

RESEARCH FOR THE MANAGEMENT
OF THE FISHERIES
ON LAKE TANGANYIKA

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Climate, limnology and fisheries
changes of Lake Tanganyika.

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, Democratic Republic of Congo, Tanzania, and Zambia).

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

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SUMMARY

Information on changes, over about the last 3 decades, in climate, limnology and fisheries of Lake Tanganyika are given. From 1964 to 1990, the yearly mean air temperature has increased by 0.7 °C in Bujumbura (northern end of Lake Tanganyika) and 0.9 °C at Mbala (southern end of Lake Tanganyika) while winds speed have decreased. The epilimnion showed a weaker tilting up toward the north causing nutrient rich layers there to be closer to the surface where average transparency decreased. A weaker tilting of the thermocline was related to decreased upwelling in the south and less warm water accumulation in the north, as a result of reduced winds speed. When the SE winds stopped blowing, less epilimnion waters than usual moved to restore equilibrium. This could be related to a lower dynamics of the lake.

The catches of *Stolothrissa tanganyicae* in the south of the lake have declined since the early 1980s. This could be explained by less favourable conditions for reproduction, increased predation and fishing. The catches of those fishes in the south are mainly seasonal (during the upwelling season). It is possible also that the observed decrease of their catches is tied with decreased upwelling intensity and less plankton production during that period. The zooplankton is now sparser in the south of the lake (Kurki and Vuorinen, 1994).

During the last 15 years *L. stappersii* catches have increased in the south. The correlation between catch per unit of effort (CPUE) of *L. stappersii* and the transparency there was significant ($P < 0.01$) in 1993-94. The increased transparency during the wet season in the south probably enhanced visual predation by *L. stappersii*. This species was often absent from the catches in the north of the lake where transparency has been reduced by 36 % from the 1955-57 values.

A "teleconnection" between the El Niño-Southern Oscillation (ENSO) and the regional air temperature was found. A significant correlation was found between ENSO and catches of the clupeids and *L. stappersii*. ENSO may be predicted 18 to 20 months in advance. Therefore an improved understanding of regional climate linked to limnological and fisheries changes, may provide a method of forecasting fisheries yields for the main pelagic species of Lake Tanganyika.

1. INTRODUCTION

Climatic change is considered to be one of the most important factors affecting fish abundance (IPCC, 1990). The evidence for the effect of such changes on the limnology and fisheries of Lake Tanganyika are outlined in the present study. Factors affecting the climate of Lake Tanganyika, including global weather patterns, are discussed and the accuracy of fishery yield prediction examined. The behaviour of El Niño/Southern Oscillation (ENSO) in the Pacific Ocean may affect the climate of Lake Tanganyika and thus be used to predict changes in its limnology and fish stocks.

1.1 Global change and effects on aquatic ecosystems

1.1.1 Global change

Since the late nineteenth century, there has been a net warming of the earth by $0.45^{\circ}\text{C} \pm 0.15^{\circ}\text{C}$ (IPCC, 1990). The periods in the mid 1920s and mid 1970s showed particularly marked increase in global temperature (Lane *et al.*, 1994). There are differences between locations in both the absolute temperature and rate of increase. In east Africa, there has been a warming trend since 1960 (Hastenrath and Kruss, 1992) which probably accompanied other related climatic changes. For example, a warmer climate could result in a decrease in high-frequency temperature variability and an increase in precipitation (Karl *et al.*, 1995).

1.1.2 Climate and aquatic ecosystems

Long term oceanographic studies in several region have established significant correlations between atmospheric conditions and the abundance and productivity of marine ecosystems. For example, during the period 1950-80 there was a decline in the abundance of plankton in the seas around the United Kingdom correlated with changes in wind strength and direction (IPCC, 1990).

Temperature is probably the most critical factor. It can act as a lethal factor or, at sublethal levels, as a metabolic controller. It influences reproductive timing and governs behaviour and distribution patterns of species. Temperature can also act synergistically with, or in opposition to, other environmental variables such as salinity and dissolved oxygen (Kennedy, 1994).

It is likely that global warming will produce collapses of some fisheries and expansion of others (UNEP, 1994).

1.2 El Niño /Southern Oscillation (ENSO)

El Niño is defined as the appearance of an anomalously high sea surface temperature (SST), exceeding one standard deviation from the long-term temperature mean, extending

along the coast of Ecuador and the Galapagos Islands and as far as 12 degrees south. The warmer water should persist for at least four months as measured at five coastal stations (Quinn *et al.*, 1987). Because this event frequently occurs during the Christmas season, it is called El Niño meaning the (Christ) child.

The sea surface temperature (SST) can be used as a direct index of ENSO. Generally anomalies of temperature from long term means are used. Several areas of the Pacific are considered for the monitoring of the SST. The main areas are Niño 1, Niño 2, Niño 3 and Niño 4 (Fig. 1A). SST in the Niño 1+2 for the period 1960-1994 shows warm events every 3 to 7 years (Fig. 1B).

Related to El Niño is the Southern Oscillation: a low pressure in the south-east Pacific corresponds automatically to a high pressure in the west and inversely. The Southern Oscillation Index (SOI) is based on the standardized SLP (sea level pressure) between Tahiti (French Polynesia) and Darwin (Australia) (Diaz and Kiladis, 1992).

ENSO is the abbreviation given to the combined El Niño/Southern Oscillation and refers to the interannual phenomenon of anomalous high sea surface temperature (SST) and other climatic changes (such as winds strength and/or direction). "La Niña" (Kawabe, 1993) is the cold phase of ENSO.

Because of the coupled ocean-atmosphere system, correlation with ENSO have been detected in many areas of the world, particularly in the intertropical belt. Many researches today deal with the physical links between the ENSO and far away climatic effects. It is widely accepted that ENSO is a major large scale oceanographic-atmospheric perturbation (Enfield, 1989; Berger, 1992) that has a considerable influence on the world climate. ENSO phenomena has been detailed by many authors such as Philander (1990) and Diaz and Markgraf (1992).

The study of correlation between ENSO and far away climatic events (even extra-tropical) is defined as the study of the teleconnections (Glantz *et al.*, 1994) . The establishment of valid teleconnections could allow the use of reliable long-range climate related forecasting for other parts of the world (UNEP, 1994).

2. MATERIAL AND METHODS

The location of the meteorological station in Bujumbura (Burundi) is 3.32°S, 29.32° E. while Mbala (Zambia) meteorological station is 8.85 °S, 31.33° E (Fig. 2).

Air temperature and wind speed data at Bujumbura Airport were kindly provided by the Institut Géographique du Burundi (IGEBU). The meteorological data at Mbala Airport (Zambia) were kindly provided by the Department of Meteorology and the Zambian Air Force. The temperature data was measured with a standard mercury thermometer under a Stevenson screen to an accuracy of +/- 0.1 °C. The wind was measured with a cup counter anemometer 2 m above the ground at Bujumbura and Mbala. The stations are part of the World Meteorological Organisation (WMO) network.

The lake temperature was measured by the LTR project with a CTD-12 plus instrument accurate to +/- 0.01 °C. The temperature data collected from an automatic ANDERAA thermistor string installed in the south of the lake were accurate to +/- 0.1 °C. Both were used to measure the temperature of Lake Tanganyika, especially in deep water. Regular measurements of temperature and other variables were taken near Bujumbura, Kigoma and Mpulungu (Plisnier *et al.*, 1996).

Dissolved Oxygen was measured with a dissolved oxygen meter model 50B from Yellow Springs Instrument Co. equipped with a YSI 5739 probe and a YSI 5795A submersible stirrer. The cable was sufficient for *in situ* measurement down to a depth of 80 m. At lower depths, the probe was carefully introduced on deck in a 7.4 l sampling bottle which had been hauled up from the measured depth. Calibration preceded each sample by the "calibration in air procedure" correcting for altitude and a zero oxygen concentration obtained with sodium sulphite and a trace of cobalt chloride as catalyst. Accuracy was +/- 0.01 mg/l DO.

The fisheries statistics compiled by Pearce (1992), Bellemans (1992) and Coenen (1993) and were used. ENSO indices are published monthly in the *Drought Monitoring Bulletin* in Nairobi and Harare (WMO-UNDP, 1993).

3. RESULTS

3.1 Changes in the climate of the Lake Tanganyika area

3.1.1 Air temperature

Since the 1960s, an increase in air temperature has been noted at two stations in the north and south of Lake Tanganyika. At Bujumbura Airport the mean increase, based on the linear regression of monthly data between 1964 and 1990, was 0.7 °C (Fig. 3A). At Mbala Airport the mean increase for the same period was 0.9 °C (Fig. 3B). Beside the trend of increasing temperature, variation was noted around the mean (Figs 3 and 4) which could be linked to the ENSO phenomena. There were significant correlations between the air temperature in Bujumbura ($r = 0.48$, $p < 0.01$) and Mbala ($r=0.34$, $p<0.05$) and the sea surface temperature of Niño 4 area.

The variation in the mean monthly temperature at Mbala airport was much greater from the 1950s to 1970s than from the 1980s to 1990s (Fig. 3B). This may be the result of increased cloud cover in the recent years. Cloudy skies are particularly effective in diminishing diel temperature variation by reducing solar heating by day and infrared cooling by night (Karl *et al.*, 1995; Harvey, 1995). Unfortunately, data are lacking for the Lake Tanganyika region.

3.1.2 Winds

Wind speed have decreased in recent years in the Lake Tanganyika area (Fig. 5). The yearly mean speeds at Bujumbura fluctuated between 1.4 and 2.5 m/s on average from 1964 to 1979. Between 1986 and 1990 the range was between 0.5 to 1.5 m/s. Unfortunately, available data were not continuous. At Mbala the mean wind also decreased from the end of the 1970s to a minimum in 1983. They then increased but not to the previous levels. However data were incomplete. Although subjective, it is interesting to note that local fishermen at the south of the lake have reported wind strength diminishing from the late 1970s. Some corroborating evidence is given in chapter 3.3.

3.2 Climatic change and hydrodynamics

A direct influence of climatic change on the hydrodynamics of Lake Tanganyika is illustrated by a simplified model (Fig. 6). Two extreme situations are given: A) During a year of high winds speeds (Fig. 6A), the wind from the south drives warmer epilimnion water to the northern part of the lake and the thermocline there is therefore deeper than normal. The return currents in the deeper layers generate a strong upwelling in the southern part of the lake (Plisnier *et al.*, 1996). B) During a year of weak seasonal wind speed (Fig. 6B), the layer of warm water in the north by the southern winds is much thinner and the thermocline is nearer the surface. The upwelling in the south is less marked (restricted in both area and the extent of mixing of the deeper layers).

When the wind stops, the metalimnion oscillates with a significant period and magnitude linked with currents that rhythmically flow back and forth in opposing direction (Mortimer, 1952). The extent of oscillation will probably depend of the strength of the preceding wind (Fig. 7).

In Lake Tanganyika, the oscillations of water noted recently (1993-94) through the measurement of pH and conductivity during a yearly cycle (Plisnier *et al.*, 1996) are probably weaker than before. Internal waves may also be affected by different wind regimes. These waves are important for the productivity of the lake because they bring rich nutrients from deep water into the euphotic and oxygenated layers of the epilimnion. The significance of 'internal loading' has been demonstrated recently for Lake Tanganyika (Plisnier *et al.*, 1996), Lake Malawi (Patterson and Kachinjika, 1993) and some temperate lakes (Goldman *et al.*, 1989).

During several experiments performed over 24 hours on Lake Tanganyika, vortex formation at the thermocline and the exchange of water masses of different composition were identified. These were indicators of a highly dynamic and turbulent system. The degree of turbulence was probably affected by the different current speeds in windy or calm years. A change in the intensity of some hydrodynamic processes such as the upwelling in the south, the oscillations of the metalimnion, the internal waves, the currents and the level of turbulence will affect the vertical and horizontal transport of solutes and thus probably alter the distribution and productivity of the plankton (Thomas, 1951). Hydrodynamics changes may also influence pelagic eggs survival and larvae feeding success.

3.3 Climate change and limnology

3.3.1 Water temperature

The temperature profiles in the upper part of Lake Tanganyika (0-100 m) near Bujumbura were significantly ($p < 0.01$) warmer in 1993-94 than in 1956-57 (the latter data from Dubois, 1958). The mean surface temperature near Bujumbura was 25.99 °C in 1956-57 compared to 26.33 °C in 1993-94. The difference in temperature between the above time periods was greater during the dry season, 0.40°C, than during the wet season, 0.28°C (Fig. 8).

In the south of the lake, Coulter (1968) recorded a range in surface temperatures from 23.3°C to 24.0°C and mentioned that the water column was frequently homothermal at c. 23.5°C. During the dry season of 1993 and 1994, LTR have recorded all surface temperature >23.90 °C in the south. Either the lake has warmed or the upwelling was weaker than before. Probably both processes were involved and therefore the increase in water temperature has been lakewide.

A similar warming has been noted in Lake Victoria. Worthington (1930) frequently recorded temperatures of 23.5°C but Hecky *et al.* (1994) found all temperatures to be >23.8°C. This apparent increase of 0.30°C is similar to the mean increase of 0.34°C for the upper 100 m of Lake Tanganyika.

There are also indications of deeper warming (table 1).

Depth (m)	1946-47	1973	1993-94
	(Van Meel, 1987)	(Craig <i>et al.</i> , 1974)	LTR
100	23.80	24.02	24.18
150	23.52	23.71	23.85
200	23.42	23.55	23.67
250	23.40	23.44	23.54
300	23.32	23.38	23.46

Table 2: Mean temperature (100-300 m) for 1946-47 (Van Meel, 1987), 1973 (Craig *et al.*, 1974) and 1993-94 (LTR, present study).

The higher readings, from those of Coulter, recorded by Craig *et al.* (1974) were thought by them to be a seasonal effect. The recent data show however also increased readings.

Number of observations published from the early period is unfortunately not sufficient for statistical test.

The water temperature >400m was recorded by Marquardsen in 1916 (Van Meel, 1987) to be almost isothermal, 23.13-23.15°C

and by Capart (1952) to be 23.25-23.35°C. The accuracy of previous measurements is however questionable. The LTR project recorded 23.41 °C at 440 m. It is noted that reported measurements for water temperature of Lake Tanganyika are showing an increase with time. At Lake Malawi, Muller and Forstner (1973 in Crossley, 1984), have suggested that the hypolimnion has progressively warmed by 0.7°C between 1939 and 1972.

3.3.2 Stratification

The productivity of African Great Lakes is determined to a large extent by the strength of stratification and the amount of the hypolimnion water brought to the surface (Beauchamp, 1964).

It is known that increase in the intensity of stratification and the resulting decrease in nutrient supply can lead to a decline in zooplankton abundance (Roemmich and McGowan, 1995).

The warming of Lake Tanganyika will probably increase the strength of stratification as it will accentuate density differences.

The stratification index, calculated from data collected by LTR in 1993-1994 (Plisnier *et al.*, 1996), was generally greater than that derived from the data of Dubois (1958), particularly during the dry season (Fig. 10). This could have affected lake mixing and especially the upwelling in the south. Cooling of the water results in the breakdown of stratification. In the past, cooler conditions may have caused not only important quantities of nutrient rich waters but also larger quantities of deep anoxic water containing hydrogen sulphide to rise up to the surface. This could have resulted in mass fish mortalities. Fishermen in the south of the lake reported that fish kills were more frequent in the 1960s and 1970s than during the last 15 yr, a period of decreased wind intensity and increased water temperature and stratification.

3.3.3 Thermocline depth

The mean thermocline depth in the north of the lake was 68 m in 1955-57 (Dubois, 1958) and 55 m in 1993-94 (Plisnier *et al.*, 1996) (Fig. 11). In the later period the nutrient rich layers are closer to the euphotic zone. In 1955-57, the thermocline was particularly deeper during the dry season than in 1993-94. This could be related to the tilting effect in chapter 3.2 (Fig. 6) if they were more winds in 1955-57 (data not available).

Hecky and Degens (1973) intimated that any change in the current hydrographic regime, which would permit greater mixing across the thermocline, could substantially alter the productivity of the lake. A thermocline depth closer from the surface may be an important cause for increase

productivity in the north of the lake since nutrient rich layers are closer from the biotic zone.

3.3.4 Transparency

Climatic change in the Lake Tanganyika area might have caused a decrease in transparency in the north and an increase in the south of the lake particularly during the dry season. Weaker winds may have caused a shallow thermocline in the north, favourable to primary production, and weak upwelling in the south, unfavourable for primary production.

Water in the pelagic zone in the north of the lake was not as clear (secchi depth 9 m) in 1993-94 (Plisnier *et al.*, 1996) as in 1955-57 (secchi depth 13.6 m) (Dubois, 1958) (Fig. 13). In 1955-57, the water increased in transparency with increasing thermocline depth (note the extreme case in June 1956, Figures 12 and 13). The positive relationship between thermocline and secchi depths has been shown elsewhere (Ferro, 1975; Plisnier *et al.*, 1996). In the south the water was clearer in the later period, mean secchi depths 12.1 m in 1993 and 9.6 m in 1994 (Plisnier *et al.*, 1996) compared to 8.0 m in 1961 (Coulter, 1991). It is not known if this reflects a general trend or was due to interannual variability.

3.3.5 Dissolved oxygen

The oxygenated layer was shallower in 1993-94 compared to 1946-47 (Fig. 14) particularly during the dry season (the oxycline depth was c. 60 m in 1993-94 and 80-100 m in 1946-47). Anoxic conditions (<1 mg/l DO) in the north were measured at 100 m during the dry season in 1993-94 compared to 130 m in 1946-47. A lower tilting of the epilimnion during the dry and windy season and increased stratification could explain the shallow oxygenated layer in the north. The seasonal differences in surface oxygenation were well marked in 1946-47 and 1955-57 but much less so in 1993-94 (Fig. 14).

3.3.6 Eutrophication

The north of the lake is now less transparent than it was between 1955-57. The surface water is regularly supersaturated in oxygen. Floating *Pistia stratiotes* is often seen in the coastal and pelagic areas. The appearance of other macrophytes such as *Elodea* sp. and *Ceratophyllum* has been reported in shallow waters near Kigoma between 1987 and 1992 (Chitamwebwa, personal communication). This could indicate eutrophication. Eutrophication has recently increased in Lake Victoria. The causes are unknown but may include higher nutrient loading and climate and food-web changes (Hecky *et al.*, 1994). If eutrophication is confirmed in the north of Lake Tanganyika, it is unlikely to be caused by higher nutrient loading. There is no evidence of more frequent use of fertilisers in the region. Furthermore runoff water rapidly descends below the

thermocline because it is often colder. Climate has therefore probably caused changes in the foodweb of Lake Tanganyika.

3.3.7 Zooplankton

In 1993-94 a higher zooplankton density was measured in the north of the lake than in the south (Kurki and Vuorinen, 1994; Bosma, personal communication). This coincides with water being less transparent in the north than in the south.

Transparency seems well correlated to phytoplankton and zooplankton biomass in Lake Tanganyika (Hecky *et al.*, 1978). Weaker upwelling in the south may have resulted in lower zooplankton abundance. In the California current, it has been observed that an increase in stratification was correlated with a decrease in zooplankton (Roemmich and McGowan, 1995).

Shrimps may have increased in abundance in the south of Lake Tanganyika. *Lates stappersii* there is feeding heavily on shrimps (Mannini *et al.*, 1996) rather than on *S. tanganyicae*, rare in the catches since a few years. In the last decade, the increase of shrimps has been noted in Lake Victoria (Ochumba *et al.*, 1992).

3.4 Climate change and the seasonal pelagic fishery

3.4.1. Effect of winds and transparency on *L. stappersii* catchability

From data between 1967 and 1994 for the south of the lake it was observed that *L. stappersii* is seldom caught during the dry and windy season (from June to September). The regression line between the catches per unit of effort (one industrial boat fishing during one night is one unit of effort) of *L. stappersii* are inversely related to the wind speed. The relation is significant ($p < 0.01$) (Fig. 15A).

During the windy season the transparency decreases in the south. In 1993-94, the catches of *L. stappersii* were very significantly correlated to the transparency ($r=0.75$) (Fig 16). This indicates that *L. stappersii* (adult) is probably a strong visual predator. Hence, when the winds is strong, the transparency decreases and the catchability of *L. stappersii* decreases. It can be suggested that those fishes have moved to more transparent waters further north.

Another observation strengthens this positive relation between the transparency and the catches of *L. stappersii* : *L. stappersii* is seldom caught actually in the north of the lake, an area that shows a reduced transparency (cf. 3.3.4.). Historical data show that *L. stappersii* used to be mainly captured in the north during the dry season, a period when higher transparency was observed (Dubois, 1958) (Fig. 12).

The juveniles *L. stappersii* have some similar feedings habits as the clupeids (Coulter, 1991). They also live together in the pelagic with the main annual *Stolothrissa* cohort, which originate in the same months (Chapman and van Well, 1978). Lower transparency and higher zooplankton production could favourably influence the survival of juveniles *L. stappersii*. The effect of this on *L. stappersii* fishing recruitment is observed with a delay longer than the clupeids because of a slower growth rate of *L. stappersii* (Mannini *et al.*, 1996).

3.4.2. Effect of winds on clupeids seasonal abundance

Catch per unit of effort of total clupeids (Fig. 15B), *Limnothrissa miodon* (Fig. 15C) and *S. tanganyicae* (Fig. 15D) was positively correlated ($p < 0.001$) with wind speeds. *L. miodon* catches increased simultaneously with an increase in wind speed but for *S. tanganyicae* there was a two month time lag. The higher catches of clupeids were linked to the upwelling and to phytoplankton abundance which peaked in August-September in the south and November-December in the north (Coulter, 1991).

In the south, during the dry season when the SE winds have started, *L. miodon* migrates into the pelagic probably from littoral areas while *S. tanganyicae* probably migrates from a more distant location (Pearce, 1992). They are then heavily fished by local fishermen. In recent years however, clupeids (especially *S. tanganyicae*) have become rare in the pelagic.

As commonly occurs in the sea, productivity of clupeids is associated with a deeply mixed pelagic system and an upwelling zone. It is suggested that decreased winds result in weaker upwelling and reduced catches of clupeids through a change in migrating behaviour (see section 4.2) and poor recruitment.

3.5 El Niño and interannual fisheries changes

The catches of clupeids in the south and north of the lake was positively correlated ($p < 0.01$) to the southern oscillation index (SOI) linked to El Niño from 1963 to 1993 (Fig. 17). The most significant relationship ($r = 0.58$) was found in the south (Fig. 17A) between the mean SOI for February and March and the yearly difference in the CPUE from the 1963 to 1993 mean for clupeids caught between June and September (3 to 6 months later than the SOI). In the north the relationship was significant ($r = 0.62$) between the mean SOI for February and March and the yearly difference in the CPUE from the 1976 to 1994 mean for clupeids caught from November to January, 8 to 10 months later than the SOI values (Fig. 17B). The difference between the north and south appears to be linked to the time lag between the upwelling in the south and secondary upwelling and increased primary production in the north (Plisnier *et al.*, 1996).

The cpue of *L. stappersii* was negatively correlated with Southern Oscillation Index (Fig. 18). The most significant relationship ($r=-0.60$) was found in the south (Fig. 18A) between the mean SOI for March and April and the yearly difference in the CPUE from the 1963 to 1994 mean for fish caught between June and September (3 to 6 months later than the SOI). In the north the relationship was significant ($r=-0.52$) between the mean SOI for August to October and the yearly difference in the CPUE from the 1976 to 1994 mean for fish caught from November to February, 13 to 16 months later than the SOI (Fig. 18B).

It is interesting to note that in 1983, a year of very strong El Niño, the catches of clupeids were particularly low near Bujumbura (low also at Mpulungu) while inversely, CPUE of *L. stappersii* showed strongest peaks at Bujumbura and Mpulungu.

3.6 Climate change and long term fishery changes

In the south of the lake, CPUE of the industrial clupeid fishery (Fig. 19A) has decreased since the early 1980s, possibly caused by increased fishing effort (Fig. 21). In the north of the lake catches of clupeids have also decreased since the end of the 1970s but so has the fishing effort (Figs 20A and 21). A fast recovery should have been observed because of the fast turn-over and high resilience of the clupeids. This has not been observed. We suggest that the fishing effort is not the main cause for the decreased catches of the clupeids. One strong reproductive (or larval survival) peak each year gives rise to the dominant annual cohort. The life span of *Stolothrissa* can conveniently be regarded as a year (Coulter, 1991). As Lasker (1985) pointed out, with the clupeids, there may be an important year class success arising from a small to virtually non existent population. There may always be enough fertilised eggs produced, no matter how small the population, to produce a good year if the conditions are right. It is suggested that lower catches of clupeids in the last 15 yr may be more strongly influenced by factors other than fishing such as climate change.

Since the mid-1970s, the CPUE of *L. stappersii* in the south has increased and in 1994 represented 96% of the industrial catch (Plisnier, 1995). The increase may be related to the warming as measured by air temperature and the decrease in wind speed (Fig. 19B). A negative relationship between the seasonal catches of *L. stappersii* and the wind speed has already been established (Fig. 15A). Increased catches have been noted during El Niño years when the SOI was low and zonal winds were reduced (Figs 18A and 18B). Increased transparency in the south may have assisted visual predation and increased attraction to the lights used by the fishermen. In the north the CPUE of *L. stappersii* has decreased (Fig. 20B) as has the extent of the industrial fishing effort (Fig. 21). The decrease in CPUE may have been caused by climatic changes which reduced water

transparency there making it unfavourable for visual predation (Figs 11 and 16).

4. DISCUSSION

4.1 Trends and variability in climate, limnology and fisheries

It is generally agreed that the world's climate is becoming warmer (Healey, 1990). There has been an observed increase in air temperature and a reduction in wind speeds in the Lake Tanganyika region (this report) for about the last 2-3 decades. Thermal stratification has increased and upwelling decreased and these changes are expected to continue. This should favour increased catches of *L. stappersii* and reduced catches of the clupeids.

The overall productivity of the lake will probably be reduced. A 5% reduction in primary production could lead to a 6 to 9% reduction in fish yields (Nixon, 1988). Reduced upwelling, lower turbulence level, decreased amplitude of internal waves, increased stratification and shallower oxygenated layers resulting from climatic changes might induce changes in energy transfer and the food web of the lake.

The north of the lake may increase in primary productivity because of the close proximity of the nutrient rich layers to the surface. This does not mean that it will necessarily favour pelagic fish as the anoxic hypolimnion will be nearer the surface as well. Eggs released in pelagic area may show increase losses if they reach faster abiotic layers.

For the future, some modelers expect hurricanes and monsoons to intensify (Haines, 1993). If stronger South East trade winds are observed in Africa, it might counterbalance the observed trend.

Considerable variation in air temperature and fish catches have been observed. They may have been partially linked to the El Niño phenomenon. Oscillations about the mean will certainly continue but their frequency might change because of increased El Niño compared to La Niña phases. A period of more frequent El Niños has been evident throughout much of the 1900s (Diaz and Pulwarty, 1994; Wuetrich, 1995). In the mid-1970s, the frequency still accentuated with more intense El Niño characteristics (Bakun, 1993). Recently, for the first time on record, El Niño has returned for the fourth consecutive year since 1991.

It is not known why this has happened although it may signal a world-wide change in climate (Wuethrich, 1995). There could be a link between the higher frequency of El Niño and global climate change but this is not proven. The effects of climate change on fisheries will vary between regions

whereby some fisheries will benefit others will not (Kennedy, 1994).

The general trends and variation in catches observed for the main pelagic fish species of lake Tanganyika, *S. tanganyicae* and *L. stappersii* are summarised in Figure 23. The catch curves are inversely related but although a predator-prey relationship exists it is probably not the main cause for the fluctuations observed. Catch of each species show different relationships with climatic changes (Fig. 15). In the oceans, fluctuations in catches of sardines and anchovy appear to be controlled by long term environmental variations which cause large and prolonged changes in fish abundance (Lluch-Belda *et al.*, 1989).

4.2 The effect of climate on *Stolothrissa* abundance and behaviour ?

Large, natural fluctuations of fish population abundance occur which are not attributable to fishing mortality (Lasker, 1985). In the south of Lake Tanganyika it has always been observed that the dry and windy season was a time of increased clupeid abundance (Fig. 15) and it was suggested by Coulter (1991) that this was related to phytoplankton increase during the upwelling period. In the present study it has been observed (see sections 3.1.1 and 3.1.2) that in the last 10 to 15 yr climatic changes have probably reduced upwelling in the south resulting in a decrease in general turbulence and wave amplitude for the whole lake. This would cause the lake to be less dynamic.

Distribution patterns of clupeids may also have changed and *S. tanganyicae* may have reduced its migratory behaviour. Some observations have suggested that *S. tanganyicae* probably moves extensively in the lake, although others have suggested that individuals generally do not move far (Coulter, 1991). The very low level of *S. tanganyicae* catches in the south in the last decade suggest that there could be a change in their distribution pattern related to environmental conditions. World-wide distribution patterns of clupeids such as sardines and anchovy (Lluch-Belda *et al.*, 1989) show that when their abundance is low, they concentrate into a few relatively fixed locations, and migratory behaviour is greatly reduced. A similar strategy may be occurring among Lake Tanganyika clupeids.

4.3 Climate and fisheries forecast as a management tool

It is now possible to make rather accurate predictions on the state of the tropical oceans and atmosphere (Mooney, 1991). Until recently few of the General Circulation Models (GCM) took adequate account of oceanic processes (Gray, 1991). More consideration is now given to incorporating ENSO into models (Latif and Graham, 1992; Derr and Slutz, 1994; Inoue and Welch, 1993). However Healey (1990) believes that climate will become more unpredictable and the incidence of extreme events will increase. The policy of

governments in response to climate change will be driven more by uncertainty and extreme events than by predicted "average" changes in physical and biological systems. Jacobs *et al.*, (1994), describe deterministic processes relating to ENSO and indicated that the ocean system is not wholly chaotic and unpredictable. Recent ENSO events have been successfully predicted e.g. the El Niños of 1986-87 and 1991-92 (Hayward, 1993; Mooney, 1991). The forecast of these warming events allowed policy makers in Peru and Australia to make economic decisions that saved their countries significant sums of money (Mooney, 1991).

The relationship between ENSO events and yields of the main pelagic fish of Lake Tanganyika (Figs 17 and 18) can be used for forecasting. Indices of El Niño, such as the sea-surface temperature of the equatorial Pacific, can be predicted several months ahead and physical, coupled ocean-atmosphere models can be used to make predictions over one year ahead.

A recently improved model extended prediction for El Niño to 18-20 months (Chen *et al.*, 1995). However detailed models for forecasting Lake Tanganyika fish yields need more research data. The collection of meteorological data around the lake needs to be improved. For example, the projected installation of an official meteorological station in Mpulungu by the Department of Meteorology, Zambia (Chipeta, personal communication) should be implemented. A reliable network of primary and secondary meteorological stations is essential for fisheries forecasting.

5. CONCLUSIONS

Long term changes in temperature and winds in the Lake Tanganyika area have been identified over about the last 3 decades. These trends appear to have affected clupeid and *L. stappersii* yields. A comparison of limnological indices (temperature, stratification, thermocline depth, dissolved oxygen and transparency) in 1993-94 with data collected in the 1940-50s provides further evidence for climatic change.

Variations in climatic conditions and fish abundance have also been observed on a shorter time scale. They were probably linked to El/Niño-southern oscillation (ENSO) events. The latter represent one of the major mode of natural variation in global climate (Diaz and Pulwarty, 1994). ENSO has been associated with precipitation in Africa (IPCC, 1990) and the variability of ENSO influences atmospheric circulation. *S. tanganyicae* and *L. stappersii* abundance and behaviour will be strongly affected by environmental conditions of Lake Tanganyika. A highly dynamic system favours *S. tanganyicae* production while more stable conditions encourages *L. stappersii* abundance and catchability.

Improved understanding of the links between global and regional climate, lake hydrodynamics and limnology and fish biology should result in the establishment of reliable forecasting models for the fisheries with predictions of 1-2 yr ahead. To reach this objective, national meteorological recording stations should be strengthened in the lake catchment area.

As for oceanic fisheries (Beamish, 1993), it is to be expected that there will be periods when environmental conditions result in poor survival. Managers need to recognise when these conditions are occurring and make timely adjustments to fishing plans that recognise that the main changes in abundance are occurring for natural reasons. The forecast of fisheries of Lake Tanganyika would allow a better exploitation of the resource (type of nets, fishing zones, processing equipment, marketing) as well as giving useful signals for management of the resources by the Authorities of the riparian countries (preparation of stock sharing, adjustment of licensing etc...). Longer term planning could be useful for donors also in decision making concerning fisheries development around the lake. Climatic and limnological monitoring at several stations around the lake may give useful information on the ecosystem changes for a management plan of the Lake Tanganyika fisheries.

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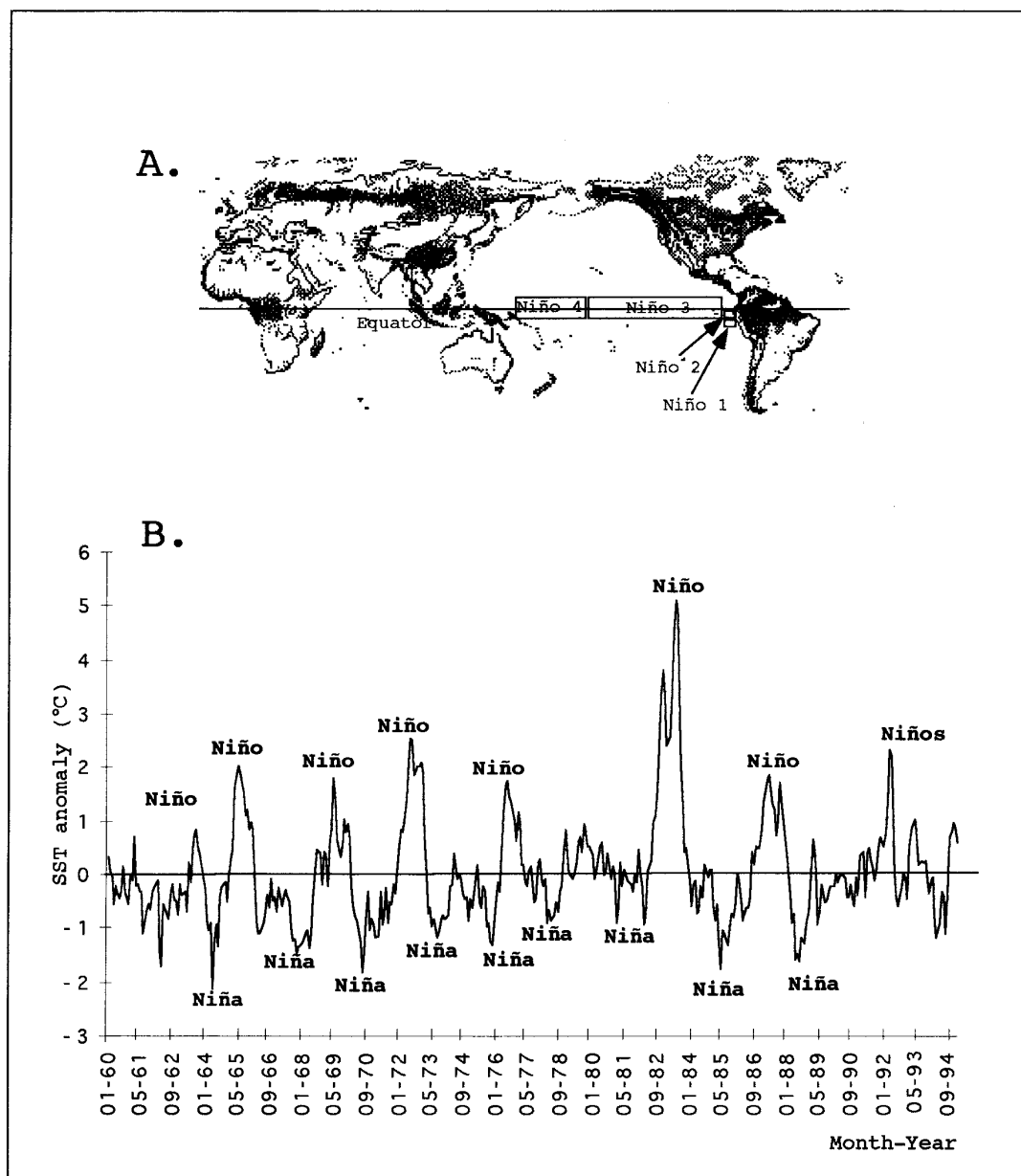


Fig. 1 (A) El Niño area for sea surface temperature (SST) recording (B) SST anomalies in Niño 1+2 area from 1960 to 1994 (South Pacific).

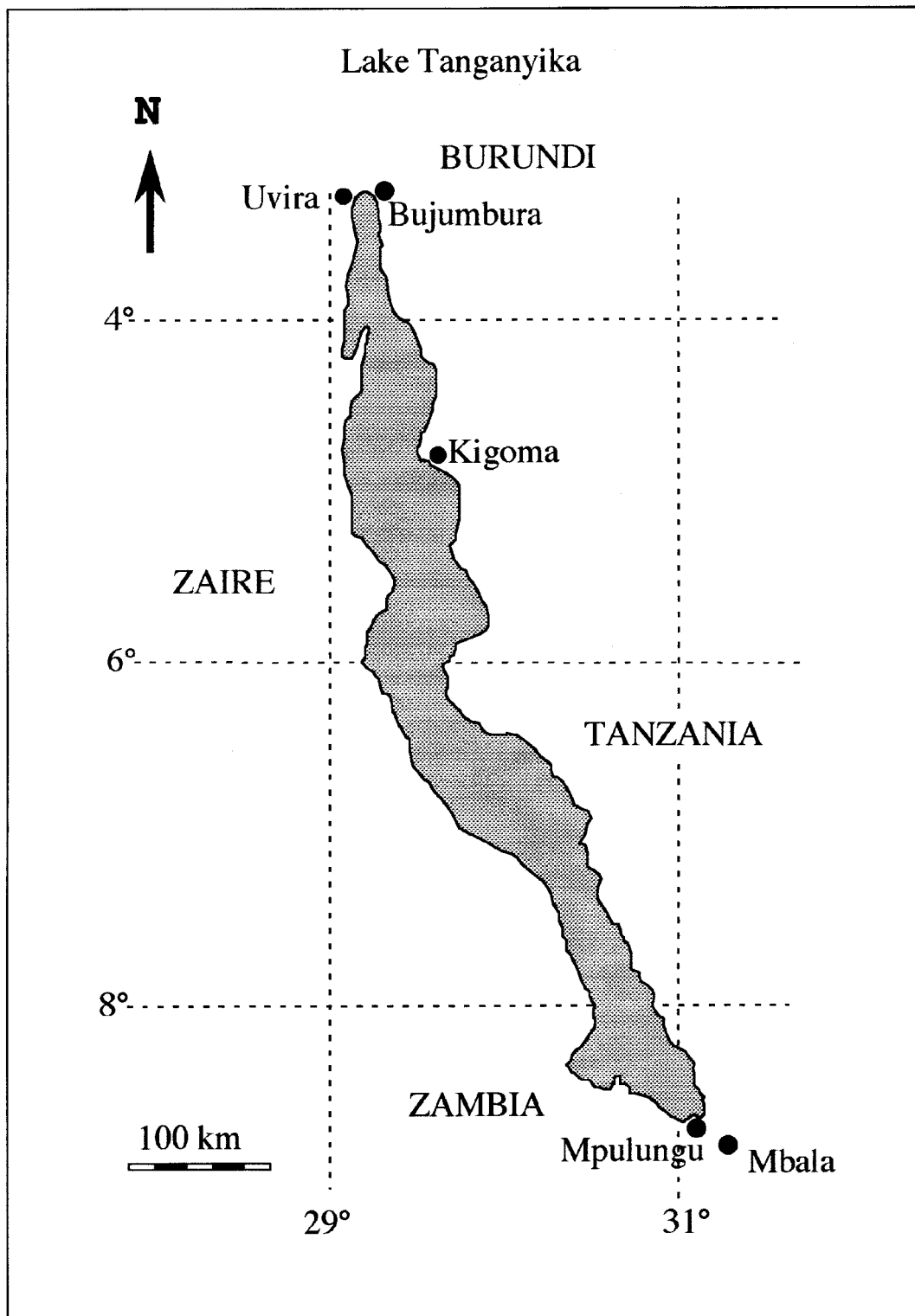


Fig. 2 Lake Tanganyika map.

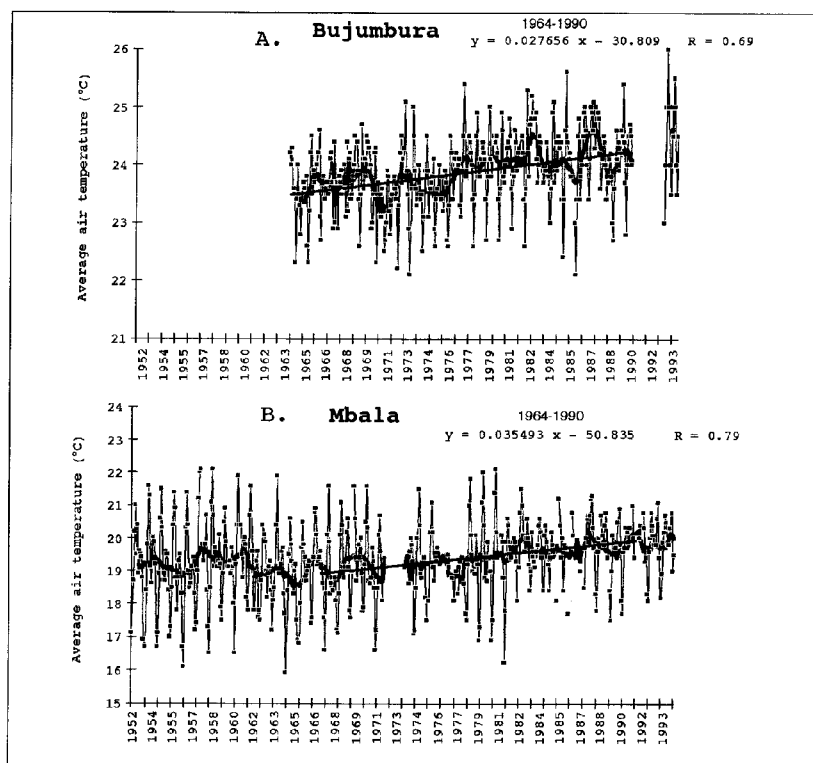


Fig. 3 Monthly average air temperature and yearly means (bold line) at (A) Bujumbura (from 1963 to 1993) and (B) Mbala (from 1952 to 1993). Regression lines are calculated for the period 1964-1990.

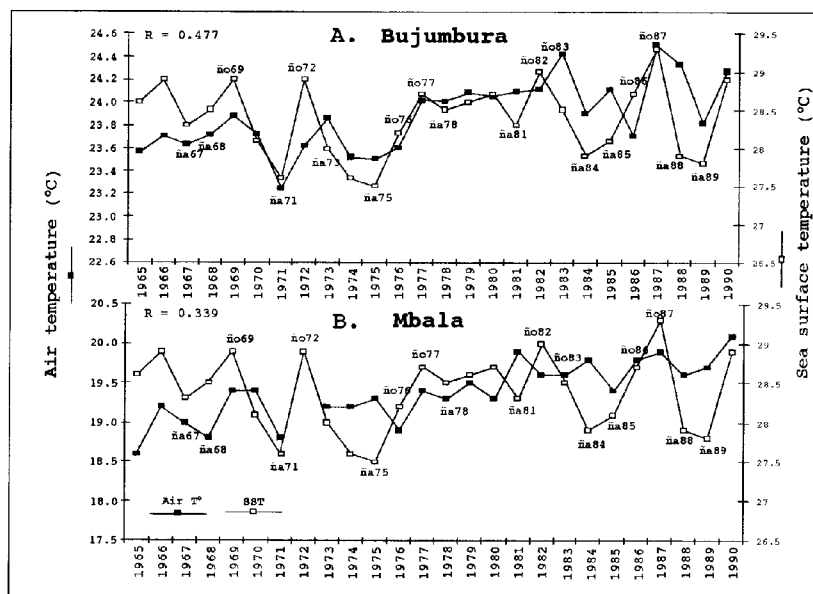


Fig. 4 Change in yearly average of air temperature at Bujumbura and Mbala compared to Sea Surface Temperature (SST) of the Pacific Ocean (Niño 4 region) ("no" for El Niño events, "na" for La Niña events).

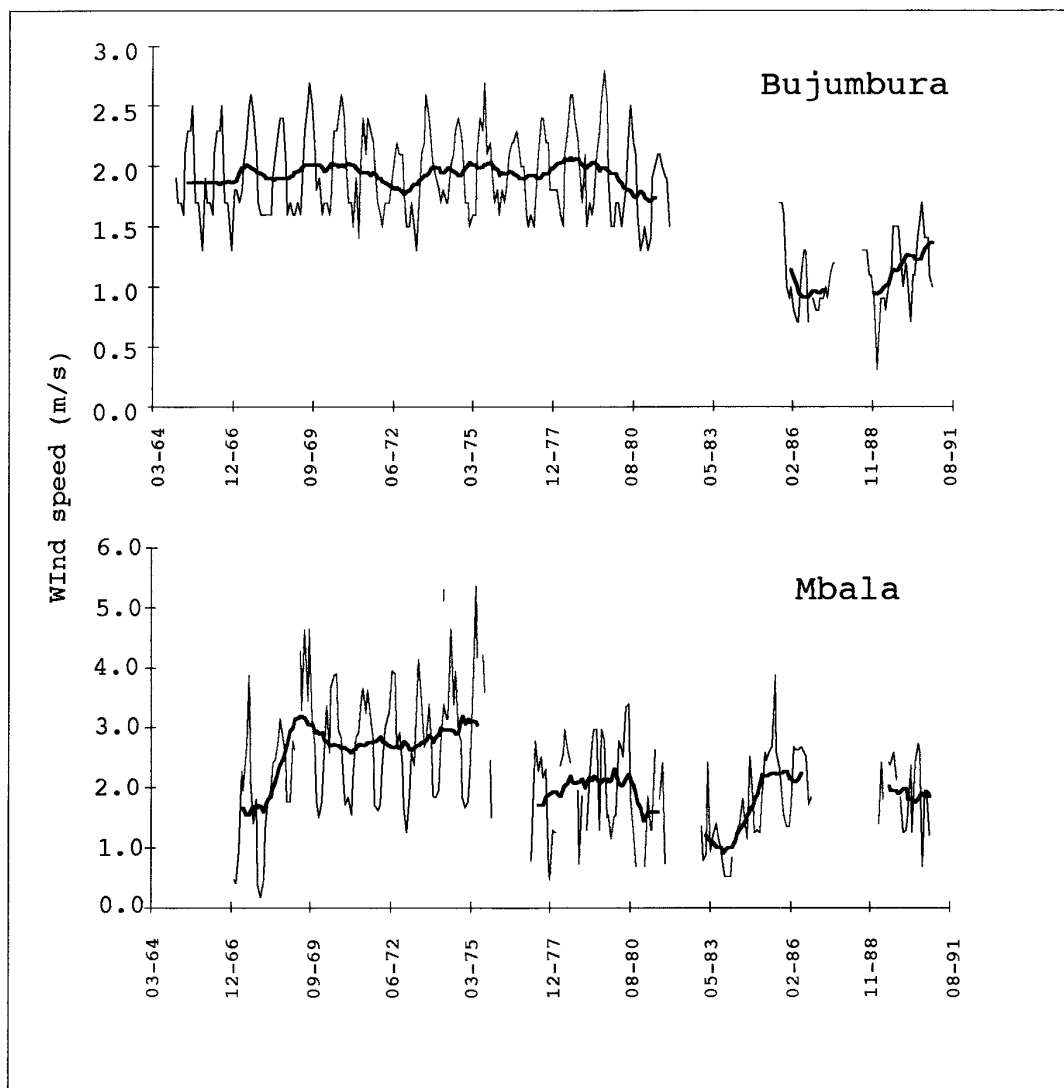


Fig. 5 Wind speed (m/s) at Bujumbura and Mbala: monthly data and running yearly means.

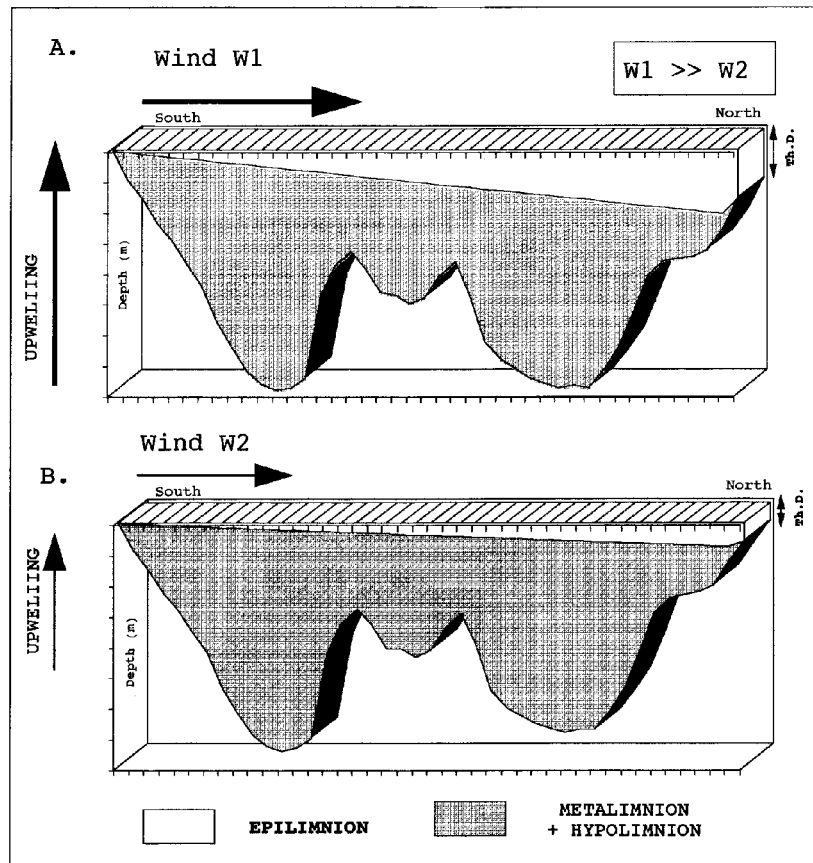


Fig. 6 Schematic representation of Lake Tanganyika showing (A) an important tilting of epilimnion and a strong upwelling during years of marked windy season and (B) a slight tilting and weak upwelling during years of weaker winds (Th.D. for thermocline depth near Bujumbura) (drawing not to scale).

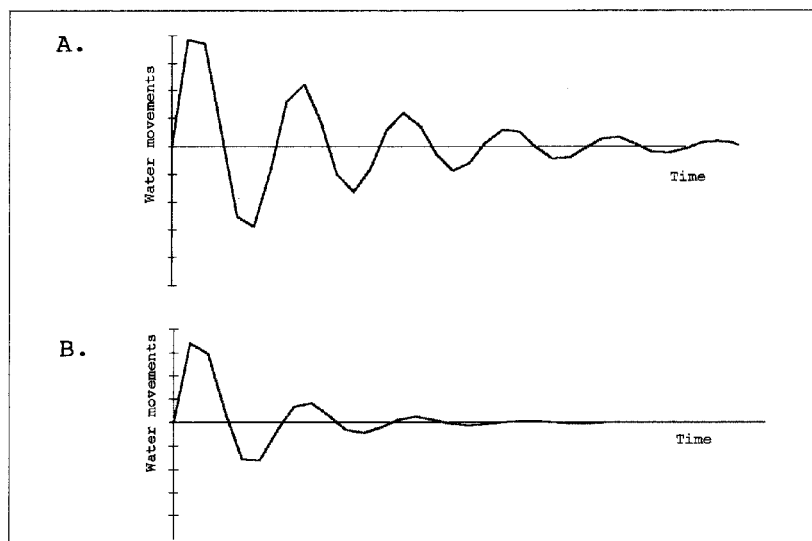


Fig. 7 Damped oscillation foreseen in a given station (Mpulungu or Bujumbura for example) when the wind season stops and the epilimnion oscillates during (A) a year with a marked windy season and (B) a year with a weak windy season (Fig. 6).

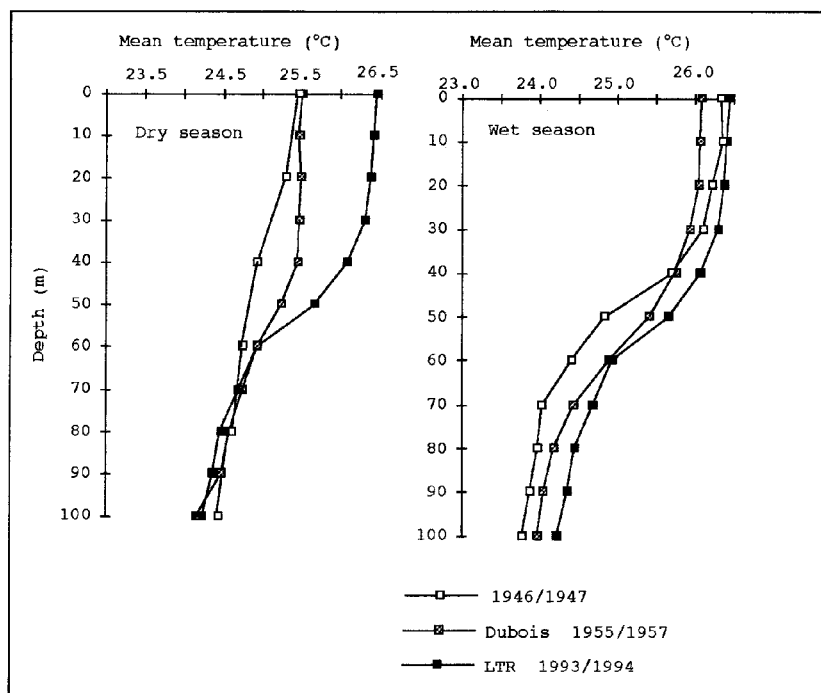


Fig. 8 Mean temperature (°C) profiles of the 0-100 m water column near Bujumbura/Uvira (Dubois, 1958; LTR, present study) and for the North basin (Van Meel, 1987) during (A) the dry season and (B) the wet season.

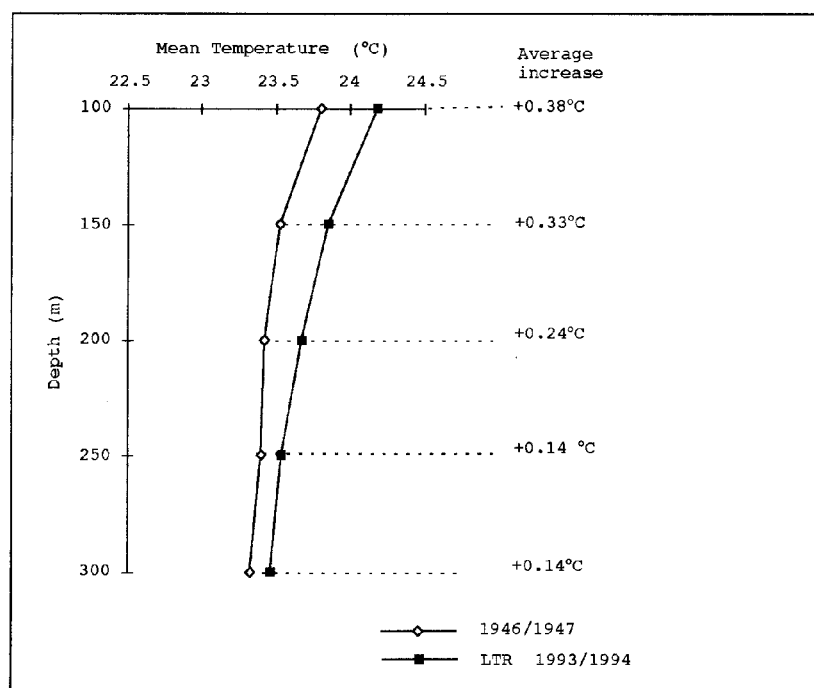


Fig. 9 Mean temperature (°C) profiles of the 0-100 m water column from 0 to 300 m in 1946-47 (Van Meel, 1987) and in 1993-94 by LTR.

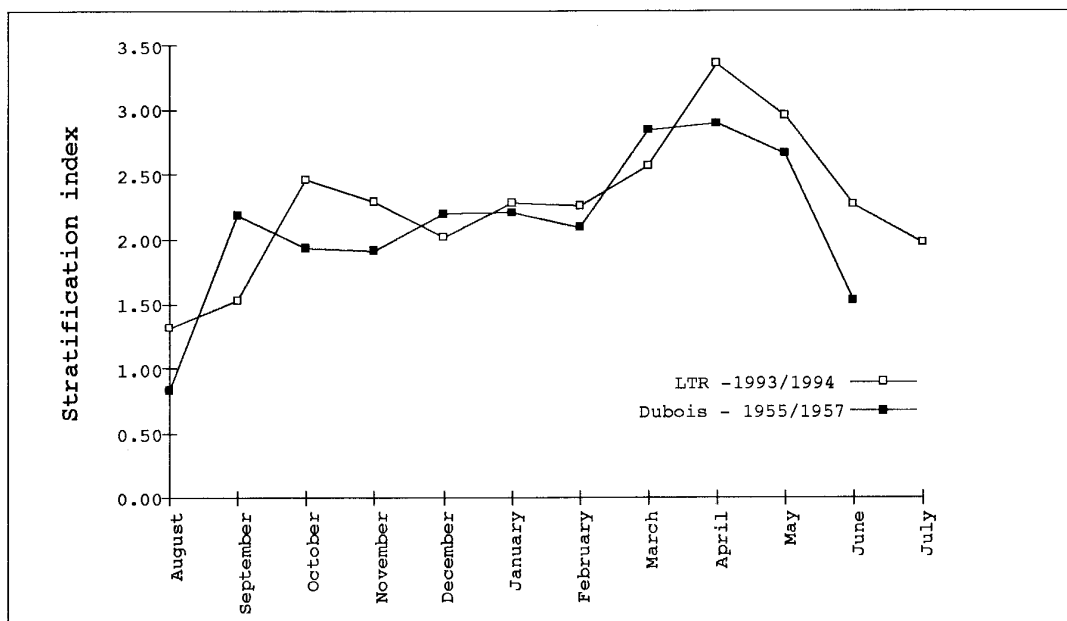


Fig. 10 Monthly stratification indices from temperature data collected near Bujumbura in 1993-94 (LTR, present study) and Uvira in 1955-57 (Dubois, 1958). Stratification indices calculated as in Plisnier et al., 1996.

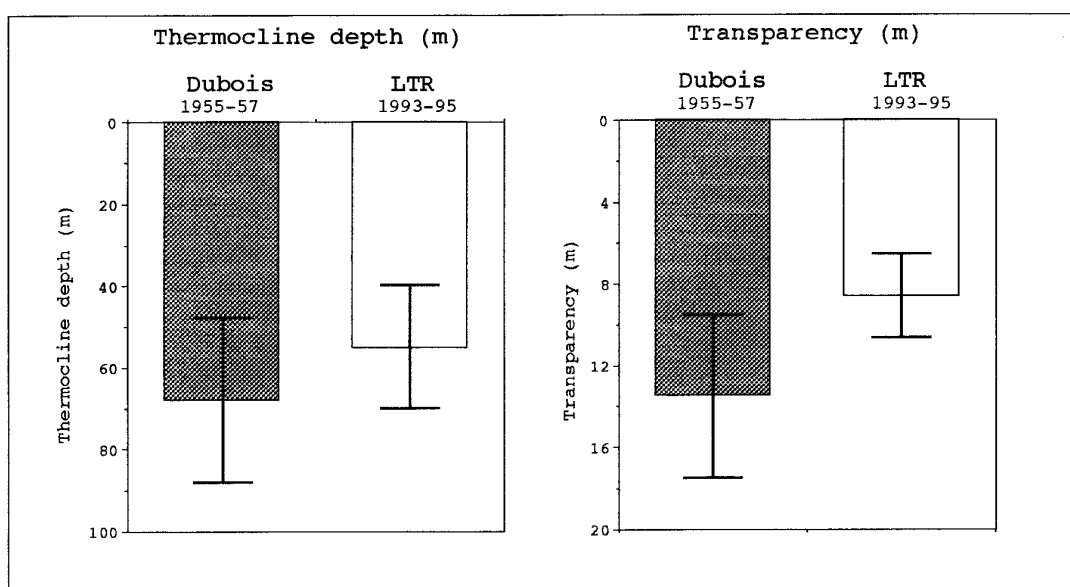


Fig. 11 Yearly mean (+ one standard deviation) thermocline and secchi depths (m) near Bujumbura in 1993-94 (LTR, present study) and Uvira (Dubois, 1958).

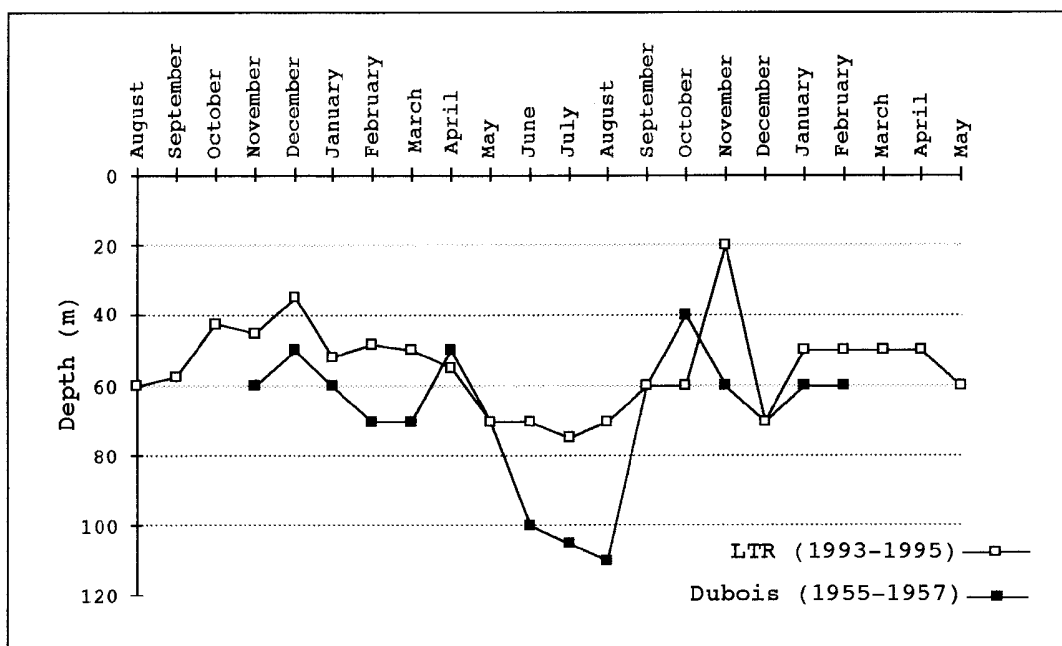


Fig. 12 Thermocline depth (m) near Bujumbura/Uvira in 1955-57 (Dubois, 1958) and in 1993-94 (LTR, present study).

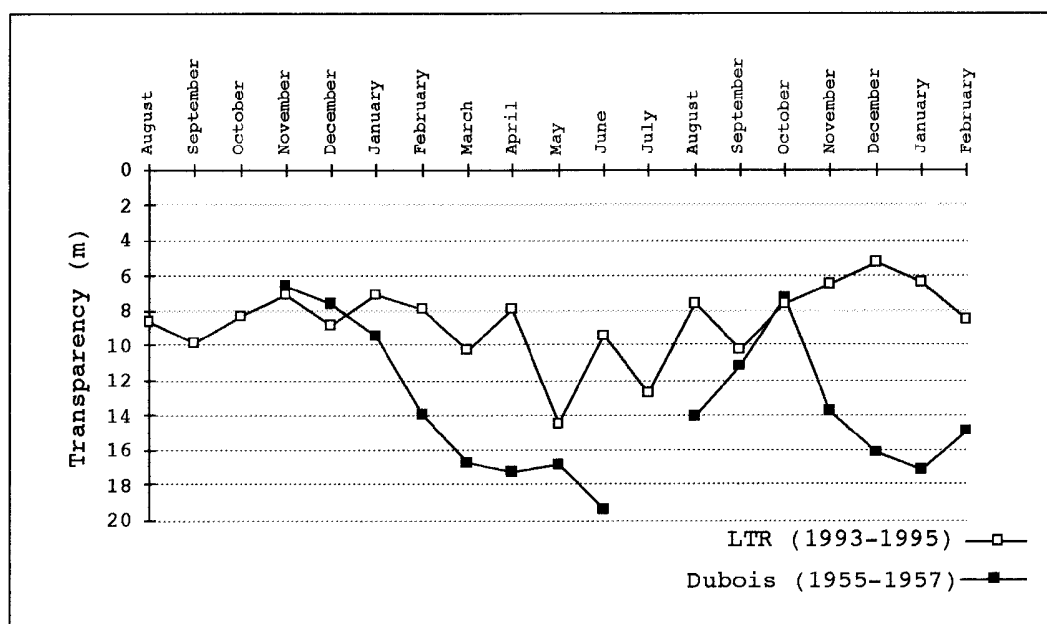


Fig. 13 Secchi depth (m) near Bujumbura-Uvira in 1955-57 (Dubois, 1958) and in 1993-94 (LTR, present study).

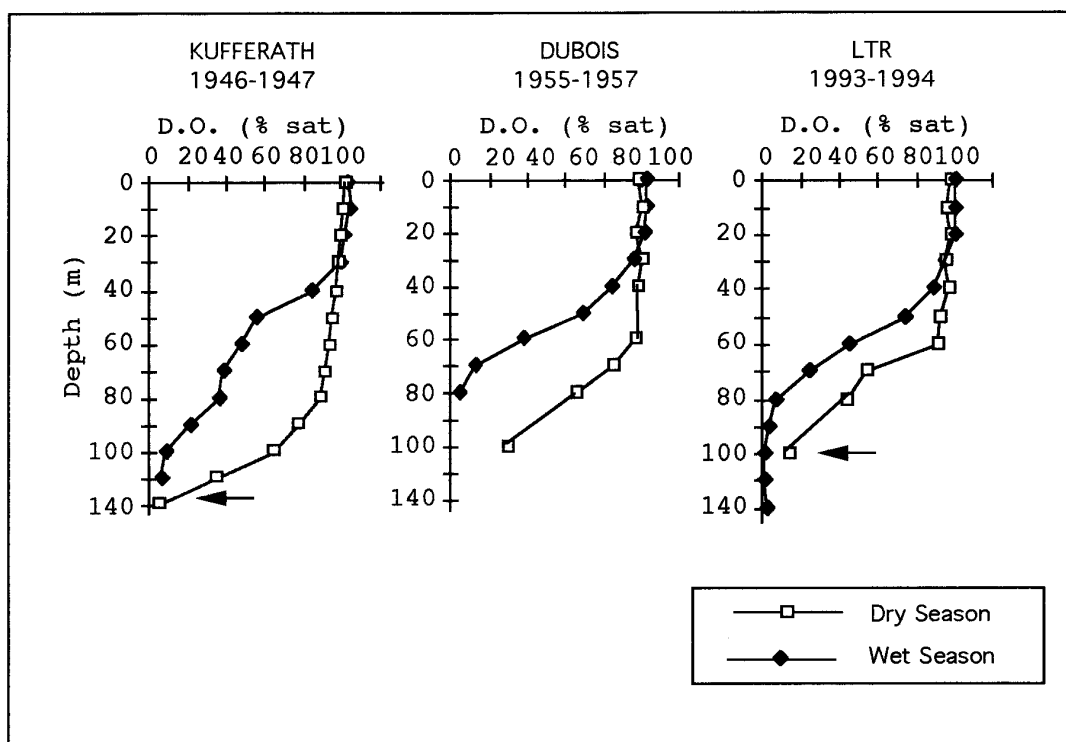


Fig. 14 Dissolved oxygen (% saturation) during the dry and wet seasons in 1946-47 (Van Meel, 1987), 1955-57 (Dubois, 1958) and 1993-94 by LTR (present study). Note the lower limit of the oxic layer (arrows) and the higher difference between seasons in 1946-47 compared to 1993-94.

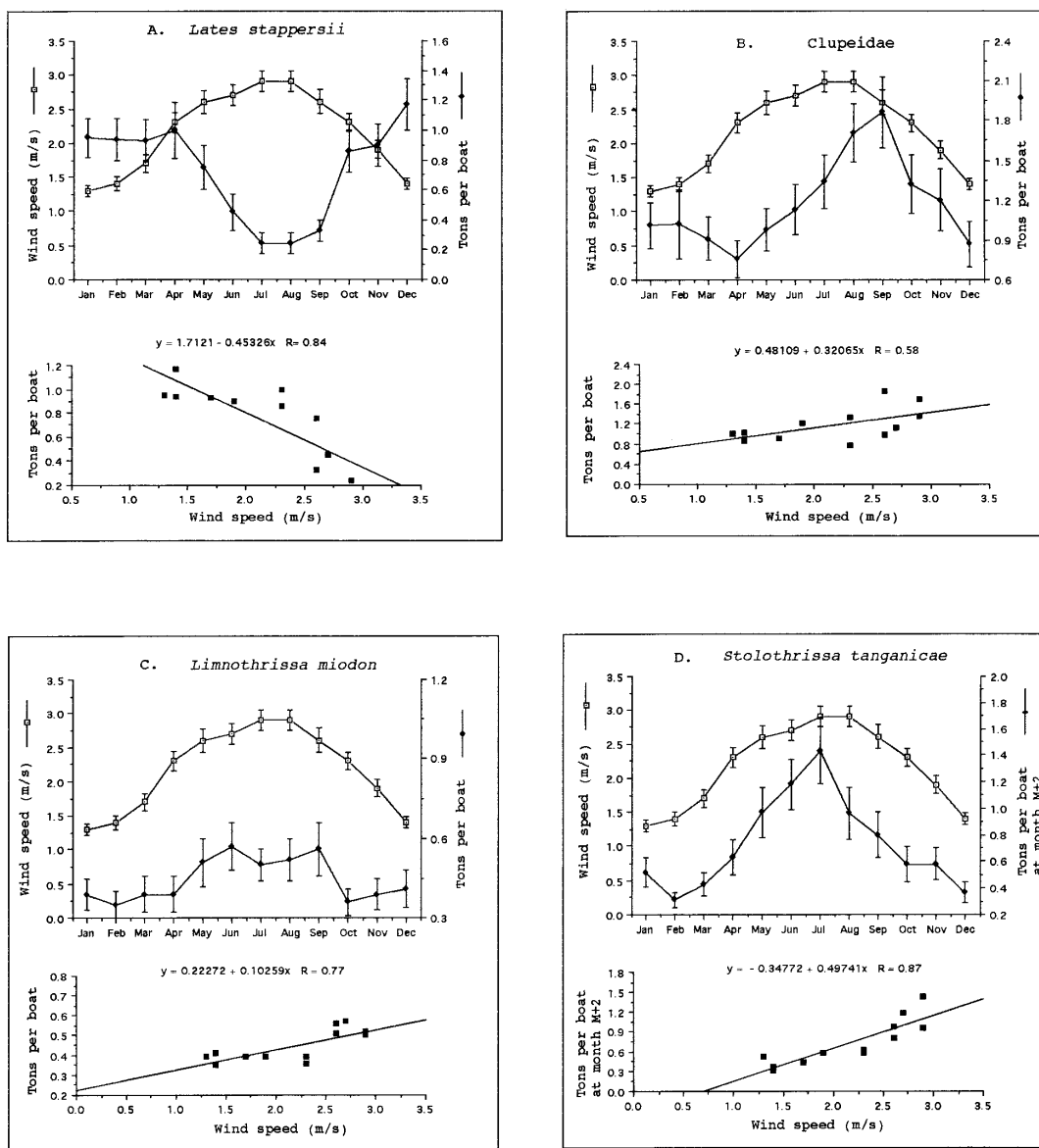


Fig. 15 Relations between monthly average (from Fig. 15 The relationships between monthly mean wind speeds (m/s) at Mbala and catch per unit effort (industrial fishery) at Mpulungu, 1967-94, for A) *L. stappersii*, B) total clupeids, C) *L. miodon* and D) *S. tanganicae*. (+ one standard error of the mean is given). (Data from the Department of Meteorology, Zambia and Pearce, 1992).

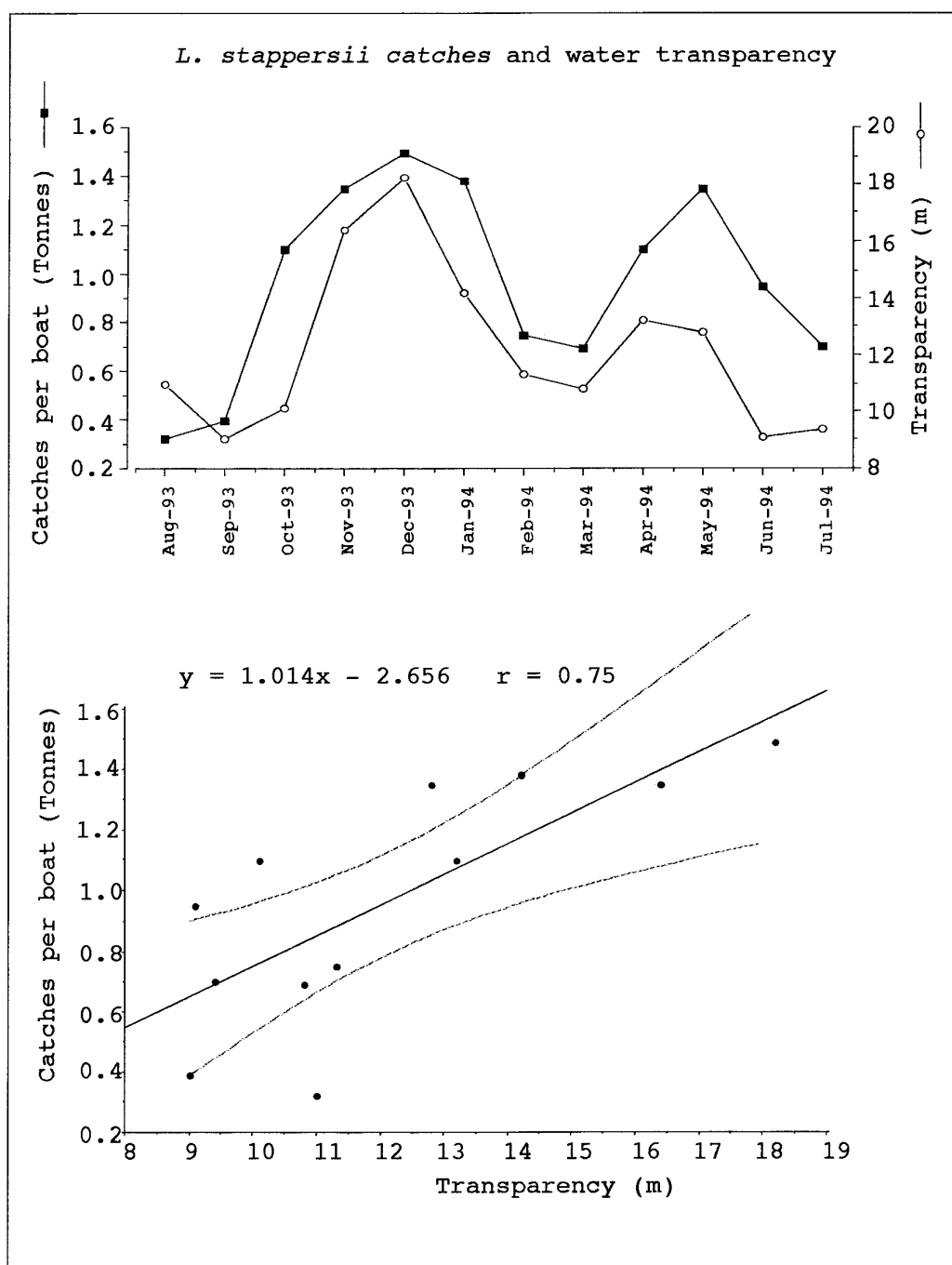


Fig. 16 The relationship between transparency (secchi disk depth, m) and CPUE of *L. stappersii* (industrial fishery) at Mpulungu, 1993-94. (+ 95% CL are given for the regression line).

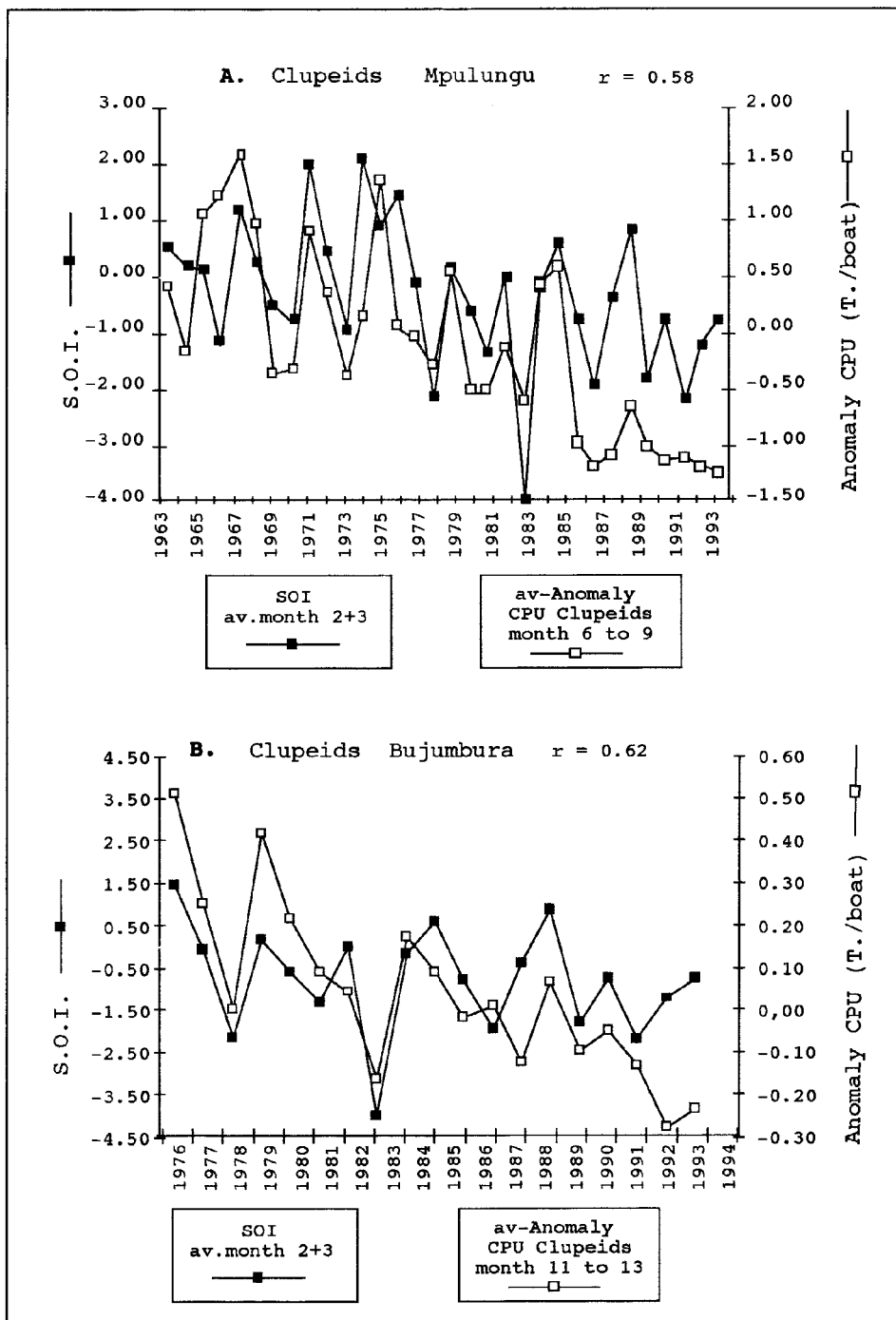


Fig. 17 The difference in clupeid CPUE (tonnes) from the long term mean (anomalies) in relation to the southern oscillation index (SOI) (mean for February and March). A) Mpulungu, CPUE for June to September, 1963-94. B) Bujumbura, CPUE for November to January, 1976-94) (All correlations are statistically significant ($p < 0.01$). (Month 11 is November of year 0, month 13 is January of year 1).

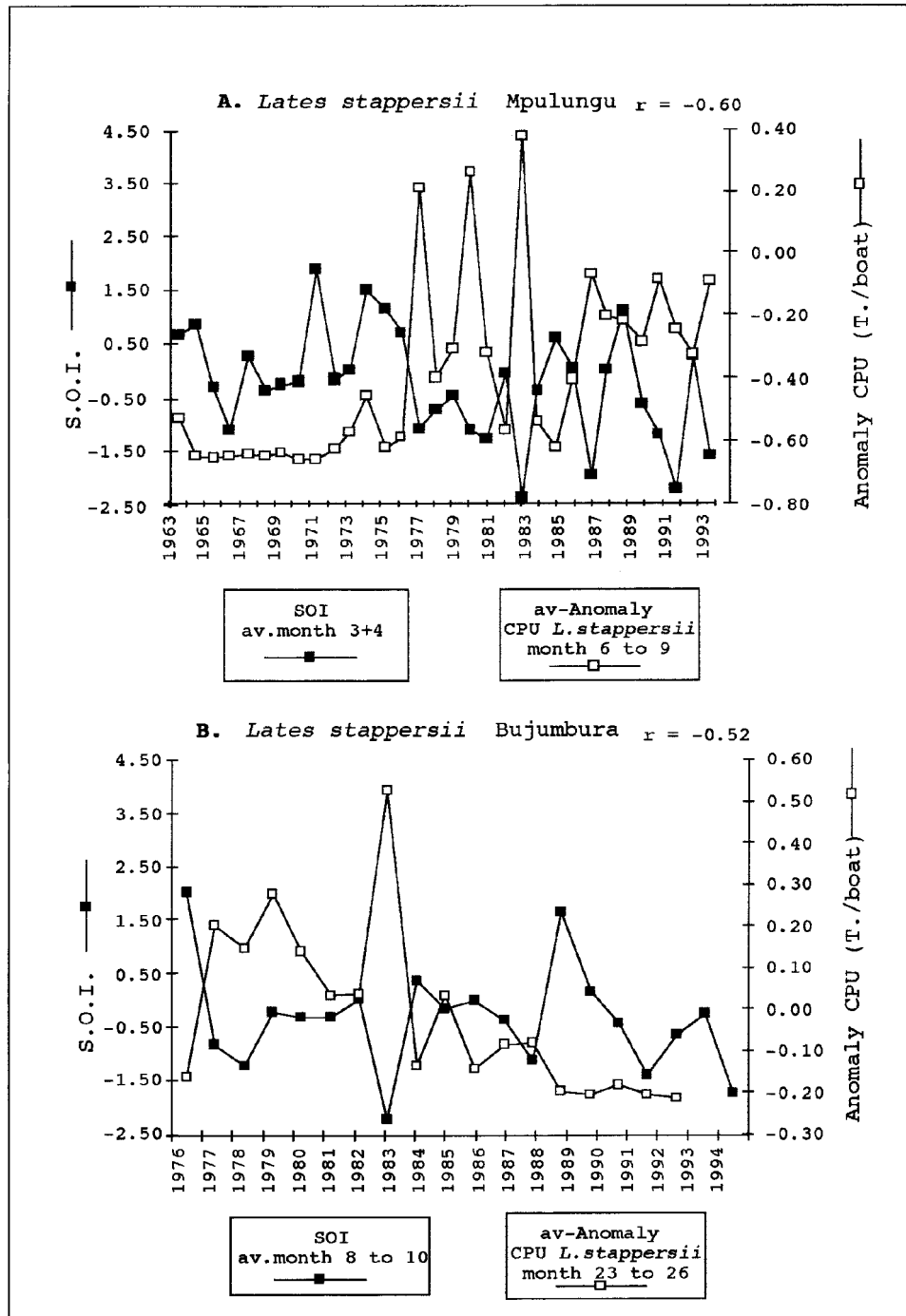


Fig. 18 The difference in *L. stappersii* CPUE from the long term mean (anomalies) in relation to the southern oscillation index (SOI) (mean of March to April in the south and August to September in the north. A) Mpulungu, CPUE for June to September (month 6 to 9), 1963-94. B) Bujumbura, CPUE for November to February (month 23 to 26), 1976-94. (All correlations are statistically significant $p < 0.01$ at Mpulungu and $p < 0.05$ at Bujumbura) (month 11 is November of year 0, month 26 is February of year 3)

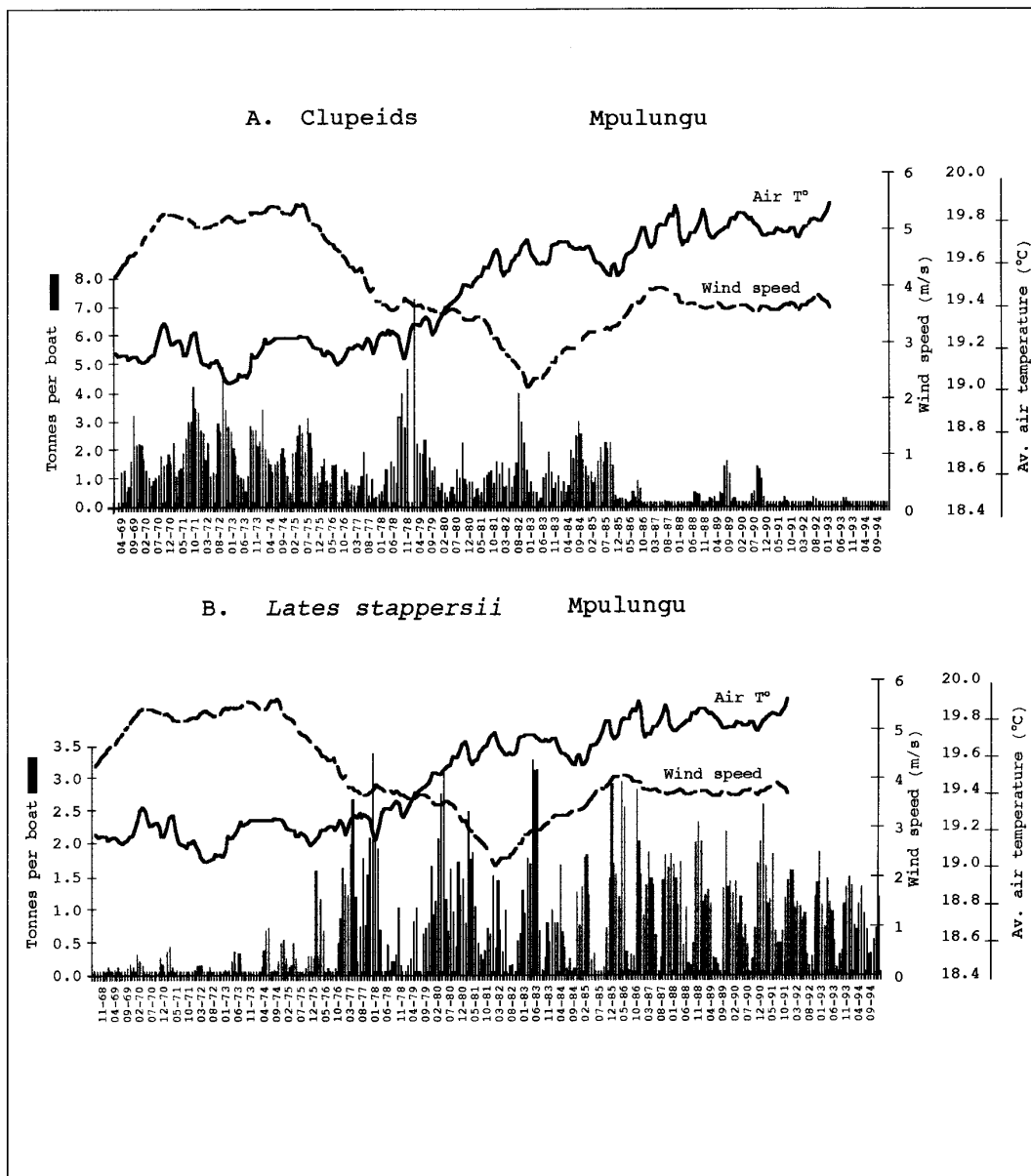


Fig. 19 Catch per unit of effort (tonnes per boat) of A) clupeids and B) *L. stappersii* (industrial fishery) at Mpulungu and mean air temperature (°C) and wind speed (m/s) (12 months), from 1968-69 to 1994. (Data from Pearce, 1992 and Department of Meteorology).

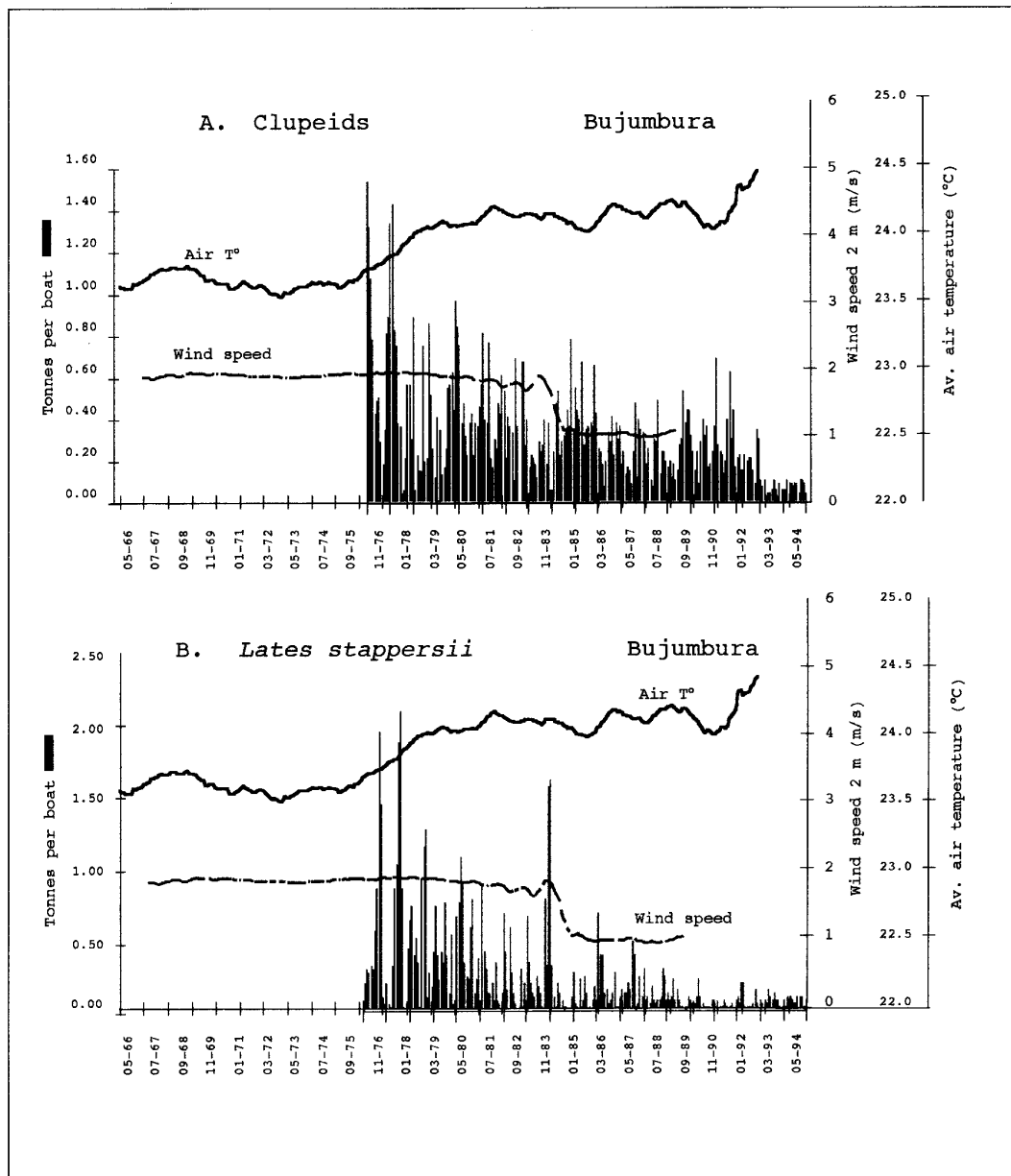


Fig. 20 Catch per unit of effort (tonnes per boat) of A) clupeids and B) *Lates stappersii* (industrial fishery) at Bujumbura and mean air temperature (°C) and wind speed (m/s) (12 months), 1966-94. (Data from Bellemans, 1992 and Institut Géographique du Burundi).

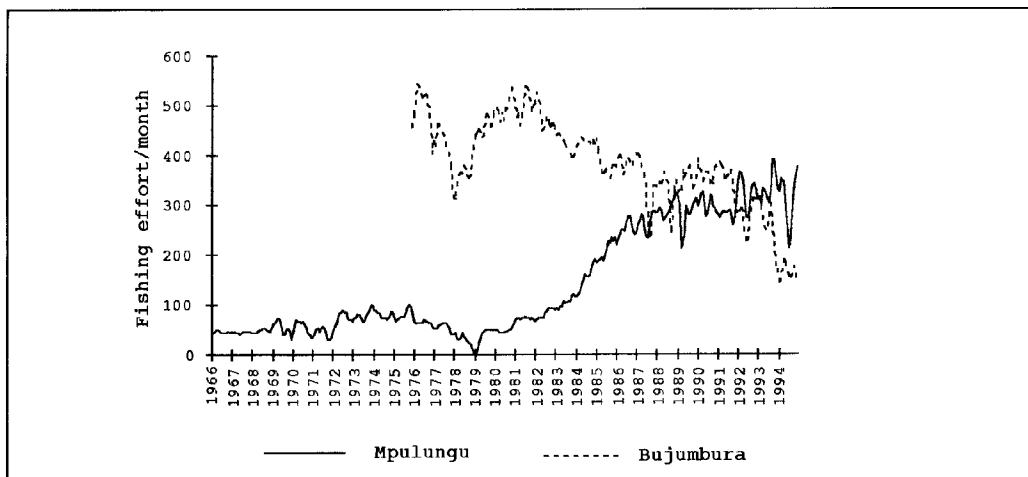


Fig. 21 Fishing effort per month (mean of 3 months) in the south (Mpulungu) and the north (Bujumbura). (Data from Pearce, 1992 and Bellemans, 1992).

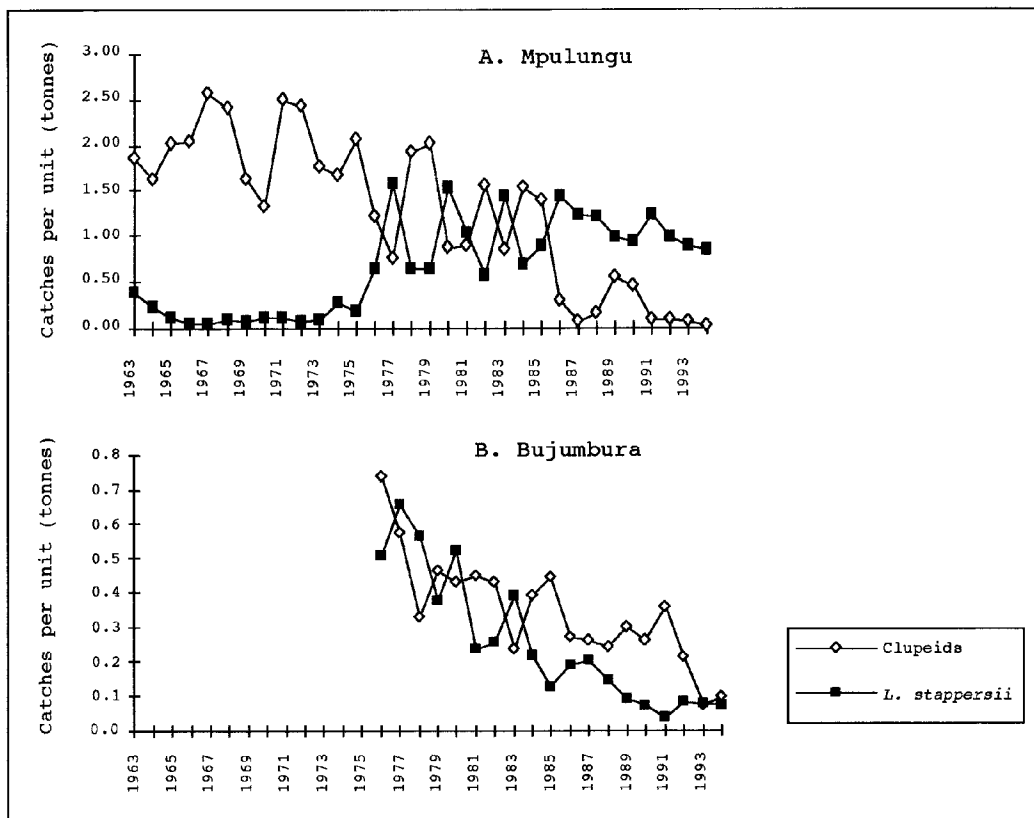


Fig. 22 Annual CPUE (one fishing trip of an industrial boat is one unit) in Mpulungu) and in Bujumbura for clupeids and *L. stappersii*. (Data from Pearce, 1992 and Bellemans, 1992).

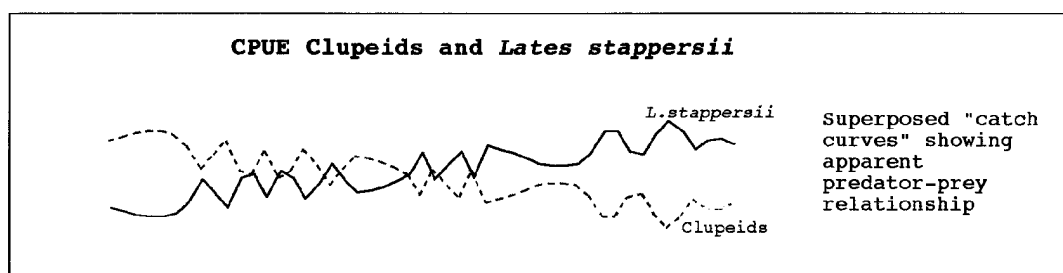
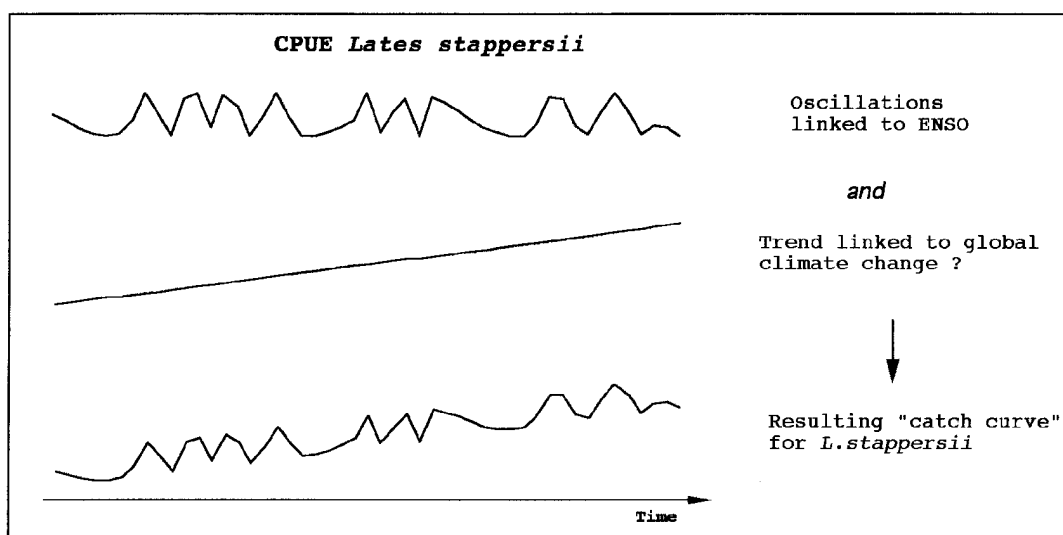
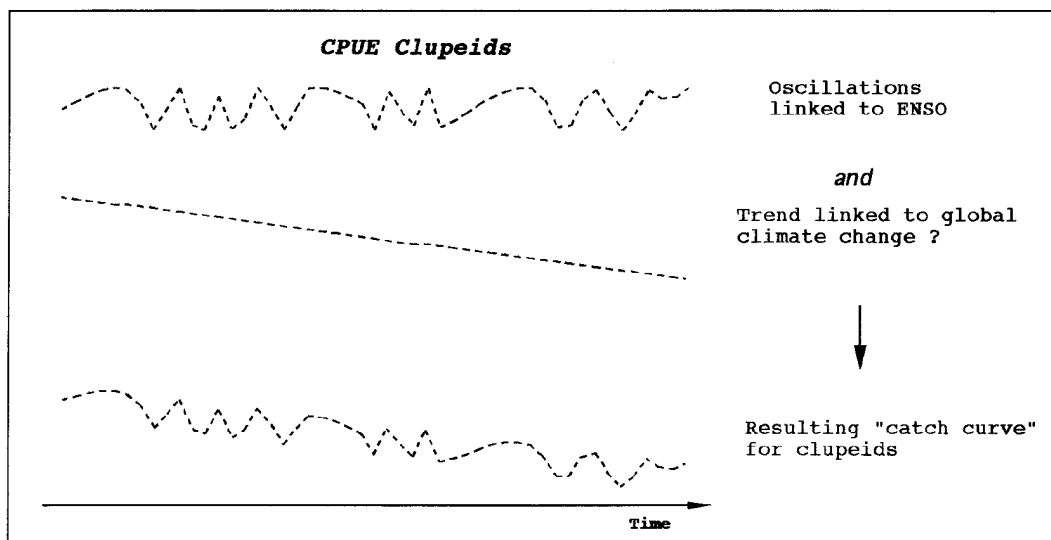


Fig. 23 Schematic representation of the possible effect of the climatic environment on catches curves (variation and trends) of A) clupeids, B) *L. stappersii* and C) catch curves combined. (based on Mpulungu industrial fishery, 1962-95; cf. fig. 22A).