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LETTER TO THE EDITOR

Comment on "Antiphasing between Rainfall in Africa's Rift Valley and North America's Great Basin"

INTRODUCTION

Johnson *et al.* (1996) presented evidence that Lake Victoria was dry before 12,800 ^{14}C years ago. Broecker *et al.* (1998) concluded from water-balance calculations that the precipitation rate when the lake was dry must have been smaller than it is now by a factor of at least four. The apparent magnitude of the change in precipitation and its near simultaneity with other changes elsewhere on the globe were advanced in support of the hypothesis that the global climate system underwent an abrupt change at the time of the Bölling–Alleröd interstade, rather than a gradual, linear response to changes in orbital forcing.

Broecker *et al.* acknowledged clearly some shortcomings of their quantitative analysis of the relation between lake area and precipitation. Specifically, they noted that their analysis excluded two positive feedbacks of climatic drying and one possible accompanying forcing function that might oppose drying:

> Of course, with drier conditions, it might be expected that the evaporation rate over the lake would rise [the first positive feedback] and that the fraction of runoff from the land portion of the basin would fall [the second feedback]. However, to the extent the tropics cooled during the glacial time, evaporation rates would have been reduced [the additional forcing]. Unfortunately, there is no way to assess how large these changes would be.

Mechanisms of the first feedback were not specified by Broecker *et al.*, but two distinct processes are potentially significant. First, regional drying would reduce the evaporation from land, causing warming and drying of the atmosphere. This would tend to increase the gradient of vapor-pressure deficit from lake to atmosphere, thereby driving up lake evaporation, according to Penman's (1948) relation; herein, this will be termed the lake-evaporation feedback. Second, a regional increase in aridity could well cause changes in surface radiative balance, for example, through decreased cloud cover and resultant enhancement of surface solar radiation. This could oppose or even outweigh any direct, orbitally forced reduction in radiation (the tropical cooling during glacial time mentioned by Broecker *et al.*). The land-runoff feedback is associated with the reduction in soil-water storage that accompanies a reduction in precipitation; this permits an increase in the fraction of precipitation that can be absorbed by the land and, hence, a suppression of runoff. Here the calculations of Broecker *et al.* are generalized to assess the importance of the lake-evaporation and land-runoff feedbacks and to estimate the sensitivity of lake area to changes in radiation that might have been induced by regional cooling and/or aridification. The implication for the hypothesis of abrupt global climatic change is noted in the conclusion.

THEORY

Land-Runoff Feedback

A simple expression for the joint control of land water balance by water and energy supplies has been developed by Budyko (1974, pp 321–330) on the basis of dimensional analysis and various empirical studies. The fraction of annual mean land precipitation P that evaporates E is given as a function of the ratio of annual surface net radiation (R, expressed here as equivalent evaporation rate) to annual precipitation,

$$\frac{E}{P} = \phi\left(\frac{R}{P}\right). \tag{1}$$

The function $\phi(x)$ is given by

$$\phi(x) = [x \tanh(x^{-1})(1 - e^{-x})]^{1/2}. \tag{2}$$

For small x, representing humid climate, the evaporation fraction ϕ is asymptotic to x, and for large x, or arid climate, it approaches 1 asymptotically. As P decreases, the index of aridity R/P increases, as does the evaporation ratio, E/P. Note that (1) and (2) also determine the runoff rate through the equation of land water balance

$$P = E + Y. \tag{3}$$

In contrast to (1) and (2), Broecker *et al.* assumed that ϕ remains constant at its estimated present-day value.

Lake-Evaporation Feedback

For the lake, variables P_w and E_w are defined by analogy to their land counterparts. It might be expected that the long-term lake radiation balance would differ from that of the land, due

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to differences in albedo and thermal state. It is not apparent, however, that such a difference would greatly affect the present analysis, and it will be ignored here.

A very small lake would be expected to lose water to evaporation at a rate greater than the rate R, because the air advects sensible heat, generated by dry land, over the lake, providing an additional source of energy, H, for evaporation; this is the "oasis effect." (Note that here the sign convention for H is positive into the lake, which is opposite the conventional definition of a surface heat flux. Additionally, R, H, and E_w are all expressed as fluxes per unit area.) Lake evaporation is then

$$E_w = R + H. \tag{4}$$

It is reasonable to expect that the importance of advection, as measured by H, will decrease as lake size increases. A very simple model of advection might specify that the total consumption of advected energy by evaporation from the lake (HA_w, in which A_w is lake area) is proportional to the linear length scale of the lake; clearly the amount of sensible heat advected over the upwind edge of the lake will be approximately proportional to the cross-wind width of the lake. It can also be expected that HA_w will increase with the size of the lake in the direction of the wind, but that this increase will be much less than linear in lake fetch (Brutsaert, 1982, Ch. 7; Garratt, 1992, Ch. 4). The advection term is also expected to be proportional to the deficit of land evaporation below the land radiation balance (Bouchet, 1963; Brutsaert, 1982). Accordingly,

$$HA_w = \alpha\lambda^{\beta}(R - E), \tag{5}$$

in which α and β are constants, and λ is a linear measure of lake size, taken here to be the square root of lake area. The exponent β ought to be in the range 1–1.5, on the basis of the foregoing discussion. When λ is expressed in terms of lake area, (5) becomes

$$H = \alpha A_w^{-\gamma/2}(R - E), \tag{6}$$

in which the exponent γ ($= 2 - \beta$) lies in the range 0.5–1. The coefficient α quantifies the overall magnitude of the advection effect. Lacking definitive lake data, we estimate the value of α from water-balance data for Tunisian oases (Oke, 1978, p. 143); the oases are taken collectively as an analogue for a lake in an arid climate. For a total oasis area A_w of 150 km^2, with negligible evaporation E in the surrounding environment, the ratio H/R has been estimated to be 0.36. Combination of these data with (4) and (6) yields

$$E_w = R + (0.36)\left(\frac{150\ \text{km}^2}{A_w}\right)^{\gamma/2}(R - E). \tag{7}$$

Just as land aridity may increase the tendency for evaporation from the lake, so the moistening and cooling of air masses over the lake would tend to suppress evaporation over land. However, given the relative areas of lake and land in the Lake Victoria basin, and the weak influence of the lake-evaporation feedback (discussed below), it does not appear necessary to consider the suppression of land evaporation by the presence of the lake.

Lake Water Balance

Following Broecker *et al.*, this analysis addresses only the equilibrium behavior of the closed-basin lake. The runoff from land balances the excess of lake-surface evaporation E_w over lake-surface precipitation P_w,

$$(P - E)(A - A_w) = (E_w - P_w)A_w, \tag{8}$$

where A is the combined area of the lake and its drainage basin. The lake area can then be expressed, using (1) and (8), as

$$\frac{A_w}{A} = \frac{[1 - \phi(R/P)]}{[1 - \phi(R/P)] - (P_w/P)(1 - E_w/P_w)}. \tag{9}$$

APPLICATION

Several numerical values used here are given in Table 1 of Broecker *et al.* (1998), which appears to be based upon the report by Kite (1982) of the annual water balance estimated for the 5-yr period 1970–1974. Thus, P_w = 1660 mm/yr and E_w = 1590 mm/yr; also, A is 263,000 km^2 and A_w is presently 69,000 km^2. From Kite (1982) it is also known that runoff Y from land (per unit area of land) is 150 mm/yr. The system (1), (2), (3), and (7) can be solved to yield consistent values of P and R for any assumed value of the lake-evaporation exponent γ. For γ equal (0.5, 1), the associated values of P and R are (950, 970 mm/yr) and (1530, 1580 mm/yr). If, instead of (7), it is assumed that E_w equals R (no lake-evaporation feedback), then P = 980 mm/yr. These values for P are all considerably smaller than the estimated lake precipitation, but they appear to be consistent with the land observational record for the Lake Victoria basin (Korzun, 1974). The small spread of the estimates of R suggests that the lake-evaporation feedback is weak.

The lake area fraction is plotted in Figure 1 as a function of P_w using (1), (2), either (7) or $E_w = R$, and (9), with the ratio P/P_w held fixed at our estimate of its present-day value. The curve is highly insensitive to assumptions about the lake-evaporation feedback, whose influence is minimal. The corresponding curve from Broecker *et al.* (1998) is also shown; it may be retrieved in the present analysis by taking $P = P_w$ and

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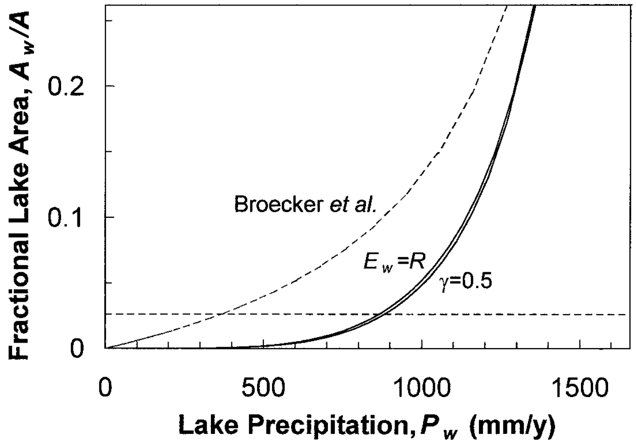

FIG. 1. Fractional lake area A_w/A as function of lake precipitation P_w. Solid curves are calculated using $\gamma = 0.5$ in (7) and using $E_w = R$ in place of (7); curve for $\gamma = 1$ lies between these and is not plotted. The dashed curve is that of Broecker *et al.* (1998). Maximum graph values of fractional lake area (0.262) and lake precipitation (1660 mm/yr) are estimated present-day values. The horizontal dashed line represents lake area at 10% of present value.

$\phi = 0.91$, and using $E_w = R$ in place of (7). (The curve of Broecker *et al.* is actually independent of the assumed ratio of P_w to P when the value of ϕ is chosen consistently.) Broecker *et al.* chose an arbitrary criterion of $A_w/A = 0.1$ to define drying of the lake and found that this implied rainfall of about 400 mm/yr, or a reduction by more than a factor of four. Using the same criterion, the present analysis implies rainfall of about 860 mm/yr, just under a twofold reduction. The difference between the two analyses is even more striking if a more stringent criterion for loss of the lake is used. Reduction of lake area to 1 and 0.1% of its maximum area results from precipitation of about 500 and 300 mm/yr in the present analysis, but would require rainfalls as small as about 40 and 4 mm/yr in the analysis of Broecker *et al.* The difference between these results obtained here and those of Broecker *et al.* is almost entirely attributable to consideration of the land-runoff feedback.

ADDITIONAL CONSIDERATIONS

A factor not yet considered is the possible difference between present-day and glacial-period surface radiation balance of the Lake Victoria region. As already noted, surface net radiation may have been either higher or lower than it is now when the lake was dry; cooling would have suppressed energy availability, while aridification may have enhanced solar radiation at the surface. We cannot evaluate which of these factors prevailed around Lake Victoria prior to deglaciation, but can only acknowledge that they may have been significant and may have been of either sign. Figure 2 illustrates the sensitivity of lake area to the value of R. If a 10% increase in R accompanied a glacial-period reduction in precipitation, then P_w would need to decrease only to 950 mm/yr to bring the lake to 10% of its present area. Conversely, if R is decreased by 10%, then P_w would need to drop to 780 mm/yr. The percentage reduction of P_w for these two cases would be 43 and 53%, respectively.

The present analysis has also ignored any change in the ratio P_w/P as lake size changes. This would be realistic if the amplification of lake precipitation were caused by some physical factor (e.g., topography) other than the presence of the lake. As an alternative to the constant-ratio assumption, one can assume that the ratio varies linearly with the lake horizontal scale, having a value of 1 for a vanishingly small lake and increasing as the square root of lake area to its present value when the lake is at its maximum size. The results for this case (not shown here) reveal that the relation between land precipitation and lake area is only weakly affected by the inclusion of a scale dependence of lake/land precipitation ratio; the effect of its inclusion is to steepen the $A_w(P)$ function.

The theory and its application here ignore any changes in seasonality of climate. There is no obvious benefit to pursuing the issue further in this direction; with increasing numbers of degrees of freedom, the problem becomes proportionately unconstrained. It may be noted, however, that the theory presented by Milly (1994) provides a framework for generalizing (1) and (2) for changing seasonality of climate.

CONCLUSION

According to this assessment, the lake-evaporation feedback has little effect on the conclusions of Broecker *et al.*, but the effect of the land-runoff feedback is substantial. Instead of the fourfold reduction in precipitation suggested by Broecker *et al.*, only a halving is needed to to dry the lake to 10% of its present area. Furthermore, consideration of the land-runoff feedback suggests that it is far easier to remove the remaining

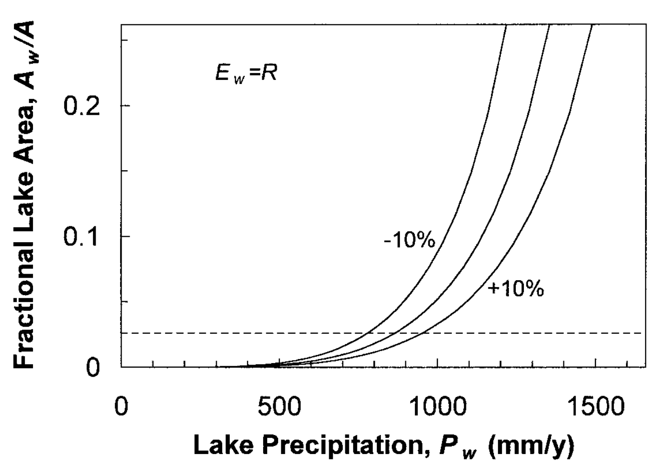

FIG. 2. Fractional lake area A_w/A as function of lake precipitation P_w, for various values of surface net radiation, R. Calculations were performed using $E_w = R$ in place of (7). The central curve uses $R = 1590$ mm/yr, while other curves use values of R 10% lower or higher than this value. Maximum graph values and horizontal dashed line are as in Figure 1.

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10% of lake area than implied by the model of Broecker *et al.* It can also be seen that changes in radiation add significant uncertainty to the calculations; a small fractional change in surface net radiation (potentially of either sign) has a non-negligible effect on the size of the reduction in precipitation that is needed to reduce lake area by 90%.

Overall, the present analysis suggests a higher sensitivity of lake area to precipitation than previously recognized. While a halving of precipitation indeed represents an "enormous change in climate," such a change is considerably smaller than the glacial–interglacial change estimated by Broecker *et al.* Arguably, this modified interpretation of the paleohydrologic record is still consistent with the abrupt global change hypothesis; in particular, the timing of lake refilling has not been questioned, and the estimated change in precipitation is still large. However, the reduced magnitude of the precipitation change presumably makes it easier to explain the drying of Lake Victoria in terms of orbital forcing, without the need to invoke an abrupt shift in global climate.

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