AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE
10.1002/2017WR021977

Special Section:
Responses to Environmental Change in Aquatic Mountain Ecosystems

Key Points:
- Snowpack magnitude affects the relative timing of snowmelt and spring lake warming in a long-residence time, snowmelt-fed lake
- Reduced snowpack increases the proportion of annual inflow entering the lake prior to stratification and with near-neutral buoyancy
- A projected shift toward decreased snowpack may increase nearshore and near-surface mixing of inflow loads in snowmelt-fed lakes

Supporting Information:
- Supporting Information S1

Correspondence to:
D. C. Roberts,
dcroberts@ucdavis.edu

Citation:
Roberts, D. C., Forrest, A. L., Sahoo, G. B., Hook, S. J., & Schladow, S. G. (2018). Snowmelt timing as a determinant of lake inflow mixing. *Water Resources Research*, *54*. https://doi.org/10.1002/2017WR021977

Received 3 OCT 2017
Accepted 26 JAN 2018

Snowmelt Timing as a Determinant of Lake Inflow Mixing

D. C. Roberts[1,2], A. L. Forrest[1,2], G. B. Sahoo[1,2], S. J. Hook[3], and S. G. Schladow[1,2]

[1]Department of Civil & Environmental Engineering, University of California, Davis, CA, USA, [2]UC Davis Tahoe Environmental Research Center, Incline Village, NV, USA, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

Abstract Snowmelt is a significant source of carbon, nutrient, and sediment loads to many mountain lakes. The mixing conditions of snowmelt inflows, which are heavily dependent on the interplay between snowmelt and lake thermal regime, dictate the fate of these loads within lakes and their ultimate impact on lake ecosystems. We use five decades of data from Lake Tahoe, a 600 year residence-time lake where snowmelt has little influence on lake temperature, to characterize the snowmelt mixing response to a range of climate conditions. Using stream discharge and lake profile data (1968–2017), we find that the proportion of annual snowmelt entering the lake prior to the onset of stratification increases as annual snowpack decreases, ranging from about 50% in heavy-snow years to close to 90% in warm, dry years. Accordingly, in 8 recent years (2010–2017) where hourly inflow buoyancy and discharge could be quantified, we find that decreased snowpack similarly increases the proportion of annual snowmelt entering the lake at weak to positive buoyancy. These responses are due to the stronger effect of winter precipitation conditions on streamflow timing and temperature than on lake stratification, and point toward increased nearshore and near-surface mixing of inflows in low-snowpack years. The response of inflow mixing conditions to snowpack is apparent when isolating temperature effects on snowpack. Snowpack levels are decreasing due to warming temperatures during winter precipitation. Thus, our findings suggest that climate change may lead to increased deposition of inflow loads in the ecologically dynamic littoral zone of high-residence time, snowmelt-fed lakes.

Plain Language Summary Winter climate conditions can affect both the timing of snowmelt and the timing of spring lake warming. Relative stream-lake temperature is an important control on how inflow plumes mix through lakes, distributing nutrients, carbon, and sediment relevant to lake ecosystems and water quality. This study examines how snow conditions have affected relative stream-lake temperature, and thus inflow mixing conditions, over the past 50 years at Lake Tahoe. Years of lower snowpack are found to favor nearshore and near-surface mixing of snowmelt inflows. Given trends toward reduced snowpack due to a warming climate, this result may indicative of future conditions in large, snowmelt-fed lakes.

1. Introduction

Spring snowmelt is a major component of the inflows that transport terrestrial carbon, nutrients, and sediments into many lakes. The thermal stratification of receiving lakes and their temperature relative to the temperature of inflowing snowmelt controls the mixing and fate of transported particulates and solutes (Alavian et al., 1992; Rueda et al., 2007; Spigel et al., 2005). Annual snowpack is decreasing across western North America (Fyfe et al., 2017), causing a shift toward earlier snowmelt (Barnett et al., 2005; Stewart, 2013; Stewart et al., 2004). The same climate patterns affecting snowpack are also expected to affect lake thermal regime (Sahoo et al., 2013, 2016; Sahoo & Schladow, 2008). In shorter residence-time lakes, snowmelt inflows can be a major driver of the lake thermal regime (e.g., Cortés et al., 2017). However, in long-residence-time lakes, where inflows annually replace only a small fraction of the lake volume, lake thermal regime is largely unaffected by inflows; the onset of stratification and snowmelt timing are independently driven through regional meteorological patterns. In such lakes, understanding how changing climate patterns will separately affect lake temperature and stream characteristics is important to understanding the effect of climate change on the delivery of stream constituents that affect nutrient, carbon, and suspended sediment concentrations in the lake.

Both inflow timing and lake thermal dynamics have been affected by climate change at Lake Tahoe, a very long-residence-time lake in the Sierra Nevada Mountains, USA. The length of the stratified season has increased by 24 days since 1968, with the onset of stratification advancing by 5 days between 1968 and 2015, and expected to advance an additional 16 days (about 2 day/decade) by the end of the century (Sahoo et al., 2016). Coats (2010) observed that peak snowmelt timing is shifting earlier at a faster rate, approximately 4 days/decade since the 1960s, than the shift in the timing of onset of stratification. Coats (2010) also found that the percentage of precipitation falling as snow is decreasing in the Tahoe basin. The change toward a more rain-dominated precipitation regime, causing a shift from spring to winter stream discharge, is expected to be most pronounced in hydrologic "transition zones," like the Tahoe basin, that are significantly affected by snowpack but where winter air temperatures average about 0°C (Njissen et al., 2001). This shift toward reduced snowpack and earlier peak streamflow is shown to be driven by warming air temperatures, rather than a reduction in precipitation, and is therefore likely to continue under projected climate scenarios in the Sierra Nevada (Hamlet et al., 2005; Kang et al., 2016; Pederson et al., 2011; Stewart et al., 2005).

As peak snowmelt shifts earlier relative to spring lake warming, a greater proportion of inflows would be expected to enter ambient lake waters of similarly cold temperatures. Low density differences between inflowing and ambient water would support high rates of near-field mixing as quantified by initial dilution (Alavian et al., 1992; Johnson et al., 1989). Reduced density differences would also lead to plume insertion closer to the surface. The latter effect could be compounded by positive buoyancy in late-spring and early summer inflows due to warmer stream temperatures associated with reduced snowpack (Ficklin et al., 2013). The insertion depth and post-insertion propagation of inflow plumes, herein referred to as far-field dynamics, is affected by lake stratification (Wells & Nadarajah, 2009). Under the expected timing shifts in snowmelt and lake stratification, plumes will be less vertically confined and will intrude at lower velocities (Imberger & Hamblin, 1982). The reduced inertial length scales associated with lower velocity plumes make the plumes susceptible to rotation closer to shore (Horner-Devine, 2009; Horner-Devine et al., 2006). In summary, as snowmelt shifts earlier relative to the onset of thermal stratification, we would expect thicker, slower-moving, and more rotationally influenced inflow plumes, as illustrated in Figures 1c/1d.

These conditions are expected to become more prevalent under a warmer climate and will affect the fate of inflow loads. Higher rates of near-field mixing would disperse inflow constituents through the ecologically dynamic littoral zone rather than allowing them to plunge into the pelagic zone with minimal dilution (Rueda et al., 2007). More near-surface insertion would potentially deposit a greater proportion of the nutrient load in the photic zone (Cortés et al., 2014). Slower-moving plumes would increase the proportion of suspended sediments deposited in the littoral zone (Scheu, 2016). Increased rotational influence could direct inflows and their constituents alongshore, rather than offshore, influencing littoral productivity as demonstrated in the coastal ocean by Kudela and Peterson (2009) and Kudela et al. (2010).

Here we explore the effect of a range of winter climate conditions on two factors known to influence inflow mixing. Long-term meteorological and stream discharge data (1968–2017) are used to quantify the effect of climate conditions on the timing of snowmelt relative to the onset of lake stratification. Shorter-term, higher-frequency stream and lake-littoral data are used to analyze the buoyancy conditions of inflows under a range of cold-to-warm and dry-to-wet conditions from 2010 to 2017. Serendipitously, this latter period encompassed a broad range of winter/spring climate scenarios, including years of average conditions, years of extreme drought, and near-record snowpack years. Our results confirm the hypothesis that inflow mixing conditions at Lake Tahoe are strongly affected by snowpack. The projected reduction in snowpack, due to a warming climate, favors higher rates of nearshore and near-surface mixing of inflows.

2. Methods

Snowmelt and lake stratification timings are calculated from long-term daily discharge data and lake temperature profile data from 1968 to 2017, and are compared to annual snowpack data. The response of inflow buoyancy conditions to snowpack is quantified by calculating a time series of inflow buoyancy using a combination of measured and modeled stream and littoral temperature data. This hourly buoyancy time series, along with hourly discharge data, allows for quantification of both the volume and proportion of annual discharge entering the lake above a buoyancy threshold. These annual values, calculated for the

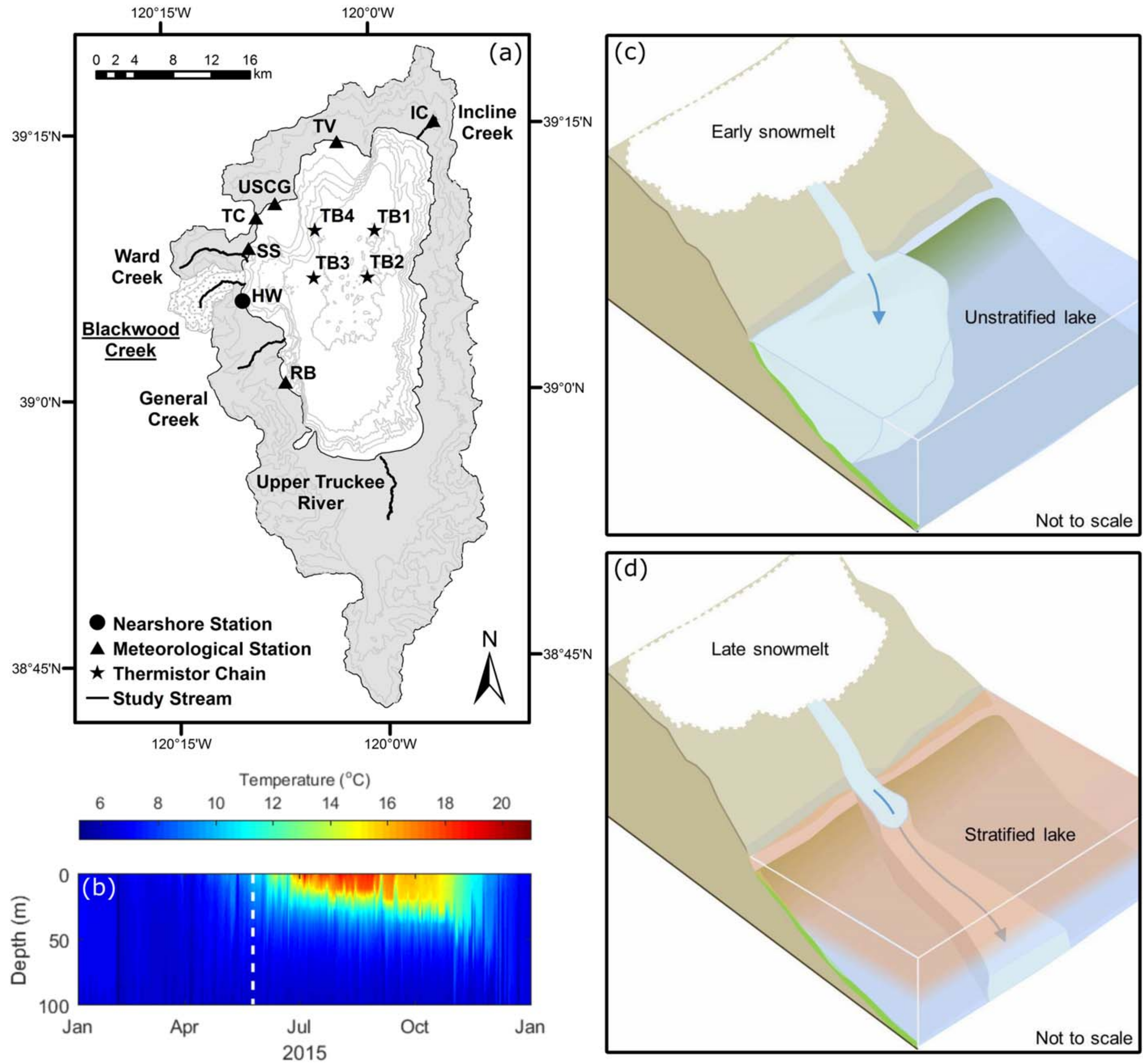

Figure 1. (a) Map of Lake Tahoe and its watershed. The lake is shown in white with 100 m depth contours. The watershed is shown in gray with 250 m elevation contours referenced to lake surface elevation of 1,897 m. The watershed for the representative stream, Blackwood Creek (underlined), is shown as a speckled region. Other streams indicated were used as part of this study. Data collection station names are: RB—Rubicon; HW—Homewood; SS—Sunnyside; TC—Tahoe City NCEI; USCG—United States Coast Guard Station; TV—Tahoe Vista; IC—Incline Creek; TBx—NASA JPL Tahoe Buoys. (b) Example of the annual cycle of thermal stratification over the upper 100 m of the water column; dashed line at 25 May, 2015 shows the day of onset of stratification as defined by Sahoo et al. (2016). (c) Schematic of inflow mixing conditions favored by pre-stratification snowmelt—high rates of initial dilution; thick, less-confined surface plumes that are influenced by rotation nearshore. (d) Schematic of inflow mixing conditions favored by postonset of stratification snowmelt—less initial dilution; thinner, more confined, plunging plumes that are influenced by rotation farther from shore.

period for which measurement occurred or modeling was possible (2010–2017), are then compared to annual winter climate conditions.

2.1. Study Site and Period

Lake Tahoe is perched in the Sierra Nevada Mountains (surface elevation about 1,897 m) on the border of California and Nevada, USA (Figure 1a). The lake is deep (maximum depth of 501 m; average depth of

305 m) and voluminous (approximately 156 km^3). Owing to a comparatively small watershed (800 km^2), the mean residence time of Lake Tahoe is extremely long, estimated at 600–700 years. This partially accounts for the lake's famed clarity (average annual Secchi depth greater than 20 m). The extremely low inflow-to-lake volume ratio implies that inflows have a minimal effect on the energy balance of the lake. Instead, lake temperature and stratification are controlled predominantly by surface heat exchange. Lake Tahoe is monomictic, typically stratifying from late-May to late-December and mixing to several hundred meters in late-winter or early spring (Figure 1b). Due to its great depth and associated thermal inertia, Lake Tahoe does not freeze.

About 85% of Tahoe basin precipitation falls between November and April; summers (June–September) are dry and mild. At lake-level, the Tahoe basin averages 55 days per year with mean-daily temperature below-freezing. However, the watershed topography ascends to over 3,000 m, with colder temperatures and more snowfall at elevation. High-elevation snowpack drives a snowmelt-dominated inflow that typically starts increasing toward the end of February, peaks in May or June, and asymptotes toward base flow in July. Winter rain events are not uncommon; these rain-on-snow events often drive large spikes in stream discharge.

We use the annual period of 1 November to 1 August to bracket the time period in which streamflows are most affected by snow conditions. Annual climate conditions, lake stratification, and snowmelt timing values were calculated for 1968–2017. Inflow buoyancy conditions were quantified for 2010–2017.

2.2. Field Data Collection

2.2.1. Historical Stream Discharge, Lake Temperature, and Climate Data

Blackwood Creek, on the west shore of Lake Tahoe (Figure 1a), was chosen as a representative inflow for this system. It has the fifth largest watershed in the Tahoe basin and exhibits a strongly snowmelt-driven discharge signal. Discharge is above the annual mean between February and June, typically peaking at over 300% of the annual mean in May or June, and decreasing to 6% of annual mean in September. Eighty-eight percent of the 30.1 km^2 watershed is undeveloped (Tahoe Regional Planning Agency Open Data). The watershed elevation ranges from 1,897 to 2,687 m, with 51% of the land area at over 2,200 m elevation. The United States Geological Survey (USGS; www.waterdata.usgs.gov) has collected Blackwood Creek daily mean discharge data since 1960 (USGS 1033660). Gaps in the recent 2017 daily record were filled using mean-daily values from the hourly discharge record described below.

Water temperature profiles have been regularly collected at Lake Tahoe since 1968. Profiles are conducted to a depth of 150 m at the LTP index station (near TB3) every 7–10 days. From 1968 to 2005, data were collected at variable intervals using reversing thermometers. Since 2005, water temperature profiles have been measured using a Sea-Bird Instruments CTD, offering submeter resolution data.

The National Centers for Environmental Information (NCEI; National Oceanographic and Atmospheric Administration; https://www.ncdc.noaa.gov) have compiled daily precipitation and maximum and minimum temperature records near lake-level in Tahoe City, CA since 1903. Yearly maximum snow depth has been recorded since 1960 at Donner Summit, CA (elevation 2,100 m) by the UC Berkeley Central Sierra Snow Lab (CSSL). While Donner Summit does not lie within the Lake Tahoe basin, it is close to the basin rim and is positioned windward relative to the prevailing storm pattern. Annual maximum snow water equivalent (SWE), recorded at CSSL since 1980, correlates strongly with yearly maximum snow depth (supporting information Figure S4); we believe that the yearly maximum snow depth data provide a reliable representation of longer-term historical snow patterns for the Lake Tahoe basin.

2.2.2. Data for Inflow Buoyancy Calculations

Nearshore temperature data have been collected at the Homewood nearshore station (Figure 1) since September 2014. The nearshore station includes an RBR Maestro conductivity-temperature-depth (CTD) instrument and a Turner Designs C3 fluorometer mounted to a weighted frame at approximately 2 m depth. Thirty-second measurements of CTD and colored-dissolved organic matter fluorescence (fCDOM) are recorded by a dock-mounted Campbell Scientific CR1000 data-logger cabled to the instruments. Instrument position on the lakebed is periodically adjusted by UC Davis Tahoe Environmental Research Center (TERC) divers to maintain consistent depth with varying lake-level. Small data gaps (up to 3 h) were filled using linear interpolation. Data records are generally continuous except one long-term gap from 27 January to 3 May 2016.

Near-surface water temperature data were collected from four NASA/JPL midlake buoys beginning in October 2009 (TBx; Figure 1). Short thermistor chains measure temperature at 0.5, 1, 1.5, 2, 3, 4, 5, and 5.5 m below each buoy at two-minute intervals. The midlake water temperature record was constructed at a 1 h time step from the TB3 buoy data. Gaps were filled using the average between TB1, TB2, and TB4 temperature data at each depth. Remaining gaps up to 5 h were filled using linear interpolation. Eight remaining single-day gaps were filled using data from the following day, matching fill-data to the time-of-day of the gaps.

Fifteen-minute Blackwood Creek water temperature data were collected at USGS gauge 1033660 beginning on 20 January 2015 up through the end of the study period on 1 August 2017. Data time step was increased to 1 h, and gaps up to 5 h were filled using linear interpolation. Gaps longer than 5 h but shorter than 3 days were filled with data from days immediately post-gap, matching fill-data to the time-of-day of gaps. This process yielded a complete hourly stream temperature record for the period 20 January 2015 to 1 August 2017.

The USGS has recorded 15 min discharge data at Blackwood Creek since 1989, but discharge data from additional streams were needed to calibrate stream-to-stream relationships for filling gaps in the Blackwood Creek record. The data record for Blackwood Creek was reduced to a 1 h time step, and gaps up to 5 h were filled using linear interpolation. Larger gaps remaining in the discharge record for the study streams were filled using calibrated interstream discharge relationships (see supporting information Text and Figure S1).

In addition to stream discharge data, shortwave radiation (SW) and air temperature data were needed to calibrate, validate, and run a stream temperature model used for extending the hourly stream temperature record. Ten-minute SW data from TERC's United States Coast Guard meteorological station (USCG; Figure 1a) were used to populate the hourly record. Gaps were filled using data from the Incline Creek meteorological station (Figure 1a) maintained by the Desert Research Institute (DRI). Remaining gaps were filled using PAR data, collected on the TERC rooftop (near Incline Creek; Figure 1a) and converted to SW. The hourly air temperature data were from the USCG station. Gaps were filled with the average of the available data from three other west-shore meteorological stations maintained by TERC: Tahoe Vista, Sunnyside, and Rubicon (Figure 1a). Remaining gaps were filled with air temperature data from the DRI Incline Creek station.

2.3. Analysis of Historical Discharge, Lake Temperature, and Climate Data (1968–2017)

Data back to 1961 were used to quantify annual climate conditions and snowmelt timing, and data back to 1968 were used to calculate annual timing of onset of lake stratification.

To place each year in the context of climate conditions, annual metrics along cold-warm and dry-wet axes were calculated. We quantified the cold-warm axis using the temperatures at which precipitation fell rather than mean seasonal air temperatures. Using the long-term NCEI meteorological data, we calculated the proportion of precipitation that fell with mean-daily temperatures at or below 4°C and considered this to be snow. We use this above-freezing threshold because the majority of the basin is at higher elevation than the NCEI instruments and thus sees colder temperatures. Accordingly, this precipitation-as-snow (PAS) value, calculated for the 1 November to 1 August study period for each year from 1961 to 2017, correlates more strongly with snowpack data than PAS values calculated with a typical 0°C threshold (not shown). Years are classified along a dry-wet axis using the mean of the daily 1 November to 1 August discharge from the representative stream.

The timing of the center of mass of snowmelt inflows (center timing—CT) was calculated from Blackwood Creek daily discharge data following the method described in Stewart et al. (2004):

$$CT = \sum\nolimits_1^n (t_i q_i) \Big/ \sum\nolimits_1^n q_i \tag{1}$$

t_i is time and q_i is discharge at a given step i in the data. Yearly day-of-year of CT was calculated using daily discharge data between 1 November and 1 August. The data record yielded complete yearly CT timing values for Blackwood Creek from 1961 to 2017.

We use the simplified stability index (SI) to determine the annual timing of onset of stratification (Sahoo et al., 2016)

$$\mathrm{SI} = \sum\nolimits_{z_o}^{z_H} (z - \bar{z}) \rho_z \tag{2}$$

Here z_o is surface depth (zero), z_H is depth limit of the chosen section of water column, z is depth, $\bar{z}$ is the geometric centroid of the section of water column, and ρ_z is the density at depth z. Following Sahoo et al. (2016), we calculated the day-of-year of onset of stratification as the day on which SI becomes greater than 600 $\mathrm{kg/m^2}$ over the upper 100 m of the water column. An example thermal profile at SI $\sim$ 600 $\mathrm{kg/m^2}$ is shown at the dashed line in Figure 1b.

2.4. Calculation of Annual Inflow Buoyancy Metrics (2010–2017)

To better examine inflow mixing conditions under a range of climate conditions, annual buoyancy metrics had to be calculated for more years than were available in the nearshore and stream temperature data records. This section outlines the details of compiling and synthesizing nearshore temperature, stream temperature, and stream discharge data to complete the hourly 1 November 2009 to 1 August 2017 record needed for quantifying annual inflow buoyancy metrics over eight study seasons (2010–2017) representing a range of climate conditions.

Relationships between midlake temperatures and nearshore temperatures were used to reconstruct nearshore temperatures from 1 November 2009 up to the installation of the nearshore station in September 2014, and to fill larger gaps in the nearshore station record through 2017. The development of this empirical model is described in more detail in supporting material (supporting information Text and Figure S2). The nearshore-midlake (NS-ML) relationship was used to generate a complete hourly time series of nearshore temperature over the 2010–2017 study period. Where measured data were available (most of 2015–2017), they were used to replace the modeled data in the long-term record.

Meteorological and stream discharge and temperature data were used to train, test, and validate the empirical artificial neural-network stream temperature model developed for Tahoe basin streams by Sahoo et al. (2009). Discharge, air temperature, and SW data were used to force the model over the entire 1 November 2009 to 1 August 2017 period to populate a complete hourly time series of stream temperature for Blackwood Creek. Where measured data were available, most of 2015–2017, modeled data were replaced with measured data in the record. Additional details and validation of the model are shown in the supporting information Text and Figure S3.

Water density time series for streams and nearshore lake water were calculated as a function of temperature and conductivity using the TEOS-10 MATLAB package (IOC et al., 2010) which follows the Feistel (2008) approach. Long-term conductivity data normalized to 25°C show consistent specific conductivity (SpC) in the range of 90–100 $\mu\mathrm{S/cm}$ at the nearshore station. We therefore calculate nearshore water density as a function of variable temperature but constant SpC (90 $\mu\mathrm{S/cm}$). Since stream SpC is expected to vary with discharge, a discharge-SpC relationship was fit using using USGS Blackwood Creek SpC data recorded 1980–1983 (supporting information Figure S5), and the relationship was used to generate the time series of stream SpC used in inflow density (ρ_o) calculations. Ambient receiving water density (ρ_a) is assumed equal to density as calculated from the two-meter depth nearshore temperature measurements and estimates. Buoyancy is defined as the difference between nearshore and stream densities: $\Delta\rho = \rho_a - \rho_o$.

With continuous hourly time series of discharge and relative stream-nearshore density, we calculate both the volume-as-buoyant (VAB) and proportion-as-buoyant (PAB) of each year's 1 November to 1 August inflows entering the lake with weak to positive buoyancy:

$$VAB = \sum Q_i t_i \quad \text{where} \quad \Delta\rho_i \geq -0.1 \ \mathrm{kg/m^3} \tag{3}$$

$$PAB = VAB / \sum Q_i t_i \tag{4}$$

The inflow buoyancy value of -0.1 $\mathrm{kg/m^3}$, slightly negatively buoyant inflows, was chosen as a general threshold for dividing inflows that are likely to mix at or near the surface from those that are more likely to plunge or to insert at depth; we herein use the word "plunge" to describe any inflow that is at least 0.1 $\mathrm{kg/m^3}$ denser than the littoral waters. Cabbeling, the process whereby water on opposite sides of the temperature of maximum density mixes to form a dense, plunging flow (Carmack et al., 1979), introduces some uncertainty into this simplistic buoyancy analysis. When stream temperatures are below 3.9°C (approximate temperature of maximum density when SpC = 70 $\mu\mathrm{S/cm}$) and nearshore temperatures are warm enough for a maximum-density plume to classify as plunging ($\Delta\rho \leq -0.1$ $\mathrm{kg/m^3}$), our thresholding analysis could classify inflows as

10.1002/2017WR021977

"buoyant" when cabbeling might actually generate a plunging flow. The potential effect of cabbeling on the results of the buoyancy analysis is considered in the results and discussion.

3. Results

3.1. Climate, Stream, and Lake Stratification Conditions

From 1961 to 2017, the annual maximum snowpack at Donner Summit averaged 305 cm, with a minimum of 79 cm in 2015 and a maximum of 615 cm in 1969. Over this same period, on average 80.5% of 1 November to 1 August precipitation fell with mean-daily temperatures below 4°C at the NCEI rain gauge, near lake-level. This metric of precipitation-falling-as-snow was as low as 52.7% in 2015 and as high as 97.8% in 1962. Total precipitation (as rain or snow) at the NCEI gauge ranged from 15.4 cm in 1976 to 144.7 cm in 2017, with a mean of 75.3 cm. The highlighted years in Figure 2 (1997 and 2010–2017) offer a range of climate conditions to discuss winter climate effects on inflow mixing conditions in greater detail.

Total November–August discharge is not significantly affected by PAS ($p > 0.6$; $r^2 < 0.001$). Discharge volume is driven mostly by quantity of precipitation ($p < 10^{-15}$; $r^2 = 0.87$) and base flow rather than the form in which precipitation falls. However discharge timing is affected by both snowpack and PAS. The CT shifts later with increased snowpack (7.8 days later per 100 cm of snow depth) and with increased PAS (12 days later per 10% increase in PAS); see supporting information Figure S6.

Based on temperature profile data from 1968 to 2017, annual onset of stratification at Lake Tahoe occurs, on average, on 29 May. In 1997, a very warm year, stratification occurred as early as 11 May. The latest recorded onset of stratification at Lake Tahoe occurred on 24 June 1971. Onset of lake stratification is not significantly affected by stream discharge, the temperature at which precipitation falls, or the amount of snowpack (see supporting information Figure S7); lake stratification responds to climate variability independently of the way that spring streamflow timing and temperature are affected.

3.2. Effect of Winter Climate Conditions on Snowmelt Relative to Lake Stratification

Since the snowpack affects snowmelt timing but does not affect the timing of stratification, winter conditions influence the relative timing of inflows and spring lake warming, as shown in Figure 3. The proportion

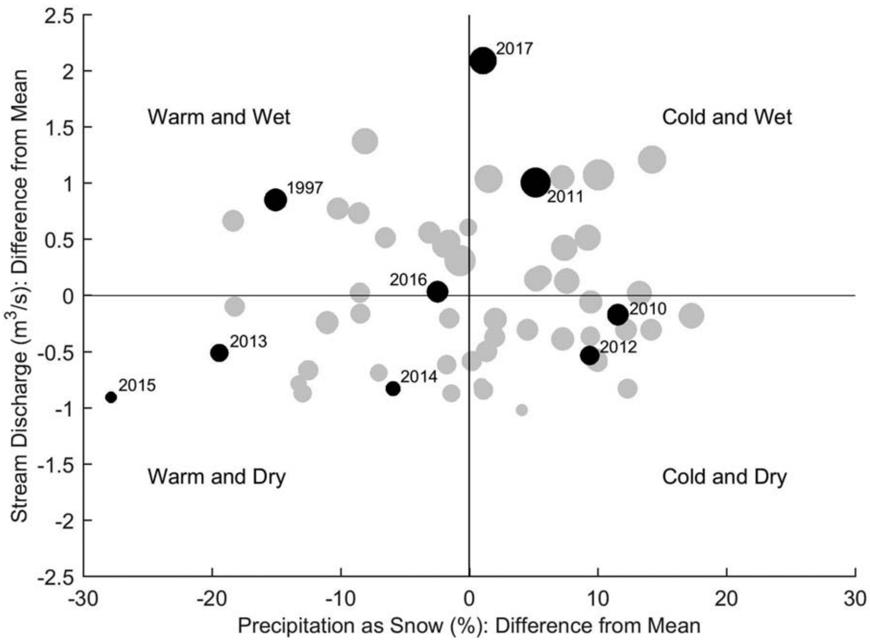

Figure 2. Annual 1 November to 1 August climate conditions relative to the long-term mean values (1961–2017). Difference between long-term mean PAS (80.5%) and annual PAS defines the horizontal warm-to-cold axis. Difference between long-term mean study-period discharge at Blackwood Creek (1.32 m^3/s) and annual mean study-period discharge defines a vertical dry-to-wet axis. Point size is scaled to snowpack, ranging from 79 cm (2015) to 615 cm (1969).

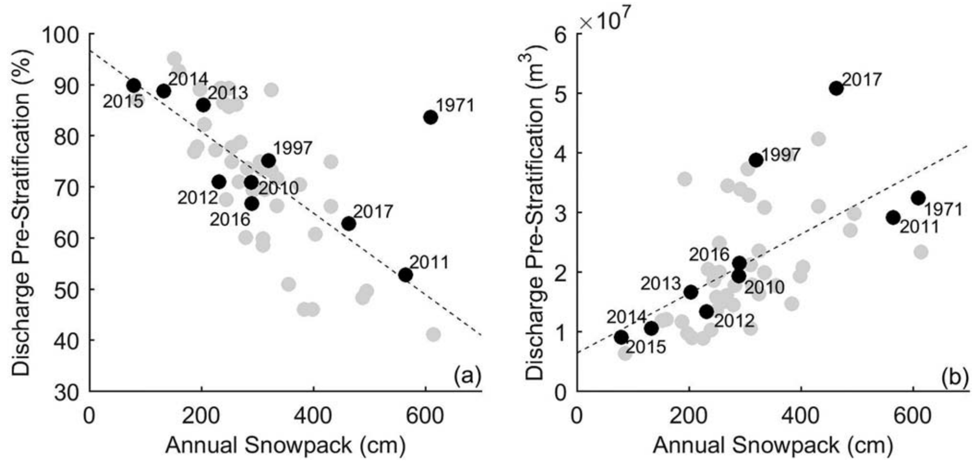

Figure 3. (a) Proportion and (b) volume of annual 1 November to 1 August Blackwood Creek discharge entering the lake prior to the onset of stratification versus annual snowpack (1968–2017). 1971 is shown as an outlier year where the lake stratified 25 days later than the long-term average due to cold late-spring air temperatures. Excluding 1971: (a) $r^2=0.64$ and $p < 10^{-7}$; (b) $r^2=0.32$ and $p < 10^{-4}$. Including 1971: (a) $r^2=0.48$ and $p < 10^{-7}$; (b) $r^2=0.33$ and $p < 10^{-4}$.

of inflows entering the lake prior to the onset of stratification (discharge pre-stratification; DPS) is significantly affected by snowpack. In years of lower snowpack, a greater proportion of annual inflows enter Lake Tahoe prior to the onset of stratification (Figure 3a). However, increased annual snowpack still leads to a greater volume of snowmelt inflow entering the lake prior to stratification (Figure 3b).

3.3. Effect of Winter Climate Conditions on Inflow Buoyancy

Annual patterns in inflow buoyancy are dependent on winter climate conditions (Figure 4). In November and early December, inflows tend to be negatively buoyant. Low streamflows are cool due to cold fall air

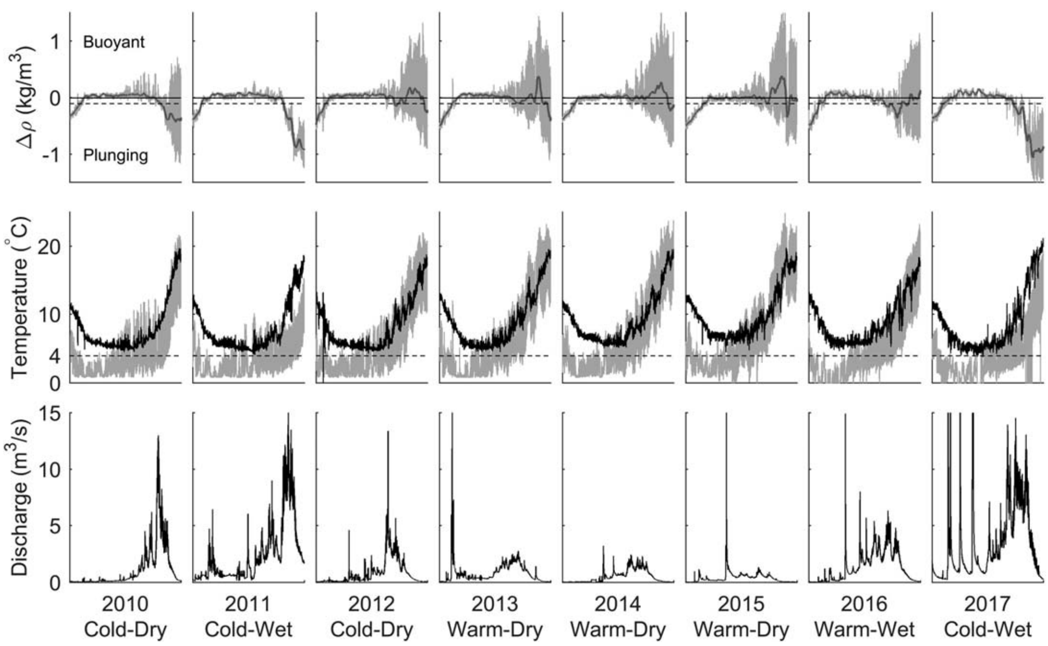

Figure 4. Hourly 1 November to 1 August Blackwood Creek inflow conditions (2010–2017). First row: Relative nearshore-stream density with dashed line at $\Delta\rho=-0.1\ \mathrm{kg/m^3}$; darker line shows 7 day smoothed data. Second row: Blackwood Creek stream temperature (gray) and Homewood nearshore temperature (black); dashed line shows the approximate temperature of maximum water density (4°C). Third row: Blackwood Creek discharge.

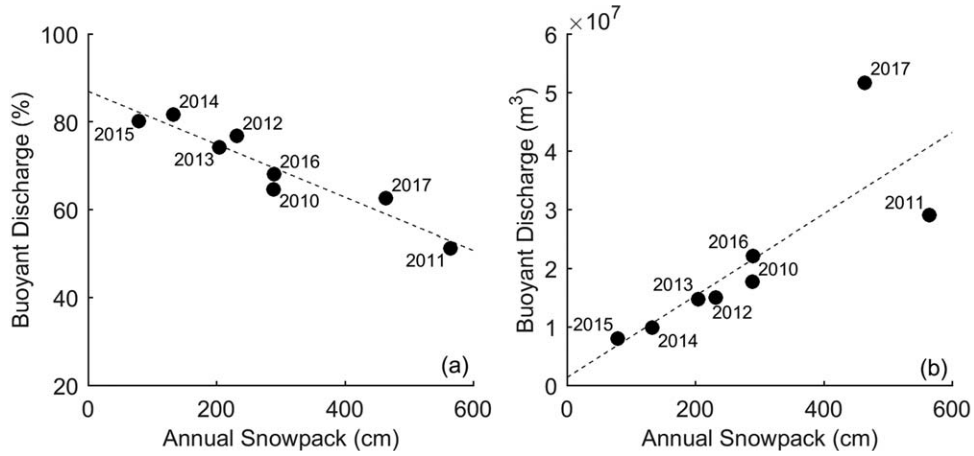

Figure 5. (a) Proportion and (b) volume of annual study-period discharge entering the lake with $\Delta\rho \geq -0.1$ kg/m^3 versus annual maximum snowpack (2010–2017). (a) $r^2 = 0.91$ and $p < 0.001$; (b) $r^2 = 0.65$ and $p < 0.02$.

temperatures and reduced sunlight, while nearshore waters remain warmer due to the thermal inertia of the lake. However, very low discharge levels render this plunging period nearly negligible to the proportional inflow conditions in a given year. From January into April, in all eight years shown, stream and nearshore water density converge to similar values as nearshore and stream temperatures straddle either side of the 4°C temperature of maximum density. As nearshore and stream temperatures begin to increase from late-April into the summer, the temperature, and thus density and buoyancy, of inflows appears to be dependent on snowmelt-driven discharge. On average, 7.5% of annual discharge volume that classified as buoyant could have plunged due to cabbeling. Given that this value represents a high-end estimate (potential for cabbeling does not equate with presence of cabbeling), the snowpack-buoyancy relationship is unlikely to be significantly affected by cabbeling in Lake Tahoe. However, this phenomenon should be considered in analyses of lakes where cabbeling plays a greater role in inflow mixing dynamics.

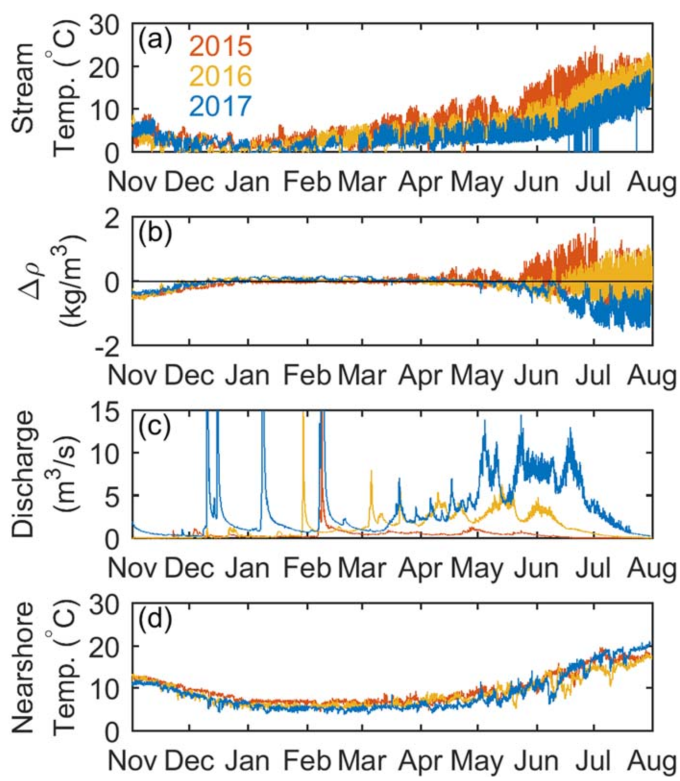

Figure 6. Comparative hourly stream and nearshore conditions for 2015 (red), 2016 (yellow), and 2017 (blue).

Decreased snowpack increases the proportion of snowmelt entering the lake at neutral to positive buoyancy (Figure 5a). However, similar to the pattern shown in Figure 3b, decreased snowpack still causes a net reduction in the volume of snowmelt entering the lake with neutral to positive buoyancy (Figure 5b). The proportion of Blackwood Creek inflows entering the west-shore waters of Lake Tahoe at or above the buoyancy threshold of -0.1 kg/m^3 is correlated with snowpack, and is accordingly related to the timing of inflows relative to the onset of stratification.

Snowmelt-driven variability in stream temperature, rather than year-to-year variability in nearshore temperature, appears to be driving the inflow buoyancy response to snowpack (Figure 6). In 2015, a year of extreme drought and record-low snowpack, late-season (June–July) discharge at Blackwood Creek was very low, stream temperatures were high, and inflow buoyancy was generally positive. The following year, 2016, saw near-average snowpack and discharge levels. Accordingly, Blackwood Creek stream temperatures were cooler in late-season 2016 than 2015, leading to inflow buoyancy values straddling neutral buoyancy (Figure 6b). After a winter of heavy snow, 2017 saw high late-season discharge levels, cooler late-season stream temperatures, and generally negatively buoyant inflows. Unlike stream temperatures, late-season nearshore temperatures do not appear to respond to snowpack conditions (Figure 6d).

4. Discussion

Our data show that inflow mixing dynamics in snowmelt-fed lakes and reservoirs will likely change as a result of a warming climate. This change will alter the fate of inflow constituents which are important drivers of water quality and lake-ecosystem function. The proportion of a given year's snowmelt inflows entering Lake Tahoe prior to the onset of stratification increases significantly as annual snowpack decreases (Figure 3). Similarly, a greater proportion of inflows enter the lake at near-neutral to positive buoyancy as annual snowpack decreases (Figures 5 and 6; Table 1). This parallel response may seem intuitive; if we assume that snowmelt is generally cold, and that surface waters in an unstratified, monomictic lake are generally cold, then it follows that increased DPS would lead to weaker and more positive inflow buoyancy. However, inflow buoyancy and lake stratification have been shown to most directly affect inflow mixing in the near-field and far-field respectively, so it is of interest to discuss their effects independent of one another.

4.1. Effects of Snowmelt Regime on Near-Field Mixing

Initial dilution, the entrainment of ambient lake water into an inflow upon entering the lake, is generally parameterized using the inflow densimetric Froude number (F_o) for negatively buoyant inflows. $F_o = U/\sqrt{g'h}$, where U is inflow velocity, h is the depth of the inflow at the stream mouth, and g' is the reduced gravity term calculated as $g' = g(\rho_o - \rho_a)/\rho_o$ (see, e.g., Cortés et al., 2014; Johnson et al., 1989; Spigel et al., 2005). Initial dilution has been found to increase more or less linearly with F_o (Johnson et al., 1989). Where inflows are positively buoyant, a variation of this relationship is used (Jirka & Watanabe, 1980; Spigel et al., 2005).

For the 8 years examined, decreased snowpack correlates with a higher proportion of inflows entering the lake at near-neutral to positive buoyancy (Figure 5), indicating generally lower g' and thus higher rates of initial dilution nearshore. Prior to the warming of lake surface waters, up to April or May, density differences between streamflow and receiving lake waters are generally very small (Figure 4). Later-season stream temperature appears to be directly affected by snowpack (see Ficklin et al., 2013), with Blackwood Creek temperatures remaining colder when snowpack continued to contribute to streamflow (Figures 4 and 6). However, Homewood littoral temperatures appear to respond only to meteorological forcing (Figure 6d). As a result, late-season inflow buoyancy is strongly affected by snowpack. In 2011 and 2017, high-snowpack years, inflows were negatively buoyant for most of June and July. In 2016, a near-average snowpack year, late-season inflows fluctuated between negative and positive buoyancy. During the 2012–2015 drought period, the majority of late-season inflows were positively buoyant (Figure 4). Higher proportions of

Table 1
Annual Climate and Inflow Mixing Conditions

Climate conditions				Snowmelt inflow properties					
Water Year	Snowpack (cm) diff. from mean	Precip (cm) diff. from mean	PAS (%) diff. from mean	Mean discharge (m^3/s)	CT (day-of-year)	DPS (%)	DPS ($m^3 \times 10^7$)	PAB (%)	VAB ($m^3 \times 10^7$)
1997	15	48.8	−15.0%	2.18	9 Mar	75.2%	3.89		
2010	−16	−11.0	11.5%	1.15	27 May	70.9%	1.94	64.7%	1.78
2011	260	35.6	5.2%	2.33	16 May	52.9%	2.92	51.4%	2.91
2012	−73	−24.6	9.4%	0.80	24 Apr	71.1%	1.35	76.9%	1.51
2013	−101	−17.1	−19.4%	0.82	19 Mar	86.1%	1.67	74.3%	1.48
2014	−172	−32.2	−5.9%	0.50	17 Apr	88.8%	1.06	81.8%	0.99
2015	−226	−31.7	−27.9%	0.43	14 Mar	89.9%	0.91	80.3%	0.81
2016	−15	0.0	−2.5%	1.36	16 Apr	66.8%	2.16	68.1%	2.22
2017	159	69.4	1.1%	3.42	10 Apr	62.8%	5.09	62.7%	5.17

Note. Differences from 1961 to 2017 mean maximum-annual snowpack (305 cm), 1 November to 1 August precipitation (75.3 cm), and 1 November to 1 August PAS (80.5%); mean 1 November to 1 August discharge; annual snowmelt timing (CT); proportion and volume of discharge entering the lake prior to the onset of stratification (DPS); proportion and volume of discharge entering the lake at neutral to positive buoyancy (PAB and VAB).

10.1002/2017WR021977

positively buoyant inflows in low-snowpack years are driven by compounding factors: (1) late-season inflows are warmer due to lower snowmelt contributions; (2) a greater proportion of the melt-season inflow occurs earlier in the spring when density differences tend to be very small. The statistically significant connection between snowpack and inflow buoyancy points toward higher rates of initial dilution and thus proportionally more nearshore mixing in lower snowpack years.

4.2. Effects of Snowmelt Regime on Far-Field Mixing

Ford and Johnson (1983) suggested that the thickness and speed of inflow intrusions are dependent on buoyancy frequency across the inflow plume. Extending from this theory, Scheu (2016), were able to model the extent of sediment deposition from an inflow plume as a function of only volumetric discharge and the first-mode internal wave speed (a measure of bulk lake stratification that is independent of the insertion depth of the intrusion). In essence, ambient lake stratification plays an important role in the formation and propagation of inflow intrusions regardless of the buoyancy of the inflows and their subsequent initial dilution and insertion depth. Weaker stratification should lead to thicker, slower intrusions that are influenced by rotation closer to shore (Scheu, 2016). Figure 3 shows that the proportion of inflows entering Lake Tahoe prior to the onset of stratification tends to increase as snowpack decreases, suggesting slower, more rotationally influenced plumes in low-snowpack years.

4.3. Aggregate Effects of Snowmelt Regime on Inflow Mixing

Inflows that are near-neutrally or positively buoyant will dilute at high rates as they enter lakes, entraining significant volumes of nearshore water and spreading as less-cohesive, slower-moving plumes through surface and/or near-surface waters (Jirka & Watanabe, 1980; Johnson et al., 1987). Inflows entering lakes that are weakly stratified or unstratified will propagate as thicker, slower-moving intrusions that are susceptible to rotational effects closer to shore, potentially creating nearshore recirculation zones and/or leading to alongshore, rather than offshore, plume flows (Scheu, 2016). The aggregate of these effects suggests more nearshore and near-surface mixing of a given year's inflows, as illustrated in Figures 1c/1d. Thus, we expect that in lower snowpack years, a greater proportion of the year's snowmelt inflow constituents will be mixed in the littoral zone, an area of particularly variable and complex ecosystem function in Lake Tahoe (Beauchamp et al., 1994) and in lakes globally (Strayer & Findlay, 2010; Vadeboncoeur et al., 2011).

At the Blackwood Creek inlet into Lake Tahoe, the relative range of stream and nearshore temperatures, and thus densities, is such that snowpack-driven variability in seasonal stream temperature may determine whether late-season inflows plunge or mix into the surface waters (Figure 4). However, the specific range of inflow timing and buoyancy may depend on characteristics of individual subwatersheds and the thermal patterns of adjacent littoral waters.

4.4. Potential Effects of a Warming Climate on Inflow Mixing in Lake Tahoe

An increase in the proportion of annual inflows entering the lake as buoyant and/or prior to the onset of stratification is not the same as an increase in total discharge volume entering the lake under these conditions; the opposite tends to be true (Figures 4b and 6b). Historically, lower snowpack years are more strongly correlated with dry winters than with warm winters. There is an obvious positive relationship between precipitation and snowpack ($r^2=0.47, p < 10^{-8}$). Warmer winters, as measured by lower PAS, tend to decrease snowpack ($r^2=0.15, p < 0.003$) but seem to have a weaker effect on snowpack than dry winters. To gain insight from historical patterns to specifically address the question of the potential effects of a warming climate, it is useful to examine inflow mixing conditions during specific years that may be representative of specific climate conditions.

We use 1997, 2011, 2012, and 2013 as representative years for each of the four quadrants defined by the warm-cold and dry-wet axes in Figure 2. Isolating temperature effects from precipitation effects, and exploring both proportion and volume of annual inflow pre-stratification, offers insight into the potential effect of a warming climate on the fate of inflow loads. Figure 7 compares discharge hydrographs for warm versus cold conditions within both dry and wet contexts. Mean study-period discharge between the 2 dry years, 2012 and 2013 (0.80 and 0.82 m^3/s, respectively), and between the 2 wet years, 1997 and 2011 (2.18 and 2.33 m^3/s, respectively), was similar. Comparing 2013–2012 and 1997–2011 serves to isolate the effect of variable air temperatures on inflow mixing conditions.

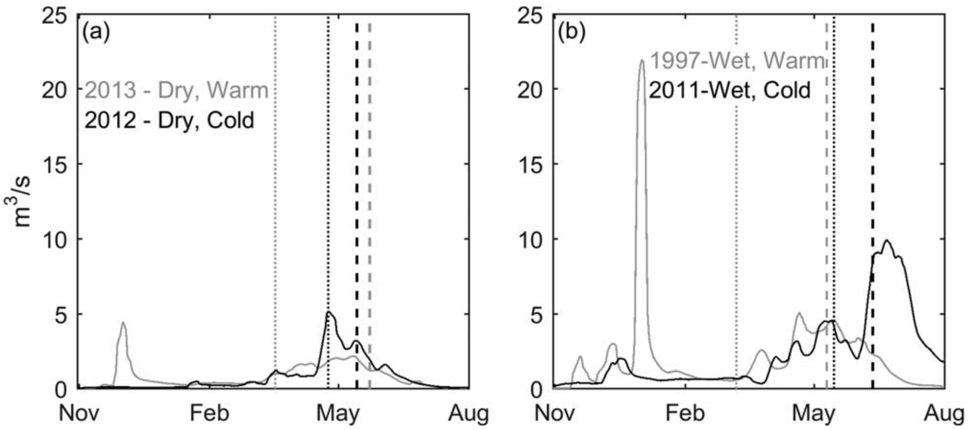

Figure 7. Blackwood Creek discharge hydrographs for (a) representative dry years; and (b) representative wet years. Black lines represent cold years (high PAS) and gray lines represent warm years (low PAS). Hydrographs are smoothed with a 7 day moving average filter for clearer comparison. Dashed lines show the corresponding timings of onset of lake stratification. Dotted lines show the corresponding discharge CT's.

The warm-dry 2013 conditions led to the lowest snowpack of any of the four representative years (101 cm below the long-term average). Dry conditions in 2012 also led to below-average snowpack, but an above-average proportion of precipitation fell as snow, causing the 2012 snowpack (232 cm) to exceed the 2013 snowpack (204 cm) despite more total precipitation falling in 2013 (Table 1). As expected, the warmer 2013 conditions led to both a higher annual proportion and a greater total volume of inflows to enter the lake prior to the onset of stratification compared to 2012 (Table 1). Interestingly, this pattern did not translate to a greater proportion or volume of discharge to enter the lake as buoyant; buoyancy values were similar in 2012 and 2013 (Table 1).

A similar pattern in DPS holds when comparing warm-wet 1997 to cold-wet 2011. In 1997, an above-average proportion of precipitation fell as rain under warm winter temperatures, but large quantities of total precipitation still generated slightly above-average snowpack (320 cm). In 2011, above-average precipitation and cold temperatures combined to generate well-above-average snowpack (565 cm). Once again, the warmer of the two years saw both a higher annual proportion and a greater total volume of inflow to enter the lake prior to the onset of stratification (Table 1). Buoyancy estimates were not possible for 1997 for comparison to 2011.

Warmer winter temperatures (lower PAS) led to drastically earlier CT's, and thus increased DPS, compared to colder years with comparable discharge volumes (Figure 7 and Table 1). Figure 8 further differentiates the effect of PAS from quantity of precipitation on inflow conditions. Given the historically stronger correlation between precipitation and snowpack versus the correlation between PAS and snowpack, it is not surprising that precipitation has a more significant effect than air temperatures on mixing conditions (Figures 8b and 8d versus Figures 8a and 8c). However, there is still a significant correlation between warmer conditions (lower PAS) and increased discharge pre-stratification (Figure 8a). Further, the effect of warming temperatures on snowpack may become more pronounced in the coming decades at Lake Tahoe (Hamlet et al., 2005); four of the last 5 years (2013–2016) have seen below-average PAS in the Tahoe basin (Table 1).

Given established trends toward a warming climate and reduced snowpack in the Sierra Nevada, our results indicate that there will be a shift toward inflows entering Lake Tahoe earlier and under conditions conducive to nearshore and near-surface mixing. This effect will be more pronounced in wet years when PAS affects a greater volume of discharge. Based on historic data, dry years will lead to reduced pre-stratification discharge volume compared to wet years regardless of the effect of air temperatures on snowpack. However, comparing wet years to each other and dry years to each other, the effect of PAS on inflow conditions is clear. In this analysis, we do not directly consider the effect of inflow velocity on mixing. However, it easy to infer that the discharge spikes due to winter rains in 1997 and 2013 (Figure 7) caused high inflow velocities, compounding already-high dilution rates expected during weakly buoyant winter inflows (Figure 4); warmer winters may increase inflow mixing beyond what we show in this analysis.

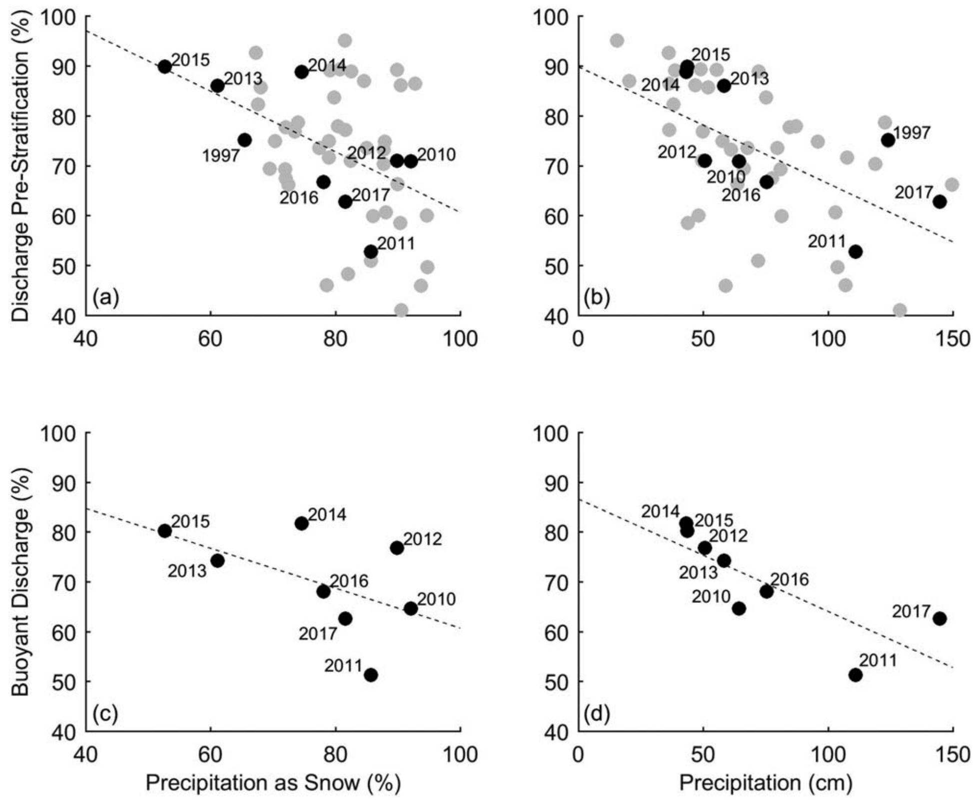

Figure 8. Proportion of discharge pre-stratification, (a) and (b), and proportion of discharge as buoyant, (c) and (d), versus precipitation-as-snow and total precipitation. Dashed lines show linear best fit relationships. (a) $r^2=0.17$ and $p < 0.003$; (b) $r^2=0.31$ and $p < 10^{-4}$; (c) $r^2=0.29$ and $p=0.17$; (d) $r^2=0.63$ and $p < 0.02$.

In the three seasons in which the Homewood nearshore station was deployed (2015–2017), average May–July nearshore fCDOM values correlated positively with snowpack; 5.4, 16.9, and 30.7 RFU, respectively (controlling for wind-wave resuspension effects). This finding is in line with the VAB and volumetric DPS values shown for these years in Table 1 and, importantly, is indicative of the fact that, historically, increased snowpack has led to a proportional decrease but volumetric increase in littoral inflow mixing. A comparison of nearshore water quality data for a wet-warm and wet-cold year might reveal the relationship between decreased snowpack and increased littoral mixing of inflow loads expected in response to a warming climate.

It is important to consider that Lake Tahoe represents an end-member in the spectrum of lake residence times. The decoupling of lake thermodynamics from inflows occurs as residence time increases. Compared to small alpine lakes that can be flushed in less than a day during peak snowmelt, Lake Tahoe offers an opposing-end bracket for investigating the effect of shifting snowpack on inflow mixing dynamics in snowmelt-fed lakes. In evaluating the effect of shifting snowmelt timing on inflow mixing conditions in other lakes, we must consider how much the inflows themselves define the density conditions of the receiving lake. In Lake Tahoe, the thermal mass of the lake is enormous relative to the inflow heat flux; lake temperature and stratification respond to climate forcing almost independently of the watershed. However, Cortés et al. (2017) show that in a smaller lake, snowmelt can have a very significant effect on lake temperature and stratification. In these smaller lakes, a climate-driven shift in snowmelt timing could wholly shift the annual stratification cycle and associated processes, rather than simply the fate of inflow loads. Evaluating how the mixing of snowmelt inflows will be affected by shifting snowmelt timing over a range of lakes of different residence times would further elucidate the potential effect of decreasing annual snowpack on the fate of terrestrial loads in mountain lakes.

Inflow mixing dynamics are governed by a range of conditions beyond inflow buoyancy and lake stratification. Stream mouth geometry and inflow velocity and depth play important roles in the initial dilution of inflows (Alavian et al., 1992; Johnson et al., 1989). Depth of intrusion of negatively buoyant inflows is directly related to initial inflow dilution and lake density stratification (Rueda et al., 2007; Wells & Nadarajah, 2009). Internal waves can mix even very negatively buoyant inflow plumes into surface waters (Fischer & Smith, 1983). Inflows can interact with ambient lake stratification, generating intrusions at multiple depths (Cortés et al., 2014). The effect of these factors on inflow mixing dynamics is highly specific to individual streams and is dependent on temporally variable lake dynamics. In this study, we focus on two factors, inflow buoyancy and the presence of lake stratification, that we believe can be generalized to the full lake basin. The specific mixing conditions of individual streams were not evaluated, but a shift in pre-stratification discharge and/or buoyancy at one stream is likely indicative of a similar shift in other Tahoe subbasins, albeit within a different range of values.

The net effect of the shifting snowmelt mixing regime on the fate of ecologically significant inflow constituents is a subject of ongoing research, with many outstanding questions. How will earlier snowmelt timing affect nutrient loads in streams? How will the littoral ecosystem respond to a shift in timing between nutrient availability and temperature and sunlight conditions? Will more buoyant inflows increase nutrient availability in the photic zone, or will pre-stratification inflow loads ultimately be mixed through the less vertically stable water column and diluted to lower concentrations? Will climate change-induced shifts in inflow mixing contribute to spatial heterogeneity in large lakes, and if so what are the consequences for both littoral and pelagic lake water quality?

5. Conclusions

Our analysis shows that lower snowpack has caused inflows to enter Lake Tahoe earlier relative to the onset of thermal stratification and with more positive buoyancy. With projections of warming air temperatures and a reduction in snowpack, inflow mixing conditions are likely to increasingly favor nearshore and near-surface mixing. While much remains to be explored, this study provides an example of how climate change may result in the amplification of spatial heterogeneity in large lakes, with inputs from inflows increasingly becoming trapped in the littoral zone rather than plunging to depth. Many of the world's lakes are located in alpine and subalpine environments. This phenomenon is therefore likely to be applicable to a large number of lakes globally, particularly those with long-residence times.

Acknowledgments
This material is based upon work supported by a National Science Foundation Graduate Research Fellowship (NSF grant 1650042). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. Support for the nearshore water quality station at Homewood is provided by Paula Mathis. Extensive field support was provided by Brant Allen, Katie Senft, and Raph Townsend of UC Davis TERC. The long-term record of Lake Tahoe onset of stratification and records of air temperature and shortwave radiation were curated by Shohei Watanabe, UC Davis TERC, and have been funded by the Tahoe Regional Planning Agency and the California State Water Resources Control Board. Midlake water temperature data were provided by Gerardo Rivera of the NASA Jet Propulsion Laboratory. Long-term snowpack data were kindly provided by Randall Osterhuber of the UC Berkeley Central Sierra Snow Laboratory. Long-term daily discharge data from Blackwood Creek are available through the USGS National Water Information System (www.waterdata.usgs.gov), site 10336660. Tahoe basin elevation and land use data are available on the Tahoe Regional Planning Agency GIS database (http://www.trpa.org/gis/). All other data associated with this manuscript, including (a) curated hourly Blackwood Creek temperature, discharge, conductivity, and density (2009–2017); (b) curated hourly Homewood nearshore water temperature and density (2009–2017); (c) curated hourly air temperature and incoming shortwave radiation (2009–2017); (d) curated daily air temperatures and precipitation (1960–2017); (e) annual snow depth (1960–2017); (f) curated hourly midlake temperature data from NASA JPL buoys (2009–2017); and (g) annual onset of stratification at Lake Tahoe (1968–2017), are available through a UC Davis Library DASH repository at https://doi.org/10.25338/B8QG63.

References

Alavian, B. V., Jirka, G. H., Denton, R. A., Johnson, M. C., & Stefan, H. G. (1992). Density currents entering lakes and reservoirs. *Journal of Hydraulic Engineering*, *118*(11), 1464–1489. https://doi.org/10.1061/(ASCE)0733-9429(1992)118:11(1464)

Barnett, T. P., Adam, J. C., & Letternmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, *438*, 303–309. https://doi.org/10.1038/nature04141

Beauchamp, D. A., Byron, E. R., & Wurtsbaugh, W. A. (1994). Summer habitat use by littoral-zone fishes in Lake Tahoe and the effects of shoreline structures. *North American Journal of Fisheries Management*, *14*(2), 385–394. https://doi.org/10.1577/1548-8675(1994)014<0385:SHUBLZ>2.3.CO;2

Carmack, E. C., Gray, C. B., Pharo, C. H., & Daley, R. J. (1979). Importance of lake-river interaction on seasonal patterns in the general circulation of Kamloops Lake, British Columbia. *Limnology and Oceanography*, *24*(4), 634–644. https://doi.org/10.4319/lo.1979.24.4.0634

Coats, R. (2010). Climate change in the Tahoe basin: Regional trends, impacts and drivers. *Climatic Change*, *102*(3), 435–466. httpd://doi.org/10.1007/s10584-010-9828-3

Cortés, A., Fleenor, W. E., Wells, M. G., de Vicente, I., & Rueda, F. J. (2014). Pathways of river water to the surface layers of stratified reservoirs. *Limnology and Oceanography Methods*, *59*(1), 233–250. https://doi.org/10.4319/lo.2014.59.1.0233

Cortés, A., Macintyre, S., & Sadro, S. (2017). Flowpath and retention of snowmelt in an ice-covered arctic lake. *Limnology and Oceanography Methods*, *62*(5), 2023–2044. https://doi.org/10.1002/lno.10549

Feistel, R. (2008). A Gibbs function for seawater thermodynamics for -6 to 80 C and salinity up to 120 g/kg. *Deep Sea Research, Part I*, *55*, 1639–1671.

Ficklin, D. L., Stewart, I. T., & Maurer, E. P. (2013). Effects of climate change on stream temperature, dissolved oxygen, and sediment concentration in the Sierra Nevada in California. *Water Resources Research*, *49*, 2765–2782. https://doi.org/10.1002/wrcr.20248

Fischer, H. B., & Smith, R. D. (1983). Observations of transport to surface waters from a plunging inflow to Lake Mead. *Limnology and Oceanography Methods*, *28*(2), 258–272. https://doi.org/10.4319/lo.1983.28.2.0258

Ford, D. E., & Johnson, M. C. (1983). An assessment of reservoir density currents and inflow processes (technical report E-83-7). Vicksburg, MS: United States Army Engineer Waterways Experiment Station.

Fyfe, J. C., Derksen, C., Mudryk, L., Flato, G. M., Santer, B. D., Swart, N. C. et al. (2017). Large near-term projected snowpack loss over the western United States. *Nature Communications*, *8*, 1–7. http://doi.org/10.1038/ncomms14996

Hamlet, A. F., Mote, P. W., Clark, M. P., & Lettenmaier, D. P. (2005). Effects of temperature and precipitation variability on snowpack trends in the Western United States. *Journal of Climate*, *18*(21), 4545–4561. https://doi.org/10.1175/JCLI3538.1

Horner-Devine, A. R. (2009). The bulge circulation in the Columbia River plume. *Continental Shelf Research*, *29*(1), 234–251. https://doi.org/10.1016/j.csr.2007.12.012

Horner-Devine, A. R., Fong, D. A., Monismith, S. G., & Maxworthy, T. (2006). Laboratory experiments simulating a coastal river inflow. *Journal of Fluid Mechanics*, *555*, 203–232. https://doi.org/10.1017/S0022112006008937

Imberger, J., & Hamblin, P. F. (1982). Dynamics of lakes, reservoirs, and cooling ponds. *Annual Review of Fluid Mechanics*, (*14*) 153–187. https://doi.org/10.1146/annurev.fl.14.010182.001101

IOC, SCOR, & IAPSO (2010). The international thermodynamics equation of seawater—2010: Calculation and use of thermodynamic properties (English). (Int. Oceanogr. Comm., Manuals and Guides No. 56, 196 p.), London, UK: UNESCO.

Jirka, G. H., & Watanabe, M. (1980). Thermal structure of cooling ponds. *Journal of Hydraulics*, *106*, 701–715.

Johnson, B. T. R., Ellis, C. R., & Stefan, H. G. (1989). Negatively buoyant flow in diverging channel. IV: Entrainment and dilution, *Journal of Hydraulic Engineering*, *115*(4), 437–456. https://doi.org/10.1061/(ASCE)0733-9429(1989)115:4(437)

Kang, D. H., Gao, H., Shi, X., Islam, S., & Déry, S. J. (2016). Impacts of a rapidly declining mountain snowpack on streamflow timing in Canada's Fraser River Basin. *Scientific Reports*, *6*, 19299. https://doi.org/10.1038/srep19299

Kudela, R. M., Horner-Devine, A. R., Banas, N. S., Hickey, B. M., Peterson, T. D., McCabe, R. M., et al. (2010). Multiple trophic levels fueled by recirculation in the Columbia River plume. *Geophysical Research Letters*, *37*, L18607. https://doi.org/10.1029/2010GL044342

Kudela, R. M., & Peterson, T. D. (2009). Influence of a buoyant river plume on phytoplankton nutrient dynamics: What controls standing stocks and productivity?. *Journal of Geophysical Research*, *114*, C00B11. https://doi.org/10.1029/2008JC004913

Njissen, B., O'donnell, G. M., Hamlet, A. F., & Letternmaier, D. P. (2001). Hydrologic sensitivity of global rivers to climate change. *Climatic Change*, *50*(1–2), 143–175. https://doi.org/10.1023%2FA%3A1010616428763

Pederson, G. T., Gray, S. T., Woodhouse, C. A., Betancourt, J. L., Fagre, D. B., Littell, J. S., et al. (2011). The unusual nature of recent snowpack declines in the North American Cordillera. *Science*, *333*(6040), 332–335. http://doi.org/10.1126/science.1201570

Rueda, F. J., Fleenor, W. E., & de Vicente, I. (2007). Pathways of river nutrients towards the euphotic zone in a deep-reservoir of small size: Uncertainty analysis. *Ecological Modelling*, *202*(3–4), 345–361. https://doi.org/10.1016/j.ecolmodel.2006.11.006

Scheu, K. R. (2016). *Sediment transport due to river plumes in stratified, rotationally-influenced lakes* (Doctoral dissertation). Stanford, CA: Stanford University. Retrieved from https://purl.stanford.edu/xc956mz8418

Sahoo, G. B., Forrest, A. L., Schladow, S. G., Reuter, J. E., Coats, R., & Dettinger, M. (2016). Climate change impacts on lake thermal dynamics and ecosystem vulnerabilities. *Limnology and Oceanography Methods*, *61*(2), 496–507. https://doi.org/10.1002/lno.10228

Sahoo, G. B., Schladow, S. G., Reuter, J. E., Coats, R., Dettinger, M., Riverson, J., et al. (2013). The response of Lake Tahoe to climate change. *Climatic Change*, *116*(1), 71–95. http://doi.org/10.1007/s10584-012-0600-8

Sahoo, G. B., & Schladow, S. G. (2008). Impacts of climate change on lakes and reservoirs dynamics and restoration policies. *Sustainability Science*, *3*, 189–199. https://doi.org/10.1007/s11625-008-0056-y

Sahoo, G. B., Schladow, S. G., & Reuter, J. E. (2009). Forecasting stream water temperature using regression analysis, artificial neural network, and chaotic non-linear dynamic models. *Journal of Hydrology*, *378*(3–4), 325–342. https://doi.org/10.1016/j.jhydrol.2009.09.037

Spigel, R. H., Howard-Williams, C., Gibbs, M., Stephens, S., & Waugh, B. (2005). Field calibration of a formula for entrance mixing of river inflows to lakes: Lake Taupo, North Island, New Zealand. *New Zealand Journal of Marine and Freshwater Research*, *39*(4), 785–802. https://doi.org/10.1080/00288330.2005.9517353

Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2004). Changes in snowmelt runoff timing. *Climatic Change*, *62*(1–3), 217–232. https://doi.org/10.1023/B:CLIM.0000013702.22656.e8

Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2005). Changes toward earlier streamflow timing across western North America. *Journal of Climate*, *18*(8), 1136–1155. https://doi.org/10.1175/JCLI3321.1

Stewart, I. T. (2013). Connecting physical watershed characteristics to climate sensitivity for California mountain streams. *Climatic Change*, *116*(1), 133–148. https://doi.org/10.1007/s10584-012-0567-5

Strayer, D. L., & Findlay, S. E. G. (2010). Ecology of freshwater shore zones. *Aquatic Sciences*, *72*(2), 127–163. https://doi.org/10.1007/s00027-010-0128-9

Vadeboncoeur, Y., McIntyre, P. B., & Vander Zanden, M. J. (2011). Borders of Biodiversity: Life at the Edge of the World's Large Lakes. *BioScience*, *61*(7), 526–537. https://doi.org/10.1525/bio.2011.61.7.7

Wells, M. G., & Nadarajah, P. (2009). The intrusion depth of density currents flowing into stratified water bodies. *Journal of Physical Oceanography*, *39*(8), 1935–1947. https://doi.org/10.1175/2009JPO4022.1