Hydrologic variation and lake sediments: a reconstruction of the Bolivian Lowlands over the last 5,500 years

by

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Abstract

Sediment cores raised from the shallow floor of Lake Opabusu in the Bolivian Gran Chaco record 5500 years of hydrologic change in the surrounding region. Sediment samples were analyzed for their organic carbon and nitrogen contents and stable isotopic ratios as well as for their $CaCO_3$ contents. These analyses indicate a general trend from drier to wetter conditions from the mid-Holocene to present. This trend is consistent with changes observed in the northern Bolivian lowlands and in the adjacent tropical Andes. Accompanying the increase in precipitation, the C/N ratio and $\delta^{13}C$ content of sedimentary organic matter indicate an apparent trend from algal to terrestrial sources as well as a possible increase in C_3 plants at the expense of drought-tolerant C_4 plants. Other studies done in the neighboring Altiplano and Amazon regions corroborate the movement toward wetter conditions, and work done in the Bolivian Amazon supports the idea of a shift of the type and amount of vegetative cover in Lake Opabusu's watershed.

This trend toward wetter conditions is likely governed by an orbitally-forced increase in summer insolation. The higher insolation at present intensifies the South American monsoon resulting in greater precipitation and higher lake levels; drier mid-Holocene conditions coincided with lower summer insolation.

Several, but not all, general circulation model simulations, suggest that the future climate of the study region will be significantly drier and warmer by the end of the 21st century. Both changes would contribute to a negative water balance and it is likely that Lake Opabusu will dry completely in the near future. Although the lake has shrunk and expanded during the last century (as seen in historic air photos), there is no evidence within the sediment core, that the lake has previously desiccated to the depth of the core site at any time in the past five millennia.

Introduction

Sediments drawn from the bottom of Lago Opabusu in the Bolivian lowlands provide a record of almost 5,500 years of climate history of the South American Gran Chaco. In such a varied and marginal region, it is possible to see changes that go beyond hydrology and get a real sense of the dynamic nature of lowland tropics of South America.

The Gran Chaco region of South America (Figure 1[1]) is a vast, wooded grassland area located between 17° 00' and 33° 20' S latitude and 57° 10' and 67° 00' W longitude. It spreads across northern Argentina, north-western Paraguay, south-western Brazil, and south-eastern Bolivia, and spans roughly 1,010,000 km^2 . The region is essentially flat, made up of approximately 3000 m of Paleozoic, Mesozoic, and Tertiary deposits beneath a layer of fine, unconsolidated Quaternary deposits that fill in a tectonic depression and form a plain that slopes gradually (0.04% gradient) from west to east. The average elevation is between 100 and 500 masl, though occasional mountains can reach as high as 2795 masl[2]. Lago Opabusu in our study area sits in the foothills to the east of the Bolivian Andes at a height of approximately 700 masl.

Figure 1: Map of the Gran Chaco

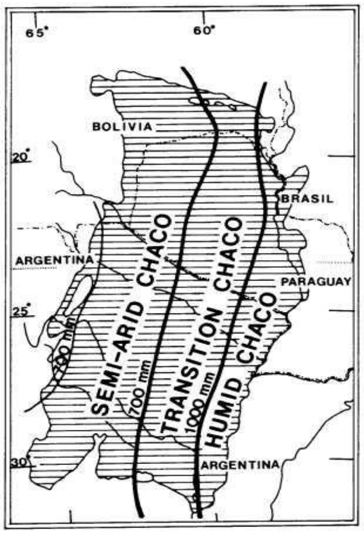

Figure 2: Precipitation based sub-regions within the Gran Chaco

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[1] https://www.cia.gov/library/publications/the-world-factbook/maps/refmap_south_america.html

[2] Galera, F.M.and Ramella, L., 2008.

Climatologically, the Gran Chaco displays the expected wet-dry cycle often seen in the tropics and subtropics, with a pronounced wet season during the austral summer, and dryer winter months. On average, 400-600 mm of rainfall during this rainy season, out of an average annual rainfall of 450-800 mm. In general, precipitation increases from west to east, breaking the region into three fairly distinct regions of semi-arid, transitional, and humid (Figure 2[3]). Mean temperature can be measured on a similar gradient, and increases from south to north[4].

The coincidence of higher temperatures with periods of greater precipitation favor the growth of C_4 plants in the region as a whole[5]. Xerophytic deciduous forest is dominant in the region, generally occurring in 3 to 4 stratified layers of canopy, sub-canopy, shrubby understorey, and herbaceous grasses. Variability in precipitation from one region to the next and proximity to perennial bodies of water allow for plenty of variation in vegetation, accounting for environments ranging from shrubby steppes, cactus stands, and savannah, to annually flooded riverine forests and wetlands[6].

Soils in the Gran Chaco are primarily fluvial in origin; the Bermejo and Polcomayo Rivers are responsible for the transport of the bulk of the sediment deposited in the region[7]. The tendency is toward neutral to slightly alkaline and a high base level of saturation. Once again, a west-east gradient exists when it comes to soil composition, with those in the west tending towards sand and loam, greater acidity, and better drainage, while those in the east have higher clay contents and poor drainage. The semi-arid to arid conditions that characterize the region also favor the presence of more saline soils[8].

Lago Opabusu (Figure 3[9]) – also known as Laguna Tatarenda – is a closed basin lake of

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[3] Riveros, F., 2007.

[4] Riveros, F., "The Gran Chaco", 2.1

[5] Riveros, F., "The Gran Chaco", 2.1

[6] Galera and Ramella, 2008.

[7] Riveros, F., "The Gran Chaco", 2.1

[8] Galera and Ramella, 2008.

[9] http://maps.google.com/maps/ms?ie=UTF8&msa=0&msid=214727311752775165585.00049f914d402e310269e&ll=-19.090347,-63.478231&spn=0.036581,0.084543&t=h&z=14

approximately 5.5 km^2 in area[10]. It is situated toward the western edge of the Bolivian Gran Chaco (19° 5' 37.80" S 63° 30' 30.40" W, approximately 700 masl), indicating that we should expect to see somewhat sandier or loamier surrounding soils with potentially more acidic pH. Lago Opabusu is also a rather shallow lake – less than a meter deep at coring sites and likely only 3-4 meters at its deepest point – though sediment records suggest that it has never dried up for any significant period[11]. The surrounding terrain is quite flat with only moderate vegetative cover, conditions which favor more evaporation than absorption or runoff.

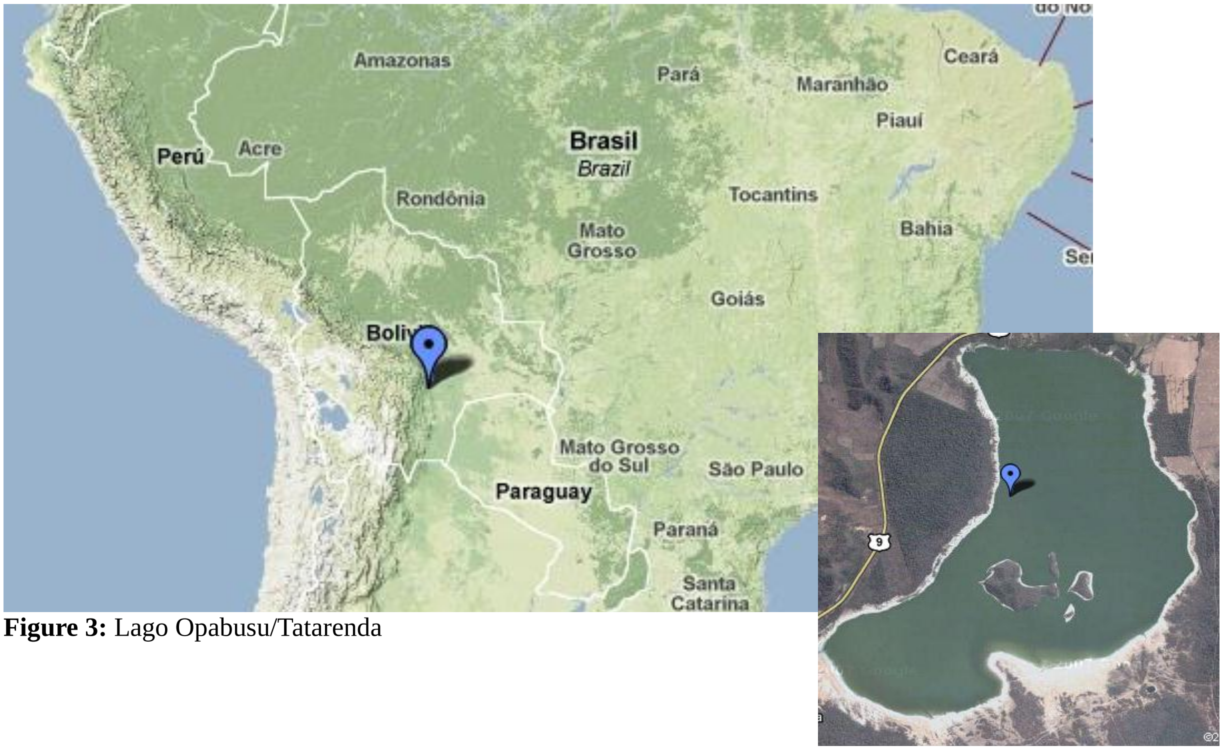

Figure 3: Lago Opabusu/Tatarenda

Satellite imagery suggests two or three small inlets into the lake, which may or may not dry up during the dryer winter months. Use of WebWIMP – the Web-based, Water-Budget, Interactive Modeling Program- calculates annual average precipitation at and around Lago Opabusu to be 804 mm, and annual loss to evaporation to be 802 mm. The projected loss to evapotranspiration is 1380mm,

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[10] http://static.panoramio.com/photos/original/769588.jpg

[11] It should be noted that aerial photographic records taken of Lago Opabusu indicate that it may have dried up completely in 1966, and experienced a partial drying (southern basin only) in 2004.

which would result in a deficit of nearly 600mm (Table 1, Figure 4[12]). Lago Opabusu is not dropping by over half a meter per year, which suggests another source of inflow into the lake.

The area around Lago Opabusu is not heavily populated, and fishing, swimming, and bathing are all prohibited within the lake itself, suggesting there is minimal direct human impact upon it. There is a road that runs fairly close to the western side of the lake, as can be seen in Figure 3, but the combination of comparatively low precipitation and the vegetation around the lake itself likely minimize the impact of any sort of industrial runoff into Lago Opabusu. The general physical integrity of the cores that were taken from the lake suggests that there was minimal disturbance from non-human sources as well.

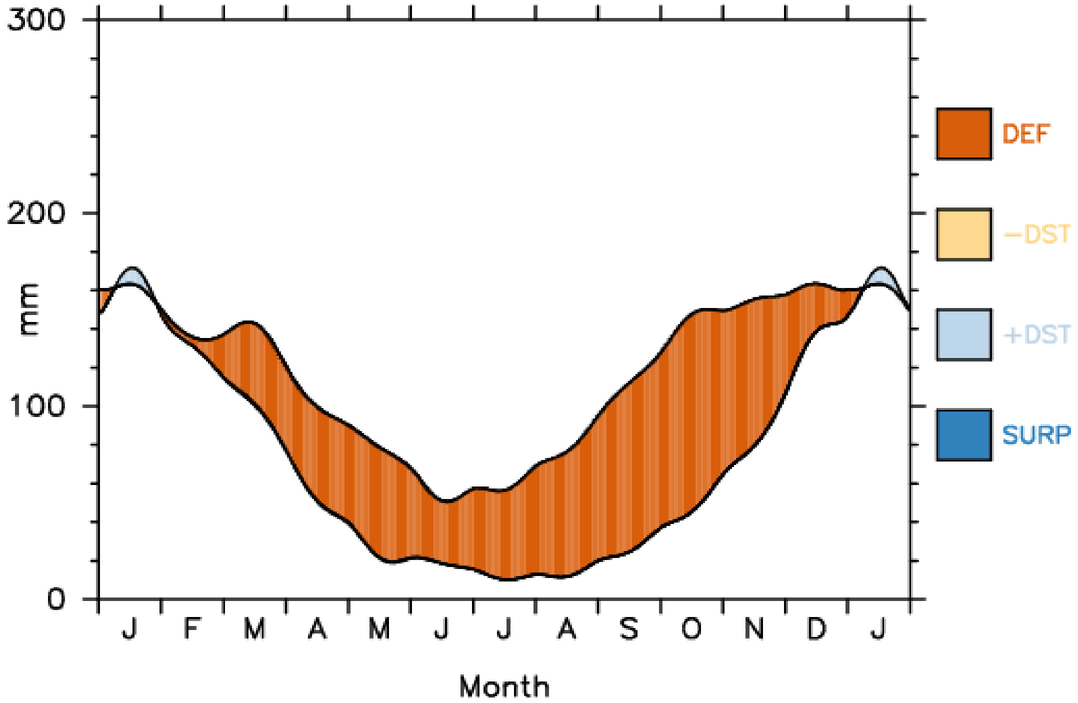

Figure 4: Water Balance at 63.5 W, 19.09 S. The model predicts a positive change in soil moisture (DST) only during the month of January, in the heart of the rainy season. A deficit (DEF) is expected for the remaining 11 months of the year.

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[12] Matsuura, K., Willmott, C., Legates, D. Rowe, C., 2009.

MON	TEMP	UPE	APE	PREC	DIFF	ST	DST	AE	DEF	SURP	SMT	SST
Jan	27.2	141	160	162	2	4	4	158	2	0	0	0
Feb	27.0	139	138	130	-8	3	-1	130	8	0	0	0
Mar	26.2	130	137	97	-40	2	-1	99	38	0	0	0
Apr	24.4	104	101	52	-49	1	-1	54	47	0	0	0
May	22.6	81	78	24	-54	1	0	25	53	0	0	0
Jun	20.6	60	55	19	-36	1	0	19	36	0	0	0
Jul	20.8	62	60	12	-48	0	-1	12	48	0	0	0
Aug	22.5	80	79	14	-65	0	0	14	65	0	0	0
Sep	25.0	112	112	27	-85	0	0	27	85	0	0	0
Oct	26.4	133	144	49	-95	0	0	48	96	0	0	0
Nov	27.3	142	155	83	-72	0	0	82	73	0	0	0
Dec	27.2	141	161	135	-26	0	0	134	27	0	0	0
Total			**1380**	**804**				**802**	**578**	**0**		

Table 1: Monthly and annual climatic water balance table for Lago Opabusu, as calculated by WebWIMP. The difference between APE (adjusted potential evapotranspiration) and PREC (precipitation) suggests that lake level should be dropping almost 600 mm per year.

Methods

Two sediment cores were taken from the bottom of Lago Opabusu using a Russian peat borer. The first (OPB1) was drawn at latitude -19° 05', longitude -63° 3' from water that was 0.72 m deep. Four overlapping drives were conducted, yielding a total of 2.08 m of sediment and reaching to a depth of 2.8 m. The second core (OPB2) was taken at latitude -19° 05', longitude -63° 29' from water that was 0.74 m deep. Five consecutive drives were taken with core OPB2, yielding 4.58 m of sediment and reaching to a depth of 4.68 m. Visual descriptions of all nine drives were notated in the field before sending the sediment back to Duke University.

Seven samples were drawn from these cores, two from OPB1 and 5 from OPB2, to be used for ^{14}C dating. The results of these tests were calibrated using the methods outlined by Fairbanks [13]. These

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[13] Fairbanks, et al. 2005.

calibrated measurements were deemed sufficiently linear to calculate a simple regression line detailing age versus depth when constructing the age model.

Smear slides were prepared from both cores prior to sampling with the thought of possibly doing some work with either diatoms or pollen. However, there was not a compelling enough yield of either sort of material to prompt further investigation at this time. Also prior to sampling, a second visual description was taken of all nine drives, this time with the aid of a Munsell book. Very minor differences were present between the two descriptions, many of which can likely be explained by a change in sediment color brought about by slight drying of the new surface of the sediment column following extraction.

All nine drives of both OPB1 and OPB2 were sampled continuously at 1 cm intervals. Each centimeter of sediment yielded two samples that were bottled and tagged accordingly. Further note was taken of changes in texture and composition, as well as of the fact that certain drives seemed to have compacted or contracted between extraction and sampling, resulting in occasional differences between the recorded length of the core at extraction and the amount of sediment available for sampling. Special care was also taken to note the presence of obvious pieces of plant matter and shell.

Once OPB1 and OPB2 had been sampled in full, the samples were dried and then crushed with a mortar and pestle. The newly powdered samples were then collected at approximately 5 cm continuous intervals, drawing from drives 2, 3 and 4 of OPB 1 and drives 3, 4, and 5 of OPB 2, encompassing 4.55 m of sediment. Steps were then taken to isolate both organic carbon for isotopic analysis and calcium carbonate.

100 mg portions of each sample were first acid fumed to remove $CaCO_3$, thus preserving only the organic carbon present in the sample. These treated samples were then sent to the Duke Environmental Stable Isotope Lab (DEVIL), where they were combusted at 1,020° F in a Carlo-Erba NA 1500 Elemental Analyzer. During combustion, purified and chromatographically separated N_2 and

CO_2 were delivered via ThermoFinnigan Conflo III interface to a ThermoFinnigan Delta+XL continuous flow isotope ratio mass spectrometer. This allowed for measurement of both $\delta^{15}N$ and $\delta^{13}C$ for each sample from the same combustion. A 0.1 per mil at 1 s.d level of reproducibility is present for both isotopes using this method. The raw values generated by this analysis were then normalized through the use of measured versus known values of both internal and international standards that were also combusted during the sample runs.

The weight percent per sample of $CaCO_3$ was also determined, both as a secondary potential proxy for precipitation and in order to determine if further isotopic analysis of oxygen might be of interest. To this end, another set of approximately 100 mg samples were taken at the same 5 cm intervals. These samples were dissolved in 50 ml 1N HCl, administered using a repipetor, agitated, and allowed to digest for approximately half an hour. Once it was clear that there was no $CaCO_3$ remaining to react with the HCl, the samples were put in a centrifuge for half an hour, after which the separated liquid was transferred into 60mL bottles. Calcium standards ranging from 1 to 10 ppm were prepared, and then all the samples were subjected to atomic absorption. AA readings were plotted against the known ppm concentration of the standards, and a regression line was calculated to provide a model for the sample results. The Ca concentration of each sample was then used to calculate the weight percent of $CaCO_3$ in each of the samples. This was then plotted versus age and eventually compared to the $\delta^{13}C$ results.

Results

The original samples taken for radiocarbon dating yielded a date for our oldest sample of that corresponded to a calendar age of 5587 years (Table 2, Figure 5).

Core Label	Section	Interval	Depth (m)	14C	Error	Cal age	1 std dev	method
OPB 1	2	59	0.59	255	30	298	49	Fairbanks0107
OPB 1	4	30	1.38	1560	25	1439	41	Fairbanks0107
OPB 2	3	20	2.3	2470	30	2561	97	Fairbanks0107
OPB 2	3	89	2.99	3330	45	3558	59	Fairbanks0107
OPB 2	4	52	3.62	3930	35	4389	48	Fairbanks0107
OPB 2	5	55	4.23	4840	30	5587	26	Fairbanks0107
OPB 2	5	90	4.58	4540	60	5231	113	Fairbanks0107

Table 2: ^{14}C dates, both calibrated and non, for samples drawn from OPB 1,2; 1,4; 2,3; 2,4; 2,5.

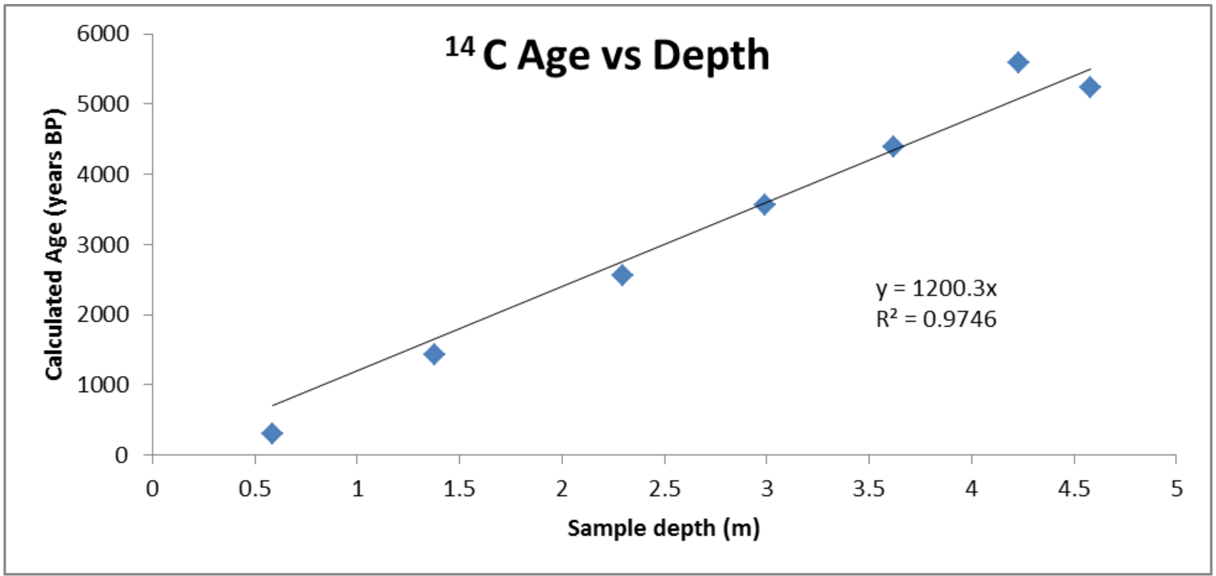

Figure 5: ^{14}C Age vs Sample Depth for Lago Opabusu. Sample ages were calibrated using Fairbanks 0107

A linear regression was run on these points, resulting in the following equation:

$$y = 1200.3x$$

This equation was then applied to the remainder of the samples, yielding a time line that extends back 5461 calendar years before present (Table 3). The disagreement between this oldest date and that which appears in table 2 can be attributed to forcing the regression line through zero, which pulled the line further from that outlying point. The fact that the age at a depth 4.23 m was calculated as greater than that ascribed to a depth of 4.55 m made this a questionable point, anyway, and so the age model was favored over the radiocarbon dating for the sake of consistency.

Sample Number	Depth (m) C and N	Cal Age	δ15N Normalized	δ13C Normalized	C/N by moles	Sample Number $CaCO_3$	Depth (m)$CaCO_3$	wt% $CaCO_3$
1	0.01	12.003	6.987347	-24.7731	12.4037	1	0.01	0.794314
2	0.05	60.015	8.918845	-22.9764	8.89198	2	0.05	0.790003
3	0.1	120.03	7.607507	-23.3045	6.968372	3	0.1	0.485057
4	0.15	180.045	7.795556	-23.7791	7.502107	4	0.15	0.485057
5	0.2	240.06	7.621511	-23.9962	9.372441	5	0.2	0.459655
6	0.26	312.078	7.154391	-24.6822	11.41156	6	0.25	0.510093
7	0.3	360.09	6.680268	-24.6172	12.66513	7	0.3	0.384571
8	0.35	420.105	7.282424	-24.8391	12.28575	8	0.35	0.301848
9	0.4	480.12	6.504223	-23.4854	9.678414	9	0.4	0.432883
10	0.45	540.135	8.346698	-22.831	9.624976	10	0.45	0.485323
11	0.5	600.15	8.118639	-23.7858	11.66931	11	0.5	1.481559
12	0.55	660.165	6.831307	-22.5191	9.741885	12	0.55	0.36078
13	0.6	720.18	7.418459	-23.5007	10.48212	13	0.6	0.54918
14	0.66	792.198	7.387451	-23.7953	11.55479	14	0.66	0.650006
15	0.7	840.21	9.496994	-23.5294	10.77679	15	0.7	0.023424
16	0.76	912.228	8.961857	-24.223	12.79912	16	0.75	0.530406
17	0.8	960.24	9.120898	-25.1175	13.03729	17	0.8	2.273491
18	0.85	1020.255	8.631771	-24.6803	11.63849	18	0.85	1.319133
19	0.9	1080.27	7.322434	-21.813	13.03308	19	0.9	0.878695
20	0.95	1140.285	6.506223	-21.062	12.23352	20	0.95	0.99395
21	1	1200.3	7.507482	-21.4457	12.3036	21	1	0.748871
22	1.05	1260.315	6.938335	-22.1115	14.47981	22	1.05	0.687755
23	1.1	1320.33	6.500222	-21.6274	10.35273	23	1.1	0
24	1.15	1380.345	7.547492	-19.3361	14.00158	24	1.15	2.168446
25	1.2	1440.36	7.264419	-21.1453	14.27906	25	1.2	2.557678
26	1.25	1500.375	9.059882	-21.8245	11.47099	26	1.25	0.220817
27	1.3	1560.39	7.923589	-20.8984	13.1916	27	1.3	1.669326
28	1.35	1620.405	8.115638	-20.9597	11.93843	28	1.35	1.018428
29	1.41	1692.423	8.194659	-20.7128	11.96603	29	1.41	0.832408
30	1.55	1860.465	8.943852	-21.8695	10.82487	30	1.45	0.048661
31	1.85	2220.555	6.496079	-21.9913	8.022781	31	1.5	0.560416
32	1.9	2280.57	6.678421	-21.708	9.828329	32	1.55	1.439276
33	2.11	2532.633	7.872305	-21.9607	10.24627	33	1.6	0.585005
34	2.15	2580.645	5.841073	-21.4342	9.591302	34	1.65	0.185993
35	2.2	2640.66	6.908641	-22.2594	11.3744	35	1.7	0.250401
36	2.25	2700.675	7.739878	-22.2842	12.83572	36	1.75	0.237113
37	2.3	2760.69	7.752102	-22.9629	13.77148	37	1.8	0.375111
38	2.35	2820.705	6.798625	-22.4077	12.44004	38	1.85	1.247575
39	2.4	2880.72	7.487247	-21.9329	11.64456	39	1.9	0.755492
40	2.45	2940.735	7.662459	-21.9655	13.78325	40	1.95	0.50803

Sample Number	Depth(m)	Calculated Age	δ15N Normalized	δ13C Normalized	C/N by moles	Sample Number $CaCO_3$	Depth (m)$CaCO_3$	wt% $CaCO_3$
41	2.5	3000.75	5.846166	-20.6186	11.72573	41	2	0.135408
42	2.55	3060.765	5.796251	-22.0066	14.33347	42	2.11	0.241056
43	2.6	3120.78	5.710683	-21.3883	12.64401	43	2.15	0
44	2.65	3180.795	6.919847	-21.0006	9.58354	44	2.2	0.609162
45	2.7	3240.81	6.219	-21.2657	10.29012	45	2.25	0.542111
46	2.75	3300.825	6.916791	-20.9384	7.566885	46	2.3	1.185193
47	2.8	3360.84	6.542938	-20.8905	7.117477	47	2.35	0.41769
48	2.85	3420.855	5.529359	-20.6732	7.112117	48	2.4	0.544357
49	2.9	3480.87	5.760598	-21.4179	9.453771	49	2.45	0.673464
50	2.95	3540.885	7.050237	-22.0344	9.647053	50	2.5	0.161039
51	3	3600.9	6.760934	-20.7488	8.498508	51	2.55	0.292233
52	3.11	3732.933	7.384361	-20.3142	8.478341	52	2.6	0.24952
53	3.16	3792.948	6.162973	-20.9977	9.897153	53	2.65	0.050921
54	3.2	3840.96	5.075031	-21.3059	8.174621	54	2.7	0.671126
55	3.25	3900.975	6.927996	-21.4342	10.0185	55	2.75	0.640389
56	3.3	3960.99	6.636656	-22.3379	12.58901	56	2.8	0.302451
57	3.35	4021.005	7.382324	-20.6521	9.953714	57	2.85	0.36145
58	3.4	4081.02	6.54905	-22.357	12.58025	58	2.9	0.281777
59	3.45	4141.035	5.859409	-21.6103	10.16526	59	2.95	0.485545
60	3.5	4201.05	7.397604	-21.9014	10.18389	60	3	0.223255
61	3.55	4261.065	5.780971	-20.7067	9.409912	61	3.11	0.132135
62	3.6	4321.08	6.86382	-20.8005	8.779963	62	3.15	0.255306
63	3.71	4453.113	6.606096	-20.6091	7.800318	63	3.2	0.603288
64	3.75	4501.125	5.652618	-20.6119	7.608139	64	3.25	0.454546
65	3.8	4561.14	6.260766	-20.2281	6.854797	65	3.3	0.375813
66	3.9	4681.17	5.755132	-19.8924	7.490795	66	3.35	0.924942
67	3.95	4741.185	6.358823	-19.8048	6.873303	67	3.4	0.808481
68	4	4801.2	6.143436	-19.6937	6.463951	68	3.45	0.825673
69	4.05	4861.215	6.006923	-19.6187	6.461964	69	3.5	1.092351
70	4.1	4921.23	5.32638	-19.6577	6.241961	70	3.56	0.556678
71	4.15	4981.245	5.504353	-19.7541	6.260008	71	3.6	1.026726
72	4.2	5041.26	4.659994	-19.1151	5.621924	72	3.71	0.604311
73	4.25	5101.275	4.738868	-18.9865	5.671915	73	3.75	0.638887
74	4.3	5161.29	4.357643	-19.2125	5.288495	74	3.8	0.510927
75	4.35	5221.305	4.149334	-19.5047	5.368664	75	3.85	0.52988
76	4.4	5281.32	4.858191	-19.531	5.631942	76	3.9	0.563798
77	4.45	5341.335	4.23023	-19.7648	6.526799	77	3.95	0.417938
78	4.5	5401.35	3.947092	-19.8184	6.289602	78	4	0.491089
79	4.55	5461.365	4.519436	-21.263	7.58261	79	4.05	0.561271
						80	4.1	0.65132
						Sample	**Depth**	**wt%**

Number $CaCO_3$	(m)$CaCO_3$	$CaCO_3$
81	4.15	0.476427
82	4.2	0.53079
83	4.25	0.509718
84	4.3	0.51917
85	4.35	0.662031
86	4.4	0.355784
87	4.45	0.465655
88	4.5	0.327315
89	4.55	0.45116

Table 3: Displaying depth, calculated age,δ15N normalized, δ13C normalized, C/N ratio by moles, and $CaCO_3$ wt % for each sample.

Talbot has argued that in closed basin lakes, $\delta^{13}C$ and $\delta^{18}O$ tend to co-vary, with heavier values corresponding with periods of greater lake volume (and, therefore, periods of greater precipitation)[14]. By plotting $\delta^{13}C$ versus age, it is possible to speculate in general terms as to the hydrologic changes that have occurred in the Bolivian Gran Chaco over the last five and a half millenia (Figure 6). Assuming Talbot's C/O isotopic correspondence holds true for Lago Opabusu, there is a very clear trend from dryer to wetter visible in this plot. There was a rather significant dry event approximately 1400 years BP, but in general the trend has been fairly steady. It appears that there is movement back toward wetter conditions just before the record that can be reconstructed from these cores ends. However, longer records reconstructed from other South American tropical lakes, such as Titicaca[15] and Potosi[16], do seem to indicate a wetter period right around 7000-8000 years BP, suggesting that such a leap might not be completely unreasonable.

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[14] Li, H. -C. and Ku, T. -L., 1997.
[15] Baker, P.A. et al. 2001.
[16] Abbot, M.B. et al. 2003.

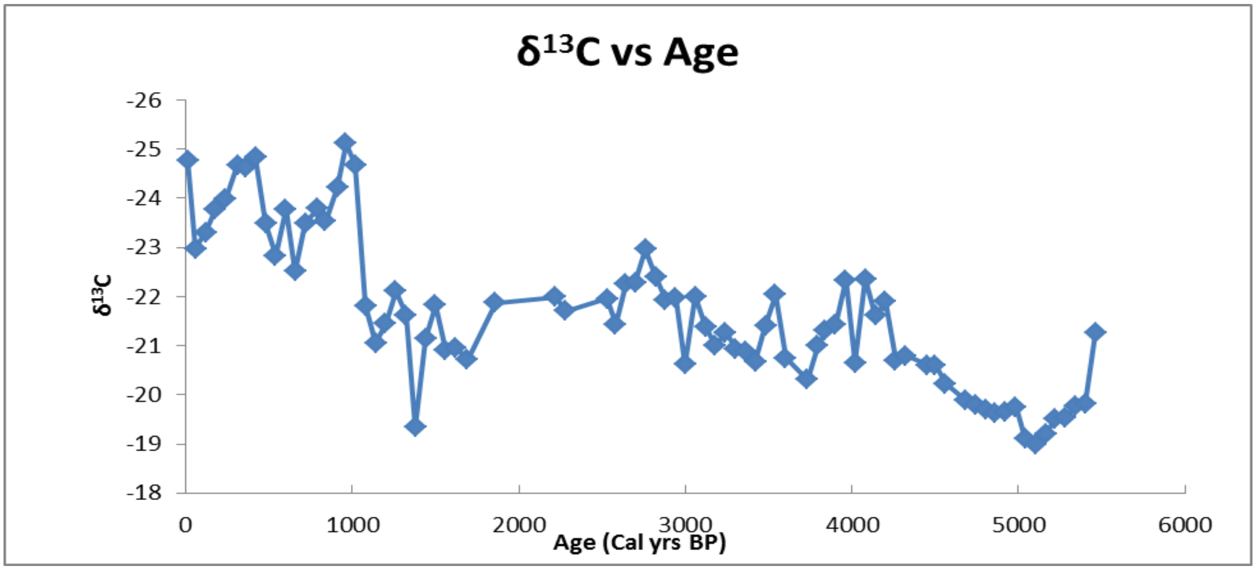

Figure 6: δ^{13}C vs sample age

If this trend toward wetter conditions is to be believed, plotting the weight percent of $CaCO_3$ against the age of the samples should result in a curve that is essentially the mirror image of that in Figure 6. Traditional interpretation depicts increases in $CaCO_3$ concentrations as a mark of dryer periods, when there is greater evaporation and more salts are precipitating out of the water column[17]. However, if that is the case, then the plot of $CaCO_3$ versus age (Figure 7) suggests a scenario that – noisy though the signal is – strongly contradicts that which is presented in Figure 6. Though the spike around 1400 years BP corresponds well with the drop visible at approximately the same time in Figure 6 – both proxies suggesting a significant dry period – there is almost an inverse relation between the contours of the two curves. If a greater weight percent of $CaCO_3$ is truly indicative of dryer conditions, then the curve in Figure 7 should be tending toward lower values as it gets closer to the present.

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[17] Baker et al, 2001.

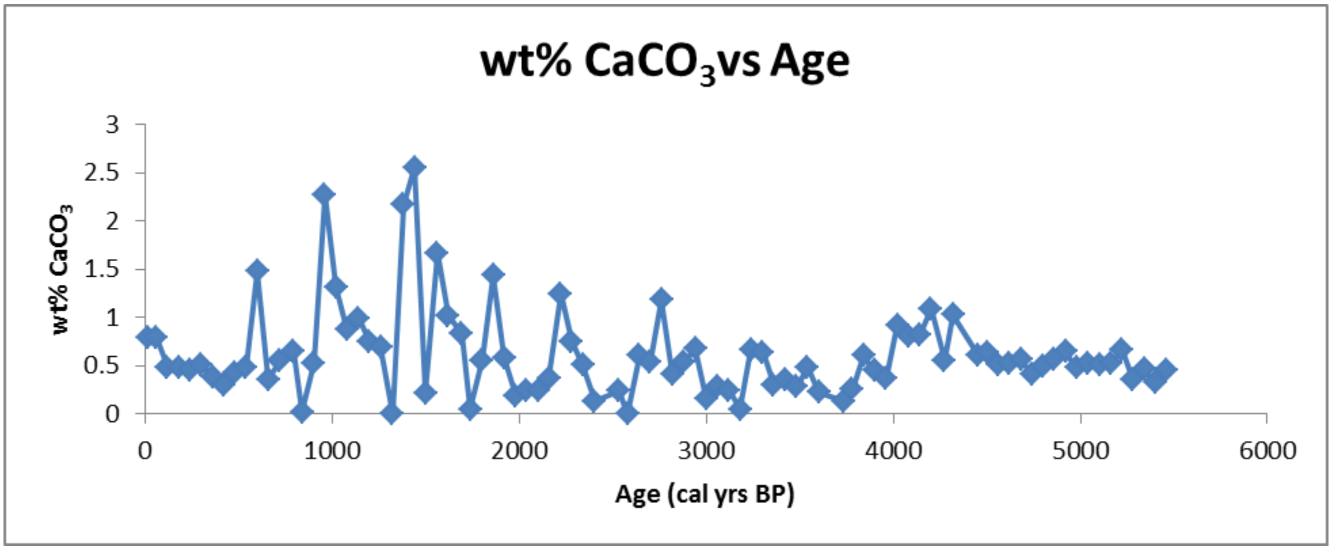

Figure 7: CaCO$_3$ wt % vs Age

While CaCO$_3$ and δ^{13}C present potentially conflicting pictures of past precipitation in the area surrounding Lago Opabusu and the Gran Chaco as a whole, δ^{15}N can be used as a proxy for types of vegetation both within the lake and in the surrounding watershed. Lower δ^{15}N values are generally associated with algal or phytoplanktonic origins, whereas higher values indicate the presence of more complex plants, both aquatic and terrestrial[18]. Figure 8 shows a fairly clear trend from lighter to heavier δ^{15}N values, potentially suggesting a move away from algae and more towards macrophytes and/or more complex vegetation in the watershed. Again, there is a break in the general trend right around 1400 years BP, possibly alluding to a dry event at that approximate time.

Potentially more revealing than changes in δ^{15}N, however, is the ratio between carbon and nitrogen. C/N ratios paint a somewhat clearer picture of the source (terrestrial versus lacustrine) of the isotopes in question. Though small C/N ratios, as with δ^{15}N, tend to indicate a predominance of algae within the lake system, higher values can be broken down further into those associated with C$_4$ plants –

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[18] Cohen, A.S., 2003. pg. 84

such as sedges and other plants typical of tropical climates – and C_3 plants – such as trees, shrubs, and temperate to cold climate grasses. In this case, values or approximately 4 to 10 tend to correspond with algal sources, those ranging from 10 to 14 indicate C_4 plants, and those in the 25-32 range are associated with C_3 plants[19].

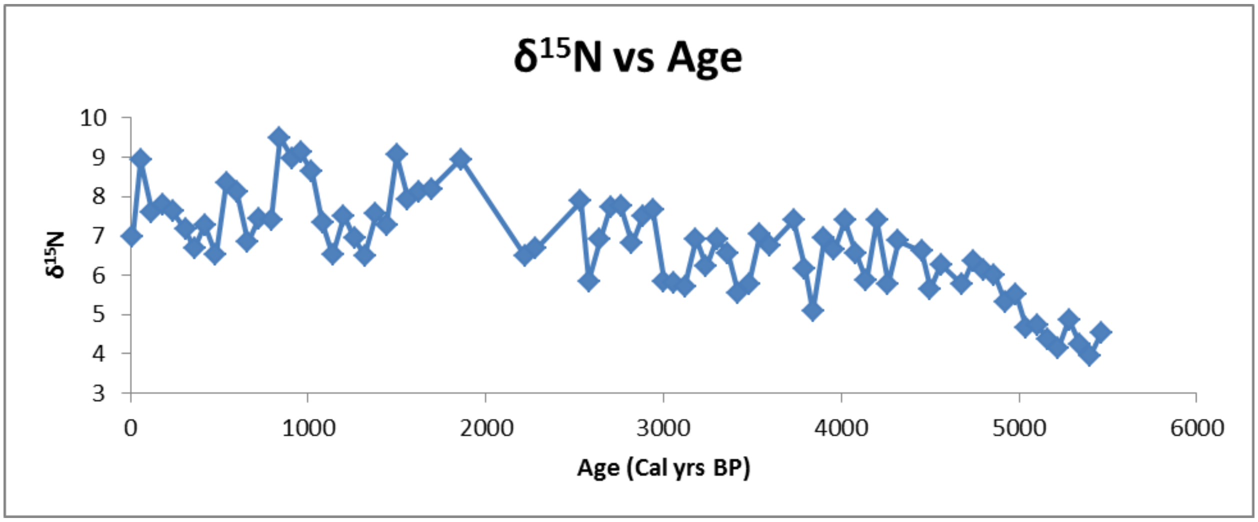

Figure 8: δ15N vs Age

Initially, plotting C/N ratios vs δ^{13}C yielded little beyond a rather noisy signal with a vaguely trimodal shape (Figure 9). Breaking the data up into groups according to depth/age of sample (four groups of approximately 20 samples each) produced a much more interesting picture, however (Figure 10). Samples 1-20 are those closest to the present day lake bottom, reaching depth of only 0.9 m and aged no more than 1,080 years. Samples get deeper and older with each successive group, ending with the very oldest Opabusu sediments to which this study has access. Breaking the data down in this way shows not only the progression from a more algae heavy system to one that features C_4 plants (C/N ratios), and from dryer to wetter conditions (δ^{13}C), but also how these changes occurred over depth and, therefore, over time.

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[19] Kaushal, S. and Binford, M.,1999.

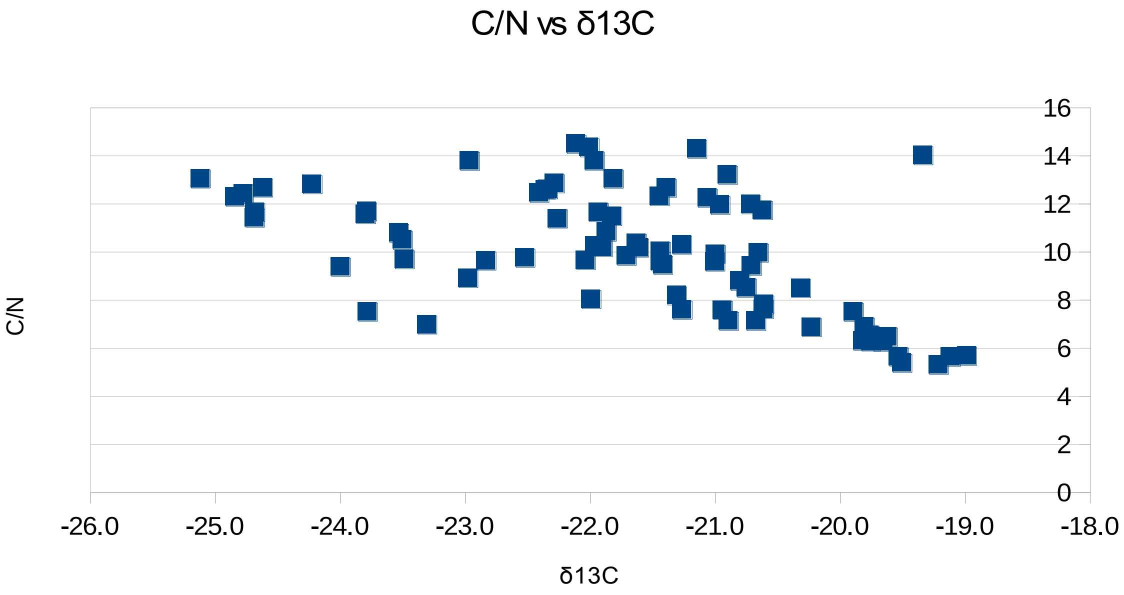

Figure 9: C/N vs $\delta^{13}C$. There is no compelling pattern to the data here, though there is an oddly trimodal shape to the cloud of points.

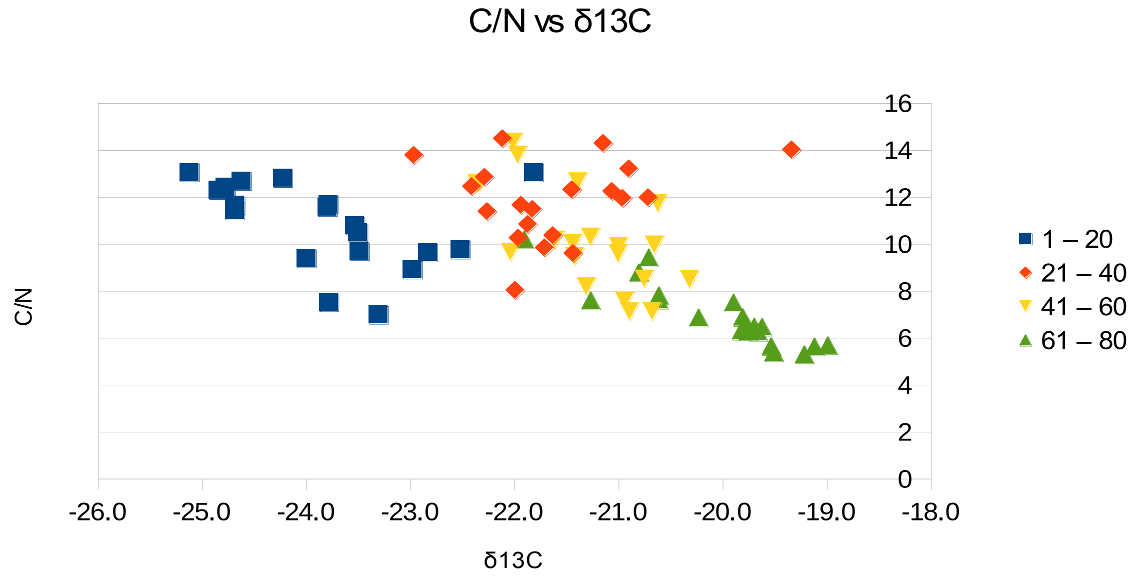

Figure 10: C/N vs $\delta^{13}C$ with data points broken up into groups according to age/depth of sample. Though there is a great deal of mixing in the middle in the sample number 21 - 60 / 1,200 – 4,201 years BP range, there is a pronounced movement from low to high and dry to wet as samples get closer to the surface of the core and present day.

Yet again, the trend seems to be moving from dryer conditions to wetter with a plateau of sorts in between the two extremes. Also of interest is the fact that the outlier of the 21 to 40 group, the red diamond that sits at about (-19.3, 14), corresponds to sample 24, which has an age of 1,380 calendar years before present. Once more, the data suggests that there was a brief, significantly dryer period approximately 1400 years ago.

Discussion

The primary force behind the changes in Gran Chaco climate and hydrology recorded in the sediment of Lago Opabusu lies in the Earth's orbital cycles, particularly that of precession. This 20,000 year cycle that heavily impacts the amount of insolation in the South American tropics exists on a scale that is too large to see in the record derived from OPB1 and 2. However, the 5,500 years it does manage to capture correspond well with the upswing in moisture and precipitation that is expected to accompany the increase in insolation that began approximately 10,000 years ago. This visible portion of the hydrologic response to precessionally forced changes in insolation also correlates well with other paleolimnological records from the Altiplano[20] and speleothem records from the Brazilian Amazon[21] that are long enough to capture one or more complete precessional cycles.

The disagreement between the $CaCO_3$ record and the other proxies studied in conjunction with Lago Opabusu is puzzling. Though the standards used for the atomic absorption registered in the expected and logical pattern, the fact remains that the $CaCO_3$ signal - when interpreted in the traditional fashion – contradicts the records provided by $\delta^{13}C$, $\delta^{15}N$, and C/N. For the bulk of the record there are “wet”, low numbers for $CaCO_3$ coinciding with light, “dry” number for $\delta^{13}C$. However, it is possible to reconcile these signals if, rather than taking the long held smaller (larger) indicates wetter (dryer) stance, one considers the possibility that periods of increased precipitation and a greater

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[20] Baker, P.A. et al. 2009. Baker, P.A. et al. 2001a. Baker et al. 2001b. Fritz, S.C. et al. 2007. Rowe, H.D. et al. 2002.

[21] Cruz Jr., F.W. et al. 2007. Cruz Jr., F.W. et al. 2005.

volume of water moving through the watershed might actually wash more $CaCO_3$ into the lake. If that is the case, then there is much better correlation between the $CaCO_3$ signal and the others under consideration. Such an inverted view does create considerable discord over the dry event that is consistently appearing around 1400 years BP, but it does provide for a better fit overall.

The C/N ratios, particularly as they relate to $\delta^{13}C$ in the Lago Opabusu sediments are particularly interesting for what they potentially imply about the changes in the vegetative cover and overall ecology of the watershed attached to the lake. Figure 10, as noted earlier, suggests not only a move from dryer to wetter over time, but also a transition from a lake system that received the bulk of its vegetative material from algae and phytoplankton to one that was surrounded by and/or supporting more complex plants. Burbridge et al have done work in the Bolivian Amazon, to the north and east of Lago Opabusu, using pollen assemblages to study the vegetative and climate history of the region. They found that savanna and seasonally dry deciduous forest dominated the region from at least 50,000 years BP up until the mid-Holocene, when evergreen and humid evergreen forests began to expand into the area. Burbridge's team attributes these changes largely to the same increase in insolation that is likely driving the move to wetter conditions visible in the Opabusu cores[22]. If such a dramatic change in vegetation has been observed just to the northeast of Lago Opabusu, it is arguable that a similar shift occurred at Opabusu and that is what we are seeing in the C/N record. Incorporating palynology and isotopic analysis of $\delta^{18}O$ into further study of the OPB core would undoubtedly provide keener insight into this issue, and perhaps some resolution with regard the the $CaCO_3$ record.

One thing that is not as visible in the OPB record, potentially because of the resolution at which it was studied, is changes that occur on a smaller than decadal scale. There is very little sensitivity in this study to things such as El Niño and short term droughts, like the one in 2005, that are caused by changes in north/south sea surface temperature (SST) gradient when the North Tropical Atlantic

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[22] Burbridge, R.E. et al. 2004.

experiences greater than average warming. Such changes in temperature have an odd impact on the Intertropical Convergence Zone (ITCZ) in that they displace it (assuming a warming in the North Tropical Atlantic) to the north, which has a strong negative effect on the South American Summer Monsoon[23]. This is of concern not only because the resulting droughts can be devastating, but because unlike the orbital cycles that feature prominently in the paleoclimate reconstruction that can be done from Lago Opabusu, we can affect these changes in SST.

The most recent IPCC report projects a likely rise in ocean temperatures of anywhere from 1 – 3° C in the next century[24]. The northern oceans are warming faster than the southern due to the uneven water to land ratios between the two hemispheres, so the odds of such drought causing shifts in the north/south SST gradient are only going to increase. In fact, the HadCM3LC climate model predicted the probability of the occurrence of another year like 2005 as 1 in 25 as of 2008, but that these odds would increase to 1 in 2 by 2025, and 9 in 10 by 2060[25]. If this modeled drying is accurate, it is likely that Lago Opabusu – already so precariously balanced between in and outflow – will eventually dry up completely.

It should be possible to use such statistics and such clear cause and effect to motivate people and governments to take action against anthropogenic climate change. Unfortunately, even if it were that easy, it's not that simple. Cox et al have determined that the removal of aerosol pollution, which improves air quality for everyone, actually will likely have a profound and negative effect on this north/south imbalance. As aerosol pollution is capable of actually increasing albedo, as the air gets cleaner, more solar radiation is actually reaching the surface of the Earth. And, since the Northern Hemisphere is home to far more of the developed/industrialized world than the Southern, much of this

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[23] Punyasena, S.W. et al. 2008.
[24] Solomon, S., D. et al. IPCC, 2007.
[25] Cox, P.M.et al. 2008.

clean air, increased radiation phenomenon is occurring in the north[26]. This will almost certainly further unbalance the SST gradient, leading not only to more frequent and severe drought in the South American tropics, but also conditions that are more conducive to stronger tropical cyclone activity in the north.

The paleoclimate record shows that such fluctuations are normal, but the frequency and strength with which they are now predicted to occur is not. However, perhaps continuing to pursue the research that allows us to make such distinctions will also lead to the point where something can and will be done about them.

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[26] Cox et al., 2008.

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