A NEW CONCEPTUAL MODEL FOR PREDICTING ISOTOPIC ENRICHMENT OF LAKES IN SEASONAL CLIMATES

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Steady-state isotope balance models have often been applied to estimate long-term average water balance conditions for lakes (Dincer, 1968; Gat 1995). Such studies have commonly employed values for the kinetic isotope fractionations for oxygen and hydrogen determined from wind tunnel experiments (e.g. Vogt, 1976; see also Gonfiantini 1986) and have assumed isotopic equilibrium between atmospheric moisture and precipitation (Rozanski et al. 2001; Gibson et al. 1993). In climates with a pronounced seasonality in evaporation rates, especially in environments where ice cover is present, such models have frequently predicted evaporative enrichment slopes that differ from observations (commonly lower than observed), and have therefore resulted in poor agreement between oxygen-18 and deuterium estimates, or have required use (or fitting) of kinetic fractionation factors that are not in agreement with the experimental studies (Zuber 1983; Gibson et al. 1993).

A program of field investigations conducted at a variety of sites in northern Canada over the past decade has focused on development and application of quantitative isotope mass balance methods for water resources assessment in seasonal climates (see Gibson et al. 1994). These studies have included detailed comparisons of weekly to monthly evaporation in small, well instrumented lakes using non-steady isotope balance methods (Gibson et al., 1996a&b; Gibson et al., 1998; Gibson, in press), regional comparisons of long-term water balance in Boreal and Arctic lakes (Gibson, 2001; Gibson et al., 2002; Gibson and Edwards, in press), and application of evaporation pans and cryogenic vapour sampling to characterize isotopic composition of atmospheric moisture near the ground (Gibson et al. 1999). Overall, these studies have shown that application of isotope mass balance using pan-derived atmospheric moisture and laboratory values for kinetic exchange parameters yields consistent results for short time periods as compared to conventional water balance where evaporation is determined using Bowen ratio and aerodynamic profiling methods. Local and regional sampling surveys have also revealed a pronounced latitudinal steepening of the slope of local evaporation lines from about 5 to 7 in $\delta^2H$-$\delta^{18}O$ space over the latitude range of 50 to 71°N.

A recent sensitivity analysis was conducted to investigate possible seasonality effects on the slope of the local evaporation lines that would explain the steeper slopes at higher latitudes, and the general lack of agreement between predicted evaporation slopes using the previously applied models. The analysis began by fitting atmospheric moisture ($\delta_A$) so that predicted values of lake water ($\delta_L$) were constrained to fall on the local evaporation line. Notably, the resulting values of $\delta_A$ were also found to be very close to the values expected if weighted according to the evaporation flux, i.e. when $\delta_A$ is assumed in equilibrium with $\delta_P$ but systematically filtered to account for the seasonality of the evaporation flux. Because the local evaporation line is a product of long-term evaporation on multiple lakes with differential throughflow, the use of flux-weighted parameters is apparently a more reasonable assumption than using mean annual values. Operational use of this refined approach has also been found to significantly improve the consistency of the water balance estimates predicted by each tracer, while maintaining the experimental values for the kinetic fractionations for both oxygen and hydrogen.

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Figure 1. Conceptual models showing isotope composition of major water balance components relative to the meteoric water line (MWL) and local evaporation line (LEL) in δ²H-δ¹⁸O space: (a) original model assuming isotopic equilibrium between atmospheric moisture and precipitation (e.g. Gibson et al. 1993). Predicted slopes fall close to 4 and require fitting of the isotope exchange parameters to obtain good agreement between tracers; (b) refined model assuming equilibrium between flux-weighted precipitation and atmospheric moisture. Predicted slopes are close to the observed LEL and do not require fitting of exchange parameters.

δ values denote isotope values where δ_p is precipitation, δ_A is atmospheric moisture, δ_e is evaporating moisture, and δ_L are various lakewaters. C_K² is the kinetic fractionation constant for deuterium, α*(T) and ε*(T) are the equilibrium fractionation and separation factors, respectively for each isotope species, and T is ambient temperature. Superscript “annual” and “evap. fw” denote mean annual and evaporation flux-weighted values.

A comparison between the original and revised conceptual model is shown in Figure 1. While the use of evaporation flux-weighting for δ_A-δ_p separation remains to be rigorously tested, the new conceptual model is capable of simulating the observed steepening of the local evaporation lines at higher latitudes and uses a consistent set of exchange parameters as verified in the shorter term field experiments. Lower slopes predicted by the original
conceptual model are evidently due to improper (or lack of) weighting for the $\delta_A-\delta_P$ separation, which does not account for the fact that evaporation and isotope exchange does not occur during periods of ice cover or that the process is seasonally variable. An interesting point that is particularly relevant to paleoclimate studies is that temporal changes in seasonality may have altered the slope of the local evaporation in the past. Application of dual oxygen-18 and deuterium tracers to lake sediment archives may therefore be able to trace changes in paleoslope of the evaporation line and provide a basis for examining past seasonality signals. For modern water balance applications, the use of non-weighted atmospheric moisture values, and standard exchange parameters can result in substantial errors in computed long-term values for evaporation to inflow ratios, particularly for strongly seasonal climates where errors may be as high as 50% for low throughflow, high evaporation lakes. One other implication is that slope of local evaporation lines are expected to vary globally with lower values near the equator and higher values at high latitudes and altitudes, which may be rigorously tested by spatial surveys of stable isotopes in lakewater.

REFERENCES


