ON THE CLIMATE IMPACT OF THE LOCAL CIRCULATION IN THE ITAIPU LAKE AREA

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Abstract. The impact of the Itaipu Lake on the climate and local circulation is investigated here using the meteorological information available in the area. The Itaipu Lake is an artificial water reservoir of 1460 km^2 (approximately 170 km by 7.5 km), formed in 1982 as part of the Itaipu Power Plant. It is situated on the Brazil-Paraguay frontier, in the central portion of Parana River Valley. The analysis of the available meteorological data (air and water temperatures, air relative humidity, precipitation and radiosonde soundings) provides observational evidences supporting the hypothesis that the Itaipu Lake presence has an important impact in the local circulation, inducing a local circulation with lake breeze characteristics showing horizontal wind divergence over the lake during daytime and convergence during nighttime. From the regional point of view, the Itaipu Lake formation has reduced the thermal amplitude of the diurnal air temperature cycle. The precipitation data, investigated here, has not indicated any systematic effect associated to the lake formation. The reason for the apparent inconsistency is that others phenomena (e.g., valley-mountain circulation and El Niño events) could be masking the impact of the lake formation on the rain deficit in the region.

1. Introduction

The formation of large body of water for hydroelectric power plants may have an important impact on the physical, biological and human subsystems of the region (Gyau-Boakye, 2001). Inundating large areas covered by vegetation have a direct impact on the local climate and may contribute to the global climate change by increasing the green house effect gases in the atmosphere (Rosa and Scheaffer, 1995; Fearnside, 2000).

Several observational (Oliveira and Fitzjarrald, 1993; Segal et al., 1997) and numerical (Neumann and Mahrer, 1975; Physick, 1976) studies have shown that lakes and other water bodies with horizontal dimension varying from 3 to 80 km are able to sustain thermal circulations known as lake breeze. The lake breeze generated by a lake depends upon its shape and size, shoreline configuration, localization, margin topography and land occupation (Segal et al., 1997).

The topography can also have an important role on the thermal circulation induced by lakes (Bitan, 1977). For instance, observations indicated that thermal circulation induced by the Dead Sea is able to sustain wind intensities of 4 m s^{-1} at

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20 km (inland). Another example of topographic effect was found in the Kenneret Lake, in Israel, by Bitan (1981). Asculai et al.(1984), following the trajectories of balloons, also confirmed that the valley-mountain circulation could intensify the lake breeze in the Kenneret Lake.

Hydroelectric power plants are responsible for about 90% of the electricity used in Brazil and 40% of all energy (ANEEL, 2003). Despite the large number and size of artificial lakes, climate modifications caused by man-made lake in Brazil have not been documented in the literature.

The major difficulty in the investigation of regional circulation impact on climate, particularly in the third world countries, is the lack of observations with the required spatial and temporal resolution.

The impact of the Itaipu Lake on the climate and local circulation is investigated here using the meteorological information available in the area. The Itaipu Lake is an artificial water reservoir of 1460 km^2 (approximately 170 km by 7.5 km), formed in 1982 as part of the Itaipu Power Plant.

The biological impact caused by the Itaipu dam has been assessed in some studies (Suzuki et al., 2000; Miranda et al., 2000; Delariva and Agostinho, 2001). The most recent inventories of seismic instability in Brazil indicate that the Itaipu reservoir has not induced any earthquake in the region (Gupta, 2002; Assunção et al., 2002). On the other hand the formation of Itaipu Lake has considerably modified the landscape in the area. An important waterfall knows as “Sete Quedas” has disappeared completely after the impounding in 1982 (Orfeo and Stevaux, 2002). No information is available about the impact caused by the Itaipu reservoir on the concentration of sediment, quality of water or presence of weeds and diseases.

Stivari et al. (2003) investigated numerically the lake breeze circulation in the Itaipu region. The numerical experiments have shown that the land use effect is important in the spatial distribution of the lake breeze circulation and that the topography contributes to modulate the breeze intensity, with the daytime valley-mountain circulation intensifying the lake breeze. However, the numerical simulation indicated that the circulation pattern observed during daytime over the region is mainly due to the presence of Itaipu Lake, that is able to generate and sustain a lake breeze, with 3.5 m s^{-1} of maximum intensity and 1500 m depth, which propagates inland at 5.1 km h^{-1} under typical undisturbed and calm wind summer conditions.

The study reported here explores all the meteorological information available in the Itaipu Lake area, located on the Brazil-Paraguay border, to investigate the local climate impact caused by the lake formation. It includes four surface stations (wind velocity and direction, air temperature and air relative humidity) located in the vicinity of the lake (<75 km); radiosonde data obtained at Foz do Iguaçu Airport, Brazil (20 km far from the lake), air temperature over the lake and surface lake water temperature. It was also included here precipitation data available from climate analysis algorithm (New et al., 2000).

It is shown here that even looking at short-term temporal series the lake presence has modified the thermal amplitude of the air temperature in the region. The early morning radiosonde sounding trajectories and the systematic horizontal wind divergence at daytime over the lake area support the idea that the circulation induced by the Itaipu Lake is deeper and stronger than previously assessed and inhibits cloud formation over the lake during daytime. This mechanism may be responsible for the rain deficit observed near the Itaipu Lake. Despite increasing the amplitude of the rain deficit around the lake after the impounding, no significant modification in rain time evolution may be associated to the lake formation.

2. Site Characteristics

The Itaipu Lake is located in the central portion of the Parana River Valley, on the Brazil-Paraguay border, within the following geographic limits: 24°05′S–25°33′S and 54°37′W–54°00′W (Figure 1). The damming of the Parana River created this lake in two stages. In the first one, in November 1982, the surface lake reached 206 m above the mean sea level and in the second stage, in June 1984, the Itaipu Lake reached its final level of 220 m, occupying a total area of 1,460 km^2 (835 km^2 located in Brazil and 625 km^2in Paraguay; Stivari, 1999). The lake width varies along its 170 km of extension, being, in average 7.5 km. At its final stage the lake occupies a total water volume of 29 billion of cubic meters. This valley is, in average, 80 km wide; raising to 400 m above mean sea level at west side (Paraguay) and 450 m at east side (Brazil). The topography indicated in Figures 2a and 3 was obtained from 1:500,000 cartographic map. The position of the major geographic features (lake, rivers etc) was verified by the satellite image, displayed in Figure 2b.

The lake vicinity presents three main types of land use: forest (∼28%), agricultural area (∼30%) and pasture (∼34%), indicated in Figure 2b by green, red and yellow colors, respectively. The Itaipu Lake (blue area in Figure 2b) occupies ∼8% of the total area of the rectangle. Most of the forested area is concentrated in the Paraguay side, at west of the lake. Deciduous trees characterize the forest in this area. Areas occupied by crops are found on both sides of the lake. Near the lake and mainly on the Brazilian side, the agricultural areas are composed of bare soil. The land use map (Figure 2b) was estimated from a color composition of band 3, 4 and 5 of the satellite image obtained by the Landsat-TM on 21 October 1995 (Stivari et al., 1997).

3. Observational Data

The observational evidences of the lake breeze in the Itaipu Lake are based on the (i) meteorological data gathered from four conventional meteorological surface stations, (ii) air temperature over the lake and (iii) surface lake water temperature (Table I). These stations are the only meteorological stations available in the area and their geographical locations can be seen in Figure 1: Foz do Iguaçu Airport (25°35′S, 54°29′ W), Itaipu Power Plant (25°24′S, 54°36′W),

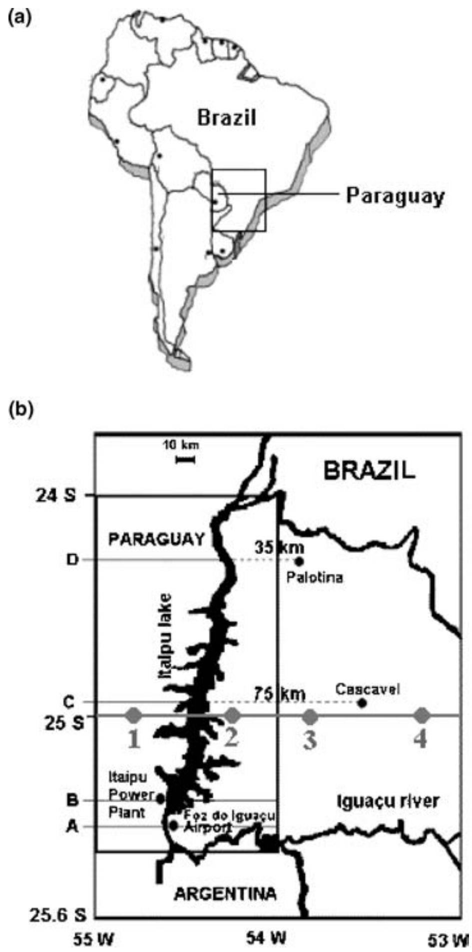

Figure 1. (a) Geographic maps indicating the region of the Lake Itaipu. (b) The rectangle covers the area of the lake. The meteorological stations Foz do Iguaçu Airport (Brazil), Itaipu Power Plant (Paraguay), Palotina (Brazil) and Cascavel (Brazil) are indicated as a black solid circles. The numbered solid gray circles represent the precipitation data positions (New et al., 2000): 1 (25°S, 54.75°W), 2 (25°S, 54.25°W), 3 (25°S, 53.75°W) and 4 (25°S, 53.25°W).

Cascavel (24°56′S, 53°25′W) and Palotina (24°16′S, 53°55′W). The air temperature over the lake and surface lake water temperature were measured at 25°24′S, 54°36′W.

Foz do Iguaçu Airport and Itaipu Power Plant meteorological stations are 13.3 km apart, in the longitudinal direction (N-S direction). These stations are located, respectively, on the Brazilian and Paraguay sides of the Itaipu Lake, at 220 m above mean sea level (Figure 3). Cascavel and Palotina stations are located approximately 65 km and 138 km from the Foz do Iguaçu Airport meteorological station.

Near to the south portion of the lake the topography is very complex (line A in Figure 3). The 120 m depression in the central region corresponds to the

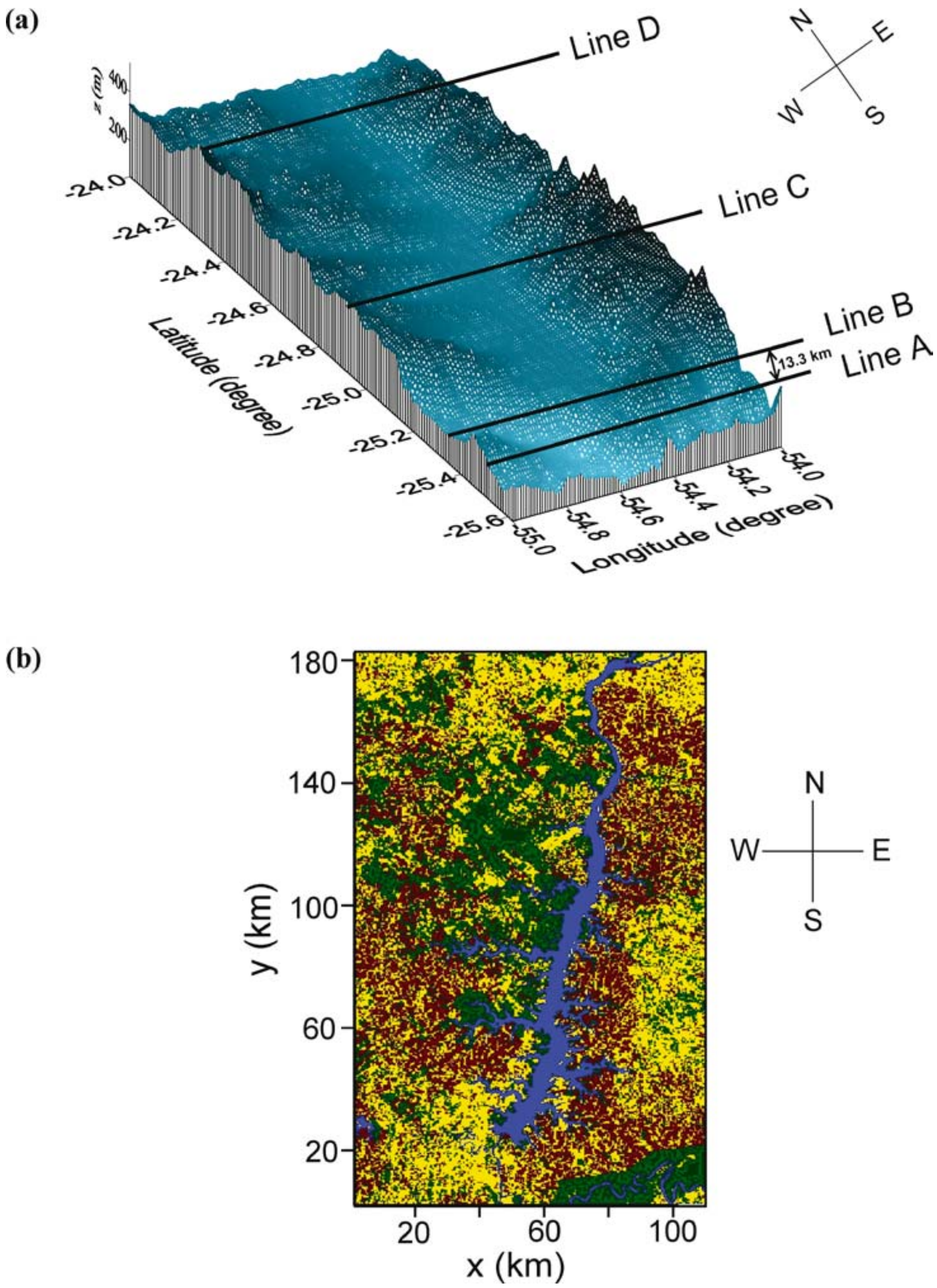

Figure 2. (a) Topography of the Itaipu Lake valley (region corresponds to the small rectangle inside Figure 1b). The Itaipu Lake is located in the central portion of the valley. The horizontal lines, indicated by A, B, C and D, correspond, respectively, to the latitude of Itaipu Power Plant, Foz do Iguaçu Airport, Cascavel and Palotina meteorological stations. (b) Land use distribution corresponding to satellite image obtained on 21 October 1995. This area presents 4 dominant classes of surface occupation: lake and rivers (blue); forest (green); pasture (yellow) and agriculture activity (red) areas.

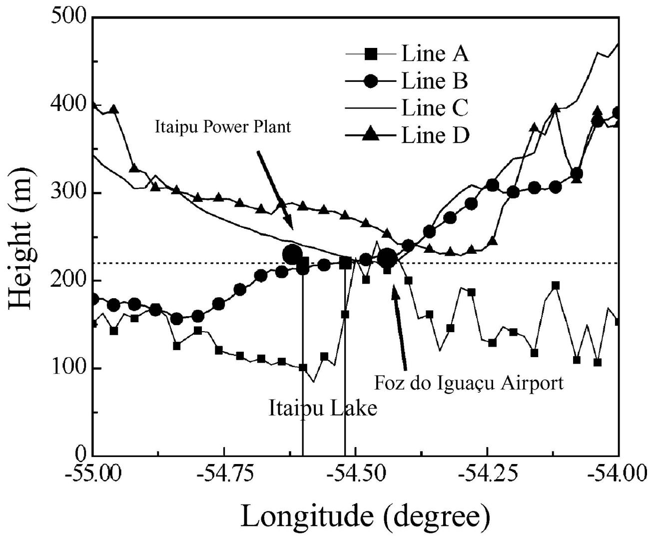

Figure 3. Surface height above the mean sea level along of the lines specified in Figure 2a. The Itaipu Lake is indicated by the intersection of the vertical lines and the B line. The lake position is shifted towards east as the lines vary from B to D. The horizontal dotted line corresponds to the lake surface height on Itaipu Power Plant latitude (line B).

location of the power plant engines. The smaller depression at 54°15′W corresponds to the position of Iguaçu Falls. The Foz do Iguaçu Airport meteorological station is located near to the Itaipu Power Plant Dam, at the same level of the lake surface.

The vertical structure of the local circulation in the Itaipu Lake area was based on radiosonde launched once a day (at 08:30 LT) at Foz do Iguaçu Airport during September and December, 1994 and from June to November, 1995, comprising 188 soundings.

The data of surface wind velocity and direction, utilized in this work, corresponds to the monthly-averaged values of hourly measurements observed in the Itaipu Power Station and Foz do Iguaçu Airport, during 1990 (January, February, March and April) and 1994 (October).

The monthly-averaged air temperature over the Itaipu Power Plant, Cascavel and Palotina meteorological stations were based on measurements carried out 4 times per day, between 1978 and 1994.

The monthly-averaged air temperature over the Itaipu Lake and the surface lake water temperature measurements were based on daily measurements carried out, between 1986 and 1994, in the vicinity of the Itaipu Power Plant meteorological station.

This work also includes monthly-averaged daily precipitation data, with 0.5° lat-long resolution, from 1980 to 1998, available from climate analysis algorithm developed by New et al. (2000).

TABLE I

Geographic position and data available on the surface meteorological stations. Grid point position of precipitation data (New et al., 2000)

Site	Position	Height (m)	Distance from the lake (km)	Parameter	Observation frequency and period of observation	Available data
Itaipu Lake	25°24′S 54°36′W	220	0	Air temperature (0.5 and 1.0 m); Water temperature at surface.	Once a day during the morning period (between 08:00 and 12:00LT) 1986–1994	Monthly averaged values
Itaipu Power Plant	25°24′S 54°36′W	230	2	Wind speed and direction at 10 m.	24 times per day 1990 (January–April) 1994 (Oct)	Hourly values
				Air temperature; Relative humidity; Precipitation; at 1.5 m	4 times per day (09:00, 12:00, 15:00 and 21:00 LT) From 1978 to 1994.	Monthly averaged values
Foz do Iguaçu Airport	25°35′S 54°29′W	247	20	Wind speed and direction at 10 m.	24 times per day 1990 (January–April) 1994 (October)	Hourly values
				Radiosonde (188 sounding)	Once a day at 08:30 LT 1994 (September and December) 1995 (June–November)	Daily values
Cascavel	24°56′S 53°25′W	760	75	Air temperature; Relative humidity; Precipitation; at 1.5 m.	4 times per day (09:00, 12:00, 15:00 and 21:00 LT) From 1978 to 1994	Monthly averaged values
Palotina	24°16′S 53°55′W	310	35	Air temperature; Relative humidity; Precipitation; at 1.5 m.	4 times per day (09:00, 12:00, 15:00 and 21:00 LT) From 1978 to 1994	Monthly averaged values
1	25°S 54.75°W	–	–	Precipitation	1980–1998 (New et al., 2000)	Monthly averaged daily values
2	25°S 54.25°W	–	–	Precipitation	1980–1998 (New et al., 2000)	Monthly averaged daily values
3	25°S 53.75°W	–	–	Precipitation	1980–1998 (New et al., 2000)	Monthly averaged daily values
4	25°S 53.25°W	–	–	Precipitation	1980–1998 (New et al., 2000)	Monthly averaged daily values

4. Observational Analysis

All the results obtained hereafter are based on the observational data described in the previous section and summarized in Table I.

4.1. THE IMPACT OF THE LAKE ON THE DIURNAL EVOLUTION OF THE SURFACE WIND

The diurnal evolution of the wind components (zonal and meridional) indicates that the amplitude in Itaipu Power Plant is systematically smaller than in Foz do Iguaçu Airport (Figure 4).

The spatial variation of the surface wind amplitude can be explained in terms of the land occupation. The area around Itaipu Power Plant is dominated by forest while the land occupation around Foz do Iguaçu Airport is dominated by agricultural areas, with significant bare soil (Figure 2b).

The diurnal evolution of the wind components indicates that in the Brazilian side the wind blows *from the lake* (smaller negative values of u and larger negative values of v) between 09:00 and 18:00 LT, and *towards the lake* (larger negative values

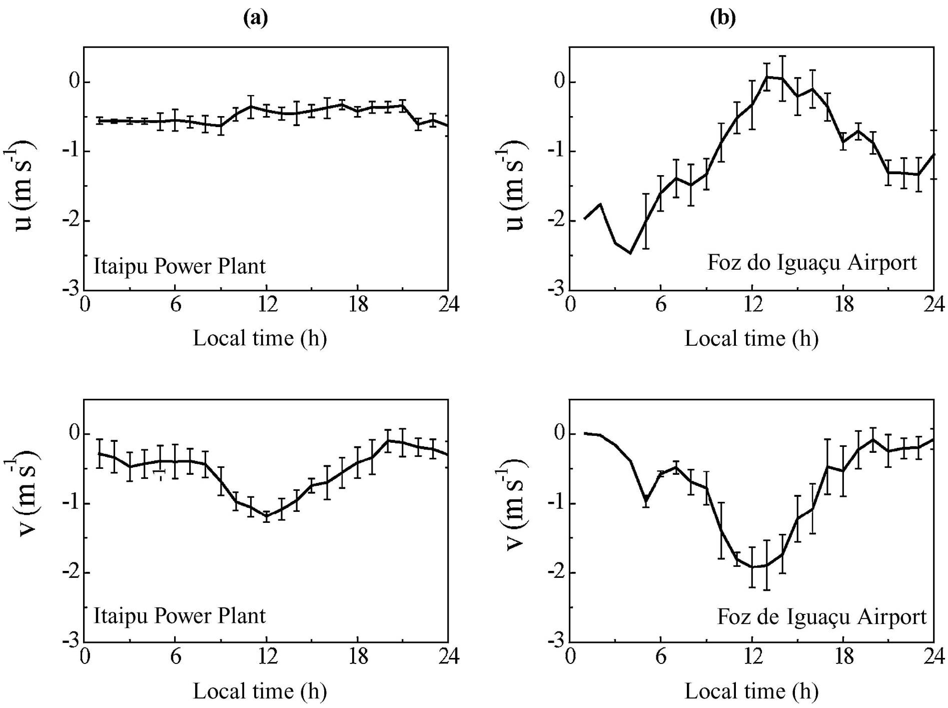

Figure 4. Diurnal evolution of the zonal (top) and meridional (bottom) wind components at (a) Itaipu Power Plant, Paraguay, and (b) Foz do Iguaçu Airport, Brazil. The vertical bars correspond to the statistical error.

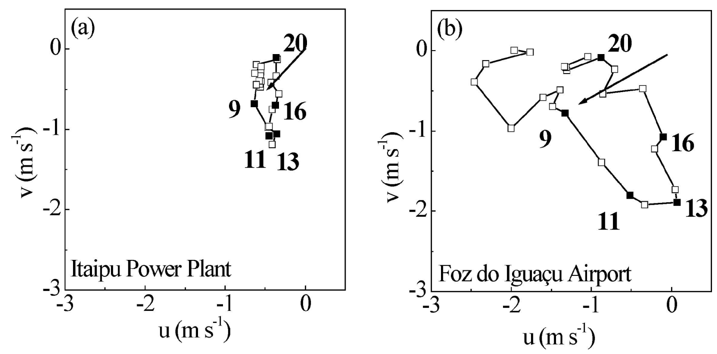

Figure 5. Hodograph for the diurnal evolution of the hourly monthly-averaged winds at (a) Itaipu Power Plant, Paraguay and (b) Foz do Iguaçu Airport, Brazil. The numbers indicate the local time. The arrows correspond to the daily-averaged wind.

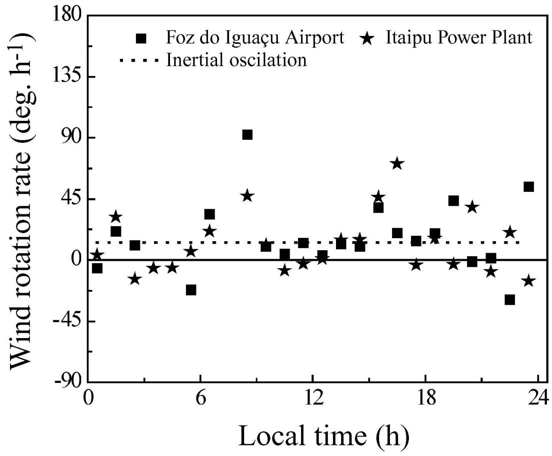

Figure 6. Wind rotation rate (degree h^{-1}) at Foz do Iguaçu Airport, Brazil (square), Itaipu Power Plant, Paraguay (star) and of the inertial oscillation (dotted line).

of u and smaller negative values of v) from 18:00 to 09:00 LT (Figure 4b). This pattern is consistent with a lake-breeze circulation and it is more clearly observed in the hodographs (Figure 5). In the Brazilian side, the main axis of the ellipsis is perpendicular to the lake shoreline and the hodograph indicates that the trajectory described by the wind vector has an elliptical shape, with mainly counterclockwise rotation. On the Paraguay side the diurnal cycle of the wind is not so clear (Figure 5a).

As shown in Figure 6, most of the time the wind rotation rate at Foz de Iguaçu Airport is more consistent with the rate of the inertial oscillation rotation than at Itaipu Power Plant (Paraguay side). The inertial period in the investigated area is around 27.7 h.

The diurnal evolution of the horizontal wind divergence (estimated considering straight line between the Itaipu Power Plant and Foz do Iguaçu Airport

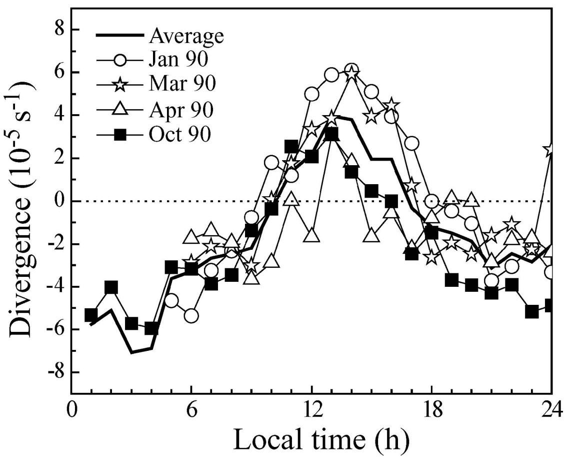

Figure 7. Diurnal evolution of the horizontal wind divergence over the Itaipu Lake, estimated from the monthly–averaged winds observed at Itaipu Power Plant (Paraguay) and Foz do Iguaçu Airport (Brazil).

meteorological stations) indicates divergence during daytime (10:00 to 17:00 LT) and convergence during the others hours (Figure 7).

The surface wind diurnal pattern corroborates with the hypotheses of lake breeze circulation induced by the Itaipu Lake. However, the contribution of a mountain-valley circulation cannot be discarded (Bitan, 1981; Asculai et al., 1984), because both investigated meteorological stations are located in the bottom of the Parana River Valley (Figure 3 and Table I).

4.2. THE IMPACT OF THE LAKE ON THE NIGHTTIME AND EARLY MORNING FLOWS

The set of radiosonde balloon trajectories were estimated from the wind velocity and direction and used to identify the vertical structure of the local circulation in the Itaipu Lake area (Asculai et al., 1984). It was investigated 188 vertical wind profiles, carried out in September and December 1994 and from June to November 1995, corresponding to radiosonde launched once a day (at 08:30 LT) at Foz do Iguaçu Airport (20 km southeastward of the Itaipu Lake). In these radiosondes, the measurements of wind velocity and direction were accomplished by the Omega navigation system.

To identify the presence of the lake breeze the balloon trajectories were obtained during undisturbed condition days—calm winds (surface wind velocity <5 m s^{-1}) and clear sky. In general, this condition was observed during winter-spring months, when the area of Itaipu Lake is under large-scale high-pressure system. Figure 8 displays the selected trajectories.

The inspection of these trajectories revealed that the balloons change systematically their direction as they move vertically up (Figure 8). Close to the surface, they

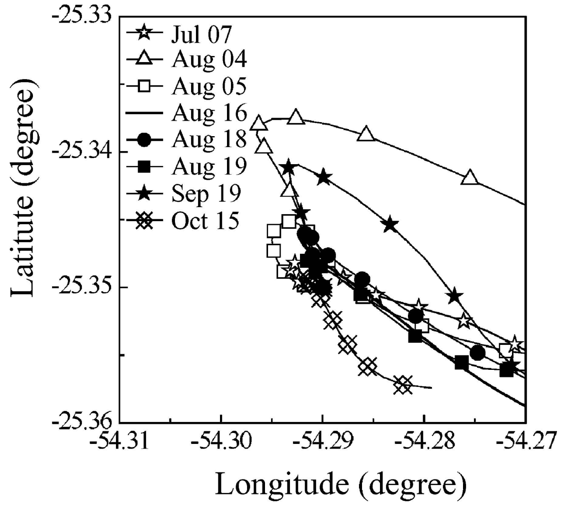

Figure 8. Trajectories described by the radiosonde balloons launched at Foz do Iguaçu Airport, during 1995.

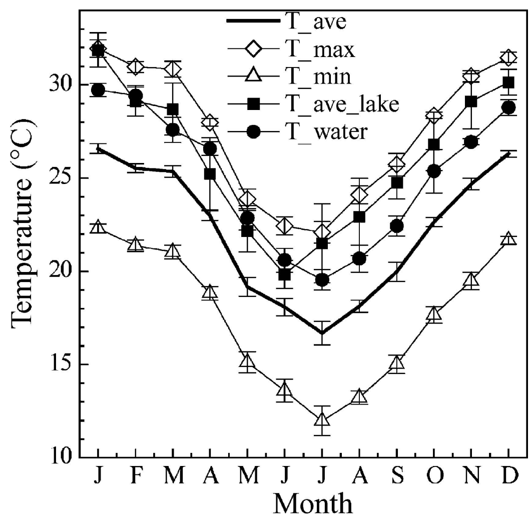

Figure 9. Time evolution of the monthly-averaged daily (T_ave), maximum (T_max) and minimum (T_min) air temperature values carried out at Itaipu Power Plant meteorological station. The monthly-averaged daily air temperature over the lake (T_ave_lake) and the monthly-averaged daily lake water temperature (T_water) were obtained in the vicinity of the Itaipu Power Plant meteorological station. The vertical bars correspond to the statistical error.

move towards the lake and as they get higher, their trajectories shift to the opposite direction, moving from the lake to the land. The change of direction, in most of the trajectories, occurs between 800 m and 1000 m above the surface.

Most of the selected trajectories are representative of winter-spring atmospheric conditions around 8:30 LT. During this period of the year, the sunrise in the Itaipu

Lake area occurs around 07:00 LT. The absence of a well-developed convective layer at 8:30 LT allows the assumption that, at the sounding time, the thermal conditions in the Itaipu Lake area are typical of the winter-spring at nighttime. In this period of the year, the horizontal thermal contrast, during nighttime (in average $+9$ °C; Figure 9) could induce a thermal circulation with the wind blowing towards the lake, at lower levels (land breeze), as shown in Figure 5b. In addition, the balloon trajectories corroborate with the expected behavior of land breeze induced by the Itaipu Lake for nighttime conditions. This pattern is also consistent with the nighttime mountain-valley circulation induced by the Parana River Valley.

4.3. HORIZONTAL THERMAL IMPACT OF THE ITAIPU LAKE

The monthly-averaged air temperature over the lake (*T_ave_lake* in Figure 9) is systematically higher than the lake water temperature from July to December (*T_water* in Figure 9). In the other months (January-February, April-June), the intersections of the error bars indicate that the air-surface differences are not statistically significant.

The horizontal thermal contrast between a lake and a surrounding land can be estimated from the air temperature difference between the lake and the land (Oliveira and Fitzjarrald, 1993). Here, the thermal contrast was estimated considering the difference between the monthly-averaged daily air temperature over the lake and the monthly-averaged daily maximum and minimum air temperature over the land.

The difference between the monthly-averaged daily air temperature over Itaipu

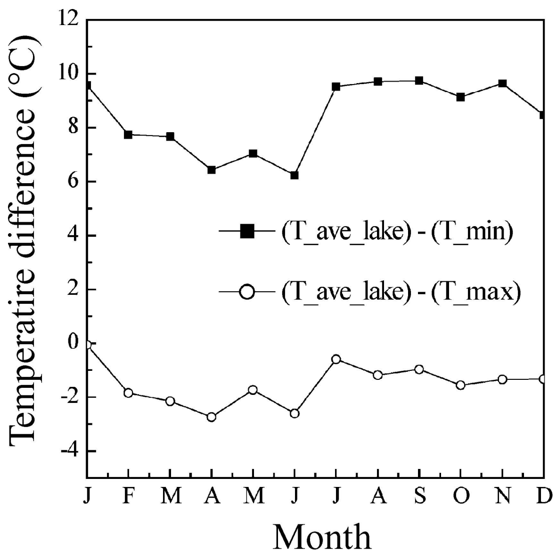

Figure 10. Monthly evolution of the temperature difference between the monthly-averaged daily over Itaipu Lake (T_ave_lake) and the monthly-averaged daily maximum (T_max)—full squared line—and minimum (T_min)—open circle line—at Itaipu Power Plant meteorological station.

Lake and the monthly-averaged daily maximum (minimum) air temperature over the Itaipu Power Plant meteorological station, were inferred from the observations assuming that the maximum (minimum) air temperature over land occurs during daytime (nighttime) and that the thermal amplitude over the lake is small—due to the large heat capacity of the water—the horizontal thermal contrast during daytime (nighttime). As can be seen in Figure 10, the horizontal thermal contrast induced by the Itaipu Lake is negative during daytime, varying from 0 to −1.5 °C, between July and January, and between −2 to −3 °C, from February to June. During nighttime, the Itaipu Lake is systematically warmer than the land, and the thermal contrast varies from +8.5 to +9.5 °C between July to January and from +6.5 to +8 °C, between February and June.

4.4. THE LAKE FORMATION IMPACT ON DIURNAL TEMPERATURE CIRCLE

The climate impact caused by a dam formation is induced by the drastic alteration in the surface energy budget caused by the land use modification. The substitution of vegetation by water reduces the surface albedo and increases the amplitude of the latent heat flux at expenses of the sensible heat flux. There is also an increase in the wind speed due to the surface roughness reduction.

Several works have shown that the global climate change has its major impact on the reduction of the amplitude of the diurnal temperature cycle mainly associated to the increasing of cloud cover (Karl et al., 1993). This effect is not likely to act in the case of Itaipu, because the lake breeze induces subsidence over the lake area, inhibiting the cloud formation in the area (Stivari et al., 2003).

The relationship between the amplitude reduction of the daily temperature and the land use is still far from established (Kalnay and Cai, 2003). Up to now, the modulation of the diurnal cycle of temperature has been verified as a local climate change caused by the urbanization which does not contribute much to the secular trend observed over a larger area (Karl et al., 1988; Sala et al., 2000).

The effect caused by the replacement of the land by the water seems to be more dramatic. For instance the numerical simulation carried by Jazcilevich et al. (2000) shows that much of the actual strength of the Mexico City heat island effect disappears when the original existing lakes are included. In the simulations carried out by Stivari et al. (2003) the inclusion of the lake alters dramatically the temperature pattern in the lower atmosphere in the region near Itaipu Lake.

The thermal impact caused by the Itaipu Lake formation (1982–1984) can be identified from the time evolution of the deviation from the area-averaged of the annual values of air temperature (daily-averaged, daily maximum and daily minimum values) at three locations: Itaipu Power Plant (2 km from the lake), Palotina (35 km from the lake) and Cascavel (75 km from the lake). For the meteorological station locations see Figure 1b and Table I.

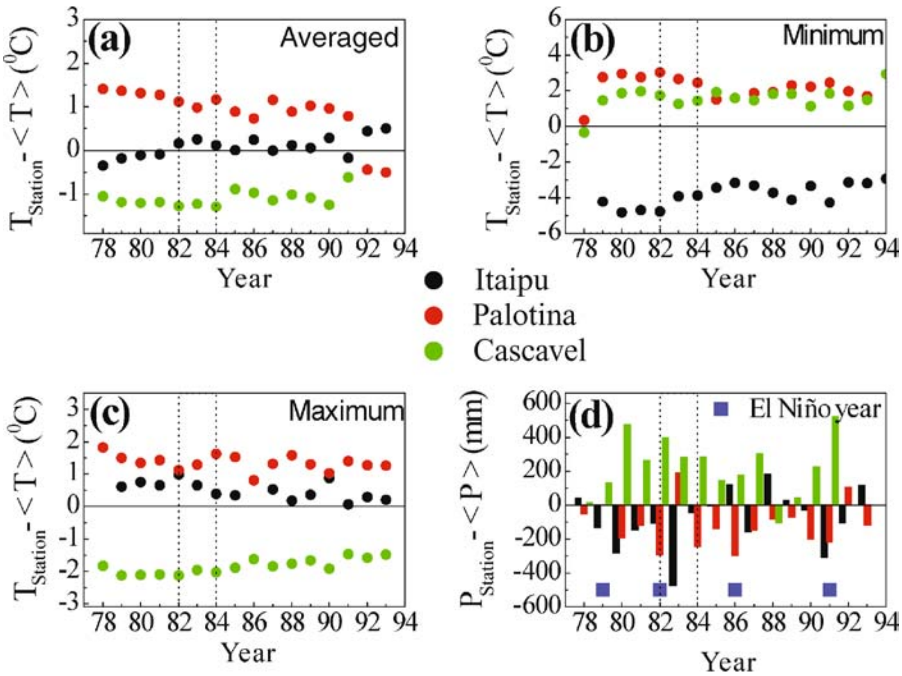

Figure 11. Time evolution of the deviation between the monthly-averaged air temperature at certain station (T_{Station}) and the area-averaged air temperature ($\langle T \rangle$) over three meteorological stations. (a) Averaged air temperature, (b) minimum air temperature and (c) maximum air temperature. (d) Time evolution of the deviation between the annual accumulated precipitation at certain station (P_{Station}) and the area-averaged precipitation ($\langle P \rangle$) over three meteorological stations. Blue boxes indicate the El Nino events. The vertical dotted lines indicate the lake formation period. Black, red and green colors represent, respectively, Itaipu, Palotina and Cascavel meteorological station data.

Comparing the amplitude of the temperature deviation before (1978–1982) and after the lake formation (1984–1994), all the stations show a tendency to decrease theirs amplitude after the lake formation (Figure 11a).

During the formation of the lake (1982–1984) there is a positive trend deviation from the area averaged for the daily minimum values and a negative trend for the daily maximum values of the air temperatures at Itaipu Power Plant (Figures 11b and 11c). On the other hand, at the stations more distant from the lake (Palotina and Cascavel) the deviation from the area averaged for daily minimum values has a negative tendency (Figure 11b) and a positive tendency for the daily maximum values of the air temperatures (Figure 11c).

According to Kalnay and Cai (2003), land irrigation could increase the heat capacity of the soil, thus increasing the minimum temperature. However, the land irrigation in the Itaipu area occupies around 13 km^2 which compared to the total inundated area (around 1460 km^2) is less than 1% (N.M. Friedrich, personal communication) and therefore does not seem to be a large factor in the temperature modulation detected in the Itaipu area.

4.5. THE LAKE FORMATION IMPACT ON THE SPATIAL DISTRIBUTION OF RAIN

The time evolution of the deviation from the area-averaged values of annual accumulated precipitation (Figure 11d) indicates, in general, a rain deficit in Itaipu Power Plant and Palotina stations and a rain surplus in Cascavel station, before and after the lake formation.

The Itaipu and Palotina stations are positioned nearer to the lake and in the bottom of the valley whereas Cascavel is located on the hills of the valley (Table I). The spatial pattern of the rain indicates that the valley–mountain circulation effect is controlling the rain in this area, inducing subsidence during daytime over the bottom of the valley and thus inhibiting the cloud formation and precipitation.

The temporal pattern of the precipitation over the region does not indicate any consistent modification in the rain regime after the lake formation (Figure 11d).

During the lake formation (1982–1984) occurred a major rain deficit in Itaipu station and unusual rain surplus in Palotina station. Besides the valley–mountain circulation effect, the augment in the rain deficit pattern in the Itaipu station may be related to the lake formation. The increase of the area covered by water intensifies the surface horizontal thermal contrast increasing the horizontal wind divergence and therefore the air subsidence over the lake, which inhibits the precipitation. However, this pattern could be masked by El Niño events that tend to increase the rain amplitude consistently in the whole area of the Parana River Valley (Grimm et al., 1998).

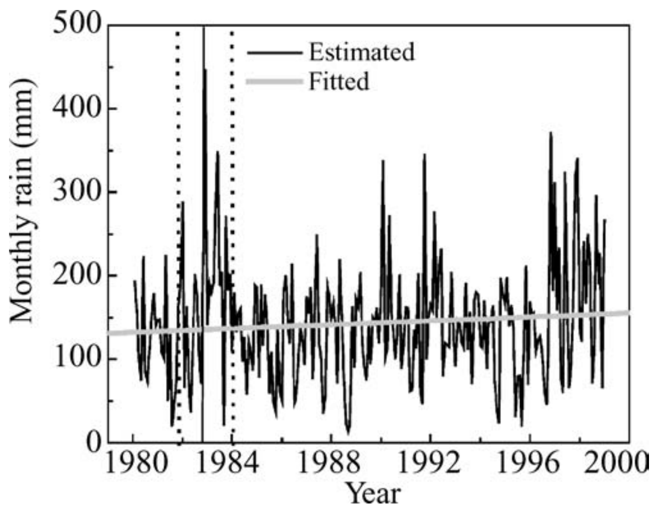

Figure 12. Temporal evolution of the monthly-accumulated precipitation averaged along the latitude line of 25°, from longitudes between 54.75°W and 53.25°W, based on (New et al., 2000). The gray line represents the fitted line. The vertical dotted lines indicate the lake formation period.

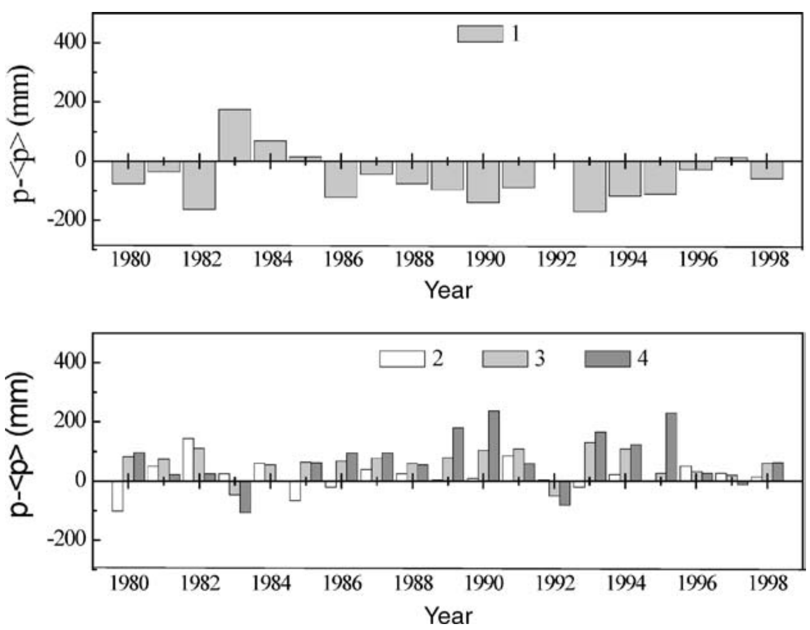

Figure 13. Time evolution of the deviation between the annual accumulated precipitation (p) and the area-averaged value ($\langle p \rangle$) based on the data set, from 1980 to 1998 (New et al., 2000). The numbers represent the positions: 1 (25°S, 54.75°W), 2 (25°S, 54.25°W), 3 (25°S, 53.75°W) and 4 (25°S, 53.25°W) as displayed in Figure 1b. The vertical dotted lines indicate the lake formation period.

An extra set of rain data available for each 0.5° latitude–longitude resolution (New et al., 2000) was used to examine large-scale precipitation pattern in the Itaipu Lake area. The monthly-accumulated precipitation averaged along the latitude line of 25°, from longitudes between 54.75° and 53.25°W, shows a slightly positive trend (Figure 12) indicating that the rain-inhibiting effect associated to the lake formation is not affecting the large-scale precipitation trend in the area. The major rain pattern disruption, observed between 1982 and 1984, occurred simultaneously to the impounding of the lake and to the strongest El Niño event observed in the investigated period (Grimm, 2000).

The temporal evolution of the deviation from the area-averaged values of annual accumulated precipitation, along the 25°S latitude, based on the data set from 1980 to 1998 (New et al., 2000) shows a systematic rain deficit in location 1 contrasting with the systematic rain surplus in locations 2–4 (Figure 13). The data geographical locations are displayed in Figure 1b. The spatial distribution of deficit and surplus of precipitation, with respect to the lake, agrees with the precipitation distribution inferred from the nearest surface stations (Figure 1b). Itaipu station, on the lake's western side presents a rain deficit and Cascavel on the lake's eastern side a rain surplus (Figure 11d).

5. Conclusion

This study investigates the impact of local circulation induced by the artificial Itaipu Lake on the climate of the region using all meteorological information available in the area.

The Itaipu Lake has a complex configuration, with areas of concave and convex curvatures along all its extension (170 km) and with changeable width, reaching 17 km (see the creeks in Figure 2b). These creeks can have a thermal behavior different from the central portion of the lake, inducing significant differences in thermal amplitude observed in the central portion of the lake (Brunkow et al., 1987).

The surface wind data set available in the studied area indicates the presence of a local circulation with lake breeze characteristics showing horizontal wind divergence over the lake during daytime and convergence during nighttime. This result is in agreement with Stivari et al. (2003).

Another important conclusion is that the intensity of the thermal contrast induced by the Itaipu Lake seems to be compatible with the lake breeze circulation hypothesis. The numerical simulations carried out by Stivari et al. (2003) had proved that it is the case for idealized spring conditions. The thermal contrast induced by the Itaipu Lake is negative during the daytime, varying from 0 to –1.5 °C, between July and January, and from −2 to −3 °C for the rest of the year. During nighttime, the Itaipu Lake is systematically warmer than the land around, and the thermal contrast varies between +6.5 and +8 °C, during February–June and between +8.5 and +9.5 °C, during July–January.

The third conclusion is that from the regional point of view, the Itaipu Lake formation has reduced the thermal amplitude of the diurnal air temperature cycle.

The fourth conclusion is that the precipitation data investigated here has not indicated any systematic effect associated to the lake formation. The reason for the apparent inconsistency is that the lake breeze circulation could be working in the same direction of the valley–mountain circulation effect existent in the area, both inhibiting the rain in the Itaipu Lake vicinity. Moreover, the rain pattern in the area is strongly affected by the El Nino events that tend to increase the rain amplitude consistently in the whole area of the Parana River Valley (Grimm et al., 1998).

Finally, it is important to emphasize that the meteorological data used here is not long enough to undoubtedly prove that the lake formation has altered the climate in the region. However, the analysis of the available data provided a list of evidences supporting the hypothesis that the Itaipu Lake presence has an important impact on the local circulation.

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References

Aneel, 2003: Agencia Nacional de Energia Elétrica (http://www.aneel.gov.br/).

Assunção, M., Marza, V., Barros, L., Chimpliganond, C., Soares, J. E., Carvalho, J., Caixeta, D., Amorin, A., and Cabral, E.: 2002, 'Reservoir-induced Seismicity in Brazil', *Pure Appl. Geophys.* **159**, 597–617.

Asculai, E., Doron, E., and Terliuc, B.: 1984, 'Mesoscale flow over complex terrain – A field study in the Lake Kinneret area', *Bound.-Layer Meteorol.* **30**, 313–331.

Bitan, A.: 1977, 'The influence of the special shape of the dead-sea and its environment on the local wind system', *Arch. Meteorol. Geophys. Bioclimatol.* **24**, 283–301.

Bitanr, A.: 1981, 'Lake Kinneret (Sea of Galilee) and its exceptional wind system', *Bound.-Layer Meteorol.* **21**, 477–487.

Brunkow, R. F., Andrade, L. F., and Xavier, C. F.: 1987, 'Processo de estratificação térmica e de oxigênio dissolvido no reservatório de Itaipu, Paraná-BR', in *Proceedings* 2*nd Seminário da Itaipu Binacional Sobre Meio Ambiente.* Foz do Iguaçu, Brazil, pp. 187–196 (in Portuguese).

Delariva, R. L. and Agostinho, A. A.: 2001, 'Relationship between morphology and diets of six neotropical locaricariids', *J. Fish Biol.* **58**, 832–847.

Fearnside, P. M.: 2000, 'Global warming and tropical land-use change, greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation', *Clim. Change* **46**, 115–158.

Grimm, A. M., Ferraz, S. E. T., and Gomes, J.: 1998, 'Precipitation Anomalies in Southern Brasil Associated with El Niño and La Niña Events', *J. Clim.* **11**, 2863–2880.

Grimm, A. M.: 2000, 'Climate variability n southern South America associated with El Nino and La Nina events', *J. Clim.* **13**, 35–58.

Gupta, H. K.: 2002, 'A review of recent studies of triggered earthquakes by artificial water reservoirs with special emphasis on earthquake in Koyna, India', *Earth-Sci. Rev.* **58**, 279–310.

Gyau-Boakye, P.: 2001, 'Environmental impacts of the Akosombo dam and effects of climate change on the lake levels', *Environ. Dev. Sustainability* **3**, 17–29.

Jazcilevich, A., Fuentes, V., Jáuregui, E., and Luna, E.: 2000, 'Simulated urban climate response to historical land use modification in the basin of Mexico', *Clim. Change* **44**, 515–536.

Kalnay, E. and Cai, M.: 2003, 'Impact of urbanization and land-use change of climate', *Nature* **423**, 529–531.

Karl, T. R., Diaz, H. F., and Kukla, G.: 1988, 'Urbanization: Its detection and effect in the United States climate record', *J. Clim.* **1**, 1099–1123.

Karl, T. R., Jones, P. D., Knight, R. W., Kukla, G., Plummer, N., Razuvayev, V., Gallo, K. P., Lindseay, J., Charlson, R. J., and Peterson, T. C.: 1993, 'A new perceptive on recent global warming: Assymetric trends of daily *maximum* and minimum temperature', *Bull. Am. Meteorol. Soc.* **74**, 1007–1023.

Miranda, L. E., Agostinho, A. A., and Gomes, L. C.: 2000, 'Appraisal of the selective properties of gill nets and implications for yield and value of the fisheries at the Itaipu Reservoir, Brazil-Paraguay', *Fisheries Res.* **45**, 105–116.

Neumann, J. and Mahrer, Y.: 1975, 'A theoretical study of the lake and land breeze of circular lakes', *Mon. Weather Rev.* **103**, 474–485.

New, M., Hulme, M., and Jones, P.: 2000, 'Representing twentieth-century space-time climate variability. Part. II: Developing of 1991-96 monthly grigds of terrestrial surface climate', *J. Clim.* **13**, 2217–2238.

Oliveira, A. P. and Fitzjarrald, D. R.: 1993, 'The Amazon river breeze and the local boundary layer: I. Observations', *Bound.-Layer Meteorol.* **63**, 141–162.

Orfeo, O. and Stevaux, J.: 2002, 'Hydraulic and morphological characteristics of the middle and upper reaches of the Paraná River (Argentina and Brazil)', *Geomorphology* **44**, 309–322.

Physick, W.: 1976, 'A numerical model of the sea-breeze phenomenon over a lake or gulf', *J. Atmos. Sci.* **33**, 2107–2135.

Rosa, L. P. and Schaefer, R.: 1995, 'Global warming potentials', *Energy Policy* **23**, 149–158.

Sala, J. Q., Olcina, G. A., Cuevas, A. P., Cantos, J. O., Amoros, A. R., and Chiva, E. M.: 2000, 'Climatic warming in the spanish mediterranean: natural trends and urban effect', *Clim. Change* **46**, 473–483.

Segal, M., Leuthold, M., Arrit, R. W., Anderson, C., and Shen, J.: 1997, 'Small lake daytime breezes: Some observational and conceptual evaluations', *Bull. Am. Meteorol. Soc.* **78**, 1135–1147.

Stivari, S. M., Oliveira, A. P., Nascimento, F. M., and Amaral, S.: 1997, 'Remote sensing applied to a mesoscale numerical model of atmospheric circulation', in *Proceedings VIII Latin American Symposium on Remote Sensing (*SELPER'97), CDROM, Mérida, Venezuela.

Stivari, S. M. S.: 1999, '*Um estudo da brisa lacustre do Lago de Itaipu*', Ph.D. thesis, Dept. of Atmospheric Sciences, University of São Paulo, Brazil, 125 pp. [Available from Rua do Matão 1226, São Paulo, SP, 05508-900, Brazil]. (in Portuguese).

Stivari, S. M. S, Oliveira, A. P., Karam, H. A., and Soares, J.: 2003, 'Patterns of local circulation in the Itaipu Lake area: Numerical simulations of Lake breeze', *J. Appl. Meteorol*. **42**(1), 37–50.

Suzuki, H. I., Agostinho, A. A., and Winemiller, K. O.: 2000, 'Relationship between oocyte morphology and reproductive strategy in loricarrid catfishes of the Paraná River, Brazil', *J. Fish Biol*. **57**, 791–807.

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