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Evaporation and transport of water isotopologues from Greenland lakes: The lake size effect

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ABSTRACT

Isotopic compositions of evaporative flux from a lake are used in many hydrological and paleoclimate studies that help constrain the water budget of a lake and/or to infer changes in climate conditions. The isotopic fluxes of evaporation from a water surface are typically computed using a zero dimensional (0-D) model originally conceptualized by Craig and Gordon (1965). Such models generally have laminar and turbulent layers, assume a steady state condition, and neglect horizontal variations. In particular, the effect of advection on isotopic variations is not considered. While this classical treatment can be used for some sections of large open surface water bodies, such as an ocean or a large lake, it may not apply to relatively small water bodies where limited fetch does not allow full equilibration between air from land and the water surface. Both horizontal and vertical gradients in water vapor concentration and isotopic ratios may develop over a lake. These gradients, in turn, affect the evaporative fluxes of water vapor and its isotopic ratios, which is not adequately predicted by a 0-D model.

We observed, for the first time, the vertical as well as horizontal components of vapor and isotopic gradients as relatively dry and isotopically depleted air advected over the surfaces of several lakes up to a 5 km fetch under winds of 1–5 m/s in Kangerlussuaq, Greenland. We modeled the vapor and isotopic distribution in air above the lake using a steady state 2-D model, in which vertical diffusive transport balances horizontal advection. The model was verified by our observations, and then used to calculate evaporative fluxes of vapor and its isotopic ratios. In the special case of zero wind speed, the model reduces to 1-D. Results from this 1-D model are compared with those from the 2-D model to assess the discrepancy in isotopic fluxes between advection and no advection conditions.

Since wind advection above a lake alters the concentrations, gradients, and evaporative fluxes of water isotopes, it alters the water balance and isotope ratios of the lake and the relationship between them. These effects are greatest for small lakes. If wind advection is neglected in the inference of water balance from lake isotopes, an error is thus introduced, the magnitude of which depends on lake size. We refer to this as the “lake size effect”. For lakes less than 500 m in length along the wind direction, the average $\delta^{18}O$ and δD of vapor flux are at least 2‰ lower than the corresponding flux values from the 1-D model. The magnitude of the resulting relative error in water balance calculations is much greater if using $\delta^{18}O$ than δD in mass balance calculations; the former is about eight times the latter. This result argues that water balance calculated with δD is less sensitive to the difference in lake size and/or its change over time.

The 1-D model result is also compared with that from a comparable 0-D model. Since vertical vapor and isotope gradients always exist (even under no advection conditions), one may not obtain correct flux values if the relative humidity and isotopic ratios in ambient air measured at an arbitrary height are used for the 0-D model calculation. Typically, the standard meteorological measurements at 2 or 10 m would result in an underestimate of the $\delta^{18}O$ and δD values of the vapor flux.

This work has provided the first quantification on the effect of advection on isotopic fluxes of evaporation. The method of mobile vapor analysis combined with 2-D modeling can be applied to other

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environmental settings, in which the size of advection effect on isotopic fluxes depends upon relationships among local meteorological and hydrological variables. Our results also suggest that incorporating isotopic vapor measurements can help constrain modeled evaporation rates, which is worth exploring further in future studies.

1. Introduction

Evaporation is a vital component of the hydrological cycle, and constraints on fluxes of vapor, heat and isotopologues associated with evaporation are important for the quantification of many processes related to the global water cycle, regional water balance, and interpretation of paleo-isotopic records. In Arctic regions, where lakes may cover as much as 30% of terrestrial surface areas (Walter et al., 2006), lake evaporation represents a significant fraction of surface water flux. Knowledge of this flux under Arctic conditions is thus important to understanding the hydrological response under rapidly changing climate in the polar environment (Zhang et al., 2011; Bourassa et al., 2013). Changes in water balance are also inferred from paleo-lake records, which reflect changes of climate variables, such as precipitation and evaporation. Quantifying evaporative fluxes is thus a critical part of paleoclimate studies that are based on lake sediment records. This study focuses on evaporation of Arctic lakes.

Stable isotopic methods have been widely used to study lake evaporation or to quantify water balance in which lake evaporation represents an important flux (e.g., Gonflantini, 1986; Gibson et al., 2002; Gat et al., 1994). Understanding lake evaporation is also important for interpreting isotopic records from lake sediments that record isotopic compositions of lake water as an important environmental indicator (Sauer et al., 2001a; Sauer et al., 2001b; Zhang and Sachs, 2007; Jones and Imbers, 2010; Steinman and Abbott, 2013). One important variable that controls evaporative isotopic fluxes is the water vapor isotopic composition above an evaporative surface (Craig and Gordon, 1965). This measurement has not been easy until recent developments in spectrum based laser technology (e.g., Gupta et al., 2009). Our project takes advantage of this new technology's ability for rapid data acquisition and mobile deployment.

In most previous studies, the evaporative isotopic enrichment of lake water is typically quantified by a zero dimensional (0-D) steady state model (e.g., Gibson et al., 1993; Yi et al., 2008; Turner et al., 2014). Craig and Gordon (1965) first incorporated isotopic tracers into such a model, in which evaporative fluxes are assumed proportional to the water vapor and isotopic ratio gradients. Near the water surface within the so-called laminar layer where molecular diffusion is important for vapor transport, the proportionality coefficient, i.e., the diffusivity, differs among different water isotopologues. Above the laminar layer, vapor transport is dominated by turbulent mixing without isotopic fractionation. The model has been widely adopted to quantify isotopic compositions of vapor and/or water in atmosphere, lakes, soil, and plant leaves (see the review by Horita et al., 2008). In using the model, it is assumed that no horizontal vapor gradient exists, so winds have no advective effects on vapor distribution.

The no advection assumption is often unrealistic for lakes of limited sizes or other liquid surfaces with limited fetches (e.g., sea ice leads). The presence of advecting air from land and moisture buildup downwind over a lake has been recognized even on rather large water bodies hundreds of kilometers off shore (e.g., Benson and White, 1994; Gat et al., 2003). In such cases, wind blowing over the lake picks up moisture from the lake, and as the air advects over the lake towards the downwind shore humidity increases. The moisture content in the air above the lake may exhibit a distribution similar to that illustrated in Fig. 1. At a given location on the lake, the moisture content decreases with height, because evaporation occurs at the surface. A horizontal vapor gradient develops as well, with humidity increasing with the distance from the upwind shore as a result of addition of vapor by evaporation (Machavaram and Krishnamurthy, 1995; Gat et al., 2003). In part because wind speed (advection rate) increases with height, the vertical gradient changes with the fetch. Similar to the vapor content, the isotopic composition of vapor in the atmosphere above the lake also has horizontal and vertical gradients. Under such conditions, the spatially averaged vapor and isotopic fluxes from the lake depend on lake size.

This project was designed to study the evaporation process for Arctic lakes under conditions shown in Fig. 1, where a full quantification of evaporative fluxes requires measurements and modeling in two dimensions. The objectives of this study are to 1) develop a method for measuring horizontal and vertical distributions of the concentration and isotopic ratios of water vapor over lakes, 2) create a physically-based model to explain observed vapor and isotopic distributions, 3) quantify and compare our modeled evaporative fluxes under advection vs. no advection conditions, and compare the latter results with those of a conventional Craig and

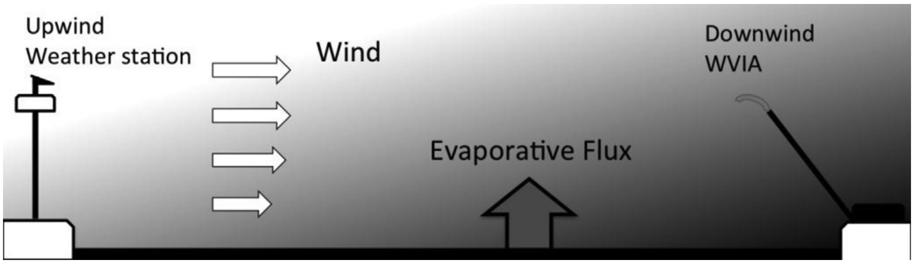

Fig. 1. Hypothetical vapor concentration distribution above a lake near the upwind shore. Both vertical and horizontal gradients develop (darker shades representing higher vapor concentrations), due to evaporation from the surface and advection of air over the lake by winds that increase in speed with height. The sketch also illustrates one example of our equipment deployment, where the weather station is installed at the upwind shore and vapor measurements using a water vapor isotope analyzer (WVIA) are taken at the downwind (as well as the upwind) shore.

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