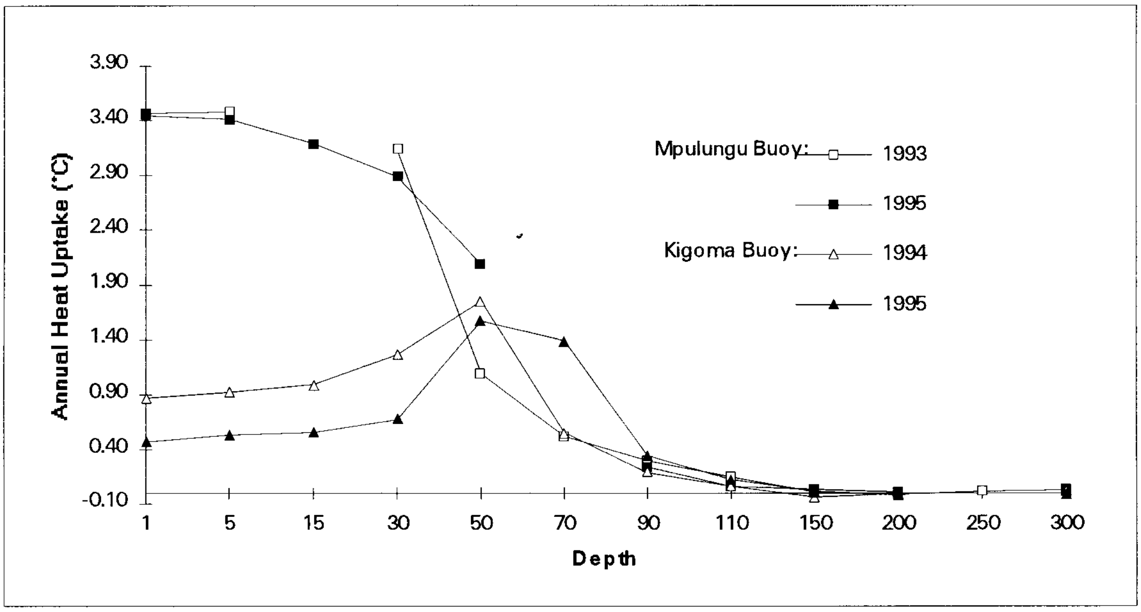


Figure A.III.11. Annual heat uptake (°C), between minimum and maximum heat content at the Mpulungu and Kigoma buoys, versus depth.

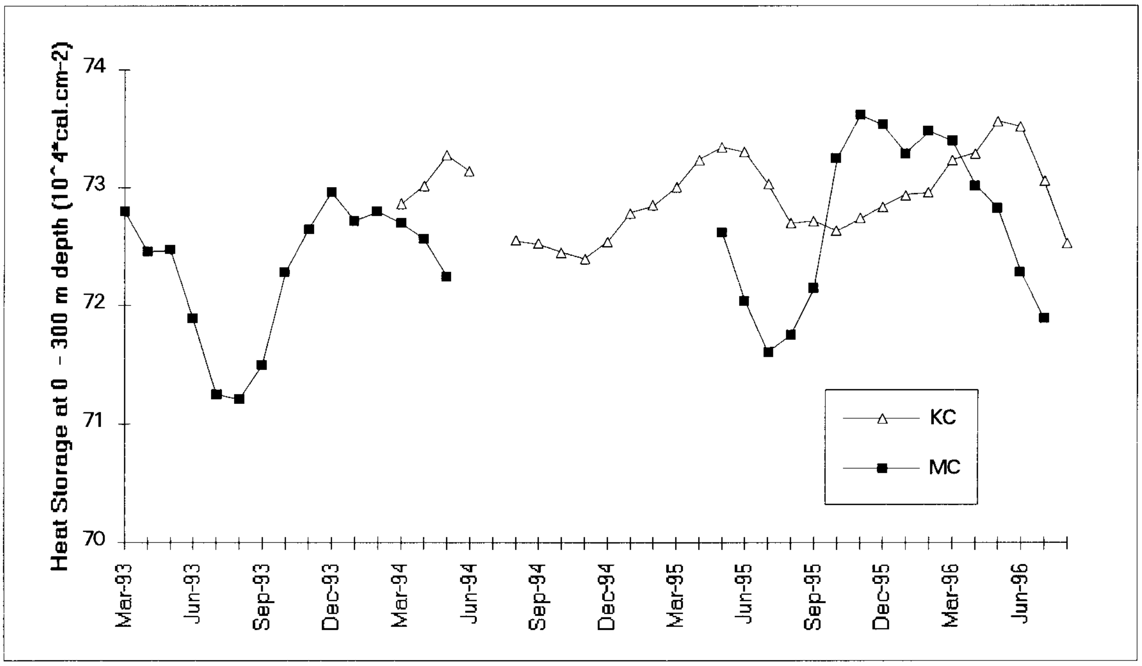
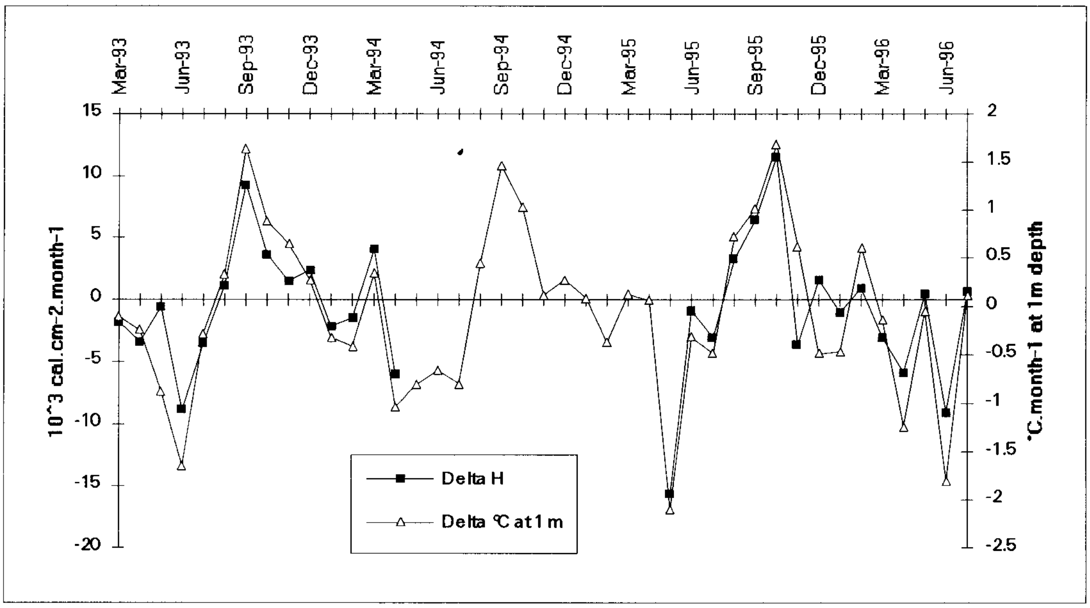


Figure A.III.12. Monthly mean heat content down to 300 m, at the Mpulungu (MC) and Kigoma (KC) buoys.

A. Mpulungu buoy



B. Kigoma buoy

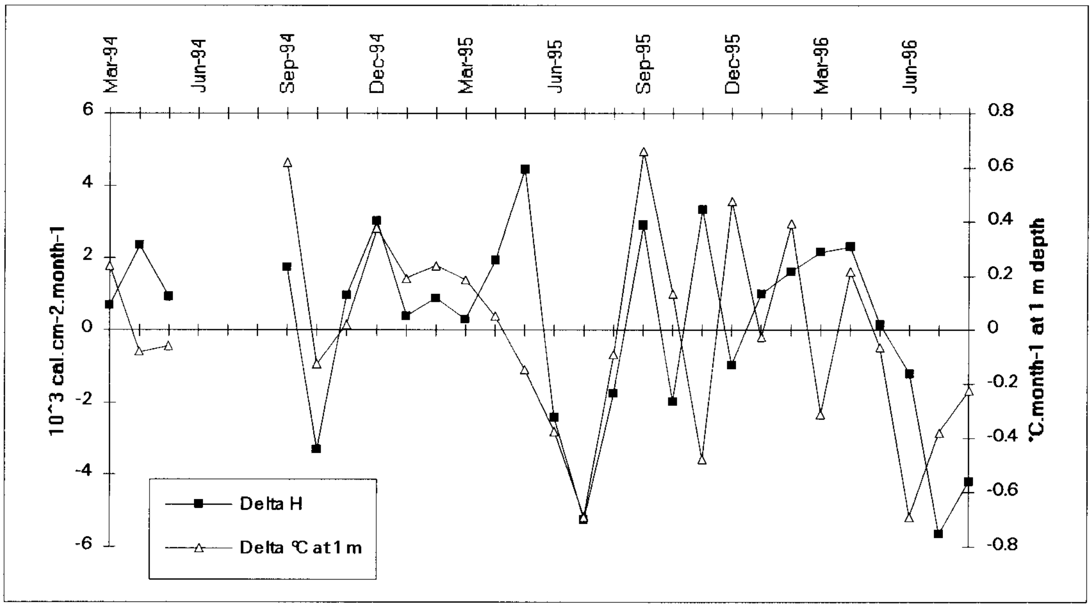


Figure A.III.13. Monthly change in heat storage in upper 150 m and in temperature at 1 m depth: A, Mpulungu buoy and B, Kigoma Buoy

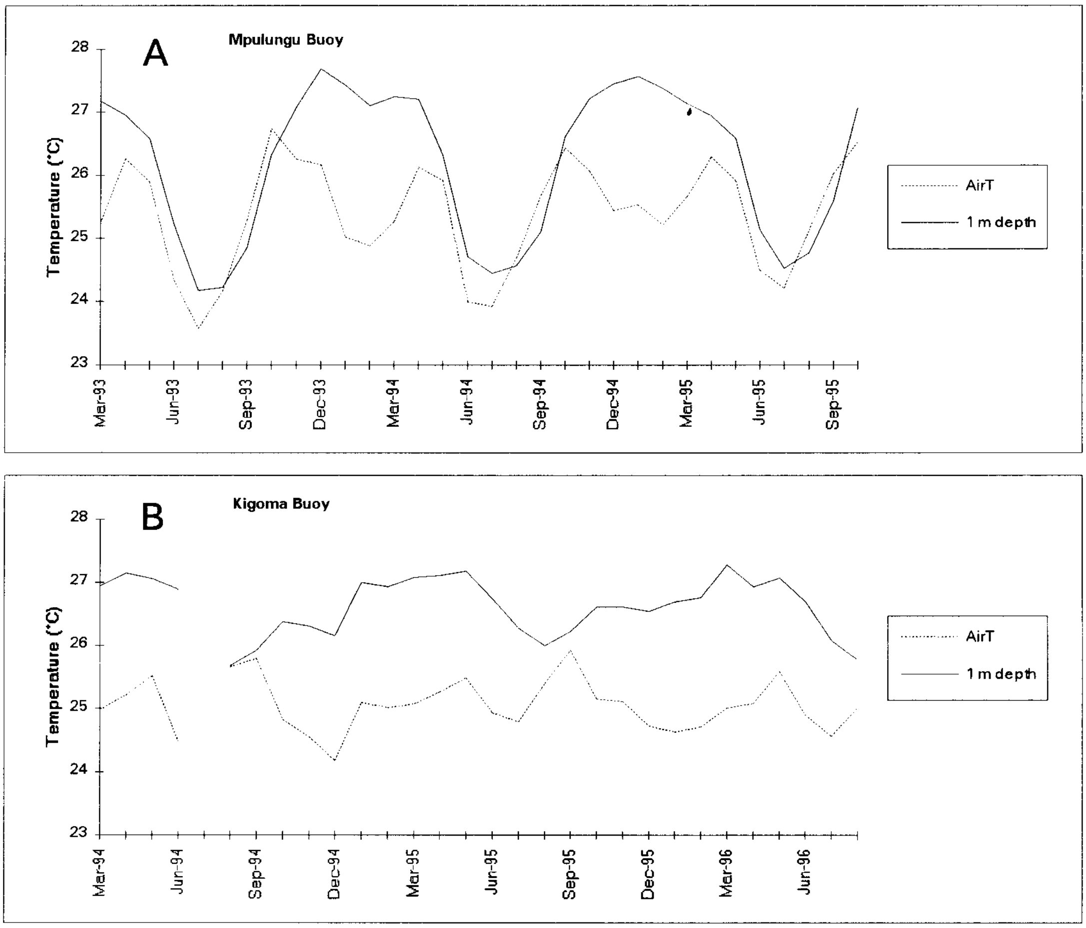


Figure A.III.14. Monthly mean air temperature and water temperature at 1 m depth at the Mpulungu (A) and Kigoma Buoys (B).

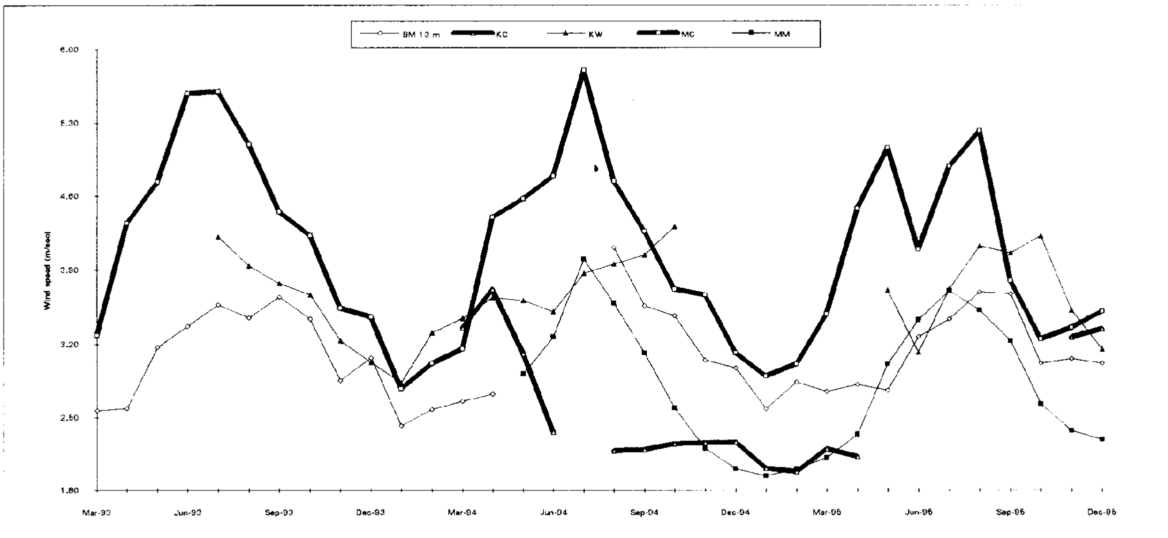


Figure A.IV.1.1. Mean monthly wind speed for Bujumbura weather station (open diamonds), Kigoma buoy and land-based wind station (open and closed triangles), and Mpulungu buoy and land-based weather station (open and closed squares), for 1 March 1993 - 31 December 1995.

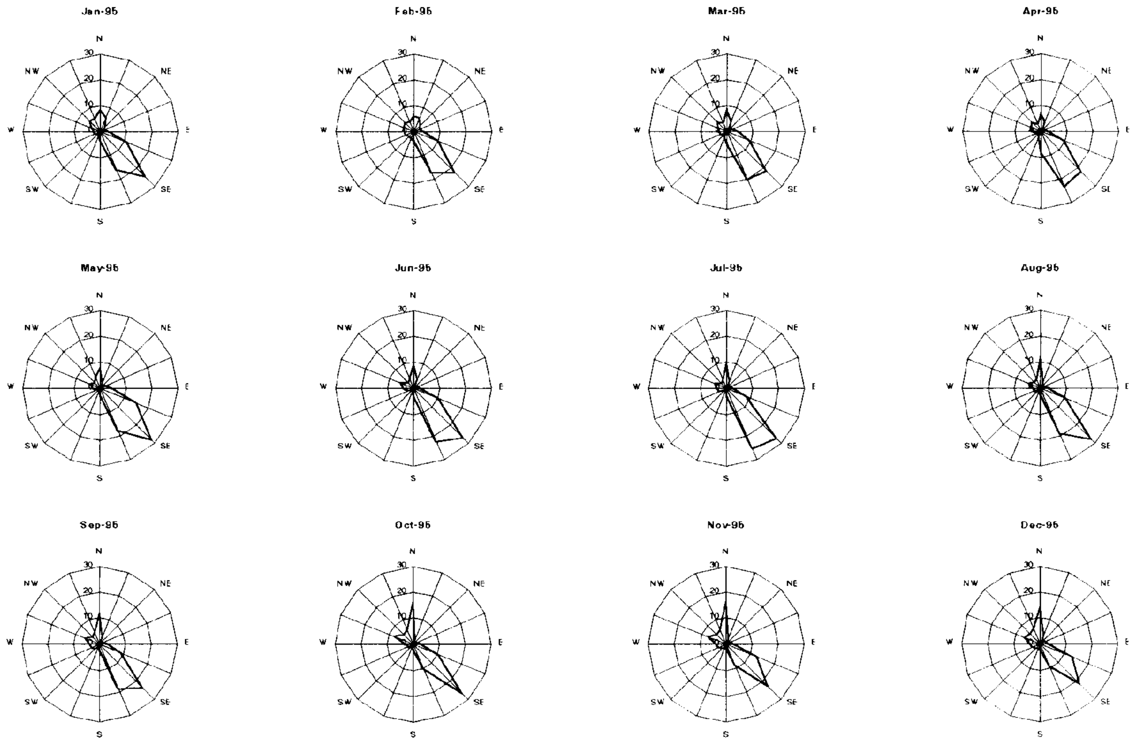


Figure A.IV.2.1. Wind direction distribution (%) on a monthly basis January - December 1995 at Mpulungu wind station.

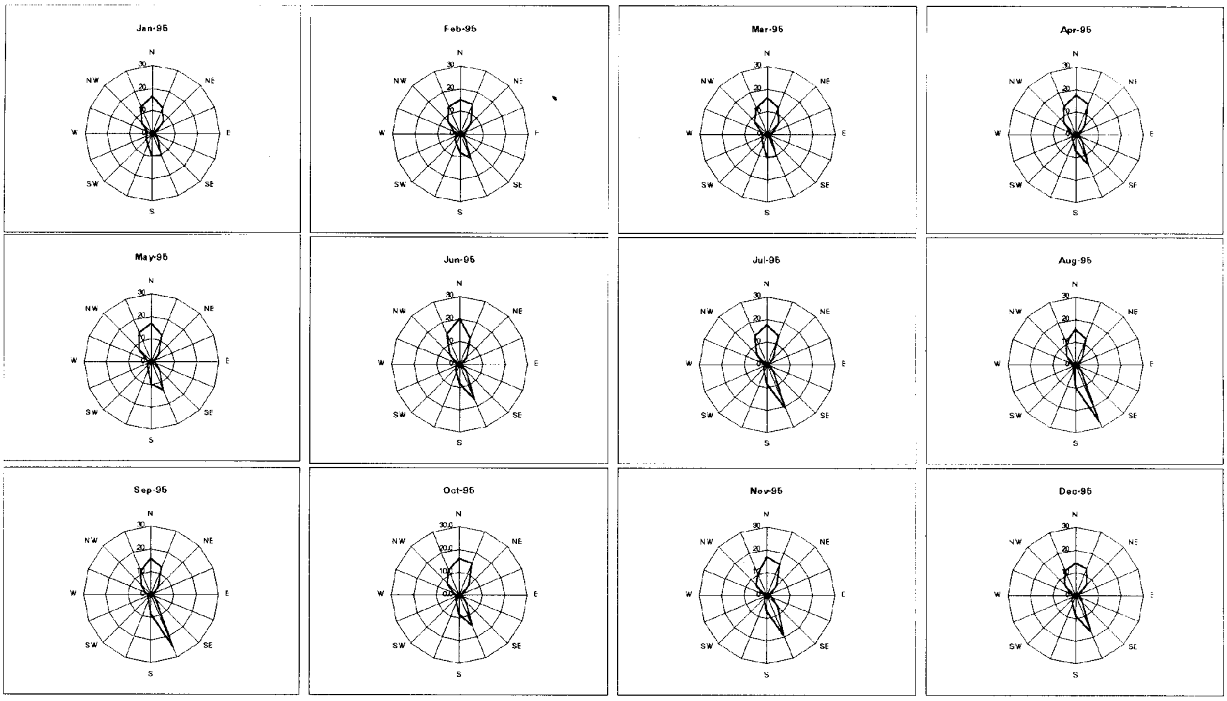


Figure A.IV.2.2. Wind direction distributions (%) on a monthly basis January - December1995, at Bujumbura weather station.

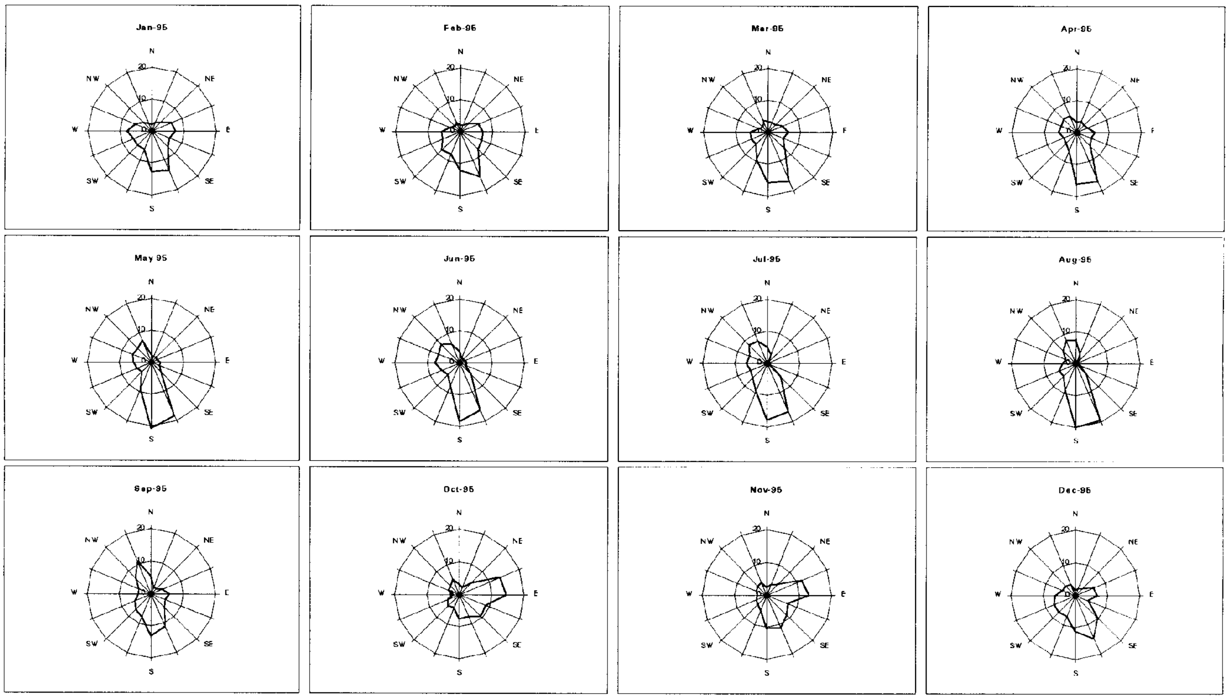


Figure A.IV.2.3. Wind direction distributions (%) on a monthly basis January - December 1995 at the Kigoma buoy.

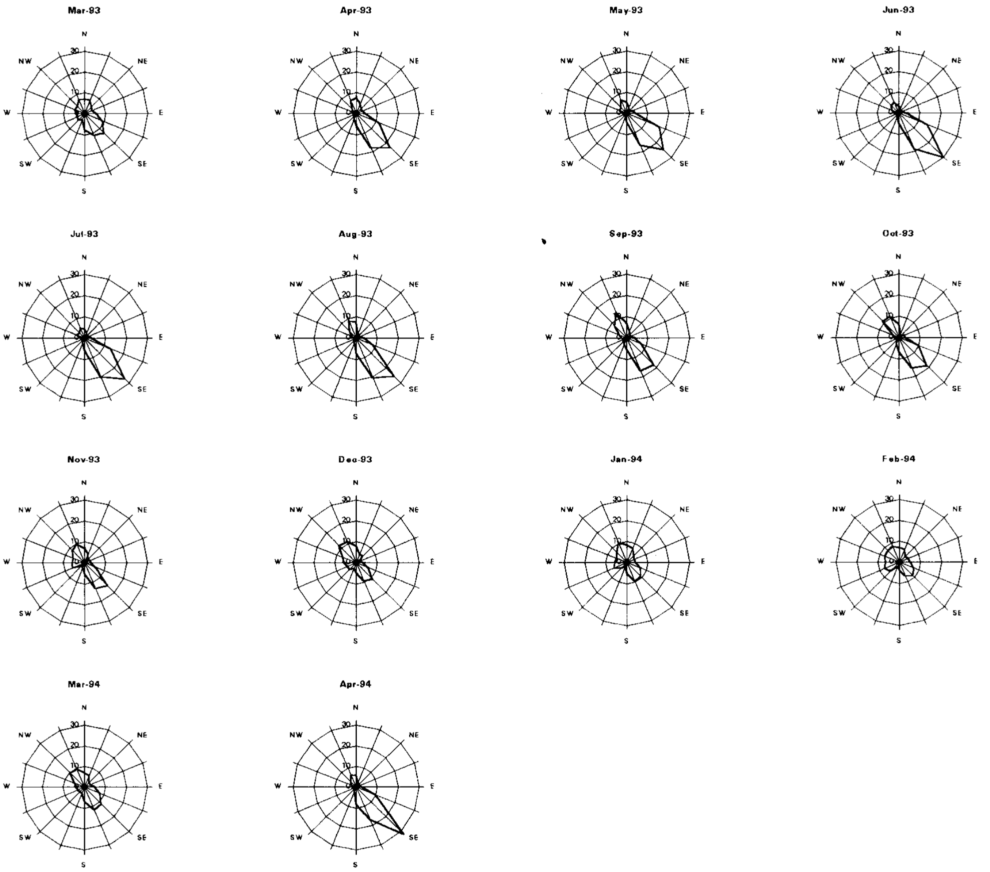


Figure A.IV.2.4. Wind direction distributions (%) on a monthly basis March 1993 - April 1994 at the lake meteo buoy off Mpulungu.

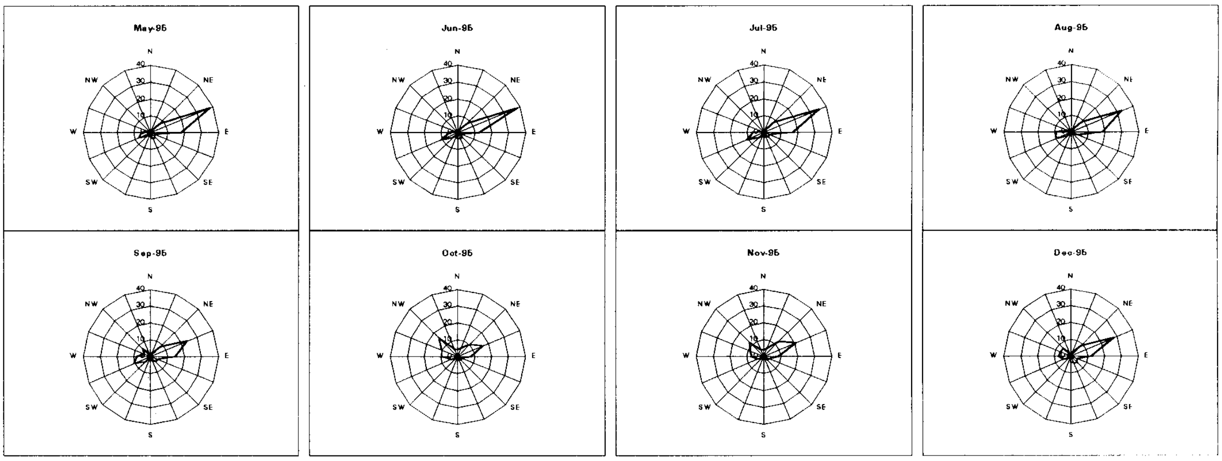


Figure A.IV.2.5. Wind distributions (%) on a monthly basis May - december 1995 at Kigoma wind station.

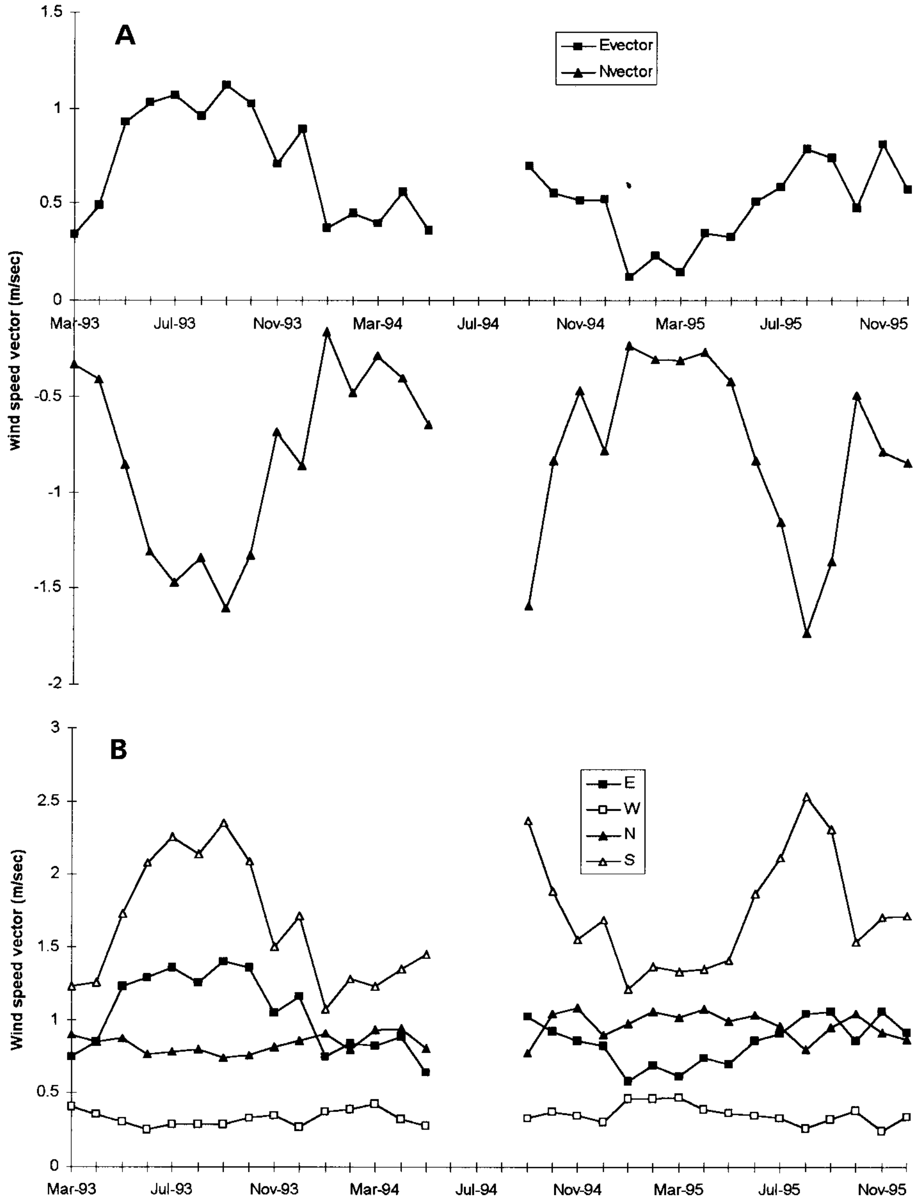


Figure A.IV.3.1. Mean monthly wind speed vector components of Bujumbura meteorological station, separate for 2 (A) and 4 (B) wind directions.

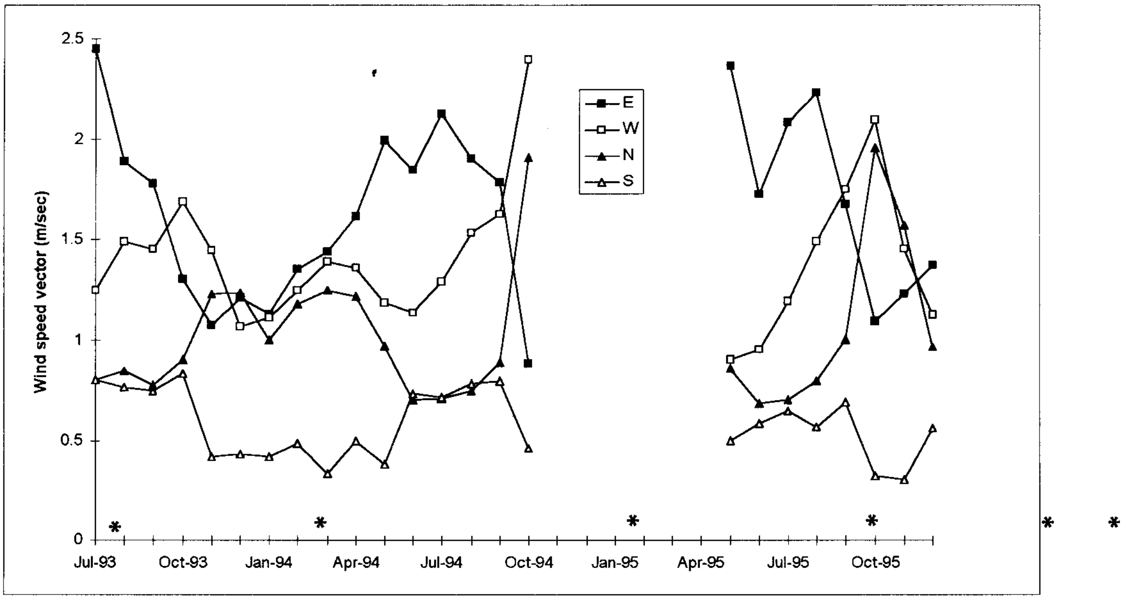


Figure A.IV.3.2. Mean monthly wind vector components at Kigoma wind station. Months with gaps in the data are indicated with an asterisk.

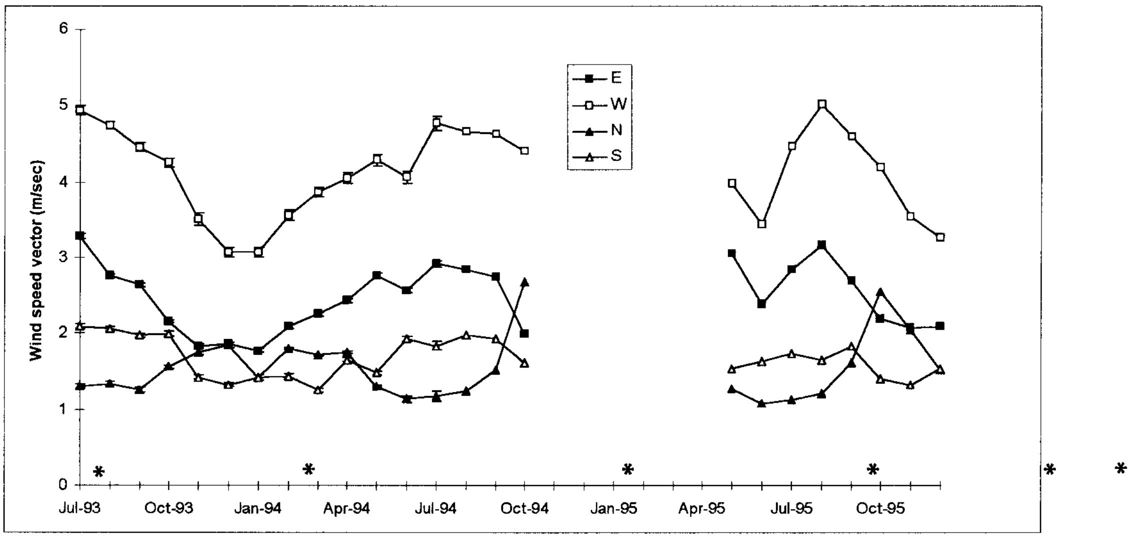


Figure A.IV.3.3. Mean monthly wind vector components at Kigoma wind station, averaged only over periods in which wind was actually blowing from a particular direction.

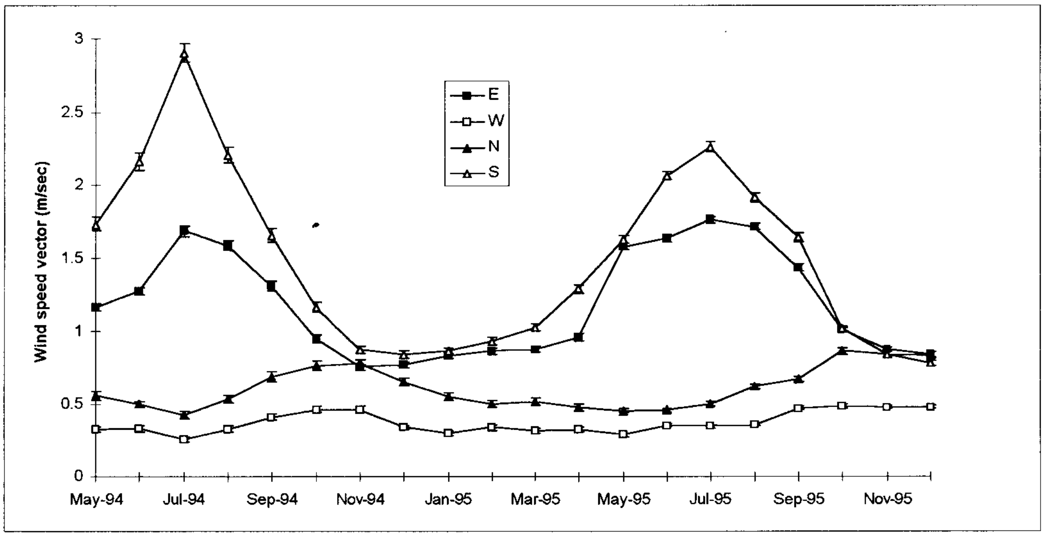


Figure A.IV.3.4. Mean monthly wind speed vector components at the Mpulungu weather station Error bars are shown, but often to small to be visible.

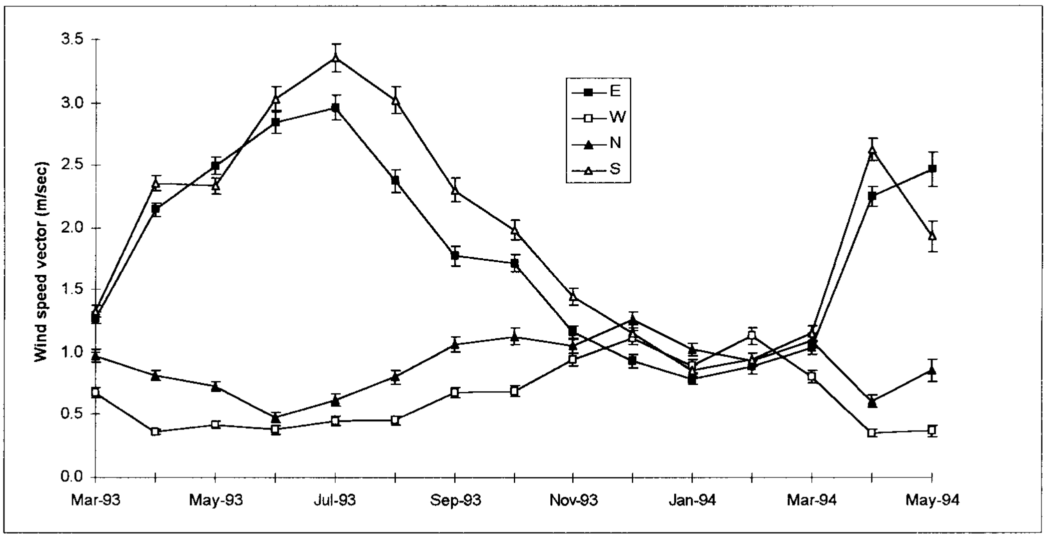


Figure A.IV.3.5. Mean monthly wind speed vector components at the Mpulungu buoy. station. Error bars are shown.

APPENDIX V - Evaporation

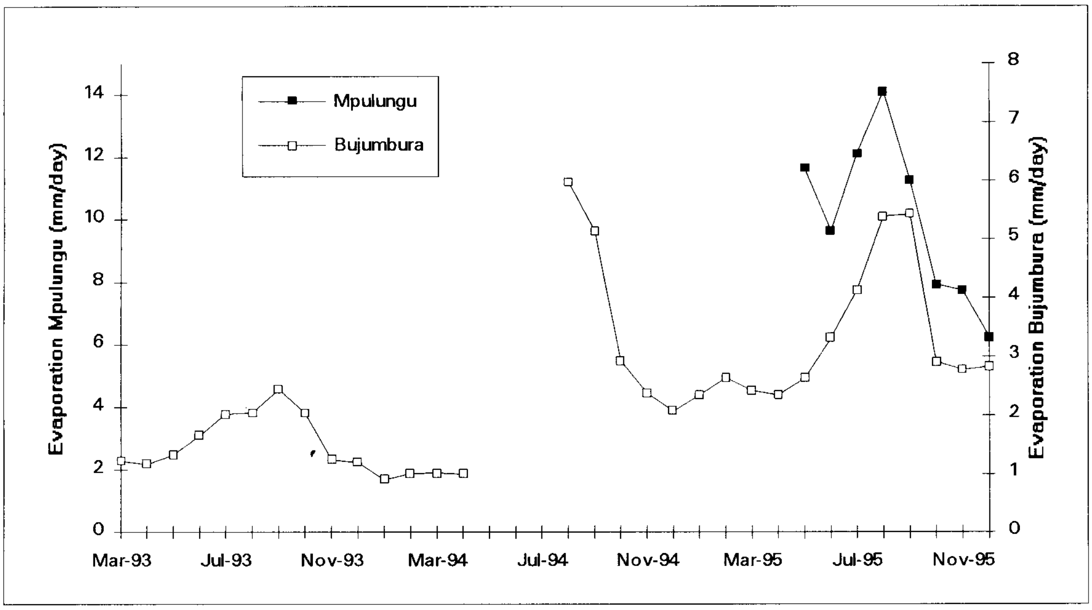


Figure A.V.1. Monthly evaporation, calculated for Bujumbura (right axis) and Mpulungu (left axis).

APPENDIX VI - Meteorology and Figures

VI.1 Air pressure

Air pressure followed a similar daily pattern in Bujumbura and Mpulungu ($r = 0.91$, higher than for any other measured meteorological parameter, for daily means, $P < 0.0001$). Air pressure was highest in June and generally low in October and April (Fig. A.VI.1.1).
The air pressure at Mpulungu was on average 2.5 mbar lower than at Bujumbura, due to the higher location (about 40 m above the lake surface and 300 m inland) of the sensor at Mpulungu. The yearly average air pressure at Bujumbura for 1995 was 923.5 mbar. Air pressure in 1995 was significantly ($P < 0.00001$) lower than in 1993 and 1994 (Table 2, -1.6 and -1.1 mbar respectively).

VI.2 Air temperature

Mean monthly air temperature was in 1993 highest in October at each station. In 1994 and 1995, the monthly mean was highest in October at Mpulungu and in September at Bujumbura and at the Kigoma buoy. Another small peak was generally measured around April (Fig. A.VI.2.1), i.e. air temperature was high when the air pressure was low. Lowest air temperatures were reached in July each year.

In general temperatures were highest at Mpulungu, lowest at Bujumbura and intermediate between the two at the Kigoma buoy. Only in June - August were temperatures at the Kigoma buoy above those at Mpulungu and at Mpulungu buoy. During the wet season differences were largest between the stations.

Daily mean air temperatures were significantly higher in 1995 compared with 1993 and 1994, both at Bujumbura ($P < 0.05$, +0.2 ℃) and at the Mpulungu buoy ($P < 0.001$, +0.4 ℃ and +0.3 ℃ respectively, Table 2). Also at the Kigoma buoy, temperature was significantly ($P < 0.01$) higher (+0.2 ℃)in 1995 compared with 1994. Between 1993 and 1994 there was no significant ($P > 0.05$) difference.

When dry seasons (May - September) were compared (Table 4), daily mean air temperature was found to be significantly ($P < 0.001$) higher at Bujumbura in 1995 and 1994 (+0.4 ℃ and +0.7 ℃ respectively), compared with 1993. At the Mpulungu buoy, the dry season of 1995 was significantly warmer than the same periods in 1993 (+0.5 ℃, $P < 0.0001$) and 1994 (+0.3 ℃, $P < 0.01$).

For the comparison of the wet seasons of 1993 - 1994 and 1994 - 1995, no significant differences were found at Bujumbura, and at the Kigoma and Mpulungu buoys. Daily mean air temperature at the Kigoma buoy and at Bujumbura was higher in the last 3 months of 1995 than in 1994 in the same period.

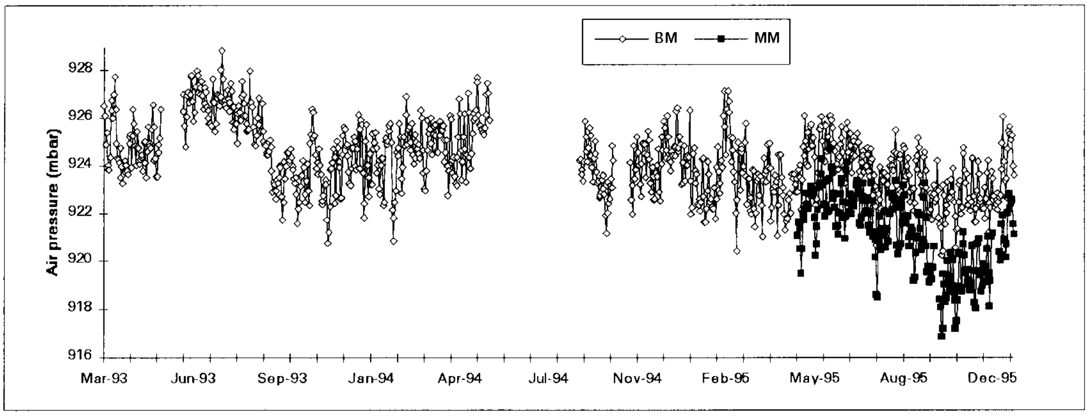


Figure A.VI.1.1. Mean daily air pressure for Mpulungu weather station (MM), and for Bujumbura weather station (BM), for March 1993 - December 1995.

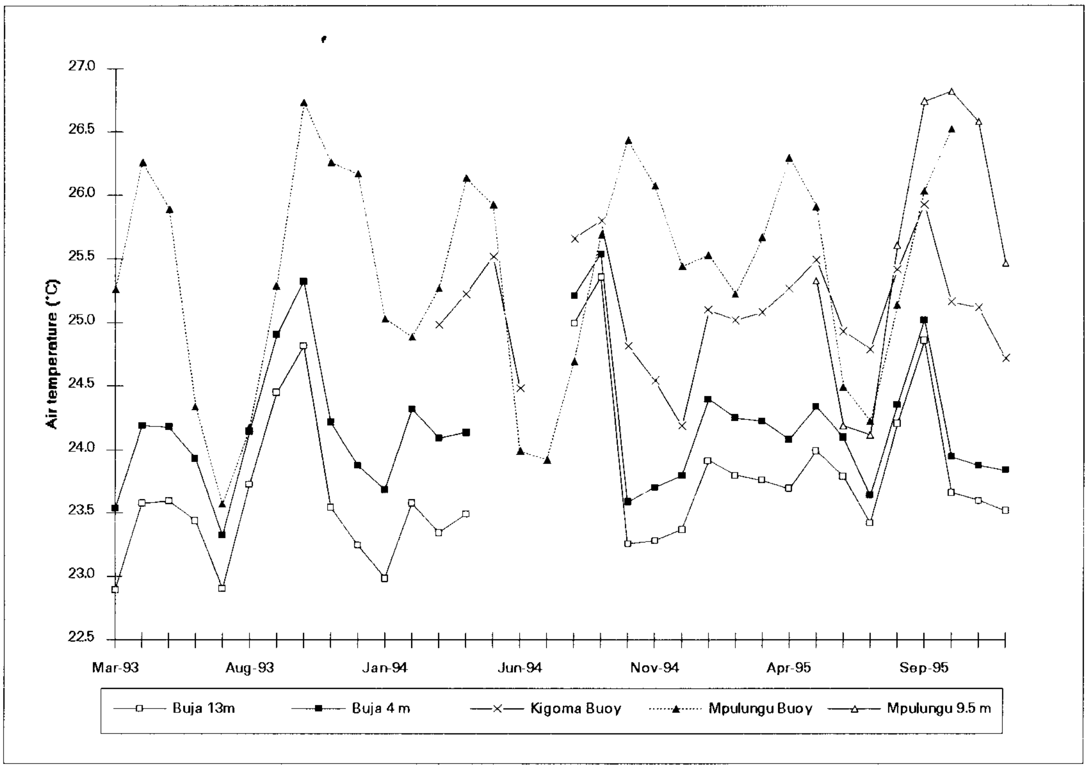


Figure A.VI.2.1. Monthly mean air temperature at Bujumbura and Mpulungu, and off shore near Kigoma and Mpulungu.

VI.3 Solar radiation

In the period in which solar radiation was measured at Mpulungu (May to December 1995), it was higher at Mpulungu (255 $W.m^{-2}$) than at Bujumbura (232 $W.m^{-2}$). There was more variance in the daily means during the wet season due to days with clouds and rain, than during the dry season (Fig. A.VI.3.1). Highest monthly means were reached at Bujumbura in September 1993, and in August 1994 and 1995. At Mpulungu the monthly mean was highest in October 1995.

The mean value for the periods of May to September in Bujumbura, was 232 W/m^2, and for the wet season (October to April) slightly lower, 218 W/m^2. None of the dry season periods between March 1993 and December 1995 had lower averages than any of the wet seasons. In 1995, during the dry season the mean midday maximum at Bujumbura was 882 W/m^2, and during the wet season months 835 $W.m^{-2}$.

Daily mean solar radiation at Bujumbura was significantly ($P < 0.05$) higher (5%) in 1995, compared with 1993 (Table 2). This was also the case when only dry seasons were compared (8%, $P < 0.01$, Table 4). When wet seasons were compared, solar radiation during the 1994 - 1995 season was significantly ($P < 0.05$) higher (7%) than during the 1993 - 1994 season (Table 5).

VI.4 Rainfall

In the wet season of 1994/95 the total rainfall at Bujumbura was 476 mm. At Mpulungu nearly 3 times more rain fell in the same period: 1262 mm. The lake water level rose appreciably during the rains, 95 cm from the minimum value in October 1994 to the maximum level in April 1995. It fell again by 75 cm to another minimum value in October 1995 (Fig. A.VI.4.1).

The value rainfall measured at Bujumbura was less than expected. The values for Mpulungu and Bujumbura were both measured on jetties on the lake shore. The average for Mpulungu, between 1974 and 1994, was 1244 $mm.yr^{-1}$ (± 254 S.D.), and for Bujumbura, measured more inland between 1931 and 1993, by IGEBU (Institute Geologique de Burundi), 841 $mm.yr^{-1}$ (±133 S.D.). The mean annual rainfall at Kigoma, about 5 km from the shore, was 984 $mm.yr^{-1}$ (±146 S.D.) between 1937 and 1993. From north to south over the lake, annual rainfall increases although the wet season shortens (Plisnier *et al.*, 1996). Rainfall around the lake is localised (Capart, 1952).

VI.5 Humidity

Relative humidity measured at 13 m in Bujumbura was on average 1.72 % lower than at 4 m (Fig. A.VI.5.1). Up to April 1994 humidity at Bujumbura at 13 m was usually > 80 % and after August 1994 it was usually < 80 %. The sensors were replaced in August 1994. Humidity was significantly ($P < 0.0001$) lower in 1995 than in 1994 and 1993 (Table 2).

Humidity at Mpulungu was usually less than at Bujumbura. Both at Bujumbura and at Mpulungu lowest values were found in August - September. Highest monthly means were reached during the wet season. At Bujumbura the humidity was highest at night when the land winds were blowing. For Mpulungu humidity was highest in the late afternoon when the lake winds were blowing.

At Mpulungu the humidity data measured at the more elevated and inland position of the weather station agreed with data measured on a jetty on the lake shore at Mpulungu. For measurements with a psychrometer at 0800 h on this jetty Phiri (1993) gave 37 % as the mean for 1991, and Pearce (1991) gave 48 % for 1990. In 1995 the mean was 53 %, and 54 % for 2 May to 31 December, measured in the same way (personal observation). At the weather station the mean for 2 May to 31 December 1995 was 53 %, and for the whole first year of data from this station 48 %. However, since humidity at the jetty was measured at 0800 h, when humidity was generally lower than the daily mean, the quoted humidity values are probably underestimations. For 2 May to 31 December, the mean of measurements at the Mpulungu weather station at 0800 h was 45 %, 9 % lower than measured with the psychrometer at the lake side.

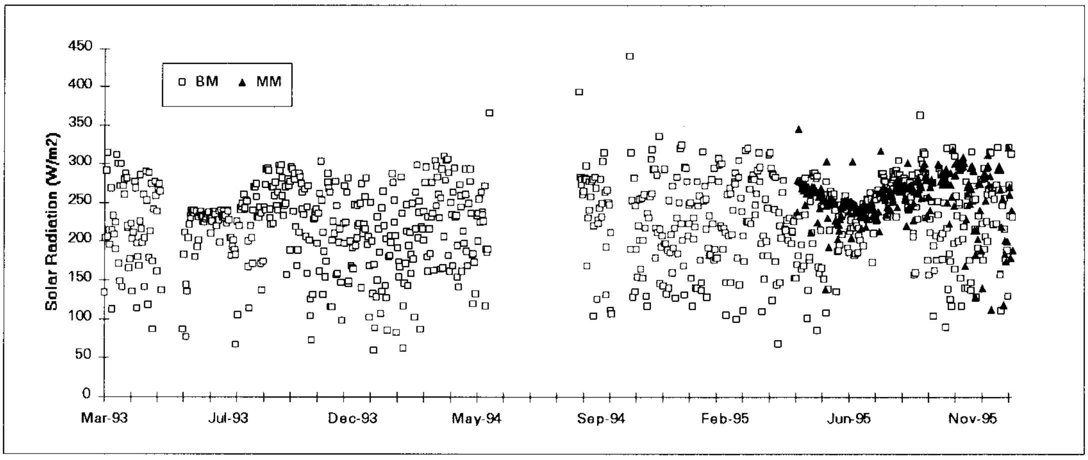


Figure A.VI.3.1. Daily means of solar radiation at Bujumbura weather station (BM) and Mpulungu weather station (MM).

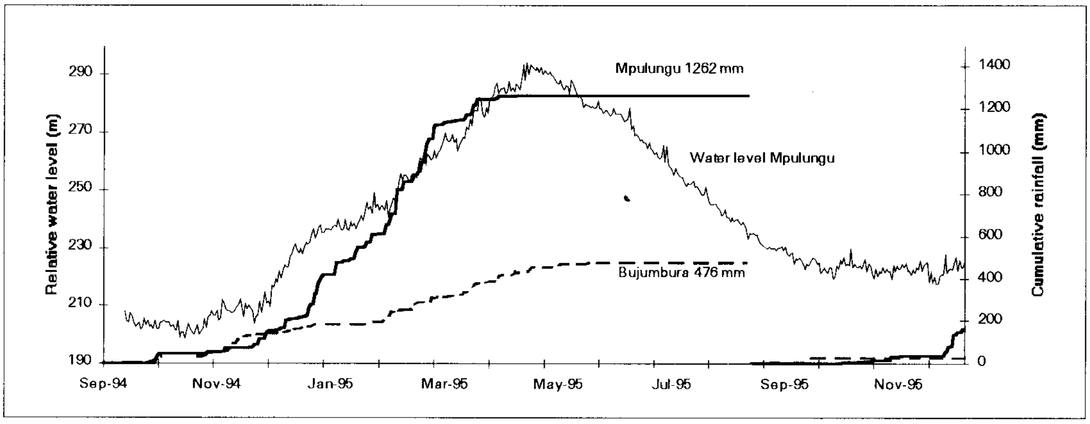


Figure A.VI.4.1. Cumulative rainfall for Bujumbura and Mpulungu, for 1 September 1994 - 31 December 1995. On the left axis the water level in Mpulungu is shown.

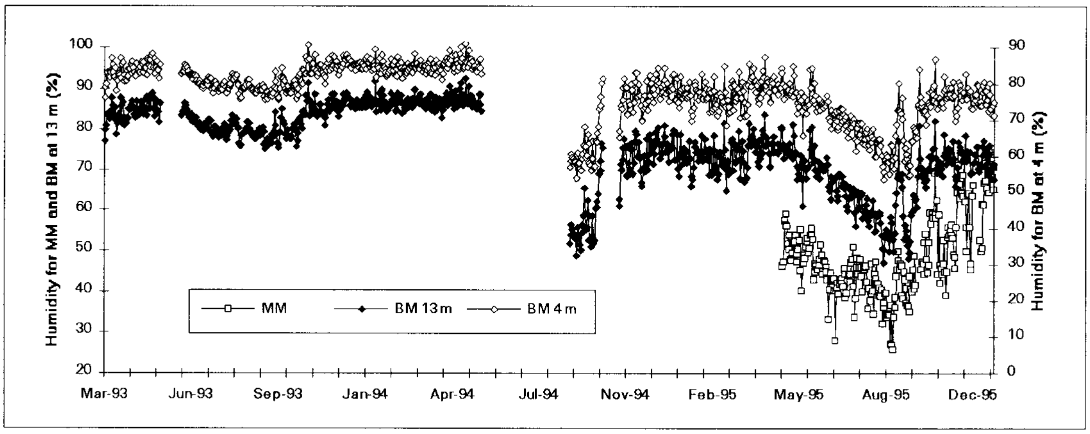


Figure A.VI.5.1. Mean daily humidity for Mpulungu weather station (MM), and for Bujumbura weather station (BM) at 13 m, and at 4 m height. The latter is shown on the right axis.

APPENDIX VII - Compilation of monthly and annual means

Table 12. Annual means for meteorological parameters of weather stations and buoys (1993-1995).

Parameter	Mpulungu buoy	Kigoma buoy	Mpulungu land station	Bujumbura land station (at13 m)	Kigoma land station
Wind speed (m/s)	4.0	2.8	2.9	3.1	3.5
Wind gust (m/s)	6.2	4.2	5.2	4.2	5.2
Air temperature (°C)	25.4	25.0	25.1	23.7	
Relative humidity (%)			54	75	
Solar radiation (W/m2)			253	225	
Air pressure (mbar)			921.1	924.3	
Water temperature at depth (m):					
1	26.4	26.6			
5	26.3	26.5			
15		26.4			
30	25.9	26.2			
50	25.0	25.7			
70	24.3	24.9			
90	24.2	24.3			
110	24.1	24.1			
150	23.8	23.8			
200	23.6	23.6			
250	23.4				
300	23.4	23.4			

Table 13. Meteorological parameters recorded at each meteorological station, as monthly means over the period March 1993 - December 1995.

Mpulungu meteorological station												
Parameter	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Wind speed (m/s)	2.1	2.4	3.0	4.1	2.6	3.1	4.0	3.5	3.2	2.6	2.4	2.3
Wind gust (m/s)	3.9	4.2	5.4	7.1	4.7	5.7	7.0	6.0	5.5	4.6	4.3	4.1
Air temperature (°C)	23.7	25.2	25.3	23.4	24.6	24.9	23.9	25.3	26.5	26.8	26.6	25.5
Relative humidity (%)	72	67	56	43	62	53	45	40	42	52	56	63
Solar radiation (W/m2)	229	268	253	244	255	251	241	253	263	283	254	241
Air pressure (mbar)	920.2	919.6	922.2	923.6	921.1	922.0	922.8	921.6	920.4	918.8	919.6	921.0
Mpulungu buoy												
Parameter	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Wind speed (m/s)	2.9	2.9	3.2	4.4	4.7	4.8	5.1	5.0	4.2	3.7	3.5	3.4
Wind gust (m/s)	5.2	5.1	5.3	6.5	6.8	7.1	7.3	7.3	6.3	5.8	5.6	5.6
Air temperature (°C)	25.3	25.1	25.4	26.2	25.9	24.3	23.9	24.7	25.7	26.6	26.2	25.8
Water temperature, at depth (m):												
1	27.5	27.3	27.3	27.0	26.5	25.1	24.4	24.5	25.2	26.7	27.4	27.7
5	27.4	27.1	27.1	26.9	26.4	24.9	24.3	24.4	25.0	26.6	27.3	27.6
30	26.7	26.8	26.7	26.1	26.0	25.0	24.2	24.2	24.6	26.1	26.7	27.1
50	25.4	25.6	25.3	25.0	24.9	24.7	24.2	24.1	24.4	25.3	25.7	25.5
70	24.4	24.6	24.5	24.5	24.5	24.4	24.1	23.9	24.0	24.3	24.5	24.4
90	24.2	24.3	24.2	24.2	24.2	24.2	24.1	24.0	24.1	24.4	24.3	24.2
110	24.1	24.1	24.0	24.1	24.0	24.1	24.0	24.0	24.1	24.2	24.1	24.1
150	23.9	23.9	23.9	23.9	23.8	23.8	23.8	23.8	23.8	23.8	23.8	23.9
200	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6
250	23.4	23.4	23.4	23.5	23.4	23.5	23.4	23.4	23.5	23.4	23.4	23.4
300	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4
Kigoma buoy												
Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind speed (m/s)	2.6	2.6	2.9	3.1	3.4	3.1	3.7	2.8	2.2	2.2	2.8	2.8
Wind gust (m/s)	4.1	4.0	4.4	4.6	4.8	4.5	5.3	3.9	3.1	3.6	4.2	4.3
Air temperature (°C)	24.9	24.9	25.0	25.2	25.5	24.8	24.7	25.4	25.9	25.0	24.8	24.4
Water temperature, at depth (m):												
1	26.8	26.8	27.1	27.1	27.1	26.8	26.2	25.8	26.1	26.5	26.5	26.3
5	26.7	26.7	27.0	27.0	27.1	26.8	26.2	25.8	26.0	26.4	26.3	26.2
15	26.5	26.6	26.8	26.9	27.0	26.7	26.1	25.7	26.0	26.3	26.2	26.1
30	26.2	26.4	26.5	26.7	26.9	26.7	26.1	25.7	25.8	26.1	25.9	25.9
50	25.7	25.7	25.8	26.1	26.5	26.6	26.0	25.5	25.4	24.9	24.9	25.3
70	24.7	24.7	24.7	25.0	25.2	25.5	25.5	24.8	24.9	24.4	24.5	24.8
90	24.3	24.2	24.3	24.3	24.4	24.4	24.5	24.3	24.3	24.1	24.2	24.4
110	24.1	24.0	24.1	24.1	24.1	24.1	24.1	24.1	24.0	24.0	24.1	24.1
150	23.8	23.8	23.9	23.8	23.8	23.8	23.8	23.8	23.8	23.8	23.9	23.8
200	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6
300	23.5	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4
Bujumbura meteorological station												
Parameter	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Wind speed (m/s)	2.6	2.6	2.7	2.7	3.0	3.3	3.5	3.7	3.6	3.3	3.0	3.0
Wind gust (m/s)	3.7	3.8	3.8	3.8	4.1	4.4	4.6	4.9	4.8	4.5	4.2	4.2
Air temperature (°C)	23.4	23.5	23.3	23.6	23.8	23.6	23.2	24.3	24.9	23.9	23.5	23.4
Relative humidity (%)	78	78	81	83	79	77	72	64	64	74	77	78
Solar radiation (W/m2)	206	218	231	222	218	214	227	263	246	220	214	221
Air pressure (mbar)	923.7	923.8	924.5	924.0	924.7	925.9	925.3	924.6	923.8	923.1	923.5	924.2
Rainfall (mm)	60.9	61.1	84.7	74.0	42.2	3.5	0.1	0.0	4.2	12.2	42.2	32.1
Wind speed (m/s, at 4 m)	1.7	1.8	2.0	2.1	2.4	2.8	2.8	2.8	2.7	2.4	1.8	2.1
Relative humidity (%, at 4 m)	79	79	82	83	81	79	74	67	67	77	79	80
Air temperature (°C, at 4 m)	23.9	24.0	23.9	24.1	24.3	24.0	23.5	24.6	25.2	24.3	23.9	23.8
Kigoma wind station												
Parameter	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Wind speed (m/s)	2.8	3.3	3.4	3.6	3.7	3.3	3.9	4.0	4.0	4.1	3.4	3.1
Wind gust (m/s)	4.3	4.8	5.0	5.3	5.4	4.8	5.6	5.7	5.7	5.8	5.0	4.6

Table 14. Meteorological parameters recorded at each meteorological station, as monthly means for 1995.

Parameter	Jan-95	Feb-95	Mar-95	Apr-95	May-95	Jun-95	Jul-95	Aug-95	Sep-95	Oct-95	Nov-95	Dec-95	Means
Mpulungu meteorological station													
Wind speed (m/s)					3.0	3.4	3.7	3.5	3.2	2.6	2.4	2.3	3.0
Wind gust (m/s)					5.5	6.2	6.5	6.2	5.5	4.6	4.3	4.1	5.4
Air temperature (°C)					25.3	24.2	24.1	25.6	26.7	26.8	26.6	25.5	25.6
Relative humidity (%)					51	46	43	41	39	52	56	63	49
Solar radiation (W/m2)					262	237	239	259	265	283	254	241	255
Air pressure (mbar)					922.1	922.6	922.0	921.7	920.8	918.8	919.6	921.0	921.1
Mpulungu buoy													
Wind speed (m/s)	2.9	3.0	3.5	4.5	5.0	4.1	4.9	5.2	3.8	3.2	3.4	3.5	3.9
Wind gust (m/s)	5.1	5.3	5.6	6.7	7.3	6.2	7.2	7.6	6.1	5.2	5.5	5.8	6.1
Air temperature (°C)	25.5	25.2	25.7	26.3	25.9	24.5	24.2	25.1	26.0	26.5			25.5
Water temperature, at depth (m):													
1	27.6	27.4	27.1	26.9	26.6	25.1	24.5	24.8	25.6	27.1	28.0	27.9	26.5
5	27.4	27.2	27.0	26.8	26.5	25.1	24.5	24.7	25.5	27.0	27.9	27.8	26.4
30					26.4	25.0	24.4	24.5	25.0	26.6	27.6	27.7	25.9
50					26.3	24.9	24.3	24.4	25.0	26.5	27.2	27.1	25.7
70					25.0	24.7	24.3	24.3	24.6	25.9	26.4	26.0	25.2
90					24.2	24.2	24.2	24.2	24.3	24.7	24.5	24.2	24.3
110					24.0	24.1	24.0	24.1	24.2	24.3	24.1	24.1	24.1
150					23.7	23.8	23.7	23.8	23.9	23.8	23.8	23.9	23.8
200					23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.7	23.6
250					23.4	23.4	23.4	23.4	23.4	23.4	23.5	23.4	23.4
300													
Kigoma buoy													
Wind speed (m/s)	2.0	2.0	2.2	2.1							3.3	3.3	2.5
Wind gust (m/s)	3.2	3.1	3.5	3.5							4.9	5.0	3.9
Air temperature (°C)	25.1	25.0	25.1	25.3	25.5	24.9	24.8	25.4	25.9	25.2	25.1	24.7	25.2
Water temperature, at depth (m):													
1	27.0	26.9	27.1	27.1	27.2	26.7	26.3	26.0	26.2	26.6	26.6	26.5	26.7
5	26.8	26.8	26.9	27.0	27.1	26.7	26.3	26.0	26.2	26.5	26.5	26.4	26.6
15	26.6	26.7	26.8	26.9	27.1	26.7	26.2	25.9	26.1	26.4	26.3	26.4	26.5
30	26.1	26.4	26.4	26.8	27.0	26.6	26.2	25.8	26.0	26.3	26.0	26.2	26.3
50	25.5	25.6	25.7	26.3	26.5	26.6	26.1	25.7	25.4	25.0	25.1	25.5	25.8
70	24.6	24.6	24.7	25.1	25.0	25.5	25.3	24.9	25.0	24.4	24.6	24.9	24.9
90	24.2	24.2	24.3	24.3	24.3	24.3	24.3	24.3	24.3	24.1	24.4	24.4	24.3
110	24.0	24.0	24.0	24.1	24.1	24.1	24.1	24.0	24.0	24.0	24.2	24.1	24.1
150	23.8	23.8	23.9	23.8	23.8	23.8	23.8	23.8	23.8	23.8	23.9	23.8	23.8
200	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.6
300	23.4	23.4	23.4	23.4	23.4	23.4	23.5	23.4	23.4	23.4	23.4	23.4	23.4
Bujumbura meteorological station													
Wind speed (m/s)	2.6	2.8	2.7	2.8	2.8	3.3	3.4	3.7	3.7	3.0	3.1	3.0	3.1
Wind gust (m/s)	3.6	3.9	3.8	3.9	3.8	4.4	4.5	4.8	4.9	4.3	4.4	4.3	4.3
Air temperature (°C)	23.9	23.8	23.8	23.7	24.0	23.8	23.4	24.2	24.9	23.7	23.6	23.5	23.8
Relative humidity (%)	73	73	74	76	73	71	64	57	59	71	73	72	70
Solar radiation (W/m2)	215	227	235	220	211	223	225	273	248	213	211	239	228
Air pressure (mbar)	924.5	924.5	923.4	922.9	924.4	924.8	923.9	923.6	923.3	922.4	922.9	923.6	923.5
Rainfall (mm)	52.8	104.1	90.1	68.9	23.7	7.0	0.0	0.0	2.5	0.0	0.0	3.0	0.9
Wind speed (m/s, at 4 m)	1.8	2.1	2.0	2.1	2.2	2.9	2.7	2.8	2.7	2.4	1.4	1.8	2.1
Relative humidity (%, at 4 m)	76	76	78	80	77	75	69	63	64	75	77	76	74
Air temperature (°C, at 4 m)	24.4	24.2	24.2	24.1	24.3	24.1	23.6	24.3	25.0	23.9	23.9	23.8	24.1
Kigoma wind station													
Wind speed (m/s)					3.7	3.1	3.7	4.1	4.1	4.2	3.5	3.1	3.7
Wind gust (m/s)					5.5	4.5	5.3	5.8	5.8	6.0	5.1	4.7	5.4