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Observations and Preliminary Modelling of over-lake Meteorology on Large African Lakes

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MANAGEMENT PERSPECTIVE

In response to the rapid development of the East African lake basins and the need to preserve its unique biodiversity integrated programmes of study of the lake were undertaken. This is a reporting on some aspects of these studies .

This document reports on the surface meteorology over two Great Lake critical to both evaporation and water quality modelling in the lake of six key nutrients which sustain biological productivity.

These results will be disseminated to the appropriate persons making the decisions on how best to manage the fisheries of Lakes Malawi/Nyasa and Tanganyika through the auspices of the United Nations University.

Abstract

Water quality models in lakes require accurate specification of the advective and turbulent transport fields. These are usually obtained from lake hydrodynamic models. In turn, hydrodynamic models require accurate specification of meteorological forcing. Uncertain specification of meteorological forcing over large lakes is one of the main reasons for the lack of correspondence between three dimensional hydrodynamic models and observations of currents, temperatures and water levels. This is especially the case of intermontane lakes where sheltering effects of the surrounding topography disturb the air flow and generate such other mesoscale meteorological features as slope winds which reinforce lake breezes.

Direct observations of meteorological variables are particularly sparse for tropical lakes. A roving meteorological station was mounted aboard the research vessel, R/V *Usipa*, on Lake Malawi/Nyasa. Ship velocity and position were recorded, thus permitting winds to be corrected aboard the moving platform. On Lake Tanganyika similar data were recorded discontinuously at two moored meteorological buoys over a period of four years. An examination of the longest running series of winds and air temperatures showed in Lake Malawi/Nyasa no obvious interannual differences in wind speed although air temperatures in the second half of 1999 were cooler than in the same period in 1998. On Lake Tanganyika wind speeds decreased in 1993 to 1996 but air temperatures were highest in 1999. By the method of spectral analysis, both lakes illustrate a strong diurnal signal of wind components and air temperatures. Calculations of an average evaporation rate for Lake Malawi/Nyasa based on observed meteorological data from all temporal scales resulted in mean of three methods of 6.4 +/- 1mm/d. Diurnal meteorological fluctuations accounted for 36% of the total evaporation. Wet and dry season evaporation rates were compared for the two extremities of Lake Tanganyika and found higher in south and during the dry season. Preliminary results of an application of a three dimensional mesoscale meteorological model to Lake Malawi/Nyasa are compared to novel direct observations of a number of forcing parameters required by hydrodynamic models. The results of over-lake comparisons of wind speed and direction are promising.

Observations et modélisation provisoire de la météorologie au-dessus des grands lacs africains

PERSPECTIVE DE GESTION

En réponse à l'évolution rapide des bassins lacustres de l'Afrique de l'Est et de sa biodiversité exceptionnelle, on a entrepris des programmes d'études intégrés. Certains aspects de ces études sont présentés.

Le présent document porte sur les conditions météorologiques enregistrées à la surface de deux grands lacs, qui sont cruciales pour la modélisation de l'évaporation et de la qualité de l'eau dans les lacs relativement à six nutriments principaux qui soutiennent la productivité biologique.

Ces résultats seront transmis aux décideurs appropriés en matière de gestion maximale des pêches dans les lacs Malawi(Nyasa) et Tanganyika sous les auspices de l'Université des Nations Unies.

Résumé

La modélisation de la qualité de l'eau dans les lacs exige une spécification précise des champs de transport par advection et turbulence. Elle se base habituellement sur des modèles hydrodynamiques lacustres. À leur tour, les modèles hydrodynamiques exigent une spécification exacte du forçage météorologique. Le fait de ne pas spécifier avec précision le forçage météorologique au-dessus de lacs de grande étendue est l'une des principales raisons du manque de correspondance entre les modèles hydrodynamiques tri-dimensionnels et les observations des courants, de la température et des niveaux d'eau. C'est particulièrement le cas des lacs intermontagneux où l'abri créé par la topographie perturbe l'écoulement de l'air et génère d'autres caractéristiques météorologiques de mésoéchelle, comme les vents de pente qui renforcent les brises de lac.

L'observation directe de variables météorologiques est particulièrement éparse sur les lacs tropicaux. On a monté à bord du navire de recherche R/V *Usipa,* utilisé sur le Malawi(Nyasa), une station météorologique mobile. En enregistrant la vitesse et la position du navire, on a pu corriger l'effet des vents. Sur le lac Tanganyika, on a enregistré des données semblables à partir de deux bouées météorologiques mouillées pendant quatre ans. L'examen de la plus longue série d'enregistrements des vents et des températures de l'air sur le lac Malawi(Nyasa) n'a montré aucune différence interannuelle évidente dans les vitesses du vent même si les températures de l'air durant le deuxième semestre de 1999 ont été plus frais que durant la période équivalente de 1998. Sur le lac Tanganyika, la vitesse des vents a diminué de 1993 à 1996, mais c'est en 1999 que les températures de l'air ont été les plus élevées. L'analyse spectrale a permis d'illustrer que les deux lacs produisent un fort signal diurne des composantes du vent et des températures de l'air. Des calculs pour obtenir un taux d'évaporation moyen du lac Malawi(Nyasa), basés sur les données météorologiques observées à toutes les échelles temporelles, a produit une valeur moyenne de 6,4 +/- 1mm/j selon les trois méthodes. L'évaporation totale est due dans une proportion de 36 % aux fluctuations météorologiques diurnes. On a comparé les taux d'évaporation saisonniers secs et humides aux deux extrémités du lac Tanganyika qui se sont révélés plus élevés dans le sud et durant la saison sèche. Les résultats provisoires de l'application

d'un modèle météorologique de mésoéchelle tridimensionnel du lac Malawi(Nyasa) sont comparés avec les observations directes inédites d'un certain nombre de paramètres de forçage utilisés par les modèles hydrodynamiques. La comparaison des données sur les vitesses et les directions du vent au-dessus des lacs donne des résultats prometteurs.

OBSERVATIONS AND PRELIMINARY MODELLING OF OVER-LAKE METEOROLOGY ON LARGE AFRICAN LAKES

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1.Abstract

Water quality models in lakes require accurate specification of the advective and turbulent transport fields. These are usually obtained from lake hydrodynamic models. In turn, hydrodynamic models require accurate specification of meteorological forcing. Uncertain specification of meteorological forcing over large lakes is one of the main reasons for the lack of correspondence between three dimensional hydrodynamic models and observations of currents, temperatures and water levels. This is especially the case of intermontane lakes where sheltering effects of the surrounding topography disturb the air flow and generate such other mesoscale meteorological features as slope winds which reinforce lake breezes.

Direct observations of meteorological variables are particularly sparse for tropical lakes. A roving meteorological station was mounted aboard the research vessel, R/V *Usipa*, on Lake Malawi/Nyasa. Ship velocity and position were recorded, thus permitting winds to be corrected aboard the moving platform. On Lake Tanganyika similar data were recorded discontinuously at two moored meteorological buoys over a period of four years. An examination of the longest running series of winds and air temperatures showed in Lake Malawi/Nyasa no obvious interannual differences in wind speed although air temperatures in the second half of 1999 were cooler than in the same period in 1998. On Lake Tanganyika wind speeds decreased in 1993 to 1996 but air temperatures were highest in 1999. By the method of spectral analysis, both lakes illustrate a strong diurnal signal of wind components and air temperatures. Calculations of an average evaporation rate for Lake Malawi/Nyasa based on observed meteorological data from all temporal scales resulted in mean of three methods of 6.4 +/- 1mm/d. Diurnal meteorological fluctuations accounted for 36% of the total evaporation. Wet and dry season evaporation rates were compared for the two extremities of Lake Tanganyika and found higher in south and during the dry season. Preliminary results of an application of a three dimensional mesoscale meteorological model to Lake Malawi/Nyasa are compared to novel direct observations of a number of forcing parameters required by hydrodynamic models. The results of over-lake comparisons of wind speed and direction are promising.

Index Words: Large lake meteorology, evaporation, climatology, modelling

2. Introduction

With the increase in computational power three dimensional mathematical modelling of water quality parameters is becoming feasible in lakes. Water quality models are coupled to hydrodynamic models through water temperatures and the advection and turbulent transport terms all of which must be calculated by hydrodynamic models. In the case of a large lake, Lake Michigan, Belitsky et al.(2000) clearly showed the sensitivity of the agreement between an unstratified three dimensional hydrodynamic model and observed velocity profiles to a more accurate specification of the wind field. The surprising fact about their comparison was that a hindcast by a mesoscale meteorological model improved wind field specification the over the open lake even though the original over-lake wind field was based on an interpolation of a dozen shore-based wind stations. African lakes of interest here generally have far fewer than a dozen meteorological stations on the shoreline. A more effective method of evaluating the hindcast meteorological parameters would be to compare mesoscale model output directly with observations taken over the lake on either a meteorological buoy or a ship.

Water quality models are presently under development in all the Great Lakes of Africa to study various environmental problems. These models require accurate hydrological and meteorological input as driving forces. As model time steps are as short as several minutes, model forcing must be highly resolved in time. This is especially the case for wind. Mortimer (1979) stated that wind stress and its horizontal distribution over the whole water surface is the critical variable and usually the least well defined. The only application of a three-dimensional mesoscale meteorological model that we are aware to a large African lake is that of Mukabana and Pielke (1996) who applied the RAMS model to Kenya and Lake Victoria. The grid resolution was 20 km, a spacing likely too coarse for 50 to 60 km wide Rift Valley lakes. Moreover, their model hindcasts were not evaluated over Lake Victoria. One of the goals of this study is to improve the understanding of the over-lake meteorology of Lakes Tanganyika and Malawi/Nyasa in order to more accurately specify the driving terms of water quality models. In this study we present a summary of the recent meteorological observations recorded on Lakes Malawi/Nyasa and

Tanganyika. The focus, where possible, will be on measurements over the water distant from shoreline disturbances.

With estimated evaporation rates of up to two metres per year (Spigel and Coulter, 1996) evaporation is the dominant term in the water balance of the African Great Lakes. Therefore, it is vital to study evaporation. Accurate estimates of evaporation are also required for the estimation of heat budgets. Evaporation will be one of the subjects of the present study.

Outlines of Lakes Tanganyika and Malawi/Nyasa and their drainage basins are shown in Fig. 1 and 2. Evident from the major topographic features is that these lakes are surrounded by steep sides and mountain ranges typical of Rift Valley lakes. Another goal is to examine the influence of basin topography on the atmospheric boundary layer over the lake surface.

There has been little prior study of the meteorology of Lakes Malawi/Nyasa and Tanganyika. Bootsma (1993) and Patterson and Kachinjika (1995) have briefly summarized the known climatology of Lake Malawi/Nyasa and presented monthly means of air temperatures and winds at several meteorological stations inland from the shoreline over a 14-yr period. They state that a hot rainy season extends from October to April chararacterized by the generally light northerly *Mpoto* winds followed by a cool dry season aqccompanied by the frequent strong south/south-easterly winds known locally as *Mwera*. Hamblin et al. (2000a) plot 10-min wind readings at one station nearby the lake and daily averaged longitudinal wind component squared at another for selected periods. Hamblin et al. (2000b) provide a detailed analysis of the over-lake wind, temperature and vapour pressure fields. Verburg (1997) and Verburg et al. (1998) have discussed in detail the over-lake wind and air temperature fields for Lake Tanganyika with particular attention to their daily variations.

3. Methods and Primary Observations

3.1. FIELD MEASUREMENTS

At four stations located within several hundred meters of the high water mark on the shoreline of Lake Malawi/Nyasa (see Fig. 3) complete sets of surface meteorological observations were taken at 10-min (Chilumba) or 30-min (Senga Bay, Itungi and Likoma Island) intervals starting in early 1997 and continuing until mid 1999. During this period a roving meteorological station was operated, concurrently with eight full-lake research surveys by the R/V *Usipa*, at 10-min sampling intervals. A track of one of the cruises is shown in Fig. 3. At typical ship speeds samples would have been recorded approximately 2 km apart. Between surveys the while R/V *Usipa* was berthed at Monkey Bay sometimes data were recorded. These data were eliminated from the analysis due to the concern that the local meteorology may be disturbed by the steep shorelines of the bay. A fairly representative coverage of the lake is evident. Beside the ship track, selected times and dates are indicated on the figure. Successful cruises were from January to early May which is normally the wet season. The ship speeds as determined by an automatically recording Global Positioning System were subtracted from the raw wind data to correct for platform motion. Next, the 10-min data were averaged to 30-min periods for comparison with the land-based stations. A total of 3316 30-min intervals were processed. Unlike the shorebased stations water temperatures were recorded aboard the R/V *Usipa* while underway. For details of the evaluation of the novel water temperature data and the classification of the data into nine zones along and across the lake, the reader is referred to Hamblin et al. (2000b).

Open-lake winds and air temperatures were measured at two recording meteorological buoys located well offshore in the southern and northern portions of Lake Tanganyika as seen in Fig. 4. They were operated from March 1993 to October 1996 but sporadic breakdowns interrupted the continuity of the records. The recording interval was 60-min at Mpulungu and 30-min at Kigoma. In order to examine evaporation the over-lake wind and air temperatures were supplemented by the extrapolation of relative humidity from the nearest land stations at Mpulungu and Bujumbura to the buoys. The details of the extrapolation procedure are given by Verburg (1997) and Verburg et al. (1998). Both methods of field measurement are illustrated schematically in Fig.5. It is noted that the shipboard measurement heights are at the standard height of 10m above the lake surface whereas the buoy heights are at a height of 2.6m.

3.2. METHODS USED FOR ESTIMATING EVAPORATION

Evaporation from the surface to the air over Lakes Tanganyika and Malawi/Nyasa was calculated by three methods currently used by limnologists. All methods are variations on the bulk transfer method. First, in the simplest method evaporation is assumed to be proportional to the wind speed at the measurement height of the specific humidity and the difference between the specific humidity at that height and the water surface (Fischer et al. 1979). The specific humidity of the air is calculated from the measured air temperature and the relative humidity while that at the water surface is assumed to be completely saturated at the water surface temperature. The constant of proportionality has been slightly adjusted from the value suggested by Fischer et al. 1979 based on the applications to numerous thermodynamic calculations in lakes by the model DYRESM (e.g. Hamblin et al., 1999). It is noted that the latent heat flux given by Fischer et al. is converted to an evaporation rate for comparison with the other methods reported in the literature by dividing the flux by the product of the latent heat of evaporation and the water density.

The second method summarized by Chow et al. (1988) takes into account the additional factors of the roughness of the surface boundary layer and the measurement height provided that wind, relative humidity and air temperature are all measured at the same level. In the case of the R/V *Usipa* these heights were nearly identical at 10m above the water surface, the standard height for surface boundary layer measurements. The roughness factor, z_0, must be specified by the user. As the authors suggest a wide range of possible roughness lengths over water it was decided to use the z_0 calculated as a byproduct of the third method by Liu et al. (1979) (order 10^{-4}m) for Lake Malawi/Nyasa. For Lake Tanganyika the evaporation was calculated by the Chow et al. method using a roughness factor of 6.10^{-4}m. Liu et al.'s method is the most sophisticated taking into account boundary layer stability based on the relative wind strength and air-water temperature difference, variable boundary roughness over water as a function of wind speed and the individual heights of all three input variables.

3.3. MESOSCALE MODELLING

A two-day pilot experiment was run on the three dimensional mesoscale meteorological model, MM5, (Grell et al. 1994) for Lake Malawi and its basin. The model is initialized at 12-hr intervals from archived output of a synoptic scale meteorological forecast model at a grid spacing of approximately 200 km and the basin terrain is input at 4-km grids based on the topographic data of Fig. 1. In the simulations reported herein the lake surface temperature is decoupled from the model and held constant at an average value of the surface temperature over the 2-d period based on data from the five thermistor chains of Fig. 3. The mesoscale model interpolates from the coarse grid to a high resolution grid of 4-km spacing and in time to one hour based on the principles of fluid mechanics and the input data. Only surface model outputs were saved for later comparison with field observations.

4. Results

4.1. ANNUAL AND INTERANNUAL VARIABILITY

Due to frequent disruptions in the Lake Tanganyika buoy data it was difficult to compare one year with another and further, no large ENSO events were thought to occur during the 4-yr study period. Consequently, as complete as possible annual cycle was assembled for each station. Meteorological conditions at the north end of Lake Tanganyika are summarized in Fig. 6. which presents monthly total rainfall (means for 1973 to 1993) and 21-d running averages of solar radiation (shortwave), air pressure, air temperature, wind speed and relative humidity at Bujumbura (1995). For the Mpulungu land station (1996) and south end buoy wind and air temperature (1995) similar quantities are compared in Fig. 7.

Due to the long intervals between full-lake cruises the data collected aboard the research vessel were unsuitable for long term analysis. Rather, the most continuous series of meteorological data was collected at the land-based station at Senga Bay. While it was anticipated that this data set might capture two opposite climatological extremes, the warmer-than-usual El Niño considered to peak in late 1997 followed by the cooler La Niña event thought to peak in late 1998, the comparison of daily averaged winds in Fig. 8 does not suggest an obvious trend. On the other hand, the air temperatures are somewhat higher in 1998 and lower in the latter half of 1999 suggesting the expected trend although delayed. No obvious trends in precipitation nor other meteorological variables were observed for the years sampled.

4.2. DIURNAL ANALYSIS

To illustrate the dominance of diurnal variability in meteorological data it is convenient to use a method of time series analysis known as spectral analysis. Unfortunately, again the shipboard data are unsuitable for this method so instead, the three concurrent land stations were chosen for analysis. For ease of computation over the approximately 120-day period of analysis the north and east components of wind were first averaged from 30-min to 3-hr intervals. Fig. 9 compares the autospectra at each location and for each wind component. All three land stations stations demonstrate remarkably high energies at the diurnal period. Only for the Senga Bay alongshore wind component does the energy at very long periods exceed the diurnal period energy. The Likoma Island easterly diurnal component is the most energetic of all corresponding to an average amplitude of 2m/s. The partition of energy into two bands, namely diurnal and very low frequency suggests that the subsequent analysis can be focused on each of the two highly energetic bands while other regions of the spectrum can be safely ignored

However, in the case of Lake Tanganyika sufficiently long continuous records were available at the two buoys spanning each of the rainy and dry seasons. Spectra of winds and air temperatures at the southern buoy, Mpulungu, demonstrate dominant diurnal variability in Fig. 10. According to Savarti (1997) dry season conditions are most favourable to diurnal winds. Remarkably, the diurnal winds are nearly as strong during the wet season, being only about 40% weaker. A similar plot at the buoy offshore of Kigoma (not shown) does not reveal any appreciable spectral differences from Fig. 10.

The R/V *Usipa* wind data are displayed as sets of wind vectors every three hours over a daily period in Fig. 11. The shipboard data are classified into nine geographical zones with the average position in each zone indicated by the origin of the wind vector in Fig. 11. When there are fewer than ten samples in a class vectors are not plotted. While only at midnight were all zones represented, there is an indication of near surface diurnal wind divergence during the daytime from 9 to 15 hr and nightly wind convergence from 21 to 6hr. Within the limitations of the data set there is no indication that the diurnal wind has a latitudinal variation in strength in Fig.11.

Air temperature is a key variable for both evaporation and specification of the driving terms for water quality models. Its diurnal behaviour in both lakes is given in detail by Hamblin et al. (2000b) and Verburg (1997). It is interesting that the midlake diurnal temperature variation in Lake Malawi/Nyasa is less than the nearshore indicating some moderation of the air mass over the lake.

4.3. EVAPORATION

First, the annual variation of evaporation rates are compared in Lake Tanganyika at the north (Bujambura) and south (Mpulungu buoy) in Fig. 12. The consistently higher evaporation in south suggests that there is a latitudinal gradient in evaporation. This is likely due to air mass modification by the prevailing southerly winds.

Next, daily rates of evaporation are compared by zone for Lake Malawi/Nyasa in Fig. 13. There appear to be three diurnal modes, one fairly constant throughout the day tending to occur on the eastern portion, another with peak evaporation around 15hr (the most prevalent and occurring at all midlake zones) and finally, one peaking at night found only in the southwest zone. Fig. 14 demonstrates a similar behaviour for Lake Tanganyika but in this case, by season and spatial position. The constant response occurs only during the wet season, January 1996 at Mpulungu in the south whereas the nightly peaking mode during the dry season, August 1995. The evaporation in the north always peaks in the afternoon but is, not surprisingly, higher in the dry season. By reference to the monthly averaged plots of wind speed, air and water temperature and relative humidity of Verburg (1997) it is apparent that the daily cycle of evaporation is mainly determined by wind speed variations.

In contrast to the above diurnal variations, the lakewide spatial distribution of evaporation in Lake Malawi/Nyasa plotted in Fig. 15 is based on horizontally smoothed estimates of evaporation. Shipboard evaporation estimates are positive as might be expected during and just after the wet season as air temperatures (not shown) were from 2 to 4 °C cooler than the lake surface water temperatures (see Hamblin et al. 2000b). Hamblin et al. (2000b) compared estimates of lakewide evaporation rates based on temporally smoothed wind, air temperature and vapour pressures with those based on raw data to study the role played by diurnal processes in evaporation. They found that evaporation based on daily or longer term averaged quantities could underestimate evaporation by as much as 36%. The peak evaporation rate to the north of Senga Bay is probably due to the high wind speeds occurring there. Similarly, sensible heat flux which is also proportional to the wind would be underestimated based on smoothed or daily winds. In Lake Tanganyika evaporation was underestimated by 10 to 15% using monthly means.

The lakewide rates of evaporation for Lake Malawi/Nyasa calculated by three variations on the bulk transfer method are summarized in Table I. The Fischer et al. (1979) result is slightly higher than that of the Liu et al. (1979) method and is apt to be higher due to the fact that in most prior applications of the Fischer et al. expression the winds were measured at a lower height than 10m. The Chow et al. (1988) expression may be less accurate as it is generalized for use over land as well as water. The most accurate is apt to be the Liu et al.(1979) method. Averaging the three methods but excluding the temporally smoothed value for the reasons discussed above gives an overall estimate of the rate of evaporation of 6.4 +/- 1mm/d

4.4. MESOSCALE MODELLING

Savijarvi (1997) was one of the first to apply a mesoscale meteorological model to a large African Lake. Since the model was two dimensional in an east-west plane across the middle of Lake Tanganyika, it would be difficult to compare its results with meteorological observations at a point. Such a model provides little practical information on the lake surface specification of wind stress and energy fluxes needed by the hydrodynamic modeller. Nonetheless, the model demonstrated an organized mesoscale wind circulation in the cross lake vertical plane, especially during the dry season. As well, the interaction of the diurnal circulation and the southeast trade winds was captured and was found to enhance the eastern shore's lake breeze system. Savarti (1997)was able with the aid of the mesoscale model to estimate the portion of the diurnal circulation attributable to land-water temperature differences, to tradewind interactions and to slope winds on the steep sided Lake Tanganyika.

In the case of Lake Malawi/Nyasa meteorological conditions were observed along the track shown in Fig. 16 which is, for the most part, beyond the influence of shoreline disturbances. Modelled and observed winds, air temperatures, relative humidities, solar radiation and barometric pressures are compared in Fig. 17 at the grid point closest to the research vessel's location at a given time. The agreement is good for wind speed and direction and relative humidity but poorer for air temperature. As well, shortwave radiation agreed well with that observed aboard the ship. Air temperature is important for the lake hydrodynamic modeller as it enters into expressions for the sensible and latent heat fluxes. These fluxes are also output by the model and compared favourably with those calculated from observed water and air temperatures and relative humidity as is evident in Fig. 18. On a daily basis the incoming longwave energy flux is the most important of all the fluxes. As it was not measured aboard the R/V *Usipa* it had to be estimated from an empirical expression involving the unknown cloud cover. The observed curve in Fig. 18 is based on an assumed value of 70% cloud cover. An assumption of 100% cloud cover brings the two curves into close agreement. In contrast to the open lake meteorological data comparisons, modelled and observed data were found to correspond poorly with one another at the three shoreline stations. As an example of a well exposed station, the Likoma Island comparison is given in Fig. 19.

5. Discussion

The lack of evidence for signatures in the precipitation, air temperature and wind strength of the recent ENSO event is surprising. It is possible that Lake Malawi/Nyasa is situated at node between two types of climatic response to the El Niño/ La Niña cycle, one to the north and the other south of the lake.

Unlike the case for Lake Tanganyika, logistics, security concerns and expense prevented the use of moored meteorological buoys from being used on Lake Malawi/Nyasa. However, with the use of an automated system of recording position and platform motion, it has been demonstrated that a reasonably comprehensive data set can be collected aboard a roving vessel. However, this approach is far from ideal when compared to a network of meteorological buoys. It suffers from a lack of synopticity and may be biased to daylight hours and fair weather. At this point, equipment failures have made it impossible to establish the seasonal differences in lake meteorology for Lake Malawi/Nyasa that have been demonstrated for Lake Tanganyika. It is likely that dry season evaporation rates would be higher than those observed herein. Water temperature errors of unknown origin were thought to be present in the shipboard observations.

It is possible to compare the evaporation rates estimated in the present study by variants of the aerodynamic method with those based on the water balance method. Owen et al. (1990) estimated an evaporation rate of 5.2mm/d for Lake Malaw/Nyasa based on water level recession over the dry season, no groundwater inflow, but allowing for precipitation and river inflows and outflows. Spigel and Coulter (1996) estimated 4.2mm/d from the mean annual water balance. As the variation between two applications of the water balance method of 1mm/d is about the same as between the aeorodynamic method the agreement is reasonable; that is, the two independent methods agree to within the uncertainty of the estimates. The average rate of evaporation of this study 6.4 +/- 1mm/d is comparable to the wet season evaporation rate quoted by Patterson and Kachinjika (1995) at Salima, a station situated 5km inland from Senga Bay.

The over-lake meteorological data sets collected by meteorological buoys and the R/V *Usipa* demonstrate the importance of the diurnal weather system in these two RiftValley lakes. This is in contrast to the Laurentian Great Lakes, where diurnal winds are barely detectable in offshore wind spectra (Hamblin, 1987, Hamblin and Elder 1973). However, there are certain similarities to the shoreline winds on the temperate zone intermontane Lake Geneva. Lemmin and D'Adamo (1996) found some stations where the cross shore diurnal energy exceeded the long-term energy but not in the longshore component unlike Lakes Tanganyika and Malawi/Nyasa. Diurnal winds have typical amplitudes of 2 to 3 m/s compared to the strength of the long-term wind of 2 to 4 m/s. However, at the extremities of the lake where smoothed winds are 2m/s or less, diurnal winds predominate. Savijarvi (1997) has pointed out that for RiftValley lakes the usual land/lake air temperature contrast driving the diurnal wind pattern is augmented by a valley or slope wind component. This slope component is evidently solely responsible for the nocturnal wind blowing from the land in tropical lakes. The addition of slope winds to those driven by land-lake thermal contrasts likely accounts for dominance of the diurnal wind systems on the two lakes of interest. Evaporation estimates may be seriously in error if this system is not taken into account. Interestingly, the east-west asymmetry in the diurnal wind system observed in Lake Malawi/Nyasa is in accordance with the mesoscale modelling results of Savijarvi (1997) which took into account the interaction of the diurnal wind system with the south-east trade winds.

The lack of low frequency fluctuations in the alongshore wind spectra, the reduction of wind speed at the extremities and the tendency of wind to blow along the major axis are indications of strong topographic sheltering by the lakes' basins. In a smaller lake Hamblin et al. (1999) demonstrated directly the sheltering effect of surrounding topography by a comparison of winds on the shoreline with winds in the middle and how the reduction of over-lake wind fields conformed to boundary layer theory.

Hamblin (1987) found that the results of an application of a wind-driven hydrodynamic model to Lake Erie were degraded when a dozen shoreline wind stations were included along with six moored stations in the interpolation of over-lake winds when compared to those for the six meteorological buoys alone. Thus, it is not surprising that the mesoscale model did not agree well at the shoreline stations. Likely, local sheltering at the shoreline sites render these stations less useful for hydrodynamic modelling purposes than well situated meteorological buoys. The 4-km grid spacing and 1-hr time step employed in this application of a mesoscale meteorological model appear to be adequate for capturing the complex atmospheric circulation over the surface of a 60-km wide lake.

6. Conclusions and Recommendations for Further Study

The pronounced diurnal wind and temperature systems suggest a strong mesoscale organization of the wind and temperature fields. A three dimensional extension of the type of two dimensional mesoscale meteorological model outlined by Savijarvi (1997) has been shown to be in reasonable agreement with over-lake field data and thus could potentially yield valuable additional information to the sparse meteorological coverage that we measured in our field experiments. In particular, it could be used on a practical basis to specify the meteorological forcing to lake hydrodynamic models. An evaluation of a similar pilot application to Lake Tanganyika would be most instructive. In other African Great Lakes where there no regular networks of meteorological buoys and the shorebased stations are few, the preliminary analysis reported herein suggests that three dimensional mesoscale meteorological models can provide useful information on the forcing needed by the lake hydrodynamic and water quality modeller.

Comparison of modelled and observed cloud cover over the lake as might be inferred from short wave radiation or satellite imagery needs to be undertaken. As well, the coupling of either observed or modelled lake surface temperature into the lower boundary condition of the mesoscale model should be examined.

The dominance of the diurnal variation of meteorological variables not only at the shoreline but in the offshore areas of the open lake has been demonstrated. This has implications for the estimation of the lake's heat budget and hydrodynamics. Neglect of shorter term winds would lead to an underestimation of the latent and sensible heat fluxes and bias the results of hydrodynamic models.

Savijarvi (1997) has shown from a mesoscale model that the diurnal atmospheric circulation over Lake Tanganyika is dominant and is composed of a slope component and a land-lake component, both of which reinforce one another. The observed over-lake wind fields of two African Great Lakes reported in the present study support this conclusion.

In the short-term while funding is being established for lakewide networks of meteorological buoys in the African Great Lakes, it is recommended that both research vessels and other ships of opportunity such as lake ferries be instrumented with recording meteorological systems similar to the one reported in the present study. Before undertaking such measurements it is strongly recommended that the source of error in underway temperature measurement be identified and corrected.

7. Acknowledgements

We are grateful for the assistance of Mr. S. Smith, Captain M. Day and the crew of R/V *Usipa* in the field programme. Environment Canada, the U.S. National Science Foundation, the Canadian International Development Agency, the Global Environmental Fund, the Department for International Development, U.K. and the Research Project for the Management of the Fisheries of Lake Tanganyika, Food and Agriculture Organization, GCP/RAF/271/FIN provided funding for this study. D.H.Eccles is thanked for insightful discussions on lake meteorology.

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List of Table Captions

List of Figure Captions

1)Lake Malawi/Nyasa and its basin topography in metres above the lake surface (471m above sea level). Origin is at 12.5° S, 35.° E. Cartographic data are taken from TOPO30 (National Geophysical Data Center).

2)Lake Tanganyika and its basin topography in metres above the lake surface (774m above sea level). Origin is at 6° S, 29.5° E. Cartographic data are taken from TOPO30 (National Geophysical Data Center).

3)Meteorological and thermistor chain (solid circle) station locations and a R/V *Usipa* Track for April 26 to May 7, 1998.

4)Meteorological station locations on Lake Tanganyika.

5)Schematic of over-lake meteorological measurement methods; upper panel, R/V *Usipa* Lake Malawi/Nyasa, lower, a Lake Tanganyika meteorological buoy.

6) Meteorological conditions at the north end of Lake Tanganyika. Monthly total rainfall (means for 1973 to 1993) and 21-d running averages of solar radiation (shortwave), air pressure, air temperature, wind speed and relative humidity at Bujumbura (1995).

7) Same as Fig. 6 but for Mpulungu land station (1996) and south end buoy wind and air temperature (1995).

8)Meterological conditions at Senga Bay smoothed by a 7-d moving average except for rainfall. Note that rainfall for 1998/99 is substituted by the station at Salima (5 km distant) due to a faulty gauge.

9)Spectra of wind components at three shore-based stations, Lake Malawi/Nyasa. The period analysed is from mid September 1998 to mid January, 1999.

10)Comparison of spectra of wind components and air temperatures at the Mpulungu buoy station, Lake Tanganyika for the rainy and dry seasons. The spectral density is logarithmic.

11)Average diurnal winds over 3hr interval in each zone for Lake Malawi/Nyasa.

12) Comparisons of evaporation over the day at the north (Bujambura) and south (Mpulungu buoy), Lake Tanganyika, during the dry seasons, August 1995 and wet season January 1996.

13) Daily evaporation fluctuations by zones for all cruises for Lake Malawi/Nyasa. Standard deviations are not defined if there are fewer than four values in a class. Some classes are not present.

14) Twenty-one-day running averages of evaporation, calculated for Bujumbura and Mpulungu buoy.

15) Contours of evaporation rate (mm/d) based on Liu et al. (1979) and unsmoothed data.

16) R/V *Usipa* track, Lake Malawi/Nyasa, for 2-d modelling period.

17) Comparison of observed (solid line) and modelled (dashed line) wind speed, direction, air temperature, and barometric pressure along track of Fig. 16.

18) Comparison of observed (solid line) and modelled (dashed line) modelled energy fluxes along track of Fig. 16.

19) Same as Fig. 17 but for the Likoma Island station.

Method	Evaporation Rate (mm/d)	Standard deviation (mm/d)
Fischer et al. 1979	7.6	3.3
Fischer smoothed data	4.1	2.4
Liu et al. 1979	6.5	2.9
Chow et al. 1988 with Liu z_0	5.2	2.3

Table I. Comparison of Lakewide Evaporation Methods

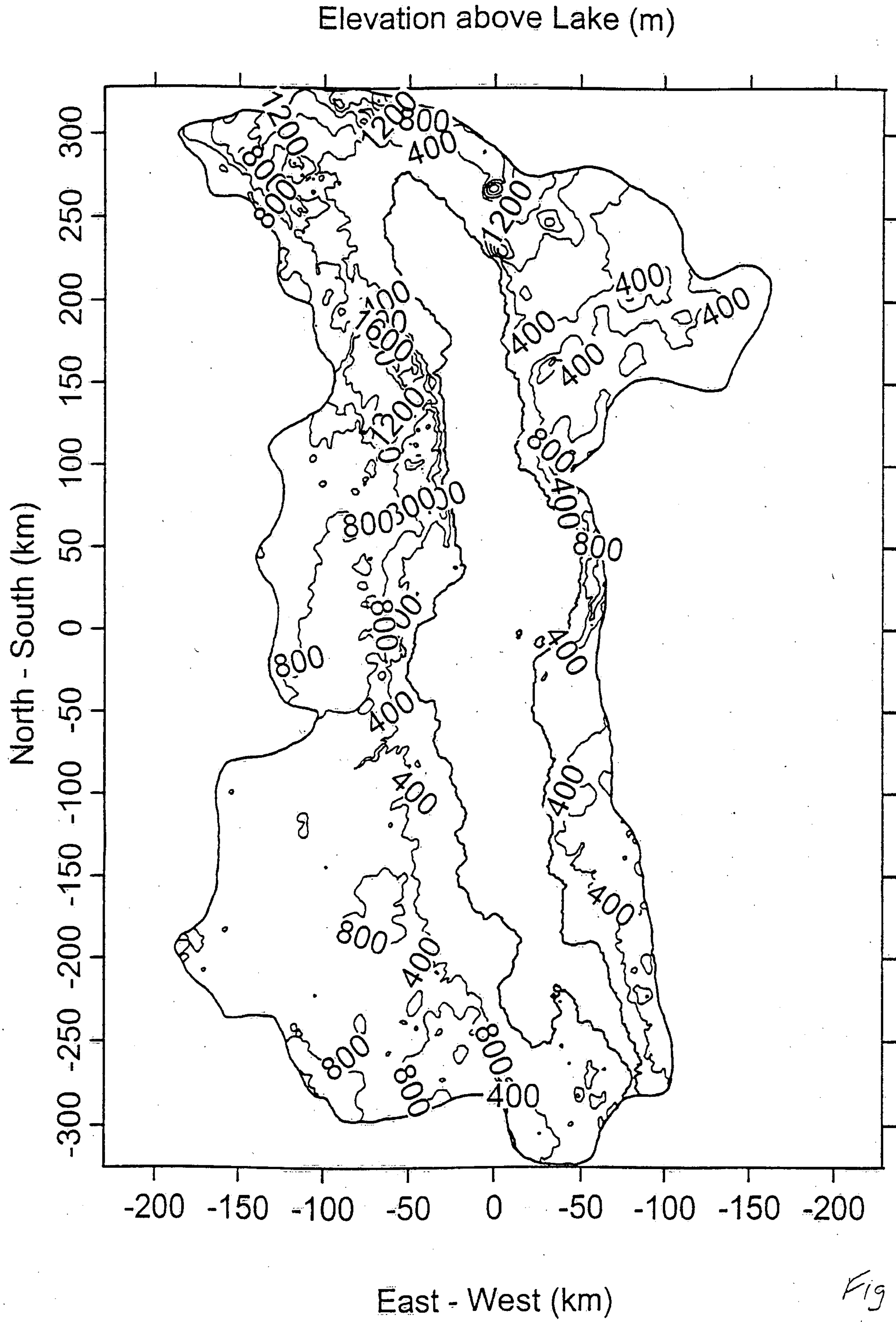

Elevation above Lake (m)
North - South (km)
East - West (km)
300
250
200
150
100
50
0
-50
-100
-150
-200
-250
-300
-200
-150
-100
-50
0
-50
-100
-150
-200
400
800
1200
1600

Fig 1

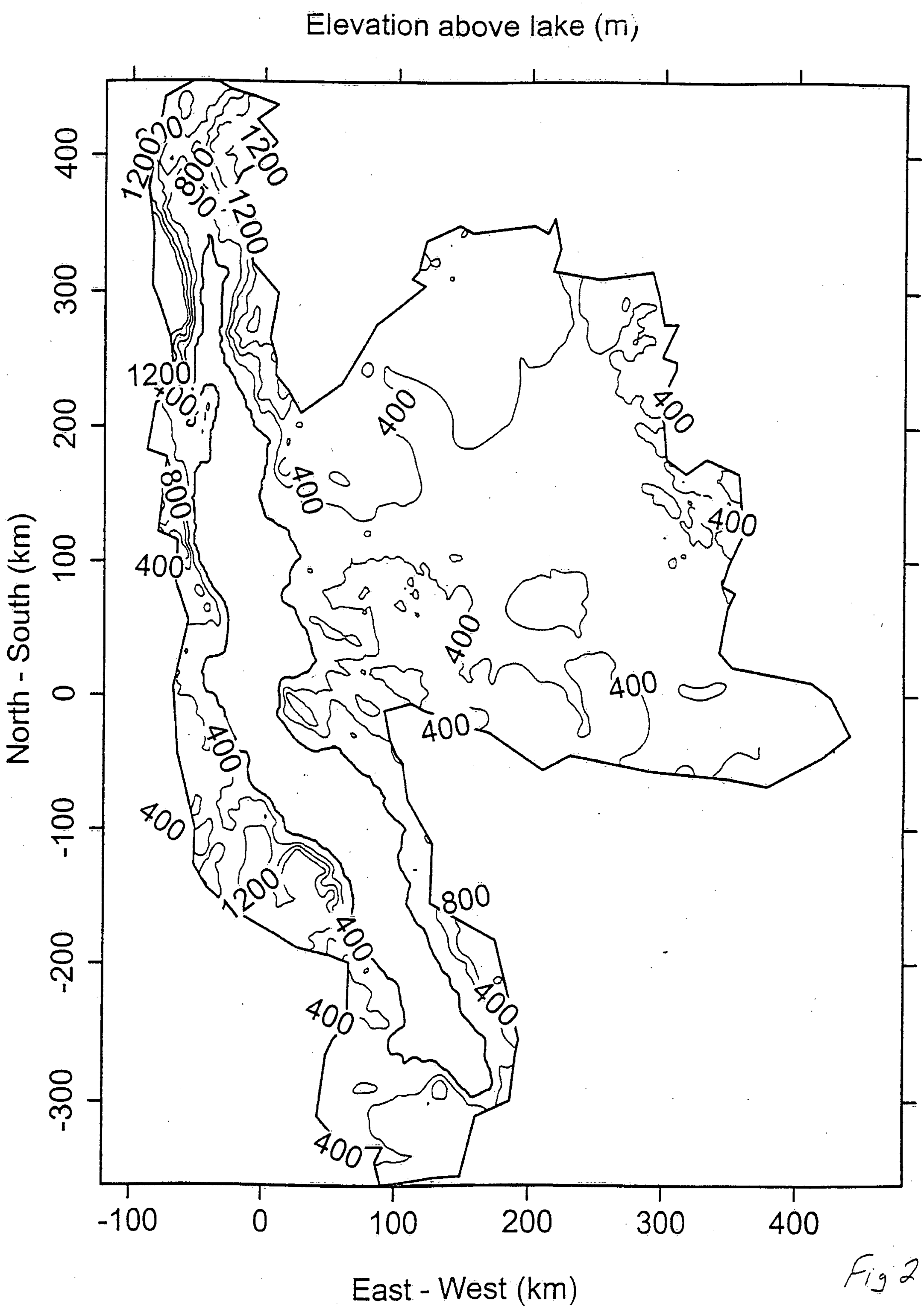
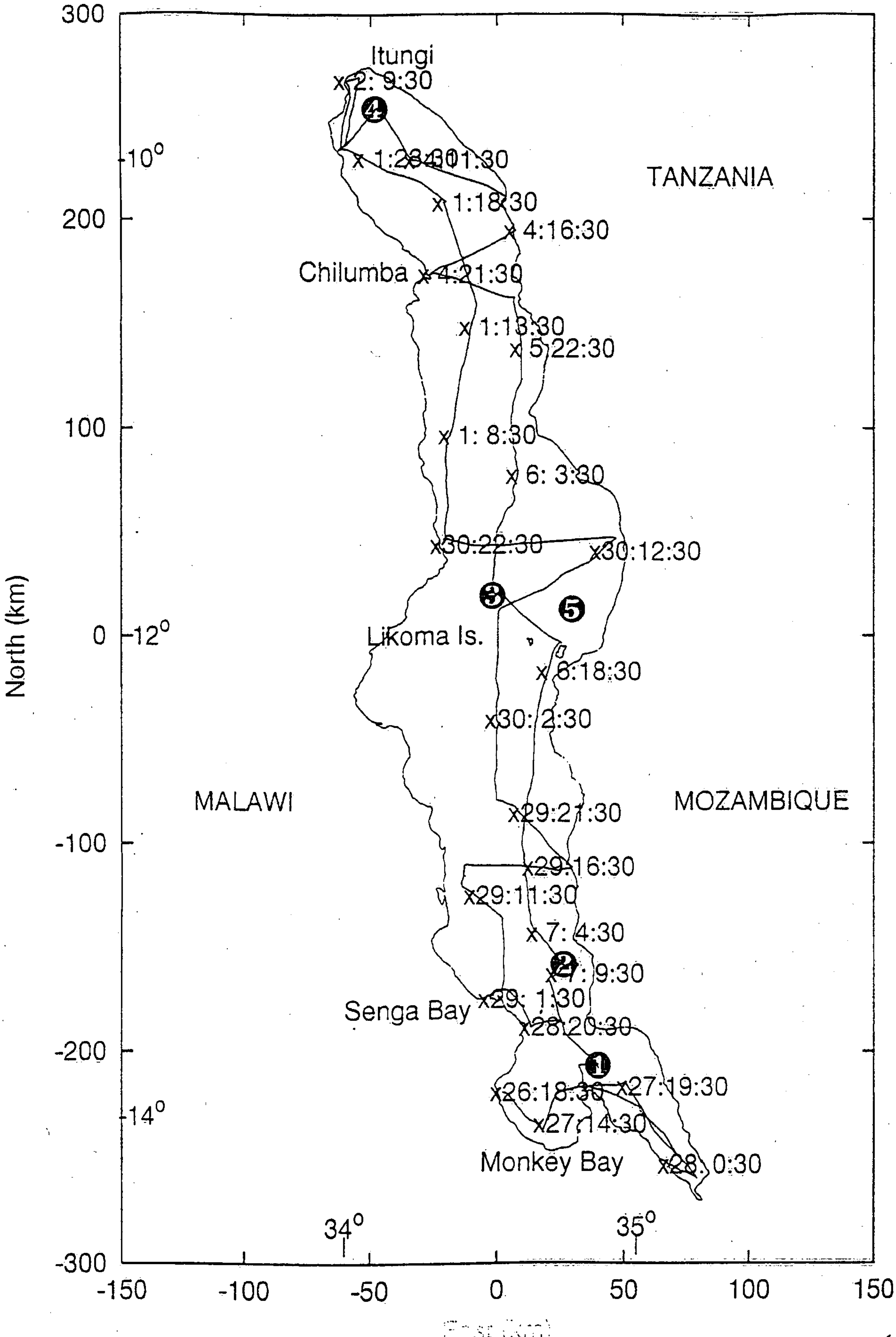

Elevation above lake (m)
North - South (km)
East - West (km)
400
300
200
100
0
-100
-200
-300
-100
0
100
200
300
400
1200
800
400

Fig 2.



300
200
100
0
-100
-200
-300
-150
-100
-50
0
50
100
150
North (km)
East (km)
10°
12°
14°
34°
35°
TANZANIA
MALAWI
MOZAMBIQUE
Itungi
Chilumba
Likoma Is.
Senga Bay
Monkey Bay
x2: 9:30
x 1:18:30
x 4:16:30
x 4:21:30
x 1:13:30
x 5:22:30
x 1: 8:30
x 6: 3:30
x30:22:30
x30:12:30
x 6:18:30
x30: 2:30
x29:21:30
x29:16:30
x29:11:30
x 7: 4:30
x7: 9:30
x29: 1:30
x28:20:30
x27:19:30
x26:18:30
x27:14:30
x28: 0:30
1
2
3
4
5

Fig. 3

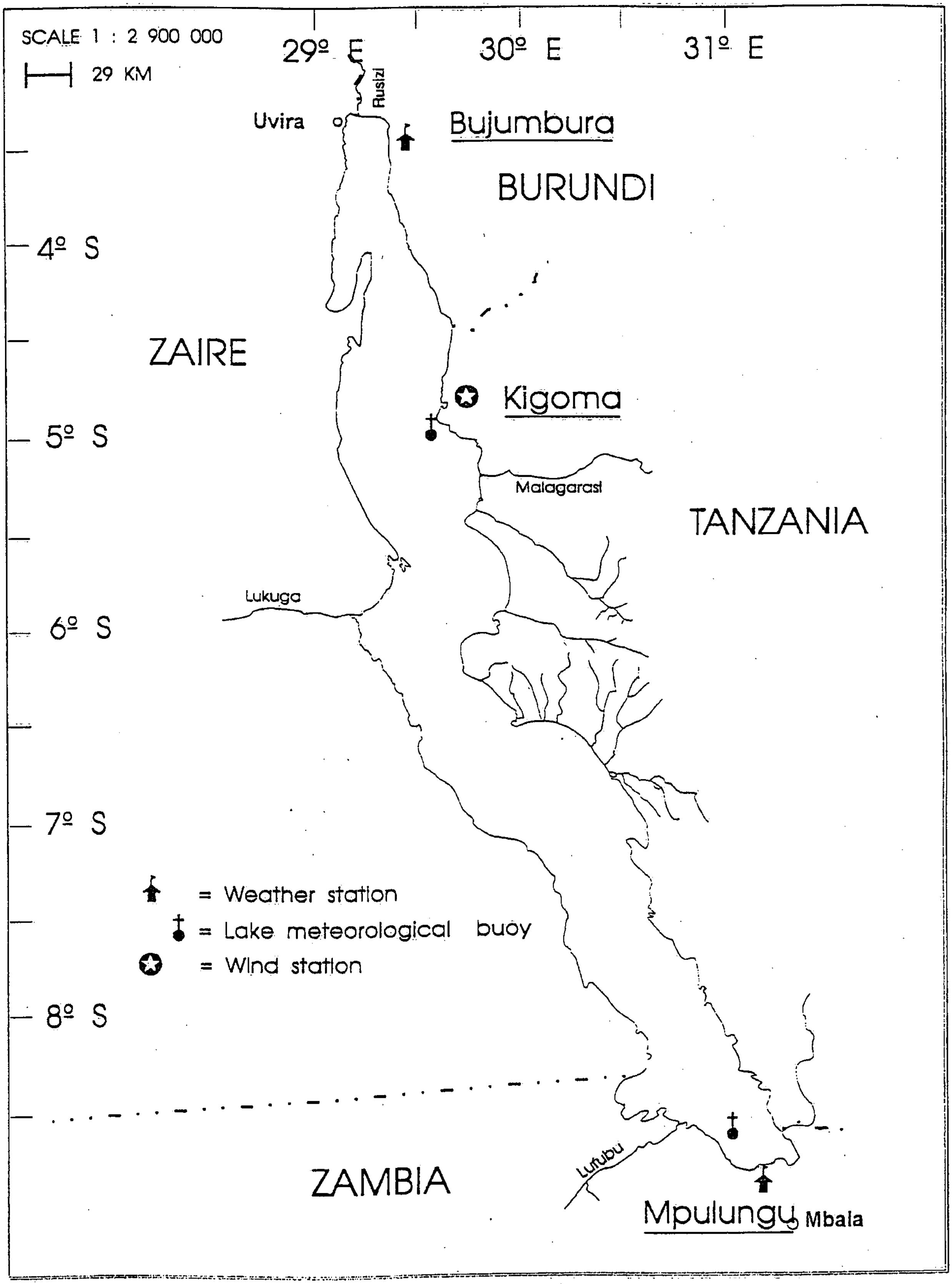
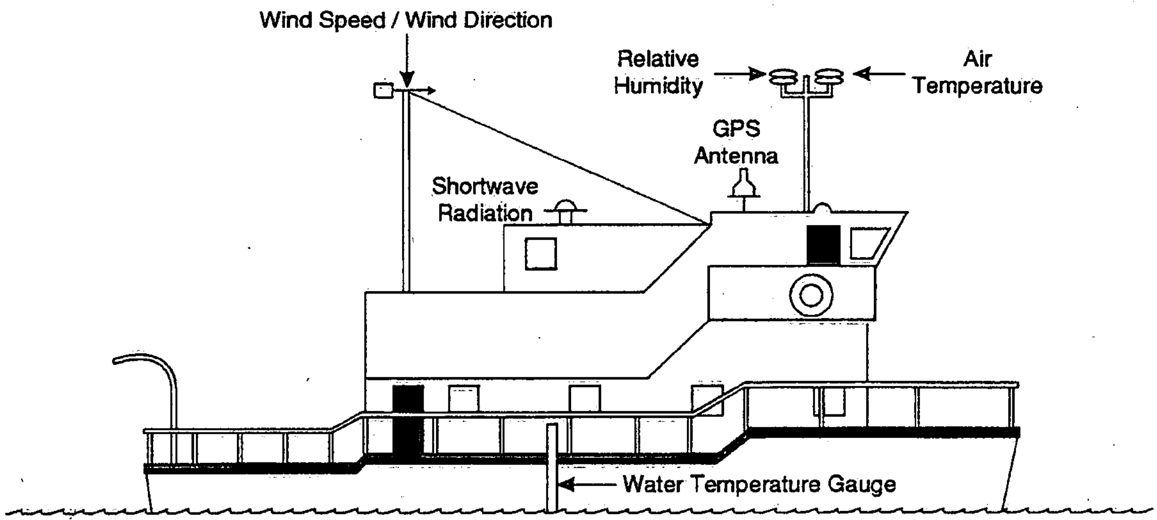
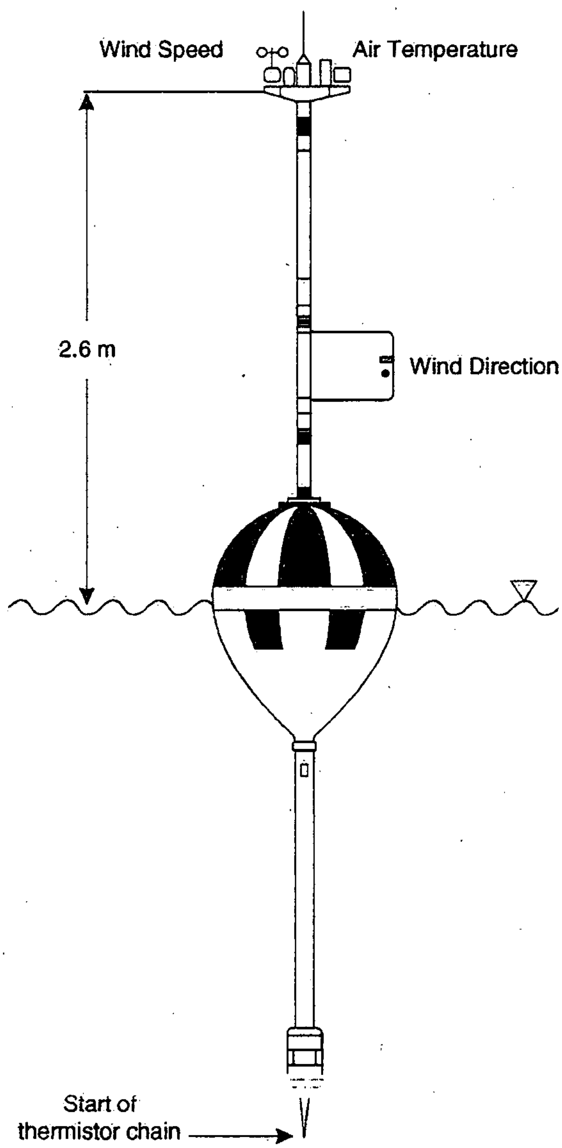
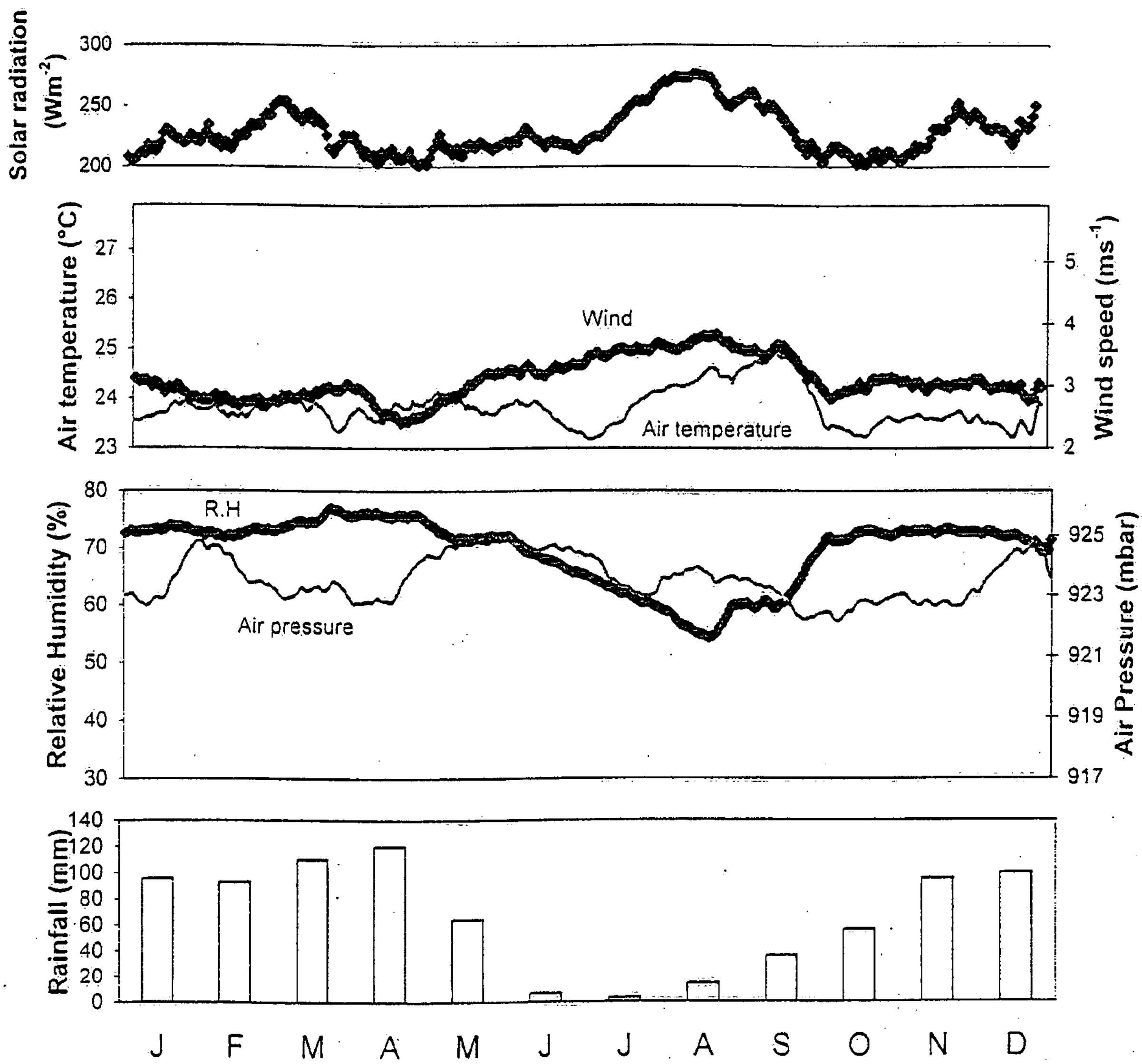

SCALE 1 : 2 900 000
29 KM
29º E
30º E
31º E
Rusizi
Uvira
Bujumbura
BURUNDI
4º S
ZAIRE
Kigoma
5º S
Malagarasi
TANZANIA
Lukuga
6º S
7º S
= Weather station
= Lake meteorological buoy
= Wind station
8º S
Lufubu
ZAMBIA
Mpulungu
Mbala

Fig. 4


Wind Speed / Wind Direction
Relative Humidity
Air Temperature
GPS Antenna
Shortwave Radiation
Water Temperature Gauge


Wind Speed
Air Temperature
2.6 m
Wind Direction
Start of thermistor chain



Solar radiation (Wm^{-2})
300
250
200
Air temperature (°C)
27
26
25
24
23
Wind speed (ms^{-1})
5
4
3
2
Wind
Air temperature
Relative Humidity (%)
80
70
60
50
40
30
Air Pressure (mbar)
925
923
921
919
917
R.H
Air pressure
Rainfall (mm)
140
120
100
80
60
40
20
0
J F M A M J J A S O N D

Fig 6

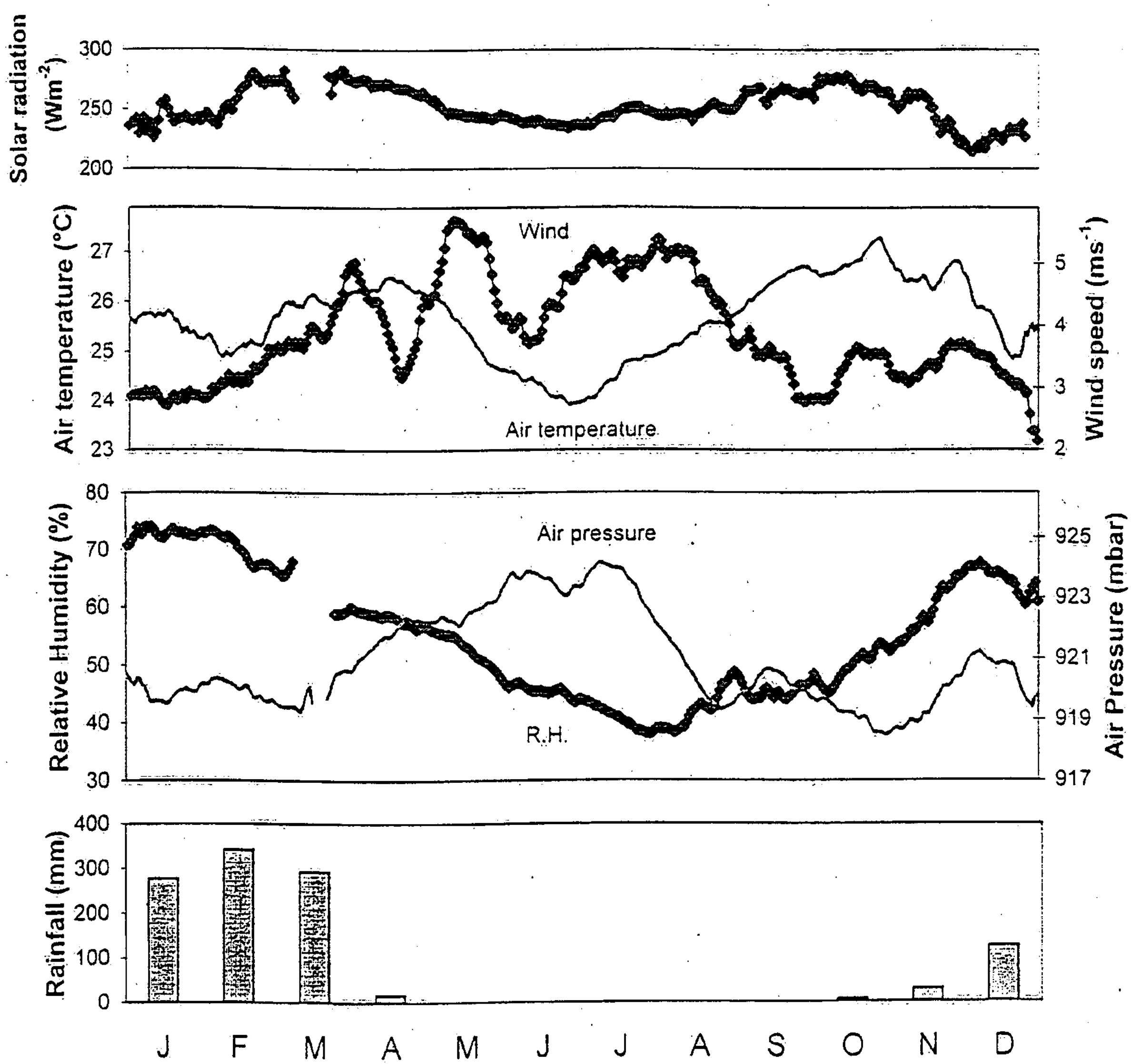

Solar radiation (Wm-2)
300
250
200
Wind
Air temperature
Air temperature (°C)
27
26
25
24
23
Wind speed (ms-1)
5
4
3
2
Air pressure
R.H.
Relative Humidity (%)
80
70
60
50
40
30
Air Pressure (mbar)
925
923
921
919
917
Rainfall (mm)
400
300
200
100
0
J F M A M J J A S O N D

Fig 7.

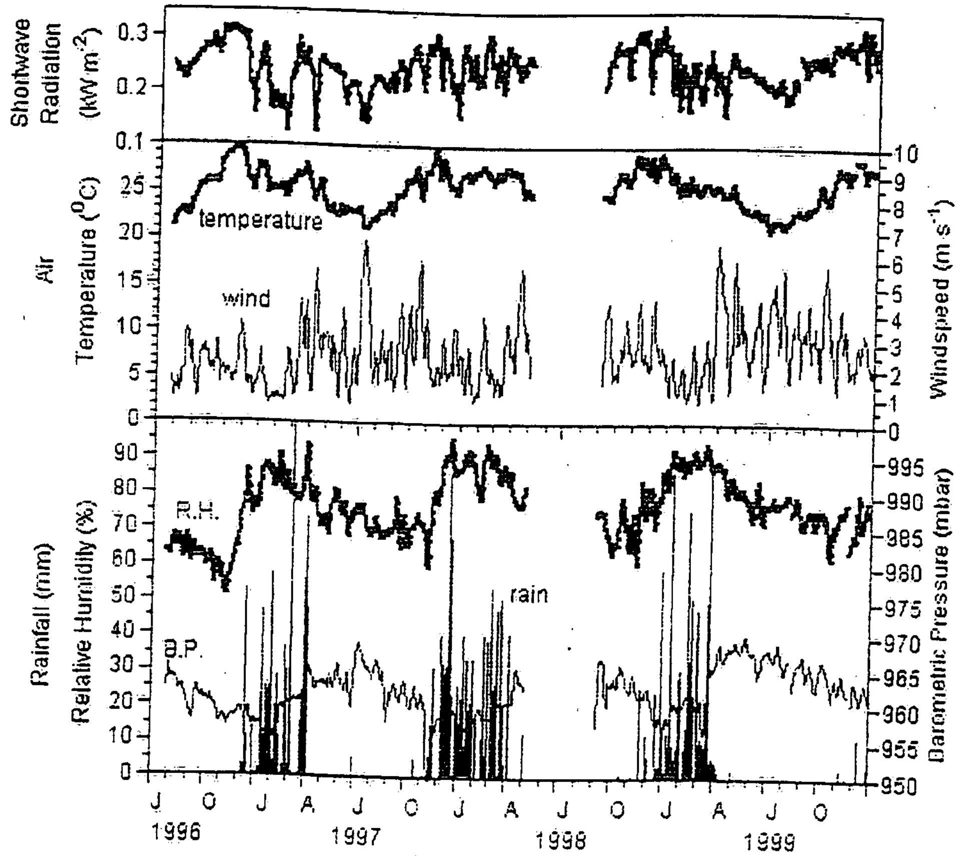
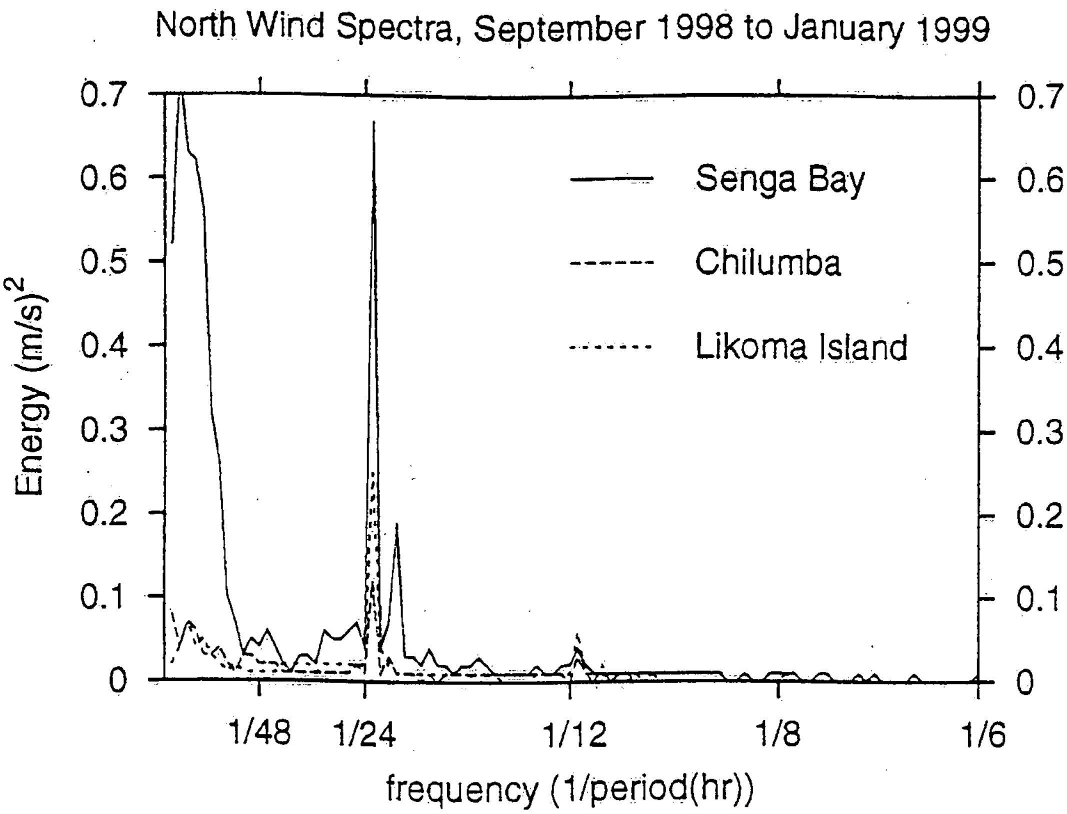

Shortwave Radiation (kW m^{-2})
0.3
0.2
0.1
Air Temperature (^{0}C)
25
20
15
10
5
0
temperature
wind
Windspeed (m s^{-1})
10
9
8
7
6
5
4
3
2
1
0
Rainfall (mm) Relative Humidity (%)
90
80
70
60
50
40
30
20
10
0
R.H.
rain
B.P.
Barometric Pressure (mbar)
995
990
985
980
975
970
965
960
955
950
J O J A J O J A J O J A J O
1996
1997
1998
1999

Fig 8


North Wind Spectra, September 1998 to January 1999
Energy (m/s)2
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Senga Bay
Chilumba
Likoma Island
1/48
1/24
1/12
1/8
1/6
frequency (1/period(hr))

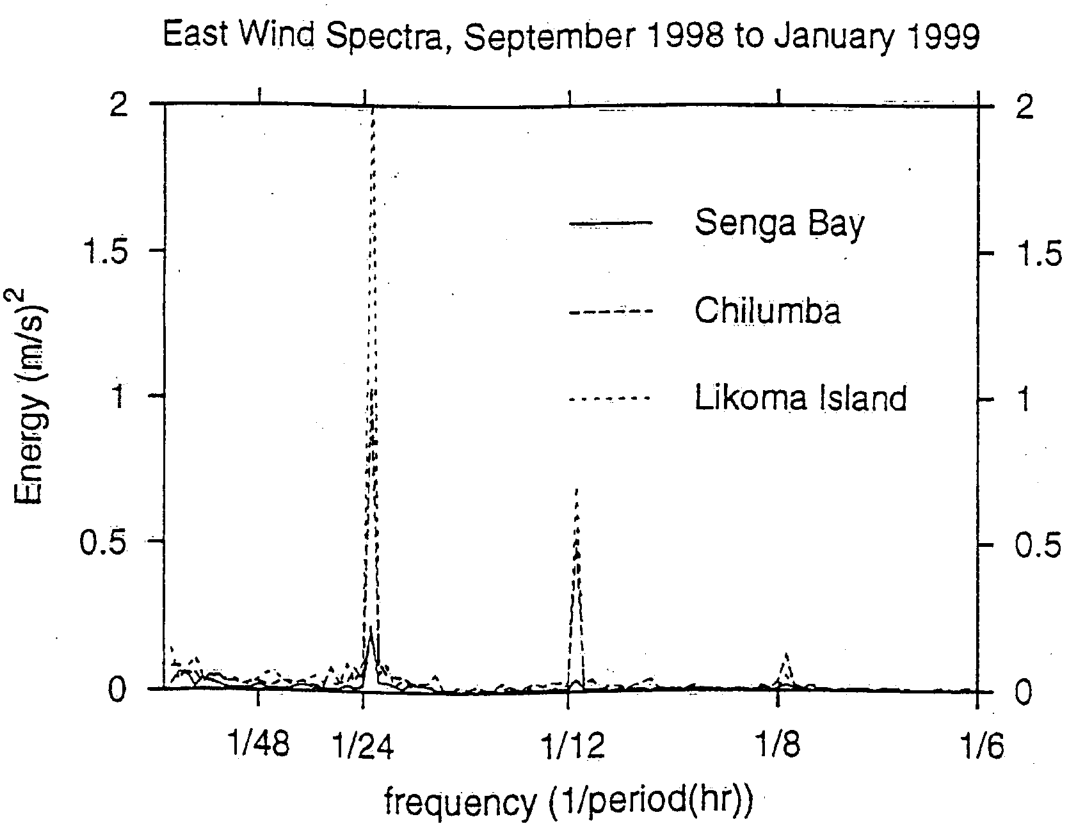
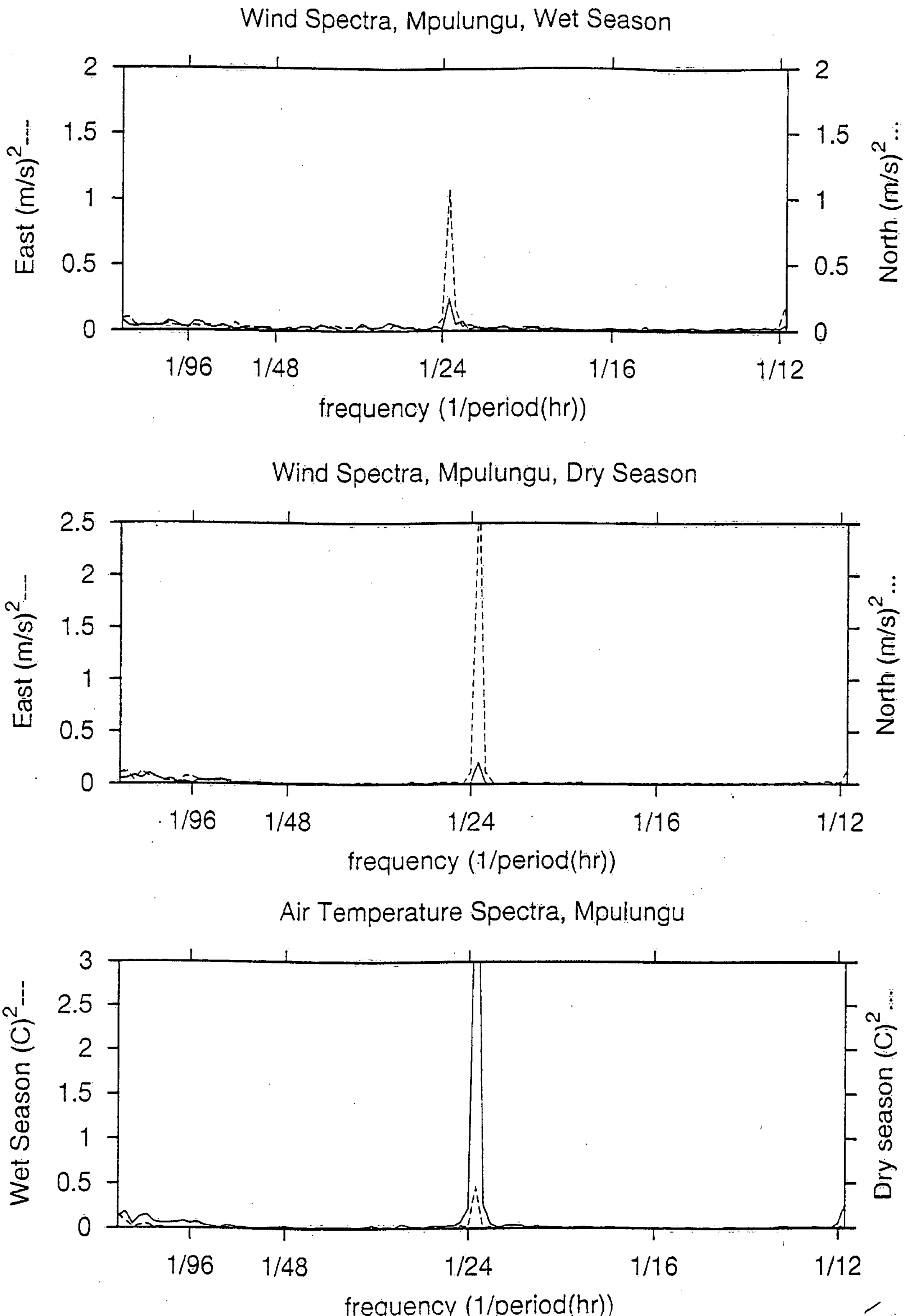

East Wind Spectra, September 1998 to January 1999
Energy (m/s)2
2
1.5
1
0.5
0
Senga Bay
Chilumba
Likoma Island
1/48
1/24
1/12
1/8
1/6
frequency (1/period(hr))

Fig. 9



Wind Spectra, Mpulungu, Wet Season
East (m/s)2---
North (m/s)2...
0
0.5
1
1.5
2
1/96
1/48
1/24
1/16
1/12
frequency (1/period(hr))
Wind Spectra, Mpulungu, Dry Season
East (m/s)2---
North (m/s)2...
0
0.5
1
1.5
2
2.5
1/96
1/48
1/24
1/16
1/12
frequency (1/period(hr))
Air Temperature Spectra, Mpulungu
Wet Season (C)2---
Dry season (C)2...
0
0.5
1
1.5
2
2.5
3
1/96
1/48
1/24
1/16
1/12
frequency (1/period(hr))

Fig 10

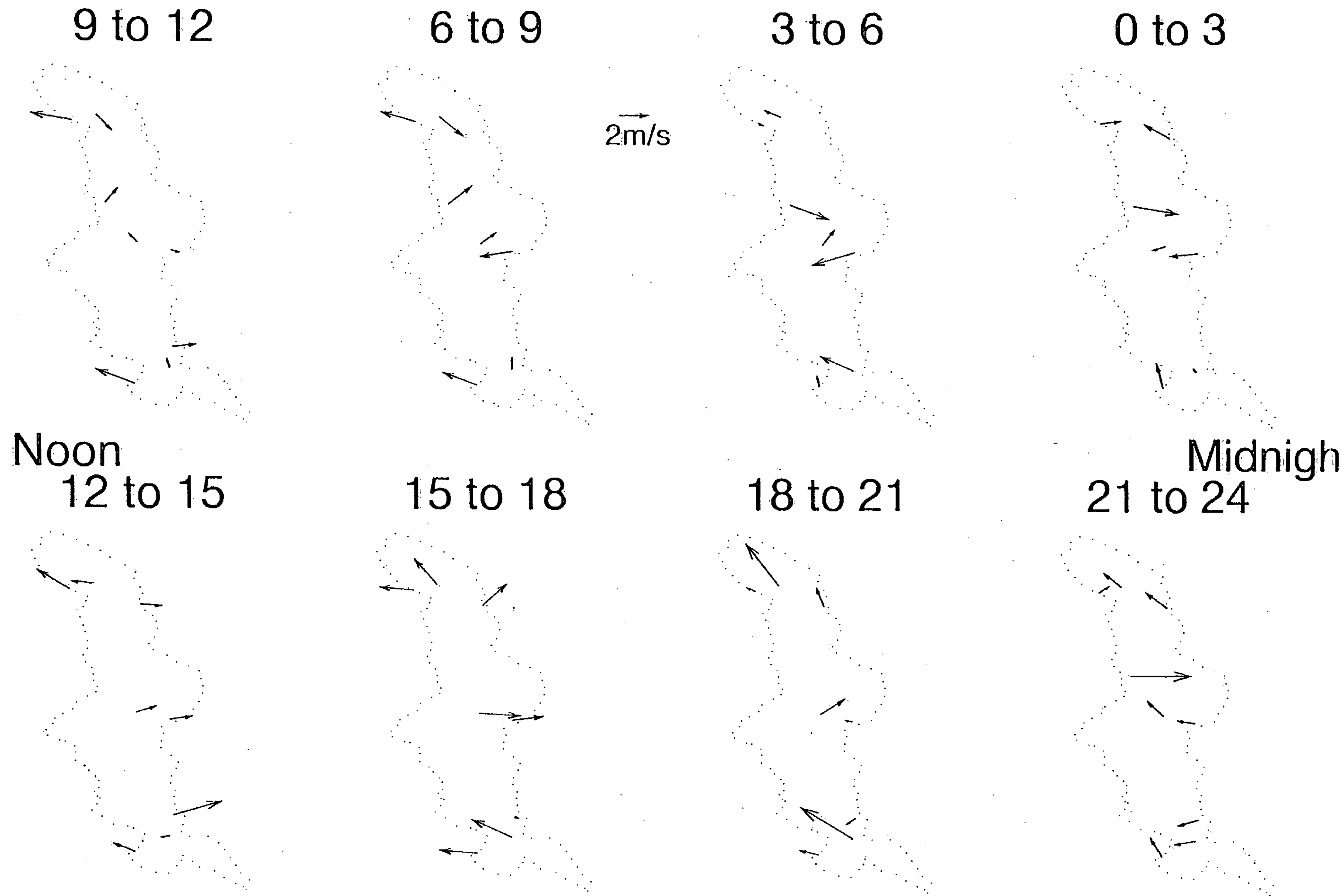

9 to 12
6 to 9
3 to 6
0 to 3
2m/s
Noon
Midnight
12 to 15
15 to 18
18 to 21
21 to 24

Fig. 11

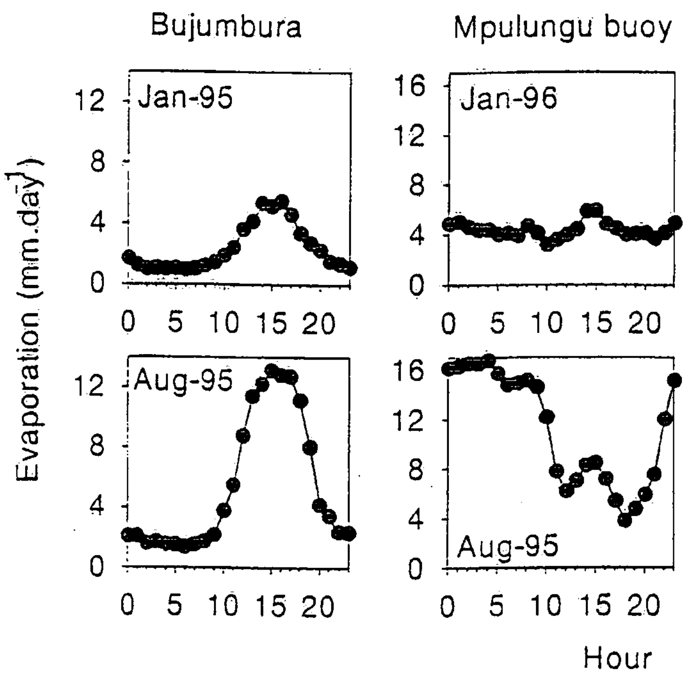

Bujumbura
Mpulungu buoy
Jan-95
Jan-96
Aug-95
Aug-95
Evaporation (mm.day^{-1})
Hour
0
4
8
12
16
0 5 10 15 20

Fig. 12

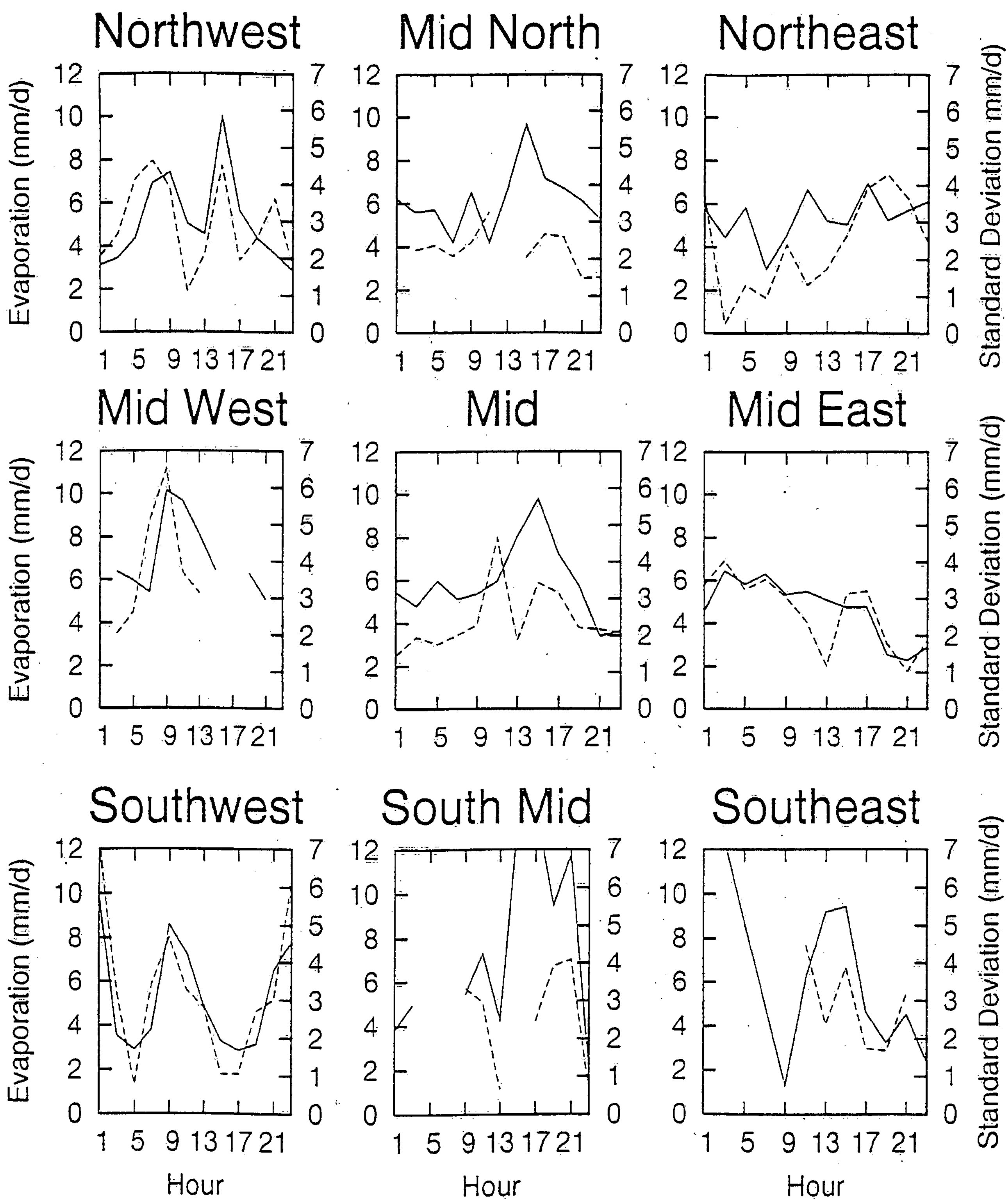

Northwest
Mid North
Northeast
Mid West
Mid
Mid East
Southwest
South Mid
Southeast
Evaporation (mm/d)
Standard Deviation (mm/d)
Hour
1 5 9 13 17 21

Fig. 13

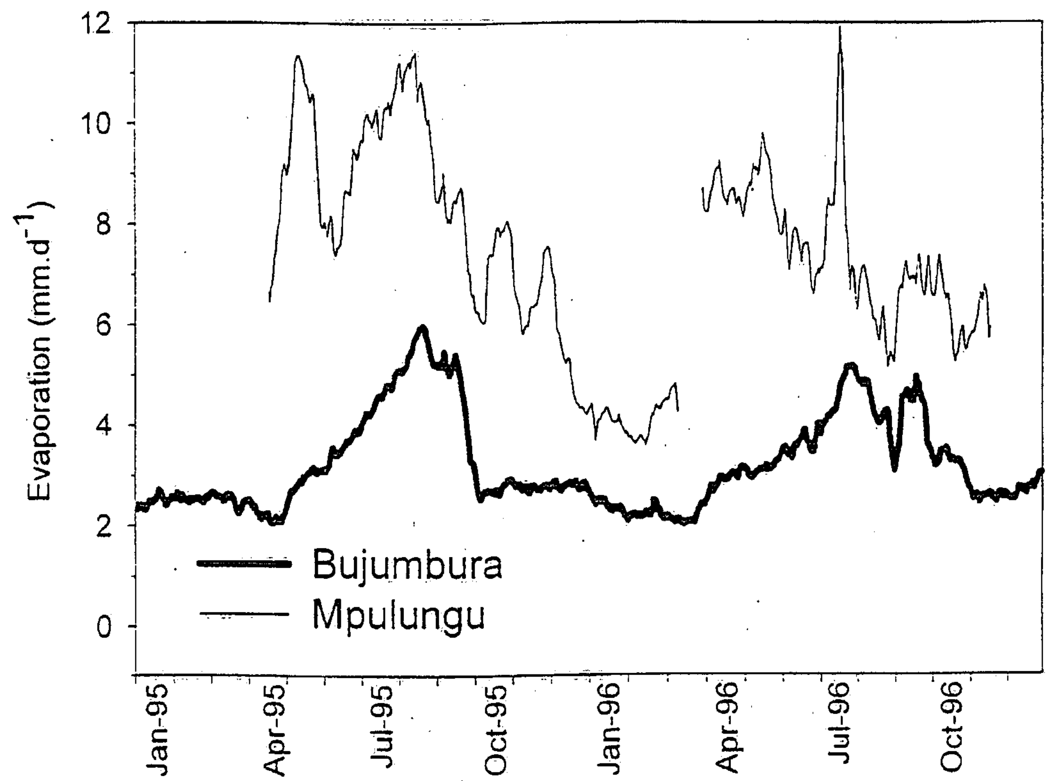

12
10
8
6
4
2
0
Evaporation (mm.d-1)
Bujumbura
Mpulungu
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96

Fig. 14

Usipa Evaporation by Liu et al.(mm/d)

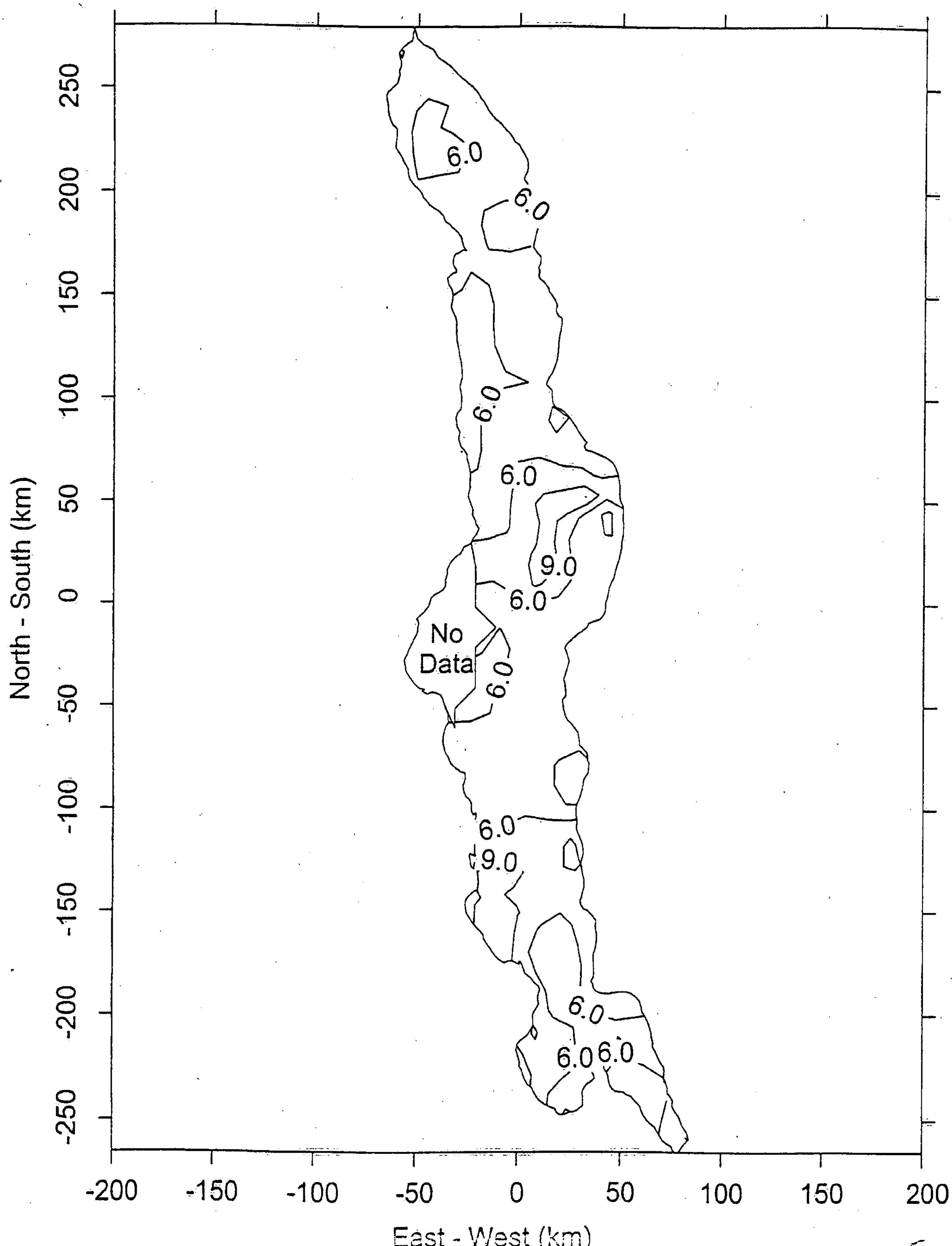


Fig. 15

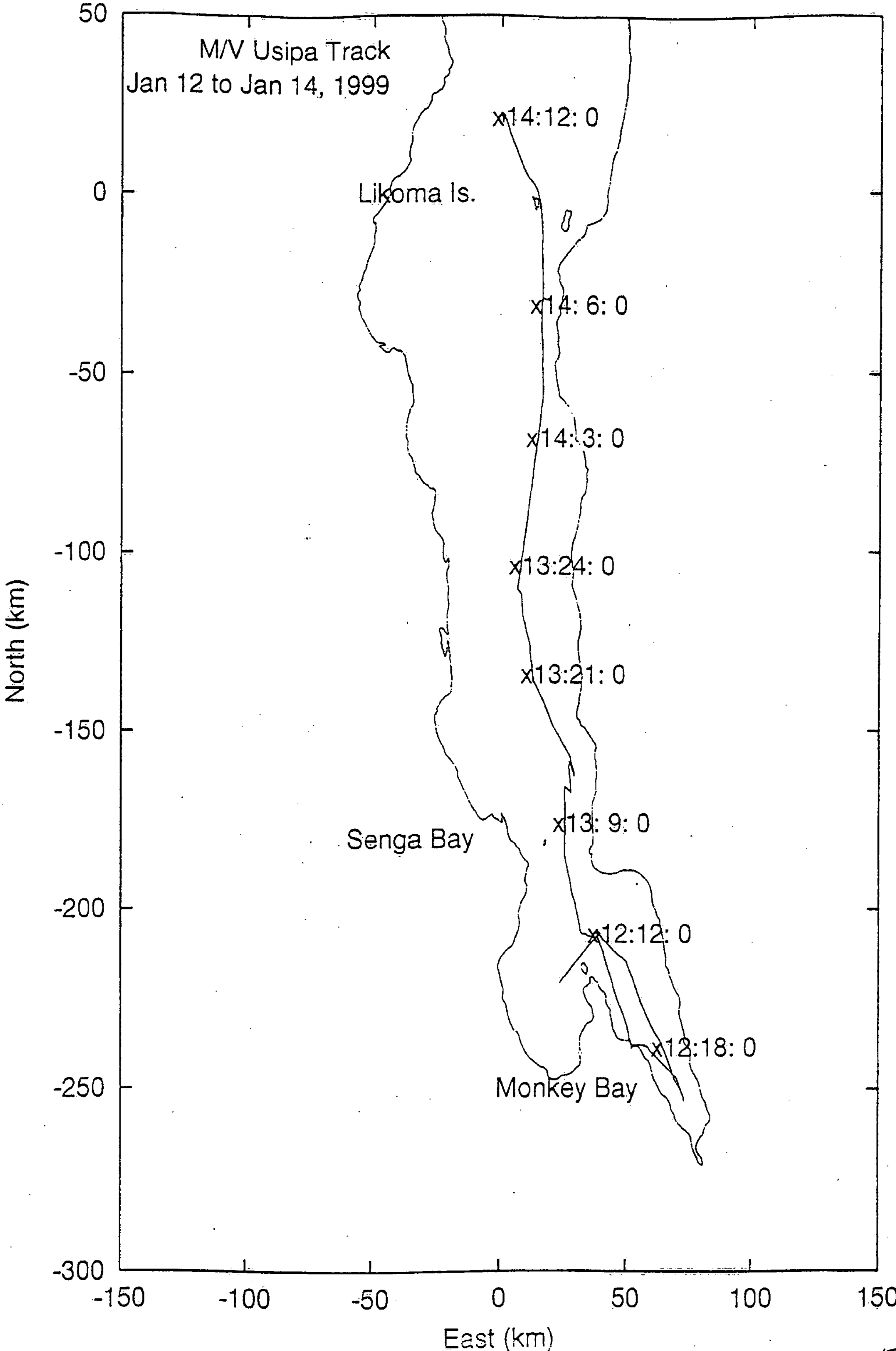

M/V Usipa Track
Jan 12 to Jan 14, 1999
14:12: 0
Likoma Is.
14: 6: 0
14: 3: 0
13:24: 0
13:21: 0
13: 9: 0
Senga Bay
12:12: 0
12:18: 0
Monkey Bay
North (km)
East (km)
50
0
-50
-100
-150
-200
-250
-300
-150
-100
-50
0
50
100
150

Fig. 6

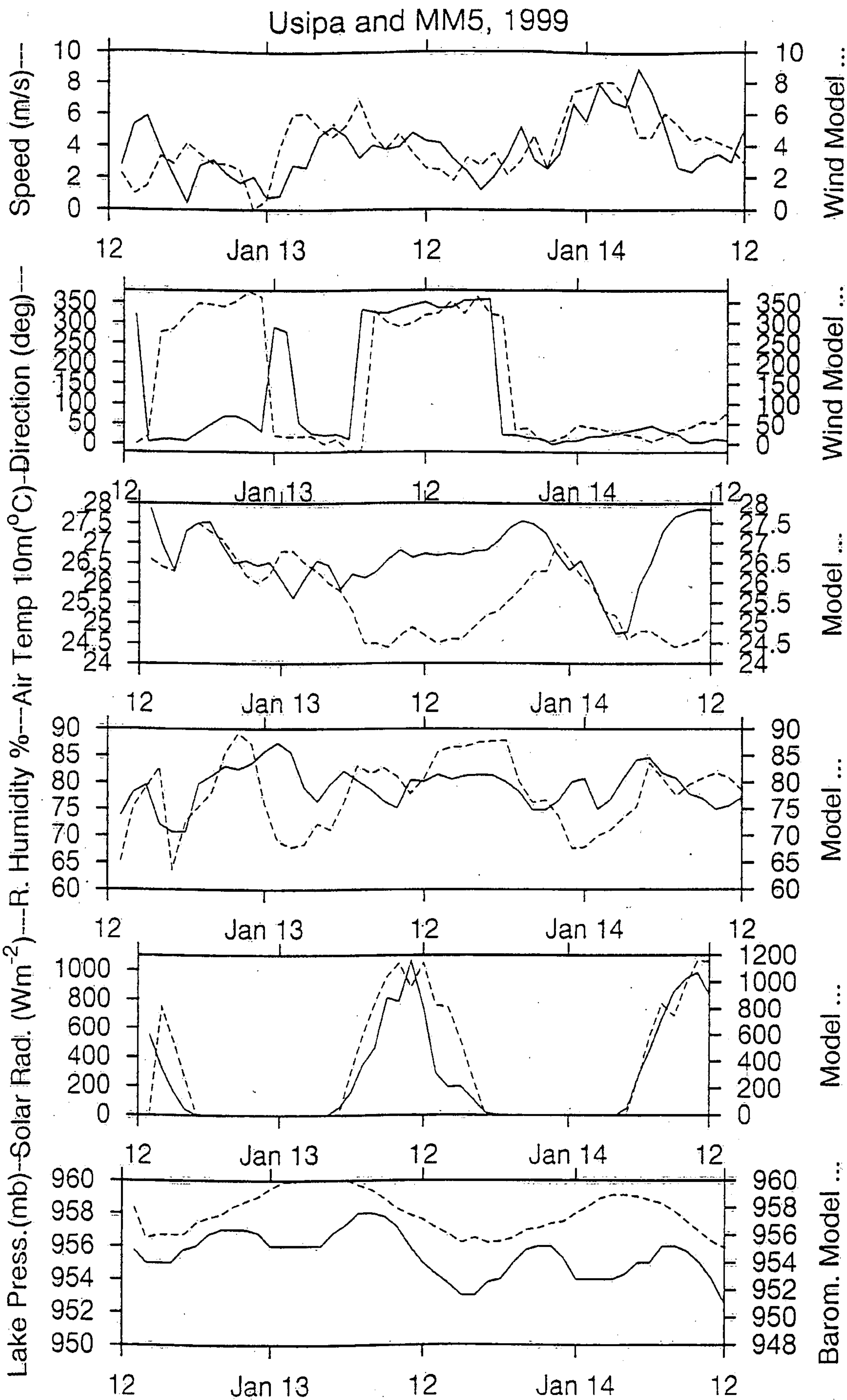

Usipa and MM5, 1999
Speed (m/s)---
Wind Model ...
Direction (deg)---
Wind Model ...
Air Temp 10m(°C)---
Model ...
R. Humidity %---
Model ...
Solar Rad. (Wm-2)---
Model ...
Lake Press.(mb)---
Barom. Model ...
12
Jan 13
12
Jan 14
12

Fig. 17

Usipa and MM5, 1999

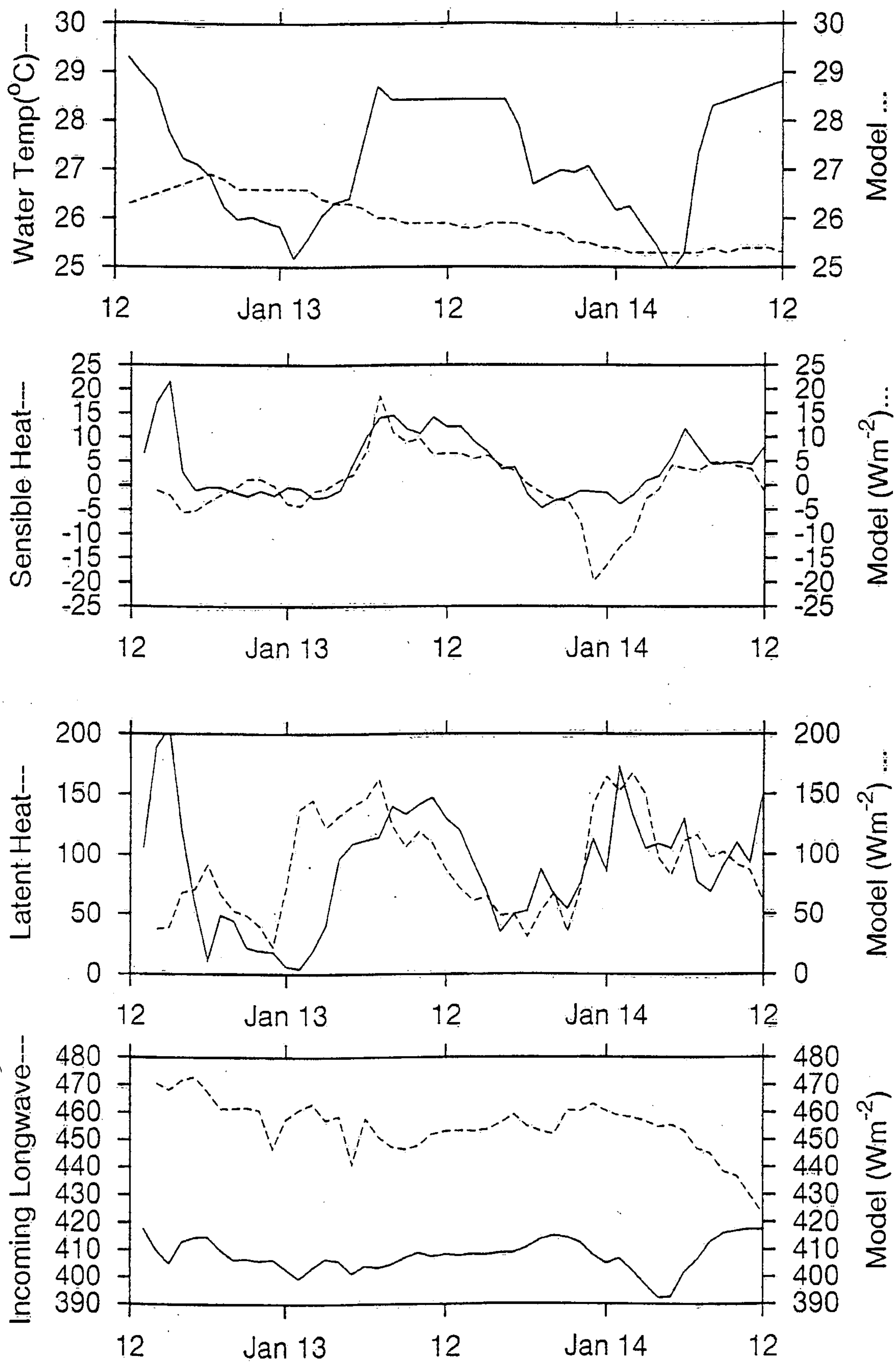


Fig 18

Likoma Island and MM5, 1999

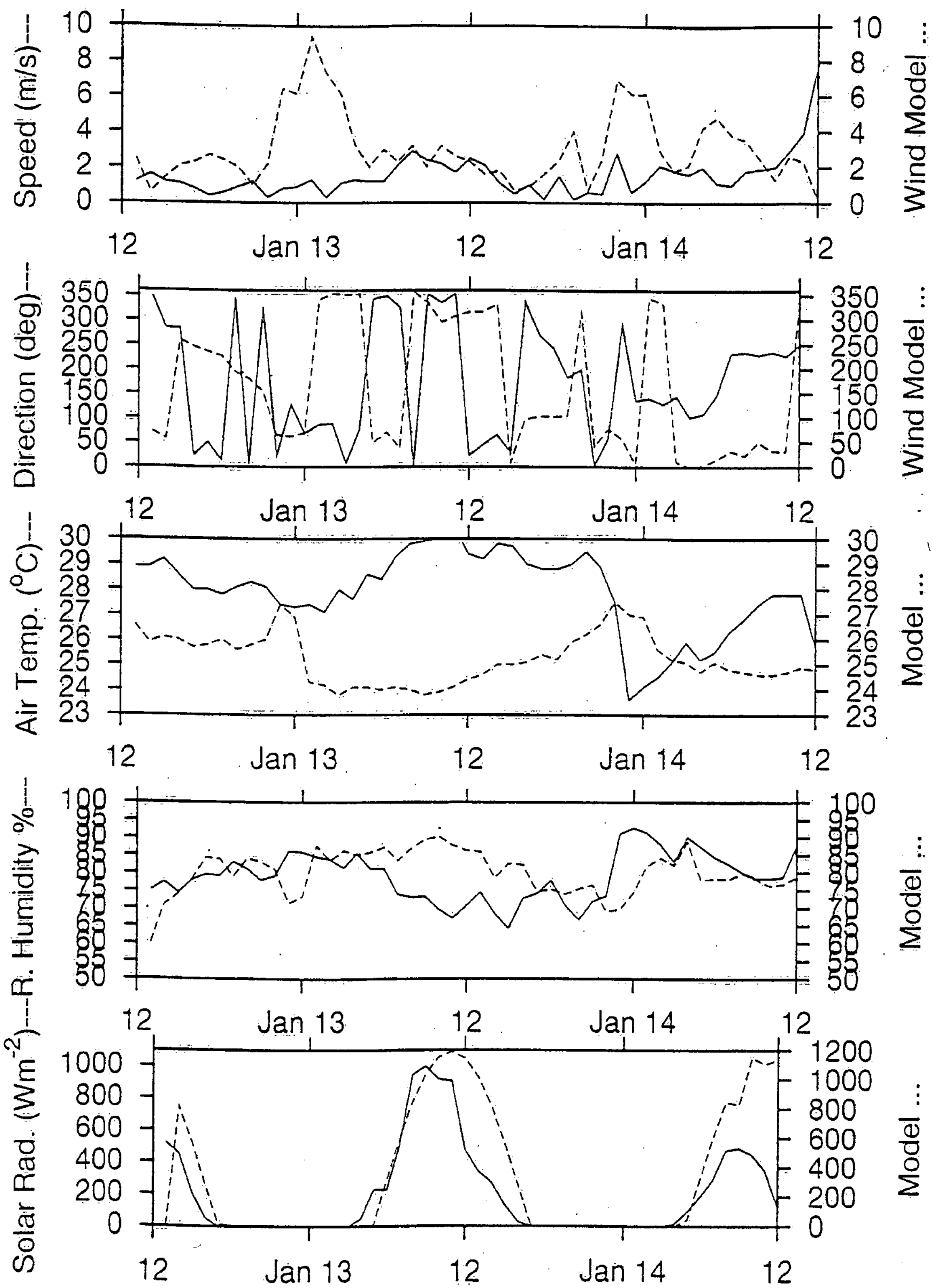


Fig. 19

Environment Canada / Environnement Canada

Canada

Canada Centre for Inland Waters
P.O. Box 5050
867 Lakeshore Road
Burlington, Ontario
L7R 4A6 Canada

National Hydrology Research Centre
11 Innovation Boulevard
Saskatoon, Saskatchewan
S7N 3H5 Canada

St. Lawrence Centre
105 McGill Street
Montreal, Quebec
H2Y 2E7 Canada

Place Vincent Massey
351 St. Joseph Boulevard
Gatineau, Quebec
K1A 0H3 Canada

Centre canadien des eaux intérieures
Case postale 5050
867, chemin Lakeshore
Burlington (Ontario)
L7R 4A6 Canada

Centre national de recherche en hydrologie
11, boul. Innovation
Saskatoon (Saskatchewan)
S7N 3H5 Canada

Centre Saint-Laurent
105, rue McGill
Montréal (Québec)
H2Y 2E7 Canada

Place Vincent-Massey
351 boul. St-Joseph
Gatineau (Québec)
K1A 0H3 Canada