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HYDRODYNAMICS OF LAKE TANGANYIKA: 1993 - 1996, SYNOPSIS AND INTERANNUAL COMPARISONS

by

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PREFACE

The Research for the Management of the Fisheries on Lake Tanganyika project (Lake Tanganyika Research) 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 Programme for United Nations Development Organizations(AGFUND).

This project aims at 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 will be also 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 buildup of effective coordination mechanisms to ensure full collaboration between the Governments concerned.

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1. INTRODUCTION

Lake Tanganyika is the second deepest lake in the world (1470 m), and the second largest in Africa. It is located between 3 and 9° S, 670 km long and has a maximum width of 48 km (Fig. 1). The warm wet season is in general from October to April but there are differences from north to south in rainfall (Fig. 2). Below about 200 m depth the lake water is permanently anoxic, and relatively rich in nutrients (Coulter, 1991). Upwelling of nutrients is considered to be of paramount importance in sustaining the food webs in the lake (Coulter, 1991). Upwelling and mixing of epilimnetic and hypolimnetic waters and upwelling occur primarily in the dry season (May - September), driven by strong tradewinds from the south-east. A fishery which is primarily active off-shore, targeting mainly pelagic fish species, supplies an important source of protein in the area around the lake.

Meteorological observations at Lake Tanganyika were first given by Burton (1860). Although several hydrological and limnological studies have been conducted on Lake Tanganyika (Stappers, 1914; Cunnington, 1920; Beauchamp, 1939; Capart, 1949, 1952; Servais, 1957; Dubois, 1958; Coulter, 1967; Ferro, 1975), the hydrodynamics of the lake are still poorly understood. Previous studies have been 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 meteorological and hydrological sampling stations around and on the lake. Data have been collected with automatic recorders since March 1993, and were in part previously presented by Kotilainen *et al*. (1995) and Verburg *et al*. (1997, 1998). The diel cycle of meteorological and hydrological parameters was presented by Verburg (1997).

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

There were significant differences between years, and in 1995 and 1996 upwelling was less than in 1993. Such differences are expected to have an important influence on primary and secondary production, with the production following the upwelling of 1993 being noticeably higher than for other years.

2. MATERIAL AND METHODS

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

2.1 Automatic recorders

Data were collected by three stations around the lake and two offshore stations (Huttula *et al.*, 1993; Kotilainen *et al.*, 1995; Verburg *et al.*, 1997a), equipped with automatic meteorological and hydrodynamical data recording instruments of Aanderaa Instruments (Fig. 1). Recording intervals, sensor types and the installation dates of the sensors of each station are presented in Table 1. Weather stations were located at the north end (Bujumbura, Burundi) and at the south end of the lake (Mpulungu, Zambia). A wind station was located at Kigoma (Tanzania), in the north-east, 150 km south of Bujumbura, and two buoys were located off Kigoma and off Mpulungu. The depth of water at the Kigoma and Mpulungu buoys was *c.* 400 and 350 m respectively.

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

Station	**Bujumbura Weather station**	**Kigoma Wind station**	**Mpulungu Weather station**	**Buoy 14 km south-west off Kigoma**	**Buoy 40 km north-west off Mpulungu**
Rec. interval	10 min	10 min	30 min	30 min	60 min
Rec. period:	3/93 - 12/96	7/93 - 11/96	5/94 - 4/95	3/94 - 11/96	3/93 - 11/96
Sensor type	at 13m height: Wind speed Wind gust Wind direction Air Temperature Air pressure Humidity Solar radiation Rainfall at 4m height: Wind speed, Humidity Air temperature	Wind speed Wind gust Wind direction	Wind speed Wind gust Wind direction 5/'95 - 12/'96: rec. int.10 min Wind speed Wind gust Wind direction Air temperature Air pressure Humidity Solar radiation	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	Wind speed Wind gust Wind direction Air temperature Water temperature 1,5,15,30,50,70,90, 110,150,200,250 and 300 m depth

Data of wind speed, wind gust, wind direction, air pressure, air temperature, rainfall, relative humidity, solar radiation and water temperature at different depths were collected from March 1993 to December 1996. At Bujumbura meteorological sensors were placed at 4 and 13 m height, at the Kigoma wind station at 6 m, at Mpulungu at 9.5 m, and at the buoys at 2.6 m height. The parameters were recorded as momentary values, except rainfall, wind speed and wind gust. The total rainfall (at Bujumbura) during the recording intervals was measured. 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 thermistor chain attached to the buoy off Mpulungu originally had eleven temperature sensors set at 1, 5, 30, 50, 70, 90, 110, 150, 200, 250 and 300 m (Table 1). From 2 May 1995 a new chain was installed with an extra sensor at 15 m and no sensor at 250 m.

2.2 The Wedderburn number

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

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

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

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

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

Daily mean wind speed data were collected at the buoy off Mpulungu, the buoy off Kigoma, the wind station at Kigoma and the weather station at Bujumbura. Daily mean water temperature data were collected at 1 m and 300 m at the buoys off Mpulungu and Kigoma. For periods without data for temperature at 300 m, the mean value was used (23.43 °C) since there was little variance in temperature at this depth. For Bujumbura, weekly temperature measurements taken offshore at 1 m were used. Water temperature at 1 m at Bujumbura was interpolated assuming a linear daily change between the weekly measurements. Epilimnion density (r_1) was calculated using conductivity data collected weekly at 10 m off Mpulungu, Kigoma and Bujumbura. Conductivity data were collected once every 6 weeks at 300 m. For the calculation of density at 300 m (r_2), the mean conductivity at 300 m was used (0.694 $mS.cm^{-1}$). To calculate daily Wedderburn numbers, weekly conductivity data were interpolated.

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

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

2.3 Wind direction and wind speed vectors

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

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

2.4 Evaporation

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

2.5 Water level recorders

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

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

3. RESULTS

3.1 Interannual comparisons

Means for all parameters measured at the five automatic stations, and for the calculated wind speed vectors and for evaporation, for dry and wet seasons, and separate for each year, are presented in Tables A1 - A7, Appendix I. In Table A8 mean depths of isotherms at the buoys are presented.

In general, the isotherms at both buoys went deeper, and the period during which isotherms were present, became longer each year from 1993 to 1996. For instance, the 23.5 °C isotherm off Mpulungu descended 50 m between 1993 and 1996, and the 24 °C isotherm 70 m. The 25 °C isotherm surfaced for 92 days off Mpulungu in 1993, compared with only 59 and 49 days in 1995 and 1996 respectively. This was related with a general warming of the lake between 1993 and 1996 and reduced upwelling in 1995 and 1996 (Table A8). Off Mpulungu, water temperatures at all depths increased between 1993 and 1996, and wind speed decreased, especially in the dry seasons, and air temperature increased (Table A3). Off Kigoma, water temperatures increased between 1995 and 1996, except in the dry season, when water at 0 - 50 m depth decreased in temperature. This coincided with increased wind speed and a decrease in air temperature in the dry season (Table A2). Also at the Mpulungu buoy, the air temperature decreased between 1995 and 1996, but the large decrease in wind speed prevented the surface layers in the south basin from cooling in 1996. Evaporation was lower in 1996 than in 1995, both off Mpulungu and Bujumbura (Table A5).

Wind speeds at Kigoma decreased between 1993 and 1995 (Table A4). At Bujumbura, wind speeds decreased between 1993 and 1996, and air temperature increased, as at the Mpulungu buoy. Air temperature decreased between 1995 and 1996, as at Mpulungu and Kigoma (Table A1). Solar radiation was highest in 1995, both at Bujumbura and at Mpulungu. Air pressure decreased each year, between 1993 and 1996, at Bujumbura, but at Mpulungu was higher in the dry season in 1996 than in 1995 (Tables A1 and A6). This coincided at Mpulungu with an increase in wind speed between 1995 and 1996, as occurred off Kigoma and contrasting with the decrease in wind speed at Bujumbura and the Mpulungu buoy between 1995 and 1996.

The decrease in wind speed at Bujumbura and at the Mpulungu buoy between 1993 and 1996 was mainly a decrease in wind from the south and east (Table A7). Winds from west and north increased at Bujumbura. At Kigoma, south winds decreased between 1993 and 1995.

At the Kigoma buoy an increase in south and east wind was prominent between 1994/1995 and 1996. Also at Mpulungu, south and east winds increased significantly between 1995 and 1996.

Lake hydrodynamic properties and each meteorological parameter are discussed in more detail below.

3.2 Lake hydrodynamics

At the south end of the lake isotherms in the upper 100 m decreased in depth from June, due to strong winds from the south east, cooling at the surface by increased evaporation and lower air temperature (Figs. 3-7). The thermocline tilted towards the north in the dry season. The tilt was highest in July (*c.* 80 m for the 24.5-25 °C isotherms, Fig. 13). At this time the isotherms along the boundary of epilimnion and metalimnion in the north were close together and the thermocline was sharp. At the south end, where cooling was strongest, the thermocline surfaced and the upper 100-150 m became almost isothermal. Mixing was most intense at the south end in this season and upwelling occurred of cold hypolimnetic water. Following upwelling and mixing in the south, cold nutrient rich water was forced northwards along the surface and dispersed along the lake The tilt of the thermocline was reversed when wind stress relaxed after the dry season, and was greatest towards the south in November (*c*. 30 m for the 24.5 - 25.5 °C isotherms in 1995 and 1996, Fig. 13).

The thermocline never disappeared in the north, and mixing off Kigoma was less than off Mpulungu (see also Wedderburn numbers).

From November a gradual deepening of the thermocline off Kigoma forced the tilt to decrease. During the wet season the surface waters warmed up, by increased air temperature and solar radiation and diminished wind speed and evaporation. Off Mpulungu the thermocline reestablished and stratification set in. Heat gain of the water column occurred off Mpulungu in August - December. During the remainder of the wet season heat gain and losses were about equal, the thermocline remained stable at *c*. 40 m and stratification was similar throughout the wet season. Off Kigoma heat was gained at a slower rate, throughout the wet season (see heat budget), and stratification was strongest at the end of the wet season.

The seasonal thermocline (Fig. 8) tended to be deeper off Kigoma than off Mpulungu (see for monthly mean depth profiles of water temperature Verburg *et al*. 1997, and 1998). The seasonal thermocline off Kigoma rose in the early part of the wet season (October - December) to *c*. 40 m depth, and remained most of the year at 60 - 80 m depth. It was found generally deeper in 1996, than in 1994 and 1995. Off Mpulungu, the thermocline surfaced in July - August, and was located most of the year at *c*. 40 m depth.

The depth of the steepest density gradients (as mean depths between the nearest thermistors) occurred shallow, in the upper 5 m, in the dry season off Mpulungu, and in the wet season off Kigoma (Fig. 8), i.e. when stratification was weak and the respective seasonal thermoclines surfaced or ascended. The next steepest density gradient occurred as deep as 150 - 200 m depth off Mpulungu in the dry season, and at 5 - 50 m off Kigoma in the wet season.

Off Mpulungu in 1993 during the dry season the 24 °C isotherm ascended from below 100 m depth and came to the surface (Fig. 3). In July - August 1993 there was <1 °C difference between 1 and 300 m depth (daily minimum 0.55 °C on 2 August 1993). Surface temperatures in 1994 and 1993 were similar (Table A3). In 1995 and 1996 no seasonal influence was noticeable on the depth of the 24 °C isotherm off Mpulungu and the 24.5 °C isotherm was the deepest isotherm which surfaced (Fig.4). Off Mpulungu, dry season water temperatures both at 1 and 5 m depth were *c*. 0.3 - 0.5 °C higher in 1995 and 1996 respectively, than in 1993 and 1994 (Table A3). The lowest daily mean temperatures at 1 m depth in 1993, 1994, 1995 and 1996 were 23.98, 24.09, 24.26 and 24.31 °C respectively. Cooling of the surface waters, mixing and upwelling at the south end of the lake was therefore less in 1995 and 1996 compared with 1993 and 1994. Also in the wet season, water temperatures were higher in 1995/96 than in the wet seasons of 1993/94 and 1994/95, especially at 50 m depth. Stratification was stronger in 1995/96, and the thermocline was deeper. The 23.5, 23.75 and 24 °C isotherms off Mpulungu were generally deeper during 1995 and 1996 than in 1993 and 1994. 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 300 m depth). On several occasions the 23.5 °C isotherm was below 300 m.

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).

Cooling and mixing was less off Kigoma than off Mpulungu and started about 1 month later than off Mpulungu. Off Kigoma only the upper 50 m became isothermal in July - August and stratification did not break down as in the south. Off Kigoma water below 60 m was hardly affected by seasonal cooling. Variation in water temperature was less than at the Mpulungu buoy (Figs 5 and 7). 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. Off Kigoma the warming up of the surface waters started later and proceeded slower than off Mpulungu. The surface temperature 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 occurred 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 °C in 1996).

Internal waves were observed during the whole measuring period (Figs 9 - 13), both in the wet and in the dry seasons. Internal wave action was evidenced by fluctuations with periods of *c*. 1 month in isotherm depths, for the shallower isotherms (>24 °C) superimposed on the major seasonal vertical movements (Figs 9-11). The period of the internal waves varied much, probably depending on higher mode frequencies and wind forcing, either dampening or enhancing internal wave amplitudes. In general temperatures at all depths decreased every 25 - 30 days, when cold water from the hypolimnion was forced upwards by internal waves Periodic changes in temperatures were highest at 30 and 50 m (Fig. 6). The amplitude of the internal waves was widest below the thermocline, where temperature differed little over a larger depth range.

The daily change in depth of the 23.5 °C isotherm was similar during the wet and dry seasons at the Mpulungu buoy (mean 7 m.day^{-1}). At the Kigoma buoy the daily change was lowest in July of each year (4 m.day^{-1}) and highest in December (c. 11 m.day^{-1}).

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, even during upwelling. There was no perceptible damping of the oscillation towards the dry season. Internal wave oscillations with a period similar to those in the south were inferred from temperature data collected at the Kigoma buoy.

Correlation between the depths of the 23.5 °C isotherms 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 negative 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 maximum tilt of the 23.5 and 23.75 °C isotherms between the Mpulungu and Kigoma buoys was *c.* 60 m (*c.* 0.12 $m.km^{-1}$). The 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. For instance, in June 1995, hourly depths of the 23.5 °C isotherm at the Mpulungu buoy showed 2 oscillations of *c.* 5 days, with an amplitude of *c.* 40 m, before the onset of the upward surge of the fundamental mode (Verburg *et al.*, 1997).

The tilt along the length of the lake of deep and shallow isotherms depended for the former on internal wave action and for the latter primarily on the seasonal wind-driven vertical water displacement, mixing and surface cooling (Figs. 12 and 13 respectively). The 24.5 - 25.5 °C isotherms surfaced in the dry seasons off Mpulungu (Fig. 13). When the 24.5 °C was close to the surface off Mpulungu, the northward tilt was 70 - 90 m. Isotherms off Mpulungu in 1995-1996 were located deeper than in 1993 and 1994, and this resulted in an almost permanently southward tilt of the deeper isotherms in 1996 (Fig. 12). The southward tilt of the thermocline (± 25°C isotherm) was greater in November 1995 and 1996, than in 1993 and 1994, due to higher wind speeds from the north in November 1995 and 1996, at the south end of the lake (Figs. 28 and 29). As a result the thermocline off Mpulungu was deeper in November 1995 and 1996, than in November 1993 and 1994 (Figs. 3,4,8 and 13).

3.3 The Wedderburn number

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

At all three stations, lowest Wedderburn numbers occurred in the dry season, generally in months with the highest wind speed, with the lowest values occurring *c.* one month later in the north (August - September) than in the south (July). The lake was most stable in January - February off Mpulungu and Kigoma and from

February to April off Bujumbura (Fig. 14). Off Bujumbura stable, stratified lake conditions developed later in the wet season than in the south, since off Bujumbura surface water temperature was generally lowest during the first half of the wet season (October - January) and highest late in the wet season, from April to May. Off Bujumbura, low Wedderburn values (1 < W < 3) often occurred in November. This coincided with significant increases in conductivity at 0 to 100 m depth, indicating upwelling and mixing.

Upwelling occurred primarily at the south end of the lake and mixing was most intense off Mpulungu and least off Bujumbura (Fig. 14 and Table 2). In the wet season, the lake reached most stable conditions off Mpulungu and stratification was weakest off Kigoma of the three stations. The seasonal differences in the Wedderburn number were thus much larger off Mpulungu, than off Kigoma. Off Mpulungu, wind speed and surface water temperature correlated more than off Kigoma and Bujumbura, with coinciding periods of highest wind speed and lowest surface temperature (July), thereby reinforcing the effects on mixing. During the dry season, density differences between epilimnion and hypolimnion (g', Table 2) were much smaller, and wind speeds higher, off Mpulungu, compared with off Kigoma, giving relatively low Wedderburn numbers for the Mpulungu area. During the wet season, the density differences over the thermocline were higher off Mpulungu than off Kigoma. The curves for g' versus time were, as expected, very similar to the curves for the temperature at 1 m depth.

Table 2. Mean seasonal Wedderburn numbers and values of g', an indication of the density jump across the thermocline (n.a. = not available).

W	Mpulungu	Kigoma	Bujumbura	g'	Mpulungu	Kigoma	Bujumbura
June-Aug							
1993	0.30	n.a.	n.a.	mean	0.0076	0.0081	0.0079
1994	0.47	1.42	n.a.	min	0.0015	0.0053	0.0045
1995	1.36	1.58	1.69	max	0.0133	0.0124	0.0126
1996	1.31	1.51	n.a.				
Nov-March							
1993-94	2.94	2.07	2.98				
1994-95	3.03	n.a.	2.60				
1995-96	3.69	2.35	3.04				

In the dry seasons off Mpulungu, mixing intensity decreased for each successive year from 1993 to 1996, as indicated by the increasing mean Wedderburn numbers (Table 2) and by the decreasing annual numbers of days on which W < 0.5 (Table 3).

Table 3. Number of days per year on which the Wedderburn number < 0.5, off Mpulungu.

	Number of days
1993	99
1994	89
1995	79
1996	38

Stratification off Mpulungu during the wet season was stronger in 1995-96 than in 1993-95 (Table 2).

3.4 Maximum heat content

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

In the south the lake gained its heat in the early part of the wet season (July - December), and more heat was absorbed at the surface than in deeper layers (Figs 15 and 16). At 150 m depth and deeper, the annual temperature increases were about zero. At the Mpulungu buoy, in 1993, from August to December, 17560 $cal.cm^{-2}$ was absorbed. In 1995 and 1996, the heat uptake by the lake was much higher, 20039 and 19079 $cal.cm^{-2}$ respectively. The difference was primarily accounted for by a larger heat uptake at 50 - 70 m depth in 1995 and 1996.

The total heat stored in the lake (0 - 300 m) increased with c. 2 $kcal.cm^{-2}$ each year from 1993 to 1996 (Fig. 16). Water at 150 to 300 m absorbed only 1 to 2 % of the heat absorbed by the entire water column between 1 and 300 m depth.

The heat gain was highest in September in 1993 and 1994, and in October in 1995 and 1996 (*c.* 350 $cal.cm^{-2}.day^{-1}$). The heat loss was highest in June (1993, 1996) and May 1995 (*c.* 370 $cal.cm^{-2}.day^{-1}$). Off Mpulungu, the heat gain at different depths to 150 m was simultaneous. The monthly heat change, or storage rate, of the upper 150 m of the water column was therefore proportional to the monthly change in surface temperature, as is clearly shown by the close correlation in Figure 17.

Off Kigoma, the heat gain and loss at different depths did not occur simultaneously, and the monthly heat storage rate in the upper 150 m and the change in surface water temperature were often not proportional (Fig. 17). The upper 30 m gained its heat mainly already in August - October, i.e. before the minimum heat content of the lake was reached, when the deeper water layers were still cooling. In November - May water at 50 - 150 m depth gained its heat. Therefore, annual temperature increases, between months of minimum and maximum heat content, were maximum at *c.* 50 m depth (Fig. 15), both in 1994/95 and 1995/96.

At the Kigoma buoy, the heat was gained during the whole wet season (Fig. 16). 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 annual heat uptake between 1 and 300 m depth. The total annual heat uptake was about 50 % of that in the south (Fig. 15 and 16). 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}. Monthly heat gain off Kigoma was irregular, compared to the south, with months of net cooling occurring during the period of heating, November - May. The loss of heat was highest in July (*c.* 180 cal.cm^{-2}.day^{-1}).

The contribution of the water layers below 150 m depth to the annual heat uptake 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

change in heat content at 150 - 300 m was regularly positive while the heat content change at 0 - 150 m was negative and vice versa.

3.5 Rainfall

Annual rainfall at Kigoma increased from 1993 to 1996 (Fig. 18). The highest rainfall among wet season periods fell in 1994-95, as at Mpulungu (Table 6, and Fig. 30 for cumulative rainfall). The rainfall at Kigoma was in 1994-95 and 1995-96 above the mean rainfall (Fig. 2). At Mpulungu it was only in 1994-95 above the mean. At Mpulungu 64 % of the rain fell at night (1900 - 0800 h).

3.6 Evaporation

The annual evaporation at the Mpulungu buoy in May 1995 - April 1996 was 2725 mm (after adjustment of the humidity values), and at the Bujumbura weather station 1191 mm in 1995 and 1160 mm in 1996 (Fig. 19). At the Mpulungu buoy it was 19 % less in May - November 1996 compared with May - November 1995, and at Bujumbura it was 3 % less in 1996 than in 1995. Adjusting the humidity values at Mpulungu for humidity at the lake shore, lowered the calculated evaporation with 12 % annually.

Monthly mean evaporation at Bujumbura was highest in August - September. At the Mpulungu buoy it was highest in 1995 in August and in 1996 in April. Maximum daily evaporation rates occurred in May and August 1995 and in July 1996, coinciding with high wind speeds.

3.7 Solar radiation

From May 1995 to December 1996 solar radiation was higher at Mpulungu (252 $W.m^{-2}$) than at Bujumbura (225 $W.m^{-2}$). At Bujumbura it was highest in September in 1993 and 1994, in August in 1995 and in April in 1996. Peaks in solar radiation at Mpulungu occurred in October 1995 and 1996 and in March 1996 (Fig. 20). At Mpulungu solar radiation during the dry and wet seasons was similar (mean 251 and 254 $W.m^{-2}$ respectively). At Bujumbura it was on average higher during the dry seasons (229 $W.m^{-2}$) than during the wet seasons (218 $W.m^{-2}$). Solar radiation was relatively high from October 1995 to April 1996 at Bujumbura (228 $W.m^{-2}$), higher than during the following dry season (223 $W.m^{-2}$).

3.8 Relative humidity

From March 1993 to May 1994 humidity at Bujumbura was significantly ($P < 0.0001$) higher than from August 1994, and humidity at 13 m was higher than at 4 m height (Fig. 21). Generally humidity higher above ground or water is less humid. Probably the sensors were not functioning properly up to May 1994. They were replaced in August 1994.

In the period August 1994 to December 1996, humidity was lowest in August - September at both stations, and maxima were reached in the wet seasons. Humidity at Mpulungu (mean 45 and 62 % in the dry and wet seasons respectively) was lower than at Bujumbura at 13 m height (63 and 73 % in the dry and wet seasons respectively). Between dry seasons and between wet seasons of different years the difference was only 1 - 2 %. The humidity at 4 m height at Bujumbura was on average 4 % higher than at 13 m height.

In the middle of the wet season (December - January), when rainfall at Bujumbura is generally less than in October - November and March - April, humidity decreased slightly at Bujumbura. This did not occur at Mpulungu, where the rainfall is generally highest in December - February. When humidity was highest at Mpulungu, in January - February, it was similar to the humidity at Bujumbura at 13 m height.

3.9 Air pressure

Air pressure was highest in June - July each year, at Bujumbura and at Mpulungu (Fig. 22). It was lowest in October - November of each year. At Bujumbura air pressure decreased with 0.6 - 0.9 mbar each year, between 1993 (mean 925.0 mbar) and 1996 (922.8

mbar). Air pressure at Mpulungu was on average 2.1 mbar lower than at Bujumbura, due to the position of the Mpulungu weather station on a hill, 40 m above the lake surface.

3.10 Air temperature

Mean monthly air temperature was generally highest in March - May and September - November at all stations. The lowest mean monthly air temperatures were reached in July at all stations, in each year. In 1996 the air temperature in July at Bujumbura (23.1 °C) and at the Mpulungu buoy (23.4 °C) was lower than in 1993 - 1995. The annual maxima were generally reached in October (Fig. 23).

The annual means for May 1995 - April 1996 and minima and maxima of mean monthly air temperature are shown in Table 4. Air temperature was on average highest at the Mpulungu buoy and lowest at Bujumbura. Only in June - August were air temperatures at the Kigoma buoy above those at the Mpulungu buoy. Only in August - October were air temperatures at Mpulungu slightly higher than at the Mpulungu buoy. There was more seasonal difference at Mpulungu and the Mpulungu buoy than at Bujumbura and the Kigoma buoy.

Air temperature at the Mpulungu buoy was on average 0.2 °C higher than at Mpulungu. This was due to the influence of the surface temperature of the lake, which was usually higher than the air temperature at 2.6 m above the lake surface. Air temperature at Bujumbura at 13 m was on average 0.4 °C lower than at 4 m height.

The difference between daily minimum and maximum temperatures was highest in the dry season, at Bujumbura and at Mpulungu.

Table 4. Annual mean, minimum and maximum values of mean monthly air temperature at Bujumbura (4 m height) and Mpulungu, and off Kigoma and Mpulungu.

	Minimum	Maximum	Annual mean (May 95 - April 96)
Bujumbura	23.1	25.5	24.0
Kigoma buoy	24.2	25.9	25.1
Mpulungu buoy	23.6	26.8	25.5
Mpulungu	23.4	26.8	25.3

3.11 Wind speed and gust

The wind speed was highest in the dry season at all stations (Fig. 24). The maximum mean monthly wind speed at Bujumbura (August - September) was usually reached two months later than at the other stations (June - August). The mean monthly wind speed was usually lowest in January. Mean annual wind speeds are shown in Table 5. It was lowest at the Bujumbura weather station at 4 m height and highest at the Mpulungu buoy. At the Mpulungu buoy the wind speeds showed the greatest seasonality. Variance in daily mean wind speed was highest at the Mpulungu buoy with maximum daily means *c.* 11 m.s^{-1} (Table 5). Maximum daily means at Bujumbura and the Kigoma wind station were *c.* 6 and 7 m.s^{-1} respectively.

Table 5. Mean annual wind speeds (m.s^{-1}) and maximum daily mean wind speeds at Bujumbura, Kigoma, Mpulungu and at the Kigoma and Mpulungu buoys, in following order of increasing mean annual wind speeds.

	Mean annual wind speed	Maximum daily means
Bujumbura weather station, 4 m height	2.20	4.11
Mpulungu weather station	2.79	6.76
Bujumbura weather station, 13 m height	3.05	5.93
Kigoma buoy	3.46	5.73
Kigoma wind station	3.55	6.82
Mpulungu buoy	3.90	10.63

The monthly maximum wind gust obtained highest values in the wet seasons, at all stations except at the Mpulungu weather station. The mean monthly maximum wind gust was between 16 and 18 m.s^{-1} at all stations, 17 - 20 m.s^{-1} in the wet season (except at the Mpulungu weather station, 15 m.s^{-1}) and 13 - 17 m.s^{-1} during the dry season. Highest wind gust was measured in October to December 1995 at the Mpulungu buoy (31 m.s^{-1}), the Kigoma buoy (30 m.s^{-1}) and the Bujumbura weather station (29 m.s^{-1}). At the Mpulungu weather station wind gust was highest in January 1996 (19 m.s^{-1}).

These maximum wind gusts occurred simultaneously with rapid and significant decreases in air temperature during the same hour (between -3.8 °C at the Mpulungu weather station and -7.2 °C at the Mpulungu buoy). Following this decrease in air temperature at the Mpulungu buoy, which occurred in November, between 2300 - 2400 h, air temperature at the buoy was 5.9 °C lower than at the Mpulungu weather station. This was unusual since in the same month, at 2400 h, air temperature at the Mpulungu buoy was on average 1.4 °C higher than at the Mpulungu weather station (Verburg, 1997b). In May 1995 - April 1996 it was on average 1.8 °C higher at the Mpulungu buoy, at 2400 h (Verburg, 1997b).

3.12 Wind direction

The different directions from which the wind blew were given by Verburg *et al.* (1997a; 1998) and Kotilainen *et al.* (1995), as monthly wind direction distributions for March 1993 - December 1996. The wind direction patterns at all stations were similar between years. Those for the Bujumbura and Mpulungu weather stations were most similar between months. The proportion of the south-east winds increased during the dry season at all stations except at the Kigoma wind station. Winds from the land were more frequent at all stations during the dry season, except at the Kigoma buoy.

At Bujumbura, the wind direction was primarily from the north and there was a slightly smaller south-south-east component. Both components were more pronounced in the dry season.

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 the Kigoma buoy the main wind direction was from the south-south-east. In October - November it was mostly from the east.

At the Mpulungu buoy, wind came primarily from the south-east during the dry season. Wind from the south-east decreased in 1996 earlier in the year (September) than in 1993 (November). In December to February 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. It only slightly increased in the dry season. In the wet season the portion of the wind coming from the north slightly increased.

3.13 Wind vector components

Seasonal patterns of the 4 wind vector components were similar at Bujumbura and at the Mpulungu buoy and weather station (Figs 25, 28 and 29). The south and east wind components were in general higher than the north and west components.

The south and east wind components were generally highest in the dry season, around the lake. The north and west wind components generally increased slightly in the wet season. At the Mpulungu buoy seasonality was greatest.

At the Kigoma wind station the east and west wind component were generally highest of all components and the south wind was the lowest (Fig. 26). At the Kigoma buoy the south wind was the highest wind component (Fig. 27).

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. Comparisons of the annual means were similar.

Diel maxima of wind vector components were highest at stations where they were lake 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.

3.14 Lake Level

Lake levels reached an annual maximum in April-May and a minimum in October-November (Fig. 30). The data collected with the Telog recorders at Mpulungu and Kigoma agreed well with the data collected with conventional gauge plates (Fig. 31). From March 1993 to March 1997, the lake level declined with 1.40 m. This was for a large part due to a relatively large fall in the dry season of 1993 (1.11 m, Table 6) and a relatively small subsequent rise in lake level during the wet season of 1993-94 (0.45 m). The lake level fall was smallest in 1995, in spite of the larger evaporation calculated for 1995 at Bujumbura and Mpulungu, compared with the calculated evaporation for 1996. The annual lake level rise was largest in the wet season of 1994-95, coinciding with the highest annual rainfall at Kigoma and Mpulungu during 1993 - 1996 (Table 6).

Table 6. Annual rises and falls in lake level (m), and rainfall at Kigoma and Mpulungu (mm).

	Falls	Rises	Rainfall at Kigoma	Rainfall at Mpulungu
dry seasons:				
1993	1.11		826	1012
1994	0.93		926	1291
1995	0.80		1008	1091
1996	0.89		1025	N.A.
wet seasons:				
1993-94		0.45	821	1176
1994-95		0.97	1078	1262
1995-96		0.63	1019	1060

4. DISCUSSION AND CONCLUSIONS

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

The density based buoyancy differences are affected by heat exchange, between water masses and between the lake water and its surroundings. The rate of heat exchange of the epilimnion with the atmosphere depends on factors such as radiation, humidity, air temperature and evaporative cooling. Annual patterns in these parameters are discussed in this report, as diel patterns were by Verburg (1997).

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

Upwelling at the south end of Lake Tanganyika can bring up anoxic water from the hypolimnion to within 80 m of the surface, due to the relative steep southern end of the lake basin. This may have influenced the evolution of the demersal fish community in Lake Tanganyika. In Lake Malawi, the shallow area at the southern end of the lake is relative large, and upwelling does not bring anoxic water over this area (Allanson, 1990).

During the dry season, which has moderate precipitation and strong, regular southerly winds, a global wind convergence zone is located in the region. Changes in the seasons are regulated by the austral and boreal trade winds, which determine the dynamics of the Inter-Tropical convergence Zone (ITCZ) and its active wet zone movement.

A coastal, diurnal, slope-lake breeze system, intensified during the dry season, while southeasterly trade winds supplied the main input of energy to the middle of the lake.

During the dry season the position of the Inter Tropical Convergence Zone (ITCZ) is found far north of Lake Tanganyika (Asnani, 1993). The local winds are then mainly caused by the temperature differences between the rift lake and the sloping coastline (Podsetchine *et al.*, 1996). Lake winds blow during the day and land winds during the night (Beauchamp, 1939; Verburg, 1997; Savijärvi, 1997). Wind speeds from the lake were higher than from the land at Bujumbura and Kigoma. 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 occurred between 1993 and 1996 are due to differences in the position of the ITCZ (Asnani, 1993).

During the wet season stratification and a strong thermocline develops and little exchange of water between epilimnion and metalimnion occurs.

In the cool dry season, epilimnion temperatures fell to values close to those of the hypolimnion, particularly in the south of the lake. The density differences between the two water masses decreased, thus facilitating mixing when wind speeds exceeded a certain threshold. In the dry season, wind speeds were high, and mixing was strong, particularly in the south.

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 accelerated 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.

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

Off Bujumbura stable, stratified lake conditions developed later in the wet season than in the south, since off Bujumbura surface water temperature was generally lowest during the first half of the wet season (October - January) and highest late in the wet season, from April to May.

The Wedderburn values found here for off Mpulungu are lower than expected since values $W < 1$ are supposed to indicate unstable conditions (Monismith, 1986; Horne and Goldman, 1994). Values for $W < 1$ occurred for a large part of the year off Mpulungu. An increase or decrease in epilimnion depth (h) by 5 m, changed the Wedderburn number by *c.* 30 %. An epilimnion depth of 50 m gives a Wedderburn number *c.* 2x that found with h = 35 m. The seasonal thermocline tended to be deeper off Kigoma than off Mpulungu. The seasonal thermocline off Kigoma was between 40 - 80 m depth. Off Mpulungu, the thermocline surfaced in July - August, and was located the rest of the year at *c.* 40 m depth. This would, if taken into account for the determination of h, increase the calculated differences in W from north to south, with lower W at the south end of the lake.

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

Patterson and Kachinjika (1995) and Patterson *et al* (1995) reported for Lake Malawi lower Wedderburn numbers for the dry season of 1993 compared with 1992 and 1994, which corresponded with findings represented here for Lake Tanganyika.

Since in the calculation of Wedderburn numbers daily means of the input data were used, variance in Wedderburn numbers over the day was ignored. Wind speed can reach high values for several hours, and mixing can increase during part of the day (Verburg, 1997).

Between 1993 and 1995 air temperature increased due to increased solar radiation, and a decrease in wind speeds from the south occurred lake wide. As a result the water column warmed up. In 1996 solar radiation was lower than in 1995 and a concomitant decrease in air temperature occurred. In the south and north a further decrease of wind speed in 1996 prevented waters from cooling. But off Kigoma, wind speeds picked up again in 1996, and with the lower air temperature, evaporative cooling was enhanced, and the upper water layers off Kigoma were comparatively cool in 1996. This pattern was confirmed by an increasing Wedderburn number (W) each year between 1993 and 1996 off Mpulungu (Table 2), while off Kigoma W was lower in the dry season of 1996 than in 1995 (although there were less days with $W < 1$ in 1996 than in 1995). Upwelling and mixing intensity therefore was less each year from 1993 to 1996 off Mpulungu, and off Kigoma mixing was somewhat more intense in 1996 than in 1995.

Temperature distributions indicated less mixing of the epilimnion in the south in the dry seasons of 1995 and 1996, compared with 1993 and 1994. The decrease in wind speed in the dry seasons from 1993 to 1996 was mainly due to less wind from the south and therefore probably due to variability in the trade wind system. It coincided with a decreasing air pressure each year from 1993 to 1996. The differences between 1993 and 1996 were highest in the south and occurred mainly between the dry seasons. The increase in air temperature was highest in the south (*c*. 0.4 °C at Bujumbura between the dry seasons of 1993 and 1995, and *c*. 0.5 °C increase at the Mpulungu buoy).

Nutrient regeneration from the hypolimnion by upwelling was probably less in 1995 and 1996 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 and 1996. 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 1996 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 in the dry season lower Wedderburn numbers 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 vertical differences in water density. 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.

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

Evaporation was highest in August - September, when the lake was warming up rapidly. Evaporative cooling was apparently offset by increased heat supply to the lake.

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

The calculated evaporation at Mpulungu (2725 $mm.yr^{-1}$) 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 increasing vapour pressure of the air downwind across an open water surface (Linsley *et al.*, 1988), and winds coming generally from the south, along the length of the lake, especially in the windy dry season.

At Mpulungu during the wet season, solar radiation was probably more intense during periods of little or no cloud cover, than in the dry season. At Mpulungu the mean mid-day maximum of solar radiation was higher during the wet season than during the dry season, unlike at Bujumbura (Verburg, 1997).

As shown by Verburg *et al*. (1997), the temperature of the surface layer of the lake water was on average several degrees (°C) higher than the temperature of the air a few metres above the lake, since lakes at high altitude and low latitude receive relatively more heat from the sun than those near sea level or nearer the north and south poles (Horne and Goldman, 1994).

In 1996, the annual mean lake level fell below 774 m for the first time since 1961 (Fig. 32), only 50 cm above the lowest lake stand of this century, which was reached in 1950 (Camus, 1965). The decline in lake level from 1993 to 1997 was primarily caused by the large difference between the fall in 1993 and the subsequent rise in the wet season of 1993-94. After the 1993-94 wet season, annual falls and rises were more alike, a mean 0.87 and 0.80 m respectively. These values were close to those mentioned by Bultot (1965) for 1941 to 1959, a period in which the lake level was also declining, 0.82 and 0.77 m respectively. Annual lake level rises correlate well with rainfall in the catchment area (Piper *et al.* 1986). Annual falls are at Lake Tanganyika primarily mediated by evaporation and generally do not vary much from year to year. However, in the dry season of 1993 relatively high wind speeds may have caused high evaporation.

Long term lake level rises tend to be more rapid than lake level declines (Fig. 32), reflecting the impact of exceptional high rainfall in some years, as in 1962 and 1963, close to average rainfall in most years, and relatively small differences in annual evaporation.

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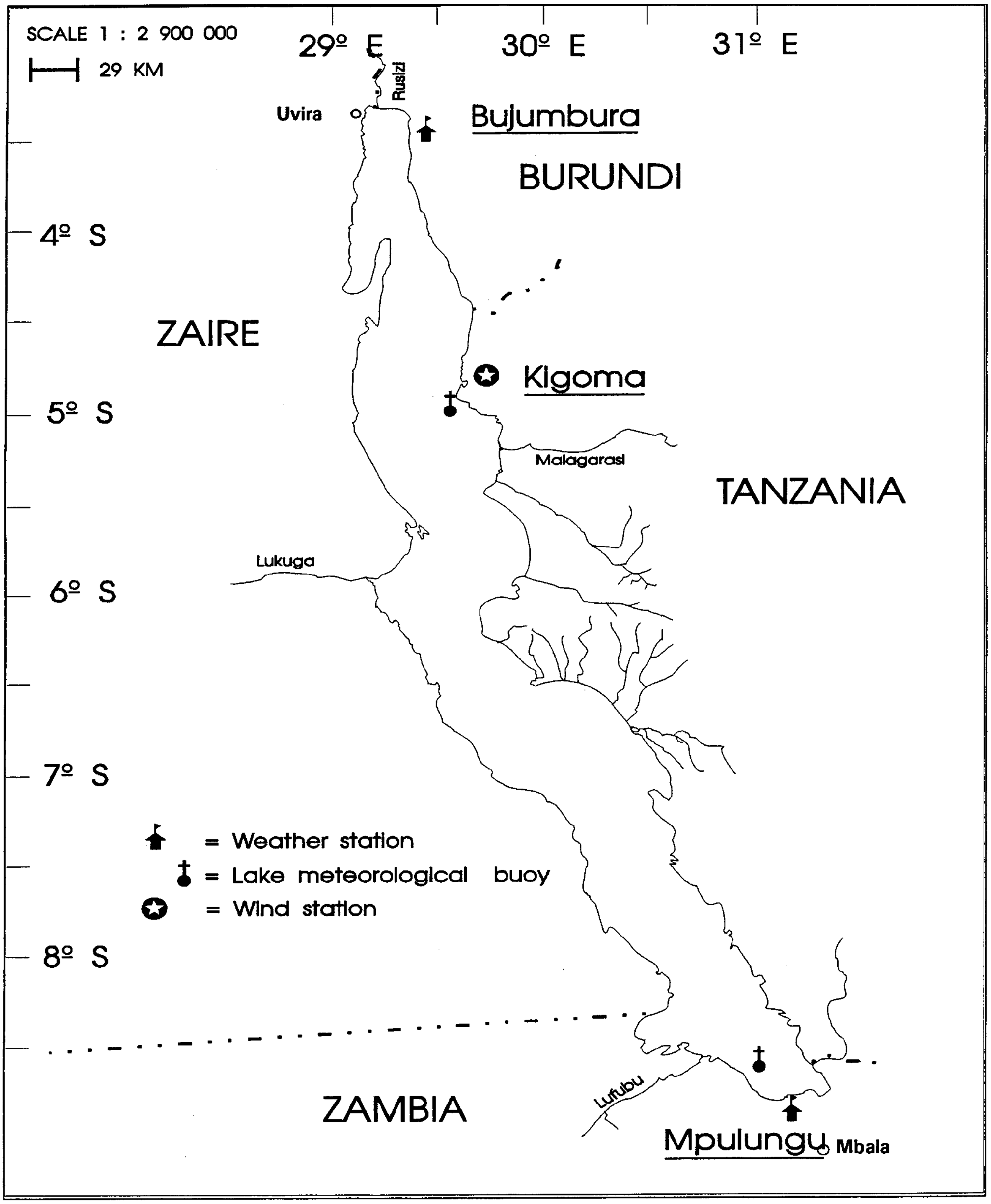


Figure 1. The positions of the meteorological instruments at Lake Tanganyika.

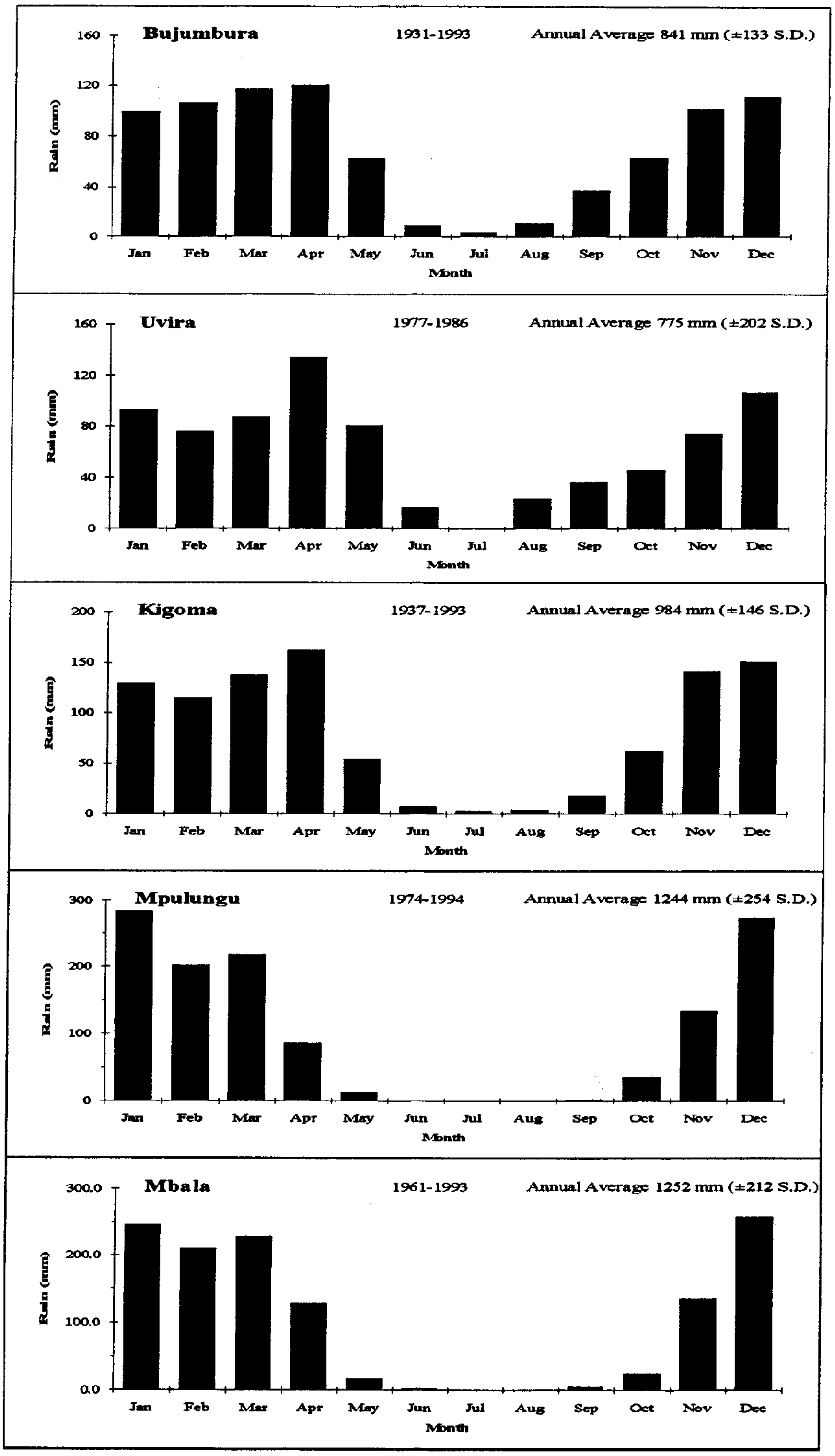


Fig. 2. Mean monthly rainfall on or near the shores of Lake Tanganyika, at Bujumbura (Burundi), Kigoma (Tanzania), Mpulungu and Mbala (Zambia) and Uvira (Zaire). Data supplied by respective national meteorological services. The data collection period and the annual average are mentioned. Note that the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

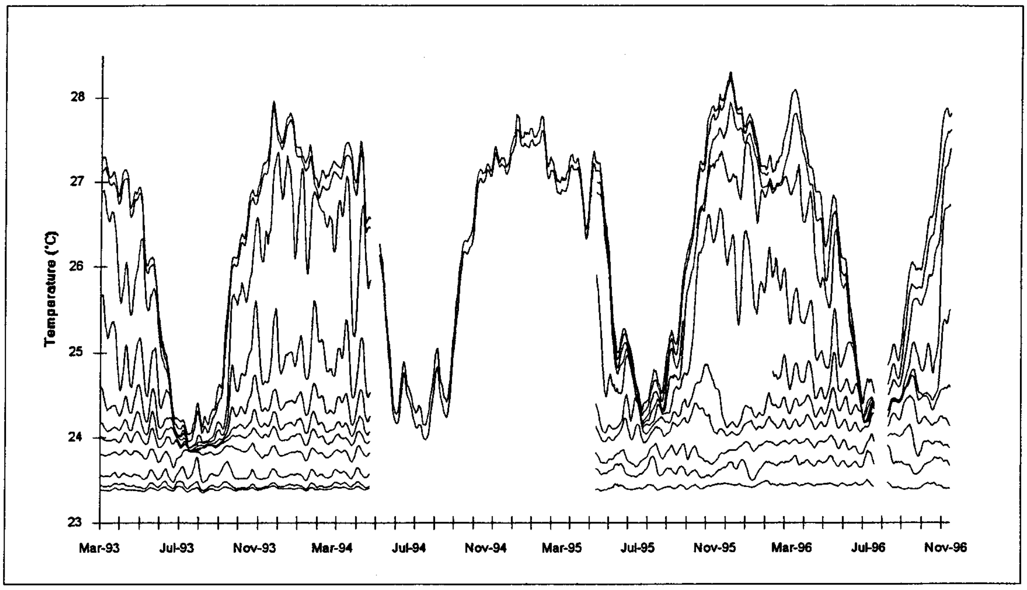


Figure 6. Seven day running averages of water temperatures at the Mpulungu buoy. Water depths were 1, 5, 30, 50, 70, 90, 110, 150, 200, 250 and 300 m up to May 1994, 1 and 5 m from May 1994 to May 1995, 1, 5, 15, 30, 50, 90, 110, 150, 200 and 300 m from May 1995 to January 1996, and 1, 15, 30, 50, 70, 90, 110, 150, 200 and 300 m from February to November 1996.

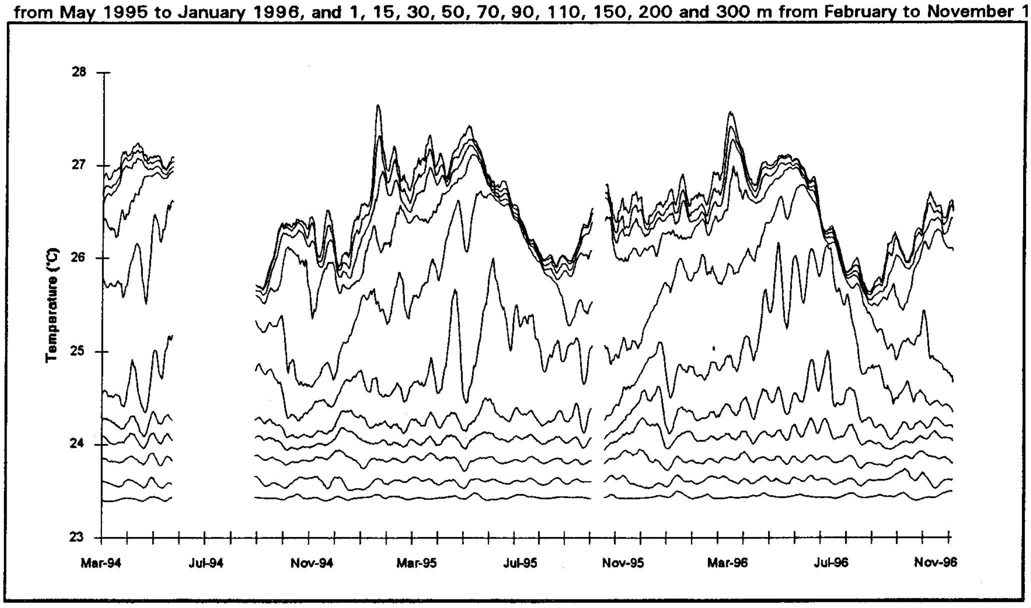


Figure 7. Seven-day running averages of water temperatures at the Kigoma buoy. Water depths were 1,5, 15, 30, 50, 70, 90, 110, 150, 200 and 300 m.

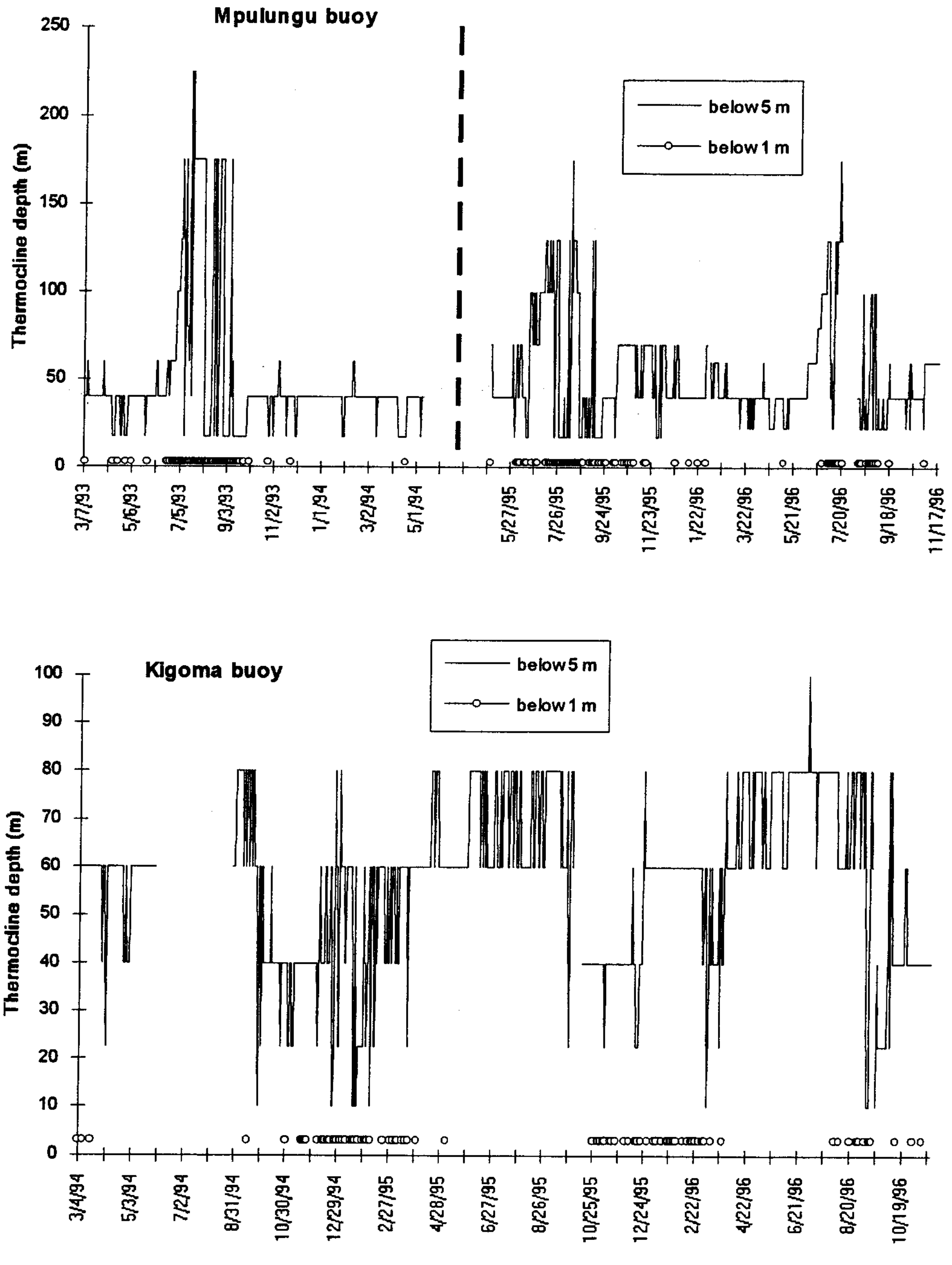


Figure 8. Daily thermocline depth (depth of steepest density gradients between thermistor sensors, below 5 m depth). Days on which the gradient was steepest between 1 and 5 m depth are shown with open circles (generally the wet season at Kigoma and the dry season at the Mpulungu buoy).

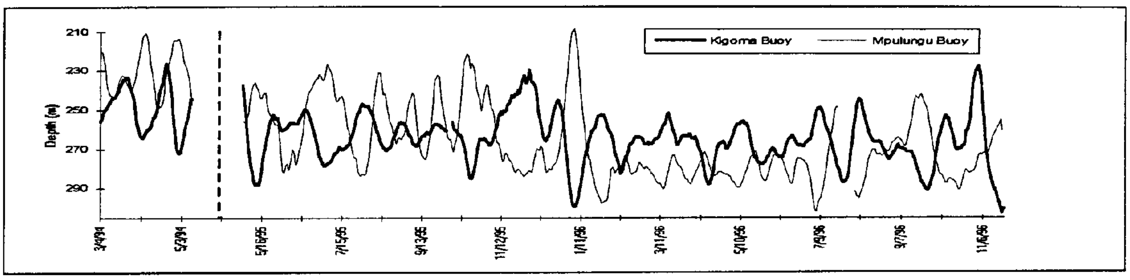


Figure 9. Seven-day running averages of depths of the 23.5° C isotherm at the Kigoma and Mpulungu buoys.

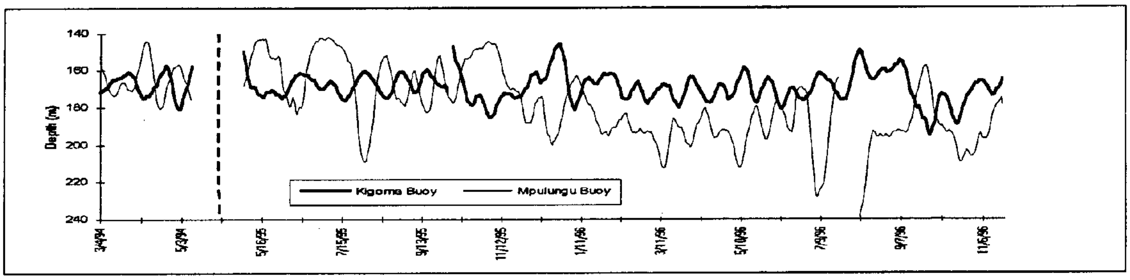


Figure 10. Seven-day running averages of depths of the 23.75° C isotherm at the Kigoma and Mpulungu buoys.

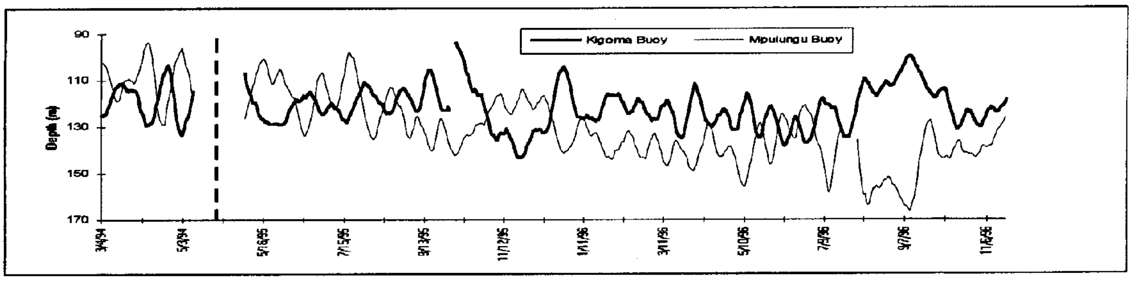


Figure 11. Seven-day running averages of depths of the 24.0° C isotherm at the Kigoma and Mpulungu buoys.

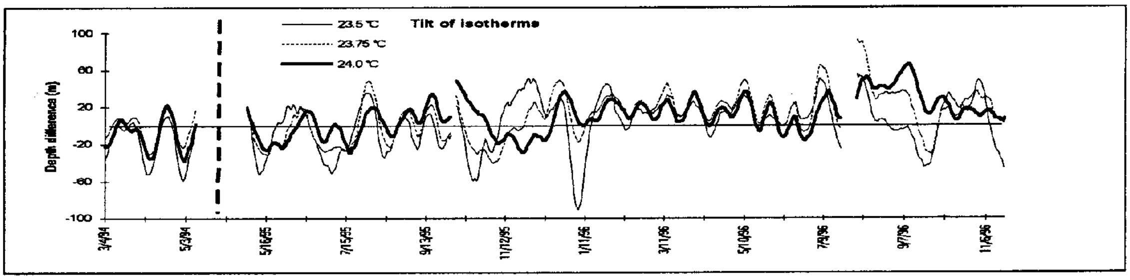


Figure 12. Seven-day running averages of the tilt of isotherms between the Mpulungu and Kigoma buoys, for 4 March 1994 - 11 May 1994 and 2 May 1995 - 20 November 1996, The depth of the isotherms at the Kigoma buoy is subtracted from the respective depths at the Mpulungu buoy.

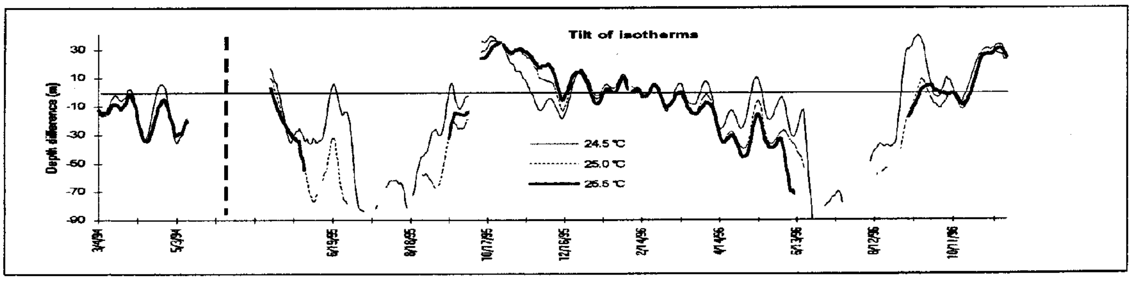


Figure 13. Seven-day running averages of the tilt of isotherms between the Mpulungu and Kigoma buoys, for 4 March 1994 - 11 May 1994 and 2 May 1995 - 20 November 1996, The depth of the isotherms at the Kigoma buoy is subtracted from the respective depths at the Mpulungu buoy.

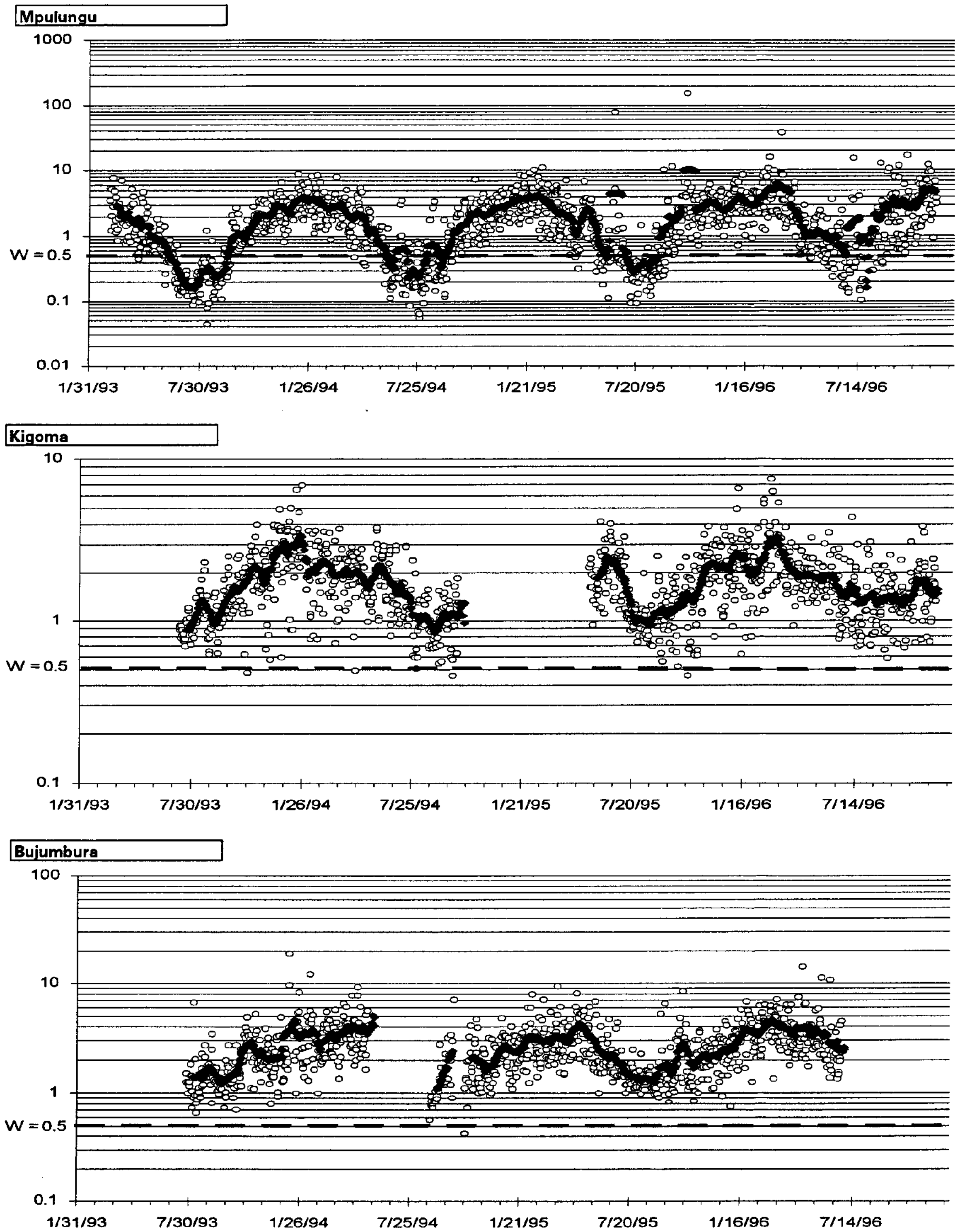


Fig. 14. Daily values of Wedderburn numbers (open circles) off Mpulungu, Kigoma and Bujumbura, with a 21 day running average to indicate the main seasonal trends (with epilimnion depth = 50 m). Notice the different scales. W = 0.5 is indicated by a broken line.

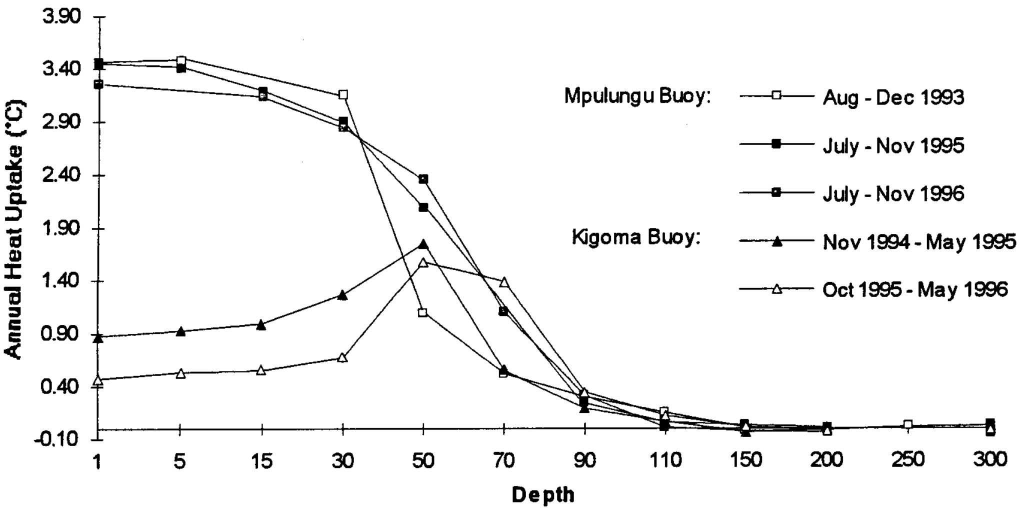


Figure 15. Annual heat uptake (°C), between minimum and maximum heat content at the Mpulungu and Kigoma buoys, versus depth.

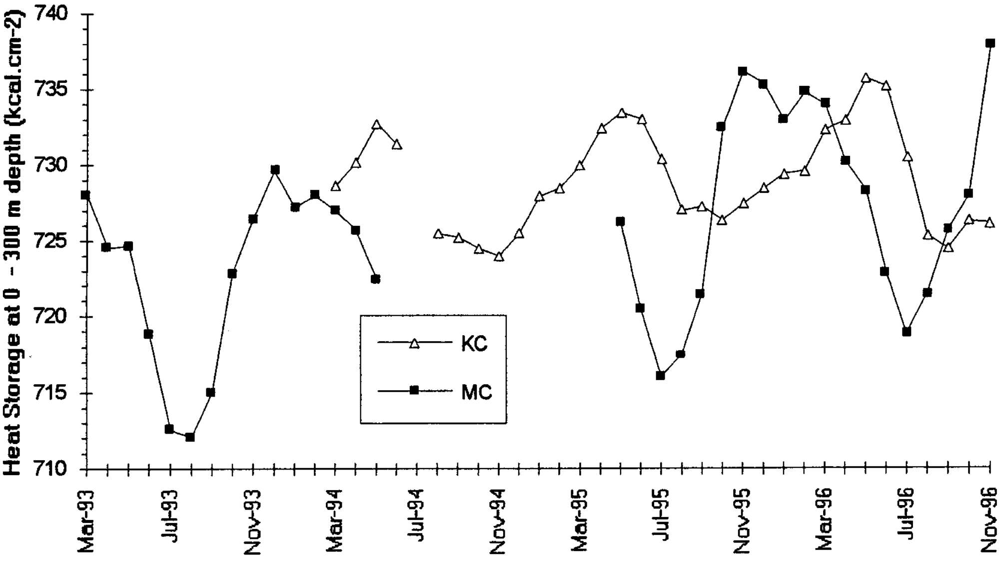
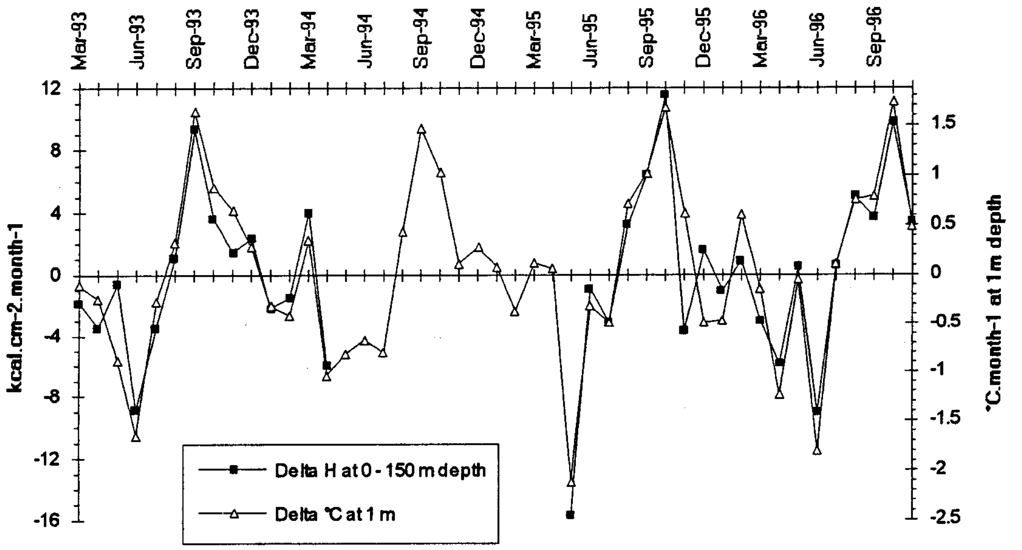


Figure 16. Monthly mean heat content down to 300 m, at the Mpulungu (MC) and Kigoma (KC) buoys.

A. Mpulungu buoy



B. Kigoma buoy

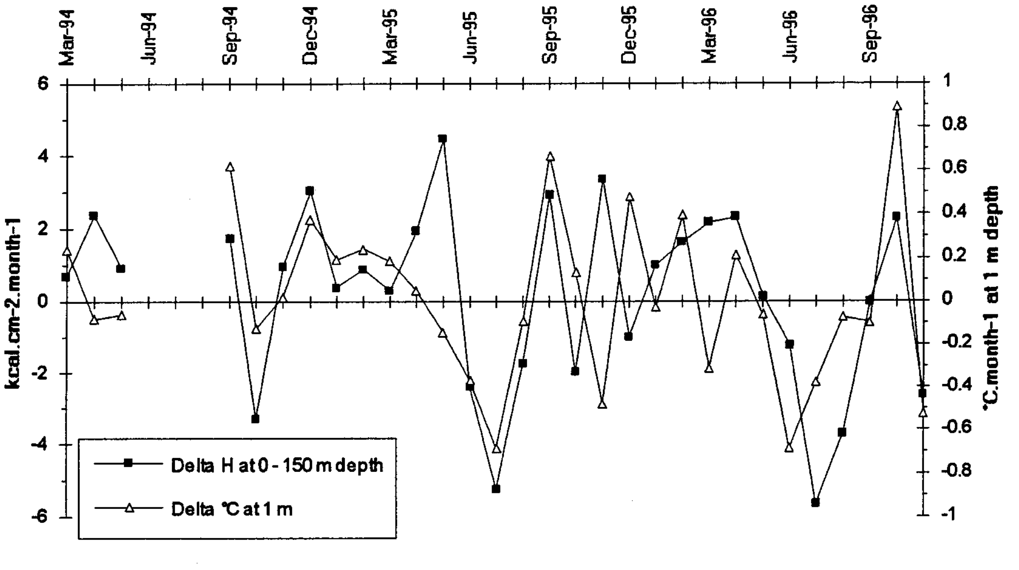


Figure 17. Monthly heat storage rate in upper 150 m, and monthly change in temperature at 1 m depth, at the Mpulungu buoy (A) and Kigoma buoy (B).

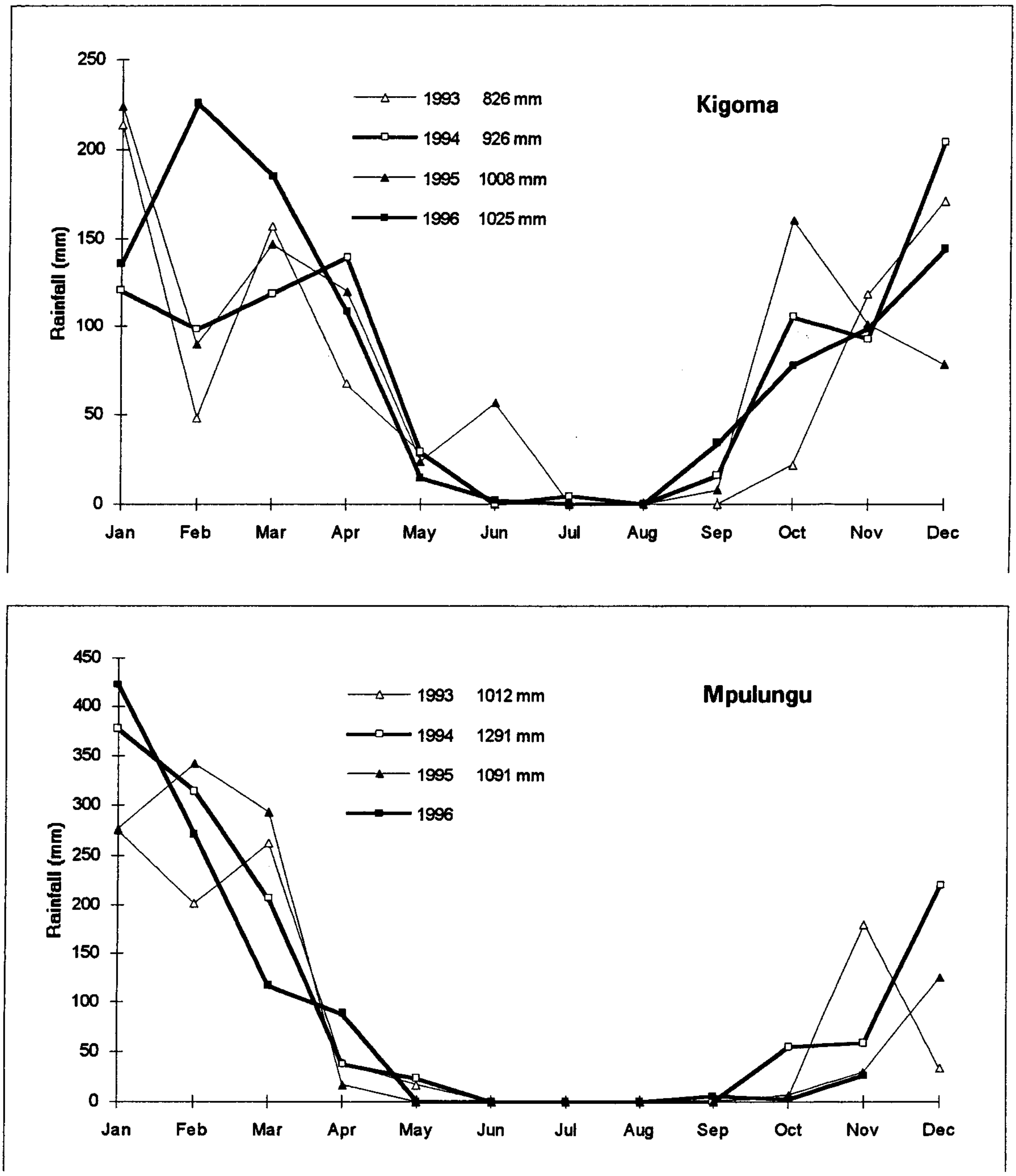


Fig. 18. Monthly rainfall at Kigoma and Mpulungu. Note that the y-axes are not drawn to the same scale.

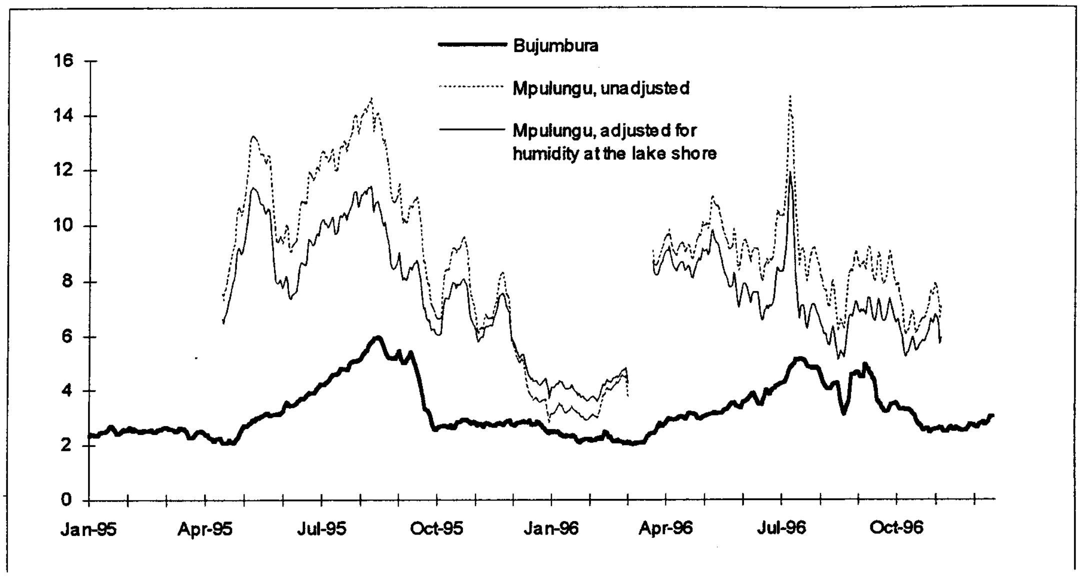


Figure 19. Twentyone-day running averages of evaporation, calculated for Bujumbura harbour and the Mpulungu buoy.

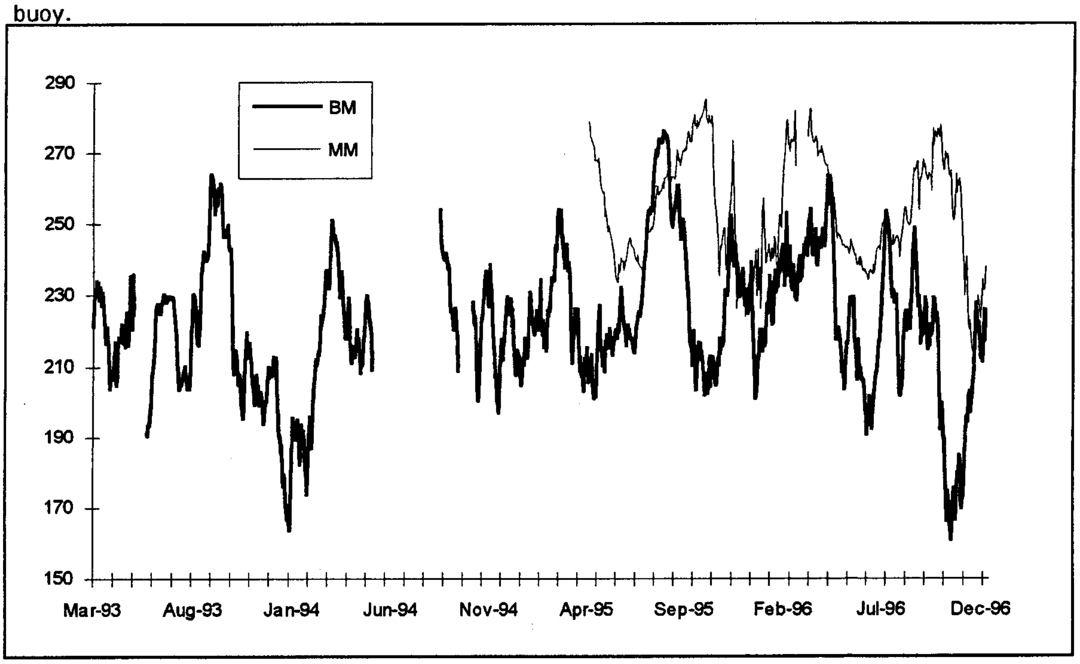


Figure 20. Twentyone-day running averages of solar radiation at the Bujumbura and Mpulungu weather stations.

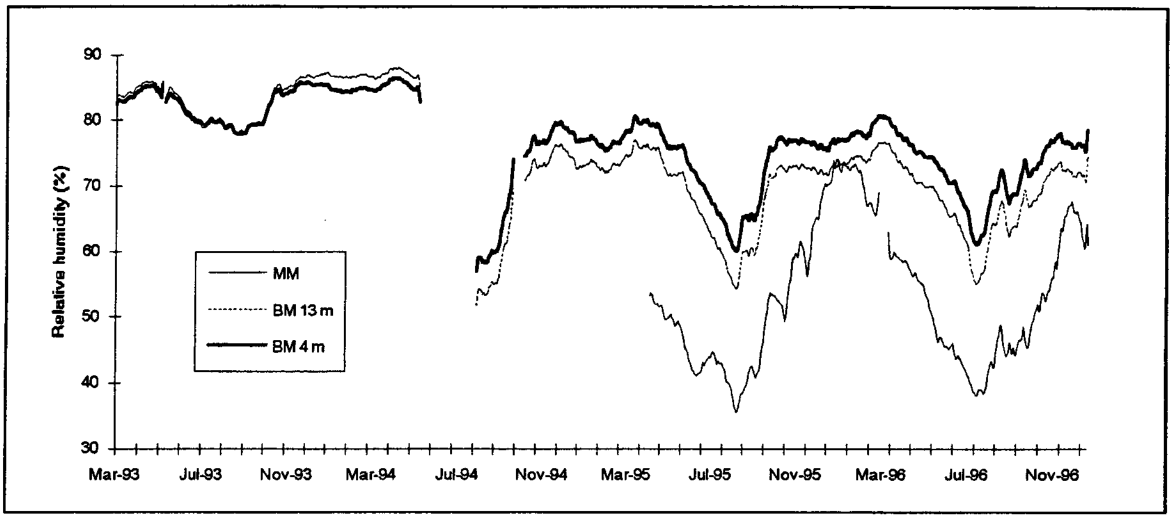


Figure 21. Twentyone- day running averages of humidity for the Mpulungu (MM, 9.5 m height) and Bujumbura (BM, 4 and 13 m height) weather stations.

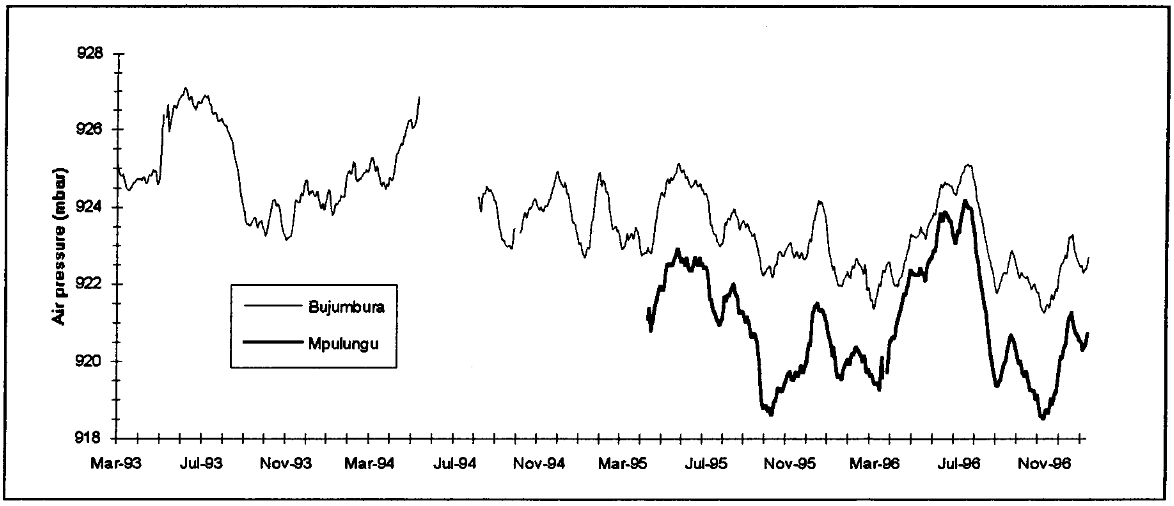


Figure 22. Twentyone-day running averages of air pressure for the Bujumbura and Mpulungu weather stations, for March 1993 - December 1996.

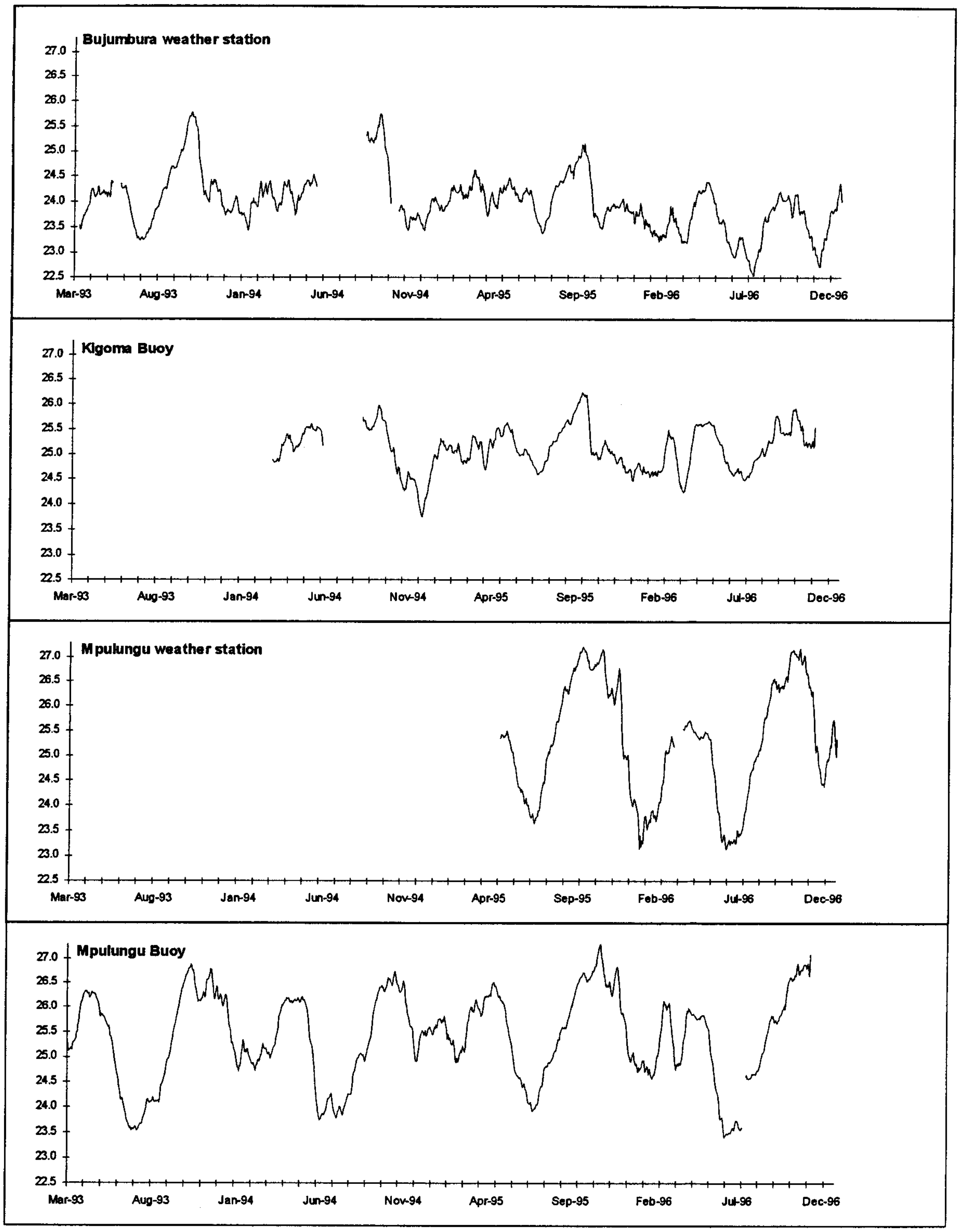


Figure 23. Twentyone-day running averages of air temperature at Bujumbura and Mpulungu, and off-shore near Kigoma and Mpulungu.

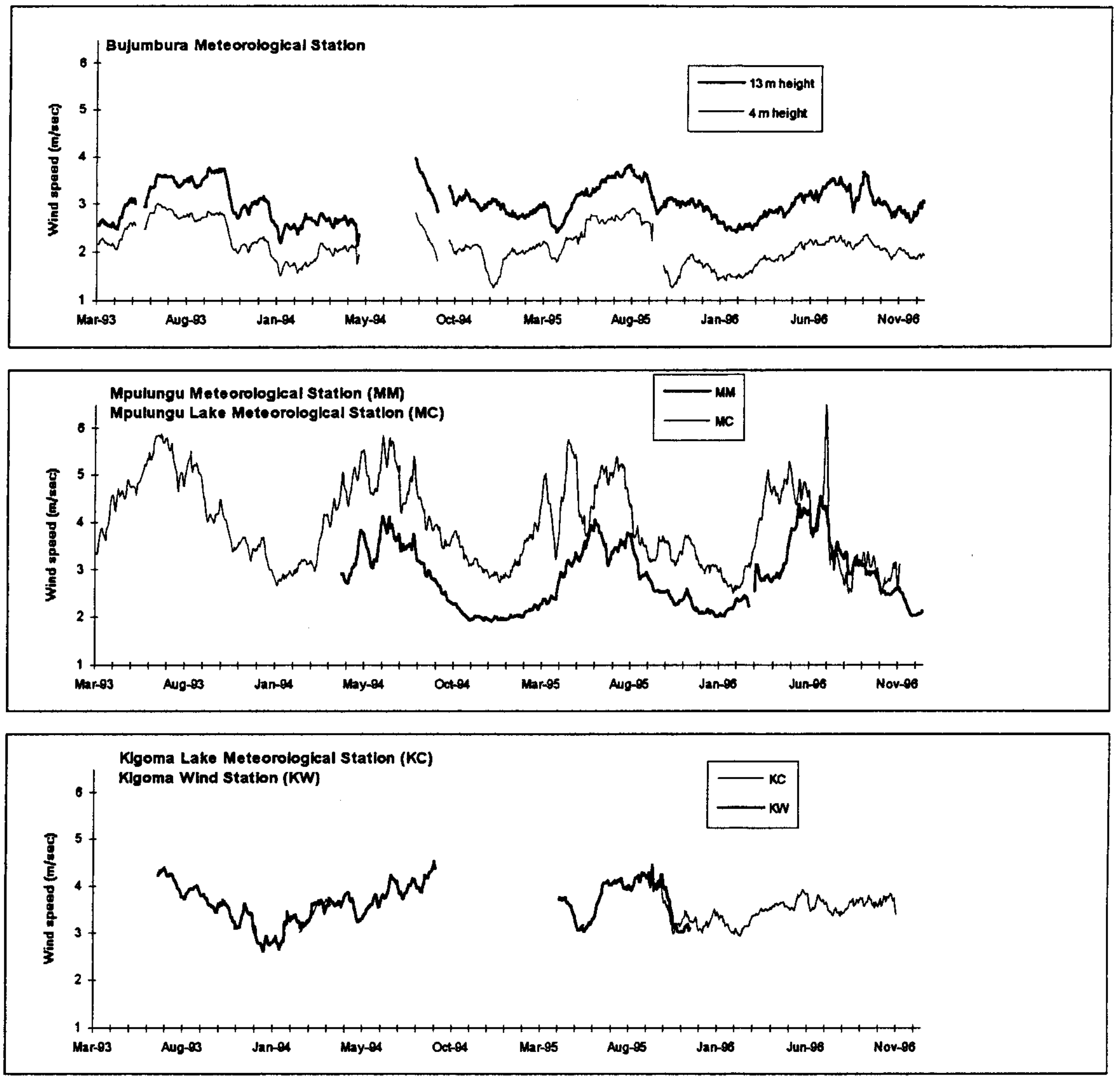


Figure 24. Twentyone-day running averages of wind speed for Bujumbura, Kigoma and Mpulungu meteorological stations (the latter two both on land and off-shore), for 7 March 1993 - 31 December 1996.

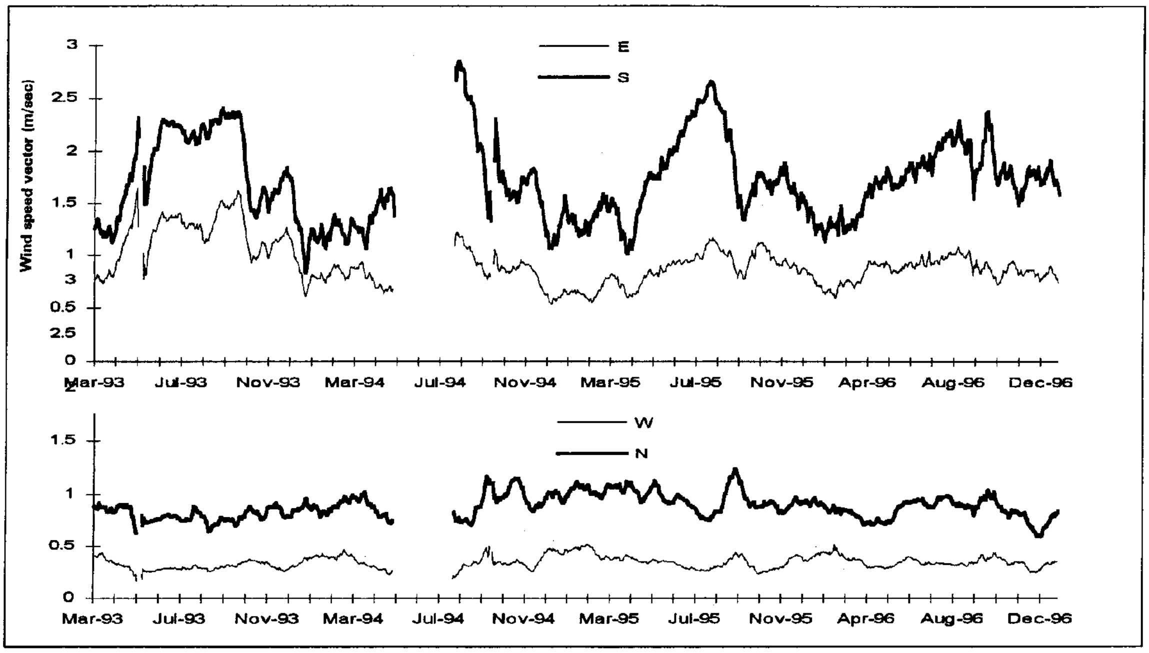


Figure 25. Twentyone-day running averages of wind speed vector components at Bujumbura for March 1993 - December 1996.

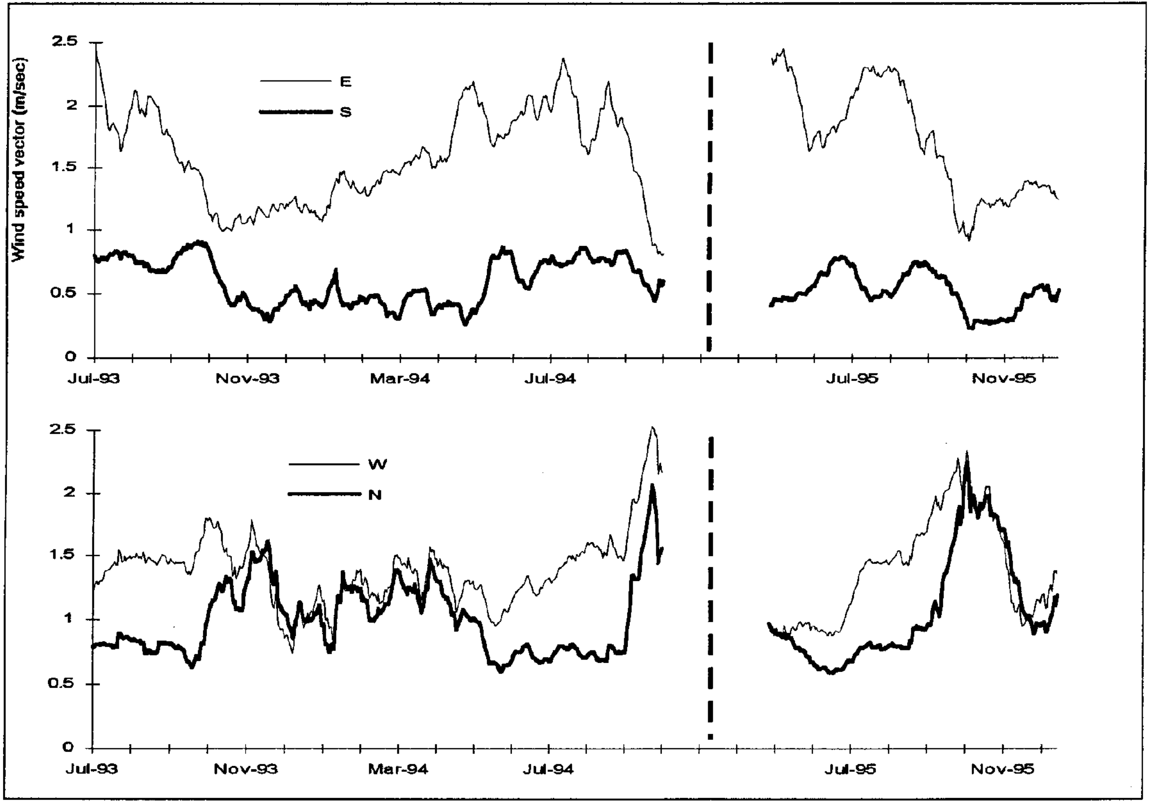


Figure 26. Twentyone-day running averages of wind speed vector components at the Kigoma wind station for July 1993 - October 1994 and May 1995 - December 1996.

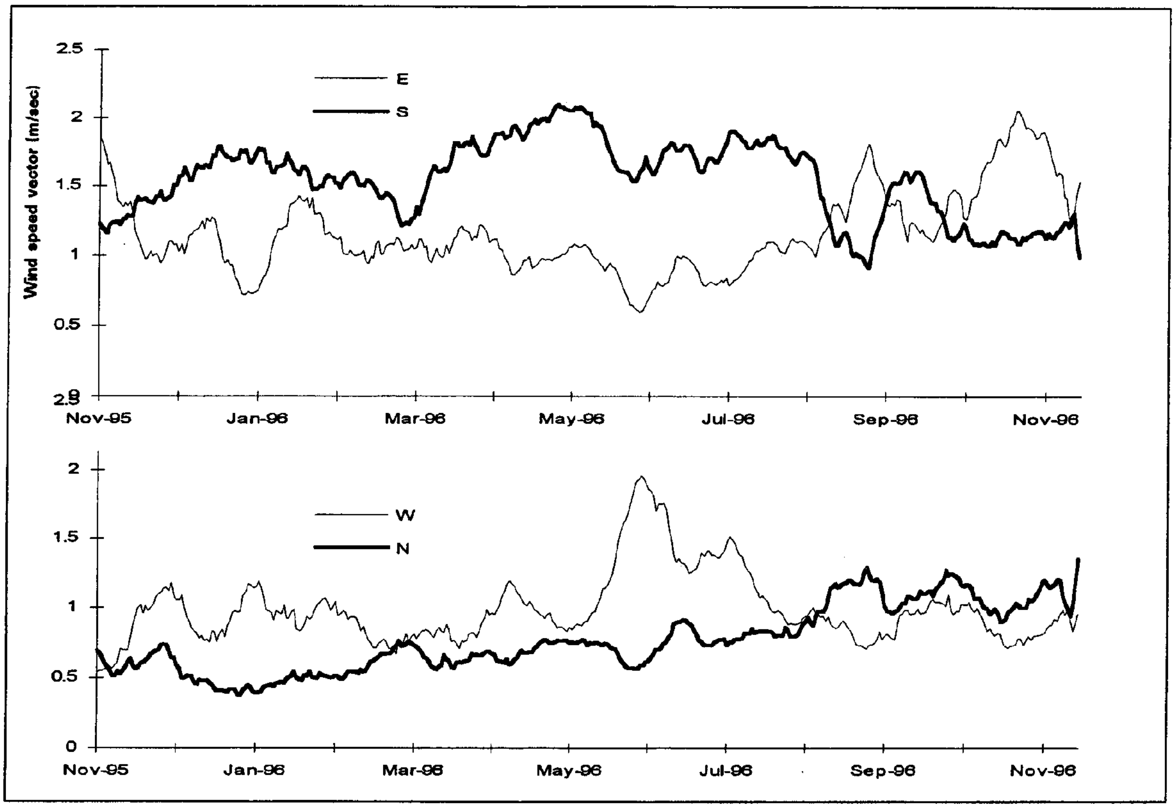


Figure 27. Twentyone-day running averages of wind speed vector components at the Kigoma buoy for November 1995 - November 1996.

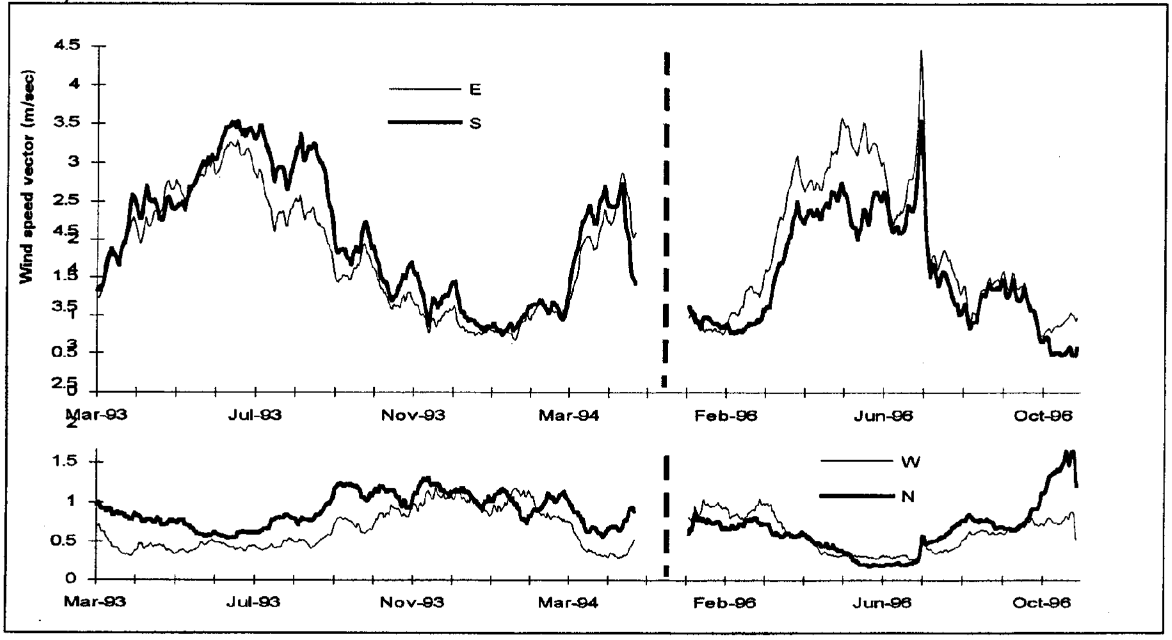


Figure 28. Twentyone-day running averages of wind speed vector components at the Mpulungu buoy for March 1993 - May 1994 and February - November 1996.

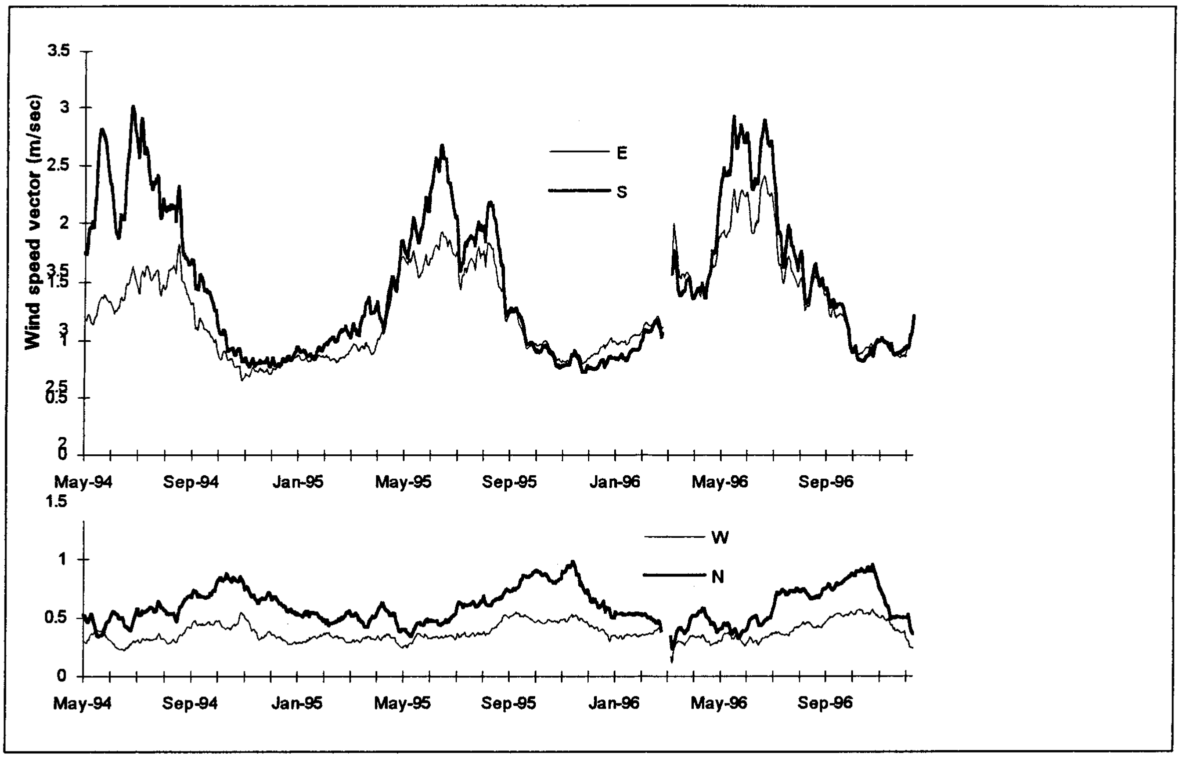


Figure 29. Twentyone-day running averages of wind speed vector components at the Mpulungu weather station for May 1994 - December 1996.

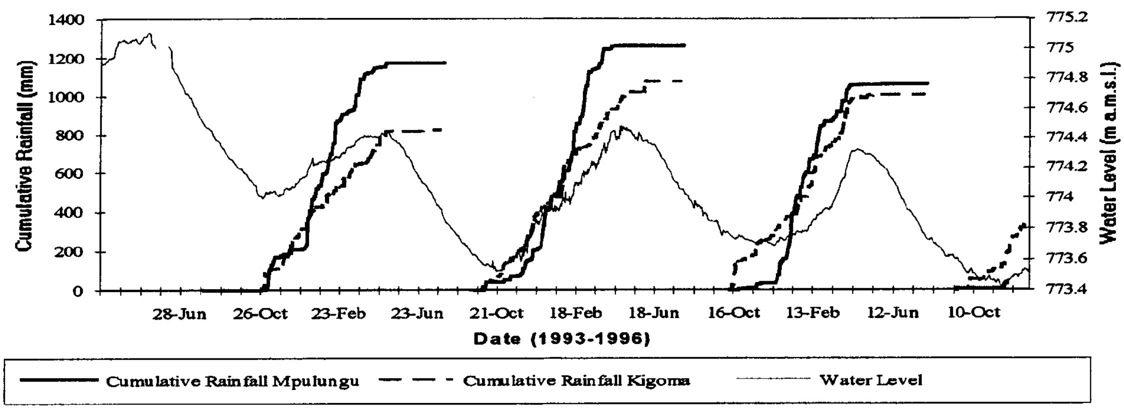


Fig. 30. Daily water level and cumulative rainfall at Mpulungu and Kigoma.

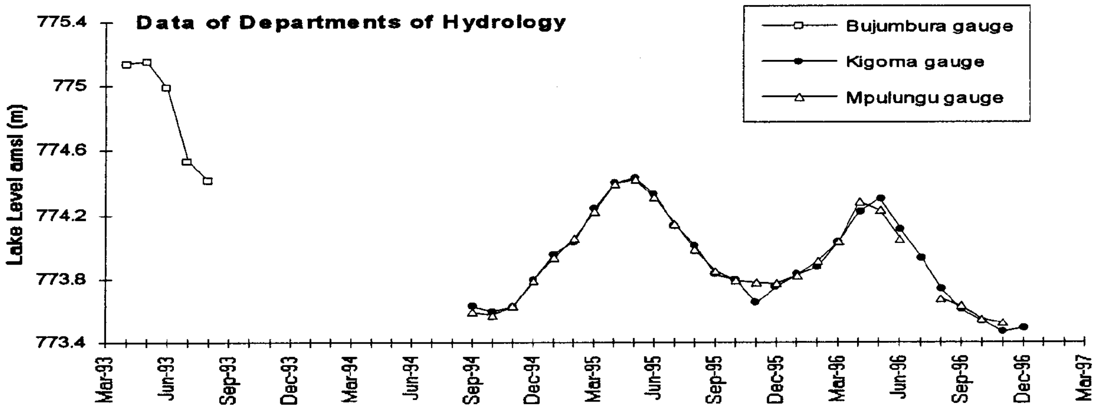


Fig. 31. Monthly mean water levels measured with conventional gauge plates by the Hydrology Departments of the riparian countries.

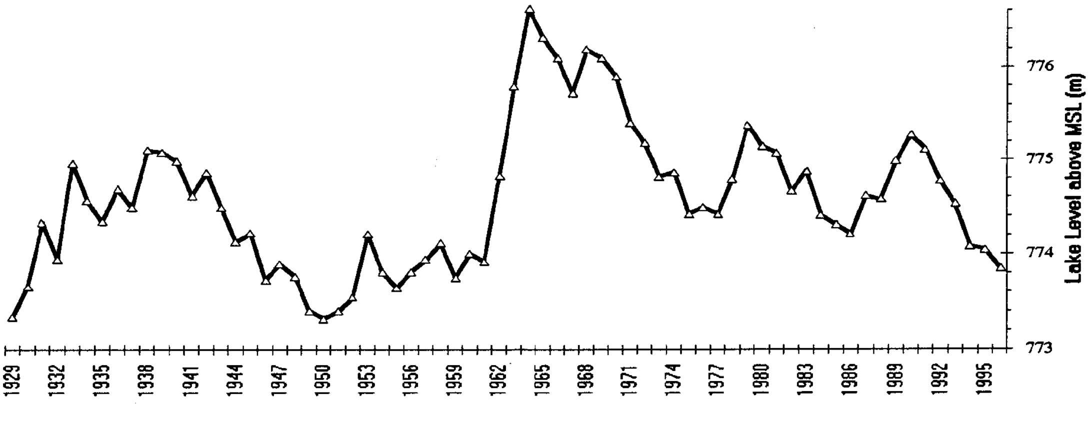


Fig. 32. Annual mean water level, 1929 -1996.

APPENDIX I

Table A1. Means of parameters measured at the Bujumbura weather station, at 13 and at 4 m height, for dry (May - September) and wet (October - April) seasons, with the number of days with measurements.

	Wind speed m/s, at 13 m	Wind gust m/s, at 13 m	Air temp °C, at 13 m	Humidity %, at 13 m	Solar radiation W/m², at 13 m	Air pressure mbar, at 13 m	Wind speed m/s, at 4 m	Humidity %, at 4 m	Air temp °C, at 4 m
Dry seasons:									
1993	3.47	4.59	23.64	81	224	925.83	2.78	80	24.09
1994	3.23	4.29	24.74	67	236	924.67	2.33	69	25.08
1995	3.35	4.47	24.04	65	236	924.01	2.57	70	24.27
1996	3.20	4.31	23.89	65	223	923.60	2.14	70	23.54
Wet seasons:									
1993	2.58	3.67	23.32	84	219	924.79	2.17	83	23.94
1993-94	2.82	3.94	23.57	86	212	924.30	2.05	84	24.23
1994-95	2.94	4.06	23.56	74	222	923.70	1.95	77	23.95
1995-96	2.82	4.11	23.54	73	228	922.59	1.65	77	23.71
1996	2.93	4.18	23.84	71	199	922.17	2.03	75	23.56
Nr of days:									
Dry seasons:									
1993	129	129	129	129	129	129	129	129	129
1994	52	52	52	52	52	52	52	52	52
1995	153	153	153	153	152	153	93	153	153
1996	120	120	153	153	153	153	142	153	153
Wet seasons:									
1993	50	50	50	50	50	50	50	50	50
1993-94	212	212	212	212	212	212	212	212	212
1994-95	193	193	192	192	191	193	192	192	192
1995-96	208	208	208	208	208	208	181	208	208
1996	82	82	92	92	92	92	84	92	92

Table A2. Means of parameters measured at the Kigoma buoy, for dry (May - September) and wet seasons (October - April), with the number of days with measurements.

	Wind speed	Wind gust	Air temp	Water temp (°C), at depth (m):										
	m/s	m/s	°C	1	5	15	30	50	70	90	110	150	200	300
Dry seasons:														
1994	2.64	3.76	25.66	26.46	26.43	26.36	26.24	25.84	24.86	24.26	24.07	23.85	23.59	23.43
1995			25.31	26.48	26.45	26.40	26.32	26.07	25.15	24.31	24.06	23.82	23.61	23.44
1996	3.60	5.19	25.10	26.34	26.31	26.24	26.15	25.94	25.38	24.45	24.10	23.83	23.62	23.45
Wet seasons:														
1994	3.53	5.12	25.11	27.05	26.96	26.87	26.54	25.78	24.55	24.22	24.04	23.83	23.58	23.41
1994-95	2.16	3.43	24.86	26.70	26.59	26.45	26.16	25.40	24.63	24.21	24.03	23.84	23.60	23.43
1995-96	3.27	4.95	24.90	26.78	26.67	26.56	26.36	25.66	24.84	24.35	24.09	23.84	23.61	23.44
1996	3.69	5.33	25.42	26.40	26.34	26.21	26.05	25.03	24.49	24.22	24.07	23.87	23.63	23.44
Nr of days:														
Dry seasons:														
1994	64	64	64	64	64	64	64	64	64	64	64	64	64	64
1995			153	153	153	153	153	153	153	153	153	153	153	153
1996	149	149	149	151	151	151	151	151	151	151	151	151	151	151
Wet seasons:														
1994	58	58	58	58	58	58	58	58	58	58	58	58	58	58
1994-95	208	208	212	212	212	212	212	212	212	212	212	212	212	212
1995-96	181	181	204	204	204	204	204	204	204	204	204	204	204	204
1996	53	53	53	53	53	53	53	53	53	53	53	53	53	53

Table A3. Means of parameters measured at the Mpulungu buoy, for dry (May - September) and wet seasons (October - April), with the number of days with measurements.

	Wind spee	Wind gust	Air temp	Water temp (°C), at depth (m):											
	m/s	m/s	°C	1	5	15	30	50	70	90	110	150	200	250	300
Dry seasons:															
1993	5.06	7.17	24.65	24.99	24.90		24.64	24.31	24.12	24.01	23.94	23.81	23.58	23.44	23.40
1994	4.84	6.99	24.79	24.97	24.81		25.90	24.53	24.24	24.06	23.96	23.81	23.56	23.43	23.40
1995	4.60	6.87	25.15	25.32	25.23	25.07	24.99	24.59		24.23	24.07	23.79	23.62		23.41
1996	3.97	6.13	24.81	25.49		25.28	25.12	24.73	24.52	24.41	24.22	23.96	23.71		23.44
Wet seasons:															
1993	3.85	5.55	25.81	27.06	26.95		26.23	25.11	24.40	24.13	23.99	23.82	23.56	23.44	23.39
1993-94	3.51	5.61	25.79	27.16	27.05		26.42	24.95	24.41	24.16	24.01	23.83	23.57	23.44	23.40
1994-95	3.47	5.64	25.81	27.18	27.06										
1995-96	3.30	5.51	25.77	27.51	27.50	27.21	26.84	25.84	24.82	24.40	24.16	23.88	23.66		23.45
1996	2.88	4.78	26.45	27.07		26.78	26.40	25.59	24.84	24.49	24.20	23.93	23.72		23.44
Nr of days:															
Dry seasons:															
1993	153	153	153	153	153	0	153	153	153	153	153	153	153	153	153
1994	146	146	146	146	146	0	11	11	11	11	11	11	11	11	11
1995	152	152	152	152	152	145	152	152	0	152	152	152	152	0	152
1996	136	136	132	136	0	136	136	136	136	136	136	136	136	0	136
Wet seasons:															
1993	55	55	55	55	55	0	55	55	55	55	55	55	55	55	55
1993-94	212	212	212	212	212	0	212	212	212	212	212	212	212	212	212
1994-95	211	211	211	211	211	0	0	0	0	0	0	0	0	0	0
1995-96	211	211	209	211	126	207	211	211	114	211	211	211	211	0	211
1996	51	51	51	51	0	51	51	51	51	51	51	51	51	0	51

Table A4. Means of wind speed and wind gust measured at the Kigoma wind station for dry (May - September) and wet (October - April) seasons, with the number of days with measurements.

	Wind speed m/s, at 13 m	Wind gust m/s, at 13 m
Dry seasons:		
1993	3.95	5.65
1994	3.79	5.43
1995	3.75	5.39
Wet seasons:		
1993-94	3.31	4.88
1994-95	4.36	6.03
1995-96	3.61	5.25
Nr of days:		
Dry seasons:		
1993	80	80
1994	153	153
1995	141	141
Wet seasons:		
1993-94	204	204
1994-95	11	11
1995-96	70	70

Table A5. Means of evaporation calculated for the Mpulungu buoy and the Bujumbura weather station, for dry (May - September) and wet (October - April) seasons, with the number of days with measurements.

(mm/day)	Mpulungu buoy	Bujumbura weather station
Dry seasons:		
1995	9.56	4.15
1996	7.53	3.89
Wet seasons:		
1994-95		2.44
1995-96	5.87	2.59
1996	6.15	2.89
Nr of days:		
Dry seasons:		
1995	151	151
1996	129	120
Wet seasons:		
1994-95	0	117
1995-96	156	201
1996	51	82

Table A6. Means of parameters measured at the Mpulungu weather station for dry (May - September) and wet (October - April) seasons, with the number of days with measurements.

	Wind speed m/s	Wind gust m/s	Air temp °C	Humidity %	Solar radiation W/m²	Air pressure mbar
Dry seasons:						
1994	3.38	6.50				
1995	3.37	5.98	25.19	44	253	921.83
1996	3.59	6.24	24.75	46	249	922.16
Wet seasons:						
1993-94	3.39	6.80				
1994-95	2.17	4.39				
1995-96	2.39	4.29	25.38	62	257	920.09
1996	2.52	4.49	26.08	56	250	919.71
Nr of days:						
Dry seasons:						
1994	138	138				
1995	152	152	152	152	152	152
1996	150	150	150	150	150	150
Wet seasons:						
1993-94	4	4				
1994-95	203	203				
1995-96	163	163	163	163	163	163
1996	92	92	92	92	92	92

Table A7. Means of wind speed vector components for dry (May - September) and wet (October - April) seasons, with the number of days with measurements.

	E	W	N	S	Days	E	W	N	S	Days
Bujumbura weather station						Kigoma buoy				
Dry seasons:										
1993	1.32	0.28	0.78	2.16	127					
1994	0.89	0.30	0.79	2.05	50	0.90	0.87	0.87	0.70	63
1995	0.91	0.33	0.94	2.04	151					0
1996	0.94	0.33	0.89	1.92	120	1.03	1.13	0.85	1.68	149
Wet seasons:										
1993	0.80	0.38	0.87	1.25	48					
1993-94	0.98	0.35	0.86	1.47	210	1.64	0.74	1.24	0.93	57
1994-95	0.73	0.40	1.02	1.45	189	0.66	0.67	0.55	0.84	205
1995-96	0.85	0.35	0.89	1.52	202	1.16	0.88	0.58	1.56	181
1996	0.83	0.33	0.78	1.76	82	1.61	0.91	1.10	1.15	53
Kigoma wind station						Mpulungu buoy				
Dry seasons:										
1993	1.98	1.41	0.81	0.76	79	2.53	0.49	0.76	2.86	153
1994	1.93	1.35	0.80	0.68	153	2.46	0.36	0.85	1.93	11
1995	1.99	1.28	0.81	0.60	141					0
1996						2.36	0.41	0.47	1.96	136
Wet seasons:										
1993						1.76	0.50	0.88	1.90	54
1993-94	1.31	1.34	1.15	0.49	202	1.25	0.84	1.01	1.45	212
1994-95	0.88	2.46	1.91	0.46	11					0
1995-96	1.22	1.55	1.51	0.38	70	1.61	0.84	0.69	1.29	85
1996						1.05	0.73	1.00	0.88	51
Mpulungu weather station										
Dry seasons:										
1994	1.40	0.33	0.54	2.15	134					
1995	1.62	0.36	0.54	1.90	152					
1996	1.78	0.35	0.56	2.04	150					
Wet seasons:										
1994-95	0.85	0.36	0.61	0.99	203					
1995-96	1.04	0.41	0.67	0.98	161					
1996	1.00	0.50	0.75	1.01	92					

Table A8. Mean depths (m) of isotherms at the Kigoma and Mpulungu buoys, for dry (May - September) and wet seasons (October - April), with the number of days on which the isotherm was found present (see Tables A2&3 for number of days with measurements of water temperature).

Isotherm (°C):	28	27.5	27	26.5	26	25.5	25	24.5	24	23.75	23.5
Kigoma buoy											
Dry seasons:											
1994			11	47	47	50	66	81	122	169	253
1995		2	28	46	45	60	73	84	120	167	262
1996			16	52	50	59	74	87	122	168	268
Wet seasons:											
1993-94			12	30	44	54	63	73	117	167	247
1994-95	2	4	9	25	34	47	58	74	116	169	255
1995-96		3	13	22	42	54	65	83	124	170	264
1996				7	28	40	52	70	123	176	265
Nr of days:											
Dry seasons:											
1994	0	0	26	31	40	64	64	64	64	64	64
1995	0	2	25	64	134	153	153	153	153	153	153
1996	0	0	30	53	106	152	153	153	153	153	153
Wet seasons:											
1993-94	0	0	36	58	58	58	58	58	58	58	58
1994-95	2	5	66	130	198	212	212	212	212	212	212
1995-96	0	7	41	164	204	204	204	204	204	204	204
1996	0	0	0	24	49	53	53	53	53	53	53
Mpulungu buoy											
Dry seasons:											
1993			1	17	22	32	38	48	74	165	225
1994				5	27	35	43	53	101	162	221
1995			18	31	30	38	31	53	120	164	254
1996			4	18	19	33	45	66	144	192	275
Wet seasons:											
1993			9	24	33	42	52	65	109	163	225
1993-94	5	10	16	28	33	41	50	65	114	165	224
1994-95											
1995-96	7	16	26	38	47	57	69	86	133	180	270
1996	3	16	32	36	39	50	61	82	139	194	277
Nr of days:											
Dry seasons:											
1993	0	0	1	15	29	45	61	83	151	153	153
1994	0	0	0	6	11	11	11	11	11	11	11
1995	0	0	10	18	33	42	93	134	152	152	152
1996	0	0	1	13	41	66	87	126	136	136	136
Wet seasons:											
1993	0	0	40	53	55	55	55	55	55	55	55
1993-94	4	42	151	188	212	212	212	212	212	212	212
1994-95											
1995-96	28	109	181	202	210	210	210	210	210	210	210
1996	2	21	24	36	49	51	51	51	51	51	51

APPENDIX II

FORMULAE

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

with

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

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

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

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