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Journal of Hydrology 308 (2005) 168–195
Journal of Hydrology
www.elsevier.com/locate/jhydrol

Effects of climate variability on lake evaporation: Results from a long-term energy budget study of Sparkling Lake, northern Wisconsin (USA)

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Received 7 October 2003; revised 20 September 2004; accepted 29 October 2004

Abstract

Variations in lake evaporation have a significant impact on the energy and water budgets of lakes. Understanding these variations and the role of climate is important for water resource management as well as predicting future changes in lake hydrology as a result of climate change. This study presents a comprehensive, 10-year analysis of seasonal, intraseasonal, and interannual variations in lake evaporation for Sparkling Lake in northern Wisconsin (USA). Meteorological and lake temperature measurements are made at a raft on the lake and are supplemented by radiation measurements from a nearby airport. The data are analyzed over 14-day periods from 1989 to 1998 (during the ice-free season) to provide bi-weekly energy budget estimates of evaporation rate (along with uncertainty estimates). The mean evaporation rate for Sparkling Lake over the study period is 3.1 mm day^{-1}, with a coefficient of variation of 25%. Considerable variability in evaporation rates is found on a wide range of timescales, with seasonal changes having the highest coefficient of variation (18%), followed by the intraseasonal (15%) and interannual timescales (12%; for summer means). Intraseasonal changes in evaporation are primarily associated with synoptic weather variations, with high evaporation events tending to occur during incursions of cold, dry air (due, in part, to the thermal lag between air and lake temperatures). Seasonal variations in evaporation are largely driven by temperature and net radiation, but are out-of-phase with changes in wind speed. This presents challenges when calculating evaporation rates by means of the simpler mass-transfer technique. On interannual timescales, changes in summer evaporation rates are strongly associated with changes in net radiation and show only moderate connections to variations in temperature or humidity. Nonetheless, we are able to identify a simple, empirical relationship for estimating interannual evaporation rates that is more accurate than the mass transfer technique.

Keywords: Evaporation; Lake; Energy budget; Climate; Water balance

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doi:10.1016/j.jhydrol.2004.10.028

1. Introduction

1.1. Background

Lakes and reservoirs provide a valuable water resource that is important for irrigation, fishing and recreation, drinking water, aquatic ecosystems, transportation and commerce, and hydropower. The availability and quality of freshwater is, in turn, closely tied to variations in climate as well as direct human influences (e.g. Schindler, 2001). One of the most significant and broadly impacting effects of climate variability on lakes is changes in water level. Such changes reflect an alteration of the lake water balance, which can result from changes in: (1) precipitation over the lake and surrounding watershed, (2) land surface evapotranspiration and snowmelt (and associated surface runoff and/or groundwater flow), and/or (3) direct evaporation from the lake surface. It is crucial for water resource management, therefore, that the effects of climate variability on each of these hydrologic processes be well understood. Lake evaporation is somewhat unique in the sense that it is influenced not only by climate, but also by characteristics of the lake itself (e.g. depth, area, color/clarity, etc.). Furthermore, evaporation plays an important role not only in the water budget of a lake, but also in the energy budget. This introduces additional complexity through changes in water temperature and vertical mixing; effects which actually feedback onto evaporation itself. Even measuring evaporation accurately (within 10%) is a difficult task without significant investment in instrumentation and data processing (Winter et al., 2003; Winter, 1981). These practical and theoretical considerations impose significant challenges for lake evaporation studies (both observational and modeling), especially when considering long time periods and/or large lakes or regions (with varying climatic and lake characteristics). Despite these challenges, it is critical that accurate, long-term studies of lake evaporation be maintained in order to better understand variations in evaporation as well as the role of climate and potential impacts of climate change.

Observational studies of lake evaporation have used a variety of different methods to measure evaporation rates. These include the mass transfer, water balance, eddy correlation, and energy budget methods, as well as others (Winter, 1981; Winter et al., 1995). The mass transfer method has been used in numerous studies (e.g. Yu and Knapp, 1985; Ikebuchi et al., 1988; Laird and Kristovich, 2002) as a result of its ease of application and suitability for modeling (e.g. Hostetler and Bartlein, 1990; Blodgett et al., 1997). Water balance studies, on the other hand (e.g. Myrup et al., 1979), can potentially provide a more reliable estimate of evaporation, so long as each water budget component is accurately measured (often a difficult task, especially for groundwater). In general, however, the energy budget and eddy correlation techniques are considered to be the most accurate methods, albeit at the cost of additional, high-quality instrumentation (Winter, 1981). Except for a recent study by Blanken et al. (2000), most applications of the eddy correlation technique have been confined to short-term studies (e.g. Sene et al., 1991; Stannard and Rosenberry, 1991), with the energy budget method being the preferred technique for accurate, long-term monitoring (e.g. Winter et al., 2003).

Despite this preference, the number of long-term (multi-year) energy budget studies of lake evaporation is rather limited (undoubtedly because of the labor and expense). Myrup et al. (1979) provide a review of some of the earlier studies of lake energy budgets, as well as their own 3-year analysis of the energy and water budgets of Lake Tahoe, California-Nevada (USA). A comprehensive, 10-year study of the energy budget of Perch Lake, Ontario (Canada) has been presented by Robertson and Barry (1985), while Sturrock et al. (1992) provide a 5-year analysis of energy budget evaporation rates for Williams Lake, Minnesota (USA). This latter study has also proven useful for evaluating alternative evaporation methods and instrumentation (Rosenberry et al., 1993; Winter et al., 1995). Sacks et al. (1994) present a brief (20-month), but interesting comparison of energy budget evaporation rates for two subtropical lakes of differing depth (in Florida, USA). dos Reis and Dias (1998) analyzed the energy budget of Lake Serra Azul (in southeastern Brazil) over a 2.5-year period and compared the evaporation results with estimates from the Complementary Relationship Lake Evaporation model (CRLE; Morton, 1983a,b, 1986). Vallet-Coulomb et al. (2001) performed a similar study of Lake Ziway (Ethiopia) over a 30-year period but made a number of simplifying assumptions in